Broadband Dielectric Waveguides for 0.5 – 1.1 THz Operation

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***Abstract*—Miniaturization of terahertz systems is necessary for a broad-scale application of Terahertz technology. Waveguides are an important component in this regard. We present design and characterization of broadband planar dielectric waveguides made of highly resistive silicon having 200 x 50 µm^2 cross-sectional area on a quartz substrate. The waveguides are characterized between 450 GHz and 1.1 THz. The waveguides show a lower cut-off frequency of ≈ 500 GHz and power transmission losses between 0.32-1 cm^{-1} over a frequency range of 0.55-1.05 THz.**

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I. INTRODUCTION

Metallic waveguides are used throughout the DC to microwave range. However, they turn lossy at frequencies beyond a few 100 GHz due to surface roughness effects, skin depth and finite conductivity. Therefore, metal-based circuits must remain small, typically in the few mm-range, particularly at frequencies beyond 1 THz. Dielectric waveguides, in contrast, are used up to the optical domain in the form of optical fibers. Dielectric waveguides (WGs) are essential for generating spatially extended circuits in the higher THz band. These WGs were first investigated by E.A.J. Marcatili[1] in 1969 for optical applications. In this work, we extend this concept to create broadband waveguides for THz frequencies. If the medium surrounding the WG is uniform, an infinite theoretical single mode bandwidth can be achieved, much in contrast to metal-based waveguides that often are just functional within a bandwidth of about 50% of the center frequency. Many low loss dielectric polymers are used to make waveguides at THz frequencies. As an example, a rectangular HDPE waveguide was demonstrated in ref. [2] with propagation losses of ≈ 4.3 dB/cm between 0.1–3.5 THz which can be further reduced by micro-structuring the waveguide core [3], however, at cost of bandwidth. Highly resistive float-zone silicon (HRFZ Si, $R > 10$ kΩ-cm) features material absorption losses < 0.2 dB/cm for frequencies below 2.5 THz [4] and is used to manufacture broadband THz waveguides described in this paper. In case of metallic waveguides, Virginia Diodes Inc. reported losses for TE$_{10}$ mode travelling in rectangular hollow metallic waveguides in the range 1.35–1.92 dB/cm for frequencies between 0.5–1.1 THz [5], whereas, hollow core circular waveguides have lowest losses ≈ 3dB/cm at 1 THz [6]. In contrast, metallic transmission lines exhibit losses higher than 6 dB/cm above 0.35 THz [7].

HRFZ Si (ε_r = 11.61) WG structures are supported by 500 μm thick quartz substrate (ε_r = 4.62), which features low absorption at frequencies below 1 THz. The waveguides are fabricated using deep reactive ion etching (D-RIE) at the Max-Planck Institute for the Science of Light in Erlangen, Germany. Additionally, a few waveguides are also produced by laser ablation using a picosecond laser. The ablation process was carried out by 3D-Mircomac AG in Chemnitz, Germany. Both the processes require a substrate with a high melting point and good thermal conductivity. Crystalline quartz satisfies both the criteria, whilst having a comparatively low permittivity and low absorption losses at THz frequencies and thus, is the substrate of choice.

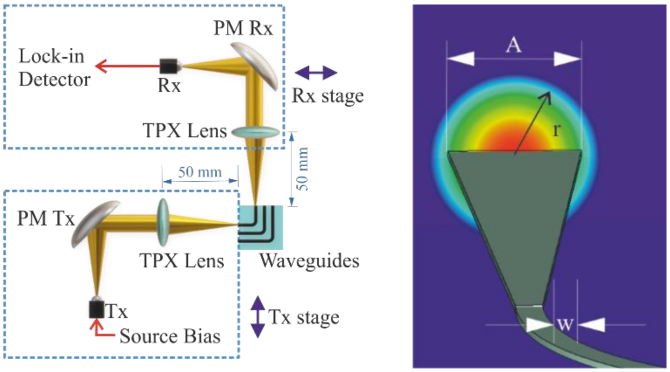

Fig. 1. (a) Schematic of the measurement setup. (b) Shows the waveguide input facet in details. A = 1 mm, r ≈ 600 µm at 1.1 THz and w = 0.2 mm. The spot size is considerably bigger than the vertical waveguide dimension and thus coupling losses are incurred.

