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Terahertz integrated H-plane bend: simulation and experimental investigation

A.K. Kozhukhovsky[1]✉, S.V. Seliverstov[1,5], S.S. Svyatodukh[2,4], G.N. Goltsman[2,3]

[1] Moscow Pedagogical State University, Moscow, Russia;

[2] National Research University Higher School of Economics, Moscow, Russia;

[3] Russian Quantum Center, Moscow, Russia;

[4] National University of Science and Technology "MISIS" (MISIS), Moscow, Russia;

[5] Russian Technological University (MIREA), Moscow, Russia

✉ ak_kozhukhovskii@student.mpgu.edu

Abstract. The usefulness of using terahertz radiation has been proven in practice. Recently we have studied how to manufacture and use silicon waveguides and obtained insignificant signal loss. Final purpose is creating the integrated photonic circuit which needs not only straight waveguide sections, which we have done before, but bend structures with minimal signal loss, which we present in this paper. The insertion loss of the structure we made is ~0.178 dB ± 0.081 dB at frequency of 145.5 GHz. This result is simulated and experimentally verified. This once again proves that it is possible to create a full-fledged design that has a lot of practical applications. It is a future of communication systems, medicine and artificial intelligence development. Eventually we will be able to create a physical structure that will be a hardware implementation of an artificial neural network with extremely low power consumption.

Keywords: terahertz photonics, waveguide, photonic integrated circuit, H-plane bend

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Интегрированный изгиб в H-плоскости в терагерцовом диапазоне: моделирование и экспериментальное исследование

А.К. Кожуховский[1]✉, С.В.Селиверстов[1,5], С.С.Святодух[2,4], Г.Н.Гольцман[2,3]

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

[2] Национальный исследовательский университет «Высшая школа экономики», Москва, Россия;

[3] Российский Квантовый Центр, Москва, Россия;

[4] Национальный Исследовательский Технологический Университет МИСиС, Москва, Россия;

[5] Российский технологический университет (МИРЭА), Москва, Россия

✉ ak_kozhukhovskii@student.mpgu.edu

Аннотация. Полезность использования терагерцового излучения доказана на практике. Недавно мы изучали изготовление и использование кремниевых волноводов и получили незначительные потери сигнала. Конечная цель — создание интегральной фотонной схемы, для которой нужны не только прямые волноводные секции, которые мы делали ранее, но и изогнутые конструкции с минимальными потерями сигнала, которые мы представляем в этой статье. Вносимые потери изготовленной нами структуры составляют примерно ~0,178 дБ ± 0,081 дБ на частоте 145,5 ГГц. Данный результат смоделирован и экспериментально проверен. Это еще раз доказывает, что можно создать полноценную интегральную структуру, имеющую множество практических применений. Это будущее систем связи, медицины и развития искусственного интеллекта. В конце концов мы сможем создать физическую структуру, которая будет аппаратной реализацией искусственной нейронной сети с предельно малым энергопотреблением.

Ключевые слова: терагерцовая фотоника, волноводы, фотонная интегральная решетка, изгиб волновода

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Introduction

The interest of big data processing is actual in our world. The processing of big data is directly related to the process of its transmission. The latest advances in the field of wired data transmission are the development of principles and design options for terabit low-power fiber optic interconnect lines of modern data centers. We have demonstrated a system with a total throughput of at least 4 Tbit/s with specific energy consumption of no more than 0.1 nJ/bit. In fact, actual energy consumption may be even lower. Achieving comparable wireless data transmission speeds is an urgent scientific and practical task. This is possible through the use of THz radiation, occupying the range 0.1–10 THz.

