Numerical Simulation of Optical Through-Silicon Waveguide for 3D Photonic Interconnections

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***Abstract*—Optical interconnections are a promising step forward to overcome the intrinsic limitations of electrical interconnections in integrated circuits. In this work, we present a finite element method (FEM) simulation study of a dielectric waveguide etched through the full thickness of a silicon substrate. In particular, it is investigated the effect of the bridge-to-core size ratio on the first two supported modes. Then, the influence of the waveguide sidewalls tapering angle on the three-dimensional beam propagation is studied. Such optical through-silicon waveguide (OTSW), if nonadiabatically tapered can provide effective mode size conversion and favour the coupling of external light sources to photonic integrated circuits.**

I. INTRODUCTION

A promising approach for 3D optical interconnections is represented by optical through-silicon vias (OTSV). Reference [1] is one of the first studies which proposes a silicon interposer that includes electrical, fluidical and optical vias.

Another recent paper [2] introduces a simulation of the coupling of a 7 µm silicon core OTSV surrounded by a SiO_2 cladding with a planar waveguide by means of a grating coupler and a distributed Bragg reflector showing a coupling efficiency of 80%. A common element of these studies is the requirement for the wafer to be thinned or the use of polymers as a waveguiding medium, which reduce compatibility with standard CMOS production chains.

In this work, we present a novel approach for the optical interconnection of the two surfaces of a standard silicon-on-insulator (SOI) wafer which can host photonic integrated circuits (PICs) and other optoelectronic devices. The proposed simulation study examines a bridged optical through-silicon waveguide (OTSW). It basically consists of a cylindrical core connected to a slab bridging structure, both made of silicon as the substrate (Fig. 1). The waveguide extends through the full wafer thickness. The bridge provides the necessary mechanical stability. Furthermore, the structure can be tapered to produce mode size conversion.

II. DESIGN AND SIMULATION SETUP

In the simulation, it was modelled a circular silicon core joined with a silicon slab of smaller width which acts as a bridge to the sidewalls of a surrounding circular hole. The finite element method (FEM) simulations were performed using the commercially available software COMSOL Multiphysics both in 2D finite difference frequency domain (FDFD) (Fig. 2) and 3D beam envelope method (Fig. 1). The goal of this study was to evaluate an acceptable bridge-to-core size ratio and to investigate the beam propagation characteristics depending on the tapering angle at the telecom wavelength of 1550 nm. The waveguide diameter at the input port was set at 50 µm in order to ideally match the mode-field diameter of an external source such as a multimode optical fiber. The silicon core and the bridge (n_{Si} = 3.48) are covered by a 2 µm thick SiO_2 cladding layer (n_{SiO2} = 1.53) and the whole structure is surrounded by air (n_{air} = 1). The axial length of the OTSW is the same as the thickness of a standard 300 mm silicon wafer, namely 750 µm. While the length of the bridge was fixed, its width was subject to a parametric sweep spanning from 10 to 50 µm corresponding to a bridge-to-core size ratio varying from 0.2 to 1. In particular, the mode-field diameter (MFD) was calculated on the entire cross-section for different effective refractive indexes as

$$MFD = 2\sqrt{2}\sqrt{\frac{\int r^2 P_z dr}{\int P_z dr}}, \tag{1}$$

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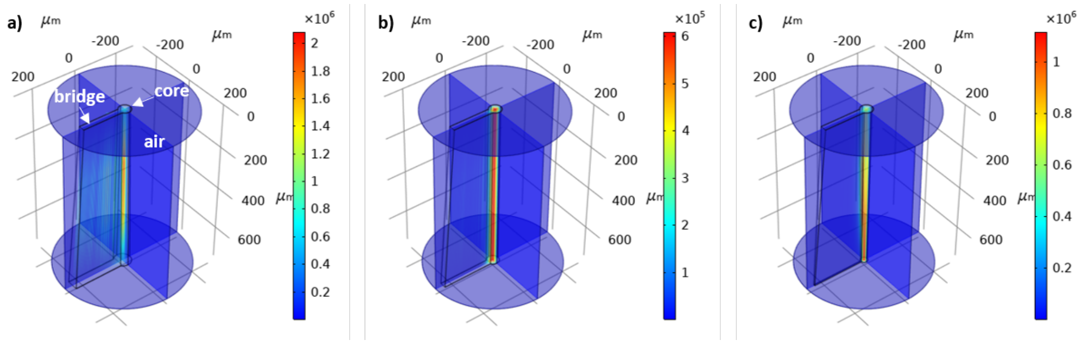

