Optical diode composed of subwavelength slit-groove arrays with ultrahigh transmission contrast based on surface plasmon polariton

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ABSTRACT

A high efficiency all-optical diode in a silver film with sub-wavelength slit-groove arrays surrounded by two slits is described and the coupling characteristics and transmission properties are numerically investigated by the finite element method. The nanoscale all-optical diode shows an extinction ratio of 90 dB corresponding to ultrahigh transmission contrast of 10⁹. The transmittance in one direction is about 80% and the operating bandwidth is 145 nm.

1. Introduction

In recent years, nano-optics has become one of the fastest growing areas in optics and optoelectronics on the nano-scale [1,2]. Motivated by the rapid advance of nanoscience and nanotechnology, various optical devices based on absorption enhancement [3,4], surface-enhanced Raman scattering [5], surface plasmon resonance [6,7] have been proposed and experimentally demonstrated at this scale. Among these devices, an all-optical diode which is an optical nonreciprocal device has great application potential in optical signal processing and integrated photonic circuits due to unidirectional transmission of optical signals [8,9]. In order to accomplish excellent performance, three parameters including as low power, large operating bandwidth, and high transmission contrast must be optimized in the design of nanoscale all-optical diodes [10].

Conventional optical nonreciprocal devices are mainly based on a photonic crystal structure such as the photonic crystal heterostructure [9–11], photonic crystal waveguide [12–14], and photonic crystal fiber [15]. Whereas the transmission contrast and operating bandwidth of these structures have magnitudes of 10⁴ and 114 nm, respectively. Recently, Zhukovsky et al. proposed a hybrid Fabry-Perot/photonic-crystal structure featuring unidirectionality and ultralow transmission with a transmissivity of more than 92% in the forward direction and approximately 22% in the backward direction [16]. Xue et al. found that the heterostructures based on light tunneling mechanism could achieve a transmission of 42% with high operating threshold intensity of 0.93 GW/cm² [17]. A thermal radiative effect based on the light transmission scheme has recently been reported. The thermal radiative effect can cause fiber displacements of up to tens of micrometers and inhibit light transmission. Nevertheless, the ultra-high route-asymmetrical transmission ratio is approximately 63 dB [18]. In addition, some structures based on non-reciprocal optical resonator on a silicon-on-insulator substrate or Fano resonances possess a poor transmission contrast [19,8]. More recently, nonlinear diodes based on asymmetric nonlinear absorption and nonlinear saturable absorption have been experimentally demonstrated, and these devices...
possess a broader bandwidth up to 1000 nm and lower transmission contrast [20,21]. The structure which utilizes a sandwich nonlinear Bragg-grating demands a picosecond Gaussian pulse as the light source with a temporal width 3.1 ps and tunable peak intensity [22]. Therefore, these issues impose rigorous challenge on the design and fabrication of all-optical diodes.

Surface plasmon (SP) which is known as surface plasmon polariton (SPP) offers the potential to develop new types of photonic devices [23–25]. Ebbesen et al. observed extraordinary optical transmission (EOT) in submicrometre cylindrical cavities in metallic films when the wavelength was larger than the array period of holes and excitation of SPP occurred at the front and rear metallic interfaces [26,27]. Subsequent studies indicated that enhancement of transmission in metallic structures such as silver or gold films originated from coupling between the incident light and SPP modes [28–32]. Moreover, optical transmission of a single slit in a corrugated silver film was shown to be different when the apertures of the structures were changed [23,24,33]. These properties pertaining to SPP in the subwavelength aperture structures suggest the possibility to create a novel nanoscale all-optical diode without considering the operation threshold intensity of the incident light. Although excitation of SPP mainly depends on wavelengths and incident angles of the light source, it has not related to energy.

Herein, we describe a novel all-optical diode with two slits surrounded by subwavelength slit-groove arrays and two-dimensional finite-element method (FEM) is utilized to calculate and investigate the characteristics using the COMSOL Multiphysics software. The simulated data and prediction by an analytical model are used to derive the optimal structure and the unidirectional transport properties are studied. An ultrahigh transmission contrast of $10^9$ is achieved. This all-optical diode exhibits a one-way transmission at near-IR frequency range with large operating bandwidth of 145 nm.