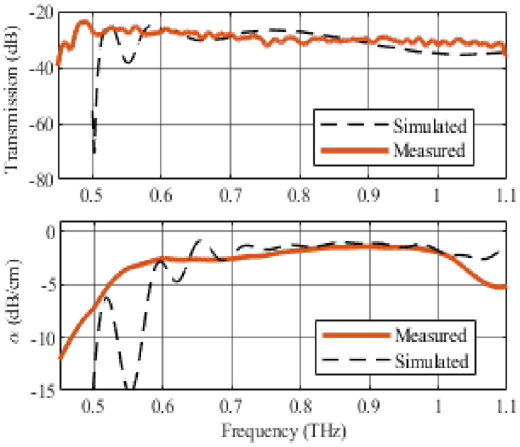

Fig. 2. Simulated and measured values of transmission losses and power attenuation coefficient (α) for the silicon waveguides on quartz substrate. Moving average filter is used to minimize standing wave fluctuations in measured attenuation.

The presence of the substrate introduces a lower cut-off frequency for the WG structures due to a mismatch in refractive indices on the top and bottom side of the WG. The lower cut-off frequency of these dielectric WGs increases with the increase in the substrate refractive index. At higher frequencies, the entire electromagnetic field is confined within the HRFZ Si and incur negligible transmission losses. However, the designed waveguides also support higher-order modes and hence, mode conversion losses occur at the structural bends, which introduces a higher cutoff frequency. These two phenomena regulate the operating region of HRFZ Si waveguides.

II. MEASUREMENT AND RESULTS

The waveguides are characterized in a free-space THz continuous wave (CW) system. Fig. 1(a) shows the measurement setup consisting of a THz source from Toptica photonics AG and an ErAs:InGaAs photoconductive receiver with comparable dynamic range to a commercially available Toptica receiver, as detailed in [7]. Two sets of parabolic mirrors (PM) and TPX lenses are used with the transmitter (Tx) and receiver (Rx), respectively, for focusing the THz beam onto the waveguide end facets. The waveguides are placed at the foci of the TPX lenses. All waveguides are fabricated with a 90° bend with 2 mm bend radius to nullify line of sight coupling between the THz source and the receiver. Fig. 1(b) shows tapered end facets for improved mode matching to the free space THz beam.

TABLE I
LIST OF TRANSMISSION (TX.) AND COUPLING (CP.) LOSSES CALCULATED AT VARIOUS FREQUENCIES FROM THE MEASURED DATA

Frequency (THz)	0.5	0.6	0.7	0.8	0.9	1.0
Tx. Losses (dB/cm)	5.86	3.11	1.55	0.79	0.92	0.59
Cp. Losses (dB)	26.21	21.85	23.70	25.64	26.23	26.35

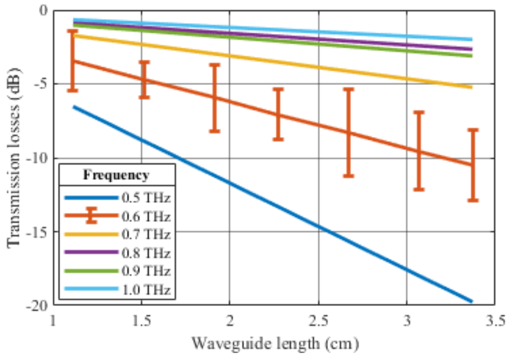

Fig. 3. Plot shows the linearly fitted values of the transmission losses in dB as a function of the waveguide length. The losses are calculated at discrete frequencies between 0.5 THz to 1.0 THz at an interval of 0.1 THz. For the sake of brevity, error margin is only shown for the fit at 600 GHz, which is also representative at other frequencies.

The permittivity and loss tangent of highly resistive Si and quartz are measured using time domain spectroscopy. Accordingly, a model is generated in CST Studio Suite and total transmission losses are simulated for a waveguide with total length of 15.14 mm. Fig. 2. shows excellent agreement between the simulated and measured transmission losses. The losses are vastly due to in- and out-coupling of a Gaussian THz beam in free-space, which can be attributed to two primary factors. Firstly, the effective input aperture of the tapered waveguide is two orders of magnitude smaller than that of the minimum spot size of the Gaussian beam, which, in turn, is limited by the free-space THz components in the setup and hence, a large amount of THz power is not coupled into the waveguide. Secondly, mode mismatch between the Gaussian profile of the incident THz beam and the fundamental propagating waveguide mode introduces further losses as higher order evanescent modes are excited in the waveguide.

