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Simulation of terahertz photonic integrated phased array antenna

Sergey Seliverstov[1,*], Sergey Svyatodukh[1,2], Aleksey Prokhodtsov[1] and Gregory Goltsman[1,2]

[1]Moscow State Pedagogical University, 1/1 Malaya Pirogovskaya Str., Moscow, 119991, Russia
[2]National Research University Higher School of Economics, 34 Tallinskaya st., Moscow, 123458, Russia

[*]Corresponding author. Email address: sv.seliverstov@mpgu.su

Abstract

A rapid development of wireless technologies is observed over the last years. This is due to the growing need of increasing the data transfer rate between mobile devices. To achieve this goal, a transition to higher frequencies is required. In this sense, the terahertz (THz) range seems to be very promising. The THz communication systems should be equipped with devices capable of rapidly controlling the output radiation pattern. One of the most hopeful approaches is the use of phased array antennas. This paper presents the results of simulations of phased array antenna on a platform of metamaterial silicon with cylindrical perforations. For the first time, the dependence of the radiation pattern of a phased antenna array on the phase difference between antenna elements at a frequency of 150 GHz was simulated. The dimensions of perforations are much smaller than the wavelength in the material. The local heating of the substrate was chosen as the phase adjustment method. The obtained results confirm the possibility of practical implementation of the proposed concept for the development of widely used new generation devices with higher data transfer rate.

Keywords: Phased array antenna, THz range, photonic integrated circuits, metamaterials

1. Introduction

In recent years, a growth in the need of increasing the wireless data transfer rate is clearly observed. This is due to the current progress in areas such as information applications based on the processing of big data (Zhang et al., 2018), as well as augmented reality technologies (Chaccour and Saad, 2020). An increase in the data transfer rate is possible due to the transition to higher radiation frequencies, namely, to the sub-terahertz and terahertz range. The efforts of many leading scientific teams around the world are aimed at developing such systems. Some positive results have already been obtained. In particular, the work (Corre et al., 2019) demonstrates the operation of a practical sub-terahertz 6G wireless communication system with a data transfer rate of up to 1 Tbit per second, which has the potential to further increase the data transfer rate in the case of a transition to terahertz (THz) signal frequencies.

At the same time, the use of THz radiation in such systems is associated with a number of difficulties. First of all this is due to the strong absorption of the THz radiation in the atmosphere, primarily by water vapor. For this reason, for example, it is necessary to place THz telescopes in the areas with an arid climate (Nyman et al., 2010) or in stratosphere (Krabbe, 2000), or best of all in space (Smirnov et al., 2012). There are some transparency windows in the sub-THz and THz ranges (Boronin et al., 2014). However, this remains a significant problem that limits the ability of THz systems to transmit data over long distances. In practice, this means that such systems can be used for indoor wireless networks, like Wi-Fi, but not for signal transmission over long distances, at least for terrestrial applications.

Another important problem is that metal waveguides used in THz systems are characterized by strong absorption. The solution to this problem can be the use of dielectric waveguides. In particular, it was shown in (Gao et al., 2019) that losses in dielectric waveguides can be several orders of magnitude smaller than in metal ones. In addition, in some cases, dielectric waveguides are easier to manufacture and also allow the integration of several elements on a single platform, which greatly facilitates the operation and repair of such THz systems.

In Section 2 we present a brief description of the literature on the current progress in investigation and fabrication of the THz dielectric waveguides, coupling elements and phased antenna arrays. Section 3 provides details of the design and simulation of the integrated structures under study based on the platform of silicon substrate with perforations. Section 4 confirms the possibility of practical implementation of the proposed concept of the THz phased antenna array in view of the simulation results. Section 5 states the main conclusions of the research and describes the future work.

2. State of the art

Many leading scientific and technical teams are working on the development of THz dielectric waveguides. For example, in (Malekabadi et al., 2014) a silicon strip waveguide with a low absorption coefficient is demonstrated. A taper was used as a matching element in this work. Among the shortcomings, the difficulty of integrating this type of waveguide with other elements should be mentioned. This is due to the peculiarities of its manufacturing technology. Also, the working band of this waveguide is relatively small. An alternative to this is a photonic crystal waveguide (Yu et al., 2019). But it demonstrates even narrower operation bandwidth as well as relatively high dispersion.

