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Ultrafast and low-power all-optical switch based on asymmetry electromagnetically induced transparency in MIM waveguide containing Kerr material

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ABSTRACT

We have proposed the analog of electromagnetically induced transparency (EIT) in a metal–insulator–metal (MIM) plasmonic waveguide side coupled with two stub resonators containing Kerr material. The mechanism of the EIT-like transmission sp ectra in our structure is theoretically analyzed and numerically investigated by using the Finite-Difference Time-Domain (FDTD) method. It is found that the symmetry of the EIT-like spectra can be broken and the asymmetry degree of the EIT-like spectra can be enhanced by increasing the width of the double stub resonators. Taking advantage of the asymmetry EIT phenomenon in the proposed plasmonic system, an ultrafast and low-power all-optical switch with femtosecond-scale feedback time and a required bistable pump light intensity as low as 24.2 MW/cm^2 was proposed and numerically investigated. The proposed all-optical switch may find potential important applications in highly integrated optical circuits.

1. Introduction

Photonic components are superior to electronic ones in terms of operational bandwidth. The diffraction limit of light, however, poses a significant challenge to the miniaturization and high-density integration of optical circuits. Surface plasmon polaritons (SPPs), propagating along the dielectric–metal interface with the capability of overcoming the diffraction limit [1], are regarded as a promising candidate for significantly miniaturizing the optical devices. Recently, numerous devices based on SPPs have been proposed and demonstrated, such as filters [2,3], interferometer [4], modulators [5], nano sensors [6,7], wavelength demultiplexer[8], high power superluminescent light emitting diodes (SLEDs) [9,10], and optical switches [11–15]. The metal–insulator–metal (MIM) structures consist of a dielectric waveguide and two metallic claddings, which strongly confine the incident light in the insulator region. A series of optical devices based on MIM waveguide have been studied numerically and experimentally [16–18]. Usually manifesting itself in a three-level system, the highly narrow pass-band spectrum of EIT is the result of destructive interference between a bright (broadband) absorption band and a dark (narrowband) resonance state [19]. Supporting a strongly dispersive and narrow band-pass in an opaque medium, EIT has been widely studied and used in slow light [20] and sensor applications [21]. So far a variety of mechanisms have been proposed, including optical antennas [22], coupled optical resonators [23,24], and array of metallic nanoparticles [25].

Recently, surface plasmon polaritons (SPPs) were found to be capable of paving another way to realize strong nonlinear optical effects and minimize all-optical components, attributing to its significant enhancement of optical field intensity and the ability of light manipulation in a nanoscale domain [1,26,27]. And using optical nonlinear effects seems an attractive approach for controlling of optical signal flexibility in plasmonic devices because those nonlinear materials can be operated in an all-optical means with ultrafast response time. Some all-optical bitable switches have been reported [13–15]. Due to the strong light confinement and small dimension of metal–insulator–metal (MIM) waveguides, some nonlinear all-optical devices based on MIM waveguides with nanometeric sizes have been investigated [28–30]. However, these researches have mainly focused on the basic properties of optical bistability or transmission response under different incident intensities. The all-optical switching assisted by pump light is an important way to control light with light. As a key factor of switching, the response time and power consumption of the all-optical switch should be taken into account before the practical applications.

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In this paper, an ultracompact plasmonic system with a bus waveguide side coupled with double stub resonators containing Kerr material was proposed and numerically investigated. The mechanism of the asymmetry EIT-like transmission spectra of our structure was theoretically studied and analyzed, both the analytical analysis and the simulation results reveal that the asymmetry degree of the EIT-like spectra can be enhanced by increasing the width of the double stub resonators. Taking advantage of the asymmetry EIT-like transmission spectra in the proposed plasmonic structure and the nonlinear optical properties of the Kerr material, an ultrafast and low-power all-optical switch with femtosecond-scale feedback time and a required bistable pump light intensity as low as 24.2 MW/cm^{2}was proposed and numerically investigated by using FDTD method. Our ultrafast and low-power all-optical switching structure has important potential applications for all-optical information processing in highly integrated optical circuits.

