A WR-4 Optically-Tunable Waveguide Attenuator with 50 dB Tuning Range and Low Insertion Loss

Zhenguo Jiang[1], Md I. B. Shams[1], Syed M. Rahman[1], Patrick Fay[1], Cheuk-yuE. Tong[2] and Lei Liu[1*]
[1]*University of Notre Dame, Notre Dame, IN 46556, USA*
[2]*Harvard-Smithsonian Center for Astrophysics, Cambridge, MA, USA*
*Contact: lliu3@nd.edu

Abstract—**We report the development of a compact WR-4 (170-260 GHz) optically-tunable waveguide attenuator based on the interaction between electromagnetic waves and photo-induced free carriers in semiconductors. This approach is promising for achieving superior performance, including a ~50 dB tuning range, low insertion loss, lowreturn loss (VSWR), and high tuning speed. Based on full-wave simulation results, an average attenuation level of ~50 dB can be achieved using a 1 mm long Ge absorber at a light intensity of 1 W/cm^2. By employing an E-plane taper design and energy absorption mechanism, return loss lower than -13 dB have been achieved. A prototype attenuator with Si absorber has been implemented using an E-plane split waveguide design. Initial measurement results show that ~14 dB attenuation can be achieved using a single illumination spot. The attenuation level can be improved by increasing the illumination region length employing multiple fibers.**

I. Introduction

Tunable attenuators/modulators are important components in millimeter wave and terahertz (THz) wave systems because many applications require the capability of controlling and varying the power of THz signals. Mechanically tunable waveguide attenuators have been widely used at microwave frequencies[1]. However, mechanically tuning approaches have the disadvantages of low tuning speed and high insertion loss. Although free space optically- and electronically-tunable attenuators have been demonstrated at THz range [2], [3], they have not yet been applied in waveguide configurations due to the challenges associated with feeding light and integrating circuits and components into waveguide structures.

In this paper, we report the development of optically-tunable terahertz waveguide attenuators with superior performance including high tuning speed, low insertion loss, low return loss and large tunable range. This is achieved using E-plane tapered high-resistivity semiconductor chips (absorbers) aligned in the wave propagation direction. The tunability is realized by illuminating the semiconductor chip using fiber-guided IR laser diodefor providing different levels of light intensity. For a prototype demonstration, a WR-4 waveguide attenuator has been designed and fully simulated, presenting lower than 1 dB insertion loss, lower than -15 dB reflection and a tuning range of ~20 dB using a Si absorber. A prototype tunable waveguide attenuator employing Si absorber has been implemented. Initial measurement results show that ~14 dB attenuation can be achieved using a single illuminationspot of ~0.5 mm × 0.5 mm. This tuning range can be further increased to larger than 50 dB usinggermanium (Ge) absorberand/orlonger illumination region based on simulation.

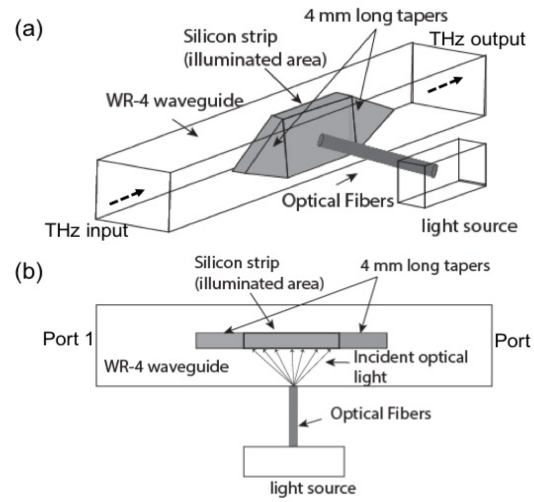

Fig. 1. The structure of a WR-4 tunable waveguide attenuator using photo-induced Si as absorber: (a) 3-D, (b) top view.

