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Research Article

Design and Fabrication of 1 × 2 Nanophotonic Switch

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We present the design and the fabrication of a novel 1 × 2 nanophotonic switch. The switch is a photonic T-junction in which a gold nano particle is being positioned in the junction using the tip of an atomic force microscope (AFM). The novelty of this 1 × 2 switch is related to its ability to control the direction of wave that propagates along a photonic structure. The selectivity of the direction is determined by a gold nanoparticle having dimension of a few tens of nanometer. This particle can be shifted. The shift of the gold nano particle can be achieved by applying voltage or by illuminating it with a light source. The shifts of the particle, inside the air gap, direct the input beam ones to the left output of the junction and once to its right output. Three types of simulations have been done in order to realize the photonic T-junction, and they are as follows: photonic crystal structures, waveguide made out of PMMA, and a silicon waveguide.

1. Introduction

Optical switches have wide usage in optics communication for various purposes including protection of an optical link [1, 2]. Reducing the dimensions of the switch can assist in its integration on a silicon chip together with other electro-optical and microelectronic processing devices that may be positioned on the chip as well. The recent development of nanotechnology fabrication capabilities allows realization of various types of nanophotonic devices on silicon chips [3–5].

Photonic structures cannot be modified after their fabrication process. Therefore modulators and switches have been developed in order to control propagation of light. Photonic structures such as single mode Y couplers are widely employed as power dividers [6, 7] and combiners in modulators [8], switches [9, 10], and interferometric devices. Several approaches have been proposed in order to control the direction of light. Photonic crystals utilizing liquid crystal orientation that can be changed by adjusting applied field [11] and photonic crystal composed of semiconductor that depends on temperature [12].

Usage of trapped nanoparticle in order to realize a nano photonic modulator has already been demonstrated before [13]. There the position of a nanoparticle that performed the modulation of the output light was controlled using external voltage command. In this paper we present a novel design of a nano photonic 1 × 2 switch having a T-junction structure in which there is one input and two outputs. The energy of the input is diverted to one of the outputs by shifting a golden nanoparticle that is positioned in the junction from one side of the junction to the other.

Note that usage of nanoparticle for electro optical applications has already been demonstrated before while the directions and ways of scattering [14, 15] the polarization of the scattered light [16, 17] and its diffraction [18] were characterized.

In Section 2 we present the design and the numerical simulation of the device. Its fabrication is demonstrated in Section 3. The paper is concluded in Section 4.

2. Numerical Simulations

The proposed device has a T-junction shape. In the simulations we used 2D, TE "in plane" mode analysis at a wavelength of 1.55 μm. The electromagnetic wave is excited and propagates along the main waveguide until it approaches the 90 degree T-junction. A hole of air gap is being produced

