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基于导模共振效应的宽带宽透射型滤波器的设计与优化

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摘 要:基于导模共振理论,设计了一种工作中心波长位于 632.8 nm 的宽带宽透射型滤波器.根据瑞利异常理论公式,计算得到瑞利波长所在的光谱位置,从而证明异常现象对滤波器的带宽产生了拓宽作用.为了优化宽带宽滤波器的结构参数,利用严格耦合波理论通过计算不同参数条件下的光谱,分析了结构参数和材料对于透射光谱在带宽和峰值效率方面的影响,选取其中最佳的结构参数数值和材料,得到峰值效率为 90%、带宽为 95 nm 的透射光谱.该宽带宽透射型导模共振器件在显示和成像领域有潜在的应用价值.

关键词:导模共振;严格耦合波分析;金属线光栅;滤波器;宽带

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Design and Optimization of Wide-band Filter Based on Guided Mode Resonant Grating

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Abstract: A kind of wide-band filter based on guided mode resonance effect was proposed. According to the theory of Rayleigh anomalies, the existence of the phenomenon was proved to have the influence to broaden the bandwidth through calculating the position of the Rayleigh wavelength. The spectrums under the conditions of different structural parameters and materials were obtained based on rigious coulped-wave analysis method. The impact of the parameters on transmittance efficiency and bandwidth could be clearly observed and concluded from the theoretical results. The parameters were chosen as the optimum values for obtaining the best trasmission peak and bandwidth. The center wavelength of the transmission spectrum is 632.8 nm, the peak transmission efficiency is nearly 90% and the bandwidth is 95 nm according to the calculation result. This kind of device has potential prospect in the application of display and image.

Key words: Guided mode resonance; Rigorous coupled-wave analysis; Metal wire grating; Filter; Wide-band

OCIS Codes: 230.7408; 120.2440; 310.3915; 310.4165; 310.6628

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0 Introduction

Guided Mode Resonance (GMR) effect has attracted wide focus for its advantages of flexibility for designing and sensitivity for the filtering wave band[1-4]. The applications of filters based on guided mode resonant gratings contain biosensing, imaging, signal processing and so on[3,5]. Wide-band filters are generally utilized to be applied in the areas of infrared therapy apparatus and color filtering[5-7]. Yeo-Taek Yoon proposed a color filter based on a sub-wavelength patterned grating in poly silicon and realized on a quartz substrate[6]. The Full Width at Half-Maximum (FWHM) of the structure can reach 90nm, but its Peak Transmission Efficiency (PTE) is only 40%. Yan Ye presented filters whose FWHMs are over 100nm and PTE is just ~75%[7-8]. Hong-Shik Lee introduced a structure with an index matching overlay that led to an increase of ~15% for the transmission efficiency and helped combine double bands into a single dominant band as well[9].

The discovery of enhanced transmission through using a metallic film perforated with a sub-wavelength array gave many researchers an original idea to investigate the periodic structures and their potential applications[10-12]. Hans Lochbihler presented a structure with wire gratings exhibiting enhanced transmission for TE polarized light[13] and colored images generated by adding metallic sub-wavelength gratings[14].

In this paper, we introduced a filter based on GMR grating, whose FWHM is about 95nm, PTE is ~90% and its center of filtering band is 632.8nm. The structure parameters are discussed and optimized through comparing the transmission spectrums under the conditions that structural parameters are set as different values. Therefore, the relationship between structural parameters and transmittances can be summarized and the best value can be decided.

1 Structure design

For obtaining a wide-band filter in visible spectrum region, a dielectric guided-mode resonant grating is utilized to be integrated with a metal wire. We numerically analyzed the spectrums under the sub-wavelength grating without and coated with different metal wires by using the Rigorous Coupled-Wave Analysis (RCWA) method[15-16]. RCWA is a relatively straightforward technique that can be used to obtain exact solutions of Maxwell′s equations for electromagnetic diffraction. Under normal incidence of TE polarization, the transmitted diffraction efficiency D_{ti} can be expressed as

$$D_{ti} = T_i T_i^* \operatorname{Re}\left(\frac{k_{II,zi}}{k_0}\right)$$

where $k_0 = 2\pi/\lambda_0$. $k_{II,zi}$ is the vector component of the ith transmitted wave in the z-axis direction. T_i and T_i^* are the normalized electric-field amplitude of the forward diffracted (transmitted) wave and its conjugation, respectively.

