SPECIAL TOPIC — International Conference on Nanoscience & Technology, China 2013

A tunable infrared plasmonic polarization filter with asymmetrical cross resonator*

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(Received 4 September 2013; revised manuscript received 18 March 2014; published online 10 June 2014)

A tunable infrared plasmonic polarization filter is proposed and investigated in this paper. The filter is based on the sandwich absorption structure which consists of three layers. The top layer is an array of asymmetrical cross resonator. The middle and bottom layers are dielectric spacer and metal film respectively. By absorbing specific wavelength of the incident light perfectly, the reflection spectrum of the structure shows filter performance. The calculated results show that the absorption wavelength is strongly dependent on the length of branch of the asymmetrical cross resonator which is parallel to the light polarization and independent of the length of the vertical one. Therefore, the asymmetrical cross resonator filter structure opens the way for freely tuning the filtering wavelength for a different light polarization. We can fix a resonant wavelength (absorption wavelength) corresponding to one polarization and change the resonant wavelength for the other polarization by adjusting the corresponding branch length of the asymmetrical cross resonator, or change the two resonant wavelengths of both two polarizations at the same time.

Keywords: polarization filter, asymmetrical cross resonator, numerical simulation

PACS: 78.67.Pt, 42.25.Bs, 78.20.Bh **DOI:** 10.1088/1674-1056/23/8/087806

1. Introduction

Metamaterial[1] with a sub-wavelength artificial composite structure has attracted considerable attention because of its unique properties, such as optical perfect absorption,[2] negative refraction index,[3] optical cloaking,[4] and superlenses.[5] Recently, the research on perfect absorber based on metamaterial has achieved rapid development since Landy *et al.* proposed a perfect absorber[6] in 2008. The metal–insulator–metal structures are used in their designed absorber to obtain perfect absorption by adjusting the appropriate equivalent parameters ε and u. In contrast to the conventional absorber, absorber based on metamaterial has two important advantages: one is flexible and adjustable wavelength and the other is small device size, which play an important role in nano-scale integrated circuits.

Now, plasmonic filter becomes an important research field because electromagnetic filter is a kind of the essential component of the optical and telecommunication system. In the past few years, types of plasmonic filters have been investigated, such as nanodisk resonator,[7] tangular resonators,[8] ring resonators,[9] etc. Recently, plasmonic filter based on the metamaterial absorber was reported. Mohammed *et al.* showed a tunable plasmonic polarization filter based on metal ellipctical disc resonator.[10] The wavelength of polarized light can be tuned by changing the axis ratio of the elliptical disc, however, it is obvious that the elliptical shape is strictly required in the fabrication process and the modulation range is limited. In order to overcome this problem, a new polarization filter structure is needed.

In this paper, a tunable infrared plasmonic polarization filter with an asymmetrical cross resonator is proposed and investigated. The filter is based on the sandwich absorption structure, which is composed of metal asymmetrical cross resonator, dielectric spacer, and metal film. By absorbing specific wavelength of the incident light perfectly, the reflection spectrum of the structure shows filter performance. It is found that the resonant wavelength (absorption wavelength) of the reflection dip is strongly dependent on the length of branch of the asymmetrical cross resonator, which is parallel to the light polarization and independent of the length of the vertical one. Thus the resonant wavelength for a different polarization can be modulated independently by adjusting the length of the corresponding branch. In addition, it can be seen that the filter exhibits a good filtering performance in the wavelength range of interest because the intensities of the reflection dips are close to zero with different lengths of branches of the metal asymmetrical cross resonator.

*Project supported by the National Natural Science Foundation of China (Grant Nos. 61178089 and 51277091) and the Natural Science Foundation of Fujian Province, China (Grant No. 2013J05095).

