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Optimization of a prism coupler for a THz photonic integrated metamaterial Si waveguide: simulation and experiment

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Abstract. The use of terahertz radiation to create data transmission systems with ultra-high transfer rate still remains a kind of *terra incognita* of our time. The main difficulty in using terahertz radiation for these purposes is associated with high losses in standard metal waveguides at these frequencies. One of the possible solutions is the use of all-dielectric waveguides. So, the coupling waveguides of this type with other devices is an actual and scientifically significant task. In this paper we present the results of simulating and measuring the insertion loss of a coupling prism interface for a terahertz waveguide based on metamaterial high resistive silicon platform. The obtained S_{21} parameter value of −0.5 dB for a coupler apex width of 90 μm and a coupler length of 3500 μm at frequency of 0.15 THz is in good agreement with the experimentally measured one. These devises will be a part of the future next-generation terahertz data communication system with a high data transfer rate.

Keywords: terahertz photonics, waveguide coupling, photonic integrated circuit, metamaterial waveguide

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Оптимизация согласующей призмы для ТГц фотонного интегрального метаматериального кремниевого волновода: моделирование и эксперимент

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Аннотация. Использование терагерцового излучения для создания систем связи со сверхвысокой скоростью передачи данных до сих пор остается своего рода *terra incognita* нашего времени. Основная трудность использования терагерцового излучения для этих целей связана с большими потерями в стандартных металлических волноводах на этих частотах. Одним из возможных решений является использование полностью диэлектрических волноводов. Таким образом, согласование волноводов данного типа с другими устройствами является актуальной и научно значимой задачей. В этой статье мы представляем результаты моделирования и измерения вносимых потерь согласующего интерфейса на основе призмы для интегрированного терагерцового волновода на платформе метаматериального высокоомного кремния. Полученное значение S21-параметра в -0.5 дБ для ширины острия призмы в 90 мкм и длины призмы в 3500 мкм на частоте 0.15 ТГц хорошо согласуется с экспериментальными данными. Эти устройства станут частью будущей терагерцовой системы передачи данных нового поколения с высокой скоростью передачи данных.

Ключевые слова: терагерцовая фотоника, согласование волноводов, фотонная интегральная схема, метаматериальный волновод

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Introduction

Latest advances in such modern fields as internet of things [1] or big data processing [2] have led to the need to dramatically increase the rate of wireless data transmission. The solution to this problem is possible by transfer to higher frequencies of the carrier signal. In particular, the use of terahertz (THz) range of the electromagnetic radiation spectrum looks promising. For the effective use of radiation in this range, it is necessary to solve a number of problems related primarily to the fact that THz radiation is strongly absorbed by water vapor contained in the atmosphere. There are some transparency windows in the THz water vapor absorption spectrum, but their use makes it possible to create a THz data transfer system that operates only at short distances (about the size of a room) [3]. These systems will operate like Wi-Fi, but will have a much higher data transfer rate. For example, a such system with data transfer rate reaches of up to 1 Tbit/s has been previously demonstrated [4].

Such systems should be equipped with compact receiving and transmitting devices, the basic element of which is a THz waveguide. The main challenge here is that standard waveguides (including coplanar waveguides, metallic microstrip lines, hollow metallic waveguides) used for similar tasks today are not acceptable in THz range, because they demonstrate a rather high insertion loss in this range [5–7]. An obvious solution under such conditions is the use of all-dielectric waveguides [8]. In this regard, matching waveguides of this type with other devices is an actual and scientifically significant task.

Materials and Methods

In this paper we present the results of simulating and measuring the insertion loss of a coupling interface based on a prism geometry for a THz waveguide formed on metamaterial high resistive silicon (HRSi) platform. Waveguide structures designed for a frequency of 0.15 THz were fabricated on the HRSi substrate of 400 μm thick. The spread in thickness at different points of the substrate does not exceed 12.5%. To create an effective medium, a square grid of through openings was created on both sides of the waveguide core. The grid period was 165 μm. The hole radius was 36.5 μm. The waveguide width was taken equal to the wavelength in the material, which was 585 μm. The width is the distance between the tangents to the holes in the upper part of the substrate on both sides of the waveguide core. Details can be found in our previous articles [9, 10]. The parameters of the waveguide and the effective medium around it were chosen in such a way that a single TE_1 radiation mode could propagate inside it. We used the finite element method in the simulation.

The process of manufacturing of the experimental samples consisted of applying a Cr mask, plasma-chemical etching of Si unprotected by the mask (so called Bosch Process [11]), and subsequent separation of the substrate into individual chips. A photograph of the fabricated sample obtained with an electron microscope is shown in Fig. 1,*b*. In the experiment, the fabricated waveguide sample with prism couplers on both sides of the waveguide was installed in a metal holder, which made it possible to place the coupler exactly in the center of a rectangular hollow metal waveguide. A backward wave oscillator was used as a radiation source. A THz calibrated calorimeter-style power meter was used as a detector.

