Fibre Bragg Grating Components for Filtering, Switching and Lasing

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Abstract

Fibre Bragg gratings (FBGs) are key components for a vast number of applications in optical communication systems, microwave photonics systems, and optical sensors, etc. The main topic of this thesis is fibre Bragg grating fabrication and applications in direct microwave optical filtering, high speed switching and switchable dual-wavelength fibre lasers.

First, a brief overview is given about the photosensitivity in optical fibre, basic FBG fabrication techniques, the popular coupled-mode theory for describing fundamental characteristics of FBGs and the Transfer Matrix method for the numerical simulations of complex-structured FBGs.

An advanced FBG fabrication system based on the technique of multiple printing in fibre (with a continuous-wave source) has been used to write complex FBGs incorporating phase shifts, apodization and chirp.

A single double-peaked superimposed grating working in reflection can be employed as a direct optical filter for millimetre-wave signals. Bit error rate measurements confirmed that the filter exhibited nearly on-off behaviour in the passband with a 3-dB bandwidth of 2 GHz for a central frequency of 20 GHz, as expected from the optical reflection spectrum. The presented technique can be used in radio-over-fibre systems or simultaneous up-conversion of ultra-wide band signals and filtering.

This thesis focused mostly on the research of two 4-cm long Hamming-apodized gratings written in side-hole fibres with internal electrodes. The temperature dependence measurements showed that the birefringence of the component increased with the temperature. Dynamic measurement has shown nanosecond full off-on and on-off switching. During the electrical pulse action, the grating wavelength was blue-shifted for the x-polarization and red-shifted for the y-polarization due to the mechanical stress. Both peaks subsequently experienced a red-shift due to the relaxation of mechanical stress and
the increasing core temperature transferred from the metal in many microseconds. All the wavelength shifts of the two polarizations depend quadratically on the electrical pulse voltage and linearly on the pulse duration. Numerical simulations gave accurate description of the experimental results and were useful to understand the physics behind the birefringence switching.

Finally, two switchable dual-wavelength erbium-doped fibre lasers based on FBG feedback were proposed. In one method, an overlapping cavity for the two lasing wavelengths and hybrid gain medium in the fibre laser were introduced. Dual-wavelength switching was achieved by controlling the Raman pump power. The other method employed an injection technique and the dual-wavelength switching was controlled by the power of the injection laser. The switching time was measured to be ~50 $\mu$s. Detailed characteristics of the dual-wavelength switching in the two fibre lasers were experimentally studied and corresponding principles were physically explained.

**Keywords:** fibre Bragg grating, photosensitivity, apodization, chirp, phase-shift, microwave optical filtering, incoherent filtering, direct optical filtering, direct detection, side-hole fibre, switching, high speed, internal electrode, birefringence, dual-wavelength, fibre laser.
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List of Acronyms

FBG  Fibre Bragg grating
MWP  Microwave photonics
MMW  Millimetre-wave
RF   Radio frequency
RoF  Radio-over-fibre
HiBi High birefringence
WDM  Wavelength-division multiplexing
EDF  Erbium-doped fibre
SLR  Sagnac loop reflector
MPF  Multiple printing in fibre
CW   Continuous-wave
TMM  Transfer matrix method
UV   Ultraviolet
GODC Germanium-oxygen deficiency centre
FWHM Full width at half maximum
SMF  Single mode fibre
EDFA Erbium doped fibre amplifier
FSR  Free spectral range
HF   High frequency
IF   Intermediate frequency
LO   Local oscillator
BER  Bit error rate
<table>
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<tr>
<th>Abbreviation</th>
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<tr>
<td>PC</td>
<td>Polarization controller</td>
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<tr>
<td>LPF</td>
<td>Low-loss filter</td>
</tr>
<tr>
<td>UWB</td>
<td>Ultra-wide band</td>
</tr>
<tr>
<td>TLS</td>
<td>Tuneable light source</td>
</tr>
<tr>
<td>OSA</td>
<td>Optical spectrum analyzer</td>
</tr>
<tr>
<td>LD</td>
<td>Laser diode</td>
</tr>
<tr>
<td>DCF</td>
<td>Dispersion compensation fibre</td>
</tr>
<tr>
<td>OC</td>
<td>Optical circulator</td>
</tr>
<tr>
<td>TLD</td>
<td>Tuneable laser diode</td>
</tr>
<tr>
<td>ISO</td>
<td>Isolator</td>
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Chapter 1

Introduction

1.1 Background

The field of fibre Bragg gratings (FBGs) is almost thirty years old, dating back to its discovery by Hill and co-workers in Canada [1]. It grew slowly in the beginning, but an important technological breakthrough by Meltz and co-workers 10 years later [2] renewed worldwide interest in FBGs. People have paid a lot of attention to study the foundation of fibre photosensitivity, to improve the FBG fabrication technology, to develop the FBG theory and simulation methods. Evidently, FBGs have been recognized as key components in a variety of applications [3-5]. Their unique filtering properties and versatility as in-fibre device is illustrated by their use in optical communication systems, microwave photonic systems and fibre sensors, etc. This thesis is focused on the applications of FBGs for microwave optical filtering, high speed switching and switchable dual-wavelength fibre lasers.

The area of microwave photonics (MWP) has evolved in parallel to the development of optical communication, as optical components have become operational up to millimetre frequencies. Referring to Ref. [6, 7], MWP can be defined as the study of photonic devices operating at microwave frequencies and their applications in microwave and optical systems. The interdisciplinary field of MWP covers applications within a frequency span from MHz to THz. The term microwave will be freely used throughout this thesis to designate microwave, millimetre-wave (MMW) or radio frequency (RF). One of the most common MWP processing is optical filtering. FBGs are the most widely used microwave photonic filters, with advantages of low loss, large bandwidth and electromagnetic
interference immunity, etc. Hence FBGs have a vast number of MWP applications, including communications (such as radio-over-fibre (RoF) systems, wireless bidirectional communication and broadcasting), high performance microwave and MMW signal generation and for antennas beam-forming arrays.

In 1986, Xie et al. first reported that the side-hole fibres could be used in a simple and sensitive fibre-optic pressure sensor [8]. Compared with high birefringence (HiBi) fibres, side-hole fibres have the advantage of higher sensitivity to pressure and lower sensitivity to temperature [8-14]. FBGs imprinted in side-hole fibres have been shown to be good candidates for simultaneous sensing of hydrostatic pressure and temperature [15-17]. Side-hole fibres with internal electrode can be exploited in applications where light propagation is controlled electrically. Besides electro-optical switching and modulation, nanosecond polarization switching has recently been demonstrated [18]. Hence high speed switching of a FBG written in a side-hole fibre with internal electrodes was made possible, as it is shown in Chapter 4 of this thesis.

Wavelength-switchable fibre lasers have important applications in wavelength-division multiplexing (WDM) fibre communication systems, fibre sensors, spectroscopy and optical instrument testing, etc. Several techniques have been reported to achieve wavelength switching in Erbium-doped fibre (EDF) lasers. These include the use of sampled FBGs [19], cascaded FBGs [20-22], multimode FBGs [23, 24], a Bragg grating-based acoustooptic superlattice modulator [25], a spectral polarization-dependent loss element [26], a Sagnac loop reflector (SLR) [27], distributed-feedback mode oscillation [28], a multi-section HiBi fibre loop mirror [29] and a hybrid gain medium (semiconductor optical amplifier) [30, 31]. Wavelength-switchable lasers based on some EDFs co-doped with other rare-earth ions [32] and based on yetterbium-doped fibre [33] have also been reported. Meanwhile, Raman fibre lasers have also been developed for high power, multiwavelength (however, non-switchable) applications [34-36]. Most of these techniques are based on some special devices or manual adjustments to achieve wavelength switching.

1.2 Motivation and outline

The motivation for this thesis was mainly to investigate applications of FBGs for optical filtering of microwave signals, for high speed switching and for switchable dual-wavelength fibre lasers. The main focus has been on experimental work, but theoretical work and simulations have also been carried out, to better understand and
It is the author’s intention that this thesis be readable for an audience that has a general knowledge in the field of physics, optics and mathematics. The introductory part of the thesis is to give a short background of FBGs and their importance in various applications.

Chapter 2 briefly reviews the history of the photosensitivity in optical fibres, the major accepted mechanisms of photosensitivity and techniques to enhance the fibre’s photosensitivity. The basic external techniques for recording Bragg gratings in optical fibres are described. An advanced fabrication system based on the technique of multiple printing in fibre (MPF) using a continuous-wave (CW) source has been used in the work and presented here. Chapter 2 also introduces the use of the coupled-mode theory to describe the fundamental properties of FBGs, and the Transfer matrix method (TMM) for the numerical simulation of complex-structured FBGs.

Chapter 3 briefly reviews the incoherent and coherent optical filtering of microwave signals. A direct microwave optical filtering technique combined with direct detection has been proposed, employing a superimposed FBG working in reflection as a filter. The principle and experiment results based on this technique and its applications in RoF have been discussed.

Chapter 4 gives an overview of the static and dynamic experimental results of two FBGs written in side-hole fibres with internal electrodes under the excitation of nanosecond electrical pulses. The behaviour of the wavelength shifts for the fast and slow polarization states has been explained in details. Numerical simulations give accurate description of the experimental results and help to understand the physics behind the birefringence switching.

Chapter 5 proposes two methods to achieve dual-wavelength switching in erbium-doped fibre laser using FBGs. The detailed characteristics of the dual-wavelength switching in the two fibre lasers have been experimentally studied and the principles have been explained physically.

Conclusions of the thesis are presented in Chapter 6 followed in Chapter 7 by short summaries of the nine included papers.
Chapter 2

Fibre Bragg Gratings Background

An FBG consists of a periodic modulation of the refractive index along a fibre waveguide. It is fabricated by exposure of the fibre to an intense optical interference pattern. Light propagating in the fibre waveguide will be reflected by each grating plane. If the Bragg condition is satisfied, the contributions of the light reflected from each grating plane add constructively in the backward direction within a wavelength band whose centre wavelength is defined by the grating parameters. Otherwise, the reflected light becomes progressively out of phase and will eventually cancel out.

The Bragg condition is simply the requirement which satisfies both energy and momentum conservation. The first-order Bragg condition is defined as \([4, 5]\)

\[
\lambda_B = 2n_{\text{eff}} \Lambda \tag{2.1}
\]

where the Bragg wavelength \((\lambda_B)\) is the free-space centre wavelength of the input light that will be reflected back from the FBG, \(n_{\text{eff}}\) is the effective refractive index of the fibre core at the free-space centre wavelength and \(\Lambda\) is the period of the gratings. Fig. 2.1 illustrates a uniform FBG, where the phase fronts are perpendicular to the fibre axis and the grating planes have a constant period \(\Lambda\). As shown in the insets of Fig. 2.1, a well defined peak with wavelength \(\lambda_B\) exists in the reflection spectrum, resulting in a notch in the transmission spectrum.
2.1 Photosensitivity in optical fibres

2.1.1 History of photosensitivity in optical fibres

The photosensitivity in optical fibres refers to a permanent change in the refractive index of the fibre waveguide induced by exposure to light radiation with characteristic wavelength and intensity that depends on the fibre material [3, 4]. The photosensitivity of optical fibres was first observed at the Canadian Communication Research Centre in 1978 by Hill and co-workers during experiments using germanosilica fibre and visible argon ion laser radiation (488 nm) [1, 37]. They explained the permanent FBG written in the fibre core as a result of the standing wave intensity pattern due to the Fresnel reflection from the cleaved end of the fibre (4% reflection). This particular grating had a very weak index modulation, which was estimated to be of the order of $10^{-6}$ resulting in a narrow-band reflection filter at the writing wavelength. This discovery led to the internal inscription technique.

In 1981, Lam and Garside [38] demonstrated that the magnitude of refractive index change reported by Hill [1] depended on the square of the writing power at 488 nm. This suggested a two-photon process as the possible mechanism of refractive index change. In 1987, Stone et al. [39] showed that a refractive index change could be induced in all
2.1. Photosensitivity in optical fibres

germanium doped fibre, but he was still using blue-green irradiating light launched in the fibre waveguides.

The major breakthrough came with the report on holographic writing of gratings using single-photon absorption at 244 nm by Gerry Meltz et al. in 1989 [2]. They demonstrated that a reflection grating in the visible range of 571-600 nm was formed when a germanium-doped fibre was exposed to two interfering ultraviolet (UV) beams. The scheme provided the freedom of shifting the Bragg wavelength to longer and more useful wavelengths, determined by the angle between the interfering beams. The first reflection gratings at around 1500 nm written into germanosilicate fibres was reported [40]. The UV-induced refractive index change in untreated germanosilicate fibres was typical of ~10^{-5}-10^{-4}.

Since then, several developments have taken place that have pushed the index change in optical fibres up a hundredfold. Fibres doped with europium [41], cerium [42], and erbium:germanium [43] showed varying degrees of sensitivity in a silica host optical fibre, but none of these were as sensitive as the germanosilicate fibres. One fibre doping producing large index modulations (of the order of 10^{-3}) is germanium-boron codoping [44].

2.1.2 Mechanism of photoinduced refractive index change

The photosensitivity in optical fibres was discovered almost 30 years ago, but the mechanism behind it is still not fully understood. Several models [3-5] have been proposed for these photoinduced refractive index changes, such as colour centre model, dipole model, compaction model and stress-relief model. The only common element in these theories is that the germanium-oxygen deficiency centre (GODC) defect, Ge-Si or Ge-Ge (the so-called “wrong bonds”) is the trigger mechanism for the photoinduced index changes.

Glasses usually contain many defects that have strong photon absorption, also called colour centres. The peak wavelength of absorption of the well-known GODC defect is at ~240 nm [45], with a full width at half maximum (FWHM) of ~35 nm. This absorption band was shown to be bleached when exposed to UV radiation [46, 47]. Hand and Russell [48] proposed a model to explain the refractive index change by relating it to the absorption changes via the Kramer-Kronig relationship. The GODC defect, which initially absorbs the UV light, is transformed to GeE’ with the release of an electron (free to move within the glass until it is trapped). According to this model, the refractive index at a point is related
only to the density and orientation of defects in that region and is determined by their electronic absorption spectra. It allows for the refractive index change from $10^{-5}$ to $10^{-4}$ but can not account for changes much greater than $10^{-4}$. The colour centre model for photosensitivity was supported by many experiments [46, 47, 49-51]. However, it can not completely explain all the experiment observations [52, 53]. To date, the colour centre model is the most widely accepted model for the formation mechanism of FBGs.

2.1.3 Enhanced photosensitivity in silica optical fibres

Since the discovery of photosensitivity and the first demonstration of grating formation in germanosilicate fibres, there has been considerable effort to understand and increase the photosensitivity in optical fibres. Standard single mode fibres (SMFs), doped with 3% germanium, typically display index changes of $\sim 10^{-6}$-$10^{-5}$ [3] (except one report of $\sim 1 \times 10^{-3}$ [54]). Increasing the dopant level or subjecting the fibre to reducing conditions at high temperatures result in larger index changes of $\sim 5 \times 10^{-4}$ [4]. Over the years, hydrogen loading, flame brushing and boron codoping have been developed to enhance the photosensitivity of silica optical fibres. Refractive index changes of $\sim 10^{-3}$-$10^{-2}$ then become possible.

(1) Hydrogen loading

Hydrogen loading of optical fibres is the most commonly used technique for achieving high UV photosensitivity in germanosilica optical fibres and was first developed by Lemaire et al. [55, 56]. Fibres are soaked in hydrogen gas at temperatures ranging from 20-75 °C and pressures from $\sim 20$ atm to more than 750 atm (typically 150 atm), which results in diffusion of hydrogen molecules into the fibre core. Under UV laser radiation, the hydrogen molecules react with the Ge-O-Si bonds in the glass, forming OH species which increases the level of oxygen-deficiency in the glass matrix and hence increases the absorption at $\sim 240$ nm. The obtainable index change in the fibre is increased to the magnitude of $10^{-3}$-$10^{-2}$. It typically takes a week of hydrogen soaking at room temperature in order to obtain the desired photosensitivity in the fibre. The required time can be reduced to a few days by increasing the temperature or the pressure during the loading process. It should be pointed out that high-pressure hydrogen is dangerous and requires special precautions.
One advantage of hydrogen loading is the fabrication of FBGs in any germanosilicate fibres, and even in germanium-free fibre when shorter wavelength UV light is used (typically 193 nm). Additionally, permanent changes occur only in regions that are UV irradiated. In unexposed fibre sections the molecular hydrogen does not react with the glass matrix and diffuses out, leaving an increased absorption loss at 1.38-1.45 μm, but relatively small excess loss at the important optical communication windows (1.3 μm and 1.5 μm).

(2) Flame brushing

Flame brushing is a simple and effective way of enhancing the photosensitivity in germanosilicate fibres [57]. The region of the optical waveguide to be photosensitized is brushed repeatedly by a flame fuelled with hydrogen a small amount of oxygen, reaching a temperature of ~1700 °C. The photosensitization process takes approximately 20 mins to complete. At these temperatures, the hydrogen diffused into the fibre core very quickly and reacts with the germanosilicate glass to produce GODC defects, creating a strong absorption band at 240 nm and rendering the core highly photosensitivity. This method has been used to increase the photosensitivity of standard telecommunication fibres by a factor greater than 10, achieving changes in the refractive index >10^{-3} [57]. The increased photosensitivity in the fibre by flame brushing technique is permanent, as opposed to hydrogen loading where the fibre loses its photosensitivity as the hydrogen diffuses out of the fibre. However, one major drawback of this technique is that the high temperature flame weakens the fibre which increases the likelihood of the fibre breaking.

(3) Boron codoping

Germanosilicate fibre codoped with boron has larger photosensitivity than the fibre with higher germanium concentration and without boron [44]. In addition, saturated index changes are higher and achieved faster in Boron codoping germanosilicate fibre. Boron codoping increases the photosensitivity of the fibre by allowing photoinduced stress relaxation to occur, which initiated by the breaking of the wrong bonds by UV light.

2.2 Basic techniques for fibre Bragg grating fabrication

Most FBGs are fabricated through side-exposure of the fibre to two interfering beams from the same UV laser, also called external writing technique. Different techniques are briefly described below.
2.2.1 Interferometric fabrication technique

The interferometric fabrication technique, demonstrated by Meltz et al [2], was the first external writing technique to form Bragg gratings in photosensitive fibres. It utilized an interferometer that split the incoming UV light into two beams and then recombined them to form an interference pattern. The fringe pattern was used to expose a photosensitive fibre, inducing a refractive index modulation in the core. Bragg gratings in optical fibres have been fabricated using both amplitude-splitting and wavefront-splitting interferometers.

(1) Amplitude-splitting interferometer

In an amplitude-splitting interferometer (see Fig. 2.2), the UV writing laser light is divided by a beam splitter into two equal intensity beams and are later recombined after propagation over different optical paths. This forms an interference pattern at the core of a photosensitive fibre. Cylindrical lenses are normally placed in the interferometer to focus the interfering beams perpendicular to the fibre axis to a fine line matching the fibre core. This results in high intensities at the core, thereby improving the grating inscription. The Bragg grating period $\Lambda$, which is identical to the period of the interference fringe pattern, is given by:

$$\Lambda = \frac{\lambda_{UV}}{2 \sin \varphi} \quad (2.2)$$

where $\lambda_{UV}$ is the irradiation UV wavelength and $\varphi$ is the half-angle between the intersecting UV beams. Given the Bragg condition $\lambda_B = 2n_{\text{eff}} \Lambda$, the Bragg resonance wavelength $\lambda_B$ can be expressed as a function of $\lambda_{UV}$ and $\varphi$ as

$$\lambda_B = \frac{n_{\text{eff}} \lambda_{UV}}{\sin \varphi} \quad (2.3)$$

From Eq. 2.3 one can easily see that the Bragg grating wavelength $\lambda_B$ can be varied either by changing $\lambda_{UV}$ and/or $\varphi$. The choice of $\lambda_{UV}$ is limited to the UV photosensitivity region of the fibre; however there is no restriction for the choice of the angle $\varphi$ (limited of course to $\varphi < 90^\circ$).
2.2. Basic techniques for fibre Bragg grating fabrication

The most important advantage of this technique is the ability to inscribe Bragg gratings at various wavelengths, accomplished by simply changing the intersecting angle between the UV beams. This method also offers a large flexibility for what concerns the length of the gratings, which allows for adjusting the bandwidth of their spectral response.

The main disadvantage of this method is its sensitivity to mechanical vibrations. Displacements as small as submicrons in the optical components can cause the fringe pattern to drift and wash out the grating. Furthermore, due to long separate optical path lengths involved in the interferometers, fluctuations of the air refractive index may also deteriorate the formation of a stable fringe pattern. In addition, quality gratings can only be produced with a laser source that has good spatial and temporal coherence with excellent wavelength, output power and beam-pointing stability.

(2) Wavefront-splitting interferometer

Wavefront-splitting interferometers, not as widely used as the amplitude-splitting interferometers, have some useful advantages. Two examples of wavefront-splitting interferometers used to fabricate Bragg gratings in optical fibres are the prism interferometer [40, 58] (shown in Fig. 2.3(a)) and the Lloyd’s interferometer [59] (shown in Fig. 2.3(b)). Both of them require a UV source with good spatial coherence.

An advantage of this method is that only one optical component is used, which causes a reduction in the sensitivity to mechanical vibrations. In addition, the short distance where the UV beams are separated reduces the wavefront distortion induced by air currents and
Chapter 2. Fibre Bragg Grating Background

temperature differences between the two interfering beams. The Bragg wavelength is easily varied by rotating the set-up around the point of intersection between the fibre and the reflecting surface. The major disadvantage of the two wavefront methods is that the gratings’ length is limited to half of the beam width and to the asymmetrical intensity distribution. Nevertheless this method is suitable for fabricating short quasi-uniform FBGs for the investigation of the fibre’s photosensitivity.

Figure 2.3. Setup of the wavefront-splitting interferometers [5] used for Bragg grating fabrication: (a) prism interferometer; (b) Lloyd interferometer.
2.2.2 Phase-mask technique

The phase-mask technique is one of the most effective methods for inscribing Bragg gratings in photosensitive fibre [60, 61]. This method employs a diffractive optical element (phase mask) to spatially modulate the UV writing beam. Phase masks may be formed holographically or by electron-beam lithography [62]. The benefit of the holographic method over the electron-beam is that there is no stitching error in the grating pattern on the mask [63]. On the other hand, complicated patterns can be written into the electron beams fabricated masks, such as quadratic chirps, Moiré patterns, etc. The period of phase mask $\Lambda_{pm}$ is two times the period of the grating $\Lambda$ ($\Lambda_{pm} = 2\Lambda$) [3]. When a UV beam is perpendicularly incident on a phase mask with a proper depth, the zero-order diffracted beam can be nearly cancelled out and the plus and minus first-order diffracted beams are maximized, each typically containing more than 35% of the transmitted power (see Fig. 2.4). This is used to create an interference pattern with a period of $\Lambda$ in the photosensitive optical fibre which is placed in contact with or in close proximity to the phase mask.

![Figure 2.4. Setup of the phase-mask technique for Bragg grating fabrication [5].](image)

The phase mask greatly reduces the complexity of the fibre grating fabrication system. The simplicity of using only one optical element provides an inherently stable method for reproducing FBGs. Since the fibre is usually placed directly behind the phase mask in the near field of the diffracting UV beams, sensitivity to mechanical vibrations is minimized.
Low temporal coherence does not affect the writing capability due to the geometry of the problem, opposite to the interferometric technique.

The main disadvantage of this technique is the limitation of the tuneability in the inscribed Bragg wavelength, which is basically determined by the fixed periodicity of a phase-mask. Prohaska et al. [64] have shown experimentally that magnifying the phase-mask periodicity by using extra lens only achieved tuneability in the order of a few percent.

2.2.3 Point-by-point technique

The point-by-point technique for fabricating Bragg gratings is accomplished by inducing the refractive index change one step at a time along the core of the fibre. In a typical experimental setup shown in Fig. 2.5, a single pulse of UV light from an excimer laser is passed through a slit and then focused onto the fibre at one point. As a result, the refractive index of the core in the irradiated fibre section increases locally. The fibre is then shifted by a distance $\Lambda$, corresponding to the period of the grating, in a direction parallel to the fibre axis. The process is repeated to form the grating structure in the fibre core. Essential to the point-by-point fabrication technique is a very stable and precise submicron translational system.

Figure 2.5. Setup of point-by-point technique for Bragg grating fabrication [5].
2.3 Advanced technique for fibre Bragg grating fabrication

There is a rapidly growing demand for high-quality optical Bragg gratings with arbitrary phase and index profiles, because these gratings are important elements in WDM systems, wireless communication systems, optical sensors, etc. In the past few years, several methods have been developed for realizing gratings with complex structures using phase-mask based techniques [66-71]. While having the benefit of a potentially high reproducibility, the disadvantage of all these methods is that they rely on phase masks that have to be of very high quality with a low amount of fabrication errors (and therefore rather expensive) to ensure high quality gratings. In many cases, new complex grating designs will require special phase masks, which substantially lower the flexibility and raises costs.

In the following section, an advanced fabrication system in Acreo will be briefly introduced, where no phase masks are necessary to form the grating.

2.3.1 Multiple printing in fibre technique

In 1995, Stubbe et al. [72] first proposed the multiple printing in fibre (MPF) technique for writing long and complex fibre gratings. The idea was to consecutively expose short subgratings consisting of a few hundred periods with a pulsed UV source while at the same time moving the fibre. With a high precision translation of the fibre along its axis relative to the interference pattern, the phase and position of each subgrating is precisely controlled. The interference pattern can be generated by an interferometer with an ordinary beam splitter. Different grating designs, such as phase shifts, chirp and apodization, are realized by changing the relative phase between the subgratings [73, 74]. Therefore, new grating designs can be easily implemented by mere programmatic changes in the software.
Chapter 2. Fibre Bragg Grating Background

synchronizing the fibre movement and UV pulse generation. There are some drawbacks in using pulsed operation of the UV source [75], which are beyond the scope of this thesis. One of them is that the fibre can easily be destroyed due to high peak intensities impinging on the fibre and the not perfectly constant pulse-to-pulse energy when using excimer lasers.

2.3.2 Sequential exposure with a continuous-wave UV laser source

A fabrication scheme comprising a CW UV laser source can overcome all the problems mentioned above. In this system, the pulses are replaced by a sawtooth movement of the interference pattern. Apart from lower power consumption and shorter fabrication times, it is easy to keep a constant distribution of the UV dose in the fibre and a static environment without sudden bursts of heat, as is the case with pulsed irradiation. The basic concept of this method was proposed in Ref. [76, 77].