1.1 GMR grating structure

The structure showed in Fig. 1 is a schematic of basic GMR grating structure, which is composed of a substrate layer, a dielectric grating layer and an overlay layer. The structural parameters of the device are denoted as T for the grating period and f for the dielectric grating duty cycle. The height of the overlay layer and the dielectric grating layer are denoted as h_1 and h_2, respectively. The refractive indices for the substrate, dielectric grating and the overlay are denoted as n_s, n_1 and n_2. Here $f=0.39$, $T=408$ nm, $h_1=95$ nm, $h_2=235$ nm, $n_s=1.5$, $n_1=2.4$, $n_2=1.49$. The features of spectrum are the fairly narrow FWHM and the high peak efficiency of nearly 100%. Fig. 2. shows the numerical results under the condition of TE polarization, the transmittance intensity reaches 100% at 659.7 nm and the corresponding FWHM is approximately 76.5 nm.

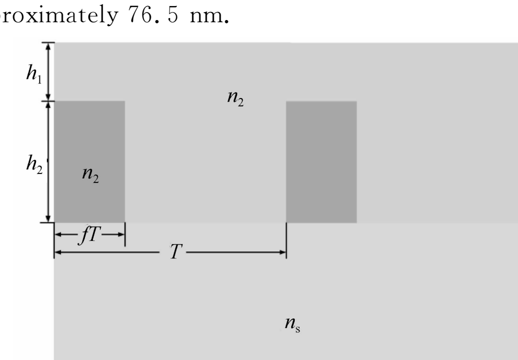

Fig. 1 Profile of the simple structure

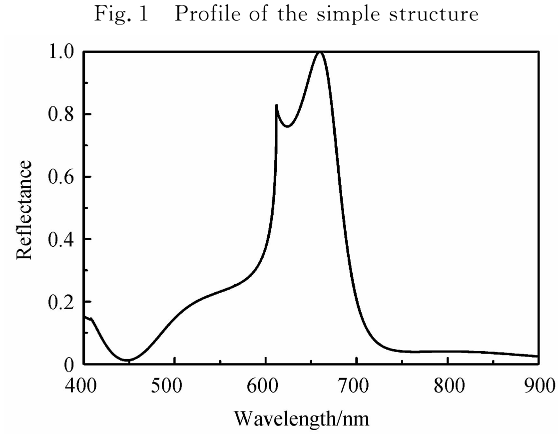

Fig. 2 Reflection efficiency of the simple structure

We should notice that there is another sharp peak at 612 nm and the efficiency is about 81.9%, which is located beside the resonant wavelength. This phenomenon is caused by Wood - Rayleigh anomalies[17-19]. When it appears, the relationship between the Rayleigh wavelength λ_R and the Rayleigh incident angle θ_{iR} can be obtained through the condition of phase matching

$$\lambda_R = \frac{T(n_c \sin\theta_{iR} \pm n_s)}{i}$$

where T is the grating period, i is the diffraction order, n_c is the refractive index of the cover layer and n_s is the refractive index of the substrate layer. In this case, $i=1$.

It must be pointed out that Rayleigh anomalies exist in all the cases when we analyze the structures and the structural parameters. Furthermore, we utilize the existence of the anomalies to broaden the filtering spectrum of the device.

1.2 Addition of metal wire grating

On the foundation of the simple structure of GMR grating, we present the device with a wire grating as illustrated in Fig. 3. If a dielectric grating with a rectangular groove profile is evaporated with metal under a non-normal angle (non-conical case), a non-adjacent film will be deposited on the grating. It will form a wire grating with "Z" shaped wire on the dielectric grating and the substrate. The material of the wire grating should be discussed before we optimize the parameters.

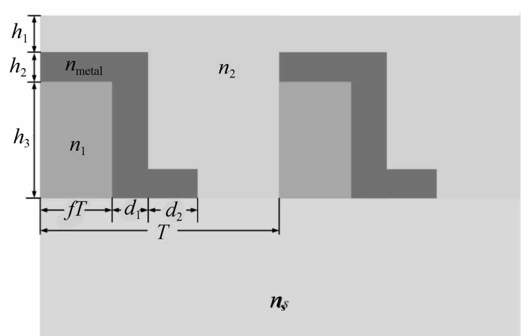

Fig. 3 Profile of the proposed structure

For this structure, the height of the overlay layer, the metal wire grating and the dielectric grating are h_1, h_2 and h_3, respectively. The grating period is T, the dielectric grating duty cycle is f, the refractive indices of the substrate is $n_s=1.5$, the dielectric grating is n_1 and the overlay is n_2. Other parameters are donated as: the width and refractive index of the wire grating are d_1 and n_{metal}, and the defined length is d_2. We choose Ag, Al and Cu as the materials of metal wire grating, whose dispersion information was derived from the Lorentz - Drude model[20].

