Waveguide-Integrated MEMS Concepts for Tunable Millimeter-Wave Systems

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Front cover picture:
Scanning electron microscope (SEM) images of a fabricated device, consisting of a MEMS-reconfigurable surface and on-chip electrostatic combdrive actuators, to be integrated in a WR-12 rectangular waveguide as the first millimeter-wave MEMS waveguide switch (left) and close-up view of the MEMS-reconfigurable surface showing gold-covered 5-µm wide vertical cantilevers and 25-µm wide horizontal suspension bars (right).
Abstract

This thesis presents two families of novel waveguide-integrated components based on millimeter-wave microelectromechanical systems (MEMS) for reconfigurable systems. The first group comprises V-band (50–75 GHz) and W-band (75–110 GHz) waveguide switches and switchable irises, and their application as switchable cavity resonators, and tunable bandpass filters implemented by integration of novel MEMS-reconfigurable surfaces into a rectangular waveguide. The second category comprises MEMS-based reconfigurable finlines integrated as phase shifters into a rectangular waveguide array to demonstrate beams steering with a phased array antenna.

The first group of the presented reconfigurable waveguide components is based on a novel MEMS-reconfigurable surface structured in the device layer of a silicon-on-insulator (SOI) wafer using metallized mono-crystalline silicon as structural and functional material. The chip containing the reconfigurable surface is integrated in the cross-section of a WR-12 rectangular waveguide perpendicular to the wave propagation. The reconfigurable surface is modified for different states by on-chip push-pull electrostatic comb-drive MEMS actuators. The switch is ON when the reconfigurable surface is in its transmissive state and OFF when the reconfigurable surface is in its blocking state for the propagating wave. This millimeter-wave waveguide switch shows an insertion loss and isolation very similar to high-performance but bulky mechanical rotary waveguide switches, despite being extremely compact (30 µm thick), and thus combines the high electrical performance of mechanical switches with the size of (high power consuming and inferior performance) PIN-diode waveguide switches. This thesis also investigates the optimization to decrease the number of contact points for the OFF state and presents a device yield analysis. The same concept is developed further to MEMS-switchable inductive and capacitive irises, with the performance similar to ideal irises. With such MEMS-reconfigurable irises a switchable cavity resonator was implemented and the potential of tunable bandpass filters are demonstrated. Since these devices feature all-metal design as no dielectric layers are utilized, no dielectric charging effect is observed. Furthermore, this thesis investigates the low-loss integration of millimeter-wave MEMS-reconfigurable devices into rectangular waveguide with conductive polymer interposers.

The second group of components comprises finlines which are fabricated out of two bonded silicon wafers with bilateral gold structures integrated into a WR-12 rectangular waveguide. A 2-bit waveguide phase shifter is designed for 77-GHz automotive radar. Such phase shifters are used as individual building blocks of a two-dimensional antenna array for beam steering front-ends.

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To Zhaleh and Rahim, my parents, whom I always adore,
and to Farzam, my lovely brother, whom I always admire
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List of Publications

The thesis is based on the following peer-reviewed international journal papers:

1. “MEMS reconfigurable millimeter-wave surface for V-band rectangular-waveguide switch,”

2. “Integration of microwave MEMS devices into rectangular waveguide with conductive polymer interposers,”

3. “Waveguide-integrated MEMS-based phase shifter for phased array antenna,”

4. “Parameter analysis of millimeter-wave waveguide switch based on a MEMS-reconfigurable surface,”

5. “MEMS-reconfigurable irises for millimeter-wave waveguide components,”

6. “MEMS-reconfigurable transmit-array antenna for 77-GHz automotive radar applications,”
The contribution of Zargham Baghchehsaraei to the different publications:

1. major part of design, all fabrication, all experiments, and major part of writing
2. part of design, part of fabrication, part of experiments, and major part of writing
3. part of design, major part of fabrication, and major part of writing
4. major part of design, all fabrication, all experiments, and major part of writing
5. major part of design, all fabrication, all experiments, and major part of writing
6. part of fabrication and major part of writing

The work has also been presented at the following reviewed international conferences:


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Comments:

- (*) This conference paper received one out of four Outstanding Student Paper Awards at 2014 IEEE International Conference on Micro Electro Mechanical Systems, San Francisco, CA, USA.

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- (***) This conference paper was finalist for Best Paper Award at 2012 IEEE European Microwave Conference, Amsterdam, The Netherlands.

- (****) This workshop presentation received a Best Poster Award at 2013 Micromechanics and Microsystems Europe Workshop, Espoo, Finland.
List of abbreviations

3D  Three dimensional
BOX  Buried oxide
CPW  Coplanar waveguide
DC  Direct current
DLP  Digital light processing
DMTL  Distributed MEMS transmission lines
DRIE  Deep reactive ion etching
FCR  Fire-control radar
HPBW  Half power beamwidth
HRSS  High-resistivity silicon substrate
MEMS  Microelectromechanical systems
RF  Radio frequency
RIE  Reactive ion etching
RMS  Root mean square
SEM  Scanning electron microscopy
SIW  Substrate integrated waveguide
SOI  Silicon on Insulator
SPDT  Single pole double throw
SPST  Single pole single throw
TRL  Thru-reflect-line
TTD  True-time delay
VNA  Vector network analyzer
YIG  Yttrium iron garnet
# List of radar-frequency letter bands
*(IEEE standard 521-1984)*

<table>
<thead>
<tr>
<th>Letter Designation</th>
<th>Frequency Range</th>
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<tbody>
<tr>
<td>HF</td>
<td>3–30 MHz</td>
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<tr>
<td>VHF</td>
<td>30–300 MHz</td>
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<tr>
<td>UHF</td>
<td>300–1000 MHz</td>
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<td>1–2 GHz</td>
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<td>S</td>
<td>2–4 GHz</td>
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<td>C</td>
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<td>W</td>
<td>75–110 GHz</td>
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Chapter 1

Introduction and outline

This thesis presents novel works in the field of radio-frequency microelectromechanical systems (RF MEMS) for V-band (50–75 GHz) and W-band (75–110 GHz) reconfigurable waveguide components. The main motivation of doing research on MEMS for microwave applications emerges from excellent signal handling performance of microwave MEMS devices in terms of insertion loss, isolation, linearity, as well as, large tuning range over a large bandwidth, besides, low power consumption of MEMS actuators, e.g. for electrostatic actuation mechanism.

The millimeter-wave spectrum, historically mainly exploited for defense and space applications, is of increasing interest for civilian applications, including automotive radar at 76–81 GHz [1], high speed wireless communications at 60 GHz [2, 3] and E-band (71–76 GHz, 81–86 GHz) [4], remote sensing for security and surveillance [5, 6], and medical diagnosis [7]. Advantages of going to higher frequencies are larger available bandwidths, higher spatial resolution, better discrimination between materials, and smaller antenna and sensor interfaces [8–10].

Over the past several decades, the need for versatile devices with the ability to process and transfer high amount of data, on one hand, and the trend in extending the application of the millimeter-wave spectrum, on the other hand, drive the development of new technologies. Most of these technologies for microwave frequencies are based on planar transmission lines, e.g. microstrip and coplanar waveguides (CPW). Nevertheless, waveguide technology is still necessary at microwave and millimeter-wave frequencies due to low signal loss, but also at radio frequencies where high Q-factor or high power handling is required. In order to make full advantage of waveguide technology, components inserted in the waveguide for signal manipulation should be of equally low loss. Although waveguide systems can benefit significantly from the characteristics of RF MEMS, there has been very limited research work on waveguide-integrated RF MEMS systems, where numerous specific challenges arise such as complexity of the reliable low-loss integration of the MEMS chip into the waveguide and consideration requirement for the interference of MEMS actuators, including the bias routing, with the RF signal.
Novel concepts and fabricated components are presented in this thesis to address the limitations of the state-of-the-art waveguide switches, cavity resonators, filters and phase shifters. In addition, a novel method for integration of MEMS chips into rectangular waveguides based on commercial conductive polymer interposer is presented which features very low insertion loss.

The remainder of this thesis is divided into seven chapters and is organized as follows.

**Chapter 2** gives a brief introduction to microelectromechanical systems in general and focuses, in particular, on RF and microwave MEMS sub-field. The last section of the chapter gives a short overview of RF MEMS devices based on silicon-on-insulator (SOI) technology which is the main fabrication platform used in Chapter 5.

**Chapter 3** gives a background on conventional methods for tunable waveguide components such as waveguide switches, tunable cavity resonators, and tunable waveguide filters.

**Chapter 4** covers the previous works of various research groups on tunable waveguide components based on integrated MEMS devices.

**Chapter 5** presents millimeter-wave waveguide switches and switchable cavity resonators based on novel MEMS-reconfigurable surfaces, and demonstrates a concept for tunable waveguide bandpass filter.

**Chapter 6** introduces a novel concept of tunable waveguide phase shifters with integrated MEMS elements and application of such phase shifters for a two-dimensional antenna array for beam steering front-ends at 77 GHz.

**Chapter 7** investigates a novel integration method based on commercial conductive polymer sheets to address the challenges for integration of MEMS devices into waveguides, such as increased insertion loss, spurious resonances, reliability of mechanical mounting, and routing of the actuation voltage.

**Chapter 8** summarizes the conclusions of this thesis.
Chapter 2

Background to RF and microwave MEMS

This chapter starts with a brief introduction to microelectromechanical systems, with focus on RF/microwave MEMS, and ends with RF MEMS devices based on silicon-on-insulator (SOI) technology, which is the main fabrication platform used in this thesis.

2.1 Microelectromechanical systems

Microelectromechanical systems (MEMS) are integrated micro-scaled devices extending microelectronics with miniaturized mechanical structures and transducers which provide a link to the physical surroundings. Transducers, which are defined as components converting energy from one form to another, are categorized into sensors and actuators. Sensors are mostly used to measure a physical parameter by taking energy from the surrounding and report in form of a transduced energy to the device, whereas, actuators, which work the other way, are used to manipulate the surroundings by converting an input energy from the device into a mechanical work output. Among many physical principles which can be used as actuation mechanism for MEMS actuators, electrostatic, thermal, piezoelectric, and magnetic mechanism are employed most commonly. MEMS devices are fabricated using lithography-based microfabrication techniques, which are heavily borrowed from the semiconductor industry and further enhanced with other micromanufacturing techniques. Typical examples for MEMS-based sensors are accelerometers, gyroscopes, microphones, pressure sensors, and gas sensors; and examples for commercially successful MEMS actuators are inkjet printhead nozzles and micromirror arrays for digital light processing (DLP) video projectors [11–16].

2.2 RF and microwave MEMS

MEMS devices are extremely diverse and they are divided into a number of categories based on the application area, with devices for radio frequency (RF) applica-
tions defined as RF MEMS. RF MEMS devices include, basically, micromachined parts which are interacting with electrical signals of the RF range to provide RF functionalities such as switching, filtering, tuning, phase shifting, matching, and polarization changing. The mechanical nature of their interaction with high frequency electrical signals offers numerous advantages over semiconductor counterparts such as lower insertion loss, higher isolation, better linearity, higher Q-factors, wider tuning range over a wider bandwidth, and extremely low power consumption [17–20].

The most basic RF MEMS devices are RF MEMS switches [17, 21–24] and tunable capacitors [22, 25–27], which have been developed to very mature RF components [28–31] since their introduction. The majority of more advanced reconfigurable RF MEMS systems typically feature conventional RF circuits which are enhanced by integrated MEMS actuators, mostly switches and varactors, to provide new reconfigurable functionality [32]. Besides RF MEMS switches and tunable capacitors, examples of RF MEMS devices include tunable inductors [33, 34], tunable phase shifters [35–38], tunable filters [39–41], MEMS resonators for filters and reference oscillators [42], tunable impedance matching circuits [43–45], and reconfigurable antennas [46–48]. Furthermore, micromachined inductors [49–51], micromachined transmission lines [52] and waveguides [53, 54], and microwave acoustic devices [55] are typically considered RF MEMS components since they involve micromachining processes in their fabrication.

