Conference materials
UDC 537.876
DOI: https://doi.org/10.18721/JPM.153.268

Simulation of terahertz photonic integrated antenna

S. V. Seliverstov [1]✉, S. S. Svyatodukh [1, 2], A. I. Prokhodtsov [1], G. N. Goltsman [1, 2]

[1]Moscow State Pedagogical University, Moscow, Russian Federation;

[2] HSE Moscow Institute of Electronics and Mathematics, Moscow, Russian Federation

✉ seliverstovsv@mail.ru

Abstract. The rapid development of wireless devices, that take place over the last decade, is associated with an increase in the need to achieve a higher data transfer rate. To achieve this goal, it is necessary to use the terahertz (THz) range. The vast majority of THz devices (no matter bulk or integrated) require fast, non-mechanical beam shape control, which is generally defined as the ability to manipulate the shape of the radiation pattern in the desired way. But it is hard to implement without the use of photonic integrated phased array antennas. In this paper, the possibility of the creation of photonic integrated antenna which is a basic element of such a system is investigated and confirmed. The antenna is based on a platform of metamaterial silicon with perforations, the dimensions of which are in the deep subwavelength region, which makes it possible to provide a wide bandwidth with low dispersion.

Keywords: Phased array antennas, THz range, photonic integrated circuits, coupling devices, metamaterials

Funding: Russian Science Foundation Grant 21-72-10119.

Citation: Seliverstov S. V., Svyatodukh S. S., Prokhodtsov A. I., Goltsman G. N., Simulation of terahertz photonic integrated antenna, St. Petersburg State Polytechnical University Journal. Physics and Mathematics. 15 (3.2) (2022) 370–374. DOI: https://doi.org/10.18721/JPM.153.268

Материалы конференции
УДК 537.876
DOI: https://doi.org/10.18721/JPM.153.268

Моделирование терагерцовой фотонной интегральной антенны

С. В. Селиверстов [1]✉, С. С. Святодух [1,2], А. И. Проходцов [1], Г. Н. Гольцман [1,2]

[1] Московский педагогический государственный университет, г. Москва, Россия;

[2] Московский институт электроники и математики НИУ ВШЭ, г. Москва, Россия

✉ seliverstovsv@mail.ru

Аннотация. Бурное развитие беспроводных устройств, наблюдающееся в последнее десятилетие, связано с увеличением потребности в достижении более высокой скорости передачи данных. Для достижения этой цели необходимо использовать терагерцовый (ТГц) диапазон. Подавляющее большинство ТГц-устройств (независимо от того, объемные они или интегрированные) требуют быстрого немеханического управления диаграммой направленности выходного излучения. Эту задачу трудно реализовать без использования фотонных интегрированных фазированных антенных решеток. В данной работе исследуется и подтверждается возможность создания фотонной интегральной антенны, которая является базовым элементом такой системы. В основе антенны лежит платформа из метаматериального кремния с перфорациями, размеры которых находятся в глубоко субволновой области, что позволяет обеспечить широкую полосу пропускания при малой дисперсии.

Ключевые слова: фазированная антенная решетка, ТГц-диапазон, фотонные интегральные схемы, устройства связи, метаматериалы

Финансирование: Грант РНФ № 21-72-10119.

Ссылка при цитировании: Селиверстов С. В., Святодух С. С., Проходцов А. И., Гольцман Г. Н. Моделирование терагерцовой фотонной интегральной антенны // Научно-технические ведомости СПбГПУ. Физико-математические науки. Т. 15. № 3.2. С. 370–374. DOI: https://doi.org/10.18721/JPM.153.268

Introduction

In recent years, there has been a significant increase in the need to achieve higher wireless data transfer rates. This is due to progress in such fields as big data processing [1] and applications related to augmented reality [2]. This can be achieved by using higher signal frequencies. The most promising is the terahertz (THz) range. It has already been demonstrated that the data transfer rate can be increased to 1 Tb per second and higher due to the transition to the THz frequency region [3]. At the same time, the transition to THz radiation is associated with a number of difficulties. First of all, this is a high absorption of THz radiation in the atmosphere, which limits the use of such systems over long distances. Because of this, in particular, the most powerful telescopes in the THz range are placed in the stratosphere [4] or in space [5]. There are some transparency windows in the THz range, but they still do not allow signals to be transmitted over long distances [6]. In practice, this means that such THz data transfer systems can be used inside buildings, like Wi-Fi, but with orders of magnitude higher data transfer rate. Another problem is the large signal loss during radiation propagation in metal waveguides (on the order of several dB per cm [7]). The solution to this problem can be the use of dielectric waveguides, which are characterized by much lower values of absorption of THz radiation [8].