2. Structure and simulation model

Fig. 1 shows the schematic diagram of the coupling mechanism. A single subwavelength slit in a silver film symmetrically surrounded by a finite array of grooves can enhance the optical transmission and these grooves can be patterned either on the input or the output surface of the film. Fig. 1(a) and (b) displays the position of grooves patterned in the incident direction and exit direction of light, respectively.
In the case of a single-slit, single-groove structure, the transmission spectrum is dominated by the mode caused by the slit–groove distance \( d \) \([34]\). Models are constructed to analyze the transmission spectrum as a function of the slit–groove distance when the silver film is symmetrically surrounded by two grooves. Detailed models are shown in the insets in Fig. 1(c) and (d). As shown in Fig. 1, a beam of incident light (TM-polarized plane wave) is perpendicular to the surface of the silver film with a thickness of \( h = 200 \) nm and the wavelength of the incident light in vacuum is fixed as 850 nm. The parameters \( h_1 \) and \( h_2 \) are taken as 100 nm and the effective surface index of refraction (\( n_1 \) and \( n_2 \)) in vacuum and slit-groove structures are 1 and 1.04, respectively. Silver which is the metal with the lowest losses in the visible spectrum and near-IR frequency is chosen here and the relative permittivity (\( \varepsilon_{Ag} \)) can be obtained by the Lorentz–Drude (LD) model:

\[
\varepsilon_{Ag} = 1 - \frac{\Omega_p^2}{\omega(\omega - i\Omega_p)} + \sum_{j=1}^{5} \frac{f_j\omega_j^2}{\omega_j^2 - \omega^2 + i\omega\Gamma_j},
\]

where \( \omega_p \) is the plasma frequency expressed as \( \hbar \omega_p = 9.03 \) eV and \( \hbar \) is the Planck constant here. \( \Omega_p = \sqrt{f_0\omega_p} \) is the plasma frequency and the oscillator strength \( f_0 \) and damping constant \( \Gamma_0 \) are 0.845 and 0.048, respectively. The values of \( f_j \), \( \omega_j \) and \( \Gamma_j \) can be obtained according to Ref. \([35]\).

3. Results and discussion

Fig. 2 shows the normalized transmission spectra based on the change of slit–groove distance. The normalized transmission can be defined as \( T_n \):

\[
T_n = \frac{T}{T_0},
\]

where \( T \) is the transmittance which donated as the ratio of the output power to the input power when the incident light with a wavelength of 850 nm irradiates the structures as shown in Fig. 1(c) or (d), and \( T_0 \) is the transmittance when the structure without any grooves.

The pink curve in Fig. 2 shows that light transmission is suppressed when the grooves are patterned on the output surface and \( d \) is larger than 220 nm. The blue line indicates that when the incident light irradiates the structure in Fig. 1(c), the normalized transmission spectrum oscillates periodically and the initial amplitude of the curve decreases with increasing slit–groove distance and then stabilizes. This trend is consistent with the pattern described in Refs. \([34]\) and \([36]\) and the main difference is that only one peak exists per oscillation period of the normalized transmission spectrum here. The interaction between optical nano-objects at metallo-dielectric interfaces is driven by two different near-field contributions, SPP and creeping wave (or called evanescent wave). SPP is shown to be the primary vector and the normalized coupling efficiency \( |S_t|/|t_0| \) in the SPP propagation mode of a single-slit, single-groove structure is defined as Eqs. (3a)–(3i), where \( S \) and \( t_0 \) represent the coupling coefficient and the modal transmission coefficient between the incident plane wave and the groove (or slit) fundamental mode, respectively. Also, \( |S_t|/|t_0| \) corresponds to the SPP component of normalized transmission within the structure mentioned above.

