Ultrafast all-optical switching in nanoplasmonic waveguide with Kerr nonlinear resonator

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Abstract: A novel ultrafast all-optical switching based on metal-insulator-metal nanoplasmonic waveguide with a Kerr nonlinear resonator is proposed and investigated numerically. With the finite-difference time-domain simulations, it is demonstrated that an obvious optical bistability of the signal light appears by varying the control-light intensity, and an excellent switching effect is achieved. This bistability originates from the intensity-dependent change induced in the dielectric constant of Kerr nonlinear material filled in the nanodisk resonator. It is found that the proposed all-optical switching exhibits femtosecond-scale feedback time.

OCIS codes: (240.6680) Surface plasmons; (190.1450) Bistability; (130.4815) Optical switching devices; (140.4780) Optical resonators; (130.3120) Integrated optics devices.

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1. Introduction

All-optical signal processing in integrated photonic circuits and its applications in optical computing and communications require the ability to control light with light [1]. An amount of all-optical devices based on nonlinear optical effects have been proposed and investigated [2,3]. However, there are two main drawbacks in most of these devices. Firstly, the minimum size is limited by enough light passlength. Secondly, high operational light intensity is necessary for sizeable nonlinear response [4]. In order to overcome these drawbacks, the nonlinear devices on the basis of photonic crystal defects have been proposed by using the field confinement and enhancement in the defect areas [5,6]. 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 [7–15]. Quite recently, several types of nonlinear optical devices based on SPPs have been studied [16–23]. For instance, an all-optical switching was proposed and investigated in subwavelength metallic grating structure containing nonlinear optical materials [16]. However, the dimension of such structure may restrict its applications in highly integrated optical circuits due to the periodic array. Due to the strong light confinement and small dimension of metal-insulator-metal (MIM) waveguides [22,23], some nonlinear all-optical devices based on MIM waveguides with nanometeric sizes have been investigated [20–23]. 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 important way to control light with light. As a key factor of switching, the response time should be taken into account before the practical applications.

In this paper, we propose and numerically investigate a novel nanoscale all-optical switching structure based on MIM waveguide with a nonlinear nanodisk resonator. The dielectric constant of Kerr nonlinear medium in the resonator is changed by varying the pump

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light and the signal transmission can thus be controlled. The finite-difference time-domain (FDTD) results show that the all-optical switching exhibits ultrafast response property. Femtosecond-level response time can be realized, for example. Our ultra-compact switching structure has important potential applications for all-optical information processing in highly integrated optical circuits.

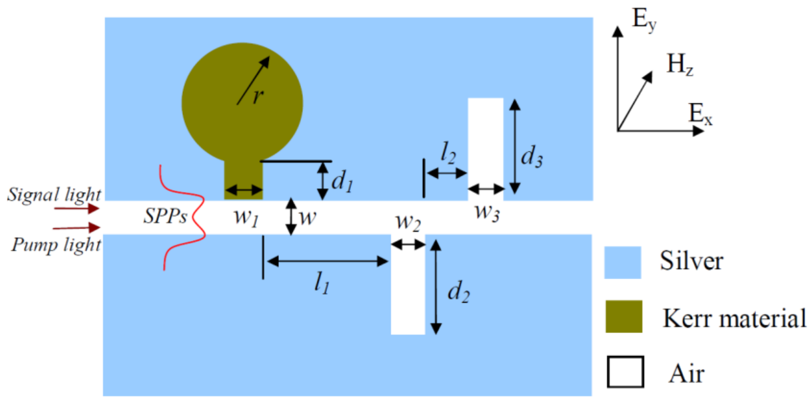

Fig. 1. Schematic diagram of the nanoscale all-optical switching structure: *r*, radius of nanodisk resonator; *w*, width of metallic waveguide; w_1, width of coupling aisle; d_1, length of coupling aisle; w_2 and w_3, tooth widths; d_2 and d_3, tooth depths.