Fig. 1. 3D beam propagation simulation of a bridged optical through-silicon waveguide with a tapering angle of a) -0.9°, b) 0° and c) 0.9°. The surrounding substrate is hidden and the electric field values are represented on the x, y and z planes.

where r is the coordinate over the cross-section and P_z is the out of plane Poynting vector in the propagation direction.

Once chosen an optimal bridge-to-core ratio, the tapering angle ϑ was studied in the 3D simulations ranging from -0.9° to 0.9°. Therefore, the waveguide axial profile changed from diverging (negative taper) to converging (positive taper) as well as the bridge. The losses due to the sidewall roughness, were in this case neglected and only the intrinsic interaction of electromagnetic field with the represented geometry was considered for the estimation of the field confinement effects.

III. Results and Discussion

The FDFD study of the bridge-to-core size ratio is represented in Fig. 2. The MFD of the first (doubly degenerate) and the second supported modes has been plotted versus the bridge-to-core size ratio. It can be observed that the area of the graph is divided in three main sections: below a ratio 0.4, both the first and the second mode are supported and confined within the core; for a ratio between 0.4 and 0.6, only the fundamental mode is entirely confined within the core section while the second mode leaks into the bridging structure; finally, for a ratio greater than 0.6, also the fundamental mode is leaking in the slab. In the graph, there are also represented the normalized electric field distributions for the fundamental and the second mode in the three different regions. The MFD values lower than the geometrical size of the core demonstrate a strong light confinement due to the high refractive index contrast. In the central region of the graph, the structure shows characteristics similar to rib waveguides, where at large core diameters single-mode operation is still possible. For the 3D beam propagation study, based on the results of the 2D simulation, a bridge-to-core size ratio of 0.5 was chosen. In this way, only the fundamental mode should be supported by the core, thus reducing the bandwidth limitations introduced by intermodal dispersion. It can be noted that the normalized electric field of the fundamental mode is leaking in the bridge for the negatively tapered (-0.9°) waveguide (Fig. 1a), while it is well confined within the core for the non-tapered (0°) (Fig. 1b) and for the positively tapered (0.9°) (Fig. 1c) OTSW. Therefore, the modelled structure fulfils the task of confining light into the circular core section and provides mode size conversion.

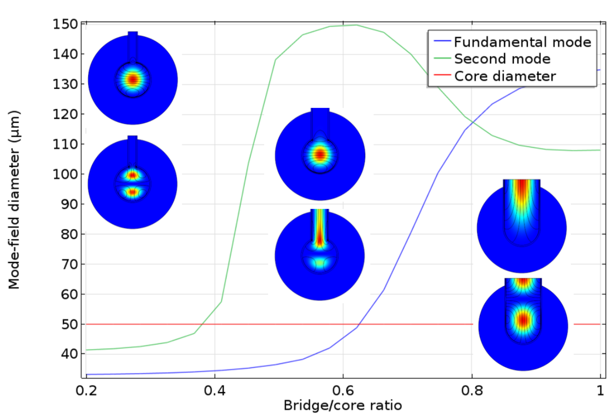

Fig. 2. 2D cross-section simulation of the first two supported modes of a bridged optical through-silicon waveguide. The mode-field diameter of the fundamental and the second supported modes are plotted versus the bridge-to-core size ratio. In addition, the normalized electrical field for the first two modes in the three different regions is shown.

IV. Conclusion

A novel bridged optical through-silicon waveguide has been proposed. The simulation study on the bridge-to-core size ratio produced three conditions: below a ratio of 0.4 the waveguide circular core supports multiple modes; between 0.4 and 0.6 higher modes than the fundamental leak into the bridge; for ratios greater than 0.6 it behaves as a slab waveguide. Also, the effects of the sidewalls tapering angle was evaluated for a bridge-to-core size ratio of 0.5, demonstrating that positively tapered OTSW can provide effective mode size conversion.

References

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