2. Structure design and analytical model

Fig. 1 shows the schematic of a generic EIT system, which compose a bus waveguide side coupled with a pair of stub cavities. The width of the bus waveguide Wi is set as 50 nm, the length of the two stub cavities are set as $L_1 = 470$ nm and $L_2 = 410$ nm, respectively. The width of the two stub cavities are defined as $W_1 = W_2 = w$. Here, w is a variable parameter and will be discussed in the following sections. The dielectric in the metal slit and the two stub cavities are filled with Kerr nonlinear material. Considering that Au/SiO$_2$ has a large value of $\chi^{(3)}(1.7\times10^{-7}$ esu) and a short response time (200 fs) [31], which is good for reducing the response time and the power consumption of the all-optical switch. So the Kerr material is chosen as Au/SiO$_2$, whose refractive index can be expressed as [13]: $n = n_0 + n_2 I$, where $n_0 = 1.47$ is the linear refractive index, $n_2 = 2.07\times10^{-9}$ cm^2/W is the nonlinear refractive index coefficient and I is the pumping beam intensity. The metal is assumed as sliver, whose frequency dependent complex relative permittivity is characterized by the Drude model [32]:

$$\varepsilon(\omega) = \varepsilon_\infty - \omega_p^2/(\omega^2 + i\omega\gamma) \tag{1}$$

here $\varepsilon_\infty = 3.7$ is the dielectric constant at infinite angular frequency, ω_p stands for the bulk plasma frequency and is 9.1 eV, which represents the natural frequency of the oscillations of free conduction electrons, γ represents the damping frequency of the oscillations and is 0.018 eV, ω is the angular frequency of the incident light. Since this work is based on the asymmetry EIT-like transmission spectra of the proposed plasmonic structure, so the mechanism of the asymmetry EIT-like spectra should be discussed at first.

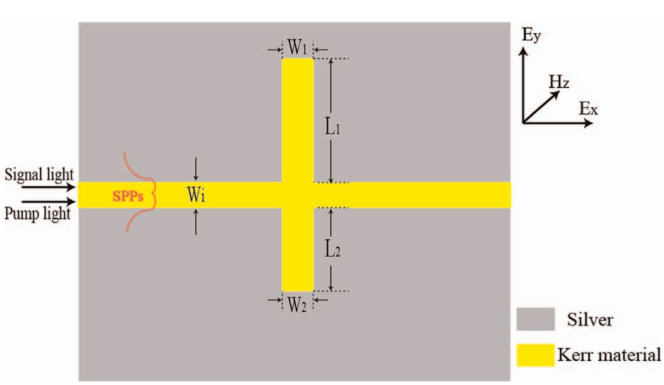

Fig. 1. Schematic diagram of the nanoscale all-optical switching structure.

Fig. 2(a) illustrates the schematic of a generic EIT system, represented with bright-state ($|\psi_b>$) and dark-state ($|\psi_d>$) resonators. As a matter of fact, the asymmetry of the EIT-like transmission spectra of our proposed structure can attribute to the activate the coupling from bright (symmetric) to the dark (anti-symmetric) mode through quasi-orthogonal mode overlap [19]. In order to derive an analytical expression for the degree of EIT asymmetry, we examine the generic spectra of the transmittance (Fig. 2(b)) and then define the degree of spectral asymmetry F to be $\Delta\omega_{high}/\Delta\omega_{low}$, the ratio of high/low wavelength transmission bandwidths (peak-to-node). It is evident that a higher value of F means a more obvious asymmetry EIT-like transmission spectrum.

By taking the differential $dT/d\lambda$ to determine the positions of the transmission peak and nodes, the derivation of F is straightforward. Especially if we introduce a Fano-like asymmetry factor by setting$\rho = (\omega_b - \omega_d)/2\kappa_{bd} = \Delta\omega_{bd}/2\kappa_{bd}$, here ω_b and ω_d are the resonance frequency of the bright mode and the dark mode, respectively, and κ_{bd} is the coupling coefficient between the bright mode and the dark mode. F becomes a function of ρ only [5]:

$$F(\rho) = \frac{\sqrt{\rho^2+1} + \rho}{\sqrt{\rho^2+1} - \rho} \tag{2}$$

The dependent of the degree of spectral asymmetry F on the asymmetry factor ρ is shown in Fig. 2(c), it is obvious that an increase of ρ would equivalently lead to the increase of the EIT asymmetry. So, in order to obtain obvious asymmetry EIT-like transmission spectra, a larger value of ρ is needed. We can increase $\Delta\omega_{bd}$ or decrease κ_{bd}. However, for a fixed length difference between the two stub resonators, increasing the width of the two stub resonators would nearly not affect the coupling coefficient between the bright–dark modes. Thus, increasing the value of $\Delta\omega_{bd}$ is an alternative means. The resonance frequency of the bright can dark mode can be expressed as [5]:

