Plasmonic switch Based on asymmetric cavities with embedding square of gold inside the cavities

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Abstract

In this paper, we proposed an all-optical plasmonic switch based on metal-insulator-metal (MIM) structures. We used the intrinsic nonlinear properties of gold to implement the switch. The proposed switch consists of a bus waveguide side coupled with a pair of asymmetric vertical cavities. We obtained the transmission spectrum of the structure for low input intensities. The results showed that a sharp dip occurs at the wavelength of 860 nm. Due to the nonlinear properties of gold and the nonlinear Kerr effects, the proposed switch has a high transmission ratio of about 0.8 and a low threshold power of 0.07 mW/μm^2. The threshold power of the structure with and without using the gold nanostructure shows a reduction of 50%. The result showed that the proposed switch has the potentiality to be applied in the plasmonic integration circuits.

1. Introduction

All-optical switches are indispensable in the integrated optical circuits and are widely applied in all-optical networks (Sasikala and Chitra 2018). The proposed structures for implementing optical switches operate based on different principles with different characteristics and applications, among which, optical switches based on the excitation of Surface plasmon polaritons have attracted attention due to their fast response time, low power consumption, and nanometer-scale (Emadi et al. 2017; Ghadrdan and Mansouri-Birjandi 2016; Ghadrdan and Mansouri-Birjandi 2017; Nurmohammadi et al. 2018; Zhang and Yang 2019; Shahamat and Vahedi 2018). Surface plasmon polaritons (SPPs) are electromagnetic waves propagating at the interface between a metal and a dielectric material. In the metal structures, only TM polarization excites the SPPs. When light with TM polarization is applied to the metal structure, SPPs are excited (Kik and Brongersma 2007; Maier 2007). Add-drop filters, logic gates, multiplexers, and specifically switches are various types of plasmonic devices that attracted lots of scientist’s attentions (Bashiri and Fasihi 2019: Fasihi 2014; Ghadrdan and Mansouri-Birjandi 2013; Mansouri-Birjandi et al. 2016; Monfared et al. 2020; Negahdari et al. 2019). Plasmonic switches are in the range of nanometres with fast response, low input power, and high transmission efficiency. One of the important and interesting approaches for the implementation of plasmonic switches is the optical nonlinear Kerr effect. Plasmonic switches are implemented based on cavities (Hocini et al. 2020; Kwon t al. 2014; Paul and Ray 2016), Mach-Zehnder interferometers (Janjan e al. 2017; Wu et al. 2015), directional couplers (Nozhat and Granpayeh 2012; Petráček 2013), and ring resonators (Ghadrdan and Mansouri-Birjandi 2018; He et al. 2015; Nozhat and Granpayeh 2014; Wu et al. 2014). In this research, we demonstrate an all-optical switch based on the plasmonic cavity. It has the potentiality to be applied in plasmonic integration circuits. The switching threshold power, and the transmission spectra for the plasmonic switch are achieved. The propagation of electromagnetic waves in the time domain is simulated with the Finite difference time domain (FDTD) (Taflove and Hagness 2005).

2. Theory And Structure

In this study, MIM structures, cavities, and nonlinear characteristics of gold are employed to implement a plasmonic switch. Using high Kerr coefficient material, cavities, and inserting a piece of gold inside the cavities, result in an all-optical switch with a low power consumption and fast speed. For the first time, in addition to the material with a high nonlinear Kerr coefficient, the inherently nonlinear characteristics of the gold are the other factor used to implement a plasmonic switch. Because the high light intensity results in significant nonlinear effects in gold that might be due to displacement of free and bonded electrons (Abajo 2008; Dadap et al. 2009; Feng et al. 2012; Gramotnev and Bozhevolnyi 2010; Lin 2011; Taher-Rahmati and Granpayeh 2014).