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2. Numerical model and simulations

The schematic cell structure of the tunable plasmonic polarization filter is shown in Fig. 1. The filter structure consists of three layers. The top layer is metal (gold) asymmetrical cross resonator which is formed by two perpendicular rectangle gold strips which are parallel and perpendicular to the x axis respectively. The two rectangles have different lengths and the same width; the bottom layer is gold film and the dielectric spacer is filled with MgF_2. The parameters of the structure are as follows: the thickness of the gold asymmetrical cross resonator $h_1 = 20$ nm; the width of the two gold strips (parallel and perpendicular to the x axis) is $w = 100$ nm and their lengths are l_x and l_y respectively; the thickness values of the MgF_2 layer and gold film are $h_2 = 50$ nm and $h_3 = 180$ nm respectively; the filter cell structure has a period of $p = 600$ nm. The dielectric function of the metal (gold) is given by the Drude model, and shown below

$$\varepsilon_{\mathrm{m}}(\omega) = \varepsilon_0\{1 - \omega_{\mathrm{p}}^2/\omega(\omega + \mathrm{i}\gamma)\}.$$

Here, ε_0 is the permittivity of the vacuum, ω_{p} is the plasma angle frequency, and $\omega_{\mathrm{p}} = 2.1804 \times 10^{15}$ rad/s, ω is the angle frequency of incident wave, and γ is the damping rate and $\gamma = 1.4 \times 10^{14}$ rad/s. In order to investigate the characteristics of the filter, the reflection spectra are simulated with the three-dimensional (3D) finite difference time domain (FDTD) method. The FDTD simulation is based on EastFDTD software.[11] In our calculations, the spatial mesh cell is set to be $\Delta x = \Delta y = \Delta z = \Delta s = 5$ nm and the time step is taken to be $\Delta t = \Delta s/2c = 8.3333 \times 10^{-18}$ s. The incident wave with polarization propagates along the negative z axis. Periodic boundary conditions are set to be in the x and y directions, and an open boundary is defined in the z direction for the electromagnetic wave incidence and transmission.

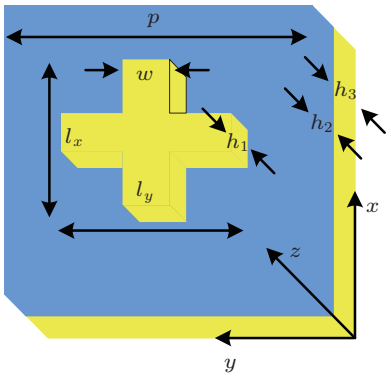


Fig. 1. (color online) Schematic plot of the polarization filter cell structure. The top layer is metal asymmetrical cross resonator. The middle and bottom layers are MgF_2 and gold film respectively.

Assume that the absorption, reflection, and transmission spectra are $A(\omega)$, $R(\omega)$, and $T(\omega)$ respectively. The absorption $A(\omega)$ can be obtained by $A(\omega) = 1 - R(\omega) - T(\omega)$. Due to the metal ground plane, the transmission $T(\omega)$ is zero in the entire investigated wavelength range, the absorptivity $A(\omega) = 1 - R(\omega)$. Therefore, minimizing the reflectivity is equivalent to maximizing the absorption in the studied wavelength range in our model. When $R(\omega)$ is zero at the resonant wavelength, the structure becomes a perfect absorber. And it is known that the zero $R(\omega)$ is caused by the destructive interference between the direct reflection of asymmetrical cross-resonator array and the following multiple reflections of the dielectric spacer and metal layer,[12] and the light is trapped in the dielectric layer.[13]

3. Results and discussion

Figure 2 shows the reflection spectra with different light polarizations of the asymmetrical cross resonator with $l_x = 400$ nm and $l_y = 500$ nm. The blue line (solid circle) represents the reflection spectrum corresponding to E_x polarization (light polarization with electric field vector parallel to x axis), and the red line (solid square) corresponding to E_y polarization (light polarization with electric field vector perpendicular to x axis). It is easily found that each of both the reflection spectra of different polarizations has one dip in the wavelength range of interest and the wavelengths of the two dips of two polarizations are 1702 nm and 2138 nm respectively. The reflectivity values of the two dips are both close to zero (0.015 for E_x polarization and 0.064 for E_y polarization). On the other hand, we can see that the reflectivity of the reflection spectrum corresponding to E_x (E_y) at the resonant dip wavelength of the other polarization E_y (E_x) is close to 1. It means that the filter has strong polarization selectivity.

