Surface plasmon polaritons broadband band-stop filter based on EIT effect modulation

Junhao Niu, Weiyu Luo, Aijun Zhu, Jiajie Wang and Benxin Zhang

Guangxi Key Laboratory of Automatic Detecting Technology and Instruments, School of Electronic Engineering and Automation, Guilin University of Electronic Technology, Guilin 541004, People’s Republic of China

Abstract

The filter is one of the most important key elements of electronic circuit. With the rapid development of information, traditional electrical filters can no longer meet the requirements of fast information processing speed and low loss. All optical information processing is considered as one of the solutions to solve this problem. Therefore, there is great significance for studying the all-optical filter. Here, we put forward a kind of broadband band-stop filter which based on surface plasmon polaritons (SPPs) resonance. We use the finite element method for numerical simulation, and further research on the factors influencing the transmission characteristics of this structure by adjusting the geometric structure. Compared with similar SPPs-based filters, the proposed structure realizes broad stopband, and we can change the EIT resonance to modulate the band-stop filter wavelength range. The proposed broadband band-stop filter based on EIT effect modulation may have great potential in the next generation of all-optical information processing and communication.

1. Introduction

With the rapid development of information technology, high density optical integrated circuit has become one of the research hotspots in recent years [1]. Due to the strong light-electron coupling at the interface of the metal and the medium, the SPPs have enticing properties such as the subwavelength confinement and surface enhancement of the optical field [2–4]. These properties contribute to that we can use the SPPs to break the diffraction limit and realize light manipulation at subwavelength scales [5–10]. More important is that we can manipulate the SPPs electronic field by designing special geometric structure and controlling the phase and polarization of the incident light. This brings high freedom of the SPPs modulation and promotes its application in on-chip optical devices [11–13], such as optical switching [14], optical logic gates [15], and polarization detecting devices [16]. And the MIM waveguide structure has many advantages such as small size, easy integration, long distance optical transmission and strong subwavelength locality. It is considered to be one of the most promising nanometer integrated optical circuit waveguide structures [17–19]. At present, there have been many theoretical, simulation and experimental studies on SPPS nanometer optical devices based on MIM waveguide structure, such as filters [20], sensors [21–24], and wavelength division multiplexers [25].

Fano resonance is a sharp asymmetric linear resonance caused by asymmetric structure. EIT effect is one of the important characteristics of Fano resonance, the superposition between the bright mode and dark mode resonance response leads to the phenomenon of abnormal transmission in a specific wavelength range. For the bright mode resonance, the transmission curves are wide and symmetrical. For the dark mode resonance, the resonance effect is only in a very narrow wavelength range. When the two resonance effect are superimposed, the original resonant wavelength no longer meets the resonance condition, resulting in an increase in the transmittance of the wavelength within a specific range. This effect has also become an important content in the
design of biological detection and communication devices [26–28]. This paper mainly concentrate on the application of MIM waveguides in band-stop filters. In recent years, several band-stop filters based on MIM waveguides have been proposed. Such as single rectangular ring resonator [29], symmetrical tooth-shaped structure [30], symmetrical multiple-teeth-shaped structure [31]. However, these structures whose stopbands are more narrow, or designs are complicated. In addition, different from other tunable band-stop filters, the proposed band-stop filter achieves the filtering function at different wavebands is based on electromagnetically induced transparency effect. Therefore, we designed a simple cascade structure to obtain a wide stopband range and modulated the wavelength range of the stopband by using EIT effect.

In this paper, a broadband band-stop filter based on SPPs with EIT effect modulation is proposed. By analyzing the response of the traditional rectangular nanoslot to the wavelength, it is found that the traditional rectangular nanoslot itself can be regarded as a wide band resonator, but its filtering range is narrow. Therefore, we propose to use the spatial cascade structure to design the three-level cascade filter to realize the function of the wideband band stop filter. In addition, EIT effect is introduced to destroy the standing wave condition of the cascade filter array, and the operation wavelength range of the broadband band-stop filter can be modulated by EIT resonance effect.