Figure 1, shows a schematic of the proposed switch comprising a bus waveguide side coupled with a pair of asymmetric vertical cavities. The complex dielectric constant of silver is determined by the Drude model (Nozhat and Granpayeh 2014):

$$\varepsilon_{m} = \varepsilon_{\infty} - \omega_{p}^{2}/(\omega^{2} - j\gamma\omega) \qquad (1)$$

, where ε_∞, ω_p, $\gamma_{p,}$ and ω are the relative permittivity at the infinite frequency, the plasma frequency, the electron collision frequency, and the angular frequency of the incident light wave, respectively. In this paper, the parameters are the following: ε_∞ = 1.95, ω_p =1.37×10^{16} (rad/s), and γ = 20×10^{12} rad/s, which taken from (Nozhat and Granpayeh 2014).

The straight waveguide and the cavities are filled with air and the nonlinear Au/SiO_2, respectively. The dielectric in the straight waveguides is air with a refractive index n_0=1. The dielectric in the cavities is Au/SiO_2 with high Kerr nonlinearity, which has the refractive index of n=1.47 and Kerr non-linear coefficient of n_2=2.07×10^{-9} cm^2/W (Liao et al. 1998).

The width of the waveguide and the width of the two asymmetric vertical cavities, w, are assumed to be 150 nm. Also, the distance between the cavities, d, is assumed to be 150 nm. A 100×100 nm square of gold is inserted inside the cavities.

When light with TM polarization is injected into the MIM structure, it couples to the waveguide and SPP waves propagate along the common metal surfaces. If the wavelength of the applied light is the same as the resonant cavity wavelength, the light does not pass. This wavelength is sensitive to the dielectric constant that can be changed due to the nonlinear Kerr effect of the material. Therefore, by increasing the intensity of the input light, the wavelength changes and switching is performed. Table 1, presents the physical and geometric parameters of the proposed switch.

Table 1

Physical and geometric parameters of the switch

Symbol	Parameter	Material	Quantity
n_b	Background refractive index	Ag	Drude model (Liao et al. 1998)
n_2	Dielectric Kerr non-linear coefficient	Au/SiO_2	$2.07 cm^2/GW$ (Liao et al. 1998)
n_0	Dielectric linear coefficient	Au/SiO_2	1.47 (Liao et al. 1998)
w	waveguide width	Air	150 nm
d	cavities distance	Ag	150 nm

3. Design And Simulation

The asymmetric nonlinear cavity pair of the nanostructure shown in Figure 1, has a strong resonant wavelength. Figure 2, shows the transmission spectrum of the structure for low and high input intensities. Considering Figure 2, at the low intensity (0.01mW/ μm^2), a sharp dip occurs at the wavelength of 860 nm. If the input light intensity is increased to 0.1mW/ μm^2, the dielectric constant of the nonlinear material also increases, and the dip is red shifted to 880 nm.

Figure 3, shows the dependency of signal transmission on the intensity of the input light. If the intensity of the input light changes, the dielectric constant changes and causes a difference in the transmission spectrum of the signal. Therefore, a mechanism is provided to the dual behavior of light at the output regarding the input light intensity. It should be noted that the constant dielectric change is due to the field intensity in the cavities. When the input light intensity is increased to 0.1mW/μm^2, the signal transmission to the output increases suddenly to about 0.8. The threshold power of the signal is about 0.07mW/μm^2, therefore, only higher light intensity than the threshold power is required to realize the switching operation.

To demonstrate the performance of the incident light signal under on/off conditions, the magnetic field distribution of the structure for low and high light intensities is shown in Figure 4. As shown, when the input light intensity is about 0.01mW/ μm^2, the signal is reflected, and when the input light intensity increases to 0.1mW/ μm^2, it can pass the straight waveguide. The results are in good agreement with the signal transmission spectrum response under on/off conditions.

In addition to the nonlinear material with a high Kerr effect, the low light intensity required for switching is due to employing gold nanostructures inside the cavities. To ensure the validity of this issue and studying the effect of these square gold nanostructures, the proposed switch structure is studied and simulated in the absence of the gold nanostructures inside the cavities. Considering the transmission spectrum of the structure in Figure 5 for low input intensity of 0.01mW/μm^2, a sharp dip in the transmission spectrum for through port at the resonant wavelengths of 818 and 698 nm. The resonant is observed at a wavelength of 740 nm. The structure is scanned at this wavelength for various light intensities and dependency of the signal transmission to the input light intensity is shown in Figure 6. When the light intensity is increased to 0.2mW/μm^2, the transmission increases to 0.62. The threshold power of the signal is 0.15mW/μm^2. Considering the results, using square gold nanostructures reduces the input light intensity from 0.15mW/μm^2 to 0.07mW/μm^2.

