Ultrahigh-contrast all-optical diodes based on tunable surface plasmon polaritons

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Abstract. We report a strategy for achieving ultrahigh-contrast all-optical diodes by using tunable surface plasmon polaritons (SPPs) in a silver grating coated with poly[2-methoxy-5-(2-ethylhexyloxy)-1,4-phenylenevinylene], a nonlinear organic material. According to the nonlinear optical Kerr effect, the coupling of SPPs on both sides of the silver grating varied with the pump intensity of incident light, which results in a shift of resonant frequencies of extraordinary transmission modes. The asymmetric configuration and the optical nonlinearity ensure unidirectional transmission properties. An ultrahigh contrast ratio of 2166 is achieved theoretically.

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1. Introduction

Recently, all-optical diodes have attracted great attention because of their important applications in fields such as integrated photonic circuits, ultrafast information processing and optical interconnection systems. Various schemes have been proposed to demonstrate all-optical diodes, including using one-dimensional nonlinear photonic crystals with a spatial graduation in the linear refractive index \([1, 2]\), two-dimensional nonlinear photonic bandgap microcavities with asymmetric configuration \([3]–[5]\), chiral photonic crystals with an anisotropic defect layer \([6]\), left-handed periodic structures with a Kerr nonlinear defect layer \([7]\), low-symmetry magnetic photonic crystals \([8]\), periodically poled lithium niobate waveguides \([9]\) and photonic crystal fibers \([10, 11]\). Recently, Hwang et al \([12]\) and Song et al \([13]\) reported an electro-tunable optical diode based on liquid-crystal photonic crystal heterojunctions. Philip et al \([14]\) reported a passive all-optical diode using asymmetric nonlinear absorption. However, the achieved transmittance contrast ratio of all-optical diodes is relatively low, usually less than 100 \([3]–[14]\). This low contrast ratio, along with the complicated microfabrication requirement, has restricted the practical applications of all-optical diodes \([15, 16]\).

The aim of this paper is to study the realization of an ultrahigh contrast ratio for all-optical diodes. A silver grating coated with poly[2-methoxy-5-(2-ethylhexyloxy)-1,4-phenylenevinylene] (MEH-PPV) on both sides is adopted to construct the all-optical diode. It is well known that extremely high transmission efficiencies can be obtained for optically thick metal films perforated with periodic arrays of subwavelength apertures or slits due to the resonant coupling between incident light and excited surface plasmon polariton (SPP) modes \([17, 18]\). MEH-PPV is a nonlinear organic conjugated polymer material, with large third-order nonlinear susceptibility in the near-infrared range \([19]\). According to the nonlinear optical Kerr effect, the refractive index \(n\) of MEH-PPV changes under excitation of incident light, which affects the coupling of SPP modes on both sides of the silver grating \([3, 17, 18]\). This will lead to a shift of resonant frequencies of extraordinary transmission modes. The asymmetric configuration and the optical nonlinearity ensured unidirectional transmission properties. A high transmission contrast can be achieved based on tunable SPP coupling. This provides a simple and efficient approach to realizing ultrahigh transmission contrast all-optical diodes.

2. Simulation model

The schematic structure of the MRH-PPV-coated silver grating is shown in figure 1. \(h_1, h\) and \(h_2\) are the thicknesses of the top MEH-PPV film, the silver grating and the bottom MEH-PPV film, respectively. \(d\) is the grating period and \(a\) is the width of air slits. The length of the structure is infinite in the \(x\) and \(z\) directions. The finite-difference time-domain (FDTD) method was used to study transmission properties \([3]\). Data of the dielectric function of silver were obtained from \([20]\). Incident light was a transverse-magnetic polarized wave with electric-field vector perpendicular to the MEH-PPV film. Incident light was normally incident on the surface of MEH-PPV films. According to the nonlinear optical Kerr effect, the refractive index \(n\) of MEH-PPV can be written as \([4]\)

\[
n = n_0 + n_2 I,
\]

(1)
where $n_0$ and $n_2$ are the linear and the nonlinear refractive indices of MEH-PPV in the near-infrared range, respectively. $n_0 = 1.7$ and $n_2 = 1.3 \times 10^{-15}$ m$^2$/W in our calculations [19]. $I$ is the intensity of the incident light.