$$\omega_{b\pm} = mc/(n_{eff} L_{1,2}) \tag{3a}$$

$$\omega_d = 2mc/(n_{eff} L_{tot}) \tag{3b}$$

Thus, the separation between the resonance frequencies of the bright–dark mode can be written as:

$$\omega_{bd} = \frac{mc}{n_{eff}}\left|\frac{1}{L_{1,2}} - \frac{2}{L_{tot}}\right| \tag{4}$$

here, n_{eff} is the effective refractive index of SPP mode in the resonators, positive integer m is the resonance order, c is the speed of light in vacuum, and $L_{tot} = L_1 + L_2 + w_i$. The effective refractive index of SPP mode in our structure as a function of the width of the two stub resonators are shown in Fig. 2(d). We can clearly see that the effective index of the SPP mode in the stub resonators is inversely related to their width. Combining with Eq. (4), we can derive that an increase of the width of the double stub can lead to a larger value of $\Delta\omega_{bd}$, and the degree of the asymmetry of the EIT-like spectra would be enhanced according to the relationship between ρ and F as shown in Fig. 2(c) as a result.

In the following works, an ultrafast and low-power all-optical switch based on the highly degree asymmetry EIT-like spectra in the proposed plasmonic system was proposed and numerically investigated.

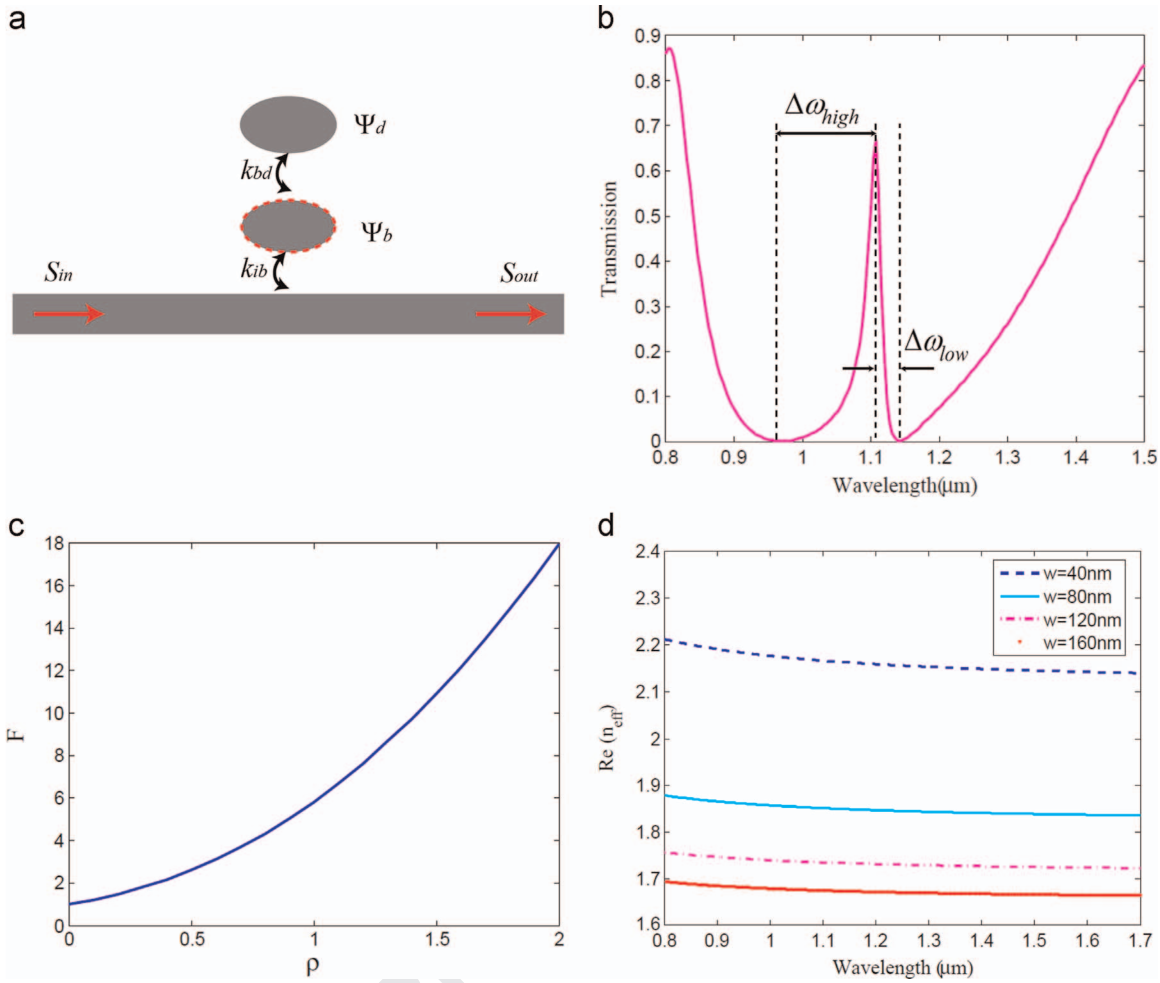

Fig. 2. (a) Schematics of a generic EIT system, represented as coupled dark- and bright mode resonators. (b) Definition of F (degree of spectral asymmetry) for EIT. (c) Behavior of F as a function of the asymmetry factor $\rho = (\omega_b - \omega_d)/2\kappa_{bd}$. (d) The dependent of the effective index of SPP mode in the proposed structure on the incident wavelength for different width of the two stub resonators.

3. Realization of asymmetry EIT-like spectra in our plasmonic system

In this section, the geometric parameters are chosen as $L_1 = 470$ nm, $L_2 = 410$ nm, $W_i = 50$ nm, these parameters are unchanged throughout this section. We define that $W_1 = W_2 = w$, and we range w from 40 nm to 160 nm to observe the transmission spectra. The transmission spectra without pumping light as a function of wavelength for different w are shown in Fig. 3. All of the following simulations are performed by using Lumerical FDTD solutions software based on the FDTD method.