The addition of metal gratings makes the band-pass reflectance turn into transmittance. The transmittance spectrums were calculated by using the RCWA method and the results are showed in Fig. 4. The accurate structural parameters are set as: $f=0.39$, $h_1=25$nm, $h_2=70$ nm, $h_3=235$ nm, $n_1=2.4$, $n_2=1.49$, $T=408$ nm, $d_1=36.7$ nm, $d_2=102$ nm. For Ag, PTE is nearly 90% at 632.8 nm and its FWHM is 95 nm. Correspondingly, PTE is 84.95% at 635.1 nm and 63.65% at 618.4 nm, FWHM is 96.6 nm and 85.8 nm for Cu and Al respectively. The FWHM values of Cu and Ag are very close, and FWHMs of all the three materials exceed 80 nm, which are wider than the simple GMR grating structure. On the other hand, both PTEs of Ag and Cu are about 20% better than that of Al, and Ag has the best performance in transmission efficiency.

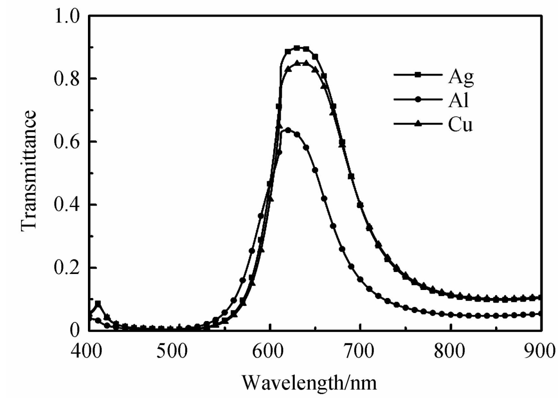

Fig. 4 Transmission efficiencies under different materials of metal wire gratings

2 Structural parameters discussion and optimization

To get the perfect filtering performance, the transmission efficiency should be as high as possible, and the FWHM should be wide enough to meet requirements of wide-band filter in the selected range. Furthermore, we will discuss and improve the grating parameters to finish the optimization of the device in the following paragraphs under the condition of keeping the transmission efficiency of sideband lower than 10%. The material of metal wire grating is set as Ag for obtaining the best performances.

2.1 Index of dielectric grating n_1

To get the best value of n_1, we analyze the spectral transmittance with n_1 changing from 2.0 to 2.8 with the step of 0.1. The structural parameters are $f=0.39$, $h_1=25$ nm, $h_2=70$ nm, $h_3=235$ nm, $n_2=1.49$, $T=408$ nm, $d_1=36.7$ nm, $d_2=102$ nm. Fig. 5 shows that PTE can reach 89.79% at 632.8nm when n_1 is 2.4, which is the highest of the 10 calculated results. At the same time we also notice that the FWHM is in direct proportion to n_1. It can reach 117nm for FWHM when we choose 2.8 as the refractive index of dielectric grating, however, PTE is only 68.8% under the same condition. So n_1 is chosen as 2.4 to be the standard value when discussing other parameters.

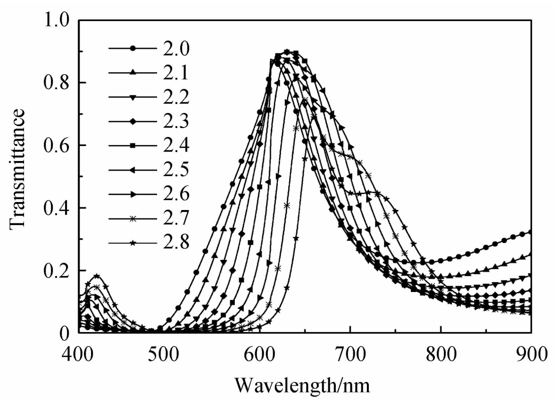

Fig. 5 Transmission efficiencies with different values of n_1

2.2 Duty cycle *f*

The dielectric grating duty cycle f is discussed for getting the best performance of transmission efficiency. We analyze the transmission characteristics by varying f from 0.35 to 0.43 with the step of 0.01. The values of structural parameters are shown as: $h_1=25$ nm, $h_2=70$ nm, $h_3=235$ nm, $n_1=2.4$, $n_2=1.49$, $T=408$ nm, $d_1=36.7$ nm, $d_2=102$ nm. Fig. 6 shows that PTE gets the highest point when f is 0.38, meanwhile, the transmittance of boundary band is over 10%, which can not meet the demand for the limiting condition of wide-band filter. Consequently we choose 0.39 for the further discussion, whose peak efficiency can reach nearly 90% and transmittance is only 10% at 900 nm.