Among different possibilities for actuation of RF MEMS devices, electrostatic drive is the most widely used actuation mechanism, due to its simplicity, compactness, good reliability, extremely low power consumption characteristics, and suitability for high-volume wafer-scale manufacturing using standard semiconductor processes and materials [56].

To clarify the RF MEMS device interacting with signals in the frequency range above 30 GHz, the term microwave MEMS is used. The MEMS switch demonstrated in 1991 by Larson [57] for DC-to-45 GHz is considered the first microwave MEMS device, and despite its immaturity, the outstanding performance in comparison to GaAs-based solid-state switches of the time, has been the main motivator for RF/microwave MEMS research. With the application frequency moving towards millimeter-wave, the advantage of RF MEMS in terms of signal performance, e.g. insertion loss, are becoming more prominent. Furthermore, increase in the application frequency leads to size reduction of the RF/microwave devices, thus allowing integration of more compact systems.

Since the novel reconfigurable millimeter-wave waveguide components presented in this thesis are based on MEMS switching elements, a general background on RF MEMS switches is given in the next part. Moreover, two relevant RF MEMS devices to this thesis, i.e. tunable filters and phase shifters, are briefly discussed below for planar circuits in the millimeter-wave frequency to cover a broader background to the field, considering that the research on RF MEMS has been extensively focused on transmission-line devices. An overview on waveguide counterparts is given in Chapter 4.
2.2. RF and microwave MEMS

2.2.1 RF MEMS switches for millimeter-wave applications

RF MEMS switches are, essentially, microfabricated miniaturized relays containing integrated MEMS actuators which conduct the electrical signal in one state and breaks the signal propagation in another state, typically to achieve open- or short-circuit. Most designs are only mechanically monostable in one state and are kept in the other state either passively by a locking mechanism or actively by an external force, and they can transit between the two states either by restoring mechanical force or by imposing an external effort. Examples of microwave MEMS switches demonstrated for V-band and W-band are [58–64]. Moreover, in [65] a DMTL component consisting of four capacitive switches is presented which is considered the first demonstration of a MEMS component at frequencies above 110 GHz (above W-band).

RF MEMS switches can, mainly, be classified according to their actuation mechanism, contact type, circuit configuration, and direction of displacement [17].

Actuation mechanism

Among widely used actuation mechanisms, electrostatic principle is usually preferred due to the advantages such as fast switching time, large actuation force, low power consumption, and simple design, in expense of high voltage requirement for a reliable switch featuring high isolation.

Contact type

The contact between the movable part of the switch and the fixed part, can be either ohmic metal-to-metal or capacitive with a dielectric layer between the two parts. The metal-contact switch can potentially conduct signals all the way from DC to 100 GHz, in contrast to capacitive switches where the low-frequency portion of the signal is blocked and only high-frequency application is feasible. To decrease the capacitance coupling of both switch types in the open state, a large switch displacement is required.

Circuit configuration

The switch can be placed either in series with the transmission line, to allow the signal to propagate in the transmission line through the switch contact in the closed state, or as a shunt to ground, to short-circuit the signal to the ground and block the propagation in the transmission line in the closed state.

Direction of displacement

The direction of displacement of the conventional MEMS switch elements with respect to the substrate can either be out of plane of the substrate for the vertical switching or in the plane of the substrate for lateral switching; much less frequently
switches employ torsional movements. Vertical switches are usually fabricated in the shape of thin metal membranes or cantilevers by surface micromachining techniques, whereas, lateral switches are typically patterned in the wafer by bulk micromachining techniques. In design of vertical switches there is excellent control over the contact surface and isolation geometry defined mainly by photolithography. On the other hand, the movable structure of vertical MEMS switches usually involves deposition of multiple layers of different materials, for achieving the right mechanical properties, resulting in residual stress and bending of the structure. To compensate for the bending and to achieve a robust switch with predictable actuation voltage, complex stress-compensation techniques during the fabrication [66] or low-stress process steps [67] are required. Furthermore, thin moving structures of vertical switches make them prone to plastic deformation and creep, especially at elevated temperatures, limiting their power handling capabilities. In comparison, lateral switches benefit from excellent mechanical properties of the bulk substrate material, e.g. monocrystalline silicon [68], and involve simple photolithography steps to define actuator geometry, but they suffer from a less controllable switch contact surface, e.g. due to difficulty in metal deposition on the side walls or scalloping of the structure from the Bosch [69] deep etching process step [70].

It is desirable to have a compact reliable MEMS switch featuring low RF insertion loss, high RF isolation, and low actuation voltage. However, there is a compromise between these features, for example, to achieve high isolation for electrostatic series MEMS switches, the contact separation has to be increased, which leads to increase in actuation voltage and decrease in contact force resulting in higher resistivity. To avoid the increase in actuation voltage, either a weaker switch membrane or a larger electrode area is necessary, with the former causing reliability issues by increasing the chance of stiction as a result of weak restoring force and the latter resulting in larger switch size. To address this issues some ideas are proposed in the literature such as curved electrodes [71], combination of vertical and lateral actuators [72], and push-pull concepts allowing active opening and active closing with external force [73–75].

2.2.2 Tunable MEMS planar filters and phase shifters for millimeter-wave applications

Most planar tunable MEMS filters working at millimeter-wave frequency band, are based on coplanar waveguide (CPW) technology and can be classified into two major groups. In the first group MEMS elements are used as localized varactors between the transmission line and the ground plane, for example as shunt capacitor to transmission line [76], as variable LC in lumped-element filters [77, 78], as tuning element of stubs to change their electrical length [77, 79], or as shunt bridges to change inter-resonator coupling [80]. In the second group, the MEMS switches are integrated only in the signal line for example to reconfigure the inter-connection of periodic structures [81]. Moreover, filter banks [82] are implemented by replacing semiconductor switching elements with MEMS switches to improve RF loss.
There are many methods in use for tunable MEMS phase shifters for microwave frequencies [17], but two widely-used concepts for the millimeter-wave portion of the electromagnetic spectrum are MEMS-switched true-time delay-line (TTD) phase shifter networks [59, 61, 83] and distributed MEMS transmission-line (DMTL) phase shifters [84, 85]. MEMS-switched TTD phase shifters consist of various phase-shifting sections in a cascade arrangement, where MEMS switches are employed in different positions to change the total length of the signal line resulting in different phase shifts. Although TTD phase shifters inherit all advantages of MEMS switches, the total insertion loss degrades significantly at millimeter-wave frequencies due to the application of multiple switches and the necessary length of the transmission line. An alternative method, DMTL phase shifting, that is typically used for broadband applications, is based on periodically loading the transmission line with capacitive MEMS bridges to change the propagation coefficient affecting the phase shift. Another novel method, presented recently, is to load the transmission line with multiple \( \lambda/2 \)-long silicon blocks that can be moved vertically to achieve binary-coded phase shifter [86].

2.3 Challenges of RF MEMS technology

The compromise in using RF MEMS devices in comparison to their solid-state counterparts is the reduced response speed [87, 88], e.g. switching time, higher manufacturing cost (including packaging), and usually design-specific process development, but the main challenges towards all-purpose mass-market application of RF MEMS devices, over the last two decades, are, besides cost, long-term reliability issues [17, 89–92], which are mainly related to high-current handling, mechanical degradation of movable electrodes, and dielectric charging phenomena.

The major failure mechanism in metal-contact RF MEMS devices is the contact degradation causing stiction in the contact area. Soft metals, such as gold, are more susceptible to stiction [93], and different approaches are suggested in the literature to overcome this problem, for example increasing the passive restoring force of the device at the cost of higher actuation voltages [94] and active opening concepts [95, 96]. Additionally, there has been intensive research effort to replace gold with hard material stacks, e.g. silver/tungsten/rhodium and copper/tungsten/gold, in order to increase the reliability of contact performance even though hard metals require higher contact forces to compensate for the higher resistivity [91].

In electrostatic MEMS devices with dielectric isolation layer between the electrodes, dielectric charging due to charge injection or charge trapping, is the major reliability issue affecting actuation behavior of the devices due to actuation voltage drift [97]. There are numerous suggestions investigated in the literature to mitigate dielectric charging issues, e.g. using bipolar actuation voltage [98, 99], reducing actuation voltage to decrease the field strength in the dielectric [98, 99], employing dielectric materials with lower trap density and fast recovery time [100], and using auxiliary (side) pull-down electrodes with stoppers [17].
Besides, the power handling capability of conventional RF MEMS devices is limited due to reliability issues. For instance, thin all-metal RF MEMS devices are prone to plastic deformation at high cycle numbers and prolonged down-state position due to creep, fatigue, and microwelding [91]. In the up-state position high RF power leads to self-actuation of the MEMS device [101, 102].

### 2.4 SOI-based RF MEMS devices

Monocrystalline silicon is an attractive material for MEMS, due to its excellent mechanical properties, good thermal conductivity, compatibility with highly developed semiconductor technology and micromachining tools. It is also available in large variety of substrates in terms of size, crystal orientation, and doping levels [68, 91].

Silicon-on-insulator (SOI) wafers have long been used for fabrication of integrated circuits to suppress parasitic effects, such as leakage currents and latch-up effects [107]. They facilitate fabrication of monocrystalline-silicon based MEMS devices to be fabricated by bulk micromachining techniques, in addition to, benefiting RF MEMS device performance, for example by blocking DC leakage current in 3D CPW structures [108]. The advantages of SOI micromachining over traditional bulk micromachining include flexibility in choosing the initial thickness of the structure based on the thickness of the device layer, as well as, availability of the insulating and etch stop layer. Examples of lateral SOI RF MEMS devices, shown in Fig. 2.1, are switches [103, 109, 110], tunable capacitors [104], tunable directional couplers [105], and tunable filters [106].
Chapter 3

Background to conventional tunable waveguide components

Waveguide technology is superior to transmission lines in terms of loss and power handling, specifically at extremely high frequencies.

The novel work presented in this thesis is primarily concerned with hollow metal waveguides and the term waveguide is reserved for this type, however, examples of dielectric waveguide and substrate integrated waveguide (SIW) components are given in this chapter and the next chapter, to cover a broader overview of tunable waveguide components. This chapter gives a background to some conventional technologies for tunable waveguide components. RF MEMS tunable waveguide components are reviewed separately in Chapter 4.

3.1 Waveguide switch technologies

Switches are utilized in various microwave systems to control signal flow or to select among different signal sources. For example, in fire-control radars (FCR) switches allow to share one power source for multiple antennas with different functionality including identification and tracking, whereas in secure communication systems switches can be employed to switch among several power sources to one output.

Conventional electrical waveguide switches comprise mainly two concepts. First, in rotary motor-based mechanical switches a metallic block is utilized to break the waveguide path [111], as shown in Fig. 3.1(a). This method has very low insertion loss and high isolation, but is heavy, bulky, very slow and requires high power for switching. Second, PIN-diode switched elements are integrated into waveguides [112], as shown in Fig. 3.1(b). This type switches in nanoseconds but has poor insertion loss/isolation performance, needs relatively high biasing currents, and introduces distortion products.

Moreover, ferrite materials are used to fabricate waveguide switches, featuring faster switching speed, lower power consumption, and longer life time com-
pared to mechanical switches, in addition to lower distortion level and better signal performance compared to PIN-diodes. Ferrite waveguide switches for single-pole double-throw (SPDT) switch configuration are available in two main types, latching junction circulator switch and differential phase shift switch, up to K_a band. In the junction circulator switch, shown in Fig. 3.1(c), the integrated ferrite resonators are magnetized by applying a current pulse through a wire loop to control the direction of circulation allowing the signal flow from one port to either of the other two [113, 114]. In the differential phase shift switch, the input power is split into two identical signals by a waveguide tee and a relative phase shift of +90° or −90° is introduced between these two signals before they are recombined through a coupler guiding the signal to one or the other of two output ports.