Fig. 2.6 shows a schematic of the FBG fabrication system based on the MPF technique and a CW UV source. Fig. 2.7 shows the interferometer for producing the interference pattern during the exposure. The fibre is mounted on an air bearing linear stage. The position of the translator stage relative to the UV interference pattern is measured either with a heterodyne interference detection system utilizing a He-Ne laser or with an encoder [72].

A frequency-doubled argon-ion laser emitting at 244 nm with a power of up to 100 mW is launched into the interferometer. A computer controlled shutter opens only when the grating is to be written.

Since the fibre is translated, with a speed which is kept by the way as constant as possible, the fringes of the CW interference pattern must follow this movement during exposure in order to maintain the visibility of the grating. To accomplish this two mirrors c (see Fig. 2.7) are mounted on a pair of piezo translators in the UV interferometer. A displacement in push-pull manner of these mirrors introduces a phase shift between the interfering beams, which shifts the fringe pattern. Driving the piezo actuators with a sawtooth signal controlled by the fibre movement causes the pattern to move together with the fibre over one grating period. At the end of the voltage ramp in each period, the fringes jump back to the original position and the constructive formation of the grating continues. During the short moment when the fringes are moved back, the fibre is evenly exposed, giving rise to a slight dc index increase. The principle of this technique was also reported in Ref. [76].
2.3. Advanced technique for fibre Bragg grating fabrication

A step motor is used to move the mirror pair \( d \) (see Fig. 2.6), which symmetrically changes the separation of the interfering beams in the plane of incidence. This modified separation is translated into an angular change \( \Delta \alpha \) by the cylindrical lenses \( e \), since the latter are placed at their focal distance from the fibre. The big advantage of this set-up is that changing the Bragg wavelength of the gratings is realized in a very precise manner and just by moving to mutually attached mirrors \( d \). No other mechanical adjustments, e.g. the lateral position of the fibre, are required (in the limit of the spherical aberrations of the lenses \( e \)). The period of the interference pattern is then changed consequently. This modification of the periodicity of the fringes can be performed during the fabrication process of chirp gratings without introducing any phase errors in the exposed grating.

A cylindrical lenses \( f \) focuses the two interfering beams perpendicularly to the fibre axis on to the fibre core. Longitudinally, the beam extends over \( \sim 70 \) \( \mu \)m, which roughly corresponds to 130 fringes for a Bragg wavelength of 1550 nm.

The speed of the translation stage is limited by the response time of the piezo actuators: for large velocities, mechanical ringing will substantially reduce the visibility of the imprinted grating. In the setup used here, writing velocities of the order of centimetres per second have been employed, but usually it is limited to a few tenths of mm/s.

Complex structures such as apodizations, phase shifts, and chirps are realized by controlling the shape of the sawtooth signal driving the piezo translators as described in more detail in Ref. [75, 78]. All grating parameters are controlled by the computer software (a Labview user interface) and new grating designs are easily implemented. The characteristics of the gratings that can be fabricated by this advanced system are:

- Bragg wavelength: \( \sim 500-1700 \) nm
- Chirp range during fabrication: \( > 100 \) nm
- Spatial resolution of the profiles: \( \sim 20-100 \) \( \mu \)m (determined by the subgrating length)
- Maximum grating length: \( \sim 30 \) cm
- Maximum writing speed: \( \sim 3 \) cm/s

Figure 2.8 shows reflection spectra of three FBGs fabricated by this system: (a) a 20-mm long hamming-apodized phase shift grating; (b) a 60-mm long 1-nm chirp grating with hamming apodization; (c) a 76-mm long superstructure grating with 511-chip gold code modulated exposure over the length of the grating. The superstructure FBG can be used as an en/decoder in 511-chip 1.25-Gbit/s optical code division multiple access systems.
Figure 2.6. Schematic of the FBG fabrication system based on the MPF technique and a CW UV laser source [78].

Figure 2.7. Interferometer for producing the interference pattern on the fibre core [78].
2.4 Fibre Bragg grating theory

Several theories have been developed to describe the behaviour of Bragg gratings. The coupled-mode theory [3, 79] is the most popular one, mainly due to its simplicity and accuracy in modelling the optical properties of most FBGs of interest. For complicated grating structures, the coupled-mode theory involves the numerical solution of two coupled differential equations. Transfer matrix method [80] has been developed for the purpose of grating analysis. This chapter briefly presents the coupled-mode theory to model the properties of most FBGs and the principle of TMM. Detailed derivation of the coupled-mode theory and TMM can be referred to the textbooks [3, 4] on FBGs and further literature [79, 81-83].

2.4.1 Fundamental properties of fibre Bragg gratings

FBGs consist of a spatial quasi-periodic variation of the refractive index along the fibre length. The variation of the refractive index is assumed small enough to be viewed as a
perturbation of the initial effective refractive index \( n_{\text{eff}} \). The total effective refractive index \( n_{\text{eff}}(z) \) at position \( z \) in the fibre takes the form:

\[
n_{\text{eff}}(z) = n_{\text{eff}} + \delta n_{\text{eff}}(z)
\]

(2.4)

If the variation is described by a cosine, the perturbation term in Eq. 2.4 can be expressed as [84]

\[
\delta n_{\text{eff}}(z) = \overline{\Delta n_{\text{eff}}}(z) \left[ 1 + \nu \cos[Kz + \phi(z)] \right]
\]

(2.5)

where \( \overline{\Delta n_{\text{eff}}} \) is the effective dc index change spatially averaged over the grating period; \( 0 \leq \nu \leq 1 \) is the fringe visibility of the index change; \( K = 2\pi / \Lambda \) is the spatial frequency of the grating having a central period \( \Lambda \); \( \phi(z) \) is a variable phase factor describing grating chirp. Inserting the last equation, Eq. 2.4 can be given by

\[
n_{\text{eff}}(z) = n_{\text{av}} + \Delta n_{\text{eff}}(z) \cos[Kz + \phi(z)]
\]

(2.6)

Where \( n_{\text{av}} = n_{\text{eff}} + \overline{\Delta n_{\text{eff}}} \) is the average refractive index, \( \Delta n_{\text{eff}}(z) = \nu \overline{\Delta n_{\text{eff}}} \) is the modulation depth. The modulation depth may in general change slowly along the length of the grating, forming an index modulation profile with apodization. Gratings with a variable spatial frequency \( K(z) = K + \Delta K(z) \) are called chirped gratings. Therefore, Eq. (2.6) is able to describe both apodization and chirp of a grating.

2.4.1 Coupled-mode theory

Coupled-mode theory has often been used to accurately model the optical properties of most gratings [3, 79]. In the presence of a dielectric perturbation associate with the FBG, a mode of amplitude \( R(z) \) is coupled into an identical counter-propagating mode of amplitude \( S(z) \) according to [4, 83]

\[
\frac{dA(z)}{dz} = i \zeta A(z) + i \kappa B(z)
\]

(2.7)

\[
\frac{dB(z)}{dz} = -i \zeta B(z) - i \kappa^* A(z)
\]

(2.8)

where \( A(z) = R(z) \exp(i\delta z - \phi / 2) \), \( B(z) = S(z) \exp(-i\delta z + \phi / 2) \), \( \zeta = \delta + \zeta - \frac{1}{2} \frac{d\phi}{dz} \) is the general dc self-coupling coefficient ( \( \delta = \beta - \pi / \Lambda \) is the detuning wave vector), and \( \kappa \) is the ac coupling coefficient.
### 2.4. Fibre Bragg grating theory

For a single-mode Bragg reflection grating, one finds the following simple relations [83]:

\[
\delta = \frac{2\pi}{\lambda} \delta n_{\text{eff}} \tag{2.9}
\]

\[
\kappa = \kappa^* = \frac{\pi}{\lambda} \nu \delta n_{\text{eff}} \tag{2.10}
\]

A solution of the coupled-mode differential Eq. 2.7 and 2.8 for a uniform FBG of length \(L\) can be found assuming that \(A(0) = 1\) and \(B(L) = 0\). The amplitude reflection coefficient of a grating \(\rho = B(0)/A(0)\) and the power reflection coefficient \(r = |\rho|^2\) can be shown to be [4, 83]

\[
\rho = \frac{-\kappa \sinh \sqrt{\kappa \lambda^2 - \zeta^2 \lambda^2}}{\zeta \sinh \sqrt{\kappa \lambda^2 - \zeta^2 \lambda^2} + i \sqrt{\kappa^2 - \zeta^2} \cosh \sqrt{\kappa \lambda^2 - \zeta^2 \lambda^2}} \tag{2.11}
\]

\[
r = \frac{\sinh^2 \sqrt{\kappa \lambda^2 - \zeta^2 \lambda^2}}{-\frac{\zeta^2}{\kappa^2} + \cosh^2 \sqrt{\kappa \lambda^2 - \zeta^2 \lambda^2}} \tag{2.12}
\]

The group delay and dispersion of the reflected light can be extracted from the associated phase \(\theta\). The time delay of the light reflected from a grating can be obtained by differentiating this variable with respect to the angular frequency \(\omega\) of the reflection mode, which results in

\[
\tau_g = \frac{d\theta}{d\omega} = \frac{d\theta}{d\lambda} \frac{d\lambda}{d\omega} = -\frac{\lambda^2}{2\pi c} \frac{d\theta}{d\lambda} \tag{2.13}
\]

The Dispersion \(D_g\), the rate of change of delay with wavelength, can be obtained by differentiating Eq. 2.13 against the wavelength, producing

\[
D_g = \frac{d\tau_g}{d\lambda} = \frac{d\tau_g}{d\omega} \frac{d\omega}{d\lambda} = -\frac{2\pi c}{\lambda^2} \beta' \tag{2.14}
\]

where \(\beta'\) is defined as the group velocity dispersion parameter (second derivative of the propagation constant with respect to frequency).
2.4.3 Transfer matrix method

Figure 2.9. A nonuniform grating of Length \( L \) is divided into a series of \( M \) uniform gratings with different periods, represented by their respective transfer matrix \( T_k \).

The piecewise uniform approach is considered flexible and accurate for modeling nonuniform gratings. It is based on multiplication of 2×2 matrices for each uniform section of the grating to obtain a single 2×2 matrix that describes the whole grating \([4, 78, 80]\). The compound grating structure can be divided into \( M \) uniform matrix components, each having a specific period \( \Lambda_k \), phase offset \( \phi_k \) and modulation depth \( \Delta n_k \) (see Fig. 2.9). By changing subgrating parameters from element to element, any grating apodization and phase profile can be approximated. \( A_k \) and \( B_k \) are the field amplitudes after traversing the \( k \)th uniform section travelling in \( +z \) and \( -z \) directions, respectively. The boundary conditions can be assumed as \( A_0 = A(0) = 1 \) and \( B_0 = B(L) = 0 \), meaning that light with amplitude \( I \) is launched at \( z = 0 \) and no light is launched or reflected beyond the grating end at \( z = L \). The propagation through each uniform section \( k \) is described by a matrix \( T_k \), which is defined such that

\[
\begin{pmatrix}
A_k \\
B_k
\end{pmatrix} = T_k \begin{pmatrix}
A_{k-1} \\
B_{k-1}
\end{pmatrix} = \begin{pmatrix}
T_{11} & T_{12} \\
T_{21} & T_{22}
\end{pmatrix} \begin{pmatrix}
A_{k-1} \\
B_{k-1}
\end{pmatrix}
\]

(2.15)

The elements in this matrix are given by

\[
T_{11} = T_{22}^* = \cosh(\Omega dl) - i \frac{\Gamma}{\Omega} \sinh(\Omega dl)
\]

(2.16)

\[
T_{12} = T_{21}^* = -i \frac{\beta}{\Omega} \sinh(\Omega dl)
\]

(2.17)

where the star (*) denotes complex conjugation, \( dl \) is the length of the \( k \)th uniform section,
\( \zeta \) and \( \kappa \) are the local coupling coefficients for the \( k \)th section, and \( \Omega = \sqrt{\kappa^2 - \zeta^2} \). The total grating structure may be expressed by the product of the different subgrating transfer matrices, i.e.

\[
\begin{pmatrix}
A_M \\
B_M
\end{pmatrix} = T_M T_{M-1} \cdots T_k \cdots T_1 \begin{pmatrix} A_0 \\ B_0 \end{pmatrix}
\] (2.18)

Moreover, the transfer matrix \( T_k \) can be easily inverted since its determinant is unity. Eq. (2.15) can be written as

\[
\begin{pmatrix}
A_{k-1} \\
B_{k-1}
\end{pmatrix} = \begin{pmatrix} T_{22} & -T_{12} \\ -T_{21} & T_{11} \end{pmatrix} \begin{pmatrix} A_k \\ B_k \end{pmatrix}
\] (2.19)

The equation for the field at the front face is given by

\[
\begin{pmatrix}
A_0 \\
B_0
\end{pmatrix} = \prod_{k=1}^{M} \begin{pmatrix} T_{22} & -T_{12} \\ -T_{21} & T_{11} \end{pmatrix} \begin{pmatrix} A_M \\ B_M \end{pmatrix} = \begin{pmatrix} I_{11} & I_{12} \\ I_{21} & I_{22} \end{pmatrix} \begin{pmatrix} A(L) \\ 0 \end{pmatrix}
\] (2.20)

The reflection coefficient at the front face of the grating is given by

\[
\rho = \frac{B_0}{A_0} = \frac{I_{21}}{I_{11}}
\] (2.21)

The reflectivity is calculated from the square of its magnitude \( |\rho|^2 \). In addition, the amplitude transmission coefficient \( t \) is simply expressed as:

\[
t = \frac{A(L)}{A_0} = \frac{1}{I_{11}}
\] (2.22)
Chapter 3

Direct Optical Filtering of Microwave Signals

This chapter briefly reviews the incoherent and coherent optical filtering techniques and describes the direct microwave optical filtering technique combined with direct detection as presented in Paper I. The principle and experiment results based on this technique and its applications in radio-over-fibre systems are presented.

3.1 Introduction

Microwave photonic filters [7, 85, 86] are photonic subsystems designed with the aim of realizing tasks equivalent to those of an conventional electrical filter [87, 88] within a RF system or link. The unique functional advantages of microwave photonic filters [89], including low loss, large bandwidth, electromagnetic interference immunity, tuneability and reconfigurability, have led to diverse applications. Optical filtering of microwave signals can be divided into two main categories, incoherent and coherent, which will be reviewed briefly below.

3.1.1 Incoherent filtering

Most of today’s microwave optical filters employ incoherent filtering. It consists of the
Chapter 3. Direct Optical Filtering of Microwave Signals

incoherent summing of delayed copies of a modulated optical signal at the photodetector [90-93]. The result of this incoherent summation is a periodic microwave response and discrete or continuous tuneability. The copies are created in a number of ways employing FBGs, circulators, recirculating lines, couplers and even erbium doped fibre amplifiers (EDFAs). Following the terminology used in digital signal processing, the incoherent filters can be divided into two main groups:

- Recursive: filters with an infinite impulse response (the number of delayed signal copies is infinite).
- Non-recursive or transversal: filters with a finite impulses response (the number of delayed signal copies is finite).

The simplest incoherent microwave optical filter can be created by summing two modulated, and delayed with respect to each other, optical signals at the photodetector. The delay time $\Delta t$ between the signals determines the frequency separation $f = 1/\Delta t$ between two neighbouring maxima in the periodic microwave frequency response of the filter and is also called the free spectral range (FSR). Employing a large number of delayed signals allows for creating more complex microwave filter responses.

Figure 3.1. Designed and measured microwave response of the incoherent filter based on 18 FBGs with appropriate weighting [94].

The Q-factor is defined as the ratio between the filter central frequency and the FWHM of the filter passband. The larger the number of taps, the higher the Q-factor will be. As a rule of thumb, one may use an approximate relationship $Q \approx N$, where $Q$ is the value of the Q-factor and $N$ is the number of taps. Figure 3.1 shows the RF response of an incoherent filter with 40-dB extinction ratio based on 18 taps with appropriate weighting,
obtained by spectrum slicing with 18 FBGs having a separation of ~1 cm [94]. The central passband frequency and the FWHM are 9.9 GHz and 0.8 GHz, resulting in $Q = 12.4$ (not 18 because of the weighting).

In non-recursive filters the number of the produced taps equals the number of delay-forming elements (most often, FBGs). In order to obtain a large number of taps with a small number of elements, one should use recursive filters. In these filters, a part of the signal taken from the filter output is supplied back to the input thus creating a long sequence of pulses. Amplification modules such as EDFAs can also be used in order to increase the number of output taps. Q factors above 3000 have been achieved by Ortega et al. by combining recursive filters (FBGs-EDFA) with small FSR with an additional filter based on an electro-optic modulator (actually an electrical filter) [95].

Most of the progress in the incoherent microwave optical filtering has been observed in the recent years in the field of so-called notch filters. In contrast to passband filters (including high-Q filters), a notch filter is designed not to select a certain bandwidth from an aggregate signal spectrum, but rather to suppress the desired range of frequencies. In some sense, the notch filters are similar to band rejection filters with a relatively narrow (as a rule, a few percent of the notch frequency) bandwidth. A simple non-tuneable notch filters consists of two delayed copies of the modulated optical signal incoherently summed at the photodetector [96]. In order to achieve a high rejection at the notch frequency, the amplitudes of the two delayed signal copies should match with high accuracy.

The principle of incoherent summing does not directly allow for the accomplishment of negative coefficients: it means that it is not possible to subtract some taps from the others. This fact imposes limitations upon the shape of the achievable frequency responses. In particular, using only positive coefficients, it is not possible to obtain high-pass filters or to achieve, e.g., flat top filters. However, there are a few techniques rendering possible to obtain negative taps in incoherent microwave optical filters. One of the ideas is to use a cross-gain modulation in a semiconductor optical amplifier [97]. A notable feature of the two-tap filter demonstrated in Ref. [97] is the null transmission at zero frequency, which is a direct consequence of using a negative tap. Another idea is to use the differential detection [98, 99]. The idea is to split the positive and negative taps in the optical domain and use separate photodetectors (inverting and non-inverting ones) for detecting the two sequences. The responses are then summed in the electrical domain.
3.1.2 Coherent filtering

The incoherent summing of modulated optical signals at the photodetector allows for creating positive and negative tap coefficients in the impulse response of a microwave optical filter. However, a much greater flexibility can be achieved if the coefficients can be made complex. This can be done by utilising information about the phase of the optical carrier. For doing this, one should employ an optical source with the coherence length substantially longer than the optical path lengths between the delayed copies of the modulated signal. In this case, the summation of the signals at the photodetector is performed coherently [100]. Though very flexible, this approach imposes extremely strict requirements of the system stability and therefore has not been widely exploited in microwave optical filtering - in fact, there are very few publications on the subject. In the example demonstrated in Ref. [100], a set of waveguides is implemented on a single silicon substrate with a temperature maintained within 0.1 °C.

An approach of coherent filtering is the direct optical filtering, proposed and demonstrated a few years ago [101-103]. It consists of using highly spectrally selective elements, FBGs, to select and isolate the double side bands corresponding to a certain microwave signals and the optical carrier on which it was transferred.

![Figure 3.2. (a) Direct filter based on three coupled integrated ring resonators [101]. (b) Principle of functioning and the microwave response of the presented filter [101].](image)

Direct optical filtering using three coupled integrated ring resonators is shown in Fig. 3.2(a) [101]. The coupled resonator structure forms a series of periodic transmission peaks in the optical domain (with the FSR of 7.5 GHz). The principle of functioning of the device as a microwave filter as well as its microwave frequency response is given in Fig. 3.2(b). The
3.1. Introduction

wavelength of the optical carrier is made to be coincident with one of the maxima in the optical transmission response of the filter. Varying the modulation frequency, one changes the separation of the sidebands from the carrier. The modulation depth of the optical signal after the filter depends upon whether the sidebands are within the transparency bands of the resonator or not (see Fig. 3.2(b)), which is correspondingly reproduced in the microwave response of the filter. The microwave response shown in Fig. 3.2(b) has the FWHM of ~1.2 GHz centred at 7.5 GHz, resulting in $Q = 6.25$.

Other configurations of direct microwave optical filtering have been demonstrated in Ref. [102, 103]. In Ref. [102], the optical filter consists of four FBGs working in transmission, creating a tuneable quasi-passband microwave response. Fig. 3.3(a) shows the principle of this filter. Four temperature-stabilising boxes are used for stable functioning of the filter and also for tuning the filter to achieve a wide range of microwave frequency responses. One big advantage of this filter is the absence of an optical circulator, which simplifies the optical part of the filter and makes it potentially cheap. In Ref. [103], the direct microwave optical filtering is demonstrated by a superimposed FBG used in reflection [104]. The principle of this filter is illustrated in Fig. 3.3(b). The ability of the filter to remove out of band signals is demonstrated. Transmission over long distances after filtering is possible with negligible deterioration of the signal quality. Contrary to the filter working in transmission reported in Ref. [102], this filter is not able to tune the passband central frequency and only little tuning of the spectral shape is possible. However, the high-pass tail of the microwave response of the filter working in transmission [102] does not exist in the filter with a grating used in reflection [103].

![Figure 3.3](image.png)

Figure 3.3. Principles of the direct microwave optical filtering using (a) four FBGs working in transmission [102] and (b) a superimposed grating in reflection [103].
3.1.3 Comparison between incoherent and direct optical filtering of microwave signals

The FSR of nearly all the incoherent filters is limited by the coherence length of the optical source, which should be shorter than optical paths existing in the filter (for a single wavelength source configuration). The main implication of this fact is that, although their Q factors can be very large, incoherent filters are usually more suitable for relatively moderate passband frequencies (around a few GHz or below). Direct microwave optical filters have no limitations on the optical source coherence length and are therefore more easily configured for large passband frequencies. In fact, for direct optical filters, the larger the operational frequency, the easier it becomes since the constraints on the filter design are increasingly relaxed.

In the moderate frequency range, microwave optical filters have to compete with relatively low-cost microwave electrical filters with rather good characteristics and large Q factors. Most incoherent filters operating in this frequency range are usually very complex and therefore expensive. Thus, expect for very specific cases where microwave electrical filters might not be available (for example in terms of tuneability), it is unclear whether incoherent optical filters of microwave signals could have a substantial commercial impact. As explained above, incoherent filters are used exactly in the same way as microwave electrical filters, i.e. they have both electrical input and output, optics being used in-between just for the actual filtering operation. These filters hence bear the cost for the electrical to optical and optical to electrical conversions which is, as everyone knows, far from being negligible. By contrast, direct optical filters have both optical input and output and are therefore especially suitable when microwave signals which need to be filtered are already in the optical domain, i.e. put on an optical carrier. This implies that electrical to optical and optical to electrical conversions are not required, making the direct optical filters potentially cost effective.

Incoherent filters using a combination of positive and negative taps give the possibility to design the shape of the microwave responses of the optical filter. However, the finer the design, the more taps are required. In the direct optical filtering, the shape of the microwave (or MMW) response is directly given by the spectral shape of the optical filter used. Since long and complex-structured FBGs can presently be realized, there is a large degree of freedom in designing such filters. However, further efforts in the development of direct
optical filters of microwave signals need to be concentrated in achieving larger Q-factors than what early demonstrations have shown. One promising direction is the use of phase-shifted strong chirped FBGs. Also, direct optical filters require a very large spectral accuracy in the adjustment of the filter with regard to the optical carrier bearing the microwave signals to be filtered. In practice, automatic adjustment can be realized with accuracy below 1 pm which is in the range of 100 MHz at 1550 nm.

3.2 Direct microwave optical filtering with direct detection

In direct optical filtering of microwave signals, the general case is that both optical carrier and side-bands corresponding to the microwave carriers are preserved after filtering and further used in the optical domain. However, when the microwave signals need to be detected, i.e. reconverted to the electrical domain, the existence of the optical carrier requires the down-conversion of the high-frequency (HF) signal to an intermediate frequency (IF) signal in the detection part. This makes the detection system cumbersome and therefore expensive. One solution, demonstrated in paper [1], is hence to remove the optical carrier and to combine direct optical filtering with direct detection, which simplifies the detection setup and significantly reduces its cost.

The direct detection requires the suppression of the optical carrier by the optical filter (together with all undesired spectral components). Only the two sidebands (20 GHz in Paper [1]) of the optical carrier are supplied to the photodetector with a good extinction ratio. The basic principle of the direct detection for the direct optical filtering of microwave signals using a superimposed FBG in reflection is illustrated in Fig. 3.4. Two Hamming-apodized gratings were written at the same location in a standard SMF with a length of 10 cm. The reflection spectrum of the gratings is shown in Fig. 3.5. They have identical spectral characteristics but different resonance frequencies and work in reflection as passband filters for the sidebands of the microwave subcarrier to be processed. The FWHM of the two gratings is ~16 pm corresponding to ~2 GHz. The pass function of the filter in the microwave domain is hence expected to be about 2 GHz and a full stop effect outside this 2 GHz range. The reflectivity of each peak in the grating is about 45% and the wavelength separation between the two reflection peaks is about 320 pm corresponding to 40 GHz (i.e. for filtering at the subcarrier frequency of 20 GHz). The extinction ratio of the grating is ~25 dB, guaranteeing the suppression of the optical carrier. Perfect co-location and close to identical characteristics of the gratings imply that a negligible delay difference
between the side modes is expected after reflection from the grating filter.

![Figure 3.4. Principle of the direct filtering combined with direct detection.](image)

Figure 3.5. Reflection spectrum of a single double-peaked superimposed FBG.

The ability of the filter to remove out-of-band signals is tested by measuring digital signals 155 MBit/s placed at a microwave subcarrier. Fig. 3.6 depicts the experimental setup for bit error rate (BER) measurement. Detailed description of the functions of each component is described in Paper 1. Contrary to the experimental setup in Ref. [103], a local oscillator (LO), a mixer and an envelope detector are not needed in the technique presented here. Moreover, a low-speed photodiode can be used here, additionally reducing the cost.

The digital 155 MBit/s payload with a pseudorandom binary sequence of $2^{31}-1$ was generated by the BER tester and then used to modulate in amplitude an electrical signal whose frequency was varied from 18.4 to 21.6 GHz. This electrical signal was then fed to
the optical modulator. The optical wavelength was set to the optimal 1534.64 nm corresponding to the centre wavelength between the two reflection peaks. The gratings were put in a temperature-stabilizing box for good function of the grating filter. The optical power and the optical signal to noise ratio before being reflected by the FBG kept constant as the frequency was changed. BER measurements and eye-diagrams as a function of the frequency have been recorded. The results of these measurements at room temperature are shown in Fig. 3.7 and 3.8.

Figure 3.6. Experimental setup used for the demonstration of the direct microwave optical filtering combined with direct detection. IF: intermediate frequency; RF: radio frequency; LO: local oscillator; PC: polarization controller; EDFA: erbium doped fibre amplifier; LPF: low-pass filter.