It should also be noted that in order to create practical THz data transfer systems, it is necessary to use devices that allow fast non-mechanical changing of the radiation pattern. This problem is difficult to solve without the use of phased array antennas. The phased array antennas is a device consisting of an array of individually excited antennas with their own specified amplitude and relative phase. With the help of phase shifters or discrete delay lines, the output radiation pattern of the array can dynamically change depending on the relative phase of each element of the array. By themselves, phased array antennas have been demonstrated many times in the optical and millimeter frequency bands (Kossey et al., 2018; Leng et al., 2021; Lu et al., 2018). At the moment, there are two main implementations of phased antenna arrays in the THz range. The first method (Lu et al., 2018) uses an optical photonic integrated circuit matched to a femtosecond laser. This method has many advantages including obtaining high power at the output from the antenna and using a well-developed optical technology. However, the use of such systems greatly increases the cost and complicates antenna systems, which makes it impossible for widespread use. In the second method (Guo et al., 2018) an array of phase-locked millimeter sources is used. The phase of these sources can be reconstructed relative to each other. The main advantage of this method is the use of available powerful millimeter sources, the frequencies of which can be multiplied up to THz. But it should be noted that the problem of such a phased array antennas is the need of synchronization of the various sources so that they have a well-defined relative phase, which is necessary for beam steering. This is the key limiting factor in the design of large 2D phased array antennas.

Another problem is the choice of a technique for obtaining a phase shift. In the optical range, the common solution is use of delay lines, which make it possible to create a discrete phase shift depending on the length of the delay line (Liu et al., 2002). Another method consists of heating a portion of the waveguide with an electrode (for example, a metal (Wang et al., 2002) or graphene (Yan et al., 2017)). This changes the refractive index of the waveguide due to the thermo-optical effect (Kim et al., 2015). As for the THz range, some methods for phase changing presented in literature. The first type includes the use of liquid crystals (Yang et al., 2018; Ji et al., 2019; Lin et al., 2011). The main advantages of liquid crystal phase-shifting devices are their small size, insensitivity to polarization, and low transmission losses. However, the technological difficulties of creating such devices and the complexity of integration with photonic integrated circuits make them unsuitable candidates for widespread practical application. Another promising phase restructuring method is based on the use of graphene. In (AzimBeik et al., 2018), phase modulators made of graphene with contact pads are demonstrated. Such devices are small and easy to fabricate by the well-known method of transferring graphene onto a substrate. The use of the thermo-optical method for tuning the refractive index in the THz range was demonstrated in (Vogt et al., 2018). This method of phase shifting seems to be the simplest one for creating the phased array antennas.

It should be noted that simulation of waveguide structures has already been carried out earlier and was published in the literature and presented at the conference in the previous years. For example, in the paper (Elmanova et al., 2021) a model of an integrated photonic device based on an O-ring resonator and loop waveguide reflector operated at telecom wavelength (1550 nm) was demonstrated. However, the study of the possibility of creating a fully integrated phased array antenna on an all-dielectric metamaterial substrate at a frequency of 150 GHz has not been carried out to date. In this work, we simulate the phased array antennas based on a perforated high-resistance silicon platform. The dimensions of the perforations are in the deep subwavelength range which makes it possible to

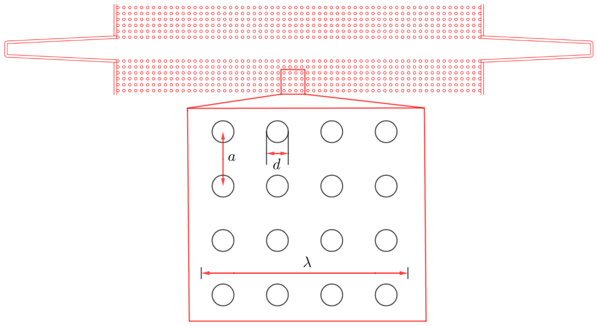

Figure 1. Waveguide topology defined by a square array of cylindrical perforations in a high-resistance silicon substrate. Taper is the possible coupling element.

