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Simulation of Thermal Phase Shift in THz Substrate Integrated All-Dielectric Waveguide

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Abstract

One of the priority technological challenges of our time is to increase the speed of wireless data transfer. The solution of this problem is associated with the transition to terahertz frequencies of the carrier signal. To create real practical terahertz data transfer systems, it is necessary to develop devices that can change the radiation pattern in a non-mechanical way. One possible solution is to use phased antenna arrays, in which radiation is applied to each antenna element with the required pre-tuned phase. However, the development of a phase shift device in the terahertz range still remains largely an unsolved problem. In this paper, we present the results of simulation the phase shift of a terahertz wave in the integrated metamaterial waveguide made of high-resistance silicon substrate with increasing of its temperature. The obtained phase shift is sufficient to make it possible to use these phase shifters in developing terahertz integrated phased antenna array. These devises will be a part of the future next-generation terahertz data communication system with a high data transfer rate.

Keywords: terahertz photonics, photonic integrated circuit, dielectric waveguide, thermal phase shifting.

1. Introduction

Increasing the wireless data transfer rate has become one of the main technological challenges of our time. This need is associated with significant progress in many advanced scientific and technical fields such as machine learning and big data processing (Zhang et al., 2018), augmented reality (Chaccour and Saad, 2020) internet of things (Khalid et al., 2019), and live streaming (Nallappan et al., 2018). The development of these areas is primarily associated with an increase in wireless traffic rate (Elayan et al., 2018). To solve this problem, a transition to a shorter wavelength range, in particular, to the terahertz (THz) region, is required.

Despite the fact that THz radiation is strongly absorbed by water vapor contained in the air, the use of this range seems justified due to the presence of transparency windows at frequencies around 150 GHz and also in the range from 200 to 300 GHz with low atmospheric losses (ITU-R, 2012). Using these windows will allow to create data transmitting systems that operate indoors, like WiFi, but with a much higher data transfer rate. Lab prototype of system at 0.2375 THz for transmitting data over 20 m at a data rate of 100 Gbps have already been demonstrated (Koenig et al., 2013).

It should be also noted that metal waveguides widely used for millimeter waves applications are not acceptable in THz range, because they demonstrate a rather high insertion loss in this range. An obvious solution under such conditions is the use of all-dielectric waveguides (Gao et al., 2019). To create real practical THz data transfer systems, it is necessary to develop devices that can rapidly change the radiation pattern in a non-mechanical way. The possible solution is to use phased antenna arrays, in which radiation is applied to each antenna element with the required pre-tuned phase (Mailloux, 2017). However, before manufacturing and subsequent measurement of the characteristics of a phased antenna array, it is necessary to simulate it in order to optimize the parameters of its components, such as the length of the waveguide phase shifters, the geometric parameters of the coupling elements and others.

2. State of the art

Based on what has been said in the previous chapter, it can be concluded that the phase shift in THz wave-guiding structures is an important scientific and practical problem. In the optical range, a delay lines are used for these purposes, which make it possible to create a discrete phase shift depending on the length of the delay line (Liu et al., 2002). Another method is based on heating part of the waveguide with an electrode (for example, a metal (Wang et al., 2019) or graphene (Yan et al., 2017)) and changing the refractive index of the waveguide in accordance with the thermo-optic effect.

At the same time, despite the recognition by the scientific community of the importance of this research area, the analysis of the literature shows that previously published papers about the simulating and experimental study of the phase shift in dielectric waveguides by heating relate mainly to the telecommunication range (1.55 μm). There are also a limited number of publications devoted to the study of the thermo-optic effect in the terahertz range. In particular, on the basis of experiments on studying the change of the resonant frequency of whispering gallery–mode resonators, the results of measurements of the thermo-optic coefficient of silicon at frequencies of 459 and 659 GHz are presented (Vogt et al., 2018). To the best of our knowledge, such methods at the frequency of 150 GHz have not yet been demonstrated.