3. Linear transmission properties

To study the linear transmission properties of the MEH-PPV-coated silver grating, we calculated the zero-order transmission spectra with different thicknesses of MEH-PPV films. The results are shown in figure 2. The grating period $d$, the width of air slits $a$ and the grating thickness $h$ were 800, 50 and 200 nm, respectively. Two extraordinary transmission modes appeared for a symmetric configuration of $h_1 = h_2$. When $h_1 = h_2 = 200$ nm, the resonant transmission

**Figure 1.** Schematic structure of a silver grating coated with MEH-PPV.

**Figure 2.** Zero-order transmittance spectra of the coated silver grating with different thicknesses of MEH-PPV films: (a) for symmetric and asymmetric configurations; (b) for asymmetric configuration only. The arrow indicates the position of the 1150 nm incident light.
modes were centered at 911 and 1360 nm, respectively. Porto et al [21] pointed out that the extraordinary transmission modes originate from the coupling of SPPs on both sides of the metal layer for $\lambda \approx d$ and the waveguide resonances for $\lambda \gg d$, where $\lambda$ is the central wavelength of extraordinary transmittance modes and $d$ is the grating period. Hence, it can be determined that the 911 nm mode originates from the coupling of SPPs on both sides of the silver grating, while the 1360 nm mode originates from the waveguide resonances. When $h_1 = h_2 = 300$ nm, the extraordinary transmission modes shifted to 1060 and 1575 nm, respectively. However, for an asymmetric configuration of $h_1 = 200$ nm and $h_2 = 300$ nm, three extraordinary transmission modes appeared, with the central wavelengths of 940 nm for mode A, 1091 nm for mode B and 1560 nm for mode C. The central wavelengths of modes A and B were close to the grating period, which indicates that modes A and B originate from the coupling of SPPs on both sides of the silver grating. The electric fields of modes A and B were mainly confined around the top and bottom surfaces of the silver grating. For the asymmetric configuration, SPP energies on the top and bottom surfaces of the silver grating do not coincide, which makes the SPP coupling inefficient. As a result, two non-degenerate transmittance modes appeared instead of only one degenerate mode [21]. It can also be seen from figure 2(a) that mode A is related to the top MEH-PPV film with a thickness of 200 nm, while mode B is related to the bottom MEH-PPV film with a thickness of 300 nm. Hence, the resonant frequency of mode B will shift when the refractive index of the bottom MEH-PPV film changes. To confirm the origin of the resonant modes, we calculated the electric-field distribution of modes B and C by using the FDTD method. The calculated electric-field distributions of modes B and C are depicted in figure 3. It is very clear that the electric-field distribution of mode B was mainly confined around the top and bottom surfaces of the silver grating. This confirms that mode B originates from the coupling of SPPs on both sides of the silver grating. The electric-field distribution of mode C was mainly confined in the air slits. As a result, the central wavelength of mode C is insensitive to the refractive index changes of the top and bottom MEH-PPV films.

4. All-optical diode performances

To study the all-optical diode functions, we calculated the transmission spectra of 1150 nm incident light through the coated silver grating with asymmetric configuration. The results are
shown in figure 4. The wavelength of incident light was close to the central wavelength of mode B and far from the central wavelength of mode A, as shown in figure 2(b). The wavelength detuning $\delta$ can be defined with respect to mode B [3]:

$$\delta = \frac{\lambda_0 - \lambda_{in}}{\gamma},$$

where $\lambda_0$ and $\lambda_{in}$ are the wavelengths of mode B and incident light, respectively. $\gamma = 20 \text{ nm}$ is the linewidth of mode B. The wavelength detuning was 2.95. Since the coated silver grating was excited with a frequency detuning, the transmission of incident light through the coated silver grating was very low for both upward and downward incidences at weak excitation. The case changes for upward incidence with an increase in the intensity of incident light. For the case of upward incidence, incident light was launched from the bottom. The electric field of the incident light was mainly distributed in the bottom MEH-PPV film. With the increase in pump intensity, the refractive index of the bottom MEH-PPV film increased remarkably, which makes mode B shift in the long-wavelength direction. Accordingly, the transmission of incident light increased. It was easy to shift mode B to the frequency of incident light under high excitation, which leads to a high transmission for incident light. The threshold intensity and the maximum transmission were 1.6 MW cm$^{-2}$ and 6.5% for the upward incidence, respectively. Owing to the wavelength-detuning excitation, the pump intensity exciting the top MEH-PPV film was far less than that of the bottom MEH-PPV film. This leads to a gradually enlarged refractive index contrast between the top and bottom MEH-PPV films with an increase in the intensity of incident light. As a result, the coupling of SPPs on both sides of the silver grating became more and more inefficient [21]. The exacerbation in SPP decoupling makes the maximum transmission of incident light less than the linear transmission of mode B, 27%. When the intensity of incident light is larger than 1.6 MW cm$^{-2}$, the transmission of incident light decreased very quickly. Mode B has shifted over the frequency of incident light under higher excitation. Moreover, the refractive index contrast of the top and bottom MEH-PPV films was enlarged greatly and the decoupling of SPPs on both sides of the silver grating was very serious. These two factors make the transmission of incident light decrease.
Figure 5. Shifts of mode B as a function of the intensity of incident light for the upward incidence case.

