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Multimode interference splitter and Mach-Zehnder interferometer based on silicon metamaterial for sub-THz range

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Abstract

THz photonics range is a rapidly developing field of science with many practical applications in medicine, telecommunications, imaging, and others. From practical point of view many applications requires compact and multifunctional solutions, with a property of scalability. Such as in visible and infrared ranges photonic integrated circuits could solve given problem. In this work we are working on enlarging element base of purely silicon THz photonic integrated circuits. We consider 1x2 splitter based on multimode interferometer and its application for Mach-Zehnder interferometer on silicon integrated platform. Both devices on their own will find a huge number of applications in the THz range.

Keywords: Optical splitters, THz range, photonic integrated circuits, metamaterials

1. Introduction

The terahertz range, which lies in the frequency range from 0.1 to 10 THz, is promising for many different applications, such as spectroscopy, telecommunications, medicine, security systems, and others (Zhou J. et al. 2019, Raddo T. R. et al. 2021, Chen T. et al. 2020). This is due to the fact that the spectrum of the terahertz range is energetically equivalent to many physical, chemical and biological processes (Chen T. et al. 2020, Hou L. et al. 2021). However, even though many results have already been obtained, the implementation of such systems is hampered by the lack of available and powerful sources, sensitive and fast detectors, as well as the lack of a platform with low losses and high functionality (such as a silicon platform in infrared photonics (Hao Y. et al. 2021, Kazanskiy N. L. et al. 2021)).

Over the past five years, much attention has been paid to the development of THz photonic integrated circuits (Gao W. et al. 2019, Yu X. et al. 2019). The most promising from them is a purely silicon integrated platform based on metamaterial – effective medium (Gao W. et al. 2019). Main advantages of this platform are – low losses, broadband, design simplicity and high fabrication tolerance, compared to its counterpart – photonic crystals (Yu X. et al. 2019). In this work we consider a modeling of one of the most important passive elements of a photonic integrated circuit – a splitter based on multimode interferometer and consider one of its possible usages – integration as a splitter for Mach-Zehnder interferometer, which could find usage as a compact, sensitive THz sensor. Design simplicity and an opportunity to get any splitting ratio with minor changes in design for multimode interferometer splitter and sensitivity and compactness for Mach-Zehnder interferometer implies practicality of our study.

2. State of the art

In recent years, there has been a rapid increase in interest in the development of passive and active components in the THz range (Hao Y. et al. 2021, Kazanskiy N. L. et al. 2021). Despite their shortcomings, namely the manufacturing and design complexity with increasing frequency, metal waveguides remain the main elements of terahertz photonics, owning to their large period of development (https://www.vadiodes.com/en/). To solve difficulties related to metallic waveguide, lots of work have been done in the field of dielectric integrated THz photonics. As an example, there are platforms based on silicon waveguide, bonded on quartz substrate with a BCB (Amarloo H. et al. 2018), also there is a platform based on pure photonic crystals (Yu X. et al. 2019). and finally, silicon waveguides without any cladding – unclad platform (Headland D. et al. 2020)

Much of the progress connected to splitters of THz radiation have been done. In work (Headland D. et al. 2020) there was an implementation of a Y-splitter for THz range on the unclad platform, 90 % splitting efficiency was shown in vicinity of 280 GHz. Work (Hu, Jian-Rong et al. 2016), demonstrates a Y-splitter implementation for THz range with a frequency of 667 GHz. Calculated efficiency of their splitter was – 93.6 %. Main disadvantage of photonic crystal platform is a strict design restriction, related to its physics. Work (Reichel K. S. et al. 2016) demonstrates a variable T-splitter on metallic waveguide platform for 150-300 GHz range. Almost 100 % efficiency was obtained, but unfortunately this design is very sensitive to a septum position – misalignment leads to large (almost 20%) back-reflections. Compered with the presented works, the MMI-splitter considered in our work has high efficiency, simple design and very flexible for a given metamaterial platform.

3. Materials and Methods

In this work we consider a modeling of multimode interference (MMI) splitter and a Mach-Zehnder interferometer on effective medium silicon platform. Effective medium in this work consists of circular holes in silicon substrate of thickness 400 μm arranged in square lattice. Figure 1 demonstrates considered platform.

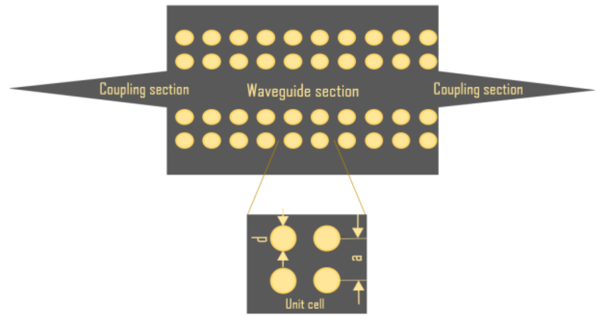

Figure 1. Illustration of a waveguide with coupling devices, for considered in this work platform.

