Millimeter Wave Phase Shifter Based on Optically Controlled Carbon Nanotube Layers

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***Abstract*—Surfaces with tunable impedance are usually lossy at high frequencies, which limits the design of millimeter wave and Terahertz devices. This work experimentally demonstrates a phase shifter based on single-walled carbon nanotubes and dielectric rod waveguides in the 220-330 GHz frequency range. Thin carbon nanotube layers are used as a tunable impedance surface with the dielectric properties optically controlled by laser illumination.**

I. Introduction

Millimeter wave and Terahertz electronics are seeing an increasing interest in the development of systems for a wide range of applications such as radar imaging, material spectroscopy, high bandwidth telecommunications, and medical imaging and diagnosis [1-5]. However, the widely used standard hollow waveguide technology becomes very lossy with increasing frequency due to metal conduction losses. Instead, the dielectric rod waveguide (DRW) is seen as a prospective platform for millimeter wave and THz electronics [6,7]. DRWs have low propagation losses and no cut-off frequency in comparison to metal waveguides, and are straightforward to integrate with existing semiconductor technologies [8,9]. Moreover, the DRW is an open waveguide system that can be influenced by external electromagnetic fields.

Several electronic devices, such as attenuators and phase shifters, require materials with tunable dielectric properties, such as high impedance surfaces. These materials, however, are often lossy at millimeter wave frequencies [10]. In this respect, novel meta- and nano-materials are widely studied. For instance, single-walled carbon nanotubes (SWCNTs) were used as a tunable impedance surface in the millimeter wave range with low insertion and return losses [11].

In this paper, we experimentally demonstrate a phase shifter in the 220–330 GHz frequency band. The device is based on optically controlled carbon nanotube layers and illustrates that the SWCNTs are a promising material for the design of novel optoelectronic devices.

II. Results

A schematic drawing of the phase shifter design is shown in Fig. 1a. A 30 mm-long sapphire DRW was covered on one side by a thin carbon nanotube layer with a length of 5 mm. SWCNTs were synthesized by aerosol chemical vapor deposition [12] with a diameter of 1.3 nm, an average length of 10–20 µm and an optical absorbance of 0.155. The rod is symmetrically tapered on both ends and was inserted in WR-3 metal waveguide ports. The SWCNT layer was illuminated by a laser with a wavelength of 532 nm and a light intensity of 9 mW/mm^2. The illumination provokes a modification of the dielectric constant of the carbon nanotube layer. The

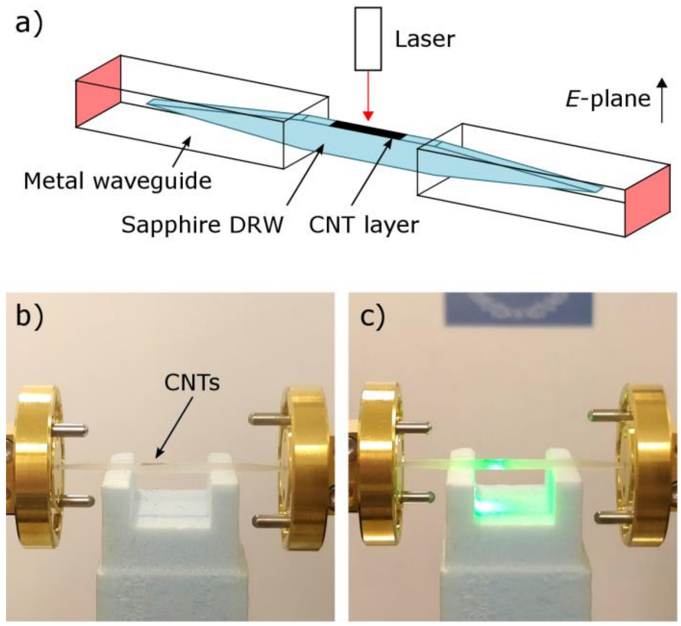

Fig. 1. a) Schematic drawing of the phase shifter measurement setup. A dielectric rod waveguide is mechanically supported by Rohacell between two WR-3 metal waveguide ports. A thin carbon nanotube layer is applied on one side of the DRW and illuminated with a laser. b) Image of the measured device in the non-illuminated state. c) Measured device in the illuminated state.