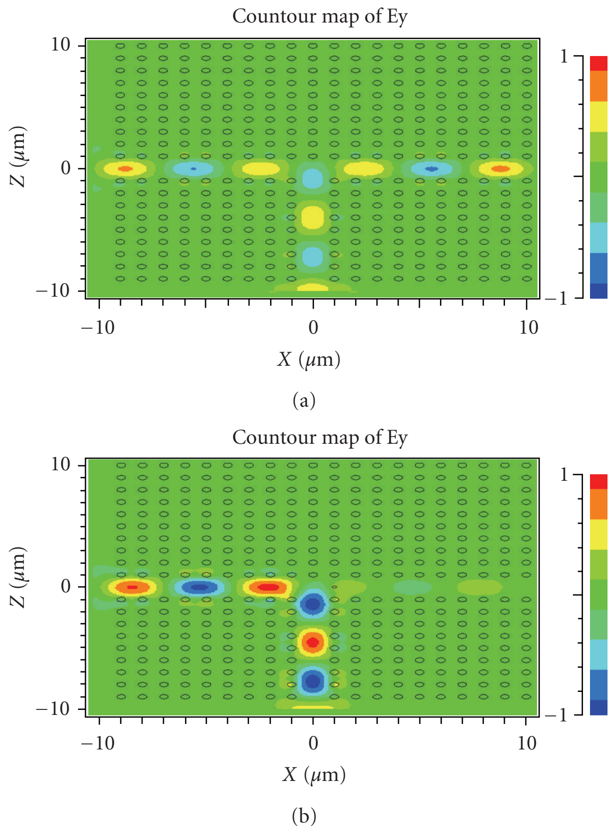

FIGURE 1: Simulations for photonic crystal T-junction. (a) Beam splitting obtained without placing the nanoparticle. (b) Addition of 100 nm particle in the T-junction diverts the light towards the left output channel.

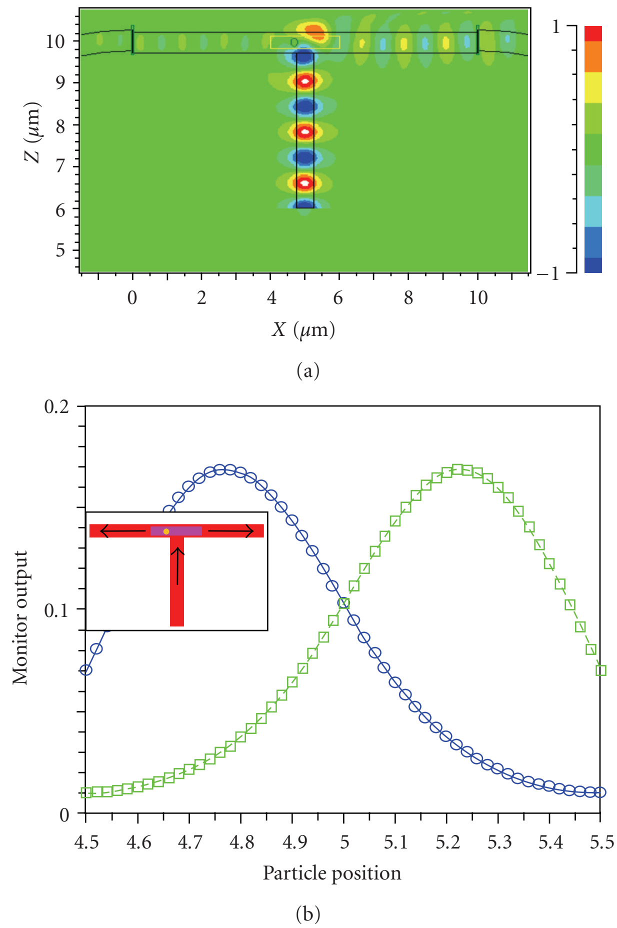

FIGURE 2: Waveguide-based T-junction. (a) Simulations for switching the output channel in a PMMA waveguide. (b) The same simulation as in Figure 2(a) versus the position of the 100 nm particle.

at the splitting point. The silicon waveguides consist of a channel waveguide with dimensions of 450 nm width and 250 nm height. Choosing the proper position of a nanoparticle in the junction can change the output channel through which the light output. All simulations in this section were performed using two numerical softwares: R-Soft and Comsol Multiphysics which both solved the Maxwell equations for radiation propagation using Finite-Difference Time-Domain (FDTD) and Finite Elements Method (FEM) approaches, respectively [19].

One way of realizing such a T-junction device is by using photonic crystal structures [20, 21]. In Figure 1(a) one may see a beam splitter having T-junction structure. This is obtained without placing the nanoparticle. When a golden nanoparticle with dimensions of 100 nm is added to the right side of the junction all the light is directed to the left output of the junction as depicted in Figure 1(b). The simulations of Figure 1 were performed using R-Soft.

