All-optical switching in subwavelength metallic grating structure containing nonlinear optical materials

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All-optical switching based on a subwavelength metallic grating structure containing nonlinear optical materials has been proposed and numerically investigated. Metal-dielectric composite material is used in the switching for its larger third-order nonlinear susceptibility ($\sim 10^{-7}$ esu) and ultrafast response properties. The calculated dependence of the signal light intensity on the pump light intensity shows a bistable behavior, which results in a significant switch effect. It rests on a surface plasmon's enhanced intensity-dependent change of the effective dielectric constant of Kerr nonlinear media, corresponding to a transition of the far-field transmission from a low- to high-transmission state. The study of this switching structure shows great advantages of smaller size, lower requirement of pump light intensity, and shorter switching time at approximately the picosecond level. © 2008 Optical Society of America

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All-optical signal processing in integrated photonic circuits and its applications in optical communications and computing require the ability to control light with light [1,2]. All-optical devices based on various optical nonlinearities have been considered during past years. However, there are two main drawbacks in the majority of such devices: (1) high operational light intensity required for a sizeable nonlinear response and (2) limitation on their minimum size needed to provide a sufficient light pass. A prominent way to overcome these two obstacles is related to the use of surface plasmons (SPs) in metallic nanostructures. Because SPs can strongly enhance the optical transmission through subwavelength structures and cause significant electric-field confinement and enhancement, they are all helpful to stronger nonlinear effects in all-optical devices [3–7]. Recently, various types of nonlinear nano-optical devices based on SPs have been studied [8–12], which offer the advantages of both smaller size and stronger nonlinear effects, especially the optical bistable devices, which have attracted much interest for their great applications in signal processing [8,10,12]. However, previous research has focused only on some basic properties of optical bistability in nanostructures; the property of the response time, which is the key parameter to switching, should be considered before being taken into applications.

In this Letter, all-optical switching based on optical bistablity has been proposed and investigated in a subwavelength metallic grating structure containing nonlinear optical materials. The metal-dielectric composite materials chosen in the switching structure, which have been widely investigated owing to their large third-order nonlinear susceptibility and ultrafast response properties [13–17]. The typical value of third-order nonlinear susceptibility, $\chi^{(3)}$, is up to 10^{-7} esu with a pulse laser duration of 200 fs at a wavelength of 532 nm. Herein, we chose $Au:SiO_2$ with $\chi^{(3)}=1.7\times10^{-7}$ esu [14] for consideration, and the results can be extended to other Kerr materials. Some important properties of the switching structure have been studied, including the far-field transmission, bistability effect, and switching time. As a result of excitation of the SPs, this switching structure shows great advantages of a lower requirement of incident light intensity, shorter switch time, and more simple structure to be easily fabricated.

In Fig. 1, we show a schematic of the switching structure under study. The whole structure is comprised of a subwavelength Ag grating coated by an $Au:SiO_2$ nonlinear layer. The parameters of the grating are chosen as period $p=500$ nm, slit width w

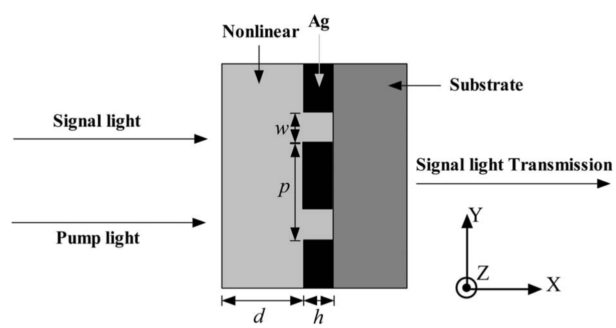

Fig. 1. Schematic of the subwavelength all-optical switching structure under study: p, metallic grating of period; h, metallic film thickness; w, slit width; and d, nonlinear material layer thickness. The signal and pump lights both vertically illuminate the structure from the left side.

=100 nm, thickness of Ag film $h=50$ nm, and thickness of nonlinear layer $d=430$ nm. The substrate was made of fused quartz, and its refractivity index is 1.5. The incident signal light in Fig. 1 is a TM-polarized plane wave with a wavelength of 633 nm, vertically illuminating the metallic grating. The transmission of the signal light through the structure can easily be turned on or off by the pump light, whose chosen wavelength is 532 nm for the strongest third-order nonlinear response.