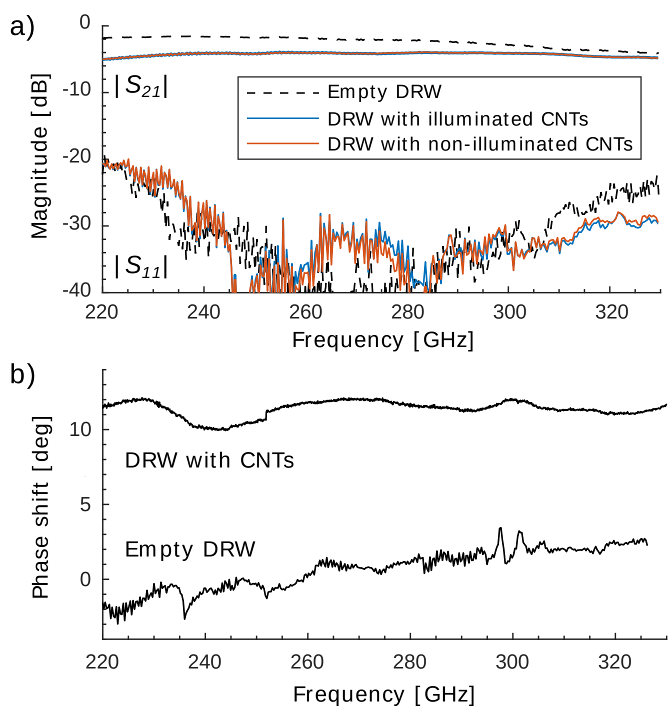

Fig. 2. a) Measured S parameters in the illuminated and the non-illuminated states of the CNT layer. b) Measured phase shift due to the illumination of the DRW coated with CNTs and the DRW alone.

impedance variation induces the change of the propagation constant in the waveguide. This effect provokes a phase shift compared to the non-illuminated state.

An image of the measurement setup in the non-illuminated and the illuminated states is shown respectively in Fig. 1b and Fig. 1c. The DRW was mechanically supported by a rigid Rohacell structure with low dielectric constant and low loss tangent. The measurements were performed with a Rohde & Schwartz ZVA-24 Vector Network Analyzer with WR-3 extension head modules. The insertion loss was between 4 dB and 5 dB, with 1 dB to 3 dB attributed to the SWCNT layer, as shown in Fig. 2a. The return loss was below -20 dB in the whole frequency range. The losses are mostly attributed to edge imperfections in the DRW due to machining difficulty of sapphire, and alignment precision of the device with respect to small metal waveguide openings at this high frequency. No additional losses were observed when illuminating the device. An average phase shift of 10 to 12 degrees was measured between the illuminated and the non-illuminated states, as shown in Fig. 2b. An empty DRW, without SWCNTs, was also illuminated as a reference. The measured phase shift of the empty waveguide was on average 0 degrees. This demonstrates the optoelectronic nature of the phase shifting, provoked by the impedance tuning of the SWCNT layer.

III. Conclusions

A phase shifter, based on optically controlled single-walled carbon nanotubes, was fabricated and measured in the 220–330 GHz frequency range. The fabricated device shows a phase shift above 10 degrees in the measured frequency band with insertion loss attributed to the SWCNTs below 3 dB. These figures of merit can be further enhanced by optimizing the illumination parameters and the SWCNT layer, such as choosing nanotubes with a lower optical absorbance. The device design can be easily adapted to other frequency bands as a broadband phase shifter. These results indicate that the thin carbon nanotube layers are suitable as optically tunable impedance surface for millimeter wave and THz applications. We think that this effect opens a new direction for the design of novel optoelectronic devices, such as THz beam steering solutions when integrated with DRW antenna arrays.

IV. Acknowledgment

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