As one can see, the passband width of the filter is about 2 GHz as expected from the optical spectrum of the grating. The BER performance in the passband of the filter shown by the flat part of the curve corresponds to the BER of $1.2 \times 10^{-11}$ or better. This performance was considered as excellent. Outside the passband the quality of the signal quickly
deteriorates demonstrating an almost on-off behaviour of the filter. The eye-diagrams are of
good quality within the passband and the eyes quickly close outside the passband.

Additional experiments were realized by using only one peak of the double-peaked
grating also demonstrated efficient filtering of the signal with the bandwidth of 2 GHz,
matching well the optical bandwidth of this single peak. These experiments proved the
possibility of using the direct detection technique for optical single sideband modulated
signals and also for tuneable filtering by tuning the central wavelength of the used
reflection peak with regards to the optical carrier.

![Figure 3.7. BER measurements as a function of microwave signal frequency.](image)

![Figure 3.8. Eye-diagrams of the detected signal at a number of frequencies within and
outside the passband of the filter: (a) at 19.5 GHz, (b) at 20 GHz, (c) at 21 GHz, (d) 21.5
GHz.](image)
3.3 Perspective and applications

In the technique presented here, the optical carrier is spared for other subcarriers it may carry and the composite signals (the optical carrier with unfiltered subcarriers) can be transported further in the optical link. Therefore, the FBG filter together with the direct detection scheme can be applied in RoF systems comprising more than one RF signal. Because of the narrow bandwidth of the superimposed FBG presented here, cascaded superimposed FBGs (with the same central wavelength but different wavelength separations of the two peaks, such as 320 pm, 384 pm and 448 pm) can be used to filter corresponding RF signals (such as 20 GHz, 24 GHz and 28 GHz, respectively). However, the narrow bandwidth of the filter also limits the maximum data rate, which would be 800 MBit/s in the case presented here.

The direct optical filtering technique has been used for simultaneous up-conversion of ultra-wide band (UWB) signals and filtering, as demonstrated in Papers X-Ⅻ. In Paper X, the UWB signals were up-converted to 40 GHz range and the extinction ratio of the suppressed optical carrier was improved by 35 dB using a 10-cm long Hamming-apodized FBG in transmission. In Papers Ⅺ and Ⅻ, the UWB signals was up-converted to 60 GHz and an extinction ratio of 28 dB was achieved at double frequency of the local carrier (60 GHz) by using a 7-cm long Hamming-apodized FBG in transmission. Due to the grating, the remaining desired signals at 56.568 GHz is attenuated by only 2.4 dB and the undesired side band is suppressed by more than 23 dB.
Chapter 4

High Speed Switching

A fibre with side-holes filled with internal electrodes can be used to electrically control the light propagating in the fibre waveguide. Besides electro-optical switching and modulation, nanosecond polarization switching has recently been demonstrated [18]. A FBG written in such fibres is an excellent tool to follow the evolution of the refractive index experienced by the light in the polarization parallel and orthogonal to the direction of the holes. In this chapter, the research on two 4-cm long Hamming-apodized FBGs written on side-hole fibres with internal electrodes (Papers II–VI) is described. Nanosecond high current pulses cause the quasi instantaneous expansion of the metallic electrodes. This increases the birefringence of the fibre and a full on-off and off-on switching of the gratings with a response time of ~29 ns have been achieved. From the spectral response of the grating, the time evolution of the mechanical stress and the heat diffusion across the fibre cross section has been studied. Numerical simulations give accurate description of the experimental results. Without the electrical pulses excitation, the temperature dependence of the grating characteristics is also presented.

4.1 Fabrication of the FBG component

The 125-μm thick silicate side-hole fibre, drawn at Acreo FibreLab, has two 28.8-μm diameter holes running parallel to the core. The core-hole separation (edge-to-edge) is 13.4 μm. The side-hole fibre has characteristics similar to those of a standard telecom fibre (core
Chapter 4. High Speed Switching

diameter 8.4 μm and Δn = 0.0056). Fig. 4.1 shows the cross section of the side-hole fibre used here. Here, the direction parallel to the two holes is defined as the x-axis; the one perpendicular to the two holes is the y-axis.

Pieces of side-hole fibre were filled with ~8-cm long metal columns which occupied the entire cross-section of the holes. Eutectic alloy Bi₄₇Sn₅₃ (melting temperature 137°C) was pushed into the fibres in the molten state using a chamber with high pressure, and employed at room temperature as solid electrodes, as shown in Fig. 4.2 [105]. The length of the alloy-filled columns and the core-hole separation were such that metal-induced loss was experimentally measured to be <0.2 dB at 1.55 μm and the polarization-dependent loss <0.1 dB. Both ends of the metal-filled fibre were free from metal to allow for convenient low-loss splicing.

Figure 4.1. Cross section of the side-hole fibre (SEM picture).

Figure 4.2. Filling a side-hole fibre with the alloy BiSn.
4.1. Fabrication of the FBG component

The metal-filled fibres were hydrogen loaded for 2 weeks at 150 bars, stripped from the acrylate coating and exposed to UV beam in a FBG writing set-up. Frequency doubled Ar+ laser was used as a source of UV radiation. In the work reported here, results obtained from two 4-cm long Hamming-apodized FBG written along the middle section of metal-filled fibres are presented. The gratings were annealed in the oven at 100 °C for 12 hours.

After annealing the gratings, the fibres were side polished to electrically access one of the two internal electrodes at two points separated by 7 cm. A 20-µm thick gold-plated tungsten wire was inserted by ~5 mm into the electrode while melting the alloy locally to ensure a robustly bonded electrical connection, as shown in Fig. 4.3. Then, the pieces of fibre were mounted on an aluminium (Al) substrate and covered with heat conductive, electrically isolating epoxy. Heat dissipation into the substrate allows switching the devices at rates of a few kHz without significant drift of polarization or wavelength. The resistance of the components was typically ~43 Ω for a BiSn device with 7 cm active length. This value implies in a small impedance mismatch between the device and the 50 Ω coaxial cable transporting the high voltage (i.e., current) pulses. Electrical SMA contacts were used and a 0.1 Ω resistive probe was connected in series with the 43 Ω load for monitoring purposes. Fig. 4.4 shows the photograph of the grating component.

Figure 4.3. Illustration of the fibre with electrodes contacted with 20-µm diameter Tungsten wires.

Figure 4.4. Photograph of the grating component.
4.2 Static experiment

Due to the intrinsic birefringence of the side-hole fibre, each grating has two reflection peaks at different wavelength corresponding to the different effective refractive indices for the two orthogonal polarization modes in this fibre [106]. Fig. 4.5 shows the reflection spectrum of FBG2 at room temperature. The reflection peak at the shorter wavelength takes place in the fast axis mode (x-axis or x-polarization, black curve in Fig. 4.5), the one at the longer wavelength in the slow axis mode (y-axis or y-polarization, red curve in Fig. 4.5) [107]. The identification of the axes will be discussed in the simulations below. The information about the Bragg wavelengths of the two polarizations at room temperature, the FWHMs and the reflectivities of two gratings are listed in Table 4.1. \( \lambda_x \) and \( \lambda_y \) denote the Bragg wavelengths of the two polarizations for each grating. \( \lambda_y - \lambda_x \) is the Bragg wavelength separation for the two polarizations. \( \Delta n \) is the refractive index difference between the two polarizations of each grating, roughly one order of magnitude lower than in typical HiBi fibres. \( \Delta n \) is inferred from:

\[
\Delta n = \frac{\lambda_y - \lambda_x}{\lambda_0} n_{\text{eff}}
\]

where \( \lambda_0 = (\lambda_y + \lambda_x)/2 \) is the average value of the Bragg wavelengths of the two polarizations and \( n_{\text{eff}} = 1.445 \).

Figure 4.5. Reflection spectrum of FBG2 at room temperature.
4.2. Static experiment

<table>
<thead>
<tr>
<th></th>
<th>$\lambda_x$ (nm)</th>
<th>$\lambda_y$ (nm)</th>
<th>$\lambda_y - \lambda_x$ (pm)</th>
<th>$\Delta n$</th>
<th>FWHM (pm)</th>
<th>Reflectivity</th>
<th>Max. index modulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>FBG1</td>
<td>1546.302</td>
<td>1546.328</td>
<td>26</td>
<td>$-2.4 \times 10^{-5}$</td>
<td>36</td>
<td>70%</td>
<td>$2.7 \times 10^{-5}$</td>
</tr>
<tr>
<td>FBG2</td>
<td>1547.280</td>
<td>1547.323</td>
<td>43</td>
<td>$-4.1 \times 10^{-5}$</td>
<td>44</td>
<td>75%</td>
<td>$3.1 \times 10^{-5}$</td>
</tr>
</tbody>
</table>

Table 4.1. Parameters of the two gratings at room temperature.

4.2.1 Temperature dependence measurement

The experimental setup for temperature dependence measurement is depicted in Fig. 4.6. The light source used was a tuneable light source (TLS) based on an external cavity diode laser with linewidth < 1 pm, and synchronized with an optical spectrum analyzer (OSA) for high resolution and high dynamic range wavelength measurements. Different input polarization states were selected with a polarization controller. The metal-filled fibre device was put in a temperature-controllable oven. When the oven temperature increased, the two internal electrodes were heated and expanded more. Consequently, the refractive indices for both polarizations and the birefringence were observed to increase as the temperature increased. $\lambda_x$ and $\lambda_y$ shifted to longer wavelengths and the splitting between them ($\lambda_y - \lambda_x$) increased. Fig. 4.7 shows the temperature dependence of $\lambda_x$ (black curve with squares), $\lambda_y$ (black curve with triangles) and $\lambda_y - \lambda_x$ (blue curve with circles) of FBG1 in a steady-state situation. The insets are the reflection spectra of x- and y-polarization at ~26 °C and at ~69 °C, shown in black and red curve, respectively. From 26 °C to 69 °C, $\lambda_y - \lambda_x$ increased from 26 pm to 87 pm. From Eq. 4.1, the refractive index difference can be calculated to increase from $-2.4 \times 10^{-5}$ to $-8.0 \times 10^{-5}$. Such a state can also be reached by heating the fibre by passing dc current in the electrode, instead of using an oven as in the characterization.
measurement presented here. Although the range of temperature reached is more limited (since the heat deposited on the electrodes needs to spread over the whole fibre), heating the electrodes with current allows for the study of the dynamics of the system. For example, the regime can be studied when the electrodes expand because of the current but no heat exchange has yet taken place, as discussed in section 4.3.

Figure 4.7. Temperature dependence of Bragg resonance for x- and y-polarization of FBG1 in a steady-state situation. Insets: reflection spectra of x- and y-polarization of FBG1 at ~26 °C and at ~69 °C, respectively.

4.2.2 Discussion and calculation

One can note from Fig. 4.7 that the measured temperature sensitivity (~37.6 pm/°C) is significantly larger than expected for a HiBi FBG fabricated in Panda fibre (~16.5 pm/°C) [108]. The Bragg-reflected wavelength depends on the period of the grating and the effective index change. By differentiating Eq. 2.1, one can find variation in Bragg centre wavelength with respect to the effective refractive index, the grating period and their variations.

\[ d\lambda_b = 2n_{\text{eff}} d\Lambda + 2\Lambda d n_{\text{eff}} \]  

(4.2)

Dividing Eq. 4.2 by Eq. 2.1, one gets the relative wavelength shift
4.2 Static experiment

\[ \frac{d\lambda_B}{\lambda_B} = \frac{dn_{\text{eff}}}{n_{\text{eff}}} + \frac{d\Lambda}{\Lambda} \]  \hspace{1cm} (4.3)

This means that a shift in the Bragg centre wavelength can be achieved either by inducing a gradient in the effective refractive index of the grating or by a change in the period of the grating or both.

To find the effect of temperature, Eq. 4.2 can be differentiated with respect to temperature \( T \).

\[ \frac{\partial \lambda_B}{\partial T} = 2\left(\Lambda \frac{\partial n_{\text{eff}}}{\partial T} + n_{\text{eff}} \frac{\partial \Lambda}{\partial T}\right) \]  \hspace{1cm} (4.4)

Thus, the whole thermal tuning scenario arises due to two mechanisms. The change in the period of the grating due to thermal expansion or contraction and the refractive index change due to the temperature change. Dividing Eq. 4.4 by Eq. 4.1, we get

\[ \frac{1}{\Lambda_B} \frac{\partial \lambda_B}{\partial T} = \left(\frac{1}{n_{\text{eff}}} \frac{\partial n_{\text{eff}}}{\partial T} + \frac{1}{\Lambda} \frac{\partial \Lambda}{\partial T}\right) \]  \hspace{1cm} (4.5)

The quantity \( (1/n_{\text{eff}})(\partial n_{\text{eff}}/\partial T) \) represents the thermo-optic coefficient \( \xi \) whose value is approximately \( 6.5 \times 10^{-6} \) K\(^{-1}\) for this side-hole fibre. The term \( (1/\Lambda)(\partial \Lambda/\partial T) \) is the thermal expansion coefficient \( \alpha \) of the fibre, optimized to be \( 0.5 \times 10^{-6} \) K\(^{-1}\) which will be discussed in the simulation section. It can be seen from Eq. 4.5 that the wavelength sensitivity is about \( \sim 11 \) pm for a thermal gradient of 1 °C.

As discussed in Ref. [109], the temperature sensitivity can be improved by increasing the contribution of thermal expansion factor in Eq. 4.5. This can be achieved by attaching the FBG to a system having very-high effective thermal expansion coefficient. In the case presented here, the FBG was written in a side-hole fibre with internal alloy and mounted on the Al substrate, which exhibits significantly larger thermal expansion coefficient than the one of usual silica fibres. In this case, the relative shift of the resonance wavelength of a Bragg grating with respect to temperature can be expressed as:

\[ \frac{1}{\lambda_B} \frac{\partial \lambda_B}{\partial T} = \xi + \alpha_f + (\alpha_A)_{\text{eff}} + (\alpha_S)_{\text{eff}} \]  \hspace{1cm} (4.6)

where \( \alpha_f \) is the thermal expansion coefficient of the fibre; \( (\alpha_A)_{\text{eff}} \) and \( (\alpha_S)_{\text{eff}} \) are effective thermal expansion coefficient of the alloy and the Al substrate to the fibre, respectively. Eq. 4.6 can be rewritten as:
\[ \Delta \lambda = \lambda_B \xi \Delta T + \lambda_B \alpha_F \Delta T + \lambda_B (\alpha_A)_{\text{eff}} \Delta T + \lambda_B (\alpha_S)_{\text{eff}} \Delta T \]  
\[ (4.7) \]

\[ \Delta \lambda = \Delta \lambda_n + \Delta \lambda_F + \Delta \lambda_A + \Delta \lambda_S \]  
\[ (4.8) \]

where \( \Delta \lambda_n = \lambda_B \xi \Delta T \), \( \Delta \lambda_F = \lambda_B \alpha_F \Delta T \), \( \Delta \lambda_A = \lambda_B (\alpha_A)_{\text{eff}} \Delta T \) and \( \Delta \lambda_S = \lambda_B (\alpha_S)_{\text{eff}} \Delta T \) are the wavelength shifts due to refractive index increase, due to the length expansion of the fibre itself, due to the alloy dilation and due to the length expansion of the Al substrate. An estimate of the various contributions follows:

**1) Calculation of the effective thermal expansion coefficient of the alloy \((\alpha_A)_{\text{eff}}\)**

A temperature change of \( \Delta T \) causes the alloy expansion:

\[ \Delta L_A = \alpha_A L_A \Delta T \]  
\[ (4.9) \]

where \( \alpha_A \) is the thermal expansion coefficient of the used alloy (BiSn) and \( L_A \) is the alloy length.

Newton’s third law gives the relation:

\[ F_{\text{alloy} \rightarrow \text{fiber}} = F_{\text{fiber} \rightarrow \text{alloy}} \]  
\[ (4.10) \]

\[ F = -kx = -\frac{EA}{L} x \]  
\[ (4.11) \]

From Eq. 4.10 and 4.11, one gets:

\[ -\frac{\Delta L_A E_A A_A}{L_A} = -\frac{\Delta L_F E_F A_F}{L_F} \]  
\[ (4.12) \]

where \( E_A \) and \( E_F \) are the Young’s modulus of the alloy and the fibre; \( A_A \) and \( A_F \) are the cross sectional area of the alloy and of the fibre.

\( \Delta L_F \) is the fibre elongation due to the expansion of the alloy:

\[ \Delta L_F = (\alpha_A)_{\text{eff}} L_F \Delta T \]  
\[ (4.13) \]

where \( L_F \) is the effective length of the fibre.

From Eq. 4.9, 4.12 and 4.13 one can get

\[ (\alpha_A)_{\text{eff}} = \frac{E_A A_A}{E_F A_F} \alpha_A \]  
\[ (4.14) \]
(2) Calculation of the effective thermal expansion coefficient of the substrate \((\alpha_S)_{\text{eff}}\)

Assuming that the Al substrate was perfectly attached to the fibre, \((\alpha_S)_{\text{eff}}\) can be calculated from:

\[
(\alpha_S)_{\text{eff}} = \frac{\alpha_F E_F A_F + \alpha_S E_S A_S}{E_F A_F + E_S A_S}
\]  

(4.15)

where \(E_S\) and \(A_S\) are the Young’s modulus and the cross sectional area of the Al substrate. Since \(A_S\) is much larger than \(A_F\), Eq. 4.15 can be simplified as:

\[
(\alpha_S)_{\text{eff}} = \frac{E_F A_F \alpha_F + \alpha_S}{E_F A_F + 1} \approx \alpha_S
\]  

(4.16)

(3) Calculations of \(\Delta \lambda_n\), \(\Delta \lambda_F\), \(\Delta \lambda_A\) and \(\Delta \lambda_S\)

The parameters for calculation are listed in Table 4.2. From Eq. 4.14 and 4.16, we obtain that \((\alpha_A)_{\text{eff}} = 1.1 \times 10^{-6}\) and \((\alpha_S)_{\text{eff}} = 2.3 \times 10^{-5}\). According to Eq. 4.7 and 4.8, the four wavelength shifts can be calculated for a \(\sim 53^\circ\)C temperature increase: \(\Delta \lambda_n = 0.533\) nm, \(\Delta \lambda_F = 0.041\) nm, \(\Delta \lambda_A = 0.088\) nm, \(\Delta \lambda_S = 1.886\) nm. One sees that the dominant contributions are the change in refractive index of the fibre and the expansion of the substrate (largest). The total wavelength shift under these conditions is calculated to be 2.55 nm, which exceeds the measured value from Fig. 4.7 of \(\sim 2.0\) nm. The lower value measured is probably caused by slippage between the substrate and the fibre [109].

<table>
<thead>
<tr>
<th></th>
<th>Fibre</th>
<th>Alloy (Bi$<em>{47}$Sn$</em>{53}$)</th>
<th>Al substrate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal expansion coeff. (K$^{-1}$)</td>
<td>(\alpha_F = 0.5 \times 10^{-6})</td>
<td>(\alpha_A = 15.35 \times 10^{-6})</td>
<td>(\alpha_S = 2.3 \times 10^{-5})</td>
</tr>
<tr>
<td>Young’s modulus (GPa)</td>
<td>(E_F = 73)</td>
<td>(E_A = 43)</td>
<td>(E_S = 69)</td>
</tr>
<tr>
<td>Cross sectional area (m$^2$)</td>
<td>(A_F = 0.4 \times 10^{-7})</td>
<td>(A_A = 0.5 \times 10^{-8})</td>
<td></td>
</tr>
<tr>
<td>Thermo-optic coeff. (K$^{-1}$)</td>
<td>(\xi_n = 6.5 \times 10^{-6})</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bragg wavelength (nm)</td>
<td>(\lambda_B = 1547.3)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperature increase (ºC)</td>
<td>(\Delta T = 53)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4.2. Data of the parameters for calculation.
4.3 Dynamic experiment

4.3.1 Experimental setup

Two sources of electrical drive pulses were used for this experiment. One consists of a high voltage dc power supply and a high speed switch. The switch is a low repetition rate spark gap circuit delivering 2-10 ns rise-time current pulses with a maximum switching voltage of 3 kV. The pulse duration is determined by the cable length used and was varied in the interval 10-241 ns in the following experiments. The other source is a home-made semiconductor-based switch delivering up to 20 A with 30 ns rise-time at a repetition rate <10 kHz and adjustable pulse length. A TLS with linewidth <1 pm, a circulator, a PC, a 3-dB splitter, a high-speed photodiode, an OSA and an oscilloscope completed the experimental set-up, schematically illustrated in Fig. 4.8. Different input polarization states were selected with the PC.

![Experimental setup for the dynamic measurement. TLS: tunable external cavity diode laser; PC: polarization controller; OSA: optical spectrum analyzer.](image)

4.3.2 Result and analysis

Dynamic measurements were performed for the x-polarization by properly aligning the input polarization and tuning TLS at different wavelengths within the grating spectrum (as shown in Fig. 4.9(a)) before the applications of electrical pulses. Nanosecond high current pulses heated the metal electrode and caused metal expansion rapidly. In consequence, refractive index changed and the grating spectrum shifted. Following the electrical pulse
**4.3. Dynamic experiment**

Excitation, different switching traces with nanoseconds response time can be measured by the oscilloscope. Fig. 4.9(b) shows the traces at different probe wavelengths for x-polarization under the excitation of electrical pulses from the second pulse generator. Each trace recorded the changes in reflectivity as a function of time at a certain probe wavelength. For example, the reflectivity increased when the TLS was tuned at the short wavelength side of the Bragg peak (such as at point A or point B), while it decreased when the probe wavelength was longer than the grating reflection peak (such as at point F or point G). From the traces in Fig. 4.9(b), we can conclude that the grating spectrum of the x-polarization shifted to shorter wavelength (blue-shift) under the electrical pulse excitation. It implies that the refractive index of x-polarization reduces due to the metal expansion.

![Graph](image_url)

Figure 4.9. (a) Reflection spectra of the x- and y-polarization of FBG1 at room temperature. The letters (A, B, C...J, K) denote the probe wavelengths of TLS before each measurement. (b) Different switching traces at different probe wavelengths for x-polarization following the electrical pulse excitation from the second pulse generator. (c) Different switching traces at different probe wavelengths for y-polarization under the electrical excitation from the first pulse generator.
Similarly, dynamic measurements were also carried out for the y-polarization. Fig. 4.9(c) shows several switching traces at different probe wavelengths within the grating spectrum under the electrical excitation from the first pulse generator. From these traces, we can find that the grating spectrum of the y-polarization experienced a positive but smaller wavelength shift (red-shift), meaning that the refractive index of y-polarization increases because of the metal expansion. Note that, the measured traces in Fig. 4.9(c) suffered more noise than those in Fig. 4.9(b). Due to the faster rise time, only the first pulse generator was continued to be used in the following measurements. Electrically driven FBG switching experiments were carried out at room temperature.

When the TLS was tuned at the short wavelength side of the x-polarization of FBG1, full off-on switching with a response time of ~29 ns was achieved, as illustrated in Fig. 4.10. The return of the Bragg peak to longer wavelengths is followed on a microsecond time scale in the inset of Fig. 4.10. Full on-off switching was also obtained with a response time of ~29 ns, as shown in Fig. 4.11, by setting the TLS wavelength to match the Bragg wavelength of the x-polarization of FBG1. The long term recovery of the grating, shown in the inset of Fig. 4.11, is not monotonic. The applied electrical pulse for full switching off-on and on-off is shown in Fig. 4.12. It was a typical pulse obtained from the first source with the pulse width ~60 ns and the amplitude ~18 A at low-repetition rate (~20 Hz). The small step on the right flank (at ~100 ns) and the undershoot observed after the main current pulse are caused by impedance mismatch into 50 Ω.

![Graph](image)

Figure 4.10. Full switching off-on is accomplished with a rise time of ~29 ns for the x-polarization of FBG1. Inset: the time evolution of signal in microseconds.
4.3. Dynamic experiment

Figure 4.11. Full switching on-off is accomplished with a rise time of ~29 ns for the x-polarization of FBG1. Inset: the time evolution of signal in microseconds.

Figure 4.12. An typical electrical pulse for full switching off-on and on-off.

The spectral response of the grating (such as the inset of Fig. 4.11) is useful to study the time evolution of the mechanical stress and the heat diffusion across the fibre cross section. The grating wavelength shifts can be divided into fast part (in tens of nanoseconds) and slow part (in hundreds of microseconds). The former is due to mechanical stress created during the electrical pulse action, while the latter is due to the relaxation of
mechanical stress and the slow increase of temperature in the core transferred from the metal electrode after each electrical pulse.

Fig. 4.13 schematically illustrates the grating wavelength shift for x-polarization at various times. For the fast part (from \( t_0 \) to \( t_1 \)), a negative wavelength shift happens during the electrical pulse excitation and reaches its maximum absolute value (\( \Delta \lambda_{x,M}^\Delta \)) at instant \( t_1 \), similar to the electrical pulse duration. Then the slow part takes effect: the grating gradually moves back with the decreasing mechanical stress and the increasing temperature in the core. The grating passes its original spectral position at instant \( t_2 \) (tens of microseconds) and red-shift continues. The maximum positive \( \Delta \lambda_{x,M}^{+} \) is reached at instant \( t_3 \), where the core temperature is near its maximum. After several milliseconds \((t_4)\), the grating returns to its original spectral position again, since the mechanical stress is released and the component is back to room temperature. It should be mentioned that the identification of the behavior schematically illustrated in Fig. 4.13 (and in Fig. 4.15 below) involved experimentally examining the response of the component for various probe wavelengths (similar to Fig. 4.9). Fig. 4.14 shows the time evolution of the signal reflected by the x-polarization of FBG2 when the TLS was tuned to match the Bragg wavelength of the x-polarization. The voltage and width of electrical pulse used for this measurement are 780 V and 241 ns. If \( t_0 \) is set to 0, the values of \( t_1, t_2, t_3 \) and \( t_4 \) are \( \sim 241 \) ns, \( \sim 68 \) \( \mu \)s, 270 \( \mu \)s and \( \sim 5 \) ms, respectively.

Similarly, schematically diagram of the grating wavelength shift for y-polarization at various times is illustrated in Fig. 4.15. For the fast part, a positive and smaller wavelength shift happens during the electrical pulse duration and reaches its maximum (\( \Delta \lambda_{y,M}^\Delta \)) at instant \( t_1 \). Then, the relaxation of the mechanical stress blue-shifts the spectrum of the grating, while the increasing temperature in the core red-shifts the grating peak. In the beginning, the former dominates and the Bragg wavelength moves back a little until instant \( t_2 \). Afterwards, the heat reaching the core dominates, so the grating continues to red-shift. The maximum positive spectral shift (\( \Delta \lambda_{y,M}^{+} \)) occurs at instant \( t_3 \). Finally, the grating also returns to its original spectral position after instant \( t_4 \). Fig. 4.16 shows a typical experiment trace for the y-polarization of FBG2 when the TLS was tuned to the grating maximum reflectivity of the y-polarization. The electrical pulse employed here was the same as that used for the measurement shown in Fig. 4.14. If \( t_0 \) is set to 0, the values of \( t_1, t_2, t_3 \) and \( t_4 \) are \( \sim 241 \) ns, \( \sim 16 \) \( \mu \)s, 190 \( \mu \)s and \( \sim 20 \) ms, respectively.
4.3. Dynamic experiment

Figure 4.13. Schematic illustration of the wavelength shift for x-polarization at various times. The pink arrows indicate the TLS wavelength during the measurement.