In our previous work presented at the symposium last year (Seliverstov et al., 2022a), we described in detail the concept of creating a THz photonic integrated phased antenna array based on metamaterial silicon substrate with perforations. This paper is a continuation of the first one. Here we present the results of simulation the phase shift of a THz wave in the integrated all-dielectric waveguide made of high-resistance silicon substrate with increasing of its temperature. The obtained phase shift is sufficient to make it possible to use these phase shifters in developing terahertz integrated phased antenna array. Together with the achievements outlined in our previous article, this result confirms the possibility of creating practical high-speed terahertz data transfer systems using the proposed approach.

The structure of this article is organized as follows. The introduction 1 describes the motivation and relevance of the study. The chapter 2 presents the current state of the research area, as well as an overview of the previous works of our research group, including a report on the related topic presented at the conference last year. The chapter 3

Figure 1. Flowing of a wave mode from one waveguide to another closely placed waveguide of the interferometer.

describes the basic principles and methods by which the simulation was carried out. The chapter 4 presents the results and their interpretation, as well as gives a brief plan of our further investigations. The article ends with a conclusion 5 with a description of the main results of our study.

3. Materials and Methods

A 3D model was used to study the dependence of the heating temperature on the voltage applied to the heater. The heater was a planar structure of contact-pads and a narrow rectangular titanium wire located on the surface of a high-resistance silicon substrate. The wire width was 50 μm. Its length was 20 mm. The thickness was 1 μm. The ambient temperature was set equal to 293 K. The simulation results showed that the substrate heats up almost uniformly at given applied voltage.

The waveguide width was chosen to be equal to the wavelength in the material, which is 585 μm. To create an effective medium on both sides of the waveguide, a periodic square-lattice structure of openings was used. The thickness of the high-resistance silicon substrate with a permittivity of 11.7 was 400 μm. The holes radius was 36.5 μm. The distance between the centers of the holes was 165 μm. Simplified, the physics of a metamaterial waveguide can be described as follows. The lattice of openings creates an efficient medium with a lower permittivity than of the Si core of the waveguide. The wave propagates along the core and is reflected from the boundaries of the waveguide created by the metamaterial cladding due to total internal reflection, similar to how it happens in an optical fiber. A detailed description of the characteristics of the employed effective medium waveguide structure can be found in the paper (Seliverstov et al., 2022b). A taper was used as a coupling element.

To study the dependence of the phase shift of the wave propagating along the waveguide on temperature, a 2D electromagnetic model with a Mach-Zehnder interferometer was used. The input power was fed into the interferometer through a directional coupler. The length of this coupler had a such value that the power was divided in half between the input ports of the interferometer. The output directional coupler connected to the output ports of the interferometer had the same length. In the model, the permittivity of one arm of the interferometer varied in accordance with the change in temperature. The permittivity of the other arm remained unchanged. Next, the fraction of power coming to one of the ports of the output coupler was calculated depending on the length of the interferometer arms. Based on the periodicity of this dependence, a conclusion about the value of required optical path length to change the phase by a given value at any given temperature was made.

The simulation was carried out under the assumption that the electric field does not change too fast compared to the phase changes. In other words, a significant change in the magnitude of the electric field occured at lengths much greater than the wavelength. In this case, the electic field $\vec{E}$ can be presented as a product:

$$\vec{E} = \vec{E}_1 e^{-i\vec{k}_1\vec{r}}, \tag{1}$$

here $\vec{E}_1$ is the envelope function, $\vec{k}_1$ is a wave vector, $\vec{r}$ is the position vector, i is the imaginary unit. The governing equation of the model that has been solved for $\vec{E}_1$ during the simulation can be written as:

$$\begin{gathered} \nabla \times \left(\nabla \times \vec{E}_1 - i\vec{k}_1 \times \vec{E}_1\right) - \\ -i\vec{k}_1 \times \left(\nabla \times \vec{E}_1 - i\vec{k}_1 \times \vec{E}_1\right) - k_0^2 \varepsilon_r \mu_r \vec{E}_1 = 0, \end{gathered} \tag{2}$$