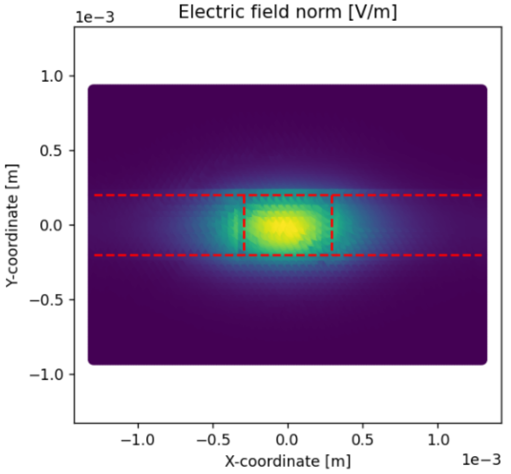

Figure 2. Field distribution inside the waveguide for given parameters. The red dotted line marks the boundaries of the substrate and the central part of the waveguide.

provide a wide bandwidth with low dispersion. The phase adjustment is carried out by local heating of the substrate on both sides of the waveguide. This approach has the potential for widespread practical application due to the ease of fabrication, operation, and repair of THz devices based on it.

3. Materials and Methods

The waveguides and integrated horns were formed by a periodic perforations in a high-resistance silicon substrate. A square lattice was used as a periodic structure (see Fig. 1). The refractive indices of the effective medium for TE and TM polarizations in the case of filling the space inside the perforations with air were calculated according to the theory presented in (Subashiev and Luryi, 2006):

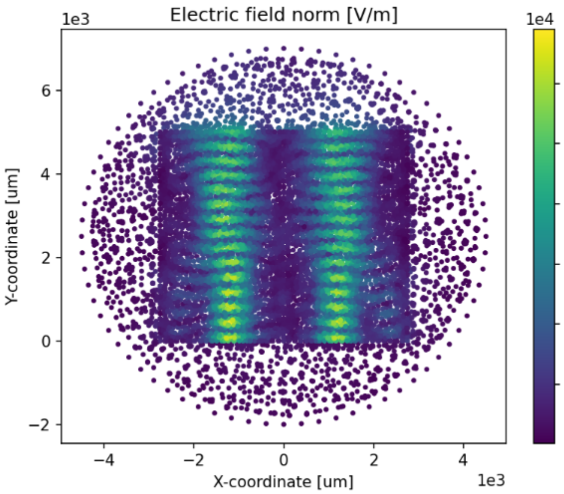

Figure 3. Electric field distribution in the central section of the phased array antenna with a phase difference at the input ports equal to $3\pi/2$.

$$n_{TE} = n_{Si}\sqrt{\frac{1+k+\varepsilon_{Si}(1-k)}{1-k+\varepsilon_{Si}(1+k)}}, \tag{1}$$

$$n_{TM} = n_{Si}\sqrt{\frac{k}{\varepsilon_{Si}}+1-k}, \tag{2}$$

$$k = \frac{\pi d^2}{4a^2}. \tag{3}$$

Here $n_{Si} = (\varepsilon_{Si})^{0.5}$ is the reflectance index of the high resistive silicon, d is the diameter of perforations, a is the distance between centers of perforations, and k is the filling factor. During the simulation, the TE polarization of radiation was studied. The following structure parameters were set in the simulation. The permittivity of high-resistance silicon was 11.7, the diameter of cylindrical perforations was 73 μm, the distance between centers of perforations was 165 μm, the silicon substrate thickness was 400 μm, the waveguide effective width was 585 μm, and the simulation frequency was 150 GHz. For the given configuration of simulated structures, a single fundamental TE_1 mode was realized in them (see Fig. 2). The calculated value of the refractive index for TE polarization was equal to 3.

A phased antenna array consisting of 2 elements was simulated. The smallest distance between the elements of the phased antenna array (between the edges of the horns at the opposite end of the substrate with respect to the input ports) was 200 μm. The radius of the sphere filled with air everywhere around the substrate with the structure under study was 4500 μm in the model. During the simula-

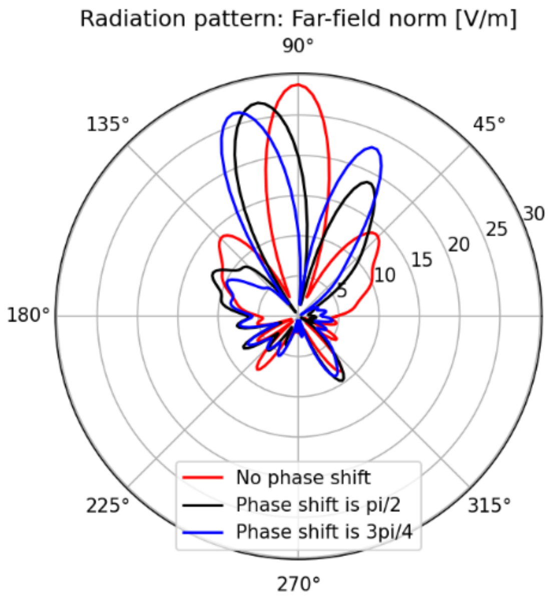

Figure 4. Dependence of the radiation pattern of phased array antenna at a frequency of 150 GHz on the phase difference of the signal radiation at each element of the array.