Figure 4.14. Time evolution of the signal reflected by the x-polarization of FBG2 when the TLS was tuned to match the Bragg wavelength of x-polarization.
Chapter 4. High Speed Switching

Figure 4.15. Schematic illustration of the grating wavelength shift for y-polarization at various times. The pink arrows indicate the TLS wavelength during the measurement.

Figure 4.16. Time evolution of the signal reflected by the y-polarization of FBG2 when the TLS was tuned to match the Bragg wavelength of y-polarization.
The values of $\Delta \lambda_M$ and $\Delta \lambda_{T+M}$ depend on the pulse voltage and the pulse duration. For a fixed pulse duration $\Delta t = 241$ ns, experimental data of the fast and slow wavelength shifts for two polarizations of FBG2 ($\Delta \lambda_M^x$, $\Delta \lambda_M^y$, $\Delta \lambda_M^{T+M}$ and $\Delta \lambda_{T+M}^y$) at different voltages are shown with blue triangles, red triangles, blue squares and red squares in Fig. 4.17 (d), 4.17(a), 4.17(f) and 4.17(c), respectively. The blue and red curves in these figures are the parabolic fits with the following expressions:

$$\Delta \lambda_M^x (pm) = -6.5 \times 10^{-5} U^2 (V)$$ (4.17)

$$\Delta \lambda_{T+M}^x (pm) = +4.5 \times 10^{-5} U^2 (V)$$ (4.18)

$$\Delta \lambda_M^y (pm) = +2.1 \times 10^{-5} U^2 (V)$$ (4.19)

$$\Delta \lambda_{T+M}^y (pm) = +7.0 \times 10^{-5} U^2 (V)$$ (4.20)

The absolute value of $\Delta \lambda_M^x$ is $\sim 3.2$ times larger than $\Delta \lambda_M^y$, while $\Delta \lambda_{T+M}^y$ is larger than $\Delta \lambda_{T+M}^x$.

Similarly, experimental data of the fast and slow wavelength shift for x-polarizations of FBG2 ($\Delta \lambda_M^x$ and $\Delta \lambda_{T+M}^x$) for a fixed voltage pulse amplitude $U = 1kV$ (20 A pulse) at different voltages are shown with blue triangles and red triangles in Fig. 4.17(e) and 4.17(b), respectively. The blue and red curves in the two figures are the linear fits with the following expressions:

$$\Delta \lambda_M^x (pm) = -0.244 \times \Delta t (ns)$$ (4.21)

$$\Delta \lambda_{T+M}^x (pm) = +1.66 \times \Delta t (ns)$$ (4.22)

One concludes that the fast and slow wavelength shifts depend quadratically on the electrical pulse voltage and linearly on the pulse duration for both polarizations states, i.e. depend linearly on the amount of energy deposited.
Chapter 4. High Speed Switching

Figure 4.17. Experimental data and fit curves of the fast and slow wavelength shifts for two polarizations of FBG2 for 241 ns electrical pulses (a, c, d, f) and for 1 kV electrical pulses (b, e).

4.4 Numerical simulation

All the above phenomena can be described by the following partial differential equations for heat diffusion and displacement in x and y-direction:

\[ \nabla \cdot (-k \nabla T) + \rho C \frac{\partial T}{\partial t} = W(t) \quad (4.23) \]

\[ \frac{\partial}{\partial x} \left[ C_{11} \frac{\partial u}{\partial x} + C_{12} \frac{\partial v}{\partial y} - b T \right] + \frac{\partial}{\partial y} \left[ C_{33} \left( \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right) \right] = 0 \quad (4.24) \]

\[ \frac{\partial}{\partial x} \left[ C_{33} \left( \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right) \right] + \frac{\partial}{\partial y} \left[ C_{12} \frac{\partial u}{\partial x} + C_{22} \frac{\partial v}{\partial y} - b T \right] = 0 \quad (4.25) \]
where $k$ is the thermal conductivity, $\rho$ is the density and $C$ is the heat capacity of the corresponding area of the cross section (BiSn and silica), $W(t)$ is the time and temperature dependent power density, $u$ and $v$ are the displacements in the x-and y-directions, respectively. Parameters $G, C_{11}, C_{12}, C_{13}, C_{22}, C_{33}$ and $b$ can be expressed by the following equations:

\[
G = \frac{E}{(1+\mu)(1-2\mu)} \quad (4.26)
\]

\[
C_{11} = G(1-\mu) \quad (4.27)
\]

\[
C_{12} = G\mu \quad (4.28)
\]

\[
C_{22} = G(1-\mu) \quad (4.29)
\]

\[
C_{33} = \frac{G(1-2\mu)}{2} \quad (4.30)
\]

\[
b = G\alpha(1+\mu) \quad (4.31)
\]

where $E$ is the Young modulus and $\mu$ is Poisson’s ratio.

In the experiment setup, 43.2-Ω component is connected to a 50-Ω RF cable and the resistance of the component changes with temperature. Taking into account both temperature dependence of the component resistance and that of the impedance mismatch, $W(t)$ can be expressed by:

\[
W(t) = \frac{4U(t)^2 R_0 (1+\alpha_R \Delta T)}{V[R_0(1+\alpha_R \Delta T)+50]^2} \quad (4.32)
\]

where $U(t)$ is the rectangular pulse with amplitude $U$ and duration $\tau$, $V = \frac{\pi D^2}{4} L$ is the volume of the BiSn cylinder (D is the diameter of the metal column and L is the length of the metal column), $R_0$ is the resistance of the component at 24 °C, $\alpha_R$ is the temperature coefficient of the resistance of BiSn alloy.

The above partial differential equations can be solved by the finite element technique using the commercial software FlexPDE. Fig. 4.18 illustrates the finite element mesh used for the presented case.
Figure 4.18. Finite element mesh. Left electrode is active, right electrode is passive.

The solutions of this set of equations allowed finding the time-dependent strain components in the x- and y-directions ($\varepsilon_x$ and $\varepsilon_y$) of the fibre, the temperature distribution over the core and to calculate the FBG wavelength shifts in x- and y-polarizations according to the following formula [110, 111]:

$$\Delta \lambda_x = -\lambda_x \frac{n_0^2}{2} \left( p_{11} \varepsilon_x + p_{12} \varepsilon_y \right) + \lambda_x \left( \alpha + \xi \right) \Delta T$$

(4.33)

$$\Delta \lambda_y = -\lambda_y \frac{n_0^2}{2} \left( p_{11} \varepsilon_y + p_{12} \varepsilon_x \right) + \lambda_y \left( \alpha + \xi \right) \Delta T$$

(4.34)

where: $\lambda_x$ and $\lambda_y$ are the initial Bragg wavelength for x- and y-polarizations of FBG2; $n_0$ is the initial effective refractive index of the core; $p_{11}$ and $p_{22}$ are the photoelastic coefficients of the fibre; $\alpha$ is the thermal expansion coefficient of silica; $\xi = (1/n)(dn/dT)$ is the thermo-optic coefficient of fused silica; $\Delta T$ is the increased temperature in the core. The first terms of Eq. 4.33 and 4.34 stand for the wavelength shift of both polarizations due to mechanical stress in the core, while the second terms of two equations indicate the wavelength shifts caused by the increased temperature in the core. The values of parameters used in the simulations are listed in Table 4.3. Note that, the exact value of the heat capacity and the thermal expansion coefficient of the Bi$_{47}$Sn$_{53}$ alloy and the Ge-doped silica fibre are...
unknown. They are optimized during the simulation process for excellent fitting of the simulation results to the experimental data in Fig. 4.17.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Bragg wavelength (nm)</td>
<td>$\lambda_x = 1547.280, \lambda_y = 1547.323$</td>
</tr>
<tr>
<td>Hole diameter ($\mu$m)</td>
<td>D = 28.8</td>
</tr>
<tr>
<td>Core diameter ($\mu$m)</td>
<td>8.4</td>
</tr>
<tr>
<td>Hole-core separation ($\mu$m)</td>
<td>13.4</td>
</tr>
<tr>
<td>Fibre diameter ($\mu$m)</td>
<td>125</td>
</tr>
<tr>
<td>Component resistance at 24 °C (Ω)</td>
<td>$R_0 = 43.2$</td>
</tr>
<tr>
<td>Length of the metal column (cm)</td>
<td>L = 7</td>
</tr>
<tr>
<td>Temperature coefficient of the component resistance (K$^{-1}$)</td>
<td>$\alpha_R = 3.368 \times 10^{-3}$</td>
</tr>
<tr>
<td>Refractive Index of silica at 1.55 μm</td>
<td>1.445</td>
</tr>
<tr>
<td>Pulse duration (ns)</td>
<td>$\Delta t = 241$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Silica</th>
<th>Bi$<em>{47}$Sn$</em>{53}$ alloy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young modulus (GPa)</td>
<td>$E = 73$</td>
<td>$E = 43$</td>
</tr>
<tr>
<td>Poisson ratio</td>
<td>$\mu = 0.17$</td>
<td>$\mu = 0.40$</td>
</tr>
<tr>
<td>Thermal expansion coefficient (K$^{-1}$)</td>
<td>$\alpha = 5 \times 10^{-7}$</td>
<td>$\alpha = 15.35 \times 10^{-6}$</td>
</tr>
<tr>
<td>Density (kg/m$^3$)</td>
<td>$\rho = 2200$</td>
<td>$\rho = 8560$</td>
</tr>
<tr>
<td>Thermal conductivity (W/(mK))</td>
<td>1.38</td>
<td>19</td>
</tr>
<tr>
<td>Heat capacity (J/(kgK))</td>
<td>$C = 736$</td>
<td>$C = 167$</td>
</tr>
<tr>
<td>Photoelastic constants of silica [112]</td>
<td>$p_{11} = 0.121, p_{22} = 0.270$</td>
<td></td>
</tr>
<tr>
<td>Thermo-optic coefficient of silica (K$^{-1}$)</td>
<td>$\xi = 6.5 \times 10^{-6}$</td>
<td></td>
</tr>
</tbody>
</table>

**Table 4.3.** Parameters used for numerical simulation.
Stress at the BiSn/cladding boundary increases approximately linearly during the electrical pulse action, and then gradually decreases with time. This stress is transferred to the core area in \( \sim 14 \ \mu m / 5720 \ m/s = 2.34 \ ns \), i.e. almost instantaneously compared to the pulse duration 241 ns. However, the heat at the BiSn/cladding interface needs several microseconds to reach the core area. As a result, the heat diffusion can be neglected during the electrical pulse action. The fast wavelength shifts \( \Delta \lambda_{M}^{x} \) and \( \Delta \lambda_{M}^{y} \) are determined by the first terms of Eq. 4.33 and 4.34 at \( t = 241 \ ns \). The choice \( C = 167 \ J/kgK \) and \( \alpha = 15.5 \times 10^{-6} \ K^{-1} \) for the alloy and \( C = 736 \ J/kgK \) for the fibre allowed for excellent fitting of the numerical simulations (blue lines) of \( \Delta \lambda_{M}^{x} \) and \( \Delta \lambda_{M}^{y} \) to the experimental data from Fig. 4.17(d) (blue triangles) and 4.17(f) (blue squares), as shown in Fig. 4.19.

As mentioned above, the slow wavelength shift is caused by the relaxation of mechanical stress and the increased temperature in the core. It can be calculated from Eq. 4.33 and 4.34 for both polarizations. The simulations of \( \Delta \lambda_{TM}^{x} \) accurately reproduce the experiment measurements when the thermal expansion coefficient for the silica fibre is optimized to the value \( \alpha = 0.50 \times 10^{-6} \ K^{-1} \), shown by the blue line and triangles in Fig. 4.20. The simulation of the wavelength shift for the y-polarization now has no free parameters for adjustment. The result (red line in Fig. 4.20) fits the experimental data (red squares in Fig. 4.20) relatively well. The numerical predictions are smaller than the measured values. The small discrepancy could possibly be attributed to a temperature variation taking place during the measurement. For example, the difference between the calculated and measured \( \Delta \lambda_{TM}^{y} \) at the pulse voltage 1015 V corresponds to a temperature shift of 0.8 °C, well within the temperature uncertainty in the laboratory, which could have been rising during the measurement. The complete simulations here agree well with a simple quadratic fit to the data for \( \Delta \lambda_{M} \) and \( \Delta \lambda_{TM} \) (for both polarizations) as a function of the pulse voltage.
4.4. Numerical simulation

Figure 4.19. Experimental data (blue triangles and red squares) and numeric simulations (blue and red lines) of the fast Bragg wavelength shifts of FBG2 for a 241-ns electrical pulse.

Figure 4.20. Experimental data (blue triangles and red squares) and numeric simulations (blue and red lines) of the slow Bragg wavelength shifts of FBG2 for a 241-ns electrical pulse.
The simulations confirm that the core area is compressed (negative) in x-direction and stretched (positive) in y-direction during the electrical pulse action, as shown in Fig. 4.21(a). Rectangular 241-ns pulse was applied at $t = 20$ ns instead of $t = 0$ in order to overcome some technical difficulties related to FlexPDE program. For the pulse with applied voltage $1080$ V, $\varepsilon_x = -1.655 \times 10^{-4}$ and $\varepsilon_y = 2.535 \times 10^{-4}$ at $t = 261$ ns. This results in a decrease of refractive index in x-direction ($-7.3 \times 10^{-5}$) and a weaker increase of refractive index in y-direction ($+2.11 \times 10^{-5}$), as shown in Fig. 4.21(b), corresponding to $\Delta \lambda^x_{M} = -75.8 \text{ pm}$ and $\Delta \lambda^y_{M} = +23.7 \text{ pm}$. One can conclude that the fast axis mode is in the direction parallel to the two holes (x-direction), and the slow axis mode is in the direction orthogonal to the two holes (y-direction).

Under a 960-V electrical pulse excitation, the wavelength shift for the x-polarization ($\Delta \lambda_x$) of FBG2 as a function of time is shown in Fig. 4.22. From this figure, one can find that $\Delta \lambda_x$ becomes negative (-57.5 pm) following the excitation of electrical pulses. Then it equals zero at a calculated time $t_2 = \sim 56$ $\mu$s, when the two terms of Eq. 4.33 compensate each other. Subsequently, the second term dominates and $\Delta \lambda_x$ becomes positive and increases gradually due to the increasing $\Delta T$. The shift reaches its maximum (+40.3 pm) at a calculated time $t_3 = \sim 250$ $\mu$s.

Similarly, Fig. 4.23 shows the wavelength shift for the y-polarization ($\Delta \lambda_y$) of FBG2 under electrical pulse excitation with different voltages. As shown in this figure, it is clear that $\Delta \lambda_y$ becomes positive during the electrical pulse action. After that, it reduces because the decay of the stress dominates over the rising effect of heat. At a calculated time $t_2 \sim 17$
μs the latter starts to dominate and the shift increases again until it reaches the maximum value at a calculated time \( t_3 \sim 200 \, \mu s \).

Figure 4.22. Wavelength shift for the x-polarization of FBG2 under a 960-V electrical pulse excitation.

Figure 4.23. Wavelength shift for the y-polarization of FBG2 under electrical pulse excitation with different voltages.
Under different pulse excitation, the simulation result of the time evolution of the temperature in the core centre is illustrated in Fig. 4.24. As shown in this figure, the heat in the metal takes ~10 µs to reach the core and increases to the maximum at ~190-220 µs. Note that the maximum $\Delta T$ in the metal is as high as ~90 ºC for a corresponding core temperature increase of only ~6.2 ºC.

Figure 4.24. Simulation results of the time evolution of the temperature in the centre of the core under different voltage pulse excitation.
Chapter 5

Switchable Dual-wavelength Fibre Lasers

FBGs are ideal components for fibre lasers due to their unique advantages such as ease of use, low cost and their extreme and designable wavelength selectivity. This chapter presents two methods to achieve dual-wavelength switching in a fibre laser based on FBG feedback (Paper VII-IX). The detailed behaviour of the dual-wavelength switching in these two fibre lasers was experimentally studied and the underlying physical mechanisms are explained.

5.1 Raman erbium-doped fibre laser

As is well known, an EDF can be regarded as a homogenously broadened gain medium at room temperature [19, 31, 113]. This property allows achieving wavelength-switching in the EDF lasers due to the gain competition between different wavelengths. Overlapping cavities can be used for multi-wavelength lasing and wavelength switching can be achieved by controlling the loss or the gain in different cavities [20, 22]. Here, an overlapping cavity is designed for lasing at two wavelengths (corresponding to the Bragg wavelengths of two FBGs) and both an EDF pump (for the EDF gain medium) and a Raman pump (for the Raman gain medium) are employed. Dual-wavelength switching can be achieved by controlling the power of the Raman pump. As far as know, this proposed fibre laser was the first one combining Raman amplification and EDF amplification to achieve multiwavelength switching.
5.1.1 Experimental setup

The schematic configuration of the proposed switchable dual-wavelength fibre laser is shown in Fig. 5.1. A 1480 nm laser diode (LD) with a maximum power of ~ 250 mW is used as the EDF pump LD1, and a 1467 nm LD with a maximum power of 350 mW is employed as the Raman pump LD2. The length of the SMF section between the two FBGs is 10 km. Sections of SMF, dispersion compensation fibre (DCF) and 4-m long EDF are the gain fibres in the present structure. Two FBGs are used as wavelength selective components. The central wavelengths, FWHMs and reflectivities are (1545.13 nm, 0.093 nm, 50.0%) and (1559.98 nm, 0.098 nm, 51.3%) for FBG1 and FBG2, respectively. An optical circulator (OC) and an isolator are used to ensure that the ring laser cavity is a oscillating counterclockwise.

There are two lasing cavities with wavelengths $\lambda_1 = 1545.13$ nm (around the EDF gain peak) and $\lambda_2 = 1559.98$ nm (around the Raman gain peak corresponding to pump wavelength 1467 nm). The power of EDF pump LD1 is always fixed at a certain level, and the power of Raman pump LD2 is used to control the output wavelength and power.

![Figure 5.1. Schematic configuration of the Raman erbium-doped fibre lasers. LD: Laser diode; WDM: Wavelength division multiplexing; EDF: Erbium-doped fibre; ISO: Isolator; OC: Optical circulator; FBG: Fibre Bragg grating; SMF: Single mode fibre; DCF: Dispersion compensation fibre.](image)

5.1.2 Results and analysis

In the experiments, the power of LD1 is fixed at 150 mW. When LD2 is switched off, the output spectrum of the laser is shown by the black solid line in Fig. 5.2, from which one can see that the structure is lasing only at $\lambda_1$ with a peak power of -11.9 dBm. However, when the drive current of LD2 is switched on to 750 mA, the structure will be lasing only at $\lambda_2$ with a peak power of 1.9 dBm (see the red dashed line in Fig. 5.2). The resolution and
sensitivity of the OSA used for all the measurements in this chapter are 0.06 nm and -65 dBm, respectively. Experimental results have shown that the laser output is rather stable. Thus, dual-wavelength switching is achieved in this fibre laser by controlling the drive current of LD2 (i.e., the power of the Raman pump LD2).

![Output spectra of the proposed fibre laser](image)

Figure 5.2. Output spectra of the proposed fibre laser when the drive current of LD2 is switched off (black solid line) or switched on to 750 mA (red dashed line). The power of the EDF pump is fixed to 150 mW.

### 5.1.3 Characteristics of the dual-wavelength switching

Fig. 5.3 shows the detailed behaviour of the dual-wavelength switching as the drive current of LD2 increases (the pump power of LD1 is still fixed at 150 mW). The variation of output power at $\lambda_1$ and $\lambda_2$ are indicated by the lines shown by circles and triangles, respectively. Obviously, there are three regions where the laser is in different operational modes. In region A (with the drive current for LD2 below switching current $I_a = 70$ mA), only $\lambda_1$ is lasing and its output power remains around -11.9 dBm. In region B (with the drive current for LD2 ranging from 70 mA to 690 mA), both $\lambda_1$ and $\lambda_2$ are lasing. In this region, as the drive current of LD2 increases, the output power at $\lambda_2$ increases while that at $\lambda_1$ decreases. In region C (with the drive current for LD2 above switching current $I_b = 690$ mA), only $\lambda_2$ is lasing and its output power remains around 1.9 dBm.

The operation principle of the present switchable dual-wavelength fibre laser can be explained as follows. When the Raman pump LD2 is off, only lasing at $\lambda_1$ can be obtained since the cavity loss at $\lambda_2$ is larger than that at $\lambda_1$ (due to the loss of the 10-km SMF) and the
EDF amplification will occur only at $\lambda_1$ (due to the gain competition). When the power of LD2 increases gradually, the Raman gain mainly contributes to the amplification at $\lambda_2$ since $\lambda_2$ is much closer to the Raman gain peak wavelength than $\lambda_1$. Thus, the structure starts lasing at $\lambda_2$ when the pump power of LD2 reaches a certain level. Consequently, the power of the lasing at $\lambda_1$ decreases as the pump power of LD2 increases since the lasing at $\lambda_2$ will reduce the population inversion in the EDF. When the pump power of LD2 increases further, lasing at $\lambda_1$ disappears finally.

![Figure 5.3](image1.png)

Figure 5.3. Output powers at the two lasing wavelengths against the drive current for LD2 for a fixed 150 mW power of LD1.

![Figure 5.4](image2.png)

Figure 5.4. Switching currents $I_a$ and $I_b$ for LD2 when the power of LD1 is set to different values.
5.2. Tuneable and injection-switchable EDF laser

The wavelength switching has also been studied when the pump power of LD1 is fixed at some other values. Experimental results show that the characteristics of the wavelength switching are similar (except the switching currents \( I_a \) and \( I_b \)) when the pump power of LD1 is set to different values. Fig. 5.4 shows the switching currents \( I_a \) (black squares) and \( I_b \) (black dots) when the pump power of LD1 is set from 20 mW to 160 mW with an increment of 20mW. The switching current \( I_a \) decreases as the pump power of LD1 increases. This can be explained as follows. The cavity gain for \( \lambda_2 \) to start lasing is a constant, which is the sum of EDF gain and Raman gain. Thus, the larger EDF pump is set, the smaller Raman gain is needed for \( \lambda_2 \) to start lasing (corresponding to a smaller switching current \( I_a \)). The variation of \( I_a \) under different pump powers of LD1 is quite small, while the variation of \( I_b \) is quite large. As shown in Fig. 6.4, the switching current \( I_b \) increases almost linearly with the pump power of LD1. This indicates that a larger drive current for LD2 is needed in order to let \( \lambda_2 \) win the gain competition over \( \lambda_1 \) when the pump power of LD1 increases.

5.2 Tuneable and injection-switchable EDF laser

Recently, Dragic et.al have reported an injection-seeded erbium-doped fibre laser [114-116], in which an injection technique was used to achieve a wavelength switchable fibre laser. A tunable laser (outside the cavity of the fibre laser) is used as seeding light. The shared cavity is for self-seeded lasing or injection-seeded lasing. Switching between the self-seeded wavelength lasing and injection-seeded wavelength lasing can be achieved by controlling the power of the injection laser. By using this technique, one of the switching wavelengths can be tuned among a large range since a tuneable injection laser is employed. In the following section, a tuneable and dual-wavelength switchable EDF laser of line structure employed an injection technique is presented. The dual-wavelength switching is achieved by controlling the power of the injection laser.
5.2.1 Experimental setup

![Schematic configuration of the injection-switchable fibre laser](image)

The experimental setup of the presented fibre laser is schematically illustrated in Fig. 5.5. A 980 nm LD with a maximum power of ~150 mW is used as an EDF pump, and a tunable (from 1500 nm to 1590 nm) laser diode (TLD) with a maximum power of about 10 mW is employed as the injection laser. The line structure cavity is formed by a wideband sagnac loop reflector and an FBG. The central wavelength, FWHM and reflectivity of the FBG are 1550.48 nm, 0.096 nm and 53.2%, respectively. The seeding light is injected into the cavity through a circulator. A section of 4-m long EDF is employed as the gain medium. Dual-wavelength switching is achieved by controlling the power of the injection laser. One lasing wavelength corresponds to the Bragg wavelength of the FBG (can be tuned by changing the temperature or stress) and the other lasing wavelength can be tuned from 1535 to 1590 nm (determined by the wavelength of the injection laser).

5.2.2 Results and analysis

In the experiment for the injection-switchable fibre laser, the power of the EDF pump LD is fixed at 16.2 mW. When the injection laser TLD is switched off, the output spectrum of the laser is shown by the black solid line in Fig. 5.6. At this state, the structure is lasing only at \(\lambda_1 = 1550.48\) nm (equal to the central wavelength of the FBG) with a peak power of -4.88 dBm. When the injection laser TLD (with tuneable wavelength \(\lambda_2\); for this figure \(\lambda_2 = 1555\) nm) is switched to -6.0 dBm (or larger), the structure will be lasing only at \(\lambda_2 = 1555\) nm with a peak power of -3.16 dBm (see the red dashed line in Fig. 5.6). In this case, the injection light is amplified by a two-pass traveling-wave amplifier. Thus, the wavelength
switching can be achieved in this fibre laser by controlling the power of the injection laser.

![Output spectra of the injection-switchable EDF laser](image)

Figure 5.6. Output spectra of the injection-switchable EDF laser when the injection laser is switched off (black solid line) or switched on to -6 dBm (red dashed line). The power of the EDF pump is fixed at 16.2 mW.

### 5.2.3 Characteristics of the dual-wavelength switching

Fig. 5.7 shows the detailed behaviour of the dual-wavelength switching as the power of the injection laser TLD increases (the power of 980 nm LD is fixed at 16.2 mW). The output powers at $\lambda_1$ and $\lambda_2$ are indicated by the lines connected with circles and triangles, respectively. Obviously, when the injection laser is switched off, the proposed fibre laser is simply an EDF laser with an output wavelength of $\lambda_1$. However, when the injection laser is switched on and its output power increases, there are two regions where the laser is in different operational modes. In region A (with the TLD power below the switching power $P_s = -6.6$ dBm), both $\lambda_1$ and $\lambda_2$ are lasing. In this region, as the TLD power increases, the output power at $\lambda_2$ increases while that at $\lambda_1$ decreases. In region B (with the TLD power larger than the switching power $P_s$), the lasing occurs only at $\lambda_2$ and its output power remains around -3.16 dBm. Fig. 5.8 shows a good linear relationship between the pump power and the switching power $P_s$ when the wavelength of the TLD is fixed at 1555 nm.