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To make a well-functioning and in-demand end device, we analyzed examples of the use of the THz range. We have to say that the basic problem of THz range is absorption by water vapor contained in the surrounding air [1], but it has many practical applications over short distances. Using the advantages of THz radiation will increase the speed of wireless internet [2] and will also contribute to the development of such areas as augmented reality [3] and high resolution live-streaming [4]. But not only for the internet sphere we are making such a device. Another example is a short-range THz radar (operating at distances of the order of several tens of meters), which can operate with high resolution in conditions of limited visibility (a large amount of fog or dust in air, etc.) when other classical systems such as a lidar or optical stereo camera cannot be used. Such a system was also demonstrated previously [5]. It can be used for delivery-robots and autopiloting of transport. All of this can serve as an example of the prospects for using the THz range. Our goal is to make a special device in the form of a photonic integrated circuit, to start to use all opportunities of THz range. For these purposes, we will need not only straight sections of the waveguide, but also bends, without which we will not be able to make a practical device.

Materials and Methods

In this paper we present the results of simulation and measuring of insertion loss of a H-plane bend based on a THz waveguide made on the basis of a high resistivity silicon substrate. The simulation model was conducted to solve the following well-known equations:

$$\begin{aligned} \Delta\vec{E} - \frac{n^2}{c^2}\frac{\partial^2\vec{E}}{\partial t^2} = 0, \\ \Delta\vec{H} - \frac{n^2}{c^2}\frac{\partial^2\vec{H}}{\partial t^2} = 0, \end{aligned} \tag{1}$$

where Δ is the Laplace operator, n is the refractive index of the medium, and c is the speed of light in vacuum.

The finite element method was used for simulation. A screenshot of the model in the used modeling environment is presented in the inset to Fig. 3, *a*. The model specified a H-plane bend of the waveguide with a turning radius of 3000 μm. The waveguide width is 585 μm. The material used was silicon with a dielectric constant of 11.9. The bend has two tapers with lengths of 3500 μm. Tapers are surrounded by metallic boundaries (as in the experiment we put them into the metal waveguides). The condition "Perfect-E" was imposed on these metal surfaces in the model (means that we assume the metallic waveguide as an ideal conductor). The parameters of the metallic waveguide are following: the height (along the Z-axis as shown in Fig.3,*a*) equals to 800 μm, the width (which is along the Y-axis) equals to 1600 μm and the length equals to 3500 μm. In the model, the tapers were installed in such a way that their axes coincided with the axes of the metal waveguides into which they were inserted. Wave ports were specified at the input and output of metal waveguides. The model of H-plane bend with tapers and metal waveguides was surrounded by an air box, on the faces of which the "Radiation" condition was set (means that this surface does not reflect radiation, but transmit it completely into surrounding space). We simulated the S21 parameter of the bend in the frequency range from 120 to 170 GHz with steps of 5 GHz.

The experimental structure consisted of an H-plane bend based on a cladding-less silicon waveguide, as well as two straight waveguide sections integrated with an effective medium that allows radiation to propagate along the waveguide due to total internal reflection [6, 7]. In the experiment, the structure was placed in a plastic holder in such a way that the plastic did not intersect the effective medium, and the input and output tapers were located as close as possible to the center of the metal waveguides connecting the structure under study to the source and detector. A Schottky diode was used as a detector, and a backward wave oscillator was used as a radiation source. Effective medium was determined by a grid of perforations. The parameters of the grid structure are the same as were in the simulation model. The study used multiple identical fabricated structures to improve measurement accuracy. All measurements were carried out at the frequency of 145.5 GHz, since the geometry of the waveguides is optimized for this frequency.

We did not use an effective medium in this simulation as we wanted to study the bend itself. In addition, in this work, the effective medium performed only an auxiliary function in order to ensure the passage of radiation through the L-shaped stiffener of the structure.

Results and Discussion

The measurement and simulation results presented in Fig.3, *a* confirmed our expectations. We observe that the signal loss decreases with increasing frequency. The nature of the dependence of transmittance on frequency has a simple qualitative explanation. As the frequency decreases, the effective refractive index of the waveguide mode decreases because the wave power of the evanescent mode, which is not localized in the core of the waveguide, increases. We carried out corresponding modeling, the results of which are presented in Fig. 2. On it we see the dotted red line showing frequency dependence of an effective refractive index of the waveguide. The field distributions in the cross section of the waveguide are presented at two frequencies (126.5 and 145.5 GHz). The field distributions in the band plane on a logarithmic scale at the same frequencies are presented in Fig. 1.