#### 3.2 Tunable cavity resonators and waveguide filters

Tunable high frequency components, including tunable filters, are some of the most essential parts of modern multi-frequency systems as they may result in reduced cost, miniaturized system size, and decreased complexity in comparison to traditional implementations, for instance switched filter banks. The same as waveguide switches, most tunable waveguide filters can be categorized in three basic types according to tuning mechanism, i.e. mechanically tunable, electronically tunable, and magnetically tunable filters [115].

Waveguide cavity filters are necessary at microwave and millimeter-wave fre-
quencies, but also at radio frequencies where high Q-factor or high power handling is required [116]. The resonant frequency of cavities can be varied by interfering with the field within the cavity, typically by mechanical means, e.g. with adjustable tuning screws or posts [117], shown in Fig. 3.2(a), as the earliest and the most popular method, generally used for post-production manual tuning, however, electromechanical tuning is possible by using motors to drive the tuning screws. This method features very good power handling capability and low insertion loss at low cost, but it increases the size and offers low tuning speed. Tuning by inserting a lumped susceptance in the cavity without modifying the coupling between the cavities imposes a limitation over the possible tuning range because the pass-band response becomes more and more asymmetric as the cavities are tuned more and more away from the reference resonance frequency, thus for wide-band tuning range, inter-resonator couplings should also be tuned.

For mechanical tuning of cavity filters piezoelectric actuators are also used, instead of stepper motors. For example, in [118, 119], shown in Fig. 3.2(b), a tunable evanescent-mode cavity filter over 3–5.6 GHz range is presented based on a substrate integrated waveguide (SIW) technique. The filter consists of two cavity resonators formed by conductive vias and connected by coupling irises. Each resonator has a capacitive post in the center formed by four vias and a cylindrical copper plate. A round metallized piezoelectric actuator is mounted on top of the substrate with the integrated cavities for tuning functionality. Unloaded quality factors ($Q_u$) between 250 and 650 have been demonstrated over an octave tuning range.

For electronically tuning mechanism, varactor diodes are employed to realize tunable waveguide filters offering very fast tuning speed over a wide tuning range, for instance a two-pole finline filter is presented in [120] for the K$_a$-band. These filters are tuned by adjusting the DC voltage supplied to reverse-biased varactor diodes to change their capacitance, and thus affecting the resonance frequency of the resonator connected to the varactor diode. The main drawbacks of varactor-tuned waveguide filters, similar to PIN-diode waveguide switches, are their relatively large insertion loss and low power handling capability, which are mainly attributed to the low quality factor and nonlinearity characteristics of varactor diodes.

Furthermore, magnetically tunable concepts have been used for tunable waveguide filters for many years by employing ferrimagnetic and ferromagnetic materials for applications requiring ultra-wideband tuning range [121, 122]. The most popular tunable microwave filters, introduced in 1958 [123], use ferrimagnetic resonators, typically yttrium iron garnet (YIG), and gyromagnetic coupling. The YIG filter, often used up to K$_a$-band, features multi-octave tuning range, spurious free response, and very high selectivity. The drawbacks of YIG filters is their moderate tuning speed in the order of gigahertz per milliseconds and low power handling capability limited by excitation of spurious resonances at high powers, and also relatively large power consumption [115, 124]. The principles to design multi-stage filters with YIG-tuned spheres from 0.5 to 40 GHz are described in [124, 125]. A tunable waveguide filter using YIG films with insertion loss of 1 dB in the range 33–50 GHz is demon-
Chapter 3. Background to conventional tunable waveguide components

(a) Manual tuning of a cavity filter

(b) Tuning of a SIW filter with piezoelectric actuators

Figure 3.2. Examples of mechanical tuning of waveguide filters. (a) Tunable cavity filter with individual tuning knobs from Ducommun Technologies. (b) Two-coupled substrate integrated evanescent-mode cavity filter tuned by piezoelectric actuators [119].

strated in [126], however, it is preferred to employ highly anisotropic hexagonal ferrites instead of YIG spheres to reduce the value of the external magnetic field, and therefore, to be able to tune to higher frequencies in millimeter-wave spectrum. For example, a four-pole filter is reported in [127] with an insertion loss of about 6 dB over 50–70 GHz tuning range. Moreover, ferrite-loaded evanescent waveguide filters and various configurations of printed E-plane filters are reported to improve the limitations of YIG filters such as low power handling capability [115]. In [128], another configuration for magnetically tunable waveguide filters is proposed by replacing the sidewalls of the iris cavity with electromagnetic crystals and tunability in 31.6–33.2 GHz range with insertion loss better than 4 dB is demonstrated.

3.3 Variable phase shifters

The most important application of tunable phase shifters, driving their development, is in phased-array/beam-steering antennas for example for radar. Major conventional concepts for phase shifting waveguide devices, the same as previously discussed waveguide components, include mechanical tuning, integration of PIN-diodes into waveguides, and ferrite-based magnetic tuning.

A variable phase change is obtained in dielectric-slab phase shifters by mechanically displacing the dielectric structure across the waveguide either manually, by plastic screws, or electronically, by step motors, with an example of such a concept shown in [129] for the K_u-band. Another method for mechanical phase shifting in waveguides is based on a rotating half-wavelength section between two fixed quarter-wave sections made of circular waveguide iris polarizers. This concept was described many years ago in [130], was discussed theoretically and experimentally
in [131], and has been improved for operation over 75–100 GHz range in a more recent publication [132], shown in Fig. 3.3(a).

Semiconductor active devices, e.g. PIN-diodes, can be integrated into waveguides to obtain electronically controlled phase shifters. For example, it is shown in [133] that by loading the sub-resonant slots of a waveguide wall with PIN-diodes, an electronically controllable phase shifter at $K_a$-band can be obtained. The slots are designed sub-resonant to avoid any significant radiation or high reflections. The structure of this phase shifter is shown in Fig. 3.3(b).

Historically, ferrite phase shifters have been the dominant technology for waveguide phase shifting. They are divided generally into four types, i.e. variable permeability, toroidal, dual mode, and rotary field. Besides, ferrite phase shifters can be divided into reciprocal or nonreciprocal depending on dependency of the variable differential phase shifts to the direction of the propagation, or they can be categorized as latching or non-latching depending on the requirement for supplying constant current to sustain the magnetic bias field. Comprehensive and chronological reviews on ferrite materials and their application for phase shifters, in addition to different concepts for implementation of ferrite phase shifters, can be found in the literature [134–138]. Some examples of millimeter-wave ferrite waveguide phase shifters from the literature and some available products should be given here.

The application frequency range of latching nonreciprocal toroid/twin-toroid and latching reciprocal dual-mode phase shifters was demonstrated up to millimeter-wave range [134]. In these phase shifters the phase change is affected by modifying the propagation constant of the transmission line, which contains the ferrite, by controlling the relative permeability of the ferrite through the flux level existing in the closed magnetic circuit. An example of ferrite-based dual-mode phase shifter is presented in [139] with insertion loss of 1.6 dB at 60 GHz for the latching phase shift below $363^\circ$ consuming switching power of 4.5 mW. Moreover, commercial and military millimeter-wave ferrite waveguide phase shifters are available from numerous producers. For example dual-mode phase shifters from MAG (Microwave Applications Group), have insertion loss of maximum 1.25 dB, maximum return loss of 15.56 dB, RMS phase error of 4 degrees and switching time of 60 µs at $K_a$-band. Ferrite Domen Co. supplies different toroidal and dual-mode phase shifters up to 40 GHz with nominal insertion loss in 1–2.2 dB range, phase shifts from 0–337.5 degrees up to 0–500 degrees, and switching time below 100 µs depending on the product model. A high power toroidal ferrite phase shifter for $K_a$-band is available from DEV COM, shown in Fig. 3.3(c), with insertion loss of less than 1 dB, phase shift range of $−360^\circ$, switching speed of faster than 15 µs and average power handling of 120 W. Besides, mechanically-tunable rotary vane phase changer from FLANN MICROWAVE has insertion loss of 2.5 dB and handles maximum power of 0.2 W at W-band.

Other technologies have also been utilized to improve the characteristics of millimeter-wave phase shifters in the recent decade. In [140], a waveguide phase shifter using tunable electromagnetic crystal sidewalls was reported with a phase shift of $360^\circ$ and an insertion loss of <2 dB at 38 GHz. A magnetic field tun-
Chapter 3. Background to conventional tunable waveguide components

(a) Mechanically tunable phase shifter
(b) Electronically tunable phase shifter
(c) Magnetically tunable phase shifter

Figure 3.3. Examples of conventional tunable waveguide phase shifters. (a) Mechanically tunable rotary phase shifter for 94 GHz [132]. (b) PIN-diode tunable waveguide phase shifter for Kα-band [133]. (c) Magnetically tunable toroidal phase shifter from DEV COM for Kα-band.

able dielectric phase shifter with maximum phase shift of 60° at a magnetic field strength of 255 000 A/m and an insertion loss of better than 4 dB at 80 GHz was demonstrated in [141].
Chapter 4

Previous work on tunable MEMS waveguide components

RF MEMS devices are promising candidates for integration into waveguides due to excellent signal handling performance, thus allowing to make full advantage of waveguide technology.

This chapter gives an overview of some tunable microwave and millimeter-wave waveguide components based on waveguide-integrated or waveguide-mounted MEMS actuators.

4.1 MEMS waveguide switches

Potentially, RF MEMS technology for waveguide switches could combine the advantages of two main conventional methods discussed in Chapter 3, i.e. an electromechanical rotary switch and a PIN-diode switch, as summarized in Table 4.1.

To the best knowledge of the author, there have only been two attempts by another research group to build a MEMS waveguide switch; one was implemented with electrothermal actuators, with insertion loss of 1–2.8 dB and return loss of 15 dB in the K_u and K-bands [142], and another one with electrostatic actuators, with an insertion loss of 0.9–1.2 dB and return loss of 20 dB over 7% of the K_u [143].
### Table 4.1. Comparison of different technologies for millimeter-wave waveguide switches.

<table>
<thead>
<tr>
<th>Technology</th>
<th>Insertion loss</th>
<th>Isolation</th>
<th>Speed</th>
<th>Power consumption</th>
<th>Volume</th>
<th>Weight</th>
<th>Reliability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotary motor</td>
<td>&lt; 0.3–0.8 dB</td>
<td>&gt; 0.3–0.8 dB</td>
<td>≈ 100 ms (Slow)</td>
<td>−</td>
<td>Very low (e.g., electrostatic actuation)</td>
<td>High</td>
<td>Requires a reliable design concept [90–92]</td>
</tr>
<tr>
<td>PIN diode</td>
<td>&lt; 2.0–6.5 dB</td>
<td>&gt; 20 dB</td>
<td>&lt; 40 ns (Fast)</td>
<td>−</td>
<td>Medium speed</td>
<td>Medium</td>
<td></td>
</tr>
<tr>
<td>MEMS</td>
<td>High</td>
<td>Medium</td>
<td>≈ 100 ms (Slow)</td>
<td>−</td>
<td>High</td>
<td>Medium</td>
<td></td>
</tr>
</tbody>
</table>

Notes: As good as rotary switches due to mechanical switching nature.
4.2 Tunable MEMS cavity resonators and waveguide filters

Although MEMS technology is mainly utilized in planar circuits, there are numerous examples of MEMS cavity resonators and waveguide filters presented in the literature, however, they are demonstrated mainly for applications below millimeter-wave range. To show the advantages and drawbacks of MEMS technology, Table 4.2 summarizes the performance of mechanical, YIG, and RF MEMS tunable waveguide filters.