For our study we choose an effective refractive index of the medium equal to 2. This choice was based of the requirement of compactness and big fabrication tolerance. In order to calculate lattice parameters, we consider a Maxwell-Garnett approximation (Krokhin, A. et al. 2002), which states, that for a square lattice, two different polarizations of the light have effective refractive indices, equal to -

$$n_{TE} = n_1 \sqrt{\frac{(n_2^2 + n_1^2) + (n_2^2 - n_1^2)ff}{(n_2^2 + n_1^2) - (n_2^2 - n_1^2)ff}} \quad (1)$$

$$n_{TM} = \sqrt{n_2^2 + (n_2^2 - n_1^2)ff} \quad (2)$$

$$ff = \frac{\pi d^2}{4a^2} \quad (3)$$

Where, for our work: n_1 - refractive index of silicon, n_2 – refractive index of air, ff – filling factor of the medium, d – diameter of the hole in lattice, a – distance between centers of the holes in lattice. During the simulation, the TE polarization of radiation was studied. For our calculations n_1 equals to 3.42, n_2 equals to 1 and ff equals to 0.582. All calculation in this work were done in *Lumerical* simulation software by FDTD and MODE modules. MODE module was used for modal properties of a waveguide – such as modal effective index, geometric modal dispersion. FDTD module was used for calculation of MMI structure – for both effective medium approximation and full structure consisting of circular holes in silicon substrate. In next section, we will give a design consideration of MMI 1x2 splitter, present simulation results of a designed MMI splitter and compare an effective medium approximation with a full structure consisting of circular holes in silicon substrate and finally present simulation results for Mach-Zehnder interferometer with a modelled MMI splitter.

4. Results and Discussion

4.1. MMI splitter design

Firstly, we simulate simple waveguide for an effective medium approximation for 150 GHz frequency – it consists of a central waveguide structure, with a refractive index of silicon, equal to 3.41, surrounded with an effective medium with a refractive index 2. To obtain a single mode regime of a waveguide, a geometric dispersion was calculated – a dependance of a propagation constant (equivalent modal effective index) on a width of central waveguide. Calculation results are presented on Figure 2, from that we choice a waveguide width equal to 300 µm.

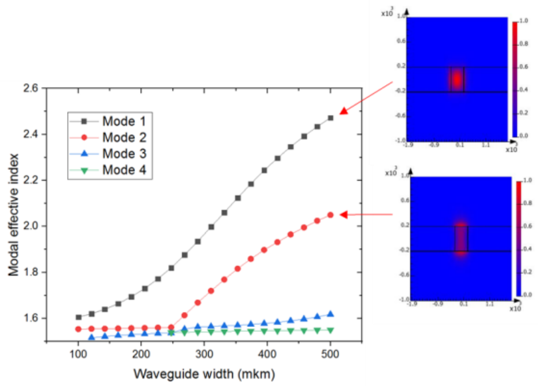

Figure 2. Geometric modal dispersion calculation results, for the first four modes of a waveguide.

Next up, MMI splitter was considered, it consists of an input waveguide, which is connected to a wide multimodal area, which is connected to two output waveguides. We designed MMI splitter as following, firstly we chose a width of a multimodal region equal to 3000 µm. This choice is justified by a large set of propagated modes that are necessary for the operation of a multimode splitter. After that we calculated a power density field distribution for an quasi-infinite structure (which is given on Figure 3) and finally placed two output waveguides at the point of multimodal part, where the power splits on two parts (this part is highlighted green on Figure 3).If ones want to obtain different splitting ratio, for example 1x4, it only requires to move four output waveguides at a position of multimodal area, where power splits in four equal parts (highlighted as red on Figure 3). Considered principle is called – self-imaging principle (Soldano L. B., et al. 1995). Design parameters obtained for an MMI 1x2 splitter are – MMI width – 3000 µm, MMI length – 8000 µm, distance between output waveguides – 1800 µm.

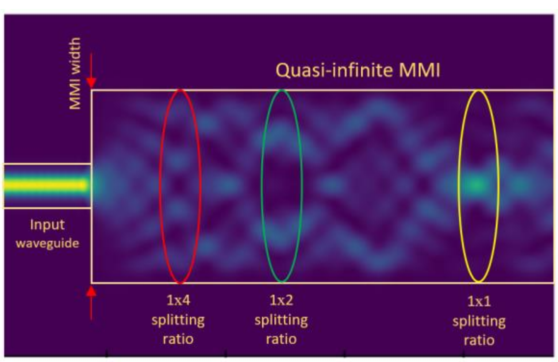

Figure 3. Calculation results of the main parameters of MMI splitter – namely its length, width, and distance between output waveguides.

4.2. Simulation results of designed MMI splitter

Lastly, we simulated transmission characteristics of designed MMI splitter. Two calculated simulations are presented on Figure 4 – simulation for an effective medium approximation and full structure consisting of circular holes in silicon substrate, respectively.

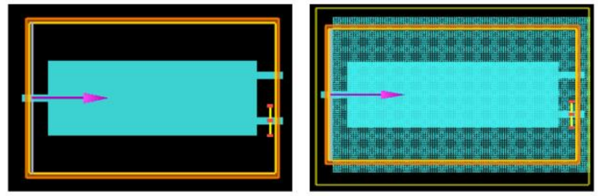

Figure 4. Illustration of two calculated simulations – effective medium approximation and full structure with circular holes in substrate.