tion, for the calculated field distribution at the boundary of the structure with the implemented wave mode and given boundary conditions, the following differential equation was numerically solved:

$$\nabla \times \frac{1}{\mu_r}\left(\nabla \times \vec{E}\right) + k_0^2\left(\frac{i\sigma}{\omega\varepsilon_0} - \varepsilon_r\right)\vec{E} = 0. \tag{4}$$

Here $\vec{E}$ is the electric field vector, μ_r and ε_r are the relative magnetic and dielectric permittivities, σ is the specific conductivity, ω is the cyclic frequency, ε_0 is the dielectric constant, k_0 is the wave number, and i is the imaginary unit.

4. Results and Discussion

As can be seen from Fig. 4, it is possible to obtain a deviation of the central lobe of the phased array antenna pattern by about 20 degrees with a radiation phase difference at the input ports equal to $3\pi/4$. The field distribution obtained in the structure for this phase difference is shown in Fig. 3.

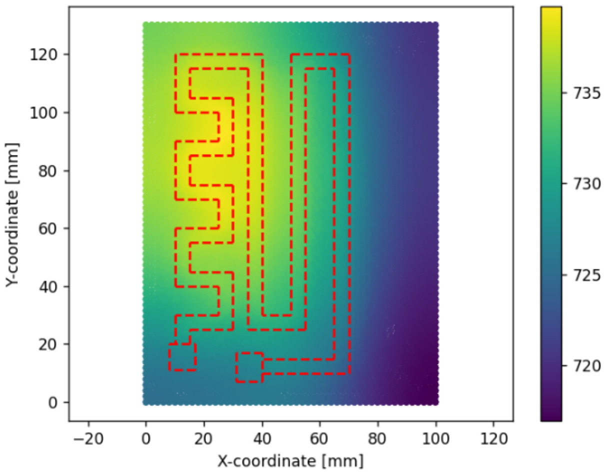

Figure 5. Temperature distribution on the substrate when it is heated by a heating element powered by 25 V direct current. The contour of the heating element is indicated by a dotted red line. The temperature of the environment (the air around the substrate) was 300 K in the simulation.

In this research, the phase adjustment will be carried out by local heating of the substrate on both sides of the waveguide. The simulation results show that when a planar heating element is powered by 25 V direct current, it is possible to increase the effective temperature of the waveguide by 400 K (see Fig. 5), which will allow the phase to be changed by

$$\Delta\varphi = \frac{l}{\lambda_0} \times 2\pi\Delta n = \frac{l}{\lambda_0} \times 2\pi\alpha\Delta T. \tag{5}$$

Here $l = 20$ mm is the length of the waveguide, $\lambda_0 = 2$ mm is the wavelength of radiation in vacuum, $\alpha = 1.37\cdot10^{-4}$ K^{-1} is the thermooptic coefficient of silicon (Vogt et al., 2018). The calculations give the result of $\Delta\varphi = 3.44$ rad. Thus, the calculations show that it will be possible to cover the entire required range of phase tuning on the array elements.

These results show that a phased antenna array on a pure THz metamaterial photonic integrated circuit can be realized using metal heaters as phase shifters. Such a device can be equipped with rather simple coupling system, in comparison with the optical range. This platform will have small geometric dimensions, and also a relatively low cost, which is important for the widespread practical applications.

5. Conclusions

The presented results of simulation confirm the possibility of practical implementation of the proposed concept of photonic phased array antennas on a perforated high-resistance silicon substrate platform with active phase adjustment by local heating of the substrate. These phased array antennas can be used to create devices for controlling the parameters of the output THz radiation beam, which will be the main components of the next-generation communication systems. At the same time, it should be noted that the thermal method of phase adjustment has some limitations associated primarily with the relatively low speed of operation. Further work will be related to the search for alternative possibilities for fast phase adjustment. The experimental verification of the simulation results is also planned.

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