Fig. 4.1 provides examples of state-of-the-art tunable MEMS waveguide cavity resonators from the literature [88, 144–147].

To realize tunable MEMS waveguide or cavity filters, cavity resonators of the top two rows of Fig. 4.1 were demonstrated, in the same papers where they were introduced, to implement two-pole filters, with 1.3–2.4 dB insertion loss and tuning range of 2.71–4.03 GHz in [144], and with 3.55–2.38 dB insertion loss and tuning range of 3.04–4.71 GHz in [146]. Furthermore, a two-pole evanescent-mode cavity filter, with electrostatic cantilever tuning elements, is presented in [145] having 4.91–3.18 dB insertion loss for tuning range of 4.07–5.58 GHz with actuation voltage of 0 to 65 V.

To the knowledge of the author, to date, there is no millimeter-wave tunable MEMS waveguide filter or cavity resonator demonstrated, even though, some attempts are reported in the literature up to K-band. For example, the feasibility of constructing a two-pole micromachined tunable ridge waveguide filter with embedded thermal MEMS actuators is demonstrated up to 24 GHz with 200 MHz tuning range and insertion loss of 3 dB in [148]. In another attempt, an all-silicon cavity tunable resonator with capacitive post, demonstrated in [149], is tuned from 6.1 to 24.4 GHz with measured unloaded Q from 300 to 1000, but with the required actuation voltage as high as 600 V.

Table 4.2. Comparison of different technologies for tunable waveguide filters, adapted from [115].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mech.</th>
<th>YIG</th>
<th>MEMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Insertion loss (dB)</td>
<td>0.4–2.5</td>
<td>3–8</td>
<td>0.8–6</td>
</tr>
<tr>
<td>Power handling (W)</td>
<td>High (&lt;500)</td>
<td>Low (&lt; 2)</td>
<td>Low (&lt; 2)</td>
</tr>
<tr>
<td>Tuning speed (GHz/ms)</td>
<td>Very slow</td>
<td>0.5–2</td>
<td>$10^2$</td>
</tr>
<tr>
<td>Tuning range</td>
<td>High</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Millimeter-wave capability</td>
<td>up to K_a-band</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>
### Actuator | Performance
--- | ---
Piezoelectric disk | Tuning range: 2.3–4.6 GHz Unloaded Q: 360–702 Actuation voltage: -10 to 90 V
Electrostatic diaphragm | Tuning range: 1.9–5 GHz Unloaded Q: 300–650 Actuation voltage: 0 to 122 V
Electrostatic curled cantilevers | Tuning range: 11.9–14.2 GHz Unloaded Q: 400–500 Actuation voltage: 0 to 120 V
Electrostatic fixed-fixed beam | Tuning range: 15.2–17.8 GHz Unloaded Q: 500–735 Actuation voltage: 0 to 77 V

**Figure 4.1.** Examples of reconfigurable MEMS cavity resonators reported in the literature [88, 144–147].

### 4.3 Tunable MEMS waveguide phase shifters

A comparative summary is presented in Table 4.3 to highlight the advantages of MEMS technology over ferrite for tunable waveguide phase shifter.

Similar to MEMS waveguide switches, there has not been much work on tunable MEMS waveguide phase shifters. A single ridge transmission type phase shifter with waveguide-integrated MEMS actuators presented in [150] has achieved a phase shift of 70° and an insertion loss of 3.6 dB at 98.4 GHz, and a triple ridge transmission type phase shifter has achieved a phase shift of 134° and an insertion loss of 2.4 dB at 92.8 GHz. In [151] an analog-type phase shifter for W-band has been
4.3. Tunable MEMS waveguide phase shifters

Table 4.3. Comparison between ferrite and MEMS tunable waveguide filters, adapted from [138].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Ferrite</th>
<th>MEMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost</td>
<td>Very expensive</td>
<td>Low</td>
</tr>
<tr>
<td>Power consumption</td>
<td>$\approx 10$ W ($\approx 1$ W latching)</td>
<td>Negligible</td>
</tr>
<tr>
<td>Power handling</td>
<td>Very high (1 kW)</td>
<td>Typically $&lt; 50$ mW</td>
</tr>
<tr>
<td>Switching speed</td>
<td>$\mu$s (medium, inductance)</td>
<td>$\mu$s (medium, mechanical)</td>
</tr>
<tr>
<td>Microwave loss</td>
<td>$&lt; 1$ dB/360° (X band)</td>
<td>$\approx 2.3$ dB/337.5° (K band)</td>
</tr>
<tr>
<td>Size</td>
<td>Large</td>
<td>Small</td>
</tr>
<tr>
<td>Reliability</td>
<td>Excellent</td>
<td>Good after billion cycles</td>
</tr>
</tbody>
</table>

demonstrated consisting of a tunable MEMS high-impedance surface placed as a back-short or as a sidewall of a rectangular waveguide with a phase shift span of 240° and an insertion loss of maximum 3.5 dB at 83.4 GHz.
Chapter 5

MEMS-reconfigurable surfaces for millimeter-wave waveguide components

This chapter introduces the concept of novel MEMS-reconfigurable surfaces for waveguide-integrated switch and switchable waveguide irises. Then, as application examples of switchable MEMS waveguide irises, an implementation of the first switchable waveguide cavity resonator and a demonstration of a switchable waveguide filter concept are presented. Further details and discussion of the material reviewed in this chapter are provided in Paper 1, Paper 4, and Paper 5.

5.1 Concept of MEMS-reconfigurable surfaces

The MEMS waveguide components presented in this chapter are based on MEMS-reconfigurable surfaces that are inserted perpendicular to the wave propagation into a WR-12 rectangular waveguide (with inner dimensions 3.099 mm × 1.549 mm and frequency range 60–90 GHz). These surfaces consist of distributed metallized elements, which can be reconfigured to total transmissive state or the blocking state for the wave propagation, by on-chip MEMS actuators outside the waveguide cross-section. A simplified 3D schematic of the proposed concept is shown in Fig. 5.1, designed as a waveguide switch component. The distributed metallized elements of the reconfigurable surface, designed in shape of vertical cantilevers, are divided into a set of fixed and a set of movable elements via horizontal suspension bars. Horizontal suspension bars of the fixed set are anchored at the narrow waveguide sidewalls in the waveguide cross-section, whereas, of the movable set are connected to electrostatic comb-drive push-pull MEMS actuators, outside the waveguide narrow walls, providing synchronous lateral movement. In the surface-deactivated state, shown in Fig. 5.1(b), there is a gap between the vertical cantilevers of the fixed and the moving elements and, thus, electromagnetic wave can freely propagate through the transmissive surface. In the surface-activated state, shown in Fig. 5.1(c), the movable vertical cantilevers are laterally moved into contact with the non-movable
vertical cantilevers, to form vertical columns which are blocking the wave propagation as they are short-circuiting the electric field lines of the dominant $\text{TE}_{10}$ mode.

The MEMS-reconfigurable surfaces utilized in this thesis have the following dimensions. The width (horizontal) and thickness (in direction of the wave propagation) of the vertical cantilevers are 5 µm and 30 µm, respectively, and thus provide minimum insertion loss in the transmissive state and very high isolation in the blocking state. In the surface-activated state, the moving and the fixed vertical cantilevers are in contact with 5 µm overlap, whereas, in the surface-deactivated
5.1. Concept of MEMS-reconfigurable surfaces

Figure 5.2. SEM images of a MEMS-reconfigurable surface for waveguide switch application. (a) Overview of a sample chip consisting of a reconfigurable surface, one stage of comb-drive actuator with folded beam springs on each side. (b) Close-up view of different elements of the reconfigurable surface including vertical cantilevers, as well as, two sets of movable and fixed horizontal bars.
state, they are 24 µm apart.

Fig. 5.2 shows SEM images of an overview and close-up view of a MEMS-reconfigurable surface designed for switch application.

5.2 SOI RF MEMS fabrication platform

The two-mask SOI MEMS process flow outline in Fig. 5.3 are used to fabricate the chips for MEMS-reconfigurable waveguide components presented in this chapter. A silicon-on-insulator (SOI) wafer with resistivity of 1–20 Ω-cm is used as substrate [see Fig. 5.3(a)], which consists of a 30-µm thick device layer, 2-µm thick buried-oxide (BOX) layer, and 450-µm handle wafer. The fabrication process starts with thermal oxidation of the wafer and patterning of the oxide for the deep-silicon etching hard mask, followed by anisotropic deep reactive ion etching (DRIE) of the handle wafer [see Fig. 5.3(b)] and subsequently of the device layer [see Fig. 5.3(c)] using Bosch process [152]. Then wet etching in hydrofluoric acid (HF) is done to remove the sacrificial BOX layer under the moving structures [see Fig. 5.3(d)] followed by critical point drying to avoid any stiction of the released structures. A 1-µm thick layer of gold is sputtered on both sides of the wafer using 50 nm of titanium tungsten as adhesion layer [see Fig. 5.3(e)] to completely metallize both the switching elements and the walls of the handle wafer. Since the entire chip, including the top and the bottom faces and the sidewalls, is completely covered in this last step, SOI wafer of any resistivity can be used for the fabrication of MEMS-reconfigurable devices and there is no need for expensive high-resistivity SOI wafers which are common in RF MEMS devices. Fig. 5.4 shows a cross-sectional 3D illustration of the chip with a MEMS-reconfigurable surface and an
5.3 Waveguide integration and RF measurement setup

**Figure 5.4.** Cross-sectional views of the chip containing a MEMS-reconfigurable surface and a vertical cantilever. (a) 3D schematic cross-sectional view of the final chip. (b) Wafer cut of a vertical cantilever, by ion-milling, showing the metal coverage on the sidewalls of the reconfigurable surface elements.

**Figure 5.5.** 3D exploded view of different components used to securely integrate the MEMS chip containing the reconfigurable surface into a WR-12 waveguide. The main components are two tailor-made flanges with recesses for chip self-alignment and two pieces of conductive polymer interposers, besides, the MEMS chip.

SEM image of the cross section of an ion-milled vertical cantilever element showing the metal coverage on the sidewalls.

**5.3 Waveguide integration and RF measurement setup**

Fig. 5.5 shows an exploded 3D rendered schematic of the chip-to-waveguide assembly, including the details of the tailor-made WR-12 flanges with recesses for chip
self-alignment to the waveguide. The figure also shows conductive polymer interposers applied only between the wide walls of the waveguide and the device layer of the chip, leaving a gap between the surface of the narrower wall of the waveguide and the chip, which allows for the mechanical connection between the reconfigurable elements in the waveguide cross-section and the on-chip actuators outside the waveguide walls. The details of this integration method and a discussion are provided in Chapter 7 and Paper 2.

The RF measurements of the fabricated chips integrated into the WR-12 waveguide were performed using an Agilent E8361A vector network analyzer (VNA) with 110 GHz millimeter-wave test heads, calibrated using thru-reflect-line (TRL) calibration and a V-band waveguide calibration kit.

5.4 Waveguide switches

This section discusses the parameters involved in the design of a waveguide switch, which can be switched ON or OFF by a MEMS-reconfigurable surface, and shows measurement results of such a device.

5.4.1 Design

As mentioned in the previous section, in practice, conductive polymer interposers are applied only between the wide walls of the waveguide and the top surface of the fabricated chips. Therefore, it is of interest to compare two different assembly cases, with the interposer layer covering all walls of the waveguides or only the wide walls, before discussing the waveguide switch design. Since the wide waveguide walls are primarily carrying the surface currents, it is expected to observe insignificant difference on the performance between these two cases for thin conductive polymer interposers. Fig. 5.6 shows the simulation results of an assembly consisting of conductive polymer layer between two WR-12 waveguide sections. The simulation is done for two above cases with the polymer thickness as a parameter. For polymer layer thickness of 120 µm, which is equal to the nominal thickness of the polymer sheet used in this chapter, the simulated insertion loss for both cases is below 0.02 dB, i.e. negligible.