We also investigate the influence of permittivity (ε) of the dielectric spacer on the reflection spectrum, and show the results in Fig. 3. It is found that the resonant wavelength exhibits redshift and the dip intensity has a small change with ε increasing from 1.5 to 2.3. However, the dip intensities are all below 0.1, which shows weak sensitivity to the permittivity of the dielectric spacer.

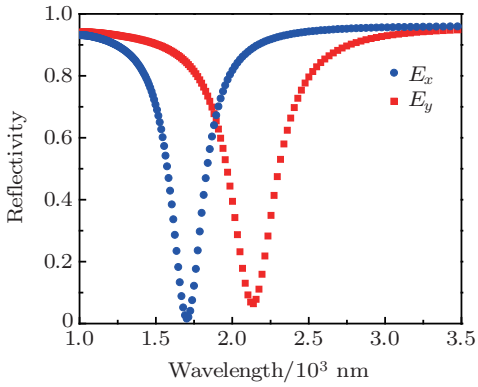


Fig. 2. (color online) Simulated reflection spectra of the filter with $l_x = 400$ nm and $l_y = 500$ nm for E_x (solid circle) and E_y (solid square) polarizations.

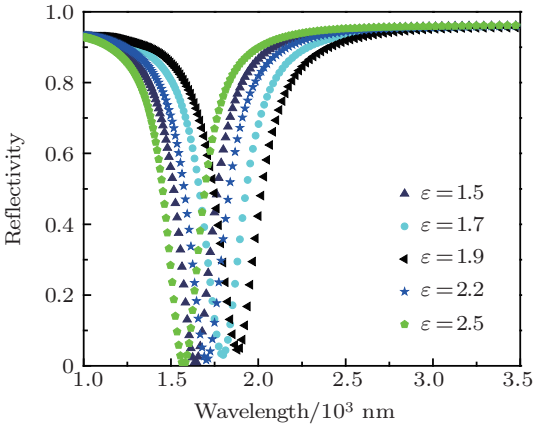


Fig. 3. (color online) Simulated reflection spectra of the filter structure as a function of permittivity (ε) of the dielectric spacer with the $l_x = 400$ nm and $l_y = 500$ nm for E_x polarization.

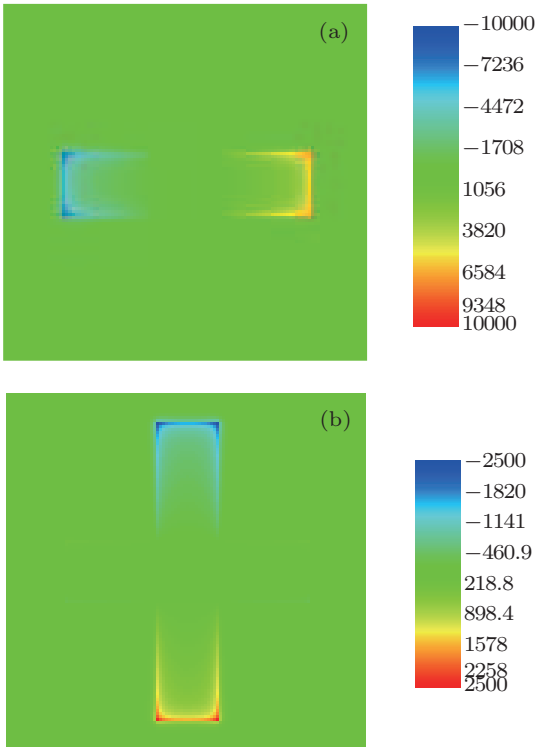


Fig. 4. (color online) Electric field distributions of the xy plane on the metal surface corresponding to (a) E_x polarization at the resonant dip 1702 nm and (b) E_y polarization at the resonant dip 2138 nm.

For well recognizing the characteristics of the dips, figure 4 shows the distributions of the electric field of E_z at the surface of metal asymmetrical cross resonator at the wavelengths of the two dips, i.e., 1702 nm for E_x polarization and 2138 nm for E_y. From Fig. 4(a), we can see that the electric field at 1702 nm for E_x polarization is only distributed at the edges of the rectangle gold strip of the asymmetrical cross resonator which is parallel to light polarization direction, and there is no distribution of electric field along the vertical gold strip. That is to say, the gold strip of the asymmetrical cross resonator perpendicular to the light polarization has no effect on the resonant wavelength of E_x. From Fig. 4(b), we can observe the same characteristics of the dip at 2138 nm for E_y polarization. The above discussion reveals that the wavelength of reflection dip of the filter can be modulated only by changing the parameter of the corresponding gold strip.