2. Model and principles

Figure 1 shows the all-optical switching structure which consists of two metallic claddings, a side-coupled nanodisk resonator, and an asymmetric tooth-shaped filter. The metal is assumed as silver, whose relative permittivity can be described by the well-known Drude model with (ε_∞, ω_p, γ) = (3.7, 9.1 eV, 0.018 eV) [24], where ε_∞ is the dielectric constant at the infinite frequency, γ and ω_p represent the electron collision frequency and bulk plasma frequency, respectively. The increased loss of silver in the nanostructure [13] is neglected and not involved in our simulations. The nanodisk resonator is filled with Kerr nonlinear material whose dielectric constant ε_c depends on the intensity of electric field $|E|^2$: $\varepsilon_c = \varepsilon_0 + \chi^{(3)}|E|^2$. The value of linear dielectric constant ε_0 is set as 2.0. The Kerr nonlinear material is assumed to be Ag-BaO, and its third-order nonlinear susceptibility at wavelength of 820 nm is $\chi^{(3)} = 4.8 \times 10^{-10}$ esu [25]. The two photon absorption and induced free carrier effect in the nonlinear material are not considered in our numerical model. When TM-polarized lights are injected to the MIM structure, the incident light will be coupled into the waveguide and the SPP waves are formed on metal interfaces as shown in Fig. 1. Meanwhile, the incident light is coupled into the nanodisk resonator through the coupling aisle. The standing wave modes in the nanodisk resonator will be excited if the resonant condition is satisfied [26]. It is well-known that the resonant mode is sensitive to the dielectric constant [27,28] which can be altered by pump light owing to the optical Kerr effect of nonlinear material. Due to the high quality factors of disk-shaped cavities [28,29], the resonance field intensity in the cavity will be greatly enhanced and then causes strong nonlinear effect. The transmission spectrum near the resonant mode can be described by the temporal coupled mode theory [30], and the transmission is described as $T(\omega) = [(\omega-\omega_0)^2 + (1/\tau_i)^2]/[(\omega-\omega_0)^2 + (1/\tau_i + 1/\tau_\omega)^2]$, where ω is the frequency of incident light and ω_0 represents the resonance frequency, $1/\tau_i$ stands for the decay rate of the field induced by the internal loss in the resonator, and $1/\tau_\omega$ is the decay rate by the power escape through the waveguide. At the resonance frequency ω_0, the transmission spectrum has a dip with minimal value of $(1/\tau_i)^2/(1/\tau_\omega + 1/\tau_i)^2$. At the right side of the nanodisk resonator, the simple tooth-shaped waveguide can function as a filter [31,32] which is employed to reflect the pump light. The FDTD method is utilized to calculate the linear and nonlinear responses of our structure [33]. In the FDTD algorithm, the spatial and temporal

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steps are set as $\Delta x = \Delta y = 5$ nm and $\Delta t = \Delta x/2c$ [34], which are found to be sufficient for the convergence of numerical results.

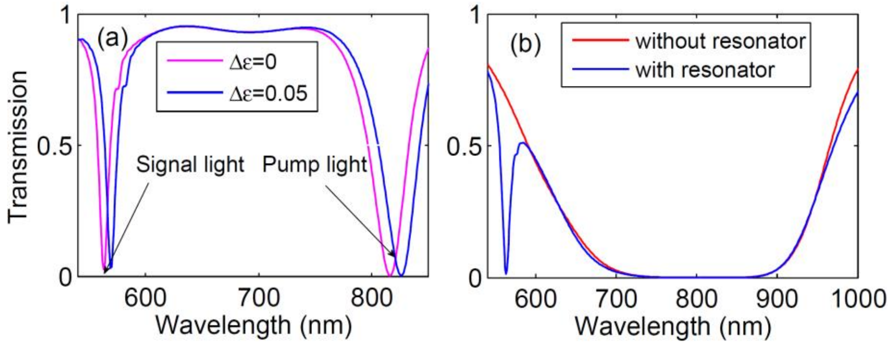

Fig. 2. (a) Transmission spectra with different changes of dielectric constant. (b) Transmission spectra without nanodisk resonator (only tooth-shaped filter) and with nanodisk resonator (whole waveguide).