The waveguide-switch performance in the blocking and in the non-blocking state is determined by the number of vertical columns and the number of sections of the columns, i.e. the number of horizontal suspension bars with associated vertical cantilevers, and on the distribution of these elements in the cross-section of the waveguide. First, we study the influence of vertical cantilever columns and horizontal suspension bars on the performance for a reconfigurable surface with uniform distribution of vertical cantilever elements along the wide wall of the waveguide. Then, we study the optimization for decreasing the number of contact points based on non-uniform distribution.

The switch design study, presented here, is based on simulations of an ANSYS HFSS model shown in Fig. 5.7(a). The reconfigurable surface elements are modeled
5.4. Waveguide switches

Figure 5.6. Simulated comparison of interface performance between two WR-12 waveguides with conductive polymer interposer with polymer thickness as parameter for two cases: interposer layer covering all walls of the waveguides or only the wide walls.

as 30-μm thick gold blocks with a resistivity of 2.049 μΩ-cm taking into account all metal losses, as compared to the elements of the fabricated devices consisting of silicon blocks with 1-μm gold coverage. The simulation model includes all vertical cantilever elements and all horizontal suspension bars of the same geometry as in the final mask layout. For high-accuracy simulation results, the waveguide feedthroughs are also considered in the model, even though the simulation results of Fig. 5.6 confirmed that an opening in the narrow walls of the waveguide in the order of polymer thickness used here, has negligible effect on the assembly loss. Fig. 5.7(b) and (c) show the HFSS-simulated RF performance of the waveguide switch for the uniform distribution of vertical cantilever elements, with the number of horizontal suspension bars and vertical cantilever columns as parameters, at 75 GHz (E-band center frequency). Vxx marks on the figure indicates the number of vertical cantilever columns.

Vertical cantilever columns are parallel to the electric field lines, therefore, increasing their number improves the blocking of the wave propagation in the OFF state resulting in better isolation, however, it impacts negatively the ON-state insertion loss. On the other hand, being perpendicular to the electric field lines inside the waveguide, horizontal suspension bars have a very weak effect on the RF performance of the switch in the OFF state. However, increasing the number of horizontal bars results in shorter vertical cantilevers and thereby a higher degree of splitting of the sections which are intended to short-circuit the electric field lines in the OFF (blocking) state. Consequently, less fraction of the wave is reflected in
Figure 5.7. Simulated study of different MEMS-reconfigurable waveguide switches changing the number of horizontal suspension bars and vertical cantilever columns. (a) HFSS model shown for the switch with 21 horizontal bars and 35 vertical columns in the OFF state (blocking). (b) OFF-state (blocking) simulation results. (c) ON-state (non-blocking) simulation results.

the ON (non-blocking) state resulting in lower insertion loss due to longer path of the electric field lines. As a design guide, if a larger number of vertical columns is desired to increase the isolation of the switch, the degradation in insertion loss can be compensated by also increasing the number of horizontal suspension bars, however, beyond a certain number, increasing the number of horizontal suspension bars does not significantly improve the insertion loss (saturation effect), for instance beyond 17 for 20 vertical columns, thus a compromise has to be made. A combination of 20 vertical columns with 21 horizontal suspension bars was found to achieve an optimum compromise in performance between the ON and the OFF
state, resulting in an ON-state insertion loss and return loss better than 0.035 dB and 22.55 dB, respectively, and OFF-state isolation and reflected power better than 28.49 dB and 0.023 dB, respectively, for a total of 840 vertical cantilevers and 440 contact points. In conclusion, the blocking quality of the switch is determined by the number of vertical columns and weakly depending on the number of horizontal suspension bars, whereas the transmissive properties of the switch are dependent on the ratio of the horizontal bars to the vertical columns.

The density of the electric field lines of the dominant TE_{10} mode has a sinusoidal distribution along the axis parallel to the wider walls of the rectangular waveguide.
with a maximum at the center [153]. Thus, it is expected to gain an improved OFF-state isolation by sinusoidally distributing the same number of columns as uniformly distributed design, or, to have similar OFF-state isolation at a reduced number of vertical columns and thus improved ON-state performance.

A comparative investigation is performed for five structures, by simulation in HFSS, while varying number and distribution of vertical columns to confirm the above expectation. The other parameters of these five structures are identical, in particular having 17 horizontal bars. Drawings of the distributions of the cantilever columns of these five structures are shown in Fig. 5.8(a) and the simulation results are presented in Fig. 5.8(b) and 5.8(c). Comparing Structure 1 with Structure 2, shows that removing a total four cantilever columns and thus decreasing the total number of columns by 20%, has negligible effect on the performance. Structure 5 with 14 sinusoidally distributed cantilevers (30% decrease in the number of contact cantilevers as compared to the structure with 20 cantilever columns) and highest column density in the center shows a better performance than Structure 4 with uniform distribution of 16 cantilevers. As a conclusion, as expected, the important factor is the column density in the center where the intensity of the electric field is very strong, and a non-uniform distribution can substantially decrease the number of contact points with just slight decrease in the performance.

Further elaboration on the design steps and parameters of the waveguide switch, consisting of a MEMS-reconfigurable surface, is given in Paper 1 and Paper 4.

### 5.4.2 RF characterization

A photograph of the RF measurement setup of the fabricated chips with the reconfigurable surface integrated into a WR-12 waveguide is shown in Fig. 5.9. The calibration is performed at the coaxial-to-waveguide adapters. Therefore, the measurements show the performance of the integrated chips combined with the tailor-made assembly setup, including the modified flanges and the conductive polymer interposers.
Fig. 5.10 shows measured performance of six test waveguide switches, in addition to the results of a reference chip. The data of six test chips includes losses by the chip-to-waveguide assembly and, therefore, to show the loss of the assembly setup.
Chapter 5. MEMS-reconfigurable mm-wave waveguide components

<table>
<thead>
<tr>
<th>Actuation mechanism</th>
<th>Frequency (GHz)</th>
<th>Insertion loss (dB)</th>
<th>Return loss (dB)</th>
<th>Isolation (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrothermal</td>
<td>Ku and K-band</td>
<td>1–2.8</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>Electrostatic</td>
<td>7% of Ku-band</td>
<td>0.9–1.2</td>
<td>20</td>
<td>&gt;15</td>
</tr>
<tr>
<td>Electrostatic</td>
<td>V-band</td>
<td>0.65</td>
<td>36–40</td>
<td>&gt;30</td>
</tr>
</tbody>
</table>

Figure 5.11. RF MEMS waveguide switches reported in the literature [142, 143] and Paper 4 [154].

separately, the measurement is done on a reference chip which does not have any MEMS elements and consists of only a micromachined waveguide frame (V00H00). The test chips contain either 20, 30, or 35 vertical columns (chip nomenclature Vxx), and either 9, 17, or 21 horizontal suspension bars (chip nomenclature Hxx). These different implemented designs contain from 360 to 1470 vertical cantilevers and between 200 and 770 parallel-actuated contact points.

In the OFF state (blocking), in the investigated frequency range of 60–70 GHz, the three chips with 30 or 35 vertical columns with an isolation of 35–45 dB have better RF perform than the three chips with 20 vertical columns, which have an isolation of 30–35 dB, thus the behavior is consistent with the expectations of simulation study. The best ON-state performance is measured for the V20H21 and V35H21 devices at 60 GHz with insertion loss of 0.4 dB while all devices have ON-state insertion loss between 0.4 and 1.1 dB over the whole frequency range. Device V20H9 has an overall best insertion loss, which is below 0.6 dB from 60 to 69 GHz. The measurement of the reference chip shows that the setup itself contributes about 0.3 dB to these losses, which is the major part of the losses of the best-performance measurements. The reference loss includes the losses due to chip mounting imperfections, polymer interposers, tailor-made flanges, and standard flanges for connection to the waveguide adapters.

The ON-state return loss is between 15 and 25 dB for all devices over the 60–70 GHz frequency range while the reference chip has a return loss between 25 and
5.5. Switchable waveguide irises

30 dB.

As a conclusion, the ON-state insertion loss of the MEMS waveguide switches presented here is significantly better than PIN-diode waveguide switches with insertion loss in the range 2–6.5 dB, and it performs as good as rotary motor waveguide switches with insertion loss in the range 0.3–0.8 dB (Table 4.1), even including the losses of the chip-to-waveguide integration. The measured isolation is 10–20 dB better than PIN-diode waveguide switches and the designs with 30 and 35 vertical columns have an isolation equal to rotary motor waveguide switches.

The comparison among the performance of the MEMS-reconfigurable waveguide switch presented in this chapter and the MEMS waveguide switches reported in the literature [142, 143] is summarized in Fig 5.11.

Further discussion on the RF characterization of the novel MEMS waveguide switch is available in Paper 4.

5.5 Switchable waveguide irises

If the vertical cantilevers are only placed on specific areas of the waveguide cross-section, other microwave structures such as MEMS-reconfigurable waveguide irises are possible. This section gives an overview of the design concept and RF characterization of inductive and capacitive irises. Some application examples of such reconfigurable-irises are given in Section 5.6.

5.5.1 Concept

A simplified schematic view of the chips with a MEMS-reconfigurable inductive and capacitive iris is shown in Fig. 5.12. The vertical cantilevers of the MEMS-reconfigurable surface are placed in the areas mimicking the standard inductive (Fig. 5.12(a)) and capacitive (Fig. 5.12(b)) irises while the switching from the deactivated state to the activated state and vice versa, are provided by on-chip MEMS actuators similar to the MEMS waveguide switch discussed in the previous section. In the deactivated-iris state the transmissive surface is transparent, and in the activated-iris state the vertical cantilevers are short-circuiting the electric field lines of the TE$_{10}$ mode and thus, blocking the wave propagation in the iris areas. The electric field lines in the iris-activated and iris-deactivated states of an inductive iris and a capacitive iris are shown in Fig. 5.12(c) and Fig. 5.12(d), respectively.
5.5.2 RF simulation and characterization

The measured performance of a reconfigurable inductive iris, compared to HFSS-simulation results, is shown in Fig. 5.13. The inductive iris has 21 horizontal bars and seven cantilever columns on each side, with an opening of 1.075 mm in the waveguide H-plane. For the *activated-iris* state the simulation result is also compared to an ideal reference iris with filled metal areas, and for the *deactivated-iris* case it is compared to a reference chip, with no MEMS elements, in the same setup. The measurements fit the simulations very well. The insertion loss of 0.4–1.0 dB in the deactivated-iris state is mainly attributed to the waveguide assembly as shown by the reference-chip measurements.

Fig. 5.14 shows the HFSS-simulated and experimental performance of a capacitive iris with 20 vertical cantilever columns and an E-plane opening of 0.777 mm. Also here, the measurements fit the simulations very well (insertion loss increased by 0.2–0.4 dB due to assembly).
5.6 Application examples of reconfigurable waveguide irises

As application examples of switchable waveguide irises, we demonstrate the first switchable waveguide cavity resonator and present the concept of a tunable / switchable waveguide filter. Further details of this application examples are provided in...
Chapter 5. MEMS-reconfigurable mm-wave waveguide components

5.6.1 Switchable cavity resonator

By placing a switchable inductive iris at an odd-number multiple of a half wavelength from the back-shorted end of a rectangular waveguide, as shown in Fig. 5.15, a switchable cavity resonator was implemented. The measurement and simulation results of the cavity resonator in the \( ON \) and the \( OFF \) states are shown in Fig 5.16. The simulations were done with a gold thickness of only 0.5 \( \mu \)m for appropriate modelling of the metal losses. The resonator can clearly be switched \( ON \) and \( OFF \), shown by the sharp \( ON \)-state resonance with a Q-factor of 186.13 at 68.87 GHz. In the \( OFF \) state, the insertion loss is less than 2 dB, including the measurement setup, without any resonance in the frequency range of interest.
5.6. Application examples of reconfigurable waveguide irises

5.6.2 Tunable/switchable waveguide filters

By using multiple MEMS-switchable irises in a waveguide, more complex components such as switchable/tunable millimeter-wave waveguide filters can be implemented.