Figure 5 shows the reflection spectra of the filter with different lengths of the gold strip of the asymmetrical cross resonator parallel to x axis. The length l_x increases from 300 nm to 500 nm in steps of 50 nm and l_y is fixed at 500 nm. From Fig. 5(a), it is easily found that with l_x increasing, the wavelength of the dip for E_x polarization exhibits redshift. However, the wavelength of the dip for E_y polarization has no change as shown in Fig. 5(b). By fixing $l_x = 400$ nm and changing l_y from 350 nm to 550 nm in steps of 50 nm, we obtain the similar results, as shown in Fig. 6. The wavelength of the resonant dip for E_x polarization has no change and possesses redshift for E_y polarization. It can be seen that the resonator dip wavelength is strongly dependent on the length of the branch of the asymmetrical cross resonator which is parallel to the light polarization and independent of the length of the vertical one.

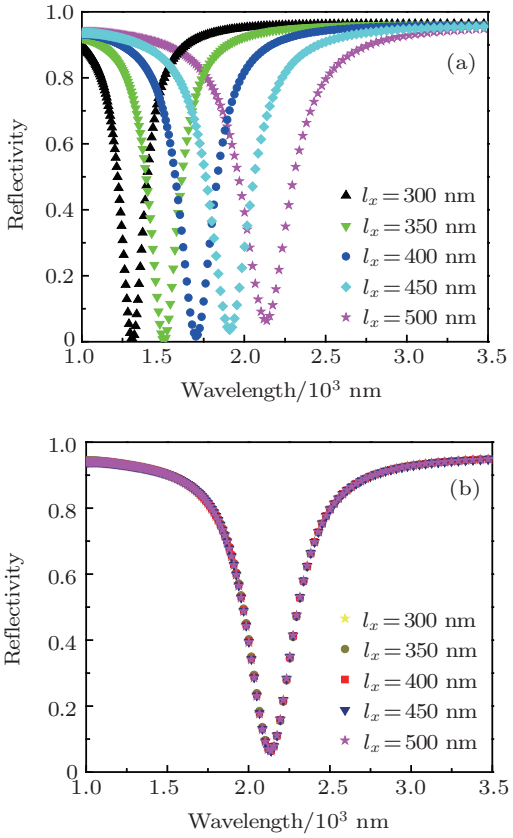


Fig. 5. (color online) Simulated reflection spectra of the filter structure as a function of the length of the gold strip $l_x = 300$ nm to 500 nm in steps of $\Delta l_x = 50$ nm and $l_y = 500$ nm for (a) E_x polarization and (b) E_y polarization.

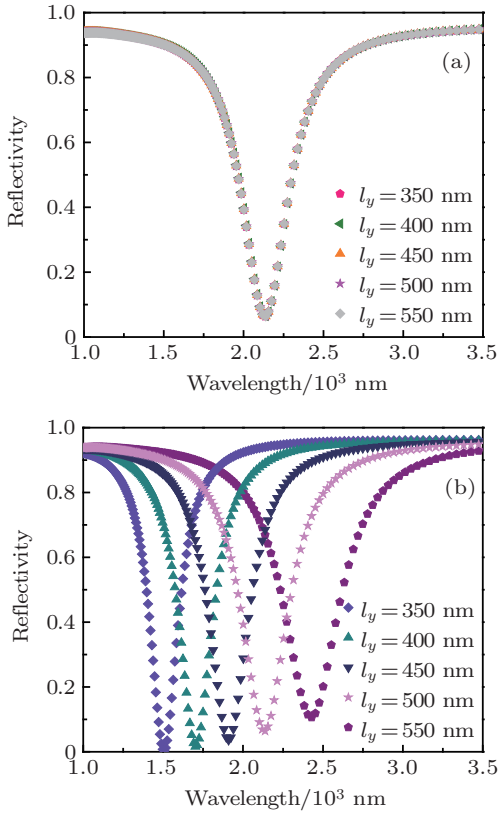


Fig. 6. (color online) Simulated reflection spectra of the filter structure as a function of the length of the gold strip $l_y = 350$ nm to 550 nm in steps of $\Delta l_y = 50$ nm and $l_x = 400$ nm for (a) E_x polarization and (b) E_y polarization.