Results and Discussion

We fabricated a set of waveguide samples of various lengths l_i to estimate the insertion loss for energy leakage into free space, characterized by the corresponding loss per unit length α and the insertion loss of input and output of radiation into the waveguide through the coupling prism L_m. The total insertion loss, expressed in decibels, was $L_{tot,i} = 2L_m + \alpha l_i$. For two samples of the waveguide of length l_1 and l_2 with the corresponding measured losses $L_{tot,1}$ and $L_{tot,2}$, the value of α can be calculated by the formula: $\alpha = (L_{tot,2} - L_{tot,1})/(l_2 - l_1)$. At the same time, the value of L_m can be calculated by the formula: $L_m = (L_{tot,1}l_2 - L_{tot,2}l_1)/(2(l_2 - l_1))$.

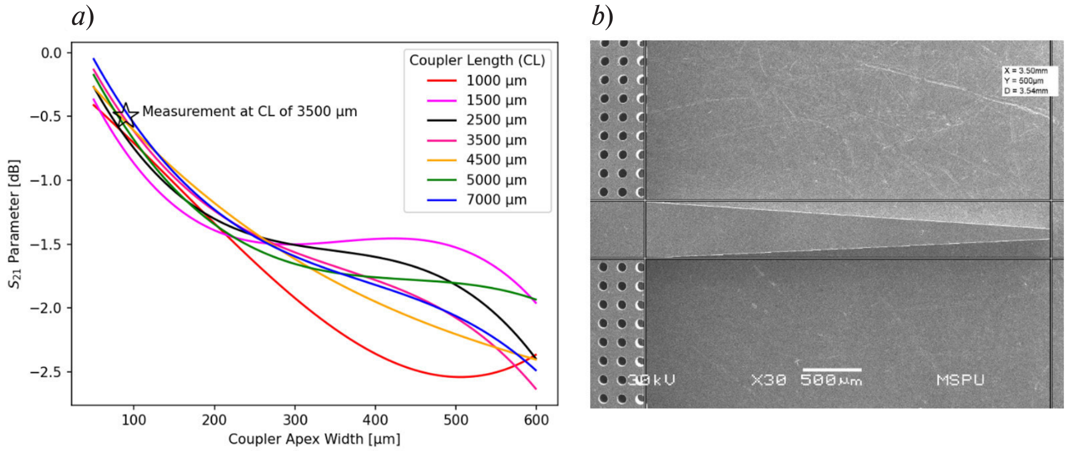

Fig. 1. Dependencies of the S_{21} parameter on the coupler apex width at different values of the prism length (*a*) and SEM photos of the fabricated structures (*b*)

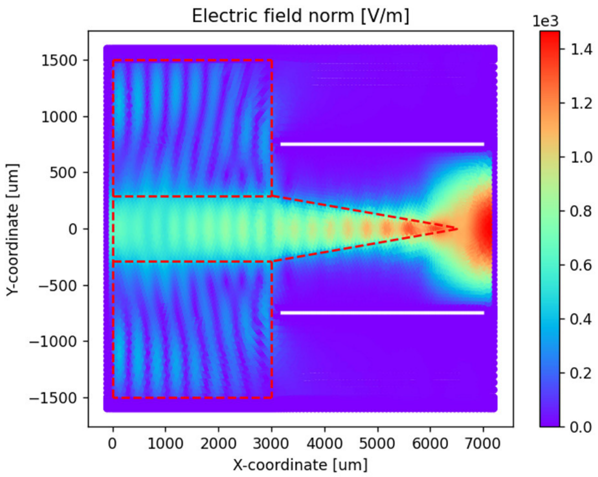

Fig. 2. Simulated electric-field distribution inside the transition from the metal rectangular waveguide (on the right) to the prism coupled dielectric waveguide (on the left)

At the frequency of 0.15 THz, the dependences of the S_{21} parameter on the width of the coupler apex for various values of its length were simulated. The measurements were carried out with a sample in which the width of the coupler apex was 90 μm and the coupler length was 3500 μm. The results of the simulation and experiment are shown on Fig. 1,*a*.

One can see that the insertion loss decreases when the coupler apex width goes down. This can be explained by a smoother change in the average value of the permittivity in the direction along the waveguide at small values of the coupler apex width. This results in a better match between two waveguides. The measured S_{21} parameter value of −0.5 dB for the waveguide sample under study is in good agreement with the simulation.

The electric-field distribution inside the transition from a metal rectangular waveguide to a prism coupled dielectric waveguide is presented on Fig. 2. The boundaries of the metal waveguide are indicated in the figure by white horizontal lines. The boundaries of the substrate, the coupling prism, and the core of the dielectric waveguide are marked with red dotted lines.

Conclusion

The proposed prismatic coupling interface has demonstrated low insertion loss at THz band. The developed structures will become the basic elements of an array of THz emitters with active adjustment of its radiation pattern. These devises will be a part of a future next-generation THz data communication system with a high data transfer rate.

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