From Fig. 3(a) to (d), we can clearly see that there are two dips appeared at the transmission spectra, and there is a transparency window between the two dips. When $w = 40$ nm, the transparency peak is nearly locate at the center of the two dips. However, when increasing w from 40 nm to160 nm, the transparency peak does not locate at the center of the two dips anymore, it gets away from the left dip and gets close to the right dip, the left dip gets wider and wider and the line shape from the transparency peak to the right dip gets sharper and sharper. The simulation results shown here is consist with the theoretical analysis in Section 2, increasing the width of the double stub will lead a lower value of n_{eff} as shown in Fig. 2(d), which will increase the resonance frequency separation between the bright and dark mode according to Eq. (4). Considering that $\rho = (\omega_b - \omega_d)/2\kappa_{bd}$ and the relationship between ρ and the degree of asymmetry EIT-like spectra, we can obtain that a wider width of the two stub resonators can lead to a higher asymmetry degree of the EIT-like transmission spectra. Namely,$\Delta\omega_{high}$ would become wider and wider and $\Delta\omega_{low}$ would become narrower and narrower.

In order to utilize the nonlinear Kerr effect to design an all-optical switch, pump light should be introduced to the proposed structure. However, the pump light should not affect the signal light. Taking into account this principle, we should make sure that the wavelength of the pump light must have strong resonance in the proposed structure both before and after introducing the pump light. Fig. 4 shows the transmission spectra with different changes of refractive of the nonlinear material with $L_1 = 470$ nm, $L_2 = 410$ nm, $W_i = 50$ nm and $w = 120$ nm. According to Eq. (3), increasing the refractive index of the dielectric filled in the stub resonators would make the resonance wavelength of both the bright mode and the dark mode has a red-shift. As shown in Fig. 4, we can see that when the refractive index of the nonlinear material is increased by 0.05, the transmitted dips have a red-shift and the transmission at 1144 nm wavelength jumps from 0.003 to 0.663. Therefore, the signal light wavelength is chosen as 1144 nm. On the other hand, the transmission at 980 nm wavelength near the resonance modes stay very low (0.005) before and after the change of the refractive index of the nonlinear material. Thus, the light at wavelength of 980 nm will keep strong resonance in the stub resonators, which is helpful for the enhancement of the nonlinear effect. In addition, 980 nm is a common output wavelength of some kinds of lasers. Thus, the wavelength of the pump light is chosen as 980 nm. It should be noted that, since the