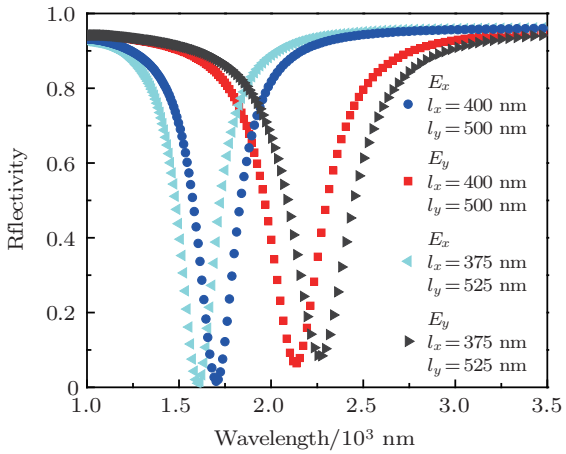


Fig. 7. (color online) Simulated reflection spectra $l_x = 375$ nm, $l_y = 525$ nm, and $l_x = 400$ nm, $l_y = 500$ nm for E_x polarization and E_y polarization.

By changing the lengths of the gold strip along two directions from $l_x = 400$ nm, $l_y = 500$ nm to $l_x = 375$ nm, $l_y = 525$ nm and $l_x = 425$ nm, $l_y = 475$ nm we obtain the results as shown in Figs. 7 and 8 respectively, the wavelengths of dip at the reflection spectra exhibit redshift (blueshift) with the gold strip length increasing (decreasing) in the direction that is parallel to the light polarization. The wavelengths of the dips for E_x polarization and E_y polarization move away from each other with l_x decreasing and l_y increasing, and close to each other with l_x increasing and l_y decreasing, which is consistent with the discussion above. From the analysis, the asymmetrical cross filter structure opens the way for freely tuning the filtering wavelength for specific polarization. We can fix a resonant wavelength for one polarization and change the resonator wavelength for the other polarization by adjusting the corresponding length of the branch of the asymmetrical resonator, or change the two resonant wavelengths for both two polarizations at the same time.

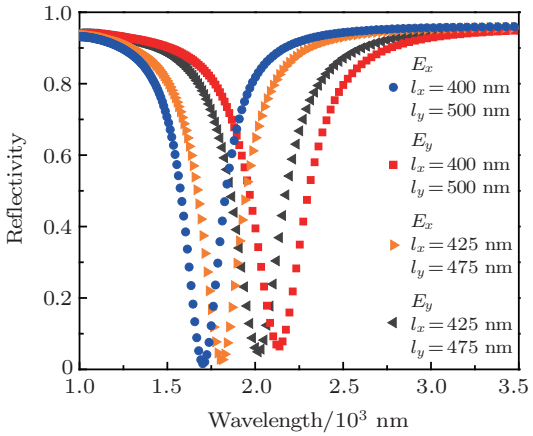


Fig. 8. (color online) Simulated reflection spectra with $l_x = 425$ nm, $l_y = 475$ nm, and $l_x = 400$ nm, $l_y = 500$ nm for E_x polarization and E_y polarization.

4. Conclusions

In this paper, a tunable infrared plasmonic polarization filter with asymmetrical cross resonator is proposed and investigated. The reflection spectrum of the filter structure is calculated. It is found that the resonant dip wavelength is strongly dependent on the length of branch of the asymmetrical cross resonator which is parallel to the light polarization and independent of the vertical one. Therefore, we can change the resonant wavelength by adjusting the corresponding branch length of the asymmetrical cross resonator. In addition, the calculated results show that all the intensities of the reflection dips are close to zero, which implies that the filter can exhibit good filtering performance.

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