4. Conclusion

In this study, MIM structures, cavities, and intrinsic nonlinear properties of the gold are used to implement an all-optical plasmonic switch. The proposed switch is comprised of a bus waveguide side coupled with a pair of asymmetric vertical cavities. The dielectric in the waveguide and the two cavities are filled with air and Kerr nonlinear material, respectively. A 100×100nm square of gold is also inserted inside the cavities. The transmission spectrum showed that for low input intensities, a sharp dip occurs at the wavelength of 860 nm. When the input light intensity is increased to 0.1mW/μm^2, the dip of the transmission spectrum changes and the transmission power increases to 0.8. The threshold power of the structure with and without using the gold nanostructure is 0.15mW/μm^2 and 0.07mW/μm^2, respectively showing a reduction of 50%.

Declarations

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Conflicts of interest/Competing interests

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Figures

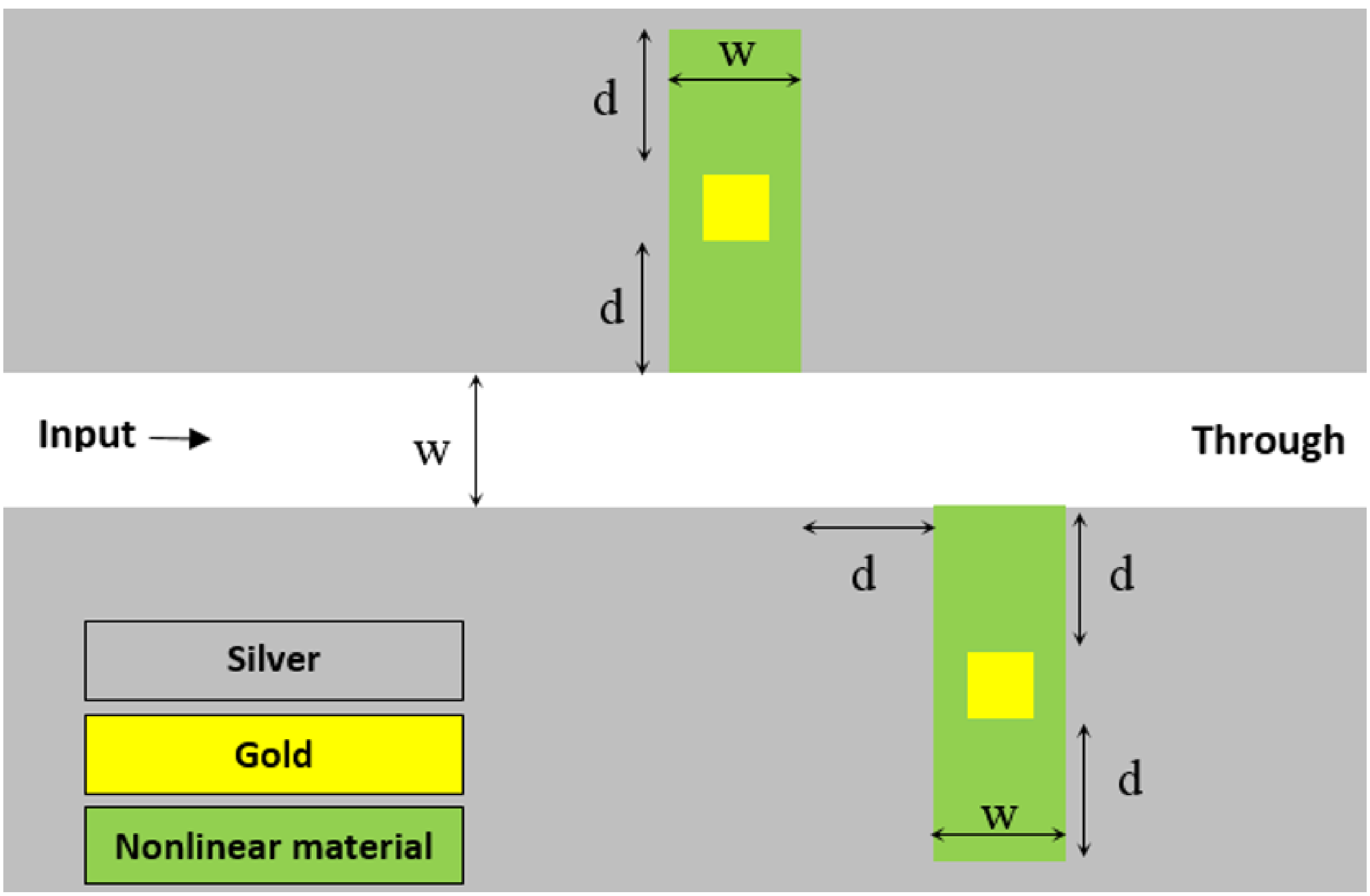

Figure 1

The schematic of the proposed plasmonic switch

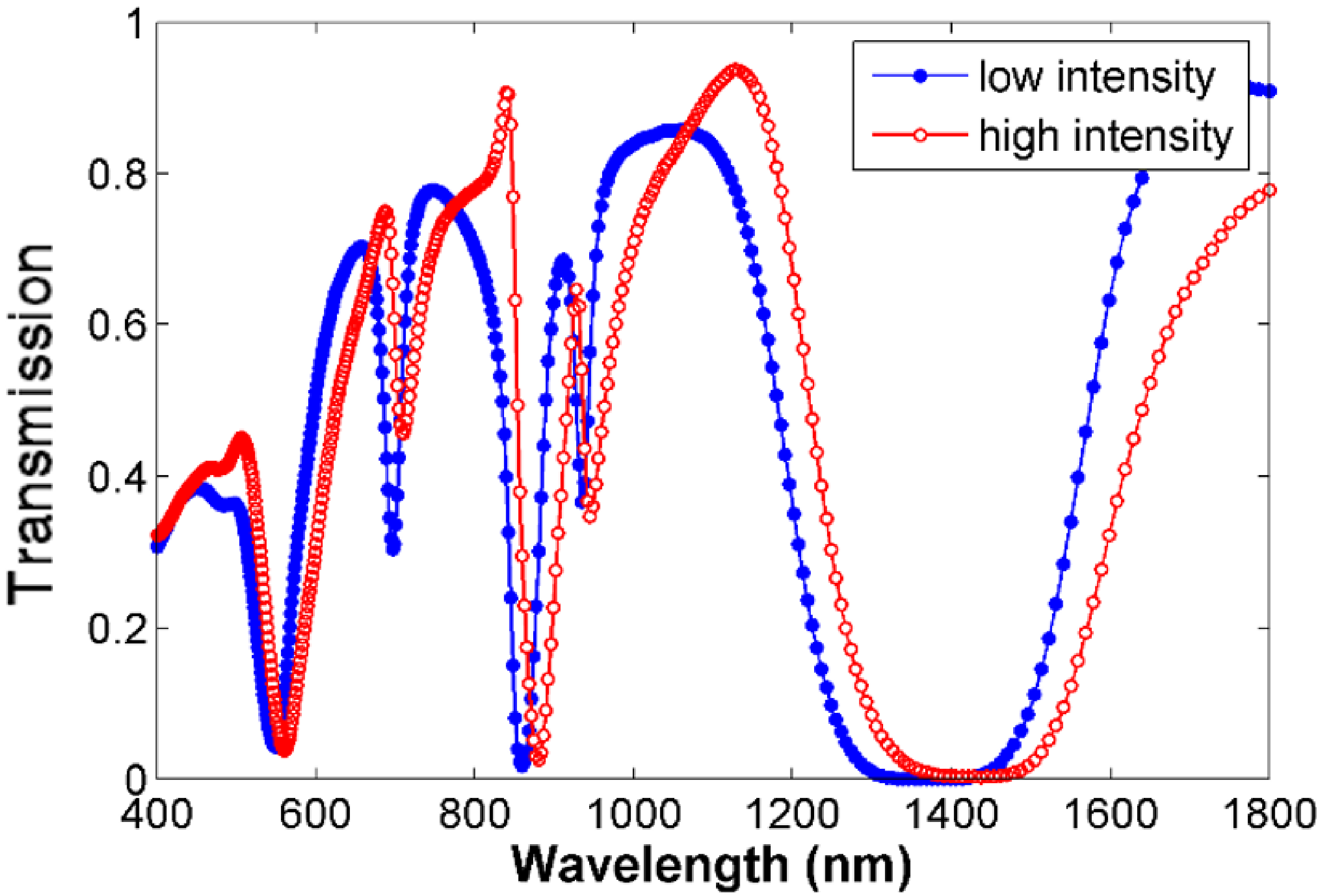

Figure 2

The transmission spectrum of the proposed plasmonic switch for low and high input intensities

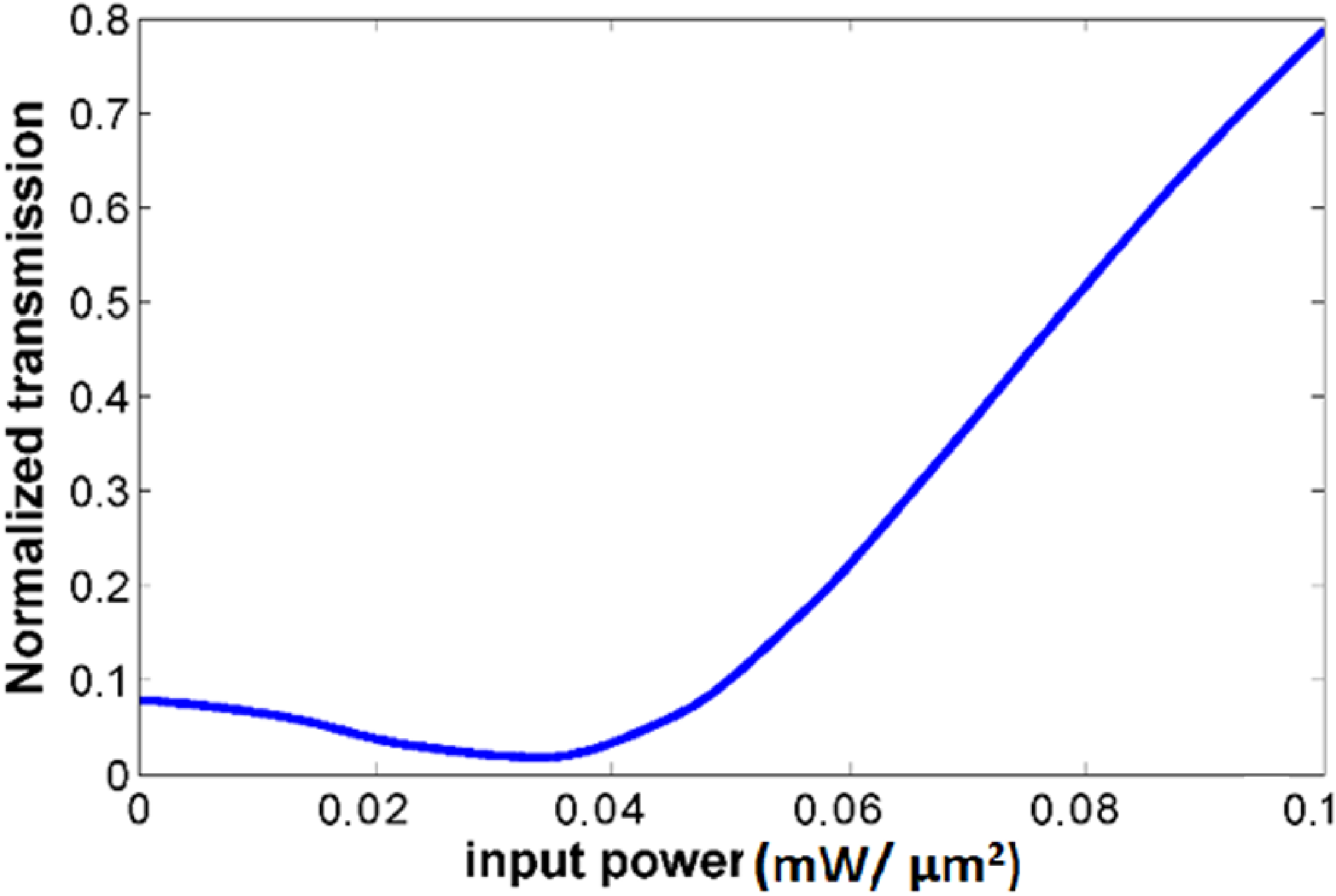

Figure 3

The dependency of signal transmission to the intensity of the input light with gold nanostructures