As shown in Fig. 1, the width of plasmonic waveguide is set as $w = 50$ nm [31]. The geometric parameters of nanodisk resonator is assumed as $r = 145$ nm and $w_1 = 50$ nm. Figure 2(a) shows the transmission spectra of MIM waveguide with the disk-shaped resonator. Two transmitted dips corresponding to wavelengths of 816 nm and 563 nm are observed, respectively. They represent two different resonance wavelengths. When the dielectric constant of the nonlinear material is increased by 0.05, the transmitted dips have a red-shift and the transmission at 563 nm wavelength increases from 0.03 to 0.5. Therefore, the signal light wavelength is set to be 563 nm. Meanwhile, the transmission values at 820 nm wavelength near the resonant modes are very low (0.08) before and after the change of dielectric constant. Thus, the light at wavelength of 820 nm will keep strong resonance in the nanodisk resonator which is helpful for the enhancement of nonlinear effect. The wavelength of 820 nm is suitable for pump light wavelength and corresponds to the test wavelength of the chosen Kerr nonlinear material [25]. In addition, the asymmetric tooth-shaped waveguide is utilized to filter the pump light in our structure [31,32]. We choose the parameters as $w_2 = w_3 = 40$ nm, $d_1 = 55$ nm, $d_2 = d_3 = 110$ nm, $l_1 = 205$ nm, and $l_2 = 60$ nm. As can be seen in Fig. 2(b), the tooth-shaped waveguide filter can efficiently reflect the pump light, while has no influence on the transmission at wavelengths around 563 nm (i.e., signal light wavelength).

3. Simulation results and discussions

This nanostructure has strong resonance in the nonlinear resonator at the control-light wavelength, which can enhance the nonlinear Kerr effect of the signal light. Figure 3 shows the transmission responses with pump light off and on. It is found that the transmission of signal light (563 nm) jumps from 0.03 to 0.504 when the pump light (820 nm) is turned from off to on, which shows a significant switching effect. Figure 4 shows the dependence of signal transmission on the intensity of control-light. It is observed that an obvious bistability loop is formed in our structure. If the incident control-light intensity is altered, the changes of the dielectric constant induced by spatial field intensity in the resonator gives rise to different transmission effect of signal light. This provides a mechanism for bistable behavior of the signal light with the intensity of the control light. When the pump intensity increases, the signal transmission will increase rapidly and jump suddenly to a higher value at about 410 MW/cm^2. When the pump intensity decreases, the signal transmission will sustain higher values until the dropping point of about 330 MW/cm^2. The bistability effect will be influenced by the structure geometry [35] and, thus, a better bistability could be achieved by the optimization of the structure geometry. The realization of optical bistability only requires the pump intensity of less than 650 MW/cm^2 which is lower than the result obtained in Ref [35].

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The pump intensity may be decreased by optimizing the geometry of our structure for the highest local field in the resonator.

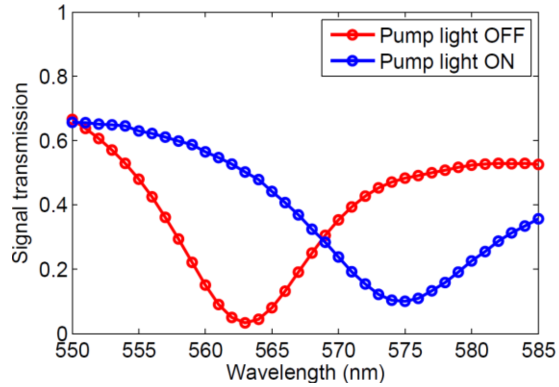

Fig. 3. Signal transmission with pump light off and on. The pump and signal wavelengths are 820 nm and 563 nm, respectively. The pump intensity is 650 MW/cm^2.

