Adiabatic Passage of Light in CMOS-Compatible Silicon Oxide Integrated Rib Waveguides

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***Abstract*— We experimentally demonstrate that a system of three CMOS-compatible total internal reflection waveguides allows a highly efficient and robust transfer of visible light between the outermost waveguides by adiabatically following one eigenmode of the system.**

Adiabatic passage of light; Integrated optical circuits; Silicon technology; total internal reflection (TIR) waveguides

I. Introduction

During recent years, photonics based on silicon has gained a lot of attention because it offers the possibility to revolutionize computing platforms by manufacturing optical devices using traditional and low-cost complementary metal-oxide-semiconductor (CMOS) technology [1, 2]. Nevertheless, there is still a long way to go in order to implement photonic integrated circuits able to replace and improve the traditional electronic integrated circuits. Thus, new techniques allowing full control of light propagation in silicon based optical devices are very desirable.

Recently, it has been shown that it is possible to transfer a light beam between the outermost waveguides of a system of three identical coupled waveguides in a very efficient way by adiabatically following one eigenmode of the system [3, 4]. In this paper, we present for the first time the implementation of the adiabatic passage technique for visible light in total internal reflection (TIR) waveguides [5] using a fully CMOS-compatible technology [6]. This represents an important technological step forward compared to previous works [3, 4] since it allows a massive and low-cost fabrication of these devices and their incorporation to realistic photonic integrated circuits.

II. Adiabatic Passage Mechanism

The adiabatic passage of light in systems of three identical single-mode coupled optical waveguides (as the one schematically depicted in Fig. 1(a)) resembles the well known stimulated Raman adiabatic passage (STIRAP) technique [7]. Light can be efficiently transferred from the right to the left waveguide with almost null intensity in the central waveguide for the whole propagation by following one of the eigenmodes of the system that only involves the external waveguides [6]. To this aim, light is initially injected into the right waveguide and the evanescent couplings are adiabatically modified along the propagation direction by approaching first left and central waveguides and, later on and with a certain overlap, right and central waveguides. Furthermore, it is important to remark that the adiabatic passage in waveguides is a robust process, i.e., insensitive to small variations in the parameter values of the waveguides, a property that previously published directional couplers do not exhibit [5].

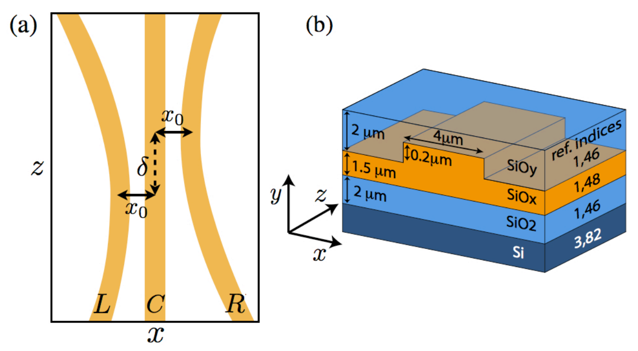

Figure 1. (a) Schematic top view of the geometry of the system of three waveguides consisting of two circularly bent outermost waveguides, left (L) and right (R), and one straight central waveguide (C). The minimum distance between waveguides is given by x_0, and the z distance between the centers of the curved waveguides is defined by δ. (b) Schematic representation of the geometry, specifying the materials and refractive indices, of one of the three TIR waveguides that form the system.

III. DESIGN AND FABRICATION

The geometry of the adiabatic passage in a system of three coupled waveguides has been optimized by numerical simulations using the software Fimmprop and Fimmwave (Photon Design).

The fabrication process starts thermally growing a layer of 2 μm of silica SiO_2 on a (100) silicon wafer. Then, a layer of non-stoichiometric silicon oxide SiO_x with a refractive index of 1.48 [8] and a height of 1.7 μm is deposited over the silica layer by plasma enhanced chemical vapor deposition (PECVD). At this point, the ribs defining the waveguides are obtained by using the appropriate mask and dry etching in the SiO_x layer. They have a thickness of 0.2 μm and width of 4 μm. Finally, another layer of non-stoichiometric silicon oxide SiO_y of 2 μm with index 1.46, acting as a passivation layer, is deposited on the top of the device using PECVD. Fig. 1(b) depicts the transverse profile of one of the waveguides of the system including the values of the refractive indices and the sizes of the different layers.