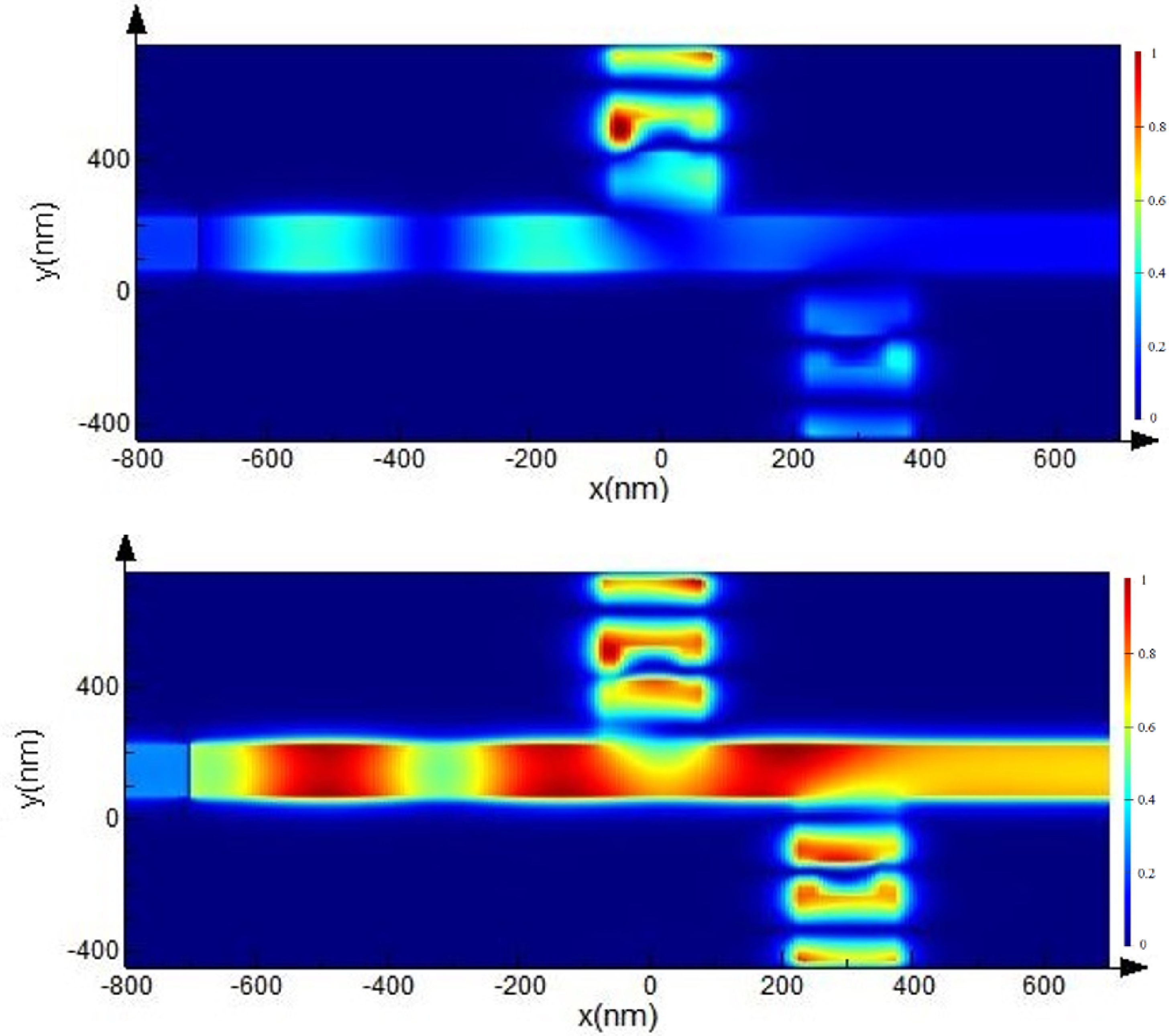

Figure 4

The magnetic field distribution of the structure for low and high light intensities

