Design and Simulation of Plasmonic NOT Gate Based on Insulator–Metal-Insulator (IMI) waveguides

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Abstract

In this work, an all-optical NOT logic gate is proposed using Insulator-Metal-Insulator (IMI) plasmonic waveguides Technology. The proposed all-optical NOT gate is simulated, investigated and realized using COMSOL Multiphysics 5.3a software. Recently, plasmonic technology has attracted considerable attention due to its full applications in all-optical signal processing. Due to its high localization to metallic surfaces, surface plasmon (SP) may have significant applications in all-optical signal processing to the light signals in the waveguides, which result in overcoming the diffraction limit problem in conventional optics. The proposed IMI structure consists of dielectric waveguides plus metallic claddings, which guide the incident light firmly in the insulator region. Our design consists of symmetric nano-rings structures with two straight waveguides, which based on the IMI structure. The operation of all-optical NOT gate is realized by employing the constructive and destructive interface between the straight waveguides and the nano-rings structure waveguides. There are three ports in the proposed design, input, control, and output ports. The activation of the control port is always ON. By changing the structure dimensions, the materials, the phase of the applied optical signal to the input, and control ports, the optical transmission at the output port is changed. In our proposed structure, the insulator dielectric material is glass, and the metal material is silver. The calculated contrast ratio between (ON and OFF) output states is 3.16 (dB).

Keywords: Surface plasmon (SP), IMI, all-optical NOT gate, all-optical signal processing.

1. INTRODUCTION

Recently, the need for enormous bandwidth has highly increased to overcome the limitations of conventional electronic and photonic devices. All-optical signal processing plays a significant role in realizing ultra-speed processing, high data rate, and overcoming the problems of heat and diffraction limit in conventional electronic and photonic devices, respectively. Currently, the necessary practical implementations of high data rate plasmonic devices are stepping out from the research laboratories. To realize all-optical signal processing technology, all-optical devices are the basic requirements, especially the logic gates, which are the main parts of all-optical systems. Surface plasmon (SP) exists at the boundary between the dielectric and metal materials of the design. The essential characteristic of surface plasmon polariton (SPP) is the ability to couple the electromagnetic waves to make the propagation of free electrons oscillations at the dielectric-metal interface [1]. Overcoming the diffraction limit problem makes the surface plasmon polariton (SPP) have a different application in highly integrated optical circuits [2]. Many all-optical devices in sub-wavelength have been proposed, such as switches [3], logic gates [4-6], modulators [6], sensors [7, 8], and nanowires [9]. Our proposed structure includes two nano-rings with two straight linear waveguides based on the IMI structure to demonstrate a plasmonic NOT gate.

2. ANALYSES AND NUMERICAL RESULTS

Generally, the boundary between two semi-infinite materials has opposite charges negative and positive dielectric constants which guide the transverse magnetic (TM) waves effectively. Because the width of IMI plasmonic waveguides is smaller than the applied wavelengths, only the low orders transverse magnetic (TM) modes can be propagated. The Equation of dispersion of (TM) mode in the waveguide is given by [10, 11]:

$$\varepsilon_d k_m + \varepsilon_m k_d \tanh\left(\frac{k_d}{2}\right) = 0 \qquad (1)$$

k_d is defined as: $k_d = (\beta^2 - \varepsilon_d k_0^2)^{\frac{1}{2}}$ and k_m is defined as: $k_m = (\beta^2 - \varepsilon_m k_0^2)^{\frac{1}{2}}$. ε_d is the insulator dielectric constant, ε_m is the metal-dielectric constant. Free space wavenumber k_0 is defined as: $k_0 = \frac{2\pi}{\lambda}$. β is the propagation constant.

Drude model [11] is used to calculate the dielectric constant ε_m is of metal as:

$$\varepsilon_m(\omega) = \varepsilon_\infty - \frac{\omega_p^2}{\omega(\omega + i\gamma)} \qquad (2)$$

at the infinite angular frequency, the dielectric constant ε_∞ is 3.7, the frequency of the bulk plasma ω_p is 1.38 × 10^{16} Hz, which is the natural frequency of free conduction electrons oscillations, the oscillations damping frequency γ is 2.73 × 10^{13} Hz, and ω is the angular frequency of the incident electromagnetic radiation. A plane wave with TM polarization is applied to excite the SPPs [12]. The transmission of the proposed system is defined as:

$$T = \frac{P_{output}}{P_{input}} = \frac{H^2_{output}}{H^2_{input}} \quad (3)$$

where P_{input} is the input power, while P_{output} represents the output power of transmission [12, 13].

3. ALL-OPTICAL NOT GATE

The proposed structure of the plasmonic NOT gate is shown in Figure. 1. The operation wavelength λ is 1310 nm, the nano-rings structure radii are R = 40 nm and r = 25 nm, the width of the straight waveguide w is 15 nm, and the coupling distances d between the nano-rings structures and straight waveguides is 5 nm. In the proposed structure, there are three ports; input, control, and output ports. The control port is always ON to provide the necessary power to the structure and to employ the light interference between the propagated signals in the control and input ports. There are two input states in NOT gate, OFF and ON states. In the case of the input port is OFF; there is no light signal launched to the input port, while the light signal is propagating in the control port. In this case, only the light in the control port is propagating towards the output port without phase difference and in the same direction of propagation. Thus, the amplification occurs due to the constructive interference between these signals in the control port. In the case of the input port is OFF, the optical transmission which described in Equation (3) is calculated by dividing the output power at the output port to the input power at control port, the transmission value of this case is (0.725) which exceeds the transmission threshold of (0.5). In the case of the input port is ON, the light signal is applied to the input port with a phase angle of (180°), while the phase angle of the light signal which is launched to the control port is (45°), due to the phase difference angle between the two light signals in the input and control ports the destructive interference between them occurs and makes the output state is in OFF because the transmission, in this case, is (0.35) below the transmission threshold of (0.5). The magnetic field distributions of the proposed gate at different input states and the normalized transmission of the proposed NOT logic gate and is shown in Figures (2-4), respectively. The operation details of the proposed all-optical NOT logic gate are presented in Table (1).