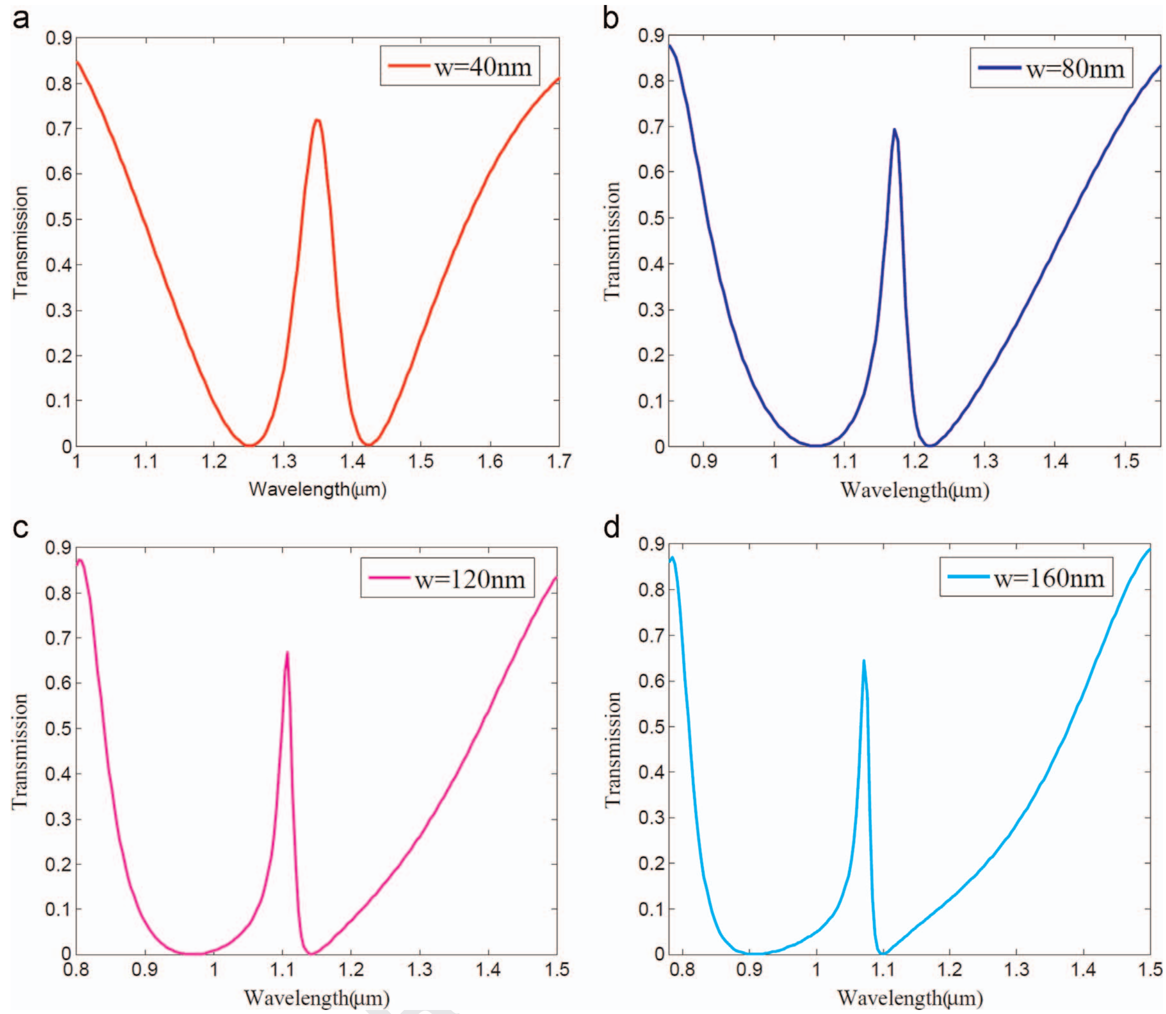

Fig. 3. (a)–(d) The transmission spectra of our plasmonic with a bus waveguide side coupled with two stub resonators as a function of the wavelength of the incident light for different stub widths with (a): $w=40$ nm, (b): $w=80$ nm, (c): $w=120$ nm and (d): $w=160$ nm, respectively. The other parameters are the same in the four figures with $L_1 = 470$ nm, $L_2 = 410$ nm, and $W_i = 50$ nm.