The next step of simulations was to simplify the photonic crystal based T-junction into a regular T-junction waveguide while a narrow slit is positioned in the junction and in which the nanogolden particle ($\sigma = 3 \cdot 10^7$ [S/m]) is placed. In Figure 2(a) one may see the simulation of such a device while the waveguide is made out of PMMA material (refraction index of about 1.6). The readout of the two outputs (the left and the right arms of the T-junction) versus the position of the nanoparticle is seen in Figure 2(b). The size of the particle is 100 nm. The units of the horizontal axis of Figure 2(b) are in microns and thus one may see that shifting the particle a distance of about 400 nm switches the output from the left arm to the right arms of the T-junction device. One may see that extinction ratio of 1 : 17 (12 dB) may be obtained in the proposed device. The simulations of Figure 2 were performed using R-Soft.

The basic configuration of photonic structures (e.g., modulator, sensor, and logic gate) is already based on silicon waveguide; therefore, in order to adapt the device for silicon a modification to the T-junction is made as depicted in Figure 3. The simulations in this part were carried out using Comsol Multiphysics that solves the second order partial differential wave equation. The wave equation can be described by

$$\nabla \times (\mu_r^{-1} \nabla \times E_z) - \left(\varepsilon_r - \frac{j\sigma}{\omega\varepsilon_0}\right) k_0^2 E_z = 0, \qquad (1)$$

where μ_r is the relative magnetic permeability, E_z is the electric field in the z component, ε_r is the dielectric