The operation principle of the present injection-switched EDF laser can be explained as follows. When the injection laser TLD is switched off, only lasing at $\lambda_1$ can occur since the cavity of the line structure only exists at the Bragg wavelength $\lambda_1$ of the FBG. When the TLD is switched on, the seeding light is injected into the cavity and is amplified (traveling
with a round trip on the EDF). In this case, the seeding light will reduce the population inversion required for lasing at $\lambda_1$ (the cavity gain at $\lambda_1$ decreases). Consequently, the output power at $\lambda_1$ decreases as the TLD power increases. When the power of the TLD is large enough and approaches $P_s$, the emission stimulated by the seeding light at wavelength $\lambda_2$ consumes most of the pump power (i.e., reduces the population inversion) and consequently the cavity gain becomes less than the cavity loss at $\lambda_1$ (i.e., the lasing at $\lambda_1$ becomes impossible). This result in a drastic drop of the power at $\lambda_1$ and finally only the output at $\lambda_2$ can be observed.

Figure 5.7. Output power at the two wavelengths as the power of the injection laser increases when the power of the 980 nm pump LD is fixed at 16.2 mW.

Figure 5.8. Relationship between the switching power $P_s$ and the power of the 980 nm pump LD when the wavelength of the TLD is fixed to 1555 nm.
The characteristics of the dual-wavelength switching have been studied further. Fig. 5.9 shows the switching powers for different wavelengths of the TLD when the power of the 980 nm pump LD is fixed at 16.2 mW (curve connected with squares) or 19.1 mW (curve connected with circles). From this figure, one can see that the wavelength switching can be achieved over a wide wavelength range (about 50 nm) for the TLD. The V-shape curves indicate that the wavelength switching is easier when the TLD wavelength is around 1560 nm and a larger switching power is needed when the TLD wavelength is far away from 1560 nm. The saturated gain spectrum of the (one round trip) EDFA structure (just removing the FBG in Fig. 5.5) was also measured, when the pump power is 16.2mW. This figure shows that the gain peak is around 1560 nm, explaining why the switching power is minimal around 1560 nm. Furthermore, from Fig. 5.9, one can see that the difference in the switching powers for the two lines is almost a constant (4.6dBm) for different TLD wavelengths, which is due to the linear relationship between the switching power (in mW) and the power of the 980 nm pump LD (as shown in Fig. 5.8)

Figure 5.9. Switching power as the wavelength of the TLD increases when the pump power is fixed at 16.2 mW (curve connected with triangles) or 19.1 mW (curve connected with circles). Inset: The saturated gain spectrum of the one round trip EDFA at different wavelengths of the TLD when the power is fixed at 16.2 mW.
5.2.4 Measurement of the switching time

The transient switching response of the proposed laser has also been studied when the power of the 980 nm pump LD is 16.2 mW and the TLD wavelength is fixed at 1548.6 nm (due to the availability of a filter in the lab for measuring the laser output at a specific wavelength). Two InGaAs Photodetectors (PDA400, provided by Thorlabs, Ltd. UK) were employed to measure the time delay between the moment when the injection laser was switched on and the moment when the lasing at $\lambda_1$ disappears. From the results shown in Fig. 5.10, the time delay (i.e., the switching time) is measured to be less than 50 $\mu$s, indicating that the proposed laser has the ability of fast wavelength-switching.

![Figure 5.10: Transient switching response](image)

Figure 5.10. Transient switching response (measured with photodetectors) of the proposed fibre laser when the power of the 980 nm pump LD is 16.2 mW and the TLD wavelength is fixed at 1548.6 nm.
Chapter 6

Conclusions and Future Works

This thesis focuses on the applications of fibre Bragg gratings to high speed wavelength switching, direct microwave optical filtering and switchable dual-wavelength fibre lasers.

Linear FBGs were written in side-hole fibres with internal electrodes. The gratings exhibit two reflection peaks due to the intrinsic birefringence of the used fibre, the shorter one associated with the fast axis. Under the excitation of nanosecond high current electrical pulses, wavelength switching with a response time of ~29 ns has been achieved in a FBG component. As far as know, there is no published report from other people on nanosecond tuning FBGs. Besides, it is found that the results obtained with the FBG switch allow for elucidating the involved physics of fibres with metal electrodes expanding under dynamic conditions, which often deviates from intuitive. Initially, only the observations in the first 200 ns are discussed, related to the mechanical effect. Nanosecond electrical pulses heat the metal electrode and cause metal expansion on a nanosecond scale. The mechanical stress compresses the core in the direction of the holes (fast axis direction), and at the same time it stretches the core in the slow axis direction. This leads to a small increase of the index experienced by light polarized perpendicular to the direction of the holes. In contrast, light polarized along the direction of the holes experiences a larger and negative index shift. The results are at first sight puzzling, but can be simulated with excellent agreement with the experiments.
Microseconds later, the relaxation of the mechanical stress and the effect of heat reaching the core red-shifts both Bragg peaks. After a couple of hundred microseconds, the temperature of the core reaches its maximum and the increase of refractive indices for both polarization modes. Once again, simulations are in good agreement with measurements. Simulations also show that although the temperature of the metal can rise by 90 °C, the increase at the core is limited to only 6.2 °C. It is found, perhaps not surprisingly, that both the mechanical and thermal effects depend on the square of the pulse voltage (into the 50 Ω cable), and linearly on the electrical pulse duration.

Since direct optical filtering of microwave signals is still in its infancy and has not been studied very extensively, a review of the more general field of the optical microwave filtering has been presented. A general comparison has been made between direct optical filtering and the more established incoherent filtering technique. The direct optical filtering is mostly suitable for large microwave frequencies (basically MMWs) and is potentially cost effective and should probably be able to meet particular requirements of future MMW communication systems. The cost-effectiveness comes from the fact that these filters have both optical input and output, which are fully compatible with optical transmission of MMW signals (necessary at these frequencies to reduce the attenuation of their distribution). The concept of direct detection proposed in this thesis contributes to a substantial cost reduction. The direct microwave optical filtering technique combined with direct detection has been demonstrated using a single double-peaked superimposed grating working in reflection. The grating filter exhibits nearly on-off behaviour with a FWHM of ~2 GHz through BER and eye-diagram measurements. The presented technique can be applied in RoF systems comprising more than one RF signal. Thermal stabilization of grating wavelength is necessary for good function of the grating filter.

Wavelength switchable fibre lasers have a variety of important applications and FBGs are ideal wavelength selection components for fibre lasers. Two switchable dual-wavelength erbium-doped fibre lasers based on FBG feedback were proposed and demonstrated in this thesis. In one proposed fibre laser, an overlapping cavity for the two lasing wavelengths and hybrid gain medium (Raman amplification and EDF amplification) were employed. Dual-wavelength switching was achieved by controlling the Raman pump power. As far as known, this fibre laser is the first to combine Raman amplification and EDF amplification to achieve multiwavelength switching. Compared with other switchable multi-wavelength fibre lasers, which were only based on EDF amplification, the present
structure is simple (requiring no polarization controllers of special fibre/device) and the separation of the dual wavelengths can be very large (since the wavelength of Raman pump can be arbitrary, which is impossible for EDF amplification). In the other fibre laser, an injection technique was used and the dual-wavelength switching was controlled by the power of the injection laser. A fibre SLR and a FBG form the line structure cavity. Compared with a fibre ring laser, this laser has the advantages of tunability, stability, low amplified spontaneous emission noise and high injection efficiency. The detailed characteristics of the dual-wavelength switching in the two fibre lasers were experimentally studied and corresponding principles were physically explained.

Possible future works include:

1. Long and complex-structured FBGs can presently be realized, there is a large degree of freedom in designing such gratings for various applications. However, a lot of efforts still need to be put on the quality and the yield of the fabrication.

2. The nanosecond switching of the linear FBG component can have potential application in Q-switched fibre lasers, 2x2 fibre switching, high speed sensor readout, gated spectroscopy, and so on.

3. Research on phase shifted gratings and chirped gratings written in side-hole fibres with electrodes has already started. These components have potential applications in dual-wavelength single-longitudinal mode fibre lasers, microwave optical signal generators, wavelength sweeping and radar warning systems.

4. Further efforts in the development of direct optical filtering of microwave signals can be concentrated in achieving larger Q-factors. One promising direction is the use of phase-shifted strong chirped FBGs.

As a general conclusion, FBGs are important components for a large number of applications in optical communications, fibre sensors, fibre lasers, and so on. It is difficult to think of fibre-optic systems without FBGs as it is to think of bulk optics without the familiar laboratory mirrors.
Chapter 7

Summary of Papers

Paper I  Direct Detection of Direct Optically Filtered Millimeter-wave Signals.
Good performance of a direct optical microwave filter combined with direct detection consisting of a single superimposed grating used in reflection has been assessed through BER measurement. In the passband with the centre frequency of 20 GHz and a FWHM of 2 GHz (as expected from the optical reflection spectrum of the grating), the BER is below $1.2 \times 10^{-11}$, showing nearly on-off behaviour of the filter. Such an optical filter with cost effective detection scheme can be applied in RoF systems.

Contributions of the author: Part of the original idea, all the experiment work, and the first draft of the manuscript.

Paper II  High-speed control of fiber Bragg gratings.
FBGs were written in side-hole fibres with internal alloy electrodes. Nanosecond high current pulses cause metal expansion, increase birefringence and tune the gratings. Close to full on-off and off-on switching with a response time of ~60 ns was accomplished. Such a component has potential use in Q-switching fibre lasers.

Contributions of the author: Part of the original idea, most of the experiment work, and revised the manuscript.

Paper III  Nanosecond switching of fiber Bragg gratings.
A 4-cm long Hamming-apodized FBG was written in a twin-hole fibre with internal
alloy electrodes. Temperature dependence measurements showed that the birefringence increased as the temperature increased, due to the gradual expansion of metal column. A larger temperature sensitivity was obtained due to the fibre was attached to the Al substrate with a much larger thermal expansion coefficient. Dynamic measurements for the two polarizations under the electrical pulse excitations were also carried out. Nanosecond high current pulses heated the metal electrode and caused metal expansion rapidly. In consequence, birefringence was increased and the grating was tuned. Full on-off and off-on switching with a response time of ~29 ns was achieved for the fast axis mode. The nanosecond FBG response is attributed to a mechanical effect, while heat transporting to the core is slow and determines the recovery time of the device after every drive pulse. It is believed that the short length, low loss, all-spliced high-speed devices described here can find useful application for Q-switching fibre lasers.

**Contributions of the author:** Part of the original idea, most of the experiment work, and the first draft of the manuscript.

**Paper IV** Physics of electrically switched fiber Bragg gratings.

In this Paper, we report on the physics of electrically switched FBGs written in a twin-hole fibre with internal electrodes. For the fast axis mode, wavelength shifts due to mechanical effects (in tens of nanoseconds) and heat (in many microseconds) depend quadratically on the electrical pulse voltage and linearly on pulse duration.

**Contributions of the author:** Part of the original idea, all the experiment work, and the first draft of the manuscript.

**Paper V** Birefringence switching of Bragg gratings in fibers with internal electrodes.

A FBG was written in a side-hole fibre with internal metal alloy electrodes. The initial geometrical birefringence of this fibre gives rise to two Bragg resonances separated by 43 pm. Nanosecond rise time current pulses of up to 23 A were applied to the metal electrode, which heated and expanded rapidly. On a nanosecond scale, the fast Bragg wavelength shift of the fast axis mode is negative and that of the slow axis mode is positive and smaller, because of the mechanical perturbation. The fast change increased the peak separation to ~ 143 pm, corresponding to an increase in birefringence from 4.0×10<sup>-5</sup> to 1.3×10<sup>-4</sup>. Microseconds later, the relaxation of the mechanical stress and the effect of heat reaching the core red-shift both Bragg peaks.
All wavelength shifts depend quadratically on the electrical pulse voltage. Numerical simulations were developed to accurately and quantitatively explain the experimental observations.

*Contributions of the author:* Part of the original idea, all the experiment work, and the first draft of the manuscript.

**Paper VI** High-speed switching in fibres with electrodes.

Fibres with holes are provided with metal electrodes that fill the entire cross-section of the holes. Refractive index change and birefringence result from applying high current pulses for time intervals in the nanosecond range. High-speed polarization rotation and fibre Bragg grating wavelength tuning can be accomplished. Such electrically driven components are totally spliced with low insertion loss. They have no moving parts, are less than 10 cm long and can be used in fibre laser cavities for Q-switching.

*Contributions of the author:* Part of the experiment work.

**Paper VII** Switchable dual-wavelength Raman erbium-doped fibre laser.

A FBG feedback fibre laser with both Raman and EDF pumps is proposed. Dual-wavelength switching is achieved by controlling the power of the Raman pump. The characteristics of the dual-wavelength switching under different EDF pump levels are studied experimentally, and the mechanism is explained physically. The output power and wavelength of the present switchable dual-wavelength fibre laser are repeatable and uniquely determined by the Raman pump power.

*Contributions of the author:* Part of the original idea, part of the experiment work, and revised the manuscript.

**Paper VIII** Some switchable dual-wavelength fibre lasers based on fibre bragg grating feedback.

Two methods to achieve switchable dual-wavelength fibre lasers are proposed and the corresponding fibre lasers based on FBG feedback are demonstrated in this Paper. The first proposed fibre laser employs both Raman and EDF pumps and the dual-wavelength switching is achieved by controlling the power of the Raman pump. In the second fibre laser, an injection technique is used and the dual-wavelength switching is realized by controlling the power of the injection laser. The detailed
behaviour of the dual-wavelength switching in the two fibre lasers is experimentally studied and the principles are explained physically.

**Contributions of the author:** Part of the original idea, part of the experiment work, and revised the manuscript.

**Paper IX** Tunable and injection-switchable erbium-doped fiber laser of line structure.

A tunable and injection-switchable EDF laser is proposed based on a line structure formed by a fibre Sagnac loop reflector and a FBG. Wavelength switching is achieved by controlling the power of the tunable injection laser. The self-seeded wavelength corresponding to the Bragg wavelength of the FBG can be tuned by e.g. heating the FBG and the injection wavelength can be tuned over a wide range of about 50 nm. The characteristics of the wavelength switching for different levels of the EDF pump power and different wavelengths of the injection laser are studied experimentally. The presented fibre laser has the advantages of tunability, stability, low amplified spontaneous emission noise and high injection efficiency as compared with a fibre ring laser. The switching time is measured to be less than 50 microsecond.

**Contributions of the author:** Revised the manuscript.
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Paper I
Direct Detection of Direct Optically Filtered Millimeter-Wave Signals

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Abstract—Good performance of a direct optical microwave filter combined with direct detection consisting of a single superimposed gratings used in reflection has been assessed through bit-error-rate (BER) measurement. In the passband with a 3-dB bandwidth of 2 GHz, the BER is below $1.2 \times 10^{-11}$, showing nearly ON-OFF behavior of the filter.

Index Terms—Bit-error-rate (BER) measurement, fiber Bragg gratings (FBGs), optical microwave filtering.

I. INTRODUCTION

For microwave signals at frequencies higher than a few gigahertz, optical filters [1], [2] can be an advantageous alternative to conventional electrical ones [3], [4]. Most microwave optical filters use the incoherent summing of delayed copies of a modulated optical signal at the photodetector [5]–[8]. One major limitation of this technique is that it requires light sources with short temporal coherence. Direct microwave optical filtering, proposed and demonstrated a few years ago [9], [10], can, however, work with coherent light sources [11], [12]. For that purpose, fiber Bragg gratings (FBGs) [11]–[14] are usually better than Fabry–Pérot etalons [9], [10] in terms of spectral characteristics and stability.

In this letter, we demonstrate direct optical filtering combined with direct detection using a single double-peaked superimposed FBG working in reflection [15]. The direct detection requires the suppression of the optical carrier by the optical filter (together with all undesired spectral components) and only the two sidebands (20 GHz in our case) of the optical carrier with a good extinction ratio are supplied to the photodetector. The ability of the filter to remove out-of-band signals is tested by measuring digital signals at 155 MB/s placed on a millimeter-wave subcarrier. The direct-detection scheme excludes the necessity of the down-conversion of the high-frequency signal to an intermediate frequency in the detection part and thus spares a local oscillator, a mixer, and an envelope detector, which were needed in the configuration of our previous work [12]. Note that in this case the optical carrier is also spared for other subcarriers it may carry and, therefore, the composite signal (the optical carrier with nonfiltered subcarriers) can be transported further in the optical link. The possibility for heterodyne detection and active locking [12] of the remaining subcarriers is thus preserved.

II. EXPERIMENT

The basic principle of the direct detection for the direct optical filtering of microwave signals using a superimposed FBG in reflection is illustrated in Fig. 1. Two gratings are written at the same location forming what is usually called a superimposed FBG [15]. Both of them have identical spectral characteristics but different resonance frequencies and work as passband filters for the sidebands of the millimeter-wave subcarrier to be processed. Perfect colocation and close to identical characteristics of the gratings imply that a negligible delay difference between the side modes is expected after reflection from the grating filter.

The experimental setup is depicted in Fig. 2. A mixer is used to modulate a microwave carrier at around 20 GHz with the 155-Mb/s digital signal at the output of the pattern generator. This modulated signal is then amplified and connected to the radio-frequency (RF) input of the optical Mach–Zehnder modulator (MZM). Light from a tunable laser is launched into the modulator after adjusting the input polarization with a polarization controller. The modulator is direct current biased to the inflexion point to obtain quasi-linear modulation regime. The output of the modulator is first amplified with an erbium-doped fiber amplifier before reflection on the superimposed FBG filter via a circulator. With this configuration, the FBG will work both as a channel selective device as well as an amplified spontaneous emission filter.

For the detection, the beating frequency between the two subcarriers (about 40 GHz) should be completely removed by the photodiode which had a bandwidth of 2 GHz and the first two amplifiers which had a bandwidth of 400 MHz. Note that the bandwidth of the photodiode in the direct detection can be as low as the bandwidth of the digital payload signal, i.e., 155 MHz.
in our case. Using a low-speed and low-cost photodiode provides additional savings in the direct-detection schemes. The STM-1 low-pass filter (LPF) with a cutoff frequency of 75% of 155 MHz is used to shape the digital payload signal. The amplifier after the STM-1 LPF is required to amplify the digital signal to a level compatible with the error detector of the bit-error-rate tester (BERT) device. To suppress thermal noise from this broadband (10 GHz) amplifier, an STM-16 LPF with a bandwidth of 75% of 2.5 GHz has been put after it. In general, such a broadband performance is not required at this stage of the detection (the choice of the components was based upon availability) and a substantially narrowband amplifier and filter could be used here.

For this experiment, two Hamming-apodized FBGs were written in a standard single-mode fiber with a length of 10 cm. The reflection spectrum of the grating used in the setup is shown in Fig. 3. The 3-dB bandwidth of the two gratings was about 2 GHz. The pass function of the filter in the microwave domain is hence expected to be about 2 GHz. Also, a full stop effect is expected outside this 2-GHz range. The reflectivity of each peak in the grating is about 45% and the wavelength separation between the center of the two peaks is about 320 pm corresponding to 40 GHz (i.e., for filtering at the subcarrier frequency of 20 GHz).

A key issue of the direct-detection experiment was to have a sufficient suppression of the optical carrier. At the optical MZM, the amplitude of the modulating subcarrier signal was kept sufficiently small to preserve the linearity of the modulation. This implies that in the optical domain, the optical carrier is clearly stronger than the sidebands which represent the subcarrier with the digital payload. On the other hand, for a proper detection of the digital signal, the level of the optical carrier has to be lower than those of the sidebands. In our case, this was guaranteed by the more than 20-dB suppression of the optical carrier provided by the grating (see Fig. 3). Special care was also taken to avoid parasitic reflections from connectors or splices.

### III. Results

The digital 155-Mb/s payload with a pseudorandom binary sequence of $2^{31} - 1$ was generated by the BERT device and then used to modulate in amplitude an electrical signal whose frequency was varied from 18.4 to 21.6 GHz. This electrical signal was then fed to the optical modulator. The optical wavelength was set to the optimal 1534.64 nm corresponding to the center wavelength between the two reflection peaks. The optical power and the optical signal-to-noise ratio before being reflected by the FBG kept constant as the frequency was changed. The bit-error-rate (BER) measurements as a function of the frequency have been recorded and eye diagrams have been taken at a number of frequency points. The results of these measurements are shown in Fig. 4. Outside the given range of frequencies, no measurement was possible because of synchronization loss.
As one can see, the passband width of the filter is about 2 GHz as expected from the optical spectrum of the grating. The BER performance in the passband of the filter shown by the flat part of the curve corresponds to the BER of $1.2 \times 10^{-11}$ or better. This performance was considered as excellent and more precise measurements were not conducted due to time constraints. Outside the passband, the quality of the signal quickly deteriorates demonstrating an almost ON–OFF behavior. The eye diagrams (the inset of Fig. 4) are of good quality within the passband and quickly closing outside the passband.

Finally, we made a simple experiment for using only one peak of the double-peaked grating. To do so, the optical carrier was placed to a wavelength longer than that of the right-hand peak of the grating so that the spacing between the peak and the optical carrier was 19 GHz (the first test) and 20 GHz (the second test). In this way, only a single (left) sideband of the composite optical signal was supplied to the photodetector. In both tests, the configuration demonstrated efficient filtering of the signal with the bandwidth of 2 GHz which matches well the optical bandwidth of this single peak. Naturally, the energy of the detected signal in this case was only half of the signal detected using both sidebands. These experiments prove the possibility of using the direct-detection technique for optical single sideband modulated signals and also for tunable filtering of the sidebands by means of tuning the wavelength of the grating.

The FBG filter, together with the direct-detection scheme presented in this letter, can be applied in radio-over-fiber (ROF) systems comprising more than one RF signal. Because of the narrow bandwidth of the superimposed FBG presented here, cascaded superimposed FBGs (with the same central wavelength but different wavelength separations of the two peaks, such as 320, 384, and 448 pm) can be used to filter corresponding RF signals (such as 20, 24, and 28 GHz, respectively). However, the narrow bandwidth of the filter also limits the maximum data rate, which would be 800 Mb/s in the case presented here.

IV. Conclusion

The good performance of a direct optical microwave filter combined with highly simplified direct detection consisting of a single double-peaked superimposed grating used in reflection has been assessed through BER measurements. The filter exhibits nearly ON–OFF behavior, where transmission is either error-free inside the passband (with the 3-dB bandwidth of 2 GHz) or basically impossible outside. Such an optical filter with a cost-effective detection scheme can be applied in ROF systems.

References

Paper II
High-Speed Control of Fiber Bragg Gratings

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Abstract: FBGs were written in fiber with internal alloy electrodes. Nanosecond high current pulses cause metal expansion, increase birefringence and tune the gratings. High-speed wavelength switching was accomplished with potential use in Q-switching fiber lasers.

Fibers with internal electrodes can be used in a number of interesting applications. Besides electrooptical switching and modulation, another recent functionality demonstrated was nanosecond polarization switching [1]. Increased birefringence results from the application of high current electrical pulses to an internal electrode that heats up and expands. The refractive index difference between fast and slow axis of the fiber with electrodes causes polarization change, and can lead to 90° rotation with proper input polarization alignment. In the present work, we studied how the high-speed expansion of metal electrodes affects the wavelength of a fiber Bragg grating written in the core of the fiber. The grating is an excellent tool to follow the evolution of the refractive index experienced by light in the polarization parallel (P) and orthogonal (S) to the direction of the holes. Besides revealing interesting physics, the nanosecond wavelength switching obtained here has potential application in Q-switching fiber lasers.

Pieces of fiber with a pair of 27-\textmu m diameter holes running parallel to the core were filled with internal electrodes that occupied the entire cross-section of the holes. BiSn or AuSn were used as low temperature melting alloys, pumped into the fibers as a liquid and used at room temperature as solid electrodes [2]. Electrical contact was made from the side of the fiber, thus allowing for conventional low loss splicing. The fibers were single-mode at 1.5 \textmu m and were provided with 7-cm long electrode sections. The edge-to-edge hole separation was 32 \textmu m. The insertion loss of the devices before FBG fabrication was as low as 0.2 dB. The fibers were H\textsubscript{2}-loaded for 2 weeks at 150 bar, stripped from the acrylate coating and exposed to UV in a FBG writing set-up. The UV laser radiation used was a frequency doubled Ar\textsuperscript{+} laser. In the work reported here, we describe results obtained for two unchirped FBG with Hamming-apodized profile and without phase shift, with reflectivities 30\% and 70\% and FWHM \sim 20 pm and 30 pm, respectively. After writing the gratings, the pieces of fiber were mounted on a metal substrate and covered with heat conductive, electrically isolating epoxy. Heat dissipation allows switching the devices at rates of a few kHz without significant drift of polarization or wavelength. Electrical SMA contacts were used and a 0.1 \Omega resistive probe was inserted in series with the \sim 50 \Omega alloy electrode for monitoring purposes.

Two sources of electrical drive pulses were used for device characterization, one consisting of a low repetition rate spark gap delivering \textless 10 ns risetime current pulses of up to 30 A into 50 \Omega and duration 10-100 ns, and the other one of a home-built semiconductor-based switch delivering up to 20 A with 30 ns rise-time at a repetition rate 10 kHz and adjustable pulse length. The energy deposited on the electrode is a few mJ at most and causes a temperature rise of only a few degrees (typically \textless 10 °C). The light source used was a tunable external cavity diode laser (TLS) with linewidth \textless 1 pm, and synchronized with an optical spectrum analyzer for high resolution wavelength measurements. Different input polarization states were selected with a polarization controller. A circulator, high-speed photodiode
and oscilloscope completed the characterization set-up, schematically illustrated in Fig. 1.

![Fig. 1. Experiment set-up](image)

Fig. 1. Experiment set-up

Fig 2 illustrates the Bragg wavelength associated with S and P polarization of the metal-filled fiber device at various temperatures before the application of current pulses. The insets show the reflected intensity as a function of wavelength at ~26 °C and at ~69 °C, measured for the two orthogonal input polarization states that match the eigenstates of the fiber. Close to room temperature, the index difference inferred from $\delta n = n \delta \lambda / \lambda$ was $2.6 \times 10^{-5}$, one order of magnitude lower than conventional HiBi fiber. As the temperature increases, both the refractive indices for both polarizations and the birefringence increase, as shown in Fig. 2. At 69 °C the Bragg wavelength for the two polarizations are well separated (87 pm). Such a state can also be reached by heating the fiber by passing dc current through one electrode, instead of using a hot plate as in the characterization measurement here.