The power attenuation coefficient per unit length is measured using two WGs (produced by laser ablation) of different lengths, but with same bend radius and end-tapers, similar to the cut-back technique used in the optical domain for measuring fiber losses. In the frequency range 0.55–1.05 THz, the simulated power loss coefficient (α) of the WG varies between 0.2–1 cm^{-1}, whereas the measured coefficient is slightly higher, varying between 0.32–1 cm^{-1}, corresponding to 1.4–4 dB/cm. In the range between 0.8 THz and 1 THz, the dielectric waveguide features similar or lower losses than rectangular hollow-core metallic waveguides.

Further investigation is done with 7 waveguides (produced using D-RIE) of different lengths varying between 11.1 and 33.8 mm. Subsequently, the measured transmission losses (in dB) are linearly fit to the waveguide lengths. The slope of the fitted curve represents the transmission loss per unit length and the offset gives an estimate for the total coupling losses in the waveguides. The calculated aforementioned loss values are tabulated in Table I. Fig. 3. shows only the fitted transmission losses as a function of length. The calculated transmission losses from these 7 waveguides are also in good agreement with the simulated values shown in fig.2.

III. CONCLUSION AND OUTLOOK

Dielectric waveguides are viable alternatives for THz transmission to metallic waveguides due to low losses and broadband nature of operation. As losses of metallic hollow core waveguides increase with increasing frequency, it is expected that optimized dielectric waveguides outperform metal waveguides at frequencies above 1 THz. Furthermore, coupling losses in silicon WGs can be drastically reduced by nearfield coupling to appropriately designed THz emitters and receivers as proposed in [9].

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REFERENCES

[1] E.A.J. Marcatili, “Dielectric Rectangular Waveguide and Directional Coupler for Integrated Optics,” *Bell System Technical Journal*, vol. 48, pp. 2071-2102, 1969

[2] B. Bowden, J. A. Harrington, and O. Mitrofanov, “Low-loss modes in hollow metallic terahertz waveguides with dielectric coatings,” *Appl. Phys. Lett.*, vol. 93, 181104, 2008

[3] H. Han, H. Park, M. Cho, and J. Kim, “Terahertz pulse propagation in a plastic photonic crystal fiber,” *Appl. Phys. Lett.*, vol. 80, pp. 2634–2636, 2002

[4] J. Dai, J. Zhang, W. Zhang, and D. Grischkowsky, “THz time-domain spectroscopy characterization of the far-infrared absorption and index of refraction of high resistivity, float-zone silicon,” *J. Opt. Soc. Am.* B 21, 1379–1386, 2004

[5] Virginia Diodes Inc. (Sep. 4th, 2020), Waveguide Band Designations. [Online]. Available: https://vadiodes.com/VDI/pdf/waveguidechart200908.pdf

[6] R. W. McGowan, G. Gallot, and D. Grischkowsky, “Propagation of ultrawideband short pulses of terahertz radiation through submillimeter-diameter circular waveguides,” *Opt. Lett.*, Vol. 24, pp. 1431–1433, 1999

[7] D. R. Grischkowsky, "Optoelectronic characterization of transmission lines and waveguides by terahertz time-domain spectroscopy," in *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 6, pp. 1122-1135, 2000

[8] A.D.J. Fernandez Olvera, H. Lu, A. C. Gossard, and S. Preu, “Continuous-wave 1550 nm operated terahertz system using ErAs:In(Al)GaAs photo-conductors with 53 dB dynamic range at 1 THz,” *Optics Express*, vol. 25, pp. 29492-29500, 2017

[9] M.F. Abdullah, A.K. Mukherjee, R. Kumar, and S.Preu, “Vivaldi End-Fire Antenna for THz Photomixers,” *J Infrared Milli. Terahz. Waves*, vol. 41, pp. 728–739, 2020

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