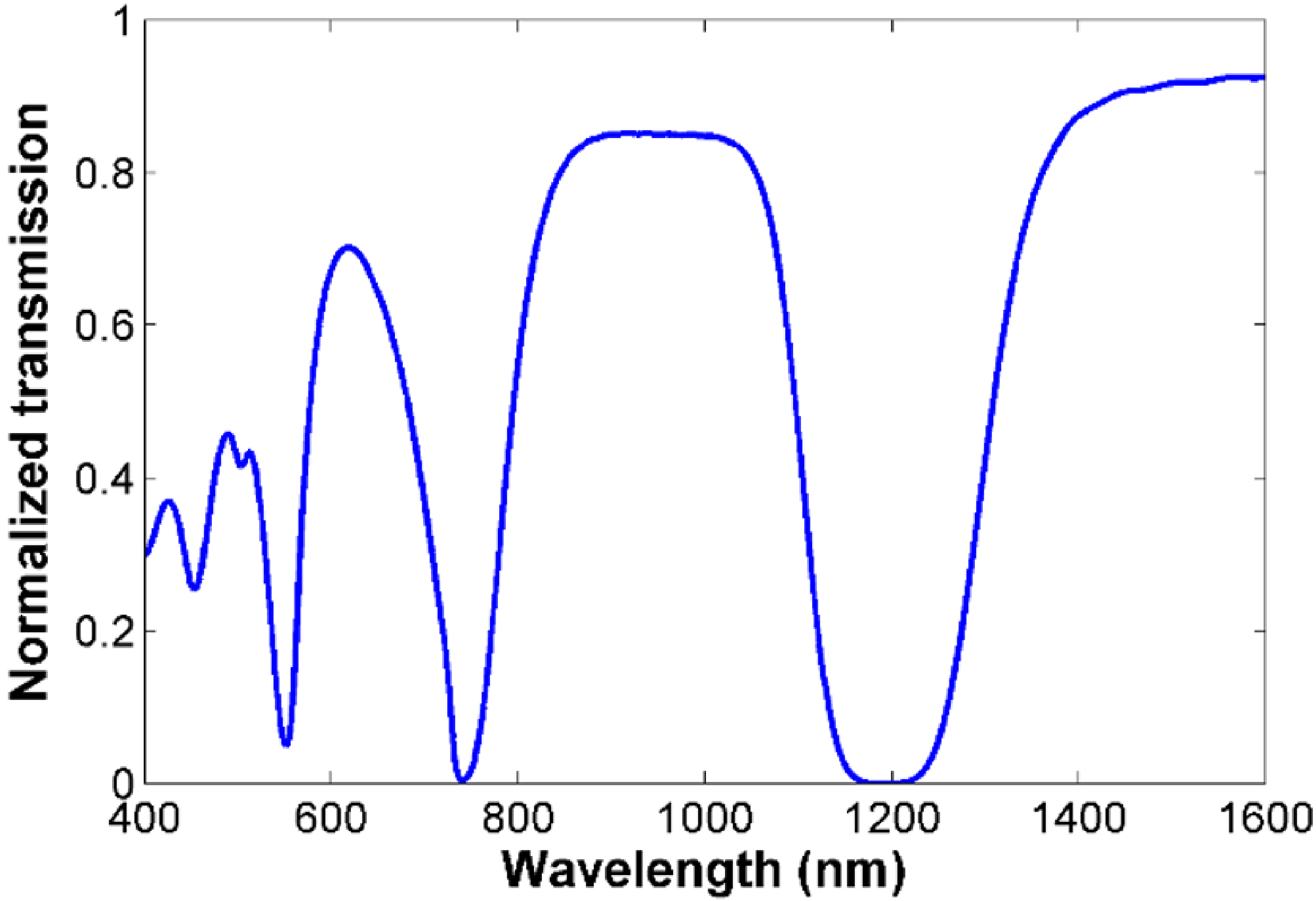

Figure 5

The transmission spectrum of the proposed plasmonic switch without gold nanostructures