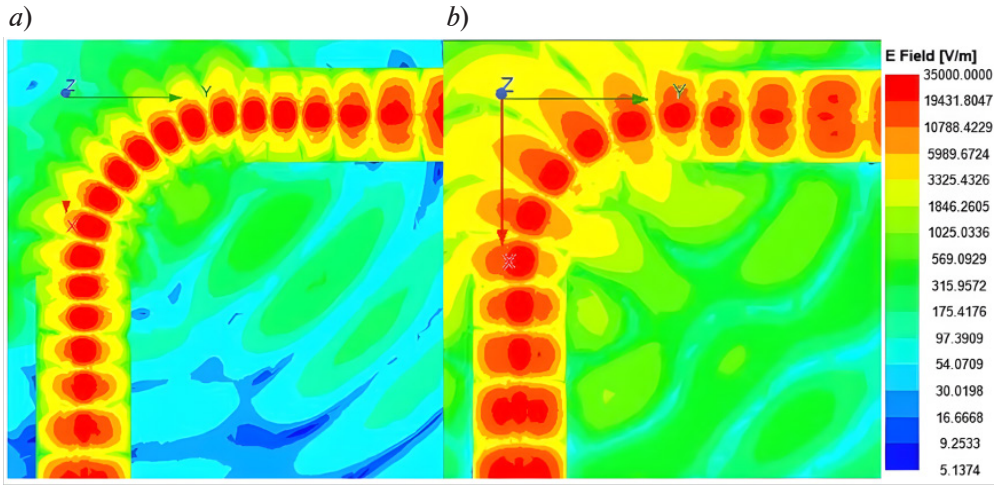

Fig. 1. Picture of scattered field at 145.5 GHz (*a*) and 126.5 GHz (*b*)

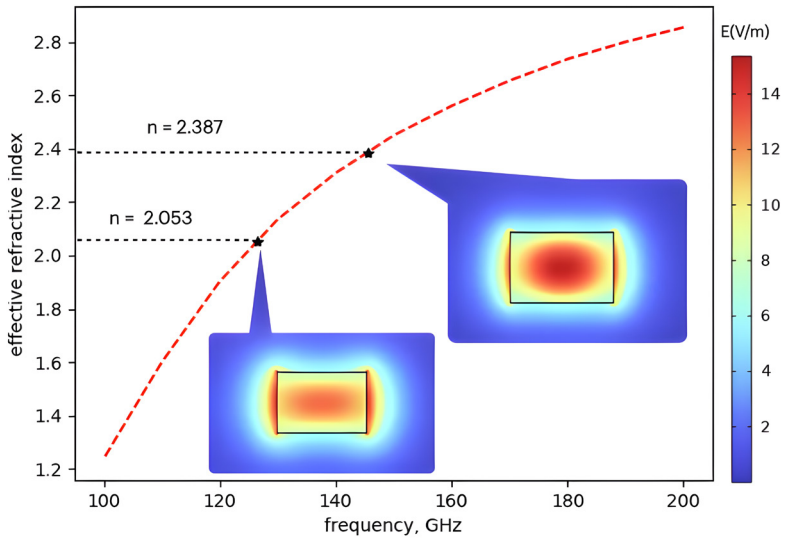

Fig. 2. Dependence of effective refractive index on frequency
The distributions of the fields of wave modes in the cross section of the waveguide at frequencies of 126.5 and 145.5 GHz are also presented

Radiation at the edges of the waveguide in the region of rotation is more strongly scattered into the surrounding air at low frequencies. As a result, less power passes through the waveguide at lower frequency. A possible solution to this problem is to increase the turning radius. We plan to carry out relevant research in the near future.