For the case of downward incidence, incident light was launched from the top. The electric field of the incident light was mainly distributed in the top MEH-PPV film due to wavelength detuning. The pump intensity of incident light exciting the bottom MEH-PPV film was very weak, and the shift of the wavelength of mode B was very small. Even under high excitation, the transmission of incident light was less than 0.5%, resulting from the serious SPP decoupling caused by the enlarged refractive index contrast between the top and bottom MEH-PPV films. When the intensity of incident light was 1.6 MW cm\(^{-2}\), the transmission of incident light was only 0.003% for the case of downward incidence. Therefore, the maximum contrast ratio, defined as the ratio of maximum transmission for the upward launch to the corresponding transmission for the downward launch, was 2166. This value is about two orders of magnitude larger than that of the previously reported results [1]–[14].

The physical mechanism responsible for this phenomenon originates from the different shifting magnitude of mode B for the upward and the downward incidence cases. Firstly, wavelength detuning leads to the pump intensity in the bottom MEH-PPV film being much higher than that in the top MEH-PPV film for the upward incidence case, and vice versa for the downward incidence case. Secondly, the large optical nonlinearity of MEH-PPV provides a strong tunability of SPP coupling and mode B under excitation of incident light. Thirdly, the asymmetric configuration ensures that the pump power felt by mode B in the upward incidence case is different for the downward incidence case. These three factors guarantee unidirectional transmission properties with a high contrast ratio. To further verify the physical mechanism of the all-optical diode, we calculated the shifts of mode B as a function of the intensity of incident light in the upward incidence case. The results are shown in figure 5. It is very clear that for the upward incidence case, mode B shifts in the long-wavelength direction with the increase of the intensity of incident light, accompanied by a decrease in the peak transmission. Under excitation of 1.6 MW cm\(^{-2}\) incident light, the wavelength of mode B shifts to the position of 1150 nm. But the peak transmission decreases to 6.5%.

To study the influence of wavelength detuning on the all-optical diode, we calculated the upward transmission spectra as a function of wavelength detuning. The results are shown in figure 6. The threshold intensity increased with the increment of wavelength detuning. The threshold intensity was 1.6 MW cm\(^{-2}\) for a wavelength detuning of 2.95. When the wavelength
detuning increased to 5.45, a 7.5 MW cm\(^{-2}\) threshold intensity was needed to reach a maximum upward transmission. Moreover, the value of the maximum upward transmission decreased with the increase of wavelength detuning. The value of the maximum upward transmission decreased from 6.5 to 1.5% when the wavelength detuning increased from 2.95 to 5.45. With the increase of wavelength detuning, larger magnitude will be needed for mode B to shift to the frequency of incident light. This requires larger variation of the refractive index in the bottom MEH-PPV film and higher threshold intensity. On the other hand, a large variation of the refractive index of the bottom MEH-PPV film also leads to a high refractive index contrast in the top and bottom MEH-PPV films. As a result, the asymmetry of the configuration was exacerbated very seriously. This exacerbates SPP decoupling and makes the maximum transmission of incident light decrease for larger wavelength detuning.

5. Conclusion

In conclusion, an ultrahigh-contrast all-optical diode is obtained theoretically based on tunable SPP coupling of a silver grating coated with MEH-PPV. A maximum contrast ratio of 2166 was achieved. These results may be useful references for the study of ultrafast integrated photonic devices.

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