II. Optically-TunableWaveguide Attenuator

Photo illuminated/induced semiconductor(e.g. Si, Ge) can be employed for effective attenuation/modulation of THz waves [4]-[6]. In order to design a high performance tunable WR-4 waveguide attenuator, a physics-based modelfor a photo induced Si wafer was established at the frequency range of 170-260 GHz. Calculation resultsusingthis physics-based model[7] indicate that at low light intensity, energy absorption dominates the attenuation process. When the light intensity is higher (e.g., larger than 2 W/cm^2) the semiconductor becomes very conductive and reflection dominates. The absorption-dominated attenuation with a lower light intensity can be adopted for developing tunable THz waveguide attenuators with superior performance.Based on this mechanism, a WR-4 tunable waveguide attenuator has been designed and simulated. In order to minimize the reflection, the proposed tunable waveguide attenuator employs an E-plane high resistivity semiconductor chip (e.g. Si or Ge) aligned in the wave propagation direction as an absorber, as shown in fig. 1(a). To further reduce reflection for optimum matching, the silicon absorber is chosen to have a thickness of only ~70 μm with both ends trimmed to be 4 mm long taper structures. As shown in fig. 1(b), the center region of the absorber is designed to be approximately 1 mm long for a maximum attenuation of~20 dB (for Si absorber). This region will be illuminated by optical fiber guided laser diode through the narrow wall of the waveguide.

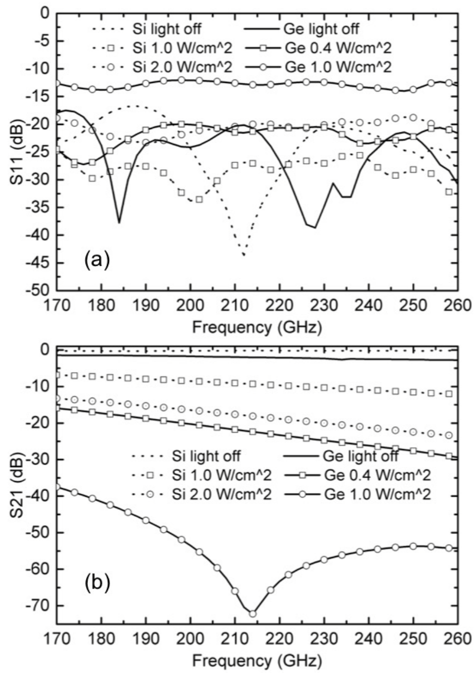

Fig. 2. Simulated s-parameters of the proposed WR-4 waveguide attenuator at different levels of illuminating light intensity.

The s-parameters of tunableattenuators implemented with Si and Ge absorbers have been simulated in HFSS at different levels of light intensity, as shown in fig. 2. Over the entire WR-4 frequency band, the attenuation can be continuously tuned with a maximum averaged value of ~20 dBfor Si based attenuator. More than 50 dB attenuation level can be achieved using Ge absorber at a lower illuminatingintensity due to Ge material's longer free carrier lifetime and higher carrier mobility. Owing to the E-plane tapered structure, THz reflection at the interface can be minimized resulting in a low simulated insertion loss.Taking into account the ohmic loss introduced by the waveguide walls, the overall device insertion loss is estimated to be lower than 1 dB for Si based absorber.Additionally, the return loss without light is lower than -13 dB owning to the absorption-dominated mechanism. The proposed attenuator can be easily implemented using E-plane split waveguide design and scaled to higher frequencies.

III. Prototype and Initial Measurement

A prototype Si based WR-4 tunable waveguide attenuator based on the above design has been implemented as shown in fig. 3 (a). A Si chip with taper structure and 1 mm long absorbing region was fabricated and installed to the block. The absorbing region was designed to be illuminated by two optical fibers through the holes. Initial measurements of tunable attenuation performance with only one illuminating spot have been performed and the results are shown in fig. 3 (b).During this testing, the Si chip was illuminated by a fibercoupled 808 nm laser diode under various biasing currents (light power levels). The quick initial test was performed using a WR-5 VDI source and a WR-10 Erickson powermeter. Therefore, the measured transmission curves show strong standing wave effect due to the reflection at both ends of the attenuator. It can be seen that tunable attenuation with a tuning range of up to ~14 dB can be achieved using a single illuminating spot of ~0.5 mm × 0.5 mm. We expect that ~ 20 dB tuning range can be achieved with a device VSWR smaller than 1.2 by using lower levels of light intensityand two illuminating spots. This result demonstrated that the proposed approach was promising for realizing THz tunable waveguide attenuator with high performance.