The plot in Fig. 3, *a* shows the dotted red line corresponding to the simulation result and the black bar with the blue point at the center of it. The blue point corresponds to the averaged measured value of all measurements of a number of manufactured H-plane bends at the frequency of 145.5 GHz. The bar shows the experimental error. The value of this error equals ±2.1% which is a good result. Fig. 3, *a* also shows that the discrepancy between the simulation and measurements is within the experimental error. Fig. 3, *b* shows the photo of the structure under study. To make this picture clearly the white contour was applied around the structure. The picture does not give us an opportunity to see the effective medium surrounding the core, that's why we showed it in the inset. The dotted white lines show the borders of the core.

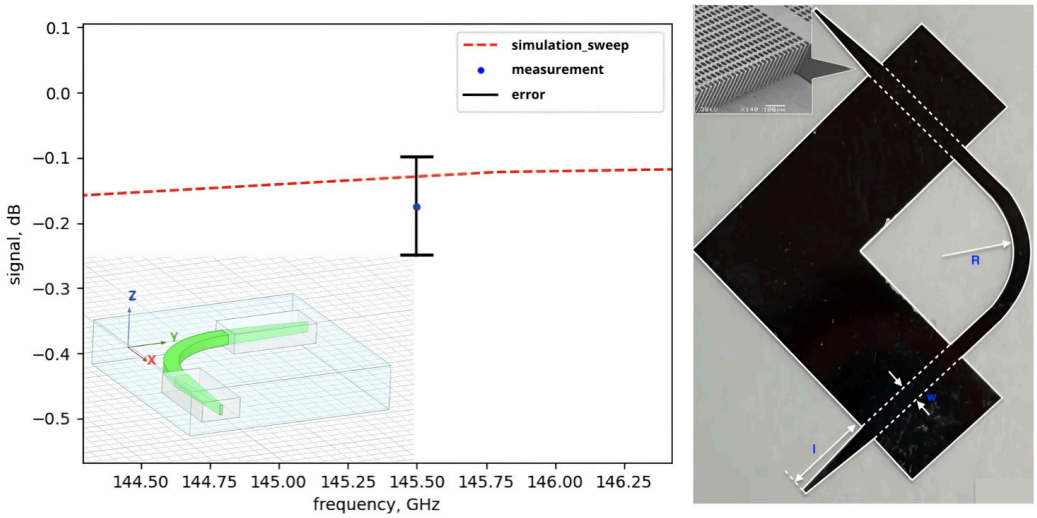

Fig. 3. Frequency dependence of S21 parameter and appearance of model in simulation environment at the bottom of the picture (*a*) Photo of manufactured structure, *w* (width of core) = 585 μm, *R* (radius of curvature) = 3000 μm, *l* (length of tapers) = 3500 μm (*b*)

We attribute the slight discrepancy between simulation and experimental investigation to possible defects in the structure that arose during its manufacture, as well as a possible small displacement of the matching tapers relative to the geometric center of the rectangular metallic waveguides when placing the structure in the holder. This displacement is associated with the 3D printing error of about 0.1 mm, which was used for the holder manufacturing. The measurement results could also be influenced by standing waves arising between the elements of the experimental setup. However, the fact is that H-plane bend works quite well and can be further improved in the future.

Conclusion

Creating the H-plane bend structure is another step towards creating a full-fledged photonic integrated circuit, which will allow us to exploit the full potential of the terahertz range in practical applications. Based on the results of the research conducted by our team, as well as the data that we obtained and published in our previous articles [6–8], we can confidently conclude that it is possible to create full-fledged practical THz devices for a number of applications using domestically produced materials. This achievement not only demonstrates the capabilities of our own production, but also allows us to lead the development of next-generation photonic technologies. The potential of integrated photonic circuits in the THz range is huge, they can be used in high-speed wireless communications, modern sensing and imaging systems. Using domestic materials, we can provide greater control over quality and supply chain, reduce dependence on foreign suppliers and improve the reliability of our products.

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THE AUTHORS

KOZHUKHOVSKY Alexey K.
ak_kozhukhovskii@student.mpgu.edu
ORCID: 0009-0003-7927-2171

SVYATODUKH Sergey S.
ssvyatodukh@hse.ru
ORCID: 0000-0001-9436-6641

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

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

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