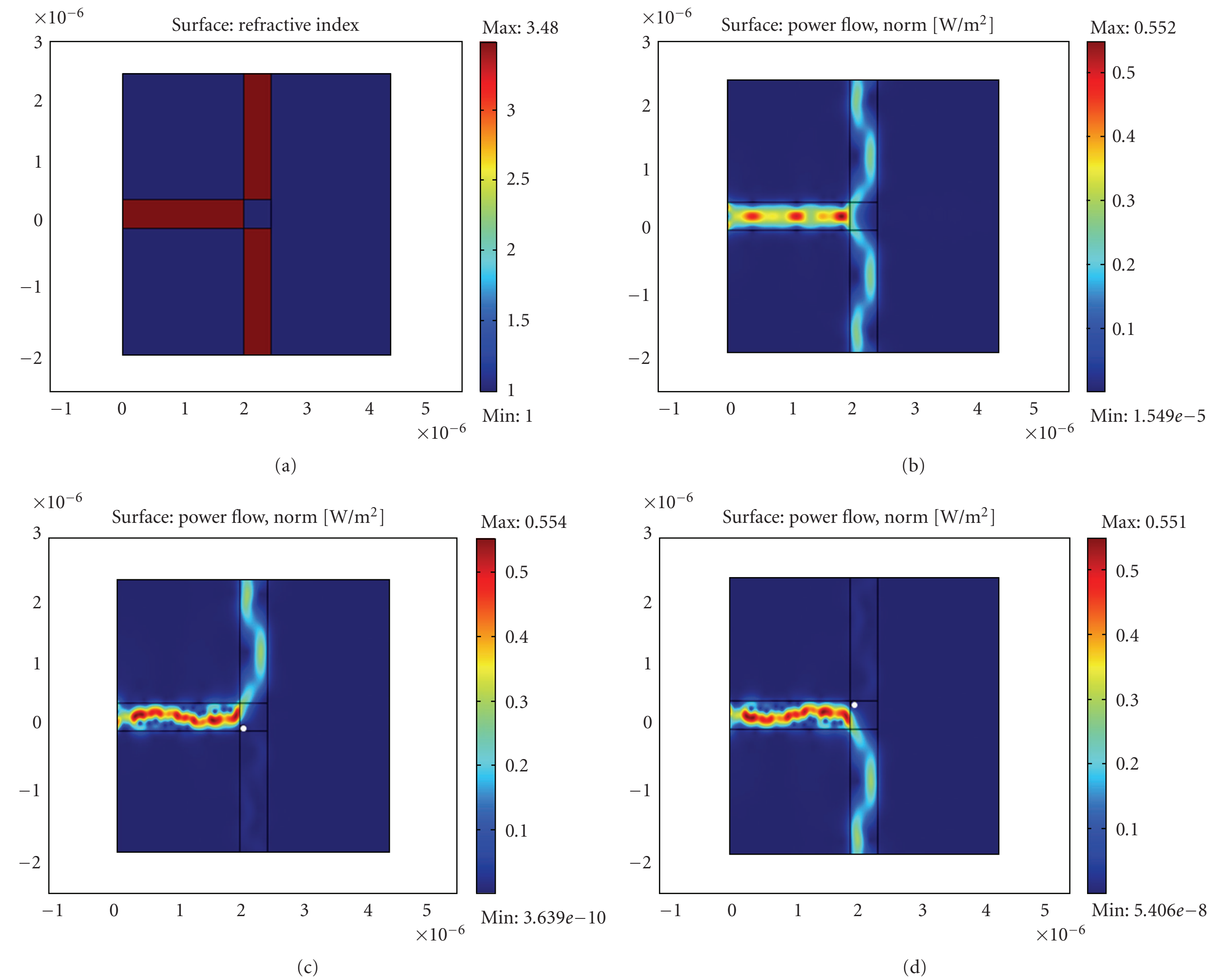

Figure 3: Numerical simulation. (a) Refractive index of the simulated device. (b) The power flow distribution along the "Y coupler" without the particle. (c) and (d) The power flow distribution along the "Y coupler" waveguide while the gold nanoparticle ($\sigma = 3 \cdot 10^7$ [S/m]) is placed in the lower and upper part of the air gap, respectively.

coefficient, σ is the conductivity, ω is the angular frequency of the propagating light, ε_0 is the vacuum permittivity, and k_0 is the wavenumber.

The boundary condition at the input of the device was selected in such a way that the Poynting vector is equal to 1. The external boundaries conditions were selected to be scattered (each one of them with a proper direction of scattering), while the internal boundaries conditions were selected to be in "continuity" mode. The "free mesh parameter" function of the Comsol simulator was used to mesh the entire device. We use the subdomain meshing function to mesh each subdomain with the proper mesh size. The mesh parameters of the waveguide region were maximum element size of 30 nm with element growth of 1.2, while in the gold nanoparticle region we choose maximum element size of 1 nm.

Figure 3(a) presents the refractive index of the simulated device. Figure 3(b) present the power flow distribution along the T-junction without the particle. Figures 3(c) and 3(d) presents the power flow distribution along the T-junction waveguide while the gold nanoparticle ($\sigma = 3 \cdot 10^7$ [S/m]) is placed in the lower and upper part of the air gap, respectively. Here one may see that the power flow extinction ratio between the unblocked and the block paths is standing on 1 : 16 (12 dB). The power flow distribution pattern at the main waveguide is related to the standing wave that is generated by the backscattering and the reflections. In Figures 3(c) and 3(d), the asymmetric location of the gold nanoparticle inside the air gap causes an asymmetric backscattering which result in an asymmetric shape of the power flow distribution along the main waveguide.

3. Fabrication and Realization

The realization of the proposed devices is presented in Figure 4. Figure 4(a) shows the top view microscope images