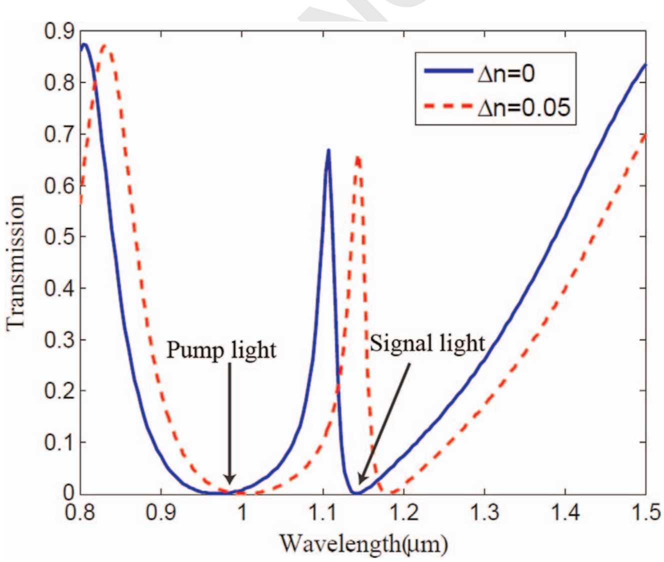

Fig. 4. Transmission spectra with different changes of refractive index of the nonlinear material with $L_1 = 470$ nm, $L_2 = 410$ nm, $W_i = 50$ nm and $w=120$ nm.

resonance wavelengths of the bright and dark mode are sensitive to the effective refractive index of the SPP mode and the length of the stub resonators according Eq. (3), so desired signal light and pimp light can be selected by tuning the length of the stub resonators or by varying the effective refractive index of the SPP mode in our structure, such as tuning the stub width or using different materials.

It worth noting that, there are two merits of utilizing asymmetry EIT-like spectra to design an all-optical switch:

(1) As we do not want the pump light has influence on the signal light, a broad band of the left dip helps to make sure that the wavelengths around the first dip keep strong resonance before and after introducing the pump light, which is helpful for choosing the wavelength of pump light. There is no need to add extra filter to reflect the pump light unlike reference [11]. Simpler structure makes it more suitable for practical use than those complicated ones.
(2) As the value of $\Delta\omega_{low}$ is getting smaller and smaller with the increase of the width of the double stub resonators. The required increment of the refractive index of the Kerr material for the signal light from off to on can be reduced as a result. Since the refractive index of the Kerr material is $n = n_0 + n_2 I$, and n_0 is a constant, I is the pump light intensity. The increment of the refractive index of the Kerr material caused by the

pump light can be expressed as $\Delta n = n_2 \Delta I$, so a smaller required Δn means a smaller required pump light intensity. Thus, the pump intensity can be reduced as low as possible by utilizing the high degree asymmetry EIT-like spectra.

4. Simulation results and discussion of the proposed all-optical switch

As has been analyzed in Section 3, the geometric parameters are set as $L_1 = 470$ nm, $L_2 = 410$ nm,$w_i = 50$ nm, and $w = 120$ nm. The pump light wavelength is set to be 980 nm and 1144 nm was chosen as the wavelength of the signal light. The signal transmission spectra of our structure with and without pump light is shown in Fig. 5(a), it is obvious that the transmission of signal light (1144 nm) jumps from 0.003 to 0.663 when the pump light (980 nm) is turned from off to on, which shows a significant switching effect, and the on/off states correspond to the presence/absence of pumping. Fig. 5(b) shows the dependence of the signal light transmission with an increase and decrease of the pump light intensity in which a clear bistability loop can be observed due to the SP's enhanced third-order nonlinear effect in the nonlinear material. While changing the intensity of the pump light, the change of the refractive index of the nonlinear in the stub resonators induced by spatial field intensity gives rise to different transmission value of signal light, which can provide a mechanism for bistable behavior of the signal light with the intensity of the pump light. When the intensity of pump light increase, the signal transmission rapidly jumps to a higher value at about

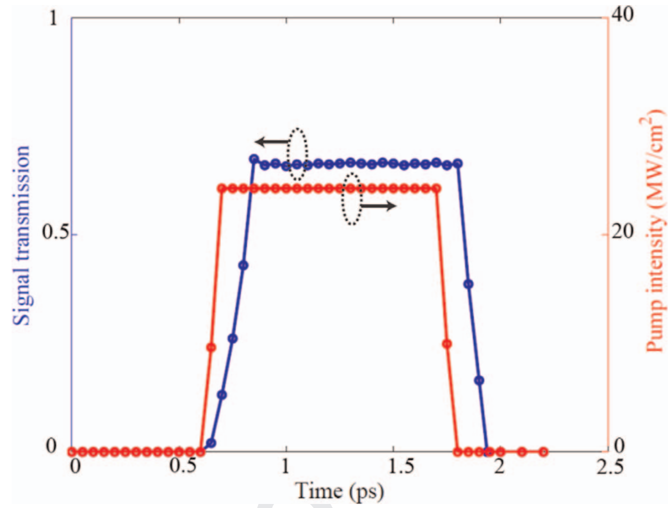

Fig. 6. Signal transmission (blue circle line) versus time. The red circle line is the temporal profile of pump light with an input intensity of 24.2 MW/cm^{2}and a duration time of 1.2 ps (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