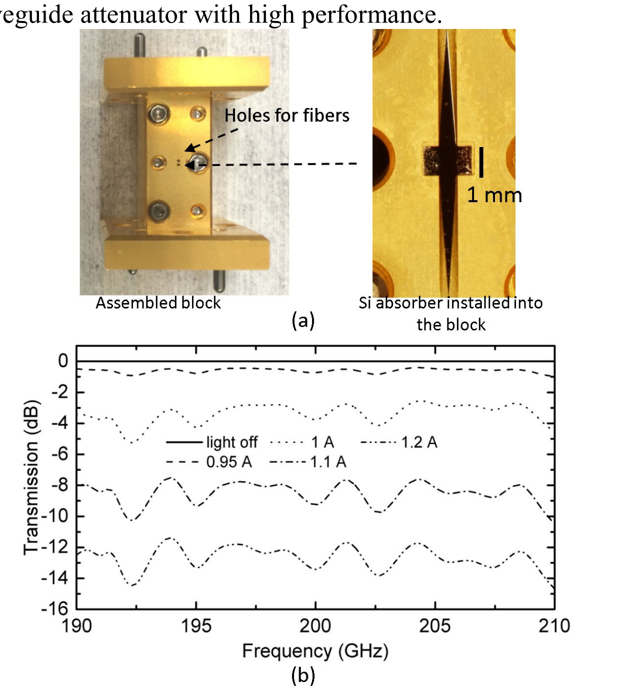

Fig. 3. (a) Pictures of the prototype WR-4 tunable waveguide attenuator. (b) Initial measurement results of the tunable attenuation operation (THz transmission at various driving currents) for the prototype attenuator.

IV. Conclusions

A novel approach for developing optically-tunable terahertz waveguide attenuators has been reported. A prototype high-speed tunable waveguide attenuator at WR-4 band has been designed and simulated. Based on the full-wave simulation results, an average of 20 dB attenuation level with an insertion loss lower than 1 dB can be achieved using Si absorber. Higher attenuation level can be obtained using longer absorber or semiconductor materials (e.g. Ge) with longer free carrier life-time and higher carrier mobility. A tuning speed of ~30 kHz has been estimated based on the linear recombination coefficient in silicon. Initial measurement results show that ~14 dB attenuation can be achieved using a single spot (~0.5 mm × 0.5 mm area)for illumination.Improved attenuator with longer absorber region employing 4 illuminating fibers (2 mm absorber region length) that can achieve ~50 dB attenuation will be fabricated and fully characterized soon.

Acknowledgment

This project is partially supported by NSF grant ECCS 1202452. The authors would like to thank NDnano at

University of Notre Dame and Harvard-Smithsonian Center for Astrophysics.

REFERENCES

[1] R. Sundararajn, E. Peterson, and R. Nowlin, "Attenuators." *Wiley Encyclopedia of Electrical and Electronics Engineering*, 1999.

[2] L-J. Cheng, and L. Liu, "Optical modulation of continuous terahertz waves towards cost-effective reconfigurable quasi-optical terahertz components." *Optics express*, vol. 21, no. 23, pp. 28657-28667, 2013.

[3] B. Sensale-Rodriguez et al., "Broadband graphene terahertz modulators enabled by intraband transitions." *Nature communications* 3, pp. 780, 2012.

[4] M. I. B. Shams et al., "Approaching real-time terahertz imaging with photo-induced coded apertures and compressed sensing." *Electronics Letters*, vo. 50, no. 11, pp. 801-803, 2014.

[5] M. Itrat B. Shams et al., "A Terahertz Reconfigurable Photo-Induced Fresnel-Zone-Plate Antenna for Dynamic Two-Dimensional Beam Steering and Forming," *International Microwave Symposium*, Phoenix, Arizona, 2015.

[6] A. Kannegulla et al., "Photo-induced spatial modulation of THz waves: opportunities and limitations," *Optics express*, vol. 23, no. 25, pp. 32098-32112, 2015.

[7] N. V. Smith, "Classical generalization of the Drude formula for the optical conductivity." *Physical Review B*, vol. 64, no. 15, pp. 155106, 2001.