\[
W = \exp(ik_{sp}d)
\]

\[
V = \exp(ik_{neff}h_2)
\]

\[
k_{sp} = k_0\sqrt{\varepsilon_{Ag}/(\varepsilon_{Ag} + 1)}
\]

\[
v = \beta + rWu
\]
\[ u = \beta + \alpha V b + r V \]  
\[ b = r_m V a \]  
\[ a = t_0 + \alpha W V + r_0 V b \]  
\[ S = t_0 + \alpha W u \]  
\[ |S/t_0|^2 = |(t_0 + \alpha W^2 V^2[(t_0 + \alpha W)/(1 - r_m r_0 V^2)])|/t_0^2. \]  

In Eqs. (3a)–(3i), the coefficients, \( a, \beta, r, r_m, n_{\text{eff}} \), and \( r_0 \) represent modal coupling coefficients. Neglecting the SPP back-reflection coefficient \( r \) at the slit interface (\( r \) is shown to be negligible, \(|r| < 0.05\)), the first two coefficients can be obtained from Ref. [37], while the last three coefficients can be obtained from Ref. [36]. \( W \) and \( V \) are donated by the phase factor resulting from light bouncing between the slit and groove and light bouncing in the groove, respectively, and \( u \) and \( v \) are the amplitudes of SPP modes propagating along the two directions between the slit and groove at the Ag/air interface. Similarly, \( a \) and \( b \) represent the amplitude coefficients propagating backwards and upwards in the groove, respectively. When a second groove is added, phase factor and amplitudes factor between \( t \) not only the second groove and slit, but also these two grooves should be taken into consideration and Eqs. (3a)–(3i) should be replaced by Eqs. (4a)–(4n). The coefficient \( r \) has also been shown to be zero [33].

\[
W_1 = \exp(ik_{sp}d) \\
W_2 = \exp(ik_{sp}2d) \\
V = \exp(ikn_{\text{eff}}h_2) \\
k_{sp} = k_0\sqrt{\varepsilon_{Ag}/(\varepsilon_{Ag} + 1)} \\
v_1 = \beta + rW_1u_1 + W_1u_2 \\
v_2 = \beta + rW_1u_2 + W_1u_1 \\
u_1 = \beta + \alpha V b_1 + r_1 W_1 + r_6 W_2 \\
u_2 = \beta + \alpha V b_2 + r_2 W_1 + r_6 W_2 \\
b_1 = r_m V a \\
b_2 = r_m V a_2 \\
a_1 = t_0 + \alpha W_1v_1 + \alpha W_2u_2 + r_0 V b_1 \\
a_2 = t_0 + \alpha W_1v_2 + \alpha W_2u_2 + r_6 V b_2 \\
S = t_0 + \alpha W_1u_1 + \alpha W_2u_2 \\
|S/t_0|^2 = \left[\left|t_0 + \frac{2\alpha W_1[\beta(1 - r_m V^2) + \alpha r_m V^2(t_0 + \alpha W_1)]}{1 - r_m V^2[\alpha^2(W_1^2 + W_2^2) + r]}\right|t_0\right].
\]

Fig. 3(a) displays the prediction by the model about the normalized coupling efficiency \(|S/t_0|^2\) according to Eq. (4n). There are no obvious peaks in each oscillation period. Actually, \( r \) represents the SPP back-reflection coefficient and it is necessary to take this factor into consideration when another groove is added. Similarly to Eq. (4n), Eq. (5) is proposed based on Eqs. (4a)-(4m).

\[
S = t_0 + \alpha W_1[\beta(1 - r_m V^2)(1 + r W_1) + \alpha r_m V^2(t_0 + \alpha W_1)] \\
/\left[1 - r_m V^2[1 - r(W_1^2 + W_2^2)] - r_m V^2W_1^2(\alpha^2 - r_0) \\
- r_m V^2W_2^2 - r[W_1^2(r + 1) + W_2^2]\right]
\]