Fig. 5.17 shows the HFSS simulation results for a first-order bandpass waveguide filter which can be switched ON and OFF with MEMS-reconfigurable inductive irises. The simulation results indicate that the filter has an insertion loss of 0.42 dB at the resonance frequency of 73.6 GHz with 3-dB bandwidth of 0.7 GHz in the ON state and reflection coefficient of better than 0.15 dB in the OFF state.

Since comb-drive actuators provide the possibility of controlled displacement along the whole movement range, it is also possible to utilize the reconfigurable surface to tune the center frequency of the bandpass filter. Fig. 5.18(a) shows the HFSS model of the first-order bandpass filter where cavity resonators are made by symmetric inductive irises and a MEMS-reconfigurable capacitive iris is placed between the fixed inductive irises to change the effective length of the cavity resonator. Fig. 5.18(b) shows that the resonance frequency can be tuned from 73.5 GHz to 78.5 GHz through a 20 µm displacement of the reconfigurable surface elements. The metal losses are modelled using a 1 µm gold cladding of the movable elements.
Figure 5.18. Simulated concept of a tunable first-order bandpass filter by integration of MEMS-reconfigurable capacitive iris within a cavity resonator: (a) HFSS model. (b) Simulated tuning performance for 20 μm MEMS displacement range.

5.7 MEMS actuator characterization and reliability features

The on-chip MEMS actuators of the MEMS-reconfigurable designs discussed above, comprise laterally-moving electrostatic comb-drives, arranged in a push-pull configuration and placed symmetrically to the left and the right of the narrow walls of the waveguide. Two designs are implemented, design I and design II, consisting of eight and sixteen total comb-drive actuators, respectively. The devices feature an all-metal design, i.e. no dielectric layers are exposed to neither the RF field nor the DC (actuation) field, which virtually eliminates the reliability limitations by dielectric charging. Mechanical stoppers are implemented for limiting the actuator movements. Furthermore, due to the SOI RF MEMS device concept, all moving elements are utilizing monocrystalline silicon as the structural material, which provides high mechanical reliability. This silicon core is symmetrically metallized, which provides temperature compensation. As the device is bulk micromachined, there are no stress control/stress uniformity problems typical for surface micromachined MEMS devices. The mechanical spring has a spring constant of 1.97 N/m (actuator design I) or 3.85 N/m (actuator design II), which is relatively soft, but in contrast to conventional MEMS switches the spring is not used to provide a restoring force but only to guide the movement of the actuator, as the device is actively pushed and pulled in both directions, i.e. featuring active opening and active closing. The total movement is 24 μm or ±12 μm around the rest position. Fig. 5.19 shows the measured actuation voltage repeatability test for a chip with actuator design I, operated by a single-stage comb-drive with 106 fingers. After an initial 40 cycles of stabilization, the mean actuation voltage is 40.0 V with a standard deviation (1σ) of 0.0605 V for the 20 subsequent cycles. The simulated passive release time for a critically-damped case is 91 μs (10%–90% fall time), which corresponds to the simulated mechanical resonance frequency of 5.85 kHz for the actuator with a spring constant of 1.97 N/m. However, the fact that the device is actively opened and actively closed allows for faster operation, in contrast to conventional MEMS...
transmission-line switches whose switching time is limited by the passive opening time and by design for critical damping.

A chip with actuator design II and a two-stage comb-drive actuator has a measured average actuation voltage of 44.13 V. This device was tested in continuous actuation in contact mode during 14 hours, achieving 4.3 million cycles with a sawtooth input signal of 80 Hz, without noticing any degradation in performance or actuation voltage. The comb-drives are designed for high lateral robustness of 92 V (measured), giving a margin of at least a factor of two to the nominal actuation voltage. Actuation voltage overdrive may be done up to this voltage which sets the limit for the switching speed.

5.8 Discussion and outlook

The millimeter-wave waveguide components based on MEMS-reconfigurable surfaces shown in Paper 1, Paper 4, and Paper 5 demonstrate a promising concept for switchable and tunable millimeter-wave waveguide systems. The proposed MEMS waveguide switch performs significantly better than PIN-diode waveguide switches, shows performance comparable to rotary motor waveguide switches, even including the assembly loss, and consumes negligible power in comparison to both waveguide switch technologies. The simulation and measurement for device-level yield analysis of MEMS waveguide switches, discussed in detail in Paper 4, shows that a device with 20 vertical cantilever columns and 21 horizontal suspension bars still achieves an OFF-state isolation of better than 20 dB with 86% yield of vertical cantilevers and this device with 95% yield performs very similar to a 100%-yield device with measured OFF-state isolation of 30–37 dB.

The switchable iris concept presented here allows for completely activating and deactivating the irises and thus enables new possibilities for MEMS-reconfigurable waveguide devices, such as resonators and filters which can be switched ON and OFF, whereas, previous attempts of tunable cavity resonators and waveguide filters only provide limited tuning functionality.
Practical challenges of the concept presented here are the difficulty in getting a thick metallization multiple of skin depth on the sidewalls in the fabrication and maintaining a very low-loss assembly during the measurement.

Initial reliability and repeatability tests were conducted for the proposed devices, and to improve the reliability of these waveguide-integrated MEMS-based concepts several suggestions are open to investigation such as replacing the gold with a harder metal stacks. Simulations of MEMS waveguide switches indicate that electrical contact is actually not necessary between the cantilevers, as capacitive contact with gaps in the order of up to few tens of nanometers is sufficient. I.e the performance in the blocking state was found not to be dependent on the contact force, contact resistance, and the number of cantilevers having physical contact. However, it is suggested to use parallel-plate actuators in combination with comb-drive actuators to increase the contact force for switchable waveguide iris concepts.

During this study, RF high-power handling performance of the MEMS waveguide switch could not be determined, as the power levels available to the authors in the V-band are limited to -19 dBm, however, it would be interesting to determine power handling capability of presented waveguide components.
Chapter 6

MEMS-based reconfigurable antenna array for beam steering front-ends

This chapter gives a short introduction to beam steering front-ends, then presents the novel work done on MEMS-based waveguide-integrated phase shifters and utilization of such waveguide-integrated phase shifters in a phased-antenna array at 77 GHz. Further details of these works are covered in Paper 3 and Paper 6.

6.1 Beam steering front-ends

Electronic beam steering, i.e. changing the direction of the main lobe of a radiation pattern of an antenna or of multiple stationary antenna elements, is widely used in military and commercial applications such as radar systems and wireless communications. The most popular method is to use phase shifters to create a variable phase gradient in the signal fed to antenna elements of an array, as shown in Fig. 6.1 [155]. Phase shifters are the critical components of such systems because their characteristics strongly influence the signal performance and they affect the cost of the system.

The phase shifting devices in modern phased array antenna systems are typically digital phase shifters, that is, the device can switch between predefined fixed phase states. Passive beam-forming is superior to active methods in terms of noise, linearity, and power handling, thus RF MEMS switches by far are the best candidates for implementing high-performance phase shifters due to the advantages discussed in Chapter 2.

There has been numerous efforts in realization of low-cost high performance beam-steering systems for the millimeter-wave range based on semiconductor devices [1, 156–160] and MEMS technology [161–164].
6.2 Novel MEMS-based waveguide-integrated phase shifters

Most MEMS-based beam-steering systems employ planar phase shifters due to technological advances and ease of fabrication, however, integration of variable phase shifting elements into the feed of an individual aperture antenna can potentially improve the performance of the phased-antenna array. In this section a MEMS-based waveguide-integrated phase shifter is presented. In the next section, 6.3, a two-dimensional antenna array is demonstrated which consists of unit cells similar to such waveguide-integrated phase shifters.

6.2.1 Concept and design

The electronically tunable waveguide phase shifter presented here consists of a finline filter integrated into a precision-machined waveguide, benefiting from low insertion-loss and high Q-factor characteristics of finline filters [165]. Finline filters allow implementation of compact and lightweight millimeter-wave components, as they are easy to integrate in millimeter-wave systems.

The 3D illustration of the basic concept is shown in Fig. 6.2, consisting of the micromachined chip with bilateral finline structure, i.e. the metallic finline elements placed on both sides of the dielectric substrate, integrated along the longitudinal direction of a WR-12 rectangular waveguide (with inner dimensions 3.099 mm × 1.549 mm, and frequency range 60–90 GHz). Slots at the bottom and the top of the waveguide allow bias feedthroughs for MEMS actuators of the microchip. Taking the biasing lines into account is important for any MEMS array device, as the routing of the biasing lines often interferes with RF performance. The phase shifter chips are designed in an X-shape form, as shown in Fig. 6.2(a), in order to reduce the slot length in the top and the bottom faces of the waveguide, thus keeping
Figure 6.2. Concept of digital finline phase shifter based on MEMS switching elements. (a) 3D rendered view of the finline chip integrated into a WR-12 waveguide. (b) Side view of one fin structure with MEMS switching elements and comb-like fixed fin slot pattern of the ground layer. (c) Open-state configuration of the MEMS cantilever switch. (d) Closed-state configuration of the MEMS cantilever switch.
Chapter 6. MEMS-based reconfigurable antenna array

State 1: only switch 6 is closed
State 2: switches 4 and 11 are closed
State 3: switches 3 and 9 are closed
State 4: switches 1 and 11 are open

Figure 6.3. Illustration of phase shifter slot configuration for four distinct phase shifter states.

the radiation loss and the disturbance of the currents in these waveguide faces at a minimum. A longitudinal slot (20 µm wide) is patterned in the middle of each fin, as shown in Fig. 6.2(b). Eleven MEMS cantilever switches are placed across each fin slot, i.e. there are 22 total MEMS switches for the bilateral structure. The cantilevers can influence the wave propagation by short-circuiting the slot. The phase of the wave transmitted from the input port to the output is controlled by a suitable combination of open and closed states of the individual cantilevers. The distance between the cantilever plate and the electrode is 2.0 and 0.8 µm in the open and closed states respectively, as shown in Fig. 6.2(c) and (d).

For the proof of concept, the prototype chips of the MEMS-based finline phase shifters are designed in fixed MEMS states, i.e. the actuators are not functional. In the fixed states, all actuation and biasing elements, e.g. all gold fin layers with all slots for the MEMS biasing lines, are included both in the simulation models and in the fabricated designs, to include their influence on the RF performance. However, all cantilevers in the closed state are realized with gold short-circuiting connection lines in the slot on the substrate surface. Moreover, the simulation model includes metal and dielectric losses.