![Fig. 2. Temperature dependence of Bragg resonance for S and P polarization](image)

Fig. 2. Temperature dependence of Bragg resonance for S and P polarization

The dynamic measurements were performed for the S and P polarization states by tuning the TLS exactly at the top of the grating reflection peak before the application of the current pulse and studying the drop in reflectivity as a function of time following the electrical excitation. Alternatively, the TLS was tuned outside the Bragg peak and the increase of reflectivity was followed on the oscilloscope trace following application of the current pulse. Intermediate (partial reflection) cases were also studied. Fig. 3 illustrates an example of 100 % wavelength switching with a response time ~60 ns for a drive pulse 100 ns long and amplitude ~30 A. The ripple seen on the traces is pick-up of the onset of the electrical pulse switched.
Three physical mechanisms have been identified in previous work on the polarization switch [1] and also observed here. The fastest one (as rapid as <10 ns) results from the mechanical pressure due to the electrode expansion and is the most useful for application in Q-switching. It lasts for a time comparable to the electrical pulse duration. The oscillating regime is associated with acoustic modes of the fiber [3] with typical period ~40-60 ns, but the acoustic oscillations induced here were limited in amplitude. The slow response is due to the propagation of the heat wave through the fiber, which reaches the core after hundreds of nanoseconds. Even when operating above room temperature and with heat sinking, the thermal component lasts for many microseconds, limiting the maximum repetition rate of the device to tens of kHz. In the traces of Fig. 3, the acoustic oscillations are not observable and the thermal response is well outside the time interval displayed.

The experiments repeatedly showed for the two devices tested that the largest wavelength shift during the application of the electrical pulse was to shorter wavelengths (typically -25 pm for 100% switching), while for the orthogonal polarization the wavelength shift was positive, but much smaller (typically +5 pm). After the electrical pulse ends, the wavelength shifts by approximately +17 pm for both polarization states due to a 2 °C temperature rise, which is expected from the amount of energy deposited. One qualitative model to explain the FBG shift to shorter wavelengths at early times is to consider that when the core is compressed in the direction of the holes, it expands in the orthogonal direction and thus the index reduces. Simulations of the effect using the elasto-optical tensor of glass confirm that the compression of the core in one direction leads to a weak increase of the index in the direction of the force, and a stronger decrease of the refractive index for the orthogonal direction.

Previous durability tests were carried out with devices pulsed $10^9$ times without degradation in performance [1]. The temperature increase produced here barely affects the grating and it is not expected to reduce the reliability of the wavelength switch demonstrated. It is believed that the short length, low loss, all spliced high-speed devices described here can find useful application for Q-switching fiber lasers.

References
Paper III
Nanosecond switching of fiber Bragg gratings

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Abstract: A FBG was written in a two-hole fiber with internal alloy electrodes. Nanosecond high current pulses cause metal expansion, increase birefringence and tune the gratings with a response time of 29 ns. This short length, low loss, all-spliced high-speed wavelength switching devices described here has potential use in Q-switching fiber laser.

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OCIS codes: (060.3735) Fiber Bragg gratings; (060.4370) Nonlinear optics, fibers; (060.7140) Ultrafast processes in fibers.

References and links


1. Introduction

High speed tuning of Fiber Bragg gratings (FBG) can be exploited in a number of fields, such as Q-switching, cavity dumping and pulse picking in a fiber laser, quickly addressing a sensor head or readjusting an optical filter. Various mechanisms have been exploited for tuning FBGs, such as bending beams [1], stretching with piezoelectric stack [2] and using magnetic fields [3]. Common to these methods are a relatively low tuning speed (microseconds) and mechanical durability issues. In recent years, there has been an increasing interest in...
exploiting strain transverse to the fiber [4-8]. The transverse stress distribution has been previously measured in a number of FBG sensor elements in high birefringence (HiBi) fibers [4], in multi-core fibers [5], in microstructured fibers [6] and in side-hole fibers [7,8]. The birefringence induced by the external load leads to both a shift and an increase in the splitting of the FBG peak associated with the two orthogonal polarization modes. This can be used to gauge the magnitude and the orientation of the transverse strain field. However, to the best of our knowledge there is no published report on fast tuning FBGs in these special fibers till now.

In previous work, we studied the applications of microstructured fibers with internal electrodes for controlling the light in the fiber. Besides electro-optical switching and modulation, nanosecond polarization switching has recently been demonstrated [9]. Increased birefringence results from the application of high-voltage electrical pulses to an internal electrode that heats up and expands. The refractive index difference between fast and slow axis of the fiber with electrodes causes polarization change, and can lead to 90° rotation with proper input polarization alignment.

In this Paper, we present how the high-speed expansion of metal electrodes affects the wavelength of a FBG written in the core of the two-hole fiber. The grating is an excellent tool to follow the evolution of the refractive index experienced by light in the polarization parallel (P) and orthogonal (S) to the direction of the holes. Besides revealing interesting physics, the nanosecond wavelength switching obtained here has potential application in Q-switching fiber lasers.

2. Experiment

The 125 μm thick silicate two-hole fiber, drawn at Acreo FiberLab, had characteristics similar to those of the standard telecom fiber (core diameter 8 μm and Δn = 0.0056) but with two ~28 μm-diameter holes running parallel to the core separated from it by 14 μm (see Fig. 1). Pieces of fiber were filled with few-centimeter-long (typically 10 cm) metal columns that occupied the entire cross-section of the holes. Eutectic alloys BiSn (melting temperature 137°C) were pumped into the fibers in the molten state and used at room temperature as solid electrodes [10]. The length of the alloy-filled holes and the core-hole separation were such that insertion loss was experimentally measured to be < 0.2 dB and the polarization-dependent loss < 0.1 dB. Both ends of the metal-filled fiber were free from metal to allow for convenient low-loss splicing.

![Fig. 1. Cross section of the metal-filled fiber used here (SEM picture).](image)

The metal-filled fibers were H₂-loaded for 2 weeks at 150 bar, stripped from the acrylate coating and exposed to ultraviolet (UV) in a FBG writing set-up. Frequency doubled Ar+ laser was used as a source of UV radiation. In the work reported here, we describe results obtained from a 4 cm-long Hamming-apodized FBG written along the middle section of metal-filled fibers. The grating was annealed in the oven at 100 °C for 12 hours.

After side polishing the fiber to electrically access one of the two internal electrodes at two points separated by 7 cm, a 20 μm thick gold-plated tungsten wire was inserted by ~5 mm into
the electrode while melting the alloy locally to ensure a robustly bonded electrical connection. Then, the pieces of fiber were mounted on an aluminum (Al) substrate and covered with heat conductive, electrically isolating epoxy. Heat dissipation into the substrate allows switching the devices at rates of a few kHZ without significant drift of polarization or wavelength. The resistance of the components was typically ~50 \( \Omega \) for a BiSn device with 7 cm active length. This allowed for simple impedance matching between the device and the coaxial cable transporting the high voltage pulses. Electrical SMA contacts were used and a 0.1 \( \Omega \) resistive probe was connected in series with the ~50 \( \Omega \) load for monitoring purposes.

A pulse generator consisting of a high voltage direct current (DC) power supply and a high speed switch was employed for the driving pulses. The switch here was a low repetition rate spark gap circuit delivering 2 ns rise-time current pulses with the maximum switching voltage 3 kV and duration 10-100 ns determined by the cable length used. The energy applied to the electrode is a few mJ at most and causes a temperature rise of only a few degrees (typically <10 °C). The light source used was a tunable external cavity diode laser (TLS) with linewidth <1 pm, and synchronized with an optical spectrum analyzer (OSA) for high resolution wavelength measurements. Different input polarization states were selected with a polarization controller (PC). A circulator, 3-dB coupler, high-speed photodiode and oscilloscope completed the experimental set-up, schematically illustrated in Fig. 2.

### 3. Results

Due to the intrinsic geometrical birefringence of the two-hole fiber, the grating has two reflection peaks at different wavelength corresponding to the different effective refractive indices for the two orthogonal polarization modes in this fiber [4]. The reflection peak at the shorter wavelength takes place in the fast axis mode (S polarization), the one at the longer wavelength in the slow axis mode (P polarization) [11]. When the metal-filled fiber device was put in a temperature-controllable oven, the two internal electrodes were heated and expanded. Consequently, the refractive indices for both polarizations and the birefringence increased as the temperature increased. The peak Bragg wavelengths associated with S and P polarization shifted to longer wavelengths and the splitting increased, as shown in Fig. 3. The insets show the reflected intensity as a function of wavelength at ~26 °C and at ~69 °C, measured for the two orthogonal input polarization states that match the eigenstates of the fiber. From room temperature to 69 °C, the Bragg wavelength separation for the two polarizations increased from 26 pm to 87 pm. The 3-dB bandwidth and the reflectivity of each peak remained about 30pm and 70%, respectively. Close to room temperature, the index difference inferred from \( \Delta n = n \times \Delta \lambda / \lambda \) was ~2.6×10^{-5}, approximately one order of magnitude lower than that of conventional HiBi fiber. Such a state can also be reached by heating the fiber by passing DC current, instead of using an oven as in the characterization measurement here.
One can note from Fig. 3 that the measured temperature sensitivity (~37.6 pm/°C) is significantly larger than expected for a HiBi FBG fabricated in Panda fiber (~16.5 pm/°C) [12]. As discussed in Ref. [13], increased temperature sensitivity can be obtained when the fiber is embedded in an environment which exhibits a large $dL/dT$. An estimate can be made, for a ~53 °C temperature increase, of the wavelength shift due to $dn/dT$ (0.65 nm), due to the length expansion of a glass fiber (0.045 nm), due to the alloy dilation (0.024 nm) and due to the expansion of the Al substrate (2.1 nm). Here it is assumed that the alloy expansion is restricted by the hard glass fiber (area ratio 1:9 and Young’s modulus ratio 1:6) and that the substrate is perfectly attached to the fiber. The total wavelength shift under these conditions is calculated to be 2.8 nm, which exceeds the measured value from Fig. 3 of ~2.0 nm. The lower value measured is probably caused by slippage between the substrate and the fiber [13].

![Fig. 3. (Color online) Temperature dependence of Bragg resonance for S and P polarization in a steady-state situation.](image)

![Fig. 4. Typical current pulse used in the dynamic experiment. Imperfect matching into 50 Ω causes the small step at 100 ns and the undershoot.](image)
Dynamic measurements were performed for the S and P polarization states by tuning the TLS at the top of the grating reflection peak before the application of the current pulse and studying the drop in reflectivity as a function of time following the electrical excitation. Alternatively, the TLS was tuned away from the Bragg peak and the increase of reflectivity was measured on the oscilloscope trace following application of the current pulse. Intermediate (partial reflection) cases were also studied. Electrically driven FBG switching experiments were carried out at room temperature. Figure 4 illustrates a typical current pulse used here with the pulse width ~ 60 ns and the amplitude ~18 A at low-repetition rate (~20 Hz). The small step on the right flank and the undershoot observed after the main current pulse are caused by electrical mismatch.

![Fig. 5](image1.png)

**Fig. 5.** Full switching off-on is accomplished with 29 ns risetime. Inset, the time evolution of signal in microseconds.

![Fig. 6](image2.png)

**Fig. 6.** Full switching on-off is accomplished with 29 ns falltime. Inset, the time evolution of signal in microseconds.

Close to full off-on switching with a response time of ~29 ns was achieved when the TLS was set at the short wavelength side of the S polarization, as illustrated in Fig. 5. The increase of the signal implies that the Bragg peak is shifted to shorter wavelengths following electrical pulse excitation. The return of the Bragg peak to longer wavelengths is followed on a microsecond time scale in the inset of Fig. 5. As heat spreads from the metal electrode into the glass fiber and eventually dissipates, the pressure wave dies and the reflection peak returns to its original spectral position. The process takes tens/hundreds of microseconds. The decay of the reflected signal seen in the inset of Fig. 5 is deceivingly simple, since the probing laser
wavelength does not follow the spectral evolution of the Bragg peak once the overlap disappears. Heating, however, red-shifts the grating wavelength.

Close to full on-off switching was also obtained with a response time of 29 ns, as shown in Fig. 6, by setting the TLS wavelength to match FBG peak of the S polarization. The long term recovery of the grating, shown in the inset of Fig. 6, is not monotonic. The reflected signal remains null as long as the overlap between the probing laser source and the FBG displaced to shorter wavelengths is zero. Since the FBG has a FWHM of 30 pm, full switching implies displacement > 20 pm. The time is typically a few microseconds. After this relatively short time, the peak reflectance wavelength overlaps once again the probing laser wavelength. The signal reflected by the FBG then returns to the maximum amplitude. The heat from the metal electrode finally reaches the core of the fiber, red-shifting the Bragg wavelength, and this leads to a second reduction of the reflected signal. This time, however, the FBG peak lies on the long-wavelength side of the laser source. The time scale involved in the heat component is slower. The device can be said to return to room temperature after a delay close to 2 ms. It may be noticed from the inset of Fig. 6, that the second (negative) peak in the reflected signal is not as deep as the first one, where 100% switching is achieved. This depth is a measure of the remaining overlap between the probing laser wavelength and the red-shifted FBG peak. From the relative amplitudes of the peaks, a thermal shift of +17 pm can be estimated for both polarization states, which corresponds to a ~1.3 °C rise after each high current pulse. Here, the Bragg wavelength dependence on the Al substrate expansion due to temperature is not considered because of the large thermal mass of the substrate and the short duration time and low repetition rate of the current pulse. The alloy was heated by ΔT ~10 °C with a current pulse of ~18 Amps over ~60 ns (with heat deposited ~1 mJ). Assuming for simplicity that the energy spreads uniformly into the fiber and taking into account typical values for the specific heat of the alloy and glass, a temperature increase in the core of ~1.6 °C is estimated, which is consistent with the value above.

The dynamic experiments repeatedly showed for the device tested that the largest wavelength shift during the application of the electrical pulse was to shorter wavelengths (typically -27 pm for 100% switching) for the S polarization, while for the P polarization the wavelength shift was positive, but much smaller (typically +5 pm). Similar behavior has also been reported in a HiBi side-hole fiber [14]. One qualitative model to explain the FBG shift to shorter wavelengths is to consider that when the core is compressed in the direction of the holes, it expands in the orthogonal direction and thus the refractive index reduces. Simulations of the effect using the elasto-optical tensor of glass confirm that the compression of the core in one direction leads to a weak increase of the refractive index in the direction of the force, and a stronger decrease of the refractive index for the orthogonal direction.

4. Conclusion

A FBG was written in a two-hole fiber with internal alloy electrodes, which has intrinsic geometrical birefringence. Nanosecond high current pulses heated the metal electrode and caused metal expansion rapidly. In consequence, birefringence was increased and the gratings was tuned with a response time of 29 ns, limited by the finite time needed to deposit heat and the inductance of the alloy electrode. The fast risetime switching results from the increased pressure, while heat transport to the core is slow and determines the recovery time of the device after every drive pulse. Previous durability tests were carried out with devices pulsed 10⁷ times without degradation in performance and high repetition rates (> 10 kHz) can be obtained by running the device above room temperature [9]. It is believed that the short length, low loss, all-spliced high-speed devices described here can find useful application for Q-switching fiber lasers.
Paper Ⅳ
Physics of electrically switched fiber Bragg gratings

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Abstract: The physics of electrically switched FBGs was studied in fibers with internal electrodes. Wavelength shifts due to mechanical effects (nanoseconds) and heat (milliseconds) depend quadratically on the electrical pulse voltage and linearly on pulse duration.

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OCIS codes: (060.3735) Fiber Bragg gratings; (060.4005) Microstructured fibers.

1. Introduction
A fiber Bragg grating (FBG) component based on a two-hole fiber with internal electrodes has showed 29 ns full off-on and on-off switching [1]. Index change and increased birefringence result from the application of a short duration high current pulse to an internal electrode that heats up and expands rapidly. The nanosecond FBG response is attributed to a mechanical effect. As a consequence, the grating wavelength was blue-shifted (~ -27 pm) for the polarization orthogonal (S) to the direction of the hole, while it was red-shifted for the other polarization (~ +5 pm). Besides, a much slower evolution of the index (many microseconds) follows from the diffusion of heat from the metal into the glass cladding and core. A thermal shift as high as +17 pm was obtained for both polarizations. In this Paper, we report on the physics of electrically switched FBGs written in a two-hole fiber with internal electrodes, studying the dependence on voltage and pulse duration of both mechanical and thermal effects.

2. Experiment
Pieces of fiber with a pair of 28 μm diameter holes running parallel to the core were filled with BiSn alloy that occupied the entire cross-section of the holes [2]. Fig. 1a shows the cross section of the fiber used here. A 4 cm-long hamming-apodized FBG was written along the middle section of fiber with 7 cm-long alloy. Due to the intrinsic geometrical birefringence of the used fiber, the grating has two reflection peaks with the separation of 38 pm. The 3-dB bandwidth and the reflectivity of each peak are 44 pm and ~ 75%, respectively (see Fig. 1b). After writing the gratings, electrical contact was made from the side of the fiber, thus allowing for conventional low loss splicing. Then, the pieces of fiber were mounted on an aluminum substrate and covered with heat conductive, electrically isolating epoxy. Heat dissipation allows switching the devices at rates of a few kHz without significant drift of polarization or wavelength. Electrical SMA contacts were used and a 0.1 Ω resistive probe was inserted in series with the ~50 Ω alloy electrode for monitoring purposes.

A pulse generator consisting of a high voltage dc power supply and a high speed switch was employed for the driving pulses. The switch here was a low repetition rate spark gap circuit delivering 4 ns rise-time current pulses with the maximum switching voltage 3 kV into 50 Ω and duration 10-240 ns determined by the cable length used. A tunable external cavity diode laser (TLS), polarization controller (PC), circulator, 3-dB coupler, high-speed photodiode (PD) and oscilloscope completed the experimental set-up, schematically illustrated in Fig. 1c.

Fig. 1. (a) Cross section of the metal-filled fiber (SEM picture). (b) Reflection spectrum of the FBG. (c) Experimental set-up. TLS: tunable laser source; PC: polarization controller; PD: photodiode; OSA: optical spectrum analyzer.
Dynamic measurements were performed for the S polarization by tuning the TLS at the grating reflection peak before the application of the current pulse and studying the changes in reflectivity as a function of time (Fig. 2a). Fig. 2b illustrates how the grating wavelength shifts in the above process: blue-shifting due to mechanical stress and red-shifting due to heat (Δλ_M) in tens of nanoseconds and red-shifting due to heat (Δλ_T) in hundreds of microseconds. The values of Δλ_M and Δλ_T depend on the pulse amplitude (U) and the duration (Δt). Experimental data of Δλ_M and Δλ_T for a fixed pulse duration Δt = 241 ns at different voltages are shown with black squares and blue triangles in Figs. 2c and 2d. The red curves in Figs. 2c and 2d are the parabolic fits Δλ_M (pm) = -6.5 × 10^{-5} U^2 and Δλ_T (pm) = +4.5 × 10^{-5} U^2, for the mechanical and thermal effect, respectively. The best fit to the experimental data is obtained for a power coefficient 2.08 in both cases. Experimental data of Δλ_M and Δλ_T for a fixed voltage pulse amplitude U=1kV (20 A pulse) under different pulse durations are shown with black squares and blue triangles in Figs. 2c and 2f. The red curves in Figs. 2c and 2f are the linear fits Δλ_M(p) = -0.244×Δt(ns) and Δλ_T (pm) = +1.66×Δt(ns), respectively.

The conclusion drawn from the experiments is that the index change due to the mechanical and the thermal effects is proportional to the heat deposited in the metal electrode, which can be described by Q = U^2 Δt/R = m_0 c_m ΔT, where R is the resistance of the electrode (50Ω by construction). This is valid even when no heat transport to the glass is involved, as seen in Figs. 2c and 2e. Dilatation of the metal (with coefficient α_m) can be related to the stress ε_i and ε_0 in the direction parallel and perpendicular to the hole through ε_i = (Y_m/Y_0)α_mΔT and ε_0 = -0.17ε_i in a model constructed with springs of different stiffness describing the metal (Y_m=12×10^10 N/m^2) and glass (Y_g=72×10^10 N/m^2). The expected change in index due to mechanical stress is then Δλ_M = -λΔα_i (0.26ε_i + 0.126ε_0)/2 ~ ΔT ~ U^2Δt, where the strain-optical constants and Poisson ratio are from Ref. [3]. The model gives Δλ_M (pm) = -7.8×10^{-8}U^2 (V^2), in reasonable agreement with the experimental data (Fig. 2c). Simulation of the thermal effect requires solving the temperature distribution in the fiber as a function of time, following the application of the heating current pulse. A simplification was attempted of assuming an average temperature across the core at the instant of maximum index change (t_3 in Fig. 2a) with the heat transferred from the metal to the core described by constant η. From this simple model Δλ_M = (λ_0/η) dn/dT ΔT_i = (λ_0/η) dn/dT (η/m_c_g) U^2Δt/R, i.e., the correct functional dependence Δλ_M ~ U^2Δt is obtained. Using one point of Fig 2d to fit the wavelength shift to the applied voltage, η is estimated to be 0.12, corresponding to a core temperature increase limited to ~ 5% of the maximum metal electrode temperature increase. The value used for the expansion coefficient of the metal was α_m = 16 × 10^{-6}K^{-1} and for the specific heat c_m=167 J/(kgK) (metal) and c_g=703 J/(kgK) (glass).

References
Paper V
Birefringence switching of Bragg gratings in fibers with internal electrodes

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Abstract: A fiber Bragg grating was written in a side-hole fiber with internal metal alloy electrodes. The initial geometrical birefringence of this fiber gives rise to two Bragg resonances separated by 43 pm. Nanosecond risetime current pulses of up to 23 A were applied to the metal electrode, which heated and expanded rapidly. This caused mechanical stress in the fiber on a nanosecond scale, resulting in a negative shift of the Bragg wavelength peak for the fast axis mode, and positive but smaller shift for the slow axis mode. The fast change increased the peak separation to ~ 143 pm, corresponding to an increase in birefringence from 4.0×10⁻⁵ to 1.3×10⁻⁴. Both peaks subsequently experienced a red-shift due to the relaxation of mechanical stress and the increasing core temperature transferred from the metal in many microseconds. Simulations give accurate description of the experimental results.

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OCIS codes: (060.3735) Fiber Bragg gratings; (060.4005) Microstructured fibers.

References and links

1. Introduction

Side-hole fibers have the advantage of high sensitivity to pressure and low sensitivity to temperature [1-4]. Fiber Bragg gratings (FBG) imprinted in side-hole fibers have been shown to be good candidates for simultaneous sensing hydrostatic pressure and temperature [5-7]. Recently Kreger, et al., [8] has reported that when the static transverse load was applied perpendicular or parallel to the direction of the two air holes, the direction orthogonal to the two holes suffered a much larger stress or strain, and the polarization parallel to the two holes has a larger wavelength shift. However, to the best of our knowledge, there is no published report on high-speed dynamic measurements of pressure and temperature in these special fibers until now. The potential application of high-speed polarization/wavelength switching in fiber lasers makes these studies particularly relevant.

In our previous work [9-11], we reported that a FBG component based on a side-hole fiber with internal electrodes has shown nanoseconds full off-on and on-off switching. Nanosecond high current pulses heated the metal electrodes and caused rapid metal expansion. As a consequence, the grating wavelength was blue-shifted (~27 pm) for the fast axis mode, while it was red-shifted for the slow axis mode (~+5 pm). Besides, a much slower wavelength red-shift (many microseconds) as high as ~+17 pm was obtained for both polarizations. Furthermore, we demonstrated that the fast and slow wavelength shifts depend quadratically on the electrical pulse voltage and linearly on the pulse duration for the fast axis mode [12], i.e. depend linearly on the amount of energy deposited.

In this Paper, we further investigate the birefringence dynamic changes of side-hole fibers with internal electrodes. The FBG used show to be an excellent tool to reveal the amplitude and sign of the mechanical and thermal perturbations, and the ensuing time evolution of the birefringence. The simulation results are consistent with the experimental dynamic measurements.

2. Experiment

The 125 μm-thick silicate side-hole fiber had characteristics similar to those of the standard telecom fiber (core diameter 8.4 μm and Δn = 0.0056) but with two 28.8 μm-diameter holes running parallel to the core. The core-hole separation (edge-to-edge) was 13.4 μm. Figure 1(a) shows the cross section of the fiber used. Pieces of fiber were filled with 7 cm-long BiSn alloy (melting temperature 137°C) that occupy the entire cross-section of the holes [13]. The length of the alloy-filled holes and the core-hole separation were such that insertion loss was experimentally measured to be < 0.2 dB and the polarization-dependent loss < 0.1 dB. Both ends of the metal-filled fiber were free from metal to allow for convenient low-loss splicing.

A 4 cm-long Hamming-apodized FBG was written along the middle section of BiSn-filled fiber, with the holes aligned perpendicular to the UV beam incidence direction [11]. The grating was annealed in the oven at 100 °C for 12 hours. Due to the intrinsic geometrical birefringence of the fiber with internal metal electrodes, the grating has two reflection peaks at different wavelengths corresponding to the differing effective refractive indices for the two orthogonal polarization modes in this fiber. The reflection peak at the shorter wavelength takes place in the fast axis mode (x-axis), the one at the longer wavelength in the slow axis mode (y-axis). The identification of the axes is discussed in the simulations below. At room temperature, the Bragg wavelengths of the two polarizations are 1547.230nm and 1547.273nm, with a separation of 43 pm corresponding to a refractive index difference of...
$\sim 4.0 \times 10^{-5}$. This is roughly one order of magnitude lower than in typical high-birefringence fibers. The 3-dB bandwidth and the reflectivity of both peaks are 44 pm and 75%, respectively.

After writing the gratings, electrical contacts were made from the side of the fiber at both extremities of the electrode. The grating was mounted on an aluminum substrate and covered with heat conductive, electrically isolating epoxy. Heat dissipation allows switching the devices at a few kHz with minor average drift of polarization. The resistance of the components was typically 43 $\Omega$ for a BiSn device with 7 cm active length. This value implies in a small impedance mismatch between the device and the 50 $\Omega$ coaxial cable transporting the high voltage (i.e., current) pulses. Electrical SMA contacts were used and a 0.1$\Omega$ resistive probe was connected in series with the 43 $\Omega$ loads for monitoring purposes.

A pulse generator consisting of a high voltage dc power supply and a high speed switch was employed for the driving pulses. The switch here was a low repetition rate spark gap circuit delivering 2 ns rise-time current pulses with the maximum switching voltage 3 kV and duration 10-241 ns determined by the cable length used. The light source was a tunable external cavity diode laser with which 1 pm wavelength resolution measurements are possible. Different input polarization states were selected with a polarization controller. A circulator, 3-dB splitter, high-speed photodiode, Ando AQ6317B optical spectrum analyzer and oscilloscope completed the experimental set-up, schematically illustrated in Fig. 1(b).