A large number of leading scientific teams around the world are working on their development, and to date, some success has been achieved. In particular, paper [9] demonstrates a silicon strip waveguide optimized for two frequency ranges: 90–140 GHz and 140–220 GHz. In this work, authors achieved low losses in the waveguide and small values of dispersion, but at the same time, this type of waveguides is poorly integrated with other components on the same chip due to its design features. These limitations can be avoided by using waveguides formed in a single dielectric photonic crystal, made on a silicon substrate platform. For example, in [10], a photonic crystal waveguide with an isosceles triangular lattice based on a silicon slab at a frequency of 0.3 THz was demonstrated. Unfortunately, this type of waveguide is characterized by a relatively low bandwidth and high dispersion. These problems greatly complicate the use of such waveguide technologies in real practical applications. In addition, the development of THz communication systems is associated with the need for a rapid (non-mechanical) change of the radiation pattern of THz emitters. But it’s hard to implement without using of phased antenna arrays [11], in which this change is carried out due to phase adjustment.

Phased array antennas in the THz range have been actively investigated in the last few years and some promising results have already been achieved. In particular, a phased array antenna based on the platform of optical photonic integrated circuits matched with femtosecond laser was demonstrated. Laser radiation undergoes a phase change like in conventional optical phased antenna arrays. The conversion of the laser infrared radiation into THz is carried out by mixing it with the tunable laser radiation using a photodiode [12]. It should be noted that the use of femtosecond laser greatly increases the cost and complexity of this system, which makes it impossible for widespread use. Another approach is based on employing of an array of millimeter-wave sources with their subsequent synchronization [13, 14]. However, synchronization of a large number of sources is an extremely difficult task both in implementation and in compact integration, and also has a rather high cost. This greatly complicates its practical application.

To solve this problem, it is necessary to develop a simple and effective technology for creating THz phased array antennas. In this article the possibility of creation of the photonic integrated horn based on a platform of metamaterial silicon with perforations is studied. It will be the key component for the future THz phased array antennas available for widespread use. The dimensions of the perforations are in the deep subwavelength region which makes it possible to provide a wide bandwidth with low dispersion.

Materials and Methods

The structures of the waveguides and the integrated horn were specified by a lattice of periodic through holes in a high-resistance silicon substrate. A square lattice of holes was chosen (see Fig. 1). The permittivity of the obtained effective medium for TE (ε_{TE}) and TM (ε_{TM}) polarizations was calculated by the following formulas [15]:

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

$$\varepsilon_{TM} = k + \varepsilon_{Si}(1-k), \tag{2}$$

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

where ε_{Si} is the relative permittivity of silicon, k is the filling factor. Note that the above formulas are valid for the case of filling the space inside the holes with air with a permittivity equal to 1.

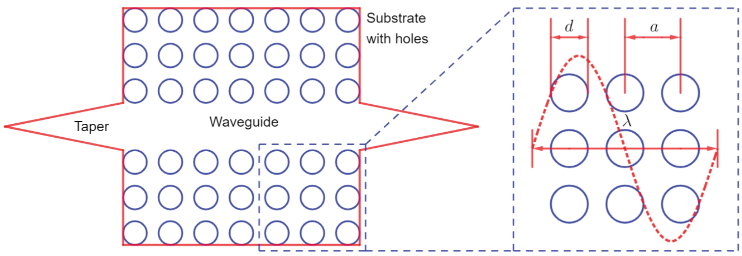

Fig. 1. Topology of the waveguide given by a square lattice of cylindrical perforations (through holes) in a high-resistance silicon substrate
A taper can be used as a coupling element