First of all, we study the properties of far-field transmission through the structure. The finite-difference time domain (FDTD) method is employed to calculate the linear and nonlinear responses of the structure. The periodic boundary conditions (PBC) are used in the boundaries parallel to the light propagating direction, and the other boundaries are considered with the perfectly matched layer (PML) absorbing boundary conditions. Figure 2 shows the normalized far-field transmission spectra obtained with the pump light "on" and "off." The peak of the spectra corresponds to the excitation of the SPs on the metallic grating surface. It is well known that the wavelength of SPs depends on the dielectric constant of material on a metal surface. In our structure, the dielectric constant ϵ_d of the nonlinear material on the metallic grating is given by $\epsilon_d=\epsilon_l+\chi^{(3)}|E|^2$ in which the electric-field intensity $|E|^2$ can be influenced by the pump light. Hence the pump light has an effect on the excitation of the SPs and finally controls the wavelength of the transmission peak. The spectra in Fig. 2 present the shift of the transmission peak controlled by the pump light being on and off, which is also in accordance with the experimental observations by Wurtz *et al.* [10]. Besides the SPs, the thick nonlinear layer in our structure supplies a metal/dielectric/air three-layer waveguide mode [12], which further enhances the transmission and reduces the requirement of the pump light intensity. Therefore the transmission peak in Fig. 2 is up to 40%. It is observed that when the pump light is turned from off to on, the transmission of signal light (633 nm) jumps from 0.012 to 0.365, showing a significant switching effect. In contrast, the pump light (532 nm) always remains in the low-transmission state, which is helpful to the pure signal light output.

Figure 3 shows the dependence of the signal light transmission with an increase and decrease of the pump light intensity in which a clear bistability loop is observed owing to the SP's enhanced third-order nonlinear effect in the nonlinear layer. When the intensity of pump light increases, the transmission jumps to a higher value at an approximate intensity of 6.5 MW/cm^2. In contrast, when the intensity decreases, the signal light keeps a high-transmission state for a long distance and then drops at an approximate intensity of 4.0 MW/cm^2. It is easy to see in Fig. 3 that the requirement of the pump light intensity is <12 MW/cm^2, which is smaller than other structures [17] and can easily be achieved by the pulse laser.

The response time of our structure is also considered and shown in Fig. 4. To determine the switching time, a square pulse pump is launched into the system with an input intensity of 12 MW/cm^2 and a duration time of ~0.9 ps. As a result, the response times of the signal light switching up and down are both ~0.2 ps, which is an ultrafast value. However, the time delay of the nonlinear material is not considered in our FDTD software; hence the switching time of 0.2 ps is only determined by the feedback of the structure, which represents the shortest switching time of the structure. If the response time of the nonlinear material used in the structure is >0.2 ps, the final switching time will be determined by the nonlinear material. For instance, the response time of the nonlinear materials and the switching time of the structure used here are approximately at the picosecond level. After all, this structure has great potential to shorten the switching time to the subpicosecond level.

To more clearly understand the switching effect, we study the electric-field $|E|^2$ distribution of signal light in the states of switching on and off as shown in Fig. 5. Figure 5(a) corresponds to the off state in which the electric field localizes only on the left side of the grating. No electric field can be observed inside

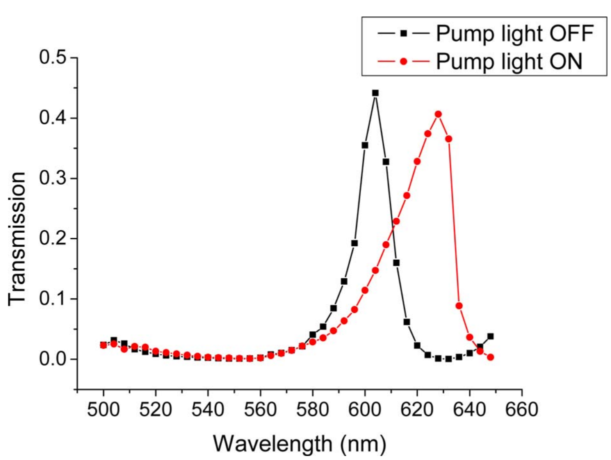

Fig. 2. (Color online) Normalized far-field transmission spectra of the structure obtained with the pump light on and off. The wavelength of the pump light is 532 nm with an incident intensity of 12 MW/cm^2.