2. Principle

The structure of the SPPs broadband band-stop filter based on rectangular filtering array designed in this paper is shown in figure 1(a). The filter consists of a straight waveguide to transmit SPPs and a rectangular filter array. The length of the SPPS straight waveguide is $D$ and the width is $W_1$. The rectangular filter array is composed of three rectangular nanoslots which have equal width $W_2$ and unequal height $h_1$, $h_2$ and $h_3$, respectively. The values of the above parameters are 1500 nm, 50 nm, 50 nm, 150 nm, 170 nm, 190 nm, respectively.

One of the excitation conditions of SPPs is that the incident light should be TM mode, the dispersion equation of its light field should meet the following requirements [32]:

$$\varepsilon_m k_d \tanh \left( \frac{\omega}{2} \right) + \varepsilon_d k_m = 0,$$

where $\omega$ denotes the incident light frequency, $\varepsilon_m$ is the permittivity of metal and $\varepsilon_d$ is the permittivity of the dielectric medium, which in this case is air. $k_j = \sqrt{\beta^2 - \varepsilon_j k_0^2}$ and $k_m = \sqrt{\beta^2 - \varepsilon_m k_0^2}$ represent the incident light transmission wave vector in the medium and the metal, respectively. $\beta$ is the propagation constant of the incident light. A rectangular nanoslot can be seen as a conventional coupling cavity which implements the filtering effect when the SPPs coupled cavity transmission phase change for $2\pi$ integer times to form a standing wave, as shown in figure 1(b). The filtering wavelength of the rectangular nanoslot can be expressed as [33]:

$$\lambda = \frac{2n_{eff} L}{N - \varphi / \pi},$$

where $n_{eff} = \beta / k_0$, $L$ denotes the effective length of the resonant cavity and $\varphi$ denotes the phase change of light during the propagation of the resonator. Compared with the classical ring resonator, the rectangular resonator has a wider resonant wavelength range. The resonant wavelength range of a single rectangular resonator is related to the structural parameters of the rectangular cavity, so the filtering effect of different wavelength ranges can be realized by changing the parameters of the rectangular resonator. So, the broadband band-stop filter can be realized by cascading the rectangular resonators with different structures in space. Because the principle of Fano resonance and EIT effect is the superposition of bright mode resonance and dark mode resonance, it is necessary to design a resonator to generate bright mode resonance in addition to the rectangular filter array structure. Another rectangular resonator is designed below the transmitting SPPs waveguide, and its resonant peak should be within the filtering range of the resonant line of the rectangular filter array. Because the phase change caused by the new resonator breaks the resonant condition of the rectangular filter array, the EIT effect is formed. After the structure of the rectangular filter array is determined, the bandwidth filter modulation can be realized by adjusting the parameters of the EIT resonator.

3. Simulation and results

In order to verify the filtering effect of the filter designed in this paper, the finite element analysis software COMSOL is used for simulation calculation. The metal in the MIM structure is silver, which dielectric constant satisfied Drude model [34]:

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where $\varepsilon_\infty = 3.7$, $\omega_p = 9.1$ eV and $\gamma = 0.018$ eV. For traditional rectangular nanoslot, it has a wide resonance wavelength range, and the resonance wavelength range is closely related to the structure parameters, which shown in figure 2(a). We can find that the wavelength corresponding to the lowest point of transmittance will produce red shift, when the height of the rectangular nanoslot increases. And the corresponding wavelengths at the trough of the filter curves are 1080 nm and 1190 nm for the rectangular nanoslot with the height of 170 nm and 190 nm respectively, which is consistent with the description in equation (2). And the magnetic field distribution of corresponding wavelength at the trough of the filter curves are shown in figures 2(b) and (c), respectively. It can be seen from the figure that the rectangular resonator with different structural parameters still has a good filtering effect and its transmittance is close to zero. In order to design a broadband band-stop filter, it is necessary to combine the above-mentioned rectangular resonators with different filtering ranges. A spatial cascade rectangular nanoslot structure is proposed to achieve broadband band-stop filter function. Since the filtering modulation of incident light can be carried out step by step, these horizontal arrangement rectangular nanoslots contribute to that the incident light will be filtered after passing through each rectangular resonator. In this way, a broadband band-stop filter is been realized, as shown in figure 2(d). As can be seen from the figure 2(d), the rectangular filter array with three-level cascade structure has the filtering wavelength range of 850 nm-1250 nm, which realizes the function of a broadband band-stop filter. And we select two incident wavelengths, 850 nm and 1250 nm, to discuss the modulation effect of cascaded rectangular resonators to a broadband band-stop filter. When the incident wavelength is 850 nm, the first and second stage rectangular resonators can couple most of the energy in the straight waveguide, but when the wavelength is 1250 nm, the first stage rectangular resonator has the main contribution to the filtering. We can see this result from the filtering effect curves of different height rectangular slots in figure 2(a).
The structure of the SPPs broadband band-stop filter based on EIT effect modulation in this paper is shown in figure 3(a). We take a filter array composed of three rectangular nanoslots as an example to analyze the modulation effect of EIT effect on the rectangular filter array. The EIT cavity is on the other side of the straight waveguide transmitting the SPPs with a height of $H$ 80 nm and a width of $L$ 250 nm. Figure 2(d) shows the resonance curve which represents the standing wave conditions are meet in 850–1250 nm wavelength range. When the external environmental change and destruct the standing wave condition, the phase changes of particular wavelength incident light does not meet the $2\pi$ integer times, EIT effect can be realized. By adding a
new rectangular resonator to the lower side of the straight SPPS waveguide, the original resonant condition is destroyed, and the EIT effect is realized within the filtering range of the broadband filter. The wavelength modulation effect of the resonator is shown in figure 3(b). We can find that the filtering wavelength range decreases because there is a new resonance of the EIT effect. And the resonance peak of EIT effect is 832 nm. Figure 3(c) represents the magnetic field distribution at the peak wavelength of the EIT effect.