The phase of the transmitted wave is controlled by short-circuiting the slot at specific points, which imitates the closed cantilever state of the non-moveable MEMS. Four different embodiments are implemented, shown in Fig. 6.3, which correspond to four different phase states, shown in HFSS-simulated results of Fig. 6.4. From the simulation data of Fig. 6.4(a), the phase responses of the four chips at the nominal design frequency of 77 GHz, normalized to State 4 are 0°, 95°, 158°, and 246°. The simulated reflection coefficient is lower than 10 dB for all states at the design frequency, and the simulated insertion loss, S21, is better than -1 dB for all states at 77 GHz. State 1 and State 2 of this design are very narrowband.
Figure 6.4. HFSS-simulated performance of the finline filter designed at 77 GHz. (a) Phase response. (b) Reflection coefficient. (c) Insertion loss.
6.2.2 Prototype fabrication

The fabrication process of micromachined phase shifters is outlined in Fig. 6.5. First, two 300-µm thick high-resistivity silicon substrates (HRSS) are bonded using benzocyclobutene (BCB) as an intermediate adhesion layer (Fig. 6.5(a)). HRSS with nominal resistivity of higher than 13 kΩ·cm is chosen because of low-loss tangent of these substrates at room temperature in the entire W-band [166]. A lift-off process is used to pattern the metal structures by evaporating of 1 µm layer of gold on the front-side (Fig. 6.5(b) and (c)). The front-side is then protected by photoresist followed by repeating the metallization lift-off process on the backside, to achieve a bilateral finline structure (Fig. 6.5(d)). Then, deep reactive ion etching of the front-side wafer is done by Bosch process (Fig. 6.5(e)). Finally, deep reactive ion etching is also done on the backside to completely free-etch the chips while they are kept in place on a temporary carrier wafer using a temporary thermal-release tape (Fig. 6.5(f)).

Camera pictures of some prototype microchips are shown in Fig. 6.6, after being released from the thermal-release adhesive tape.
6.2. Novel MEMS-based waveguide-integrated phase shifters

Figure 6.6. Photographs of finline-based phase shifter chip prototypes.

(a) (b)

Figure 6.7. Integration of X-shape phase shifter prototype chips into tailor-made WR-12 waveguide for RF measurement. (a) 3D rendered model. (b) camera picture.

6.2.3 RF characterization

A modified 120-mm long WR-12 waveguide section, shown in Fig. 6.7, is used to securely mount the X-shape micromachined phase shifter prototypes into the measurement setup. The modified section has recesses in the wide walls of the waveguide to guarantee the accurate positioning of the chip in the center, and, it includes a 10-mm long copper lid and two sliding clamps to keep the chip fixed.

The measured phase shift and S-parameters of the prototype chips mounted into the modified waveguide are shown in Fig. 6.8. The measured phase states, shown in Fig. 6.8(a), relative to State 4, are 0°, 56°, 189° and 256°, for the design frequency of 77 GHz, which corresponds to an effective 1.78 bit. The measured reflection coefficient and insertion loss of the four states are shown in Fig. 6.8(b) and (c). The measured reflection coefficients show that the reflected power is much more than the amount expected from the simulations. The insertion loss data shows the same behavior as it is measured better than 5.7 dB for the state with the lowest loss. To investigate the reason for this discrepancy, the reproducibility of the assembly and the influence of fabrication tolerances were tested, with the details provided in Paper 3. It is concluded that a major reason for the deviation of the measured S-parameters from the simulation data is the narrow-band design of the devices, which makes the performance very sensitive to design parameter variations.
Chapter 6. MEMS-based reconfigurable antenna array

6.3 Transmit-array antenna for beam steering front-ends

The MEMS-based phase shifter concept discussed above can be used as individual building blocks of a waveguide-based transmit-array antenna for beam-steering front-ends, in a configuration shown schematically in Fig. 6.9. The transmit-array antenna is fed by a pyramidal horn antenna placed at a certain distance, and the phase shifter states (four in this design) are used to compensate for the different electrical path lengths between the horn and each cell of the radiating aperture. The phase shifter elements discussed in the previous section was designed for proof-of-concept phase shifting principle, and not for antenna array application. Therefore, four rectangular-shape chips with simulated phase responses of $-90^\circ$, $15^\circ$, $110^\circ$ and $178^\circ$ at 77 GHz were designed to be used as unit-cell of the transmit-array antenna for automotive radar beam-steering front-end.

The assembled transmit-array antenna, shown in Fig. 6.10, fabricated in bronze, have $10 \times 21$ elements and a total dimension of $54.55 \text{ mm} \times 41.9 \text{ mm} \times 10.205 \text{ mm}$. There is a recess cut into the waveguide element to fix the rectangular-shape phase shifter chip.
6.3. Transmit-array antenna for beam steering front-ends

Figure 6.9. Transmit-array based on the proposed finline MEMS-based phase shifter elements.

Figure 6.10. Fabricated transmit-array antenna: (a) Integration of phase shifter chips into the array. (b) Assembly of the antenna. (c) Complete transmit-array antenna.

Since the phase shifter chips are fabricated in the fixed MEMS states, the ability of the antenna array for beam-steering is demonstrated by shifting the horn antenna feed in the E-plane parallel to the antenna array, with 4-mm step size equal to the feed aperture dimension, as shown in Fig. 6.11(a). In this case, all phase shifters are tuned to have maximum radiation at broadside. From the measurement results of Fig. 6.11(b) it can be seen that the antenna array exhibits good performance up to 15° at the designed frequency of 77 GHz, but the gain decreases rapidly and the side lobe level increases beyond this value. The half power beamwidth (HPBW) of the antenna array is 4.5°–5.5° up to 12 mm displacement of the horn feed.

Further details on the antenna array design and performance characterization
6.4 Discussion and outlook

The proof-of-concept simulation results of MEMS-based waveguide-integrated phase shifters presented in this chapter has shown promising performance, however, the characterization results demonstrated drastically higher insertion loss than expected. The discrepancy is attributed mainly to the narrow-band design, and not to fabrication process and assembly setup, confirmed by additional measurements.

It is interesting to investigate and extend this concept further to achieve a fully-functional MEMS-reconfigurable waveguide phase shifters, but it is recommended to optimize the design for wide-band performance. The fabrication process of fully-functional device is anticipated to require process-optimization iterations due to necessary surface machining techniques.
Chapter 7

Integration challenges of microwave MEMS devices into waveguides

This chapter starts with a background on challenges for integration of microwave prototype chips into waveguides and gives some application examples of adhesive tapes and sheets in microsystems. Afterwards, it presents a novel low-loss method of integrating microwave MEMS chips into rectangular waveguides using a double-sided adhesive conductive polymer interposers for reflective and transmissive surfaces. Further details and investigation of this method is provided in Paper 2.

7.1 Background

A major practical obstacle of millimeter-wave systems based on waveguides with integrated MEMS chips is the reliable, reproducible and low-loss assembly of the micromachined MEMS chips into the conventionally machined waveguides. The assembly solution needs to provide a stable chip fixture for mechanical reliability and reproducibility of the measurement without leaving any air-gap between the chip and the waveguide wall, which contributes to loss and often introduces spurious resonances. A few methods have been reported to integrate MEMS chips into waveguides including assembling the MEMS devices directly into the waveguide without any interfacing layer [142, 143] and with copper foil pads as interposer layer [150], using screws to connect the hard-wired MEMS devices and the waveguide [167, 168], and using conductive epoxy to attach the MEMS membrane to the waveguide wall [146].

In microsystems, adhesive tapes and sheets have been employed for different applications, for examples as an interface material for assembly [169] and bonding [170, 171]. Moreover, conductive tapes and sheets have been used in applications requiring electrical connection, for example, as vertical interconnects [172], as an electrical contact of sensor electrodes [173], and as an interface to mount MEMS chips onto a waveguide [174].
This chapter discusses the integration aspects of reflective and transmissive MEMS chips which are electrically connected and mechanically fixed to rectangular waveguides at 60–110 GHz frequency range using conductive polymer sheets.

7.2 Prototype integration concept

Fig. 7.1 shows an illustration of the proposed chip-to-waveguide integration concept for reflective and transmissive MEMS surface applications, based on conductive polymer interfacing layer. Furthermore, a cross-sectional view comparing the air-gap interfacing and the new interfacing, with conductive polymer interposers is shown in Fig. 7.2. For the air-gap proximity integration method, the waveguide is not electrically connected to the MEMS chip, and the resulting air gap causes radiation losses and often spurious resonances, especially in the millimeter-wave frequencies. Direct touching of the waveguide on the chip must often be avoided since the rough surface topography of conventionally machined components results in local stress maxima which break the brittle microchips. Furthermore, the lack of mechanical connections introduces complexities in the mounting and alignment. In comparison, these issues are addressed by the proposed interfacing concept, where the air gap is filled by the conductive polymer sheet. This concept combines the following features.

- **Good and uniform RF and DC electrical connection between the MEMS chip and the waveguide frame** is provided by a conductive polymer layer of low resistivity (8 mΩ·cm), avoiding any unintentional discontinuities in the high-frequency current distribution which increase the radiation loss and introduce spurious resonances.

- **Secure and reliable mechanical connections of the MEMS chip into the waveguide** by double-sided adhesive interposer as the interposer addresses the mismatch in the surface roughness and fabrication tolerances between the micro-machined MEMS chip and the waveguide with macro-scale topography. The softness of the compliant conductive polymer layer with a Young’s modulus in the lower GPa range significantly reduces the risk of breaking the brittle MEMS chip at local high stress contact points.

- **Waveguide feedthroughs for DC biasing of MEMS actuators through the polymer frame** without decreasing the RF performance or short-circuiting to the waveguide frame is easily possible by structuring the polymer interposer and passing the biasing lines along the narrow walls of the waveguide to avoid any interruption of the major waveguide surface currents in the dominant mode, thereby avoiding unnecessary radiation loss.

- **Mechanical interconnection of MEMS actuator through the polymer opening** is possible by perforating the interposer to accommodate mechanical connections in applications where the MEMS actuators are required to be placed
7.2. Prototype integration concept

Figure 7.1. 3D view of the proposed integration concept for integrating MEMS chips into a rectangular waveguide by structured double-sided adhesive conductive polymer interposers. The concept is displayed for integration of (a) a reflective surface, and (b) a transmissive surface.
Chapter 7. Integration challenges of MEMS devices into waveguides

(a) Chip-to-waveguide integration of a chip containing a reflective surface
(b) Chip-to-waveguide integration of a chip containing a transmissive surface

Figure 7.2. Schematic illustration to compare an air-gap and the proposed concepts for two types of MEMS chips. (a) MEMS chip with a reflective surface; (b) MEMS chip with a transmissive surface. In the air-gap concept substantial radiation loss could happen between the waveguides which is addressed in the new concept by replacing the gap with a compliant conductive polymer interposer. Moreover, the new concept allows connecting the waveguide to the ground plane of the MEMS chip and provides the possibility to pass DC bias lines or mechanical connection of the MEMS actuators between the two waveguide.

outside of the waveguide frame in order not to interfere with the propagating wave.

- **Reworkable bonding interface** is provided by this concept as the bonding interface between the conductive adhesive sheet and the waveguide is not permanent. Reworkable interfaces are essential in testing, calibration, and prototype development where MEMS chips are frequently replaced.

As compared to these features, the disadvantages involved with the proposed interfacing concept are as follows.

- **Lack of hermeticity** of polymer interposer. Even though it is generally a dust and a water barrier, it is not gas-tight, and if feedthroughs need to be implemented, the particle and water protection are lost.

- **Patterning of the adhesive polymer sheet** is required for shaping the openings for DC biasing or mechanical interconnection of the actuator, therefore, a cutting plotter or similar equipment is recommended. Sub-millimeter sized pieces of soft polymer sheets can be challenging to integrate on small chips into
waveguides working in the high millimeter-wave frequency range. The manual assembly demonstrated in this prototype work needs further automation to be suitable for volume production.

- **Alignment issues and safety distance requirements for MEMS designs** considering that the softness of polymer sheet results in significant extension in lateral direction under high assembly pressure between the chip and the waveguide, even though it is beneficial for secure and reliable mounting. Therefore, some alignment precaution and consideration of some design safety margins between the MEMS movable parts and the applied polymer sheet is necessary.

### 7.3 Characterization

The double-sided adhesive conductive polymer interposer utilized here, to mount the prototype MEMS chips, is commercially available Ted Pella Silver Conductive Sheet 16086-1 with a nominal thickness of 125 µm. They are patterned by a Graph-tect CE5000 cutting plotter, with a nominal positioning accuracy of 5 µm, and are manually applied to the chips.