Dynamic measurements were performed for the fast axis mode by properly aligning the input polarization and by tuning the external cavity laser source to the grating reflectivity maximum before the application of the current pulse. The changes in reflectivity as a function of time can be studied from the oscilloscope trace following the electrical excitation (Fig. 2(a)). Figure 2(b) schematically illustrates that the grating wavelength shifts in the above process can be divided into fast part (in tens of nanoseconds) and slow part (hundreds of microseconds). The former is due to mechanical stress created during the electrical pulse action, while the latter is due to the relaxation of mechanical stress and the slow increase of temperature in the core transferred from the metal electrode after each electrical pulse. The fast part corresponds to the initial reduction of the reflection of the grating at the probe wavelength (from $t_0$ to $t_1$). It reaches its maximum absolute value ($\Delta \lambda_M$) at instant $t_1 \sim 241$ ns, equal to the current pulse duration. Then the slow part takes effect: the grating gradually moves back with the decreasing mechanical stress and the increasing temperature in the core. The grating passes its original spectral position at instant $t_2 \sim 68 \mu$s and red-shift continues. At $t_3 \sim 270 \mu$s, the maximum positive $\Delta \lambda_{T+M}$ is reached, where the core temperature is near its maximum. After several milliseconds ($t_4$), the grating returns to its original spectral position again, since the mechanical stress is released and the component is back to room temperature. It should be mentioned that the identification of the behavior schematically illustrated in Fig. 2(b) (and in Fig. 2(d) below) involved experimentally examining the response of the device for various other probe wavelengths, as discussed in Ref. [11].
Similarly, dynamic measurements were also carried out for the slow axis mode, shown in a typical experimental trace (Fig. 2(c)) and the schematic diagram (Fig. 2(d)). Note that, now a positive and smaller wavelength shift happens during the electrical pulse duration and reaches its maximum ($\Delta \lambda_{M}^y$) at instant $t_1 \sim 241$ ns. Then, the relaxation of the mechanical stress blue-shifts the spectrum of the grating, while the increasing temperature in the core red-shifts the grating peak. In the beginning, the former dominates and the Bragg wavelength moves back a little until instant $t_2$ is attained at $\sim 16 \mu$s. Afterwards, the heat reaching the core dominates, so the grating continues to red-shift. The maximum positive spectral shift ($\Delta \lambda_{T+M}^y$) occurs at instant $t_3 \sim 190 \mu$s. Finally, the grating also returns to its original spectral position after instant $t_4 \sim 20$ ms. Full (100%) on-off switching is not achieved for this axis even with the highest current level ($\sim 23A$) applied here, corresponding to an electrical pulse energy $\sim 5$ mJ/pulse.

The values of $\Delta \lambda_M$ and $\Delta \lambda_{T+M}$ depend on the pulse voltage and the pulse duration. Experimental data of the fast wavelength shift for both polarization states ($\Delta \lambda_M^x$ and $\Delta \lambda_M^y$) at different voltages are shown with blue and red squares in Fig. 3(a), for pulses with duration 241 ns. The absolute value of $\Delta \lambda_M^x$ is $\sim 3.2$ times larger than $\Delta \lambda_M^y$. Similarly, experimental data of the slow wavelength shift ($\Delta \lambda_{T+M}^x$ and $\Delta \lambda_{T+M}^y$) at different voltages are shown in Fig. 3(b) with blue and red squares. Here, $\Delta \lambda_{T+M}^y$ is larger than $\Delta \lambda_{T+M}^x$.

Fig. 2. (Color online) (a) Time evolution of the signal reflected by the FBG for probe light polarized along the x-axis. (b) Schematic illustration of the wavelength shift at various times. (c) Time evolution of the signal reflected by the FBG for probe light polarized along the y-axis. (d) Schematic illustration of the wavelength shift at various times. The red arrows in Figs. (b) and (d) indicate the wavelength of the tunable laser source during the measurement.
3. Simulation

To better study the physics of the Bragg wavelength shift for both polarizations, the partial differential equations describing heat diffusion and displacement in x and y-direction were solved by the finite element technique using the commercial software FlexPDE. The solutions allowed finding the time-dependent strain components in the fiber in the x- and y-directions ($\varepsilon_x$ and $\varepsilon_y$), the temperature distribution over the core and to calculate the FBG wavelength shift in x- and y-polarizations according to the following formulae [14-15]:

$$
\Delta \lambda_x = -\lambda_x \frac{n_0^2}{2} (p_{11} \varepsilon_x + p_{12} \varepsilon_y) + \lambda_x (\alpha + \xi) \Delta T
$$

(1)

$$
\Delta \lambda_y = -\lambda_y \frac{n_0^2}{2} (p_{11} \varepsilon_y + p_{12} \varepsilon_x) + \lambda_y (\alpha + \xi) \Delta T
$$

(2)

where: $\lambda_x=1547.23$nm, $\lambda_y=1547.273$nm are the initial Bragg wavelength for x- and y-polarizations; $n_0 = 1.445$ is the initial effective refractive index of the core; $p_{11} = 0.121$ and $p_{22} = 0.270$ are the photoelastic coefficients of the fiber [16]; $\alpha$ is the thermal expansion coefficient of silica; $\xi = (1/n)(dn/dT) = 6.5 \times 10^{-6}$ K$^{-1}$ is the thermo-optic coefficient of fused silica; $\Delta T$ is the increased temperature in the core. The first terms of Eqs. (1) and (2) stand for the wavelength shift of both polarizations due to mechanical stress in the core, while the second terms of two equations indicate the wavelength shift caused by the increased temperature in the core.

Stress at the BiSn/cladding boundary increase approximately linearly during the electrical pulse action, and then gradually decrease with time. This stress is transferred to the core area in ~14 $\mu$m/5720 m/s = 2.45 ns, i.e. almost instantaneously compared to the pulse duration 241 ns. However, the heat at the BiSn/cladding interface needs several microseconds to reach the core area. As a result, the heat diffusion can be neglected during the pulse action. The fast wavelength shifts $\Delta \lambda_{Mx}$ and $\Delta \lambda_{My}$ are determined by the first terms of Eqs. (1) and (2) at $t = 241$ ns. The exact value of the heat capacity and the expansion coefficient of the BiSn alloy electrode are not known, nor the exact heat capacity for the Ge-doped silica fiber used. The choice $C_v = 167$ J/kgK and $\Delta l/l = 15.5 \times 10^{-6}$ K$^{-1}$ for the alloy and $C_v = 736$ J/kgK for the fiber allowed for excellent fitting of the theoretical equations (1) and (2) to the experimental data, as seen in Fig. 3(a). The simulations confirm that the core area is compressed (negative) in x-direction and stretched (positive) in y-direction under the applied pulses. For the pulse with applied voltage 1080 V, $\varepsilon_x = -1.655 \times 10^{-4}$ and $\varepsilon_y = 2.535 \times 10^{-4}$ at $t = 241$ ns. This results in a decrease of refractive index in x-direction (-7.3 $\times 10^{-5}$) and a weaker increase of refractive index in y-direction (+2.1 $\times 10^{-5}$), corresponding to $\Delta \lambda_{Mx} = -75.8$ pm and $\Delta \lambda_{My} = +23.7$ pm.

We can conclude (in opposition to [9, 12]) that the fast axis mode is in the direction parallel to the two holes (x-direction), and the slow axis mode is in the direction orthogonal to the two holes (y-direction).
As mentioned above, the slow wavelength shift is caused by the relaxation of mechanical stress and the increased temperature in the core. It can be calculated from Eqs. (1) and (2) for both polarizations. For the x-polarization, $\Delta \lambda_x$ equals zero at a calculated time $t_2 = \sim 56 \mu s$, when the two terms of Eq. (1) compensate each other. Subsequently, the second term dominates and $\Delta \lambda_x$ becomes positive and increases gradually due to the increasing $\Delta T$. The shift reaches its maximum at a calculated time $t_3 = \sim 250 \mu s$. For the y-polarization, initially $\Delta \lambda_y$ reduces because the decay of the stress dominates over the rising effect of heat. At a calculated time $t_2 \sim 17 \mu s$ the latter starts to dominate and the shift increases again until it reaches the maximum value at a calculated time $t_3 \sim 200 \mu s$.

The simulations of $\Delta \lambda_{T+M}^x$ accurately reproduce the experiment measurements when the thermal expansion coefficient for the silica fiber is optimized to the value $\alpha = 0.50 \times 10^{-6}$ K$^{-1}$. This is shown by the blue line and squares in Fig. 3(b). The simulation of the wavelength shift for the y-axis now has no free parameters for adjustment. The result (red line in Fig. 3(b)) fits the experimental data (squares) relatively well. The numerical predictions are smaller than the measured values. The small discrepancy could possibly be attributed to a temperature variation taking place during the measurement. For example, the difference between the calculated and measured $\Delta \lambda_{T+M}^y$ at the pulse voltage 1015 V corresponds to a temperature shift of 0.8 °C, well within the temperature uncertainty in the laboratory, which could have been rising during the measurement.

The complete simulations here agree well with a simple quadratic fit to the data for $\Delta \lambda_M$ and $\Delta \lambda_{T+M}$ (for both polarizations) as a function of the pulse voltage [12].

Figure 4 illustrates the simulation results of the time evolution of the temperature in the core center under different pulse excitation. The voltages shown in Fig. 4 are obtained multiplying the applied voltage by 2×43/(43+50) to take into account the impedance mismatch between the device and the 50 Ω coaxial cable. As shown in Fig. 4, the heat in the metal takes $\sim 10 \mu s$ to reach the core and increases to the maximum at $\sim 190-220 \mu s$. Note that the maximum $\Delta T$ in the metal is as high as $\sim 90$ °C for a corresponding core temperature increase of only $\sim 6.2$ °C.

4. Conclusion

A FBG was written in a side-hole fiber with internal metal alloy electrodes, resulting in two reflected peaks separated by 43 pm due to the intrinsic geometrical birefringence. Nanosecond risetime current pulses of up to 23 A were applied to the metal electrode, which heated and expanded rapidly. On a nanosecond scale, the fast Bragg wavelength shift of the fast axis mode is negative and that of the slow axis mode is positive and smaller, because of the mechanical perturbation. Microseconds later, the relaxation of the mechanical stress and the effect of heat reaching the core red-shift both Bragg peaks. All wavelength shifts depend quadratically on the electrical pulse voltage. Numerical simulations were developed to accurately and quantitatively explain the experimental observations. Similar components to the one used here have been tested to $10^9$ pulses without degradation of performance [17].
This component has potential applications for Q-switching fiber lasers and RF signal generation.
Paper VI
High-Speed Switching in Fibres with Electrodes

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ABSTRACT

Fibres with holes are provided with metal electrodes that fill the entire cross-section of the holes. Refractive index change and birefringence result from applying high current pulses for time intervals in the nanosecond range. High-speed polarization rotation and fibre Bragg grating wavelength tuning can be accomplished. Such electrically driven components are totally spliced with low insertion loss. They have no moving parts, are < 10 cm long and can be used in fibre laser cavities for Q-switching.

Keywords: Fibre component, microstructured fibre, internal electrodes, high-speed switching, electrical control, fibre lasers.

Highly functional optical fibre components exploit the intrinsic advantages that optical fibres have of low loss, high power damage threshold, the stability of silica as base material and above all the potential of low cost. Over the last few years, our group has carried out research on fibre components based on electrical excitation to control the light in the fibre. To this end, we have used fibres with holes disposed longitudinally parallel to the fibre core. These holes are filled with metal by means of a technique [1] briefly summarized with help of Fig. 1. A low melting temperature alloy such as BiSn (Tm = 137 °C) is pumped at high pressure into the fibre orifices as a liquid, and upon solidification used as electrode. Fibre sections of length ranging from a few centimetres to a few meters can be filled in this way. The final position of the metal column along the piece of fibre is also adjusted with high pressure, so that the fibre ends are free from metal. Electrical contact to the metal is made by side-polishing the fibre, so that the ends can be spliced with low loss to subsequent optical fibre. Besides allowing for the fabrication in parallel of a number of devices and thus reducing the final cost of the components, the filling technique we use also guarantees a good physical contact between the metal column and the walls of the holes. This in turn allows us to exploit the expansion of the electrodes under the application of current - be it dc current or short pulses - to induce electrically controlled birefringence. By adjusting the current one can impose an adjustable degree of polarization rotation. Typically, the devices developed are driven with tens of milliamps, and for an electrode with resistance ~15 - 50 Ω this corresponds to voltages 0 - 5 V. In such application, the electrically driven section of the fibre is generally 2 - 5 cm long. Full three-stage polarization controllers with drive and control electronics have been constructed with insertion loss 0.5 dB, and can reach any possible state of polarisation (SoP) for an arbitrary input SoP [2].

Figure 1. Filling a fibre with metal electrodes. The inset shows a SEM picture of one fibre used [1].

Since the devices rely on the heating of the electrode to cause heat expansion, it may be assumed that their operation is limited to the range of millisecond or slower, but this is not the case. Heat dissipation indeed determines the fall time of such components. With proper heat dissipation and operating above room temperature, the fall time can be brought to as low as ~20 μs (50 kHz). More importantly, the risetime is only limited by the time required to deposit heat into a metal wire, and with high current this can be a few nanosecond or less. We have demonstrated 90° polarization rotation in 7-cm long elements with risetime ~4 ns, driven by 20 A current pulses [2]. The temperature rise associated with every drive pulse is <10 °C. A typical example of the response achieved is illustrated in Fig. 2. The trace on the left represents the time evolution of
the electrical signal delivered by a spark gap to a device with electrode resistance 50 Ω. The trace on the right shows the optical signal measured by placing a polarisation switch between the polarised input beam at 1.55 μm and an analysing crossed polariser. Approximately 100% switching is obtained. Three physical contributions are identified, namely a mechanical component that is responsible for the fast switching shown in Fig. 2, an acoustical component that causes ringing in the nanosecond time scale if the driving pulse is short, and a thermal component that operates on the microsecond regime and is responsible for the slow decay of the signal (not apparent in the limited time range of Fig. 2).

Figure 2. Time evolution of electrical drive pulse (left) and optical signal switched between crossed polarisers (right). The mechanical (fast) and acoustic (oscillating) contributions are clearly identified.

The fibre is affected mechanically for as long as the metal electrode is heated, even if the temperature of the core is unchanged. Therefore, the switch remains “on” for a long time interval compared to the risetime (see Fig. 2). The components thus constructed find applications in Q-switching fibre lasers, where the fast risetime and long switch off time provide for sufficient delay to exhaust the laser cavity from population inversion. Other useful characteristics of such components are the low insertion loss (< 0.2 dB) and short length (does not affect the cavity roundtrip significantly).

The induced birefringence is associated to a refractive index change in the fibre core. If a Bragg grating (FBG) is recorded in the fibre section with electrodes, it is possible to shift the wavelength of the grating by means of the electrical drive pulse. Also here the risetime can be in the nanosecond range. Preliminary experiments were carried out with a 4-cm long unchirped FBG with ~20 pm bandwidth. The SoP along the direction of the holes and the one orthogonal to that experience a slightly different refractive index. This causes a splitting of the reflected light into two wavelength peaks, each one associated with one polarisation. At room temperature this splitting is only a few pm, and the two peaks overlap, but at 67 °C they separate by as much as 80 pm. We found that upon application of the nanosecond electrical pulse, the spectral separation between peaks increases, and while one peak is shifted to shorter wavelengths the other one shifts to longer. This is tentatively attributed to the compression of the core in the direction of the holes due to metal expansion, and to a distension of the core in the orthogonal direction. Such behaviour is expected, according to the simulations carried out to evaluate the elasto-optical effect throughout the cross-section of the fibre.

The wavelength switch described here and embodied by an electrically tuned FBG in a fibre with internal electrodes – like the polarisation switch – finds use in Q-switching of fibre lasers.

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Paper VII
Switchable dual-wavelength Raman erbium-doped fibre laser

D.R. Chen, Z.W. Yu, S. Qin and S.L. He

A fibre Bragg grating feedback fibre laser with both Raman and erbium-doped fibre pumps is proposed. Dual-wavelength switching is achieved by controlling the power of the Raman pump. The characteristics of the dual-wavelength switching are studied experimentally, and the mechanism is explained physically.

Introduction: Wavelength-switchable fibre lasers have attracted considerable attention recently owing to their important applications in WDM fibre communication systems, fibre sensors, spectroscopy and optical instrument testing, etc. Several techniques have been reported to achieve wavelength switching in erbium-doped fibre (EDF) lasers, such as the use of cascaded fibre Bragg gratings (FBGs) [1], spectral polarisation-dependent loss elements [2], the Sagnac loop reflector [3], few-mode fibre Bragg gratings [4], multimode fibre Bragg gratings [5], acoustic waves [6], distributed feedback (DFB) mode oscillations [7] and the multisection high-birefringence fibre loop mirror [8]. Wavelength-switchable lasers based on some EDFs co-doped with other rare-earth ions have also been reported [9]. Meanwhile, Raman fibre lasers have also been developed for high power, multiwavelength (however, non-switchable) applications (see e.g. [10–12]). Most of these techniques are based on some special devices or manual adjustments to achieve wavelength switching.

In this Letter, we propose a novel switchable dual-wavelength Raman erbium-doped fibre laser. Dual-wavelength switching is achieved by controlling the power of the Raman pump. To the best of our knowledge, the proposed fibre laser is the first to combine Raman amplification and EDF amplification to achieve multiwavelength switching.

Operation principles and experimental results: Fig. 1 shows the schematic configuration of the proposed switchable dual-wavelength fibre laser. A 1480 nm laser diode (LD) with a maximum power of about 250 mW is used as the EDF pump LD1 and a 1467 nm LD with a maximum power of 350 mW (when the drive current is 950 mA) is employed as the Raman pump LD2. The length of the singlemode fibre (SMF) section (with an attenuation coefficient of 0.19 dB/km at 1550 nm) between the two FBGs is 10 km. Sections of dispersion compensation fibre (DCF), SMF and EDF are the gain fibres in the present structure. The DCF section (with total dispersion of −986 ps/nm and total loss of 5.7 dB) used here can compensate 60 km singlemode fibre. The length, the numerical aperture, the cutoff wavelength and the peak absorption at (1531 nm) of the EDF section are 4 m, 0.25, 950 nm and 19.2 dB/m, respectively. Two FBGs are used as wavelength selection components. The central wavelengths, the full-widths at half maximum (FWHM) and the reflectivities are (1545.13 nm, 0.093 nm, 50.0%) and (1559.98 nm, 0.098 nm, 51.5%) for FBG1 and FBG2, respectively (these parameters are provided by the manufacturer). A circulator and an isolator are used here to ensure that the lasing cavity is a counter-clockwise ring.

There are two lasing cavities with wavelengths $\lambda_1 = 1545.13$ nm (around the EDF gain peak) and $\lambda_2 = 1559.98$ nm (around the Raman gain peak corresponding to pumping wavelength 1467 nm). The power of EDF pump LD1 is always fixed to a certain level, and the power of Raman pump LD2 is used to control the output wavelength and power.

In our first experiment, the power of EDF pump LD1 is fixed to 150 mW. When Raman pump LD2 is switched off, the output spectra of the laser is shown by the solid line in Fig. 2a, from which one sees that the structure is lasing only at $\lambda_1$ with a peak power of $-11.9$ dBm. However, when the drive current of LD2 is switched on to 750 mA, the structure will be lasing only at $\lambda_2$ with a peak power of 1.9 dBm (see dashed line in Fig. 2a). The solution and sensitivity of the optical spectrum analyser (OSA) used in the measurement are 0.06 nm and $-65$ dBm, respectively. Our experimental results show that the laser output is rather stable. Thus, wavelength switching is achieved in this fibre laser by controlling the drive current of LD2 (i.e., the power of the Raman pump LD2).

Fig. 2 Output spectra of proposed fibre laser, and output powers at two lasing wavelengths against drive current for LD2

Fig. 2b shows the detailed behaviour of the dual-wavelength switching as the driving current of LD2 increases (the pump power of LD1 is fixed to 150 mW). The output powers at $\lambda_1$ and $\lambda_2$ are indicated by the lines connected with squares and circles, respectively. Obviously, there are three regions where the laser is in different operation modes. In region A (with the drive current for LD2 below switching current $I_a = 70$ mA), only $\lambda_1$ is lasing and its output power remains around $-11.9$ dBm. In region B (with the drive current for LD2 ranging from 70 to 690 mA), both $\lambda_1$ and $\lambda_2$ are lasing. In this region, as the drive current of LD2 increases, the output power at $\lambda_1$ decreases while the output power at $\lambda_2$ increases. In region C (with the drive current for LD2 above switching current $I_b = 690$ mA), only $\lambda_2$ is lasing and its output power remains around 1.9 dBm.

The operation principle of the present switchable dual-wavelength fibre laser can be explained as follows. When the power of Raman pump LD2 is zero, only lasing at $\lambda_1$ can be obtained since the cavity loss at $\lambda_2$ is larger than that at $\lambda_1$ (owing to the loss of the 10 km SMF) and the EDF amplification will occur only at $\lambda_1$ (owing to the gain competition). When the power of LD2 increases gradually, the Raman gain mainly contributes to the amplification at $\lambda_2$ since $\lambda_2$ is much closer to the Raman gain peak wavelength than $\lambda_1$. Furthermore, when the LD2 pump power is large enough, the Raman gain in the SMF section can also increase the cavity gain at $\lambda_2$. Thus, the structure starts lasing at $\lambda_2$ when the pump power of LD2 reaches a certain level. Consequently, lasing at $\lambda_1$ decreases as the pump power of LD2 increases since the lasing at $\lambda_2$ will reduce the population inversion in the EDF. When the pump power of LD2 increases further, lasing at $\lambda_1$ disappears finally.

Next we study the wavelength switching when the pump power of LD1 is fixed to some other values. The inset of Fig. 3 shows the output powers at the two lasing wavelengths as the drive current for LD2 increases when the pump power of LD1 is fixed to 50 or 100 mW. One sees that the characteristics of the wavelength switching are similar (except the switching currents $I_a$ and $I_b$) when the pump power of LD1 is set to a different value. Fig. 3 shows the switching currents $I_a$ and $I_b$ when the pump power of LD1 is set from 20 to 160 mW with an increment of 20 mW. The switching current $I_a$ decreases as the pump power of LD1 increases. This can be explained as follows. The cavity gain for $\lambda_2$ to start lasing is a constant, which is the sum of EDF gain
and Raman gain. Thus, the larger EDF pump is set, the smaller Raman gain is needed for $I_s$ to start lasing (corresponding to smaller switching current $I_a$). The variation of $I_a$ under different pump powers of LD1 is quite small, while the variation of $I_b$ is quite large. As shown in Fig. 3, the switching current $I_b$ increases almost linearly with the pump power of LD1. This indicates that a larger drive current for LD2 is needed to let $I_s$ win the gain competition over $I_a$ when the pump power of LD1 increases.

![Switching currents $I_a$ and $I_b$ for LD2 when power of LD1 set to different values](image)

**Fig. 3** Switching currents $I_a$ and $I_b$ for LD2 when power of LD1 set to different values

Inset: Output powers at two lasing wavelengths as drive current for LD2 increases when pump power of LD1 set to 50 mW (curves A, B), 100 mW (curves C, D), 150 mW (curves E, F)

**Conclusion:** We have proposed and demonstrated a switchable dual-wavelength Raman erbium-doped fibre laser. The wavelength switching is controlled by the power of the Raman pump and the operation principle has been explained. The characteristics of the wavelength switching under different EDF pump levels have been studied experimentally. Unlike the other switchable multiwavelength fibre lasers, which are based on only EDF amplification, the present structure is simple (requiring no polarisation controller or special fibre/device) and the separation of the dual wavelengths can be very large (since the wavelength of the Raman pump can be arbitrary, which is impossible for EDF amplification). The output power and wavelength of the present switchable dual-wavelength fibre laser are repeatable and uniquely determined by the Raman pump power (without any hysteresis characteristic, which exists in some other switchable multiwavelength fibre lasers reported in e.g. [1, 13]).

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**References**

Paper VIII
Some Switchable Dual-wavelength Fibre Lasers Based on Fibre Bragg Grating Feedback

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ABSTRACT
Two methods to achieve dual-wavelength switching in a fibre laser are proposed and two corresponding switchable dual-wavelength fibre lasers based on fibre Bragg grating (FBG) feedback are demonstrated in this paper. In one proposed fibre laser, both Raman and Erbium-doped fibre (EDF) pumps are employed and the dual-wavelength switching is achieved by controlling the power of the Raman pump. In the other proposed fibre laser, an injection technique is used and the dual-wavelength switching is realized by controlling the power of the injection laser. The detailed behavior of the dual-wavelength switching in the two fibre lasers is experimentally studied and the principle is explained physically.

Keywords: switchable, dual-wavelength, fibre Bragg grating, fibre laser

1. INTRODUCTION
Wavelength-switchable fibre lasers have attracted considerable attention recently due to their important applications in wavelength-division multiplexer (WDM) fibre communication systems, fibre sensors, spectroscopy and optical instrument testing, etc. Several techniques have been reported to achieve wavelength switching in Erbium-doped fibre (EDF) lasers, such as the use of cascaded fibre Bragg gratings (FBGs) [1,2], few-mode fibre Bragg gratings [3], multimode fibre Bragg gratings [4, 5], spectral polarization-dependent loss elements [6], Sagnac loop reflector [7], acoustic waves [8], distributed-feedback (DFB) mode oscillations [9] and multisection high-birefringence fibre loop mirror [10]. Wavelength-switchable lasers based on some EDFs co-doped with other rare-earth ions have also been reported [11]. Most of these techniques are based on some special devices or manual adjustments to achieve wavelength switching.