where $k_0 = 2\pi/\lambda_0$ with λ_0 the vacuum wavelength, μ_r is the relative permeability, and ε_r is the relative permittivity of the medium. It should be noted, that the Eq. 2 can be solved for $\vec{E}_1$ only if $\vec{k}_1$ is known. Its value is equal to $k_1 = \beta_{||}$, where $\beta_{||}$ is the longitudinal propogation constant. It was analytically calculated using a formula:

$$\left(n\frac{\omega}{c}\right)^2 = \beta_{||}^2 + \beta_{\perp}^2, \tag{3}$$

where n is the refractive index of the waveguide, ω is the angular frequency of the elecrtomagnetic wave, c is the vacuum speed of ligth, and $\beta_{\perp}$ is the transverse propogation constant. The last one value was obtained by solving the eigenmode problem for each port of the model.

4. Results and Discussion

The electric field distribution indicated power overflow between two closely located waveguides of the interferometer is presented on the Fig. 1. The results of the simulation dependances of the temperature and phase shift on the applied voltage to the heater are presented on Fig. 2. As one can see, the temperature as well as the phase shift increasing with the increase of the voltage obeying the quadratic law as was expected.

In particular, the simulation shows that when the substrate is heated by 100 K, to change the phase of the wave passing through the waveguide by π, the required waveguide length l should be about 73 mm. This result is in a good agreement with the following simple analytical estimation:

$$l = \frac{\Delta\varphi}{2\pi} \cdot \frac{\lambda_0}{\Delta n} = \frac{\Delta\varphi}{2\pi} \cdot \frac{\lambda_0}{\alpha \Delta T}, \tag{4}$$

Figure 2. Obtained dependences of the waveguide temperature and phase shift on the voltage applied to the heater.

here $\Delta\varphi = \pi$ is the required phase shift, $\lambda_0 = 2$ mm is the vacuum wavelength, Δn is the change of the refractance index of the meduim by heating, $\Delta T = 100$ K is the temperature increase, $\alpha = 1.37 \cdot 10^{-4}$ K^{-1} is the thermo-optic coefficient of Si obtained from the paper (Vogt et al., 2018). It should be noted that the indicated value of the thermo-optic coefficient was obtained at a radiation frequency of 459 GHz. However, it was noted in the papers (Li, 1980; Frey et al., 2006) that the value of the Si thermo-optic coefficient at frequencies below 1 THz slightly decreases with decreasing frequency.

The obtained simulation results can be relatively easily verified experimentally. The scheme of the experiment may be as follows. With the help of two waveguide sections, a Mach-Zehnder interferometer with a source and a detector of terahertz radiation will be assembled. To calibrate the interferometer, a phase shifter is installed in one of its arms instead of the waveguide section. Further, when the waveguide is heated in one of the arms of the interferometer, a signal is measured by the detector, from which the phase shift is determined according to the obtained calibration.

This scheme will also allow us to study the rate of phase change by heating. To do this, the heater will be biased by alternating current, the frequency of which will change, and the signal will be measured by a fast detector. The response time of the system will be determined by the frequency of the bias current, at which the ratio of the signal amplitude to the amplitude of the bias current will be 2 times less than at a low frequency current. At the moment, the efforts of the research group are aimed at creating an experimental setup for carrying out the described experiment.

5. Conclusions

Despite the colossal efforts of leading scientific and technological groups around the world, the goals of creating an ultra-high speed terahertz data transfer system are still largely unachieved. In this article, we have outlined our latest results on the way of solving this problem. In particular, the article presents the following achievements:

1. The concept of phase shifting in a terahertz metamaterial silicon waveguide using heating is demonstrated.
2. The phase change in the range from 0 to 2π is obtained.
3. The possibility of using the proposed approach in practical applications is confirmed.