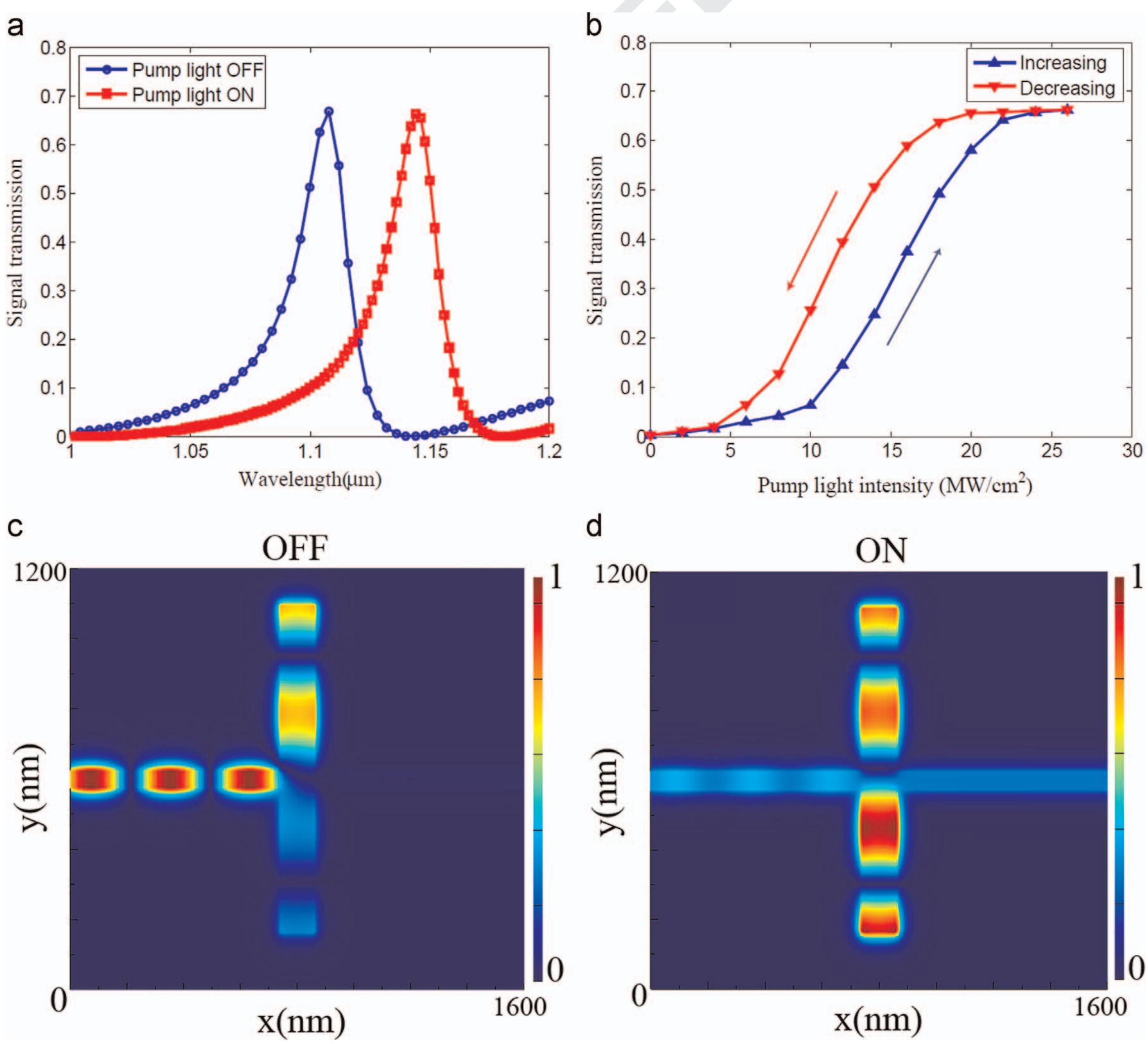

Fig. 5. (a) Signal transmission with pump light off and on. The wavelength of the pump light is 980 nm. The pump intensity is 24.2 MW/cm^2. (b) Transmission of signal light (1144 nm) by increasing and decreasing intensity of pump light. The normalized contour profiles of $|H_z|$ for signal light with pump light off (c) and on (d).