Fig. 3(b)-(e) shows the normalized coupling efficiency \(|S/t_0|^2\) based on Eq. (5) corresponding to \( r = 0.04, 0.02, -0.02, \) and -0.04, respectively. The blue line in Fig. 3(f) shows the computational data obtained by FEM and the brown line shows the theoretical prediction for \( r = -0.04 \). This phenomenon is similar to the experimental result reported in Ref. [36]. SPP mode contributes to the main vector of the slit-groove structure and the creeping wave contributes more when \( d \) is less than 4 \( \mu m \) [36]. In addition, obvious peaks can be observed at \( r = 0.04 \). It can be concluded that the proper value of \( r = -0.04 \). Following are the suitable value for an incident wavelength of 850 nm: \( \varepsilon_{Ag} = -34.71 + 0.33i, \alpha = 0.3310 + 0.0194i, \beta = -0.3246 - 0.0190i, r = -0.04, r_m = -1, r_0 = 0.5433 \) and \( n_{\text{eff}} = 1 \).

The grooves patterned on the input surface can be used to excite SPP and to enhance transmission, the grooves patterned on the output surface can be used to hinder transmission of the incident light. The peaks in the blue line in Fig. 2 denotes the positions of the grooves patterned on the input surface and the valleys denote the positions on the other surface. The slit–groove distances on the input surface are \( d_1 = 585 \text{ nm}, d_2 = 1,405 \text{ nm}, d_3 = 2,230 \text{ nm}, d_4 = 3,070 \text{ nm}, d_5 = 3,890 \text{ nm}, d_6 = 4,725 \text{ nm}, d_7 = 5,560 \text{ nm}, d_8 = 6,395 \text{ nm}, \) and \( d_9 = 7,235 \text{ nm} \) and the slit–groove distances on the output surface are \( d'_1 = 965 \text{ nm}, d'_2 = 1,790 \text{ nm}, d'_3 = 2,615 \text{ nm}, d'_4 = 3,445 \text{ nm}, d'_5 = 4,280 \text{ nm}, d'_6 = 5,110 \text{ nm}, d'_7 = 5,945 \text{ nm}, d'_8 = 6,780 \text{ nm}, \) and \( d'_9 = 7,435 \text{ nm} \). We consider a
A symmetrical structure with $N$ grooves on each side of the slit and with geometrical parameters as those of the structure in Fig. 1. For a clear distinction of the groove number on the top or bottom of the structure, $N_t$ represents the number of the grooves on each side of the slit when the grooves are patterned on the top of the film and $N_b$ represents the situation when the grooves are patterned on the bottom. One way to construct a unidirectional transmission photonic device is to ensure how many pairs of grooves should be patterned on the silver film.

Fig. 4 shows the transmission contrast ratio defined as $T_c$ as a function of the number of the grooves on each side of the slit [8]:

$$T_c = 10\lg\left(\frac{T_f}{T_b}\right)$$

where, $T_f$ and $T_b$ represent the transmittance for forward incidence and backward incidence, respectively. The transmission contrast ratio is also called the extinction ratio [38] and used to scale the effects of asymmetrical transmission of a device. The asymmetrical transmission of the structure increases with increasing extinction ratios.

As shown in Fig. 4, the red line corresponds to the condition when no grooves are on top film and the number of the grooves patterned on the bottom increases from 1 to 9. When there are two pairs of grooves on the bottom, a maximum extinction ratio of approximate 28 dB is achieved. The condition when only the upper part of the silver film is patterned on the grooves is displayed by the black line in Fig. 4 and the extinction ratio increases slowly. The blue line in Fig. 4 shows the extinction ratio at $N_b = 2$ as a function of $N_t$. The maximum extinction ratio is 47.05 dB for $N_t = 5$, indicating that the structure with 2 pairs of grooves on the bottom of the silver film and 5 pairs of grooves on top delivers good performance in one-way transmission at a fixed operating frequency.
wavelength of 850 nm. The electric field intensity distribution is presented in Fig. 5. The structure shows high transmission in one direction but blocks light transmission in the opposite direction, which means that a unidirectional transmission device is demonstrated.