As we all know, an EDF can be regarded as a homogenous gain media at the room temperature due to the homogenous line broadening of Erbium ions [12, 13]. This promises possible methods to achieve wavelength-switching in the EDF laser due to the gain competition between different wavelengths. In this paper, two methods to achieve wavelength-switching are proposed and the corresponding fibre lasers are demonstrated. One method is to introduce overlapping cavity (for two lasing wavelengths) and hybrid gain mechanism in a fibre laser. Lasing wavelength can be switched from one to the other when different pump condition is employed. In the corresponding fibre laser, an overlapping cavity is designed for lasing at two wavelengths (corresponding to the central wavelengths of two FBGs) and both EDF pump (for the EDF gain medium) and Raman pump (for the Raman gain medium) are employed. Dual-wavelength switching can be achieved by controlling the power of the Raman pump. The other method is to employ an injection technique in a normal EDF laser with FBG feedback. The lasing at the central wavelength of the FBG can be suppressed by the injection light (at a certain range of wavelength) with enough power into the cavity due to the gain competition between the lasing light and the injection light. In the corresponding fibre laser, a fibre Sagnac loop reflector and an FBG are employed to form a line structure cavity (like a Fabry–Perot cavity). The injection light is injected into the cavity through an optical circulator. Dual-wavelength switching is achieved by controlling the power of the injection laser. It is worthwhile to note that in the two proposed methods, wavelength switching is achieved by controlling the power of the pump or the injection laser and therefore this type of wavelength switching can be called optically controlled wavelength switching, which can be expected to be one type of fast wavelength switching. Our experimental results in the proposed fibre laser with an injection technique have shown the switching time is less than 50 microsecond.
2. EXPERIMENTAL STUDY AND ANALYSIS

2.1 Experimental setup

The schematic configurations of the proposed switchable dual-wavelength fibre lasers are shown in Fig. 1. For the first proposed fibre laser (shown in Fig. 1(a)), a 1480 nm laser diode (LD) with a maximum power of about 250 mW is used as the EDF pump LD1, and a 1467 nm LD with a maximum power of 350 mW (the corresponding drive current is 950 mA) is employed as the Raman pump LD2. The length of the SMF (single mode fibre) section (with an attenuation coefficient of 0.19 dB/km at 1550 nm) between the two FBGs is 10 km. Sections of DCF (dispersion compensation fibre), SMF and EDF are the gain fibres in the present structure. The DCF section (with a total dispersion of -986 ps/nm and a total loss of 5.7 dB) used here can compensate 60 km single mode fibre. The length, numerical aperture, cutoff wavelength and peak absorption (at 1531nm) of the EDF section are 4 m, 0.25, 950 nm and 19.2 dB/m, respectively. Two FBGs are used as wavelength selection components. The central wavelengths, the full-widths at half maximum (FWHM) and the reflectivities are (1545.13 nm, 0.093 nm, 50.0%) and (1559.98 nm, 0.098 nm, 51.3%) for FBG1 and FBG2, respectively (these parameters are provided by the manufacturer). An optical circulator and an isolator are used here to ensure that the lasing cavity is a counterclockwise ring. For the second proposed fibre laser (shown in Fig. 1(b)), a 980 nm LD with a maximum power of about 150 mW is used as an EDF pump, and a tunable (from 1500 nm to 1590 nm) laser diode (TLD) with a maximum power of about 10 mW is employed as the injection laser. The line structure cavity is formed by a wideband Sagnac loop reflector (a wideband 3dB 2x2 coupler with two ports connected with each other by a fibre) and an FBG whose central wavelength, FWHM and reflectivity are 1550.48 nm, 0.096 nm and 53.2%, respectively (these parameters are provided by the manufacturer). A section of EDF (the same one used in the first proposed fibre laser) is employed as the gain medium.
2.2 Experimental results and analysis for the first fibre laser

In our experiment for the first proposed fibre laser, the power of EDF pump LD1 is fixed to 150 mW. When the Raman pump LD2 is switched off, the output spectra of the laser is shown by the solid line in Fig. 2, from which one sees that the structure is lasing only at $\lambda_1$ with a peak power of -11.9dBm. However, when the drive current of LD2 is switched on to 750 mA (note that we read the current of the driver of the LD2 directly), the structure will be lasing only at $\lambda_2$ with a peak power of 1.9 dBm (see the dashed line in Fig. 2). Note that the resolution and sensitivity of the optical spectrum analyzer (OSA) used in the all measurements in this paper are 0.06 nm and -65 dBm, respectively. Our experimental results have shown that the laser output is rather stable. Thus, the wavelength switching is achieved in this fibre laser by controlling the drive current of LD2 (i.e., the power of the Raman pump LD2).
Figure 3 shows the detailed behavior of the dual-wavelength switching as the drive current for LD2 increases (the pump power of LD1 is fixed to 150 mW). The variation of output power at $\lambda_1$ and $\lambda_2$ are indicated by the lines connected with circles and triangles, respectively. Obviously, there are three regions where the laser is in different operational modes. In region A (with the drive current for LD2 below switching current $I_a = 70$ mA), only $\lambda_1$ is lasing and its output power remains around -11.9 dBm. In region B (with the drive current for LD2 ranging from 70 mA to 690 mA), both $\lambda_1$ and $\lambda_2$ are lasing. In this region, as the drive current of LD2 increases, the output power at $\lambda_2$ increases while the output power at $\lambda_1$ decreases. In region C (with the drive current for LD2 above switching current $I_b = 690$ mA), only $\lambda_2$ is lasing and its output power remains around 1.9 dBm.

The operation principle of the present switchable dual-wavelength fibre laser can be explained as follows. When the Raman pump LD2 is off, only lasing at $\lambda_1$ can be obtained since the cavity loss at $\lambda_2$ is larger than that at $\lambda_1$ (due to the loss of the 10 km SMF) and the EDF amplification will occur only at $\lambda_1$ (due to the gain competition). When the power of LD2 increases gradually, the Raman gain mainly contributes to the amplification at $\lambda_2$ since $\lambda_2$ is much closer to the Raman gain peak wavelength than $\lambda_1$. Furthermore, when the LD2 pump power is large enough, the Raman gain in the SMF section can also increase the cavity gain at $\lambda_2$. Thus, the structure starts lasing at $\lambda_2$ when the pump power of LD2 reaches a certain level. Consequently, the power of the lasing at $\lambda_1$ decreases as the pump power of LD2 increases since the lasing at $\lambda_2$ will reduce the population inversion in the EDF. When the pump power of LD2 increases further, lasing at $\lambda_1$ disappears finally.

![Switching currents $I_a$ and $I_b$ for LD2 when the power of LD1 is set to different values.](image)

We also study the wavelength switching when the pump power of LD1 is fixed to a different value. Experimental results show that the characteristics of the wavelength switching are similar (except the switching currents $I_a$ and $I_b$) when the pump power of LD1 is set to different values. Figure 4 shows the switching currents $I_a$ and $I_b$ when the pump power of LD1 is set from 20 mW to 160 mW with an increment of 20 mW. The switching current $I_a$ decreases as the pump power of LD1 increases. This can be explained as follows. The cavity gain for $\lambda_2$ to start lasing is a constant, which is the sum of EDF gain and Raman gain. Thus, the larger EDF pump is set, the smaller Raman gain is needed for $\lambda_2$ to start lasing (corresponding to smaller switching current $I_a$). The variation of $I_a$ under different pump powers of LD1 is quite small.
while the variation of $I_s$ is quite large. As shown in Fig. 4, the switching current $I_s$ increases almost linearly with the pump power of LD1. This indicates that a larger drive current for LD2 is needed in order to let $\lambda_2$ win the gain competition over $\lambda_1$ when the pump power of LD1 increases.

![Output spectra of the second proposed fibre laser](image)

**Fig. 5.** Output spectra of the second proposed fibre laser when the injection laser is switched off (solid line) or switched on to -6 dBm (dashed line). The power of the EDF pump is fixed to 16.2 mW.

### 2.3 Experimental results and analysis for the second fibre laser

In our next experiment for the second proposed fibre laser, the power of the EDF pump LD is fixed to 16.2 mW. When the injection laser TLD is switched off, the output spectra of the laser is shown by the solid line in Fig. 5, from which one sees that the structure is lasing only at $\lambda_1 = 1550.48$ nm (corresponding to the central wavelength of the FBG) with a peak power of -4.88 dBm. When the injection laser TLD (with tunable wavelength $\lambda_2$; for this figure $\lambda_2 = 1555$ nm) is switched to -6.0 dBm (or larger), the structure will be lasing only at $\lambda_2 = 1555$ nm with a peak power of -3.16 dBm (see the dashed line in Fig. 5). Thus, the wavelength switching can be achieved in this fibre laser by controlling the power of the injection laser TLD.
Figure 6 shows the detailed behavior of the dual-wavelength switching as the power of the injection laser TLD increases (the power of 980 nm LD is fixed to 16.2 mW). The output power at $\lambda_1$ and $\lambda_2$ are indicated by the lines connected with circles and triangles, respectively. Obviously, when the injection laser is switched off, the proposed fibre laser is simply an EDF laser with an output wavelength of $\lambda_1$. However, when the injection laser is switched on and its output power increases, one sees there are two regions where the laser is in different operational modes. In region A (with the TLD power below the switching power $P_s = -6.6$ dBm), the laser outputs at both $\lambda_1$ and $\lambda_2$. In this region, as the TLD power increases, the output power at $\lambda_2$ increases while the output power at $\lambda_1$ decreases. In region B (with the TLD power larger than the switching power $P_s$), the lasing occurs only at $\lambda_2$ and its output power remains around -3.16 dBm. Figure 7 shows a good linear relationship between the pump power and the switching power $P_s$ when the wavelength of the TLD is fixed to 1555 nm.

Figure 7. Relationship between the switching power $P_s$ and the power of the 980 nm pump LD when the wavelength of the TLD is fixed to 1555 nm.
The operation principle of the present injection-switched EDF laser can be explained as follows. When the injection laser TLD is switched off, only lasing at $\lambda_1$ can occur since the cavity of the line structure only exists at the Bragg wavelength $\lambda_1$ of the FBG. When the TLD is switched on, the seeding light is injected into the cavity and is amplified (traveling with a round trip on the EDF). In this case, the seeding light will reduce the population inversion required for lasing at $\lambda_1$ (the cavity gain at $\lambda_1$ decreases). Consequently, the output power at $\lambda_1$ decreases as the power of the TLD increases. When the power of the TLD is large enough and approaches $P_s$, the emission stimulated by the seeding light at wavelength $\lambda_2$ consumes most of the pump power (i.e., reduces the population inversion) and consequently the cavity gain becomes less than the cavity loss at $\lambda_1$ (i.e., the lasing at $\lambda_1$ becomes impossible). This result in a drastic drop of the power at $\lambda_1$ and finally only the output at $\lambda_2$ can be observed.

Fig. 8. Switching power as the wavelength of the TLD increases when the pump power is fixed at 16.2 mW (line connected with triangles) or 19.1 mW (line connected with circles).

We go further to study the characteristics of the wavelength switching. Figure 8 shows the switching powers for different wavelengths of the TLD when the power of the 980 nm pump LD is fixed to 16.2 mW (line connected with squares) or 19.1 mW (line connected with circles). From this figure one sees that the wavelength switching can be achieved over a wide wavelength range (about 50 nm) for the TLD. The V-shape lines indicate that the wavelength switching is easier when the TLD wavelength is around 1560 nm and a larger switching power is needed when the TLD wavelength is far away from 1560 nm. We have measured the saturated gain spectrum of the (1 round trip) EDFA structure (just removing the FBG in Fig. 1(b)) when the pump power is 16.2mW, from which we find the gain peak is around 1560 nm, and this is the reason why the switching power is minimal around 1560 nm as shown in Fig. 8. Furthermore, from Fig. 8 one sees that the difference in the switching powers for the two lines is almost a constant (4.6dBm) for different TLD wavelengths, and this is due to the linear relationship between the switching power (in mW) and the power of the 980 nm pump LD.

The transient switching response of the proposed laser is also studied when the power of the 980 nm pump LD is 16.2 mW and the TLD wavelength is fixed at 1548.6 nm (due to the availability of a filter in our lab for measuring the laser output at a specific wavelength). We employ two InGaAs Photo-detectors (PDA400, provided by Thorlabs, Ltd. UK) to measure the time delay between the moment when the injection laser is switched on and the moment when the lasing at $\lambda_1$ disappears, and the results are shown in Fig. 9. From this figure one sees that the time delay (i.e., the switching time) is less than 50 microsecond, which indicates the proposed laser has the ability of fast wavelength-switching (much faster than the switching time reported in Ref. [14]). The switching time from the self-seeded wavelength to the injection
wavelength is expected to be about several round-trip time of the laser cavity. However, we have not reached the limit of the switching time due to the limitation of our measurement equipment.

![Figure 9. Transient switching response (measured with photo-detectors) of the proposed fibre laser when the power of the 980 nm pump LD is 16.2 mW and the TLD wavelength is fixed at 1548.6 nm.](image)

3. CONCLUSION

In summary, we have proposed two methods to achieve wavelength switching in fibre lasers and demonstrated two switchable dual-wavelength fibre lasers based on FBG feedback. For the first method, both an overlapping cavity and the hybrid gain medium are employed in the fibre laser. The lasing wavelength can be switched by controlling the gain at different wavelengths. As an example, in our first proposed fibre laser, an overlapping cavity has been designed combining both the EDF gain medium and the Raman gain medium. The wavelength switching is controlled by the power of the Raman pump and the operation principle has been explained. The characteristics of the wavelength switching under different EDF pump levels have been studied experimentally. Unlike the other switchable multi-wavelength fibre lasers, which are only based on EDF amplification, the present structure is simple (requiring no polarization controller or special fibre/device) and the separation of the dual wavelengths can be very large (since the wavelength of the Raman pump can be arbitrary, which is impossible for EDF amplification). The output power and wavelength of the present switchable dual-wavelength fibre laser are repeatable and uniquely determined by the Raman pump power (without any hysteresis characteristic, which exists in some other switchable multi-wavelength fibre lasers reported in e.g. [1, 2]). To extend this method, it is expected that switchable dual-wavelength fibre laser can also been achieved by employing other hybrid gain (i.e., by using EDFA and SOA). For the second method, an injection technique is employed. As an example, an injection-switchable Erbium-doped fibre laser of the line structure has been proposed. The line structure cavity is formed by a fibre Sagnac loop reflector and an FBG. The dual-wavelength switching is achieved by controlling the power of the injection laser and the operational principle has been explained in detail. The characteristics of the wavelength switching for different levels of the EDF pump laser and different wavelengths of the tunable injection laser have been studied experimentally. The switching time from one wavelength to the other is less than 50 microsecond. Furthermore, we can also try to achieve wavelength switching in a fibre ring laser by employing an injection technique.
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Paper IX
TUNABLE AND INJECTION-SWITCHABLE ERBIUM-DOPED FIBER LASER OF LINE STRUCTURE

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ABSTRACT: A tunable and injection-switchable erbium-doped fiber (EDF) laser is proposed based on a line structure formed by a fiber Sagnac loop reflector and an fiber Bragg grating (FBG). Wavelength switching is achieved by controlling the power of the tunable injection laser. The self-seeded wavelength corresponding to the Bragg wavelength of the FBG (can be tuned by changing the temperature or stress) and the other wavelength corresponds to the Bragg wavelength of the FBG (can be tuned by changing the temperature or stress) and the other wavelength corresponds to the Bragg wavelength of the FBG (can be tuned by changing the temperature or stress) and the other wavelength corresponds to the Bragg wavelength of the FBG (can be tuned by changing the temperature or stress) and the other wavelength corresponds to the Bragg wavelength of the FBG (can be tuned by changing the temperature or stress). The characteristics of the wavelength switching for different levels of the EDF pump power and different wavelengths of the injection laser are studied experimentally. The present fiber laser has the advantages of tunability, stability, low amplified spontaneous emission noise, and high injection efficiency when compared with a fiber ring laser. Rapid wavelength switching is expected and the transient switching response of the laser is also studied. © 2007 Wiley Periodicals, Inc. Microwave Opt Technol Lett 49: 765–768, 2007; Published online in Wiley InterScience (www.interscience.wiley.com). DOI 10.1002/mop.22262

Key words: tunable; injection; switchable; line structure; Erbium-doped fiber laser

1. INTRODUCTION

Wavelength-switchable and tunable fiber lasers have important applications in WDM fiber communication systems, fiber sensors, and so forth. Several techniques have been reported to achieve wavelength switching in fiber lasers, such as the use of sampled fiber Bragg gratings (FBG) [1], cascaded FBGs [2, 3], a Sagnac loop reflector [4], a few-mode fiber grating [5], a slanted multimode FBG [6], a Bragg grating-based acoustooptic superlattice modulator [7], a hybrid gain medium [8], a multi-section high-birefringence fiber loop mirror [9], a programmable electric-actuated polarization controller [10], and hybrid pumps [11]. Overlapping cavities can be used for multi-wavelength lasing and wavelength switching can be achieved by controlling the loss or the gain in different cavities [2, 3, 11]. Recently, Dragic and coworkers have reported an injection-seeded erbium-doped fiber (EDF) ring laser [12–14], in which an injection technique was used to achieve a wavelength-switchable fiber laser. A tunable laser (outside the cavity of the fiber laser) is used as seeding light. The shared cavity is for self-seeded lasing or injection-seeded lasing. Switching between the self-seeded wavelength lasing and injection-seeded wavelength lasing can be achieved by controlling the power of the injection laser. By using this technique, one of the switching wavelengths can be tuned among a large range since a tunable injection laser is employed.

In this article we propose a novel tunable and switchable EDF laser of line structure (see Fig. 1(a)). Here a fiber Sagnac loop reflector and an FBG are employed to form a line cavity (like a Fabry-Perot cavity). The seeding light is injected into the cavity through an optical circulator. Dual-wavelength switching is achieved by controlling the power of the injection laser. One wavelength corresponds to the Bragg wavelength of the FBG (can be tuned by changing the temperature or stress) and the other wavelength can be tuned from 1535 to 1590 nm (determined by the wavelength of the injection laser).

Figure 1 The schematic configuration of (a) the proposed tunable and injection-switchable fiber laser of line structure and (b) a fiber ring laser similar to the one proposed in Ref. 13. LD, laser diode; TLD, tunable laser diode; WDM, wavelength division multiplexing; FBG, fiber Bragg grating; OC, optical circulator; ISO, isolator; EDF, erbium-doped fiber; SLR, Sagnac loop reflector.
2. EXPERIMENTAL SETUP AND RESULTS

In our experiment, a 980 nm laser diode (LD) with a maximum power of about 150 mW is used as an EDF pump, and a tunable (from 1500 to 1590 nm) LD with a maximum power of about 10 mW is employed as the injection laser. The line cavity is formed by a wideband Sagnac loop reflector (a wideband 3 dB coupler with two ports connected with each other with a fiber) and an FBG whose central wavelength, full-width at half maximum, and reflectivity are 1550.48 nm, 0.096 nm, and 53.2%, respectively (these parameters are provided by the manufacturer). A section of EDF is employed as the gain medium, and its length, numerical aperture, cutoff wavelength, and peak absorption (at 1531 nm) are 4 m, 0.25, 950 nm, and 19.2 dB/m, respectively.

In our first experiment, the power of the EDF pump LD is fixed to 16.2 mW. When the injection laser (TLD) is switched off, the output spectrum of the laser is shown by the solid line in Figure 2, from which one sees that the structure is lasing only at \( \lambda_1 = 1550.48 \text{ nm} \) (corresponding to the central wavelength of the FBG) with a peak power of \( -4.88 \text{ dBm} \). When the injection laser (TLD) (with tunable wavelength \( \lambda_2 \); for this figure \( \lambda_2 = 1555 \text{ nm} \)) is switched on and fixed to \( -6 \text{ dBm} \), the structure outputs only at \( \lambda_2 = 1555 \text{ nm} \) with a peak power of \( -3.16 \text{ dBm} \) (see the dashed line in Fig. 2). The inset of Figure 2 shows the spectrum of the injection laser (TLD), which is similar to the output spectrum of the proposed fiber laser shown by the dashed line in Figure 2. In this case, the injection light is amplified by a two-pass traveling-wave amplifier. Note that the resolution and sensitivity of the optical spectrum analyzer (OSA) used in the measurement are 0.06 nm and \( -65 \text{ dBm} \), respectively. Thus, the wavelength switching can be achieved in this fiber laser by controlling the power of the injection laser (TLD).

3. COMPARISON WITH A FIBER RING LASERS

For comparison, we have also made a fiber ring laser [see Fig. 1(b)] for the schematic configuration (similar to the one proposed recently in Ref. 13). We use a 980 nm pump LD and a section of EDF (same as the one used for Fig. 2) to form an EDF. A 3-dB coupler and an isolator are employed in the ring cavity. The injection efficiency is rather low for the fiber ring laser shown in Figure 1(b) (only half of the TLD power can be injected into the ring cavity), while our proposed fiber laser has a high injection efficiency (up to 100% if an ideal optical circulator is used). The measured output spectra of this fiber ring laser are shown in Figure 3. One can see that the amplified spontaneous emission (ASE) noise of this fiber ring laser is much larger than that of the proposed fiber laser of line structure. The ASE noise is larger for the fiber ring laser reported in Ref. 13 since a 90/10 coupler is used. One may suggest to replace with a coupler of low power ratio (e.g., a 1/99 coupler) to reduce the ASE noise. However, it will drastically reduce the injection efficiency (only 1% for a 1/99 coupler). Unlike the present fiber laser of line structure whose lasing wavelength can be tuned by, for example, heating the FBG (shown in Fig. 4), the lasing wavelength of the fiber ring laser cannot be tuned.
since there is no tunable wavelength-selection component in the ring cavity. Furthermore, the wavelength of the fiber ring laser is unstable (see the inset of Fig. 3 for the spectra measured 6 times with an interval of 2 min) since the output wavelength is determined by the length of the ring cavity, which is sensitive to an environmental (e.g., temperature and stress) change. However, the lasing wavelength of the proposed fiber laser of line structure is very stable (since it is determined by the Bragg wavelength of the FBG) and we cannot see any spectrum shift in our OSA with the resolution of 0.06 nm (see the inset of Fig. 4 for the spectra measured 6 times with an interval of 2 min).

4. CHARACTERISTICS OF WAVELENGTH SWITCHING

Figure 5 shows the detailed behavior of the dual-wavelength switching as the power of the injection laser TLD increases (the power of 980 nm LD is fixed to 16.2 mW) in the proposed injection-switchable fiber laser. The output powers at \( \lambda_1 \) and \( \lambda_2 \) are indicated by the lines connected with squares and circles, respectively. Obviously, when the injection laser is switched off, the proposed fiber laser is simply an EDF laser with an output wavelength of \( \lambda_1 \). However, when the injection laser is switched on and its output power increases, one sees there are two regions where the laser is in different operational modes. In Region A (with the TLD power below the switching power \( P_s \) = -6.6 dBm), the laser outputs at both \( \lambda_1 \) and \( \lambda_2 \). In this region, as the TLD power increases, the output power at \( \lambda_2 \) increases, while the output power at \( \lambda_1 \) decreases. In Region B (with the TLD power larger than the switching power \( P_s \)), the structure has the output only at \( \lambda_2 \) and its output power remains around -3.16 dBm. The inset of Figure 5 shows a good linear relationship between the pump power and the switching power \( P_s \) when the wavelength of the TLD is fixed to 1555 nm. The operation principle of the present tunable and injection-switchable EDF laser can be explained as follows. When the injection laser (TLD) is switched off, only lasing at \( \lambda_1 \) can occur since the cavity of the line structure only exists at the Bragg wavelength \( \lambda_1 \) of the FBG. When the TLD is switched on, the seeding light is injected into the line cavity and is amplified (traveling with a round trip on the EDF). In this case, the seeding light will reduce the population inversion required for lasing at \( \lambda_1 \) (the cavity gain at \( \lambda_1 \) decreases). Consequently, the output power at \( \lambda_1 \) decreases as the power of the TLD increases. When the power of the TLD is large enough and approaches \( P_s \), the emission stimulated by the seeding light at wavelength \( \lambda_2 \) consumes most of the pump power (i.e., reduces the population inversion) and consequently the cavity gain becomes less than the cavity loss at \( \lambda_1 \) (i.e., the lasing at \( \lambda_1 \) becomes impossible). It results in a drastic drop of the power at \( \lambda_1 \) and finally only the output at \( \lambda_2 \) can be observed.

Figure 6 shows the switching powers for different wavelengths of the TLD when the power of the 980 nm pump LD is fixed to 16.2 mW (lines connected with squares) or 19.1 mW (lines connected with circles). From this figure one sees that the wavelength switching can be achieved over a wide wavelength range (about 50 nm) for the TLD. The V-shape curves indicate that the wavelength switching is easier when the TLD wavelength is around 1560 nm and a larger switching power is needed when the TLD wavelength is far away from 1560 nm. The inset of Figure 6 shows the saturated gain spectrum of the (one round trip) EDFA structure (just removing the FBG in Fig. 1) when the pump power is 16.2 mW. From this inset one sees the gain peak is around 1560 nm, and this is the reason why the switching power is minimal around 1560 nm as shown in Figure 6. Furthermore, from Figure 6 one sees that the difference in the switching powers for the two curves is almost a constant (4.6 dBm) for different TLD wavelengths, and this is due to the linear relationship between the switching power (in mW) and the power of the pump 980 nm LD (see the inset of Fig. 5).

5. MEASUREMENT OF SWITCHING TIME

The transient switching response of the proposed laser is also studied when the power of the 980 nm pump LD is 16.2 mW and the TLD wavelength is fixed at 1548.6 nm (due to the availability of a filter in our lab for measuring the laser output at a specific wavelength). We employ two InGaAs Photo-detectors (PDA400, provided by Thorlabs, UK) to measure the time delay between the moment when the injection laser is switched on and the moment when the lasing at \( \lambda_1 \) disappears, and the results are shown in
The transient switching response (measured with photo-detectors) of the proposed fiber laser when the power of the 980 nm pump LD is 16.2 mW and the TLD wavelength is fixed at 1548.6 nm

Figure 7. From this figure one sees that the time delay (i.e., the switching time) is less than 50 μs, which indicates the proposed laser has the ability of fast wavelength-switching (much faster than the switching time reported in Ref. 15). The switching time from the self-seeded wavelength to the injection wavelength is expected to be about several round-trip time of the laser cavity. However, we have not reached the limit of the switching time because of the limitation of our measurement equipment.

6. CONCLUSIONS

In conclusion, we have proposed and demonstrated a tunable and injection-switchable EDF laser of line structure. The line cavity is formed by a fiber Sagnac loop reflector and an FBG. The dual-wavelength switching is achieved by controlling the power of the injection laser and the operational principle has been explained in detail. Both wavelengths can be tuned by adjusting the injection wavelength of the tunable laser and the Bragg wavelength of the FBG. The characteristics of the wavelengths switching for different levels of the EDF pump laser and different wavelengths of the tunable injection laser have been studied experimentally. Our experimental results have shown that the present fiber laser is more stable and has a much lower ASE noise and a higher injection efficiency when compared with a fiber ring laser. The switching time from one wavelength to the other wavelength is less than 50 μs.

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FIBER OPTIC DISPLACEMENT SENSING MONITORED BY AN OTDR AND REFERENCED BY FRENSNEL REFLECTION AND BY FIBER BRAGR GRATINGS

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ABSTRACT: This work presents a study of displacement sensing based on a fiber eight geometry shape monitored by an optical time domain reflectometer. The displacement sensor is referenced by Fresnel reflection or by a fiber Bragg grating structure located after the sensor. One of the advantages of the fiber Bragg grating as referencing device is its capability to be multiplexed by a number of displacement sensors in series along the optical fiber. This concept is also demonstrated using two Bragg gratings. © 2007 Wiley Periodicals, Inc. Microwave Opt Technol Lett 49: 768–770, 2007; Published online in Wiley InterScience (www.interscience.wiley.com). DOI 10.1002/mop.22261