16 MW/cm^2.However, when the intensity of the pump light decrease, the signal transmission will sustain higher values until the dropping point of about 14 MW/cm^2.The bistability effect will be influenced by the geometry parameters, so another geometric parameters settings for a new signal light and pump light could achieve a better bistability loop. It is clear in Fig. 5(b) that the requirement of pump light intensity is about 24 MW/cm^2, which is far lower than the result obtained in Ref. [11,33].

In order to more clearly understand the switching effect, the magnetic field distributions $|H_z|$ of signal light with pump light off and on are plotted in Fig. 5(c) and (d), respectively. It is found that the signal light is reflected when the pump light is off, while it can pass through the waveguide when pump light turned from off to on. The results are in good agreement with signal transmission response with switching off and on as shown in Fig. 5(a).

Successively, the switching time of our proposed all-optical switch is also investigated and shown in Fig. 6. To determine the switching time, a square pulse pump light (980 nm) is launched into our system with an input intensity of 24.2 MW/cm^{2}and a duration time of 1.2 ps. The transmission spectra of the signal light and the pump light intensity versus time are shown in Fig. 6. It is found that the response time of signal light switching up and down are about 150 fs, which is an ultrafast value. It should be noted that the switching time is calculated without considering the delay time of the Kerr nonlinear medium, and thus it originates from the feedback of the structure, which represents the shortest switching time of the structure [14]. In practice, the response time of the Kerr nonlinear medium can also affect the final response time of the proposed all-optical switch. The nonlinear material in our structure is selected as Au/SiO2, which exhibits an ultrafast nonlinear response of 200 fs [13]. As the response time of the Kerr material used here is larger than the feedback time of our structure, the final response time is determined by the Kerr nonlinear medium. Even so, the results denote that the femtosecond-level switching time can be realized in our nanoplasmonic structure. And we believe that the response time of the proposed all-optical switch can be further reduced by employing a proper Kerr medium which exhibits a shorter response time in our structure. In addition, it is evident that the requirement of the pump light intensity is just about 24.2 MW/cm^2, which is far less than Ref. [11,33] and can be easily achieved by pulse laser. On the other hand, the extinction ratio is defined as [34]:

$$Ex.\ R.\ (dB) = 10\ \mathrm{Lg}\left(\frac{P_{out}\,|ON}{P_{out}\,|OFF}\right) \tag{5}$$

where, $P_{out}\,|ON$ and $P_{out}\,|OFF$ are the power of the output with and without the pump light, respectively. Combining our simulation results and Eq. (5), we obtain the extinction ratio of our all-optical switch is 32.1 dB.

In fact, the requirement of the pump light intensity can be further decreased by increasing the width of the two stub resonators on condition that there exist EIT-like transmission spectra. Because the increment of the refractive index of the Kerr material caused by the pump light can be expressed as$\Delta n = n_2 \Delta I$, and increase of the width of the two stub resonators would lead to a higher asymmetry degree of the EIT-like response spectra as has been analyzed in part2. Namely, $\Delta\omega_{high}$ would get wider and wider and $\Delta\omega_{low}$ would get narrower and narrower with the increase of the two stub resonators. And the resonance wavelength of the bright and dark is proportional related to the effective index of the SPP mode according to Eq. (3). So a narrower $\Delta\omega_{low}$ means a smaller required Δn, and a smaller required Δn means a lower required pump light intensity according to $\Delta n = n_2 \Delta I$.

It worth mentioning that, dating back to the year of 2006, filling dielectric into nano cavities had been reported by using magnetron sputtering technology [18]. Thus, filling dielectric into the little slit and the two stub resonators seems possible and can be carried out by experiment, which paves a way for practical use of our all-optical switch.

5. Summary

In conclusion, we have proposed a nanoscale structure based on MIM waveguide containing Kerr material. The transmission characteristics, optical bistability, and the switching response time were investigated by FDTD method. Both the theoretical analysis and the simulation results reveal that the asymmetry degree of the EIT-like spectra could be enhanced by increasing of the width of the two stub resonators. Based on the asymmetry EIT-like spectra, we proposed and numerically investigated an ultrafast and low-power consumption all-optical switch. By properly tuning the pump light intensity, an obvious optical bistability and an intriguing switching effect of the signal light with femtosecond-scale feedback time were realized. In addition, thanks to the high degree asymmetry EIT-like phenomenon, the required pump light intensity to get the optical bistability can be as low as 24.2 MW/cm^2 and there is no need to add extra filter to reflect the pump light. This simple and ultracompact switching has significant applications for all-optical signal processing as well as optical communications and computing in highly integrated optical circuits.

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