A comparison between the RF performance of two assembly prototypes, one with a conductive polymer interface layer between the waveguide and the chip and the other with a direct metal-to-metal interface, is shown in Fig. 7.3, with the figure including also the performance of a waveguide short as a reference. A 250-µm opening is perforated the polymer ring for electrical feedthroughs on both narrow sides. The results illustrate the advantages of the compliant polymer and confirms that the conductivity of the polymer interface is high enough in this frequency range, as the prototype with conductive polymer interface performs as good as the one with metal contact interface below 95 GHz, and even better than the direct metal contact above 95 GHz. This can be explained by local air gaps in the direct waveguide-to-chip interfacing due to mismatching surface topography of the waveguide frame, in particular on the wider sidewalls of the waveguide. The introduced loss of the conductive polymer interface is less than 0.4 dB as compared to the reference standard short.

The direct metal interface is not suitable for the integration of a MEMS chip, and thus, for comparison to the above discussion, it is interesting to investigate the return loss of an assembly setup consisting of an air-gap interface between a metal waveguide and a reflective surface, imitated by a standard fixed-short flange. Fig. 7.4 shows the measured performance of such an assembly for different air-gap widths. For small air gaps below 30 µm, the return loss can be as low as 1.5 dB. However, such an air gap interface results in many spurious resonances and very small usable bandwidths. For air gaps above 50 µm, the performance drastically degrades, and the gap between the waveguide flanges results in sharp resonance peaks. This comparison emphasizes the performance improvement of the proposed polymer interface, in particular for gaps wider than 50 µm, and even if the polymer is only used on the wider sides of the waveguide.
Chapter 7. Integration challenges of MEMS devices into waveguides

Figure 7.3. RF characterization results comparing two different chip-to-waveguide connection methods for the reflective surface applications, conductive polymer interface and a direct metal interfacing, including the measurement results of a waveguide short as reference. The proposed interface performs as good as or better than direct metal contact, due to the compliancy of the polymer surface.

Figure 7.4. RF characterization of an air-gap interface to a reflective surface normalized to a standard waveguide short for different gap distances, showing the poor interface performance of such interfaces.

To investigate the integration performance for a transmissive surface application, Fig. 7.5 shows the measured performance of a complete assembly setup, where the transmissive chip is integrated into modified flanges and the WR-12 waveguide, comparing three integration cases: (1) Conductive polymer interposer applied be-
7.3. Characterization

Figure 7.5. Measurement results of a complete assembly with an integrated transmissive chip, including the two modified waveguide flanges, comparing three cases: direct contact between the metal layer on the chip and the waveguides, polymer interposer between the top metal layer of the chip and the waveguide, and polymer interposer applied on both the top and the bottom faces of the chip. The assembly using the polymer interposer shows much more stable results than the direct metal contact, as the latter case might lead to partial air gaps between the chip and the waveguide. Applying the polymer interposer on both sides of the chip improves the result slightly compared to applying the interposer only on one side of the chip.

between the top layer of the chip and the wide walls of the waveguide; (2) conductive polymer interposer covering the interface of the chip and the wide walls of the waveguide, both on the top and the bottom layer of the chip; (3) direct metal contact between the waveguide and the metal layer on the chip. The transmissive chip, which has a through-silicon opening as large as the waveguide inner dimensions, is completely covered with 1 µm layer of gold. The results confirm that the compliant conductive polymer interposer removes any partial air gap, improves the performance, and results in stable measurements over the whole frequency range. The insertion loss of the whole assembly setup is between 0.27 dB and 0.59 dB, and the return loss is better than 20.38 dB where the conductive polymer is only applied on one side of the chip, compared to the improved insertion loss between 0.21 dB and 0.53 dB, and return loss of better than 21.01 dB where the polymer interposer is applied on both sides of the chip. Therefore, applying the conductive polymer
interposer on both sides of the chip improves the performance insignificantly in comparison to the case where the interposer is only applied on one side of the chip.

Further data on performance analysis of the conductive polymer interfacing concept is provided in Paper 2, including the effect of resistivity and thickness of polymer intersposers, as well as, the width of the opening for the feedthroughs.

7.4 Discussion and outlook

The simulation and measurement results for the integration of RF MEMS chips into a waveguide with a commercial conductive polymer interposer were investigated up to 110 GHz in this chapter, showing the advantages of this method over the integration with an air-gap interfacing, with the latter method causing up to 3 dB reflected power for gaps as small as 20 µm, introducing spurious resonances, and having very small usable bandwidth. The proposed method performs as good as or better than direct-metal contact investigated for both reflective surface and transmissive surface applications.

The new method can be utilized in significantly higher frequencies, however, some additional considerations are required.

Since the cutoff frequency of the waveguide is related to the inner dimensions of the waveguide, waveguides with smaller dimensions are used for higher frequency applications, and therefore the performance becomes more sensitive to fabrication and assembly tolerances, making the manual assembly methods challenging.

The radiation loss from the opening of the waveguide is proportional to the frequency, thus to scale up in frequency without performance degradation, thinner polymer sheets should be used.

Since the silver particles introduced in the polymer sheet to provide electrical conductivity are much smaller than the wavelength even at 1 THz (free-space wavelength of 300 µm), it is believed that the conductivity of the conductive polymer sheet used in this work is suitable for even terahertz frequency range.

Other interesting aspects for industrial adaption of the method would be the investigation of other commercial conductive polymer interposers provided by different manufactures and the development of automated integrating systems.
Chapter 8

Conclusions

In this thesis novel microelectromechanical (MEMS) devices for millimeter-wave waveguide applications in two categories are presented, and, also, a novel method for integration of MEMS chips into waveguides, by using conductive polymer interposers, is investigated.

In the first part of the thesis a 30-µm thick MEMS-reconfigurable surface is introduced and it is utilized to present the first waveguide switch above 40 GHz, which has similar excellent signal performance as rotary motor-based waveguide switch, but has a drastically reduced size. Furthermore, the concept of MEMS-reconfigurable surface is extended to the first MEMS-switchable waveguide iris to demonstrate a V-band switchable waveguide cavity resonator. Besides, the potential of MEMS-reconfigurable irises for tunable/switchable waveguide bandpass filters has been shown.

Moreover, a new configuration of a digital waveguide phase shifter is proposed, based on distributing MEMS switches along the finline structure of a waveguide bandpass filter, allowing the phase shift control by changing the MEMS switch combinations. The proof-of-concept prototypes for WR-12 waveguide were fabricated and employed in a phased-antenna array for 77 GHz beam steering front-end.

In addition, to address the integration difficulties and complexities of waveguide-integrated MEMS-based high frequency systems, a mechanically-robust electrically low-loss chip-to-waveguide integration concept was investigated based on commercial conductive polymer interposers for applications of up to 100 GHz.
Summary of Appended Papers

**Paper 1:** MEMS reconfigurable millimeter-wave surface for V-band rectangular-waveguide switch

The paper presents a concept of a microelectromechanical systems (MEMS) waveguide switch based on a reconfigurable surface, whose working principle is to block the wave propagation by short-circuiting the electrical field lines of the $TE_{10}$ mode of a WR-12 rectangular waveguide. The reconfigurable surface consists of up to 1260 micromachined cantilevers, which are moved simultaneously by integrated MEMS comb-drive actuators. Measurements of proof-of-concept prototypes, which were not fully functional and were fixated mechanically, show very with promising results where the devices blocking wave propagation in the OFF-state with over 30 dB isolation for all designs, and allow for transmission of less than 0.65 dB insertion loss for the best design in the ON-state for 60–70 GHz.

**Paper 2:** Integration of microwave MEMS devices into rectangular waveguide with conductive polymer interposers

The paper investigates a novel method of integrating microwave MEMS chips into millimeter-wave rectangular waveguides. The fundamental difficulties of merging micromachined with macromachined microwave components, in particular surface topography, roughness, mechanical stress points, and air gaps interrupting the surface currents, are overcome by a double-side adhesive conductive polymer interposer. This interposer provides a uniform electrical contact, stable mechanical connection and a compliant stress distribution interlayer between the MEMS chip and a waveguide frame. Moreover, both DC biasing lines and mechanical feedthroughs to actuators outside the waveguide are demonstrated which is achieved by structuring the polymer sheet xographically. FEM simulations were carried out for analyzing the influence of different parameters on the RF performance.

**Paper 3:** Waveguide-integrated MEMS-based phase shifter for phased array antenna

The paper investigates a new concept of waveguide-based W-band phase shifters for applications in phased array antennas. The phase shifters are
based on a tunable bilateral finline bandpass filter with 22 microelectromechanical system (MEMS) switching elements, integrated into a custom-made WR-12 waveguide with a replaceable section, whose performance is also investigated in this study. The individual phase states are selected by changing the configuration of the switches bridging the finline slot in specific positions. MEMS chips have been fabricated in fixed positions, to prove the principle, that is, they are not fully functional, but contain all actuation and biasing-line elements. The measured phase states are 0, 56, 189 and 256°, resulting in an effective bit resolution of 1.78 bits at 77 GHz.

**Paper 4: Parameter analysis of millimeter-wave waveguide switch based on a MEMS-reconfigurable surface**

The paper presents a novel concept of a millimeter-wave waveguide switch based on a MEMS-reconfigurable surface with insertion loss and isolation very similar to high performance but bulky rotary waveguide switches, despite its thickness of only 30 µm. A set of up to 1470 micromachined cantilevers arranged in vertical columns are actuated laterally by on-chip integrated MEMS comb-drive actuators, to switch between the transmissive state and the blocking state. In the blocking state, the surface is reconfigured so that the wave propagation is blocked by the cantilever columns short-circuiting the electrical field lines of the $TE_{10}$ mode. A design study has been carried out identifying the performance impact of different design parameters. A device-level yield analysis was carried out, both by simulations and by creating artificial defects in the fabricated devices, revealing that a cantilever yield of 95% is sufficient for close-to-best performance. Life-time measurements of the all-metal, monocrystalline-silicon core devices were carried out for 14 hours after which 4.3 million cycles were achieved without any indication on degradation. Furthermore, a MEMS-switchable waveguide iris based on the reconfigurable surface is presented.

**Paper 5: MEMS-reconfigurable irises for millimeter-wave waveguide components**

The paper presents MEMS-reconfigurable waveguide irises based on reconfigurable surfaces integrated into a WR-12 rectangular waveguide (60–90 GHz). The reconfigurable surface is only 30 µm thick and incorporates 252 simultaneously switched contact points short-circuiting the electric field lines of the $TE_{10}$ mode. This novel concept allows for completely switching ON and OFF inductive or capacitive irises for building switchable frequency-selective waveguide devices. The measurements in the ON and OFF states match simulation results very well. Furthermore, a switchable cavity resonator was implemented with a MEMS-reconfigurable inductive iris, resulting in a measured ON-state reflection coefficient of 14.5 dB with a Q-factor of 186.13 at the resonance frequency of 68.87 GHz. Moreover, it is shown that by using multiple MEMS-reconfigurable irises in a waveguide, more complex compo-
nents such as switchable/tunable millimeter-wave waveguide filters can be implemented.

**Paper 6: MEMS-reconfigurable transmit antenna arrays for 77-GHz automotive radar applications**

The paper presents an alternative solution consisting of a waveguide-based transmit-array antenna with phase shifters used as individual building blocks. A new antenna array configuration is based on WR-12 waveguide. The proposed configuration of the integrated phase shifters is based on a bilateral finline bandpass filter associated to MEMS elements as switches and operates at 77 GHz. The phase states are controlled by changing MEMS states integrated in the finline slot. The proposed antenna array model has been prototyped and characterized.
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