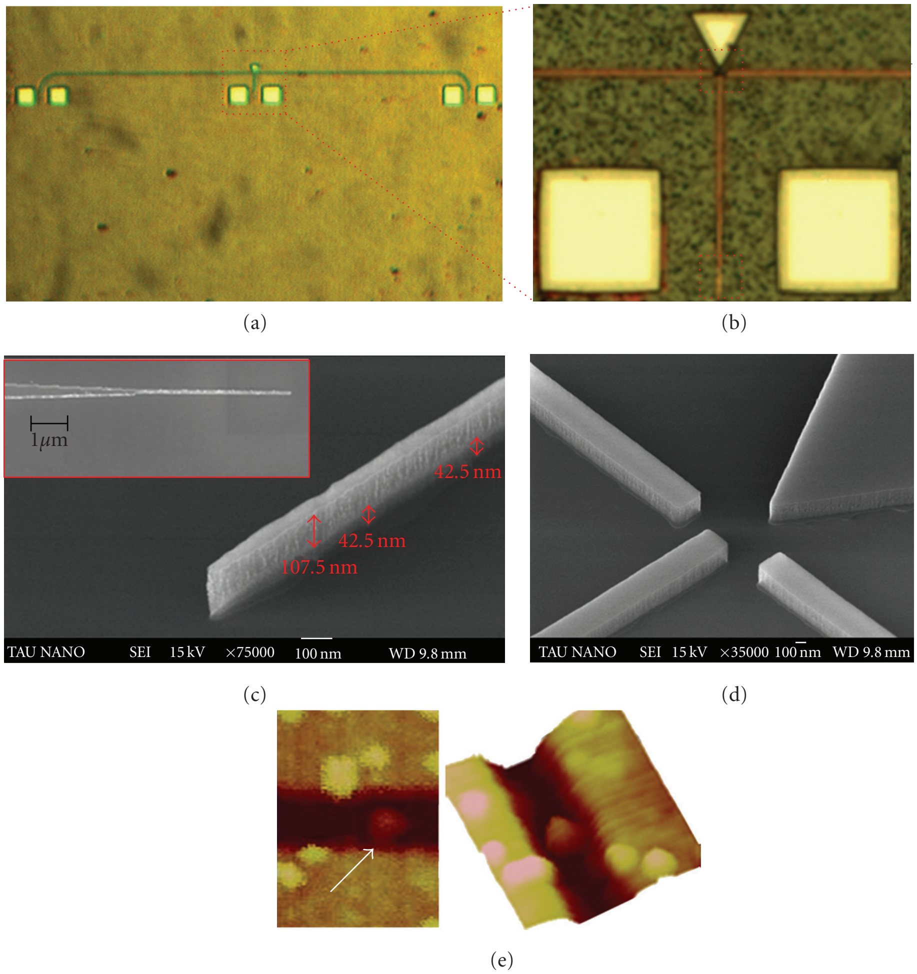

Figure 4: Fabricated "Y coupler." (a) Top view microscopic image of the overall fabricated device. (b) Enlarged image shows the input waveguide which splits into a pair of waveguides; (c) and (d) show SEM images of the lower and upper encompass areas (shown in Figure 4(b)) that define the coupling of light from fiber to the silicon waveguide and the fabrication of the T-junction itself, respectively. (e) Placing the particle in the slit (the particle is marked with white arrow). Left part is an upper view of the particle and the right part is the 3D mesh.

of the fabricated T-junction. Figure 4(b) shows enlarged image at the splitting point. In order to couple light from a fiber to the proposed waveguide-based device we used tapered fibers having edge with diameter of 3 μm.

In order to have efficient coupling of light from a fiber (having tapered edge of 3 μm) to silicon-based waveguide (having sub micron dimensions) we designed and fabricated a narrow edge to the waveguides [22, 23] as depicted in Figure 4(c) presenting the scanning electron microscope (SEM) image of our fabricated chip.

In Figure 4(d) we present the fabricated T-junction-based switch where an air hole is used instead of the slit. In this hole we will position the nanoparticle. The waveguide is a silicon waveguide fabricated on silicon on insulator (SOI) wafer.

The position of a 100 nm particle in the hole of the T-junction is made using an AFM tip. In the experiment we were able to position the nanoparticle directly into the designated hole by pushing it with the tip of the AFM (using "Nanoman" feature of the AFM). The experimental results presenting the position of the particle are seen in Figure 4(e), where in the left side of the figure we see the upper view of the particle and in the right part of the figure we present the 3D mesh.

The experimental characterization of the proposed device is our next step which will be performed in the near future.

4. Conclusions

In this paper we present a T-junction-based design for a 1×2 switch in which the output energy is directed to the output channel by shifting a nanoparticle positioned in the T-junction itself. The proposed device was fabricated and a nanoparticle was placed in its allocated proper position using an AFM tip. The anticipated performance of the proposed nano switch was numerically investigated.

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