The transmission characteristics are presented in Fig. 6. When the incident wavelength is between 780 nm and 1100 nm, it can penetrate the setting with a high extinction ratio, whereas the transmittance in the forward direction is no more than 50%.

It is noted that the performances of the all-optical diodes remarkably depend on the shapes of the grooves. Fig. 7 shows the extinction ratio curves of the structures with semi-ellipse, trapezoid and square grooves. It is seen that the shapes of the grooves have great influences on the extinction ratio. A higher extinction ratio up to 80 dB around the wavelength of 845 nm can be obtained for the semi-ellipse and trapezoid grooves. However, the bandwidth of the device with square grooves is larger than those of the devices with the semi-ellipse and trapezoid grooves. Therefore, we only consider the all-optical diodes with square grooves.

The aim of this work is to construct a structure with high transmittance in one direction and high extinction ratio [39], and for this purpose, a better structure based on the above study is proposed. The natural way to achieve high transmittance is to adopt a structure such as grating. We study the transmittance of light passing through a metal film with double slits for a single slit structure with \( N_b = 2 \) and \( N_t = 5 \). For the same structure distance changes, we know that transmission from the two subwavelength apertures is very high in one direction showing the characteristic of unidirectional transmission. The transmission characteristics in this structure are shown in Fig. 8. As demonstrated in Fig. 8(a), the extinction ratio is sensitive to the change in the distance of the two slits. It reaches a maximum of over 90 dB at a distance of 8236 nm. In other words, the forward transmittance is 10^9 times larger than that of the reverse transmittance. Fig. 8(b) presents the transmittance of the double slits structure showing a maximum up to 80%. The transmittance in the backward direction can be improved when a third slit is added, therefore, we only consider two slits here.

The extinction ratio changes for incident wavelengths ranges from 800 nm to 1000 nm and the electric field intensity distributions of the structure with a fixed operating wavelength of 850 nm are presented in Fig. 9. Fig. 9(a) shows that the extinction ratio is beyond 20 dB for incident wavelength between 824 nm and 969 nm, which is a wide operating band with 145 nm. Fig. 9(a), (b), Fig. 9(b), and (c) indicate the existence of resonance coupling between the incident light and slit-groove structures at the metal-dielectric interface. Additionally, Fig. 5(a) and Fig. 9(b) suggest that the electric field energy propagates along the slits with high intensity, proving that the incident light transmits through the slits effectively for a wavelength of 850 nm. Fig. 5(b) and Fig. 9(c)

Fig. 5. Near-field electric field time-average distribution of \(|E|\) at a fixed operating wavelength of 850 nm. 5(a) and 5(b) represent forward incidence and backward incidence, respectively.

Fig. 4. Extinction ratios dependence on the number of the grooves on the film for a fixed operating wavelength of 850 nm.
show that SPP resonance of the slit-groove structures suppresses the electric field at the silver-air interface in the slits.

4. Conclusions

A nanoscale all-optical diode composed of a two-dimensional subwavelength slit-groove arrays in silver films with extraordinary transmission properties is described and evaluated theoretically. The enhanced transmission through periodic arrays of subwavelength slits and grooves in the thick silver films results in a strong redistribution of the energy density and regions of high density are located in the vicinity of the aperture, especially near the slits. For a double slits structure, the extinction ratio can achieve 90 dB and a corresponding ultrahigh transmission contrast of $10^9$ is achieved. A wide bandwidth of 145 nm is obtained for extinction.
ratios beyond 20 dB. Besides, the transmittance of the structure with double slits is up to 80%. SPP enhances the fields associated with the evanescent waves and block backward input rendering it functionally an all-optical diode.

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References


Fig. 9. (a) Extinction ratio of the structure with the two slits structure. (b, c) Near-field electric field time-average distribution of |E| for a fixed operating wavelength of 850 nm. 9(b) and 9(c) represent forward incidence and backward incidence, respectively.