Transmission spectrum for both simulations in range from 100 GHz to 200 GHz are presented on Figure 5. From it one can see that an effective medium approximation coincides with a full structure. Obtained power on the output port for 150 GHz is equal to 3.18 dB or equivalently 92 % splitting efficiency. 3dB bandwidth of modelled structure is equal to 100 GHz (from 100 to 200 GHz). To obtain higher transmission for MMI coupler (nearly perfect 3dB), tapered structures for input and output waveguide, should be considered, to minimize reflections – main source of losses for MMI splitter.

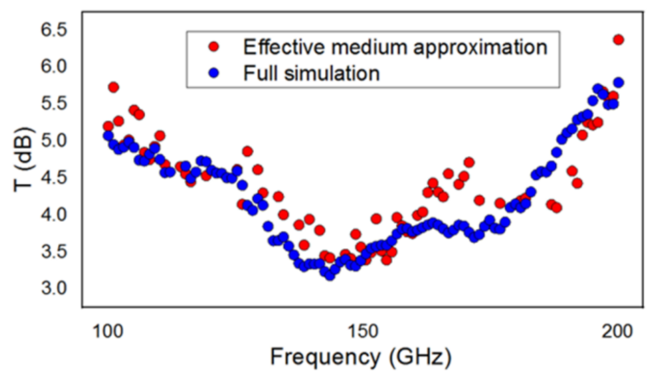

Figure 5. Transmission spectrum for both simulations in range from 100 GHz to 200 GHz

4.3. Simulation results for Mach-Zehnder interferometer with a modelled MMI splitter

In general, a Mach-Zehnder interferometer is an optical device that separates optical radiation into two parts and creates a phase difference between them by passing optical radiation through the interferometer arms of different optical lengths. Then, at the exit from the interferometer, the radiation is mixed with the help of another radiation splitter. As a result, two signals interference is analyzed. Both the Y-splitter and the MMI-splitter can be used as a beam splitter. Consequently, from the foregoing, the main elements of the Mach-Zehnder interferometer are two radiation splitters and two arms, which can have both equal (balanced) and different optical lengths. In this work, we simulated a Mach-Zehnder interferometer with a splitter based on a multimode interferometer. Figure 6 shows the appearance of a model consisting of an input waveguide, a splitter based on a multimode interferometer, two interferometer arms, in which the upper arm has two additional straight sections of the waveguide (left and right) to create an optical delay, and a multimode interferometer at the output.

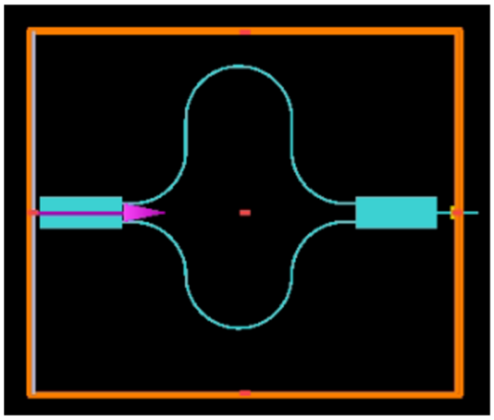

Figure 6. Illustration of calculated Mach-Zehnder interferometer, based on MMI splitters

The calculations were made in the effective medium approximation since the calculation with given holes in the entire simulation area is not possible due to the lack of necessary computational abilities. The result of radiation transmission through a given structure, for different optical delay values, is shown on Figure 7. Total length of the structure equals to 40 mm and transmission of the structure equals to 65 %. Main sources of losses for this structure are loss in MMI splitters and round turns. Calculated Mach-Zehnder interferometer will find use in sensing and others THz applications.

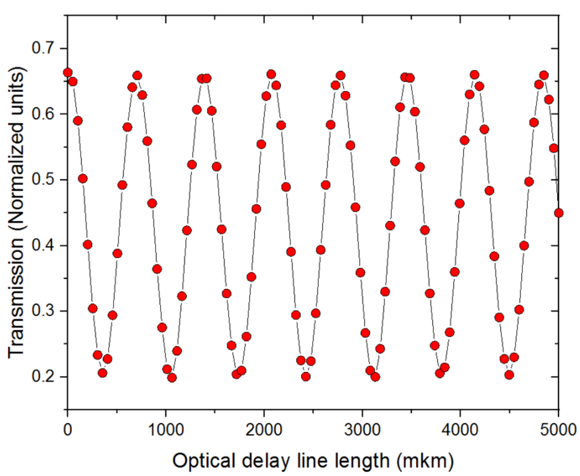

Figure 7. The result of transmission of 150 GHz through a given structure, for different optical delay values.

5. Conclusions

In this work we presented design and calculation of a multimodal interferometer splitter for different splitting ratios. Calculation for effective medium approximation and full structure were given and compered. Obtained structure have splitting efficiency equal to 92 % and 3-dB bandwidth equal to 100 GHz. Based on calculated MMI-splitter we also calculated Mach-Zehnder interferometer, which will find use in sensing and others THz applications.

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