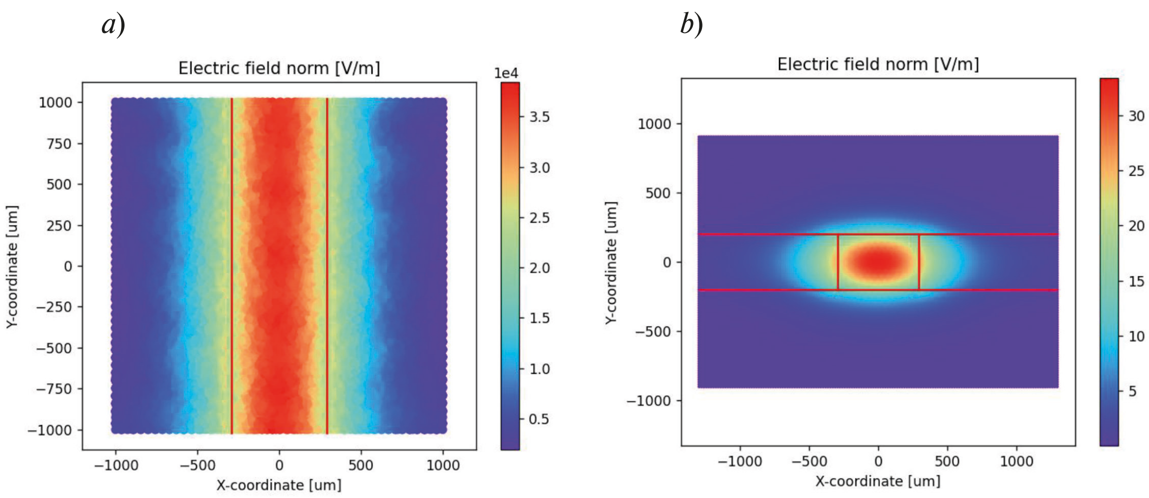

Fig. 2. Electric field distribution in the waveguide structure:
top view (a); end view (b)

The following parameters were set in the simulation. The substrate thickness was 400 μm. The radius of the air sphere around the substrate was 3500 μm. The frequency was 150 GHz. The permittivity of silicon was 11.7. The diameter of holes was 73 μm. The distance between centers of perforations was 165 μm. The waveguide effective width was 585 μm. The last value equals to the wavelength of the radiation in silicon. The permittivities of the obtained effective medium for TE and TM polarizations calculated by formulas (1) and (2) were equal to 9 and 10 respectively.

A single TE_1 mode was implemented for the given configuration of the antenna with this set of parameters (see Fig. 2).

The power of radiation supplied to the incoming ports was equal to 1 W in 3D models. The boundary conditions were defined at the edge of the substrate where the input ports were located and specified on the sphere bounding the model in such a way that it completely scattered the radiation incident on it. The given model was discretized into finite elements (tetrahedra). After that, the following equation was numerically solved for the obtained mesh of elements to find the space distribution of the electric field vector:

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

where **μ** is the relative permeability, ε is the relative permittivity, σ is the specific conductivity, ε_0 is the dielectric constant, k_0 is the vacuum wave number, ω is the angular frequency of radiation, *i* is the imaginary unit. Iterations of discretization into a smaller elements and recalculations were carried out until the required accuracy was achieve.

Results and Discussion

During the simulation of the integrated horn radiation pattern, the length of the input waveguide was fixed at 1000 μm and the flare angle of the horn was varied. One can see from the Fig. 3,*b* that the flare angle of about 10 degrees turned out to be optimal for providing the required shape of the radiation pattern and a sufficient area of overlap by the radiation beams from different elements of the proposed phased array antenna. The field distribution in the structure at the given angle is shown in Fig. 3,*a*.

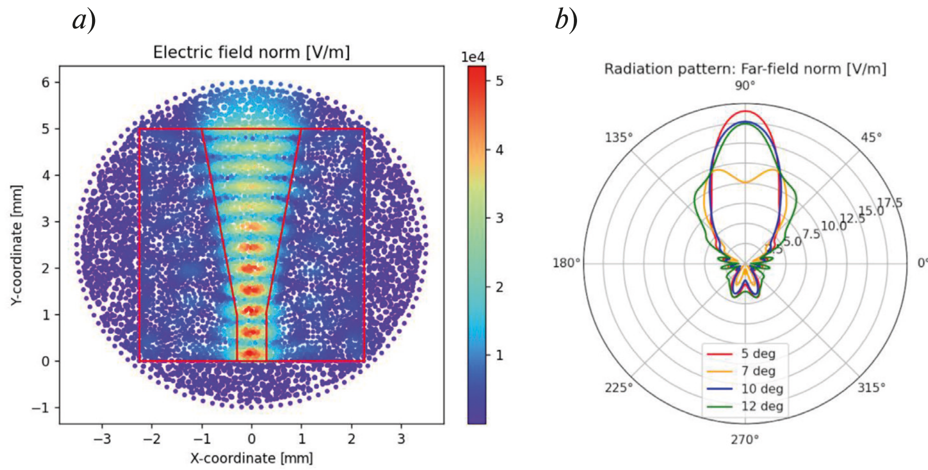

Fig. 3. Simulation results of the integral horn: distribution of the electric field in the central plane of the structure (*a*); radiation pattern of the integral horn at different values of its flare angle (*b*)

Conclusion

The presented results of simulation confirm the possibility of practical implementation of the proposed concept of integrated horn antennas on a perforated high-resistance silicon substrate platform. These antennas will be used to create devices for controlling the parameters of the output THz radiation beam, which will be the main components for next-generation data transfer systems. It should be noted that the fabrication of the simulated structures will be implemented using standard CMOS technologies, which will allow their mass production.