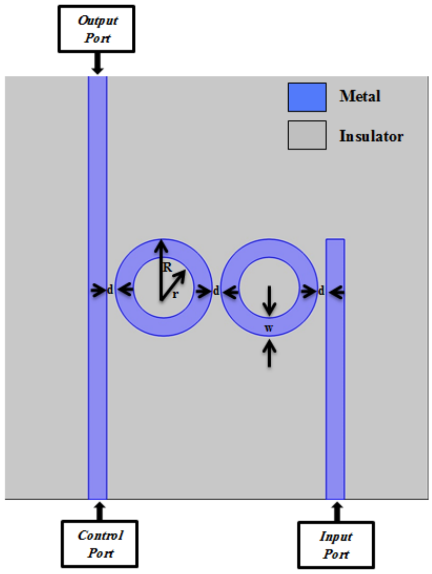

Figure 1: The Proposed Structure of All-Optical Plasmonic NOT Gate.

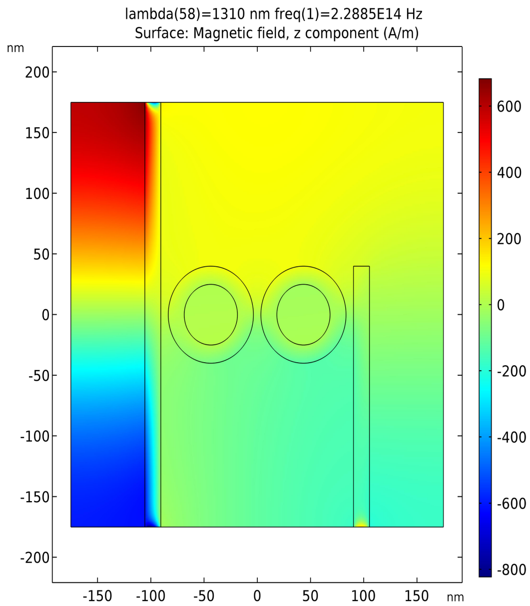

Figure 2: The Magnetic Field Profile in Case of (ON) Output State.

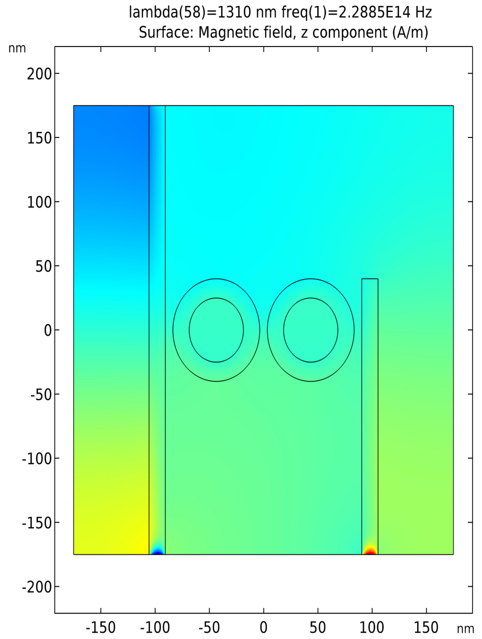

Figure 3: The Magnetic Field Profile in Case of (OFF) Output State.

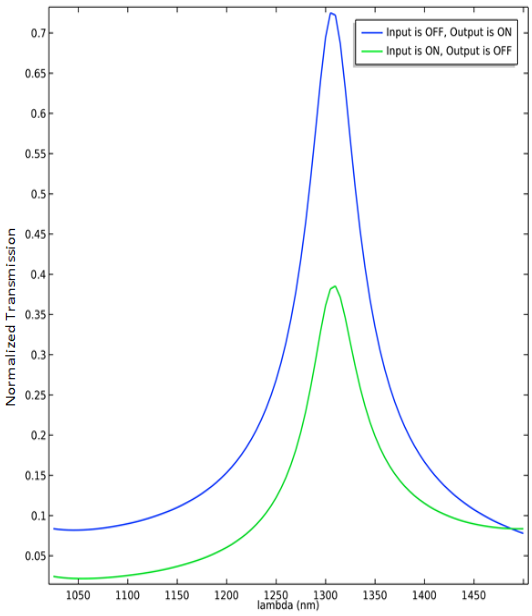

Figure 4: Optical Transmission as a Function of Wavelength at the Different Condition States.

Table 1: The realization details of the proposed all-optical NOT logic gate

Table (3.1) The Operation Details of the Proposed All-Optical NOT Logic Gate

Input Port State	Phase Angle Degree	Control Port State	Phase Angle Degree	Optical Transmission	Transmission Threshold	Output Port State
OFF	0	ON	0	0.725	0.5	ON
ON	180	ON	45	0.35	0.5	OFF
Contrast Ratio (CR) = 3.16 (dB)						

4. Conclusion

In conclusion, the plasmonic NOT logic gate is proposed, realized, and investigated based on IMI plasmonic nanostructure. The constructive and destructive interference between the straight waveguides and nano-rings structures were employed to design all-optical plasmonic NOT gate. By changing the structure dimensions, the phase angle of the incident signal, the state of the output port is also changed accordingly. The simulated results show that the proposed structure of the gate could operate as a plasmonic NOT gate. The proposed design of the plasmonic NOT gate would be the main part of many applications that used to perform all-optical signals processing.

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