Further plans for ongoing research are related to the experimental demonstration of the proposed phase shifting mechanism, as well as the development of real devices based on the obtained results.

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References

Chaccour, C. and Saad, W. (2020). On the ruin of age of information in augmented reality over wireless terahertz (thz) networks. *GLOBECOM 2020-2020 IEEE Global Communications Conference*, pages 1–6.

Elayan, H., Amin, O., Shubair, R. M., and Alouini, M. S. (2018). Terahertz communication: The opportunities of wireless technology beyond 5g. *2018 International Conference on Advanced Communication Technologies and Networking (CommNet)*, pages 1–5.

Frey, B. J., Leviton, D. B., and Madison, T. J. (2006). Temperature-dependent refractive index of silicon and germanium. *Optomechanical technologies for Astronomy. SPIE*, 6273:790–799.

Gao, W., Yu, X., Fujita, M., Nagatsuma, T., Fumeaux, C., and Withayachumnankul, W. (2019). Effective-medium-cladded dielectric waveguides for terahertz waves. *Optics express*, 27(26):38721–38734.

ITU-R (2012). ITU-R. Recommendation P. 676–9. Attenuation by atmospheric gases. Technical report, International Telecommunication Union.

Khalid, N., A., A. N., and Akan, O. B. (2019). Statistical characterization and analysis of low-thz communication channel for 5g Internet of Things. *Nano Communication Networks*, 22:100258.

Koenig, S., Lopez-Diaz, D., Antes, J., Boes, F., Henneberger, R., Leuther, A., and Kallfass, I. (2013). Wireless sub-thz communication system with high data rate. *Nature photonics*, 7(12):977–981.

Li, H. H. (1980). Refractive index of silicon and germanium and its wavelength and temperature derivatives. *Journal of Physical and Chemical Reference Data*, 9(3):561–658.

Liu, Y., Yang, J., and Yao, J. (2002). Continuous true-time-delay beamforming for phased array antenna using a tunable chirped fiber grating delay line. *IEEE Photonics Technology Letters*, 14(8):1172–1174.

Mailloux, R. J. (2017). *Phased array antenna handbook*. Artech house.

Nallappan, K., Guerboukha, H., Nerguizian, C., and Skorobogatiy, M. (2018). Live streaming of uncompressed hd and 4k videos using terahertz wireless links. *IEEE Access*, 6:58030–58042.

Seliverstov, S., Svyatodukh, S., Prokhodtsov, A., and Goltsman, G. (2022a). Simulation of terahertz photonic integrated phased array antenna. *Proceedings of the 34th European Modeling and Simulation Symposium (EMSS 2022)*.

Seliverstov, S., Svyatodukh, S., Prokhodtsov, A., Prikhodko, A., Shurakov, A., Sheveleva, E., and Goltsman, G. (2022b). Transmission and reflection spectra of si wave-guiding structures for thz integrated photonics. *Infrared, Millimeter-Wave, and Terahertz Technologies IX*, 12324:229–234.

Vogt, D. W., Jones, A. H., and Leonhardt, R. (2018). Thermal tuning of silicon terahertz whispering-gallery mode resonators. *Applied Physics Letters*, 113(1):011101.

Wang, Z., Dong, G., Yuan, S., Chen, L., Wu, X., and Zhang, X. (2019). Voltage-actuated thermally tunable on-chip terahertz filters based on a whispering gallery mode resonator. *Optics Letters*, 44(19):4670–4673.

Yan, S., Zhu, X., Frandsen, L. H., Xiao, S., Mortensen, N. A., Dong, J., and Ding, Y. (2017). Slow-light-enhanced energy efficiency for graphene microheaters on silicon photonic crystal waveguides. *Nature Communications*, 8(1):14411.

Zhang, C., Ota, K., Jia, J., and Dong, M. (2018). Breaking the blockage for big data transmission: Gigabit road communication in autonomous vehicles. *IEEE Communications Magazine*, 56(6):152–157.