REFERENCES

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

2. **Chaccour C., Saad W.** (2020, December). On the ruin of age of information in augmented reality over wireless terahertz (THz) networks. In GLOBECOM 2020-2020 IEEE Global Communications Conference (pp. 1-6). IEEE.

3. **Corre Y., Gougeon G., Doré J. B., Bicaпs S., Miscopein B., Faussurier E., Saad M., Bader F.** (2019, March). Sub-THz spectrum as enabler for 6G wireless communications up to 1 Tbit/s. In 6G Wireless Summit.

4. **Krabbe A.** (2000, June). SOFIA telescope. In Airborne Telescope Systems (Vol. 4014 276-281). International Society for Optics and Photonics.

5. **Pilbratt G. L., Riedinger J. R., Passvogel T., Crone G., Doyle D., Gageur U., Heras A. M., Jewell C., Metcalfe L., Ott S. Schmidt M.,** (2010). Herschel Space Observatory-An ESA facility for far-infrared and submillimetre astronomy. Astronomy & Astrophysics, 518, L1.

6. **Boronin P., Petrov V., Moltchanov D., Koucheryavy Y., Jornet J. M.,** (2014). Capacity and throughput analysis of nanoscale machine communication through transparency windows in the terahertz band. Nano Communication Networks, 5(3), 72–82.

7. **Frankel M. Y., Gupta S., Valdmanis J. A., Mourou G. A.** (1991). Terahertz attenuation and dispersion characteristics of coplanar transmission lines. IEEE Transactions on microwave theory and techniques, 39(6), 910–916.

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

9. **Malekabadi A., Charlebois S. A., Deslandes D., Boone F.** (2014). High-resistivity silicon dielectric ribbon waveguide for single-mode low-loss propagation at F/G-bands. IEEE Transactions on Terahertz Science and Technology, 4(4), 447–453.

10. **Yu X., Sugeta M., Yamagami Y., Fujita M., Nagatsuma T.,** (2019). Simultaneous low-loss and low-dispersion in a photonic-crystal waveguide for terahertz communications. Applied Physics Express, 12(1), 012005.

11. **Fu X., Yang F., Liu C., Wu X., Cui T. J.,** (2020). Terahertz Beam Steering Technologies: From Phased Arrays to Field-Programmable Metasurfaces. Advanced optical materials, 8(3), 1900628.

12. **Lu P., Steeg M., Kolpatzeck K., Dülme S., Khani B., Czylwik A., Stöhr A.,** (2018, September). Photonic assisted beam steering for millimeter-wave and THz antennas. In 2018 IEEE Conference on Antenna Measurements & Applications (CAMA) (pp. 1-4). IEEE.

13. **Tousi Y., Afshari E.** (2014). A high-power and scalable 2-D phased array for terahertz CMOS integrated systems. IEEE Journal of Solid-State Circuits, 50(2), 597–609.

14. **Sengupta K., Hajimiri A.,** (2015). Mutual synchronization for power generation and beam-steering in CMOS with on-chip sense antennas near 200 GHz. IEEE Transactions on Microwave Theory and Techniques, 63(9), 2867-2876.

15. **Subashiev A. V., Luryi S.,** (2006). Modal control in semiconductor optical waveguides with uniaxially patterned layers. Journal of lightwave technology, 24(3), 1513.

THE AUTHORS

SELIVERSTOV Sergey
sv.seliverstov@mpgu.su
ORCID: 0000-0001-9624-5325

PROKHODTSOV Aleksey
alexabrest@yandex.ru
ORCID: 0000-0001-5159-3043

SVYATODUKH Sergey
sergey.svetodux@gmail.com
ORCID: 0000-0001-9436-6641

GOLTSMAN Gregory
goltsman10@mail.ru
ORCID: 0000-0002-1960-9161

Received 08.08.2022. Approved after reviewing 11.08.2022. Accepted 12.08.2022.