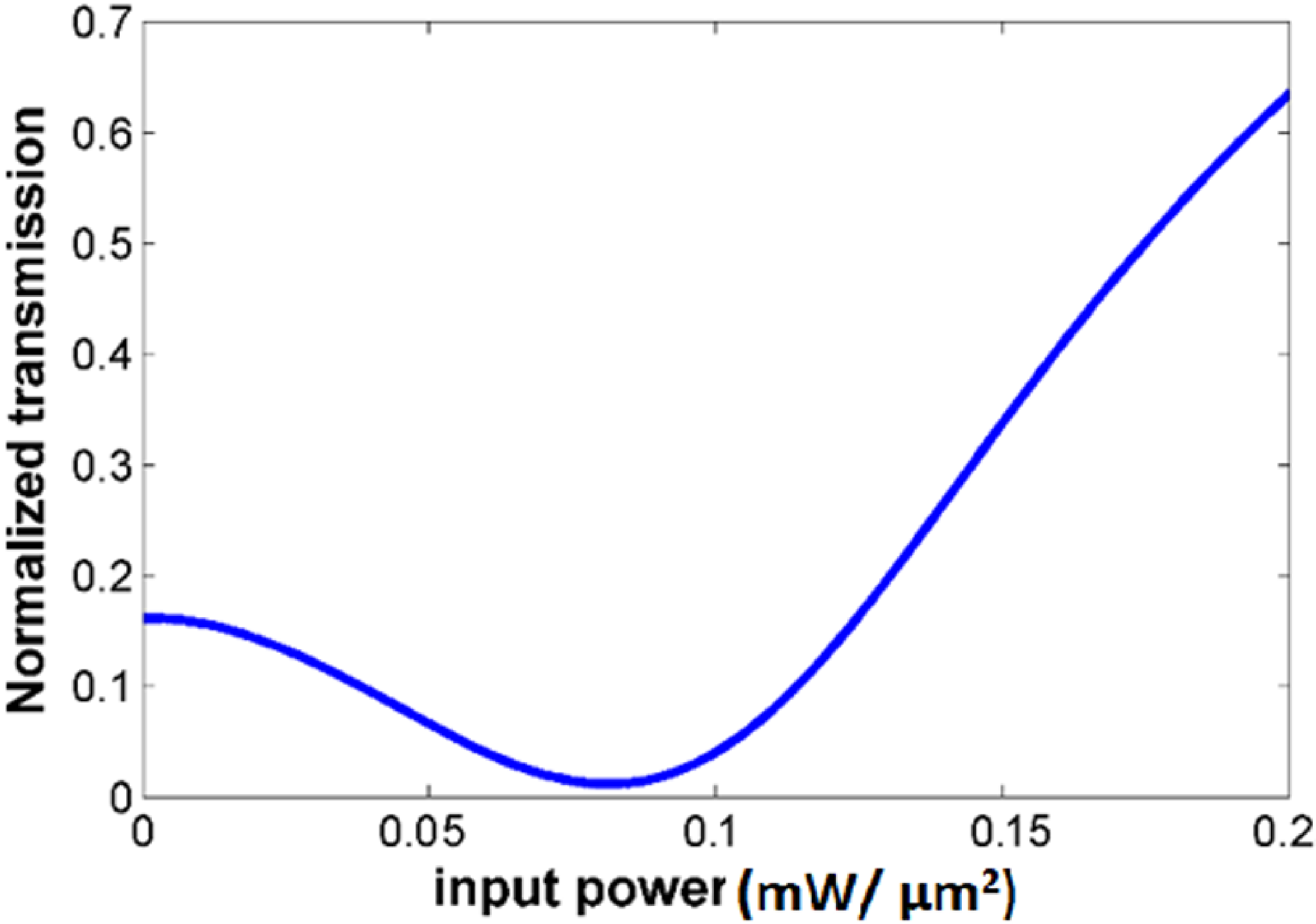

Figure 6

The dependency of the signal transmission to the input light intensity without gold nanostructures