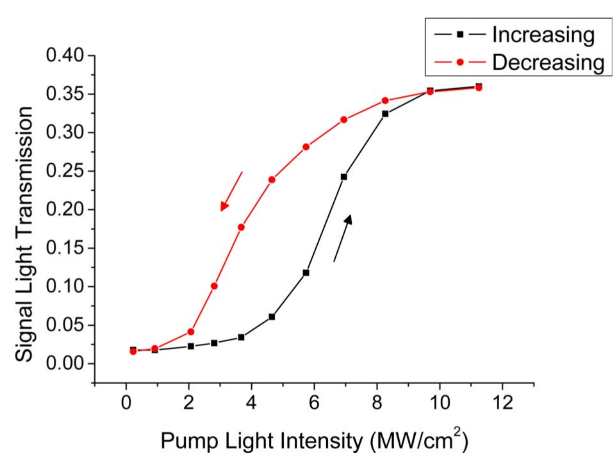

Fig. 3. (Color online) Dependence of signal light (633 nm) transmission through the structure with an increase and decrease of the pump light (532 nm) intensity.

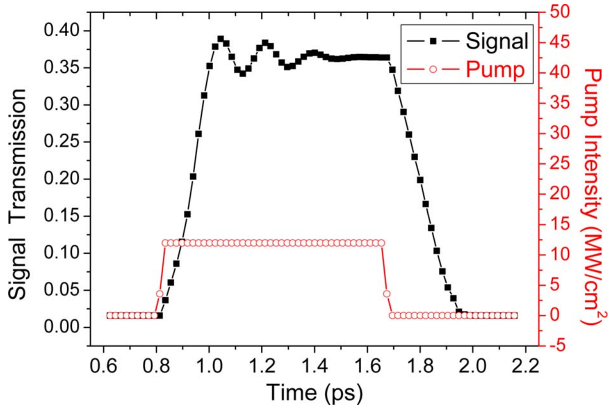

Fig. 4. (Color online) Normalized transmission of signal light (black squares) dependent on time. The curve of circles denotes the pump light of a square pulse ($12\,\mathrm{MW/cm^2}$) that switches the signal light between the low- and high-transmission states.

the slit or after the grating, which proves that the signal light is cut off by the structure. In contrast, the electric field in Fig. 5(b) distributes on both surfaces of the grating and inside the slit, which shows the excitation of SPs and an effective transmission of signal light in the on state.

In conclusion, we have numerically investigated an all-optical switching based on a subwavelength metallic grating structure containing nonlinear optical materials. The metal-dielectric composite film is used in this switching structure for its large third-order nonlinear susceptibility and ultrafast response properties. Some important optical properties of the switching structure have been studied, including the far-field transmission, bistability effect, and switching time. As a result of excitation of the SPs, this switching structure shows great advantages of smaller size, lower requirement of pump light intensity, and the potential for a shorter switching time up to 0.2 ps. The highly nonlinear behavior of the proposed switching structure can possibly be applied to all-optical information processing devices, etc.

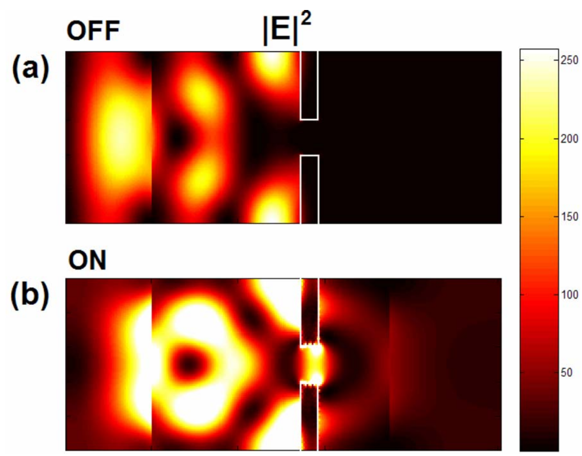

Fig. 5. (Color online) Near-field time-average distribution of electric-field intensity $|E|^2$ of signal light at situations of switching (a) off and (b) on. The longitudinal scale is one period of grating with a slit in the center. The signal light is incident from the left side.

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