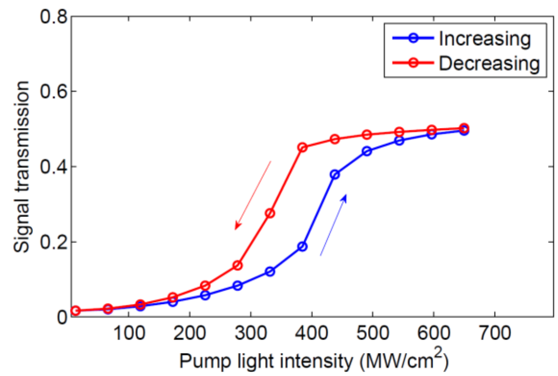

Fig. 4. Transmission of signal light by increasing and decreasing intensity of pump light.

Successively, the time response of the all-optical switching is investigated and shown in Fig. 5. A square pump pulse with an intensity of 650 MW/cm^2 and 1.2-ps duration is impinged into the structure. From Fig. 5, it is found that the response times of signal light switching up and down are about 100 fs which is only a half of the result obtained in Ref [16]. It should be noted that the switching time is obtained without considering the delay time of nonlinear material and it mainly derives from the feedback of the structure. In our FDTD software, the response time of Kerr nonlinear material is not included. The optical Kerr material in our structure is selected as the metal-dielectric composite material Ag-BaO which exhibits an ultrafast nonlinear response time of 210 fs [25]. Therefore, the result denotes that the femtosecond-level switching time can be realized in our nanoplasmonic structure.

To illustrate more clearly the performance of signal light under conditions of switching off and on, the magnetic field distributions $|H_z|$ of signal light with pump light off and on are plotted in Fig. 6. We find that the signal light is reflected when the pump light is off, and can pass through the waveguide when pump light switches on. The results are in good agreement with the signal transmission response with switching on and off.

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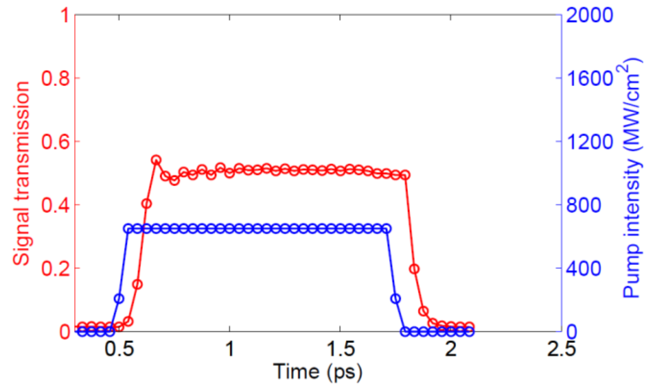

Fig. 5. Signal transmission (red circle line) versus time. The blue circle line denotes the temporal profile of pump light with an input intensity of 650 MW/cm^2.

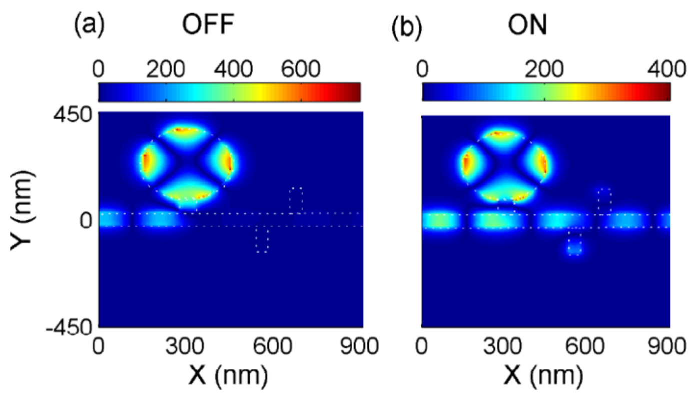

Fig. 6. Magnetic field distributions of signal light with switching (a) off and (b) on.

4. Conclusions

In this paper, we have proposed a novel nanoplasmonic structure based on MIM waveguides with a Kerr nonlinear resonator. The transmission characteristics, optical bistability, and switching effect in this structure have been investigated numerically by the FDTD simulations. By actively tuning the control-light intensity, an obvious optical bistability of the signal light and an excellent switching effect with femtosecond-scale feedback time were realized. Our ultra-compact switching has significant applications for all-optical signal processing as well as optical communications and computing in high-density nanoplasmonic integrated circuits.

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