IV. EXPERIMENTAL RESULTS

The experimental setup consists of a 635 nm diode laser (Thorlabs S1FC635) connected to one end of a single-mode optical fiber. The other end of this fiber is located on a piezoelectric 3D positioning system (piezosystem jena NV40/3), which allows accurate fiber optics-waveguide alignment. Light propagating inside the waveguides is collected by an infrared single-mode optical fiber placed on another piezoelectric positioning system (piezosystem jena d-Drive) and transferred to a power meter (Newport 1930F-SL).

Insertion and attenuation losses were measured using identical waveguides of different lengths, with values of 3.6±0.3 dB and 0.36±0.01 dB/mm, respectively. We have also characterized the coupling coefficients $\Omega_{R,L}$ as a function of the separation of two waveguides d [6]. The experimental values may be fitted by the decaying exponential curve $\Omega(d)=\Omega_0\exp(-d/l)$ with $\Omega_0=14.9\pm1.5$ mm^{-1} and $l=2.72\pm0.09$ μm. This dependence has been used to check that the coupling coefficients $\Omega_{R,L}$ along the z propagation direction fulfill the adiabaticity requirements of the adiabatic passage of light [3].

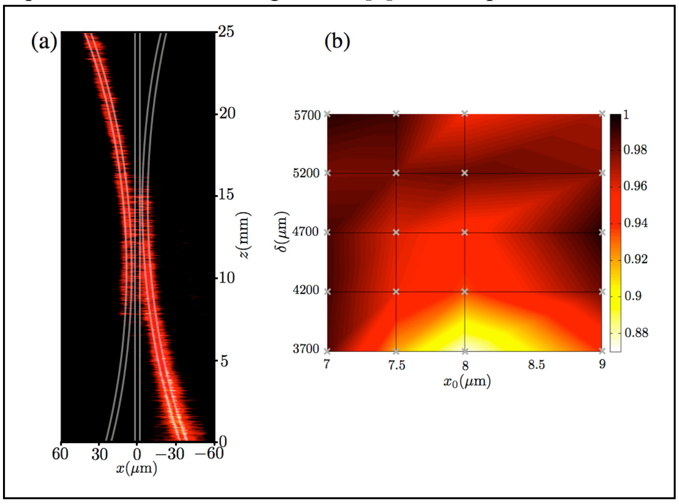

Figure 2. (a) Top view image of one of the fabricated devices in which light losses allow us to observe the adiabatic transfer of light. The radius of curvature of the outermost waveguides is 3.5m, the spatial delay is δ=4200 μm and the minimum separation between waveguides is x_0=7 μm. (b) Relative fraction of light intensity at the output of the left waveguide of the system as a function of δ and x_0. Crosses indicate the experimental measurements.

By taking several images with a CCD camera connected to an optical microscope, a top view picture of the path followed by the light beam across one of the fabricated systems of waveguides has been obtained, see Fig. 2(a). The image confirms the adiabatic transfer of light. We have also demonstrated the robustness of the adiabatic passage of light by measuring the intensity at the outputs of the three waveguides (I_L, I_C and I_R) for several devices with slightly different parameter values. Fig. 2(b) gives the relative fraction of light intensity at the left output, $I_L/(I_L+I_C+I_R)$, for different devices with δ and x_0 parameters varying from 3700 μm to 5700 μm and from 7 μm to 9 μm, respectively. The radius of the outermost waveguides is 3.5 m for all the measured devices. The lowest measured relative fraction value of light at the output of the left waveguide is higher than 0.87 whereas the highest measured relative fraction values are above 0.99, demonstrating the low sensitivity of the adiabatic passage to fluctuations of the parameters.

V. CONCLUSIONS

Using CMOS-compatible technology, we have experimentally shown that it is possible to achieve a highly efficient transfer of light between the outermost waveguides of a system of three coupled identical waveguides by adiabatically following one of the eigenmodes of the system. We have also experimentally checked the robustness of the passage against variations of the parameter values of the system. In particular, the measured relative fraction of intensity at the left waveguide output of several systems of waveguides ranges from 0.87 to values above 0.99, for variations of the geometry parameter values between 20% and 35%.

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