By changing the structural parameters of the EIT resonator, the filtering effect of the EIT resonator will change just as that of the ordinary resonator. Therefore, the wavelength range and peak value corresponding to the damaged standing wave condition will also change. The same width rectangular resonator cavity with height of 90 nm and 110 nm respectively is selected as the new EIT resonator, and its different modulation effect on the filtering effect of rectangular nanoslot array is shown in figure 4. It can be found that with the increase of the height of the EIT resonator, the peak wavelength of the EIT effect has a red shift, and the filtering effect of the wideband band stop filter has different changes. However, we can also find that the transmittance of other wavelength also decreases with the increasing of rectangular EIT resonance cavity.
In order to observe the influence of EIT resonance cavity height change on the filtering effect of the SPPs broadband band-stop filter, we simulate the magnetic field distribution of corresponding wavelength at the peak of EIT effect before and after the change of the EIT resonance cavity height.

The simulation results are shown in figure 5, shows the distribution of the surface magnetic field corresponding to the new EIT resonance peak at the wavelength 878 nm and 916 nm when the EIT resonance cavity height is 90 nm and 110 nm respectively. (c), (d) The distribution of the new surface magnetic field at the original 832 nm resonance peak when the EIT resonance cavity height is 90 nm and 110 nm respectively.

In reality, the rectangular slot antenna in practice will not be characterized by ideal 90 degrees bends. the difference of the slot antenna shape will add different phase differences on the SPPs mode. So, the practical processing error will contribute to the change of filter wavelength spectrum. Effect of finite curvature of the
rectangular slot antenna also needs to be discussed. So, we have changed the curvature radius of the rectangular angle and the simulation results is shown in figure 6. We can find that the wavelength of the EIT resonance peak will not change significantly but has a blue shift.

4. Conclusions

In this paper, we proposed a novel scheme to design the SPPS broadband band-stop filter is proposed which is based on EIT effect. By using the response of ordinary rectangular resonator to incident wavelength, a rectangular filter array is formed by using spatial cascade mode. Finally, a broadband band-stop filter at 850 nm-1250 nm is realized, which effectively improves the filtering bandwidth of on-chip filter. Based on the Fano resonance principle, a new rectangular resonator is added to make it interact with the rectangular filter array, and the EIT effect is generated in the original filtering range. Based on the principle of EIT effect, we change the structural parameters of EIT resonator cavity to destruct the standing wave conditions under different wavelengths. And the resonant peak of EIT effect has red shift with the increasing of the rectangular EIT resonance cavity, thus the broadband band stop filter based on EIT effect is realized. This novel on-chip SPPS broadband band-stop filter based on EIT effect modulation may have great potential in future on-chip communication.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

ORCID iDs

Weiyu Luo https://orcid.org/0000-0001-6318-3113

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