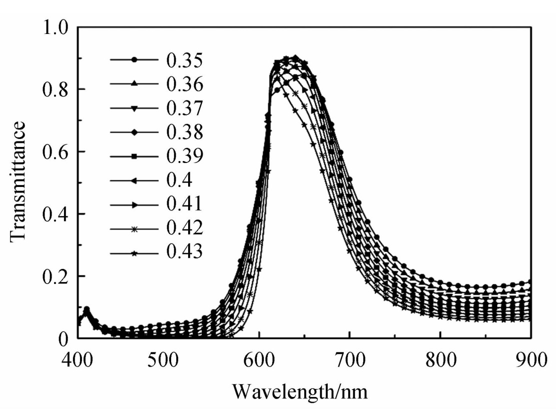

Fig. 6 Transmission efficiencies with different values of f

2.3 Height of wire grating h_2

In order to discuss the impact of the height of wire grating h_2 on the spectra, the value of h_2 is varied in the range between 30nm and 110 nm with the step of 10nm. The other structural parameters are set as: $f=0.39$, $h_1=25$ nm, $h_3=235$ nm, $n_1=2.4$, $n_2=1.49$, $T=408$ nm, $d_1=36.7$nm, $d_2=102$ nm. The transmittance spectra are gathered in Fig. 7, which shows the variation trend of peak transmittance with the height h_2 changing. It can be concluded that the top peak appears when the height is set as 70nm, and the transmittances under other heights are lower than the top efficiency to different extents.

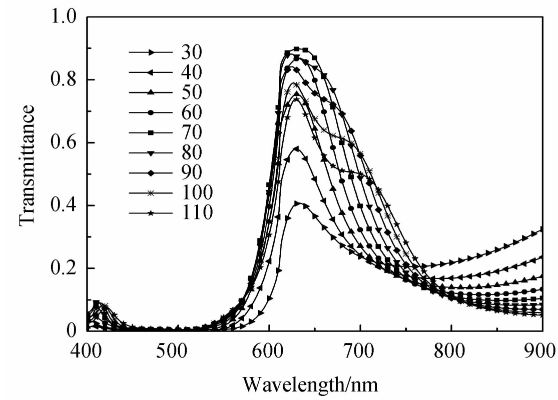

Fig. 7 Transmission efficiencies with different values of h_2

2.4 Height of dielectric grating h_3

For getting the wanted transmission characteristics, we compute the spectrum by setting the height of dielectric grating h_3 from 195 nm to 275 nm with the step of 10 nm. The specific values of structural parameters are $f=0.39$, $h_1=25$ nm, $h_2=70$ nm, $n_1=2.4$, $n_2=1.49$, $T=408$ nm, $d_1=36.7$ nm, $d_2=102$ nm. It can be noted from Fig. 8 that all of the boundary transmission efficiencies are higher than 10% except the condition of h_3 being 235nm. Synthesizing the peak efficiencies, FWHMs and requirements of wide-band filters, we choose 235 nm as the height of dielectric grating.

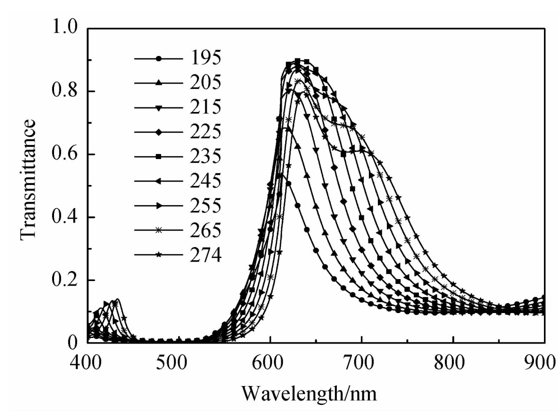

Fig. 8 Transmission efficiencies with different values of h_3

2.5 Width of wire grating d_1

The width of Ag wire grating d_1 is changed from 20.3 nm to 53.1 nm with a step of 4.1 nm (approximately 0.01 of T) to get a perfect performance of transmittance spectrum. The values of other parameters are $f=0.39$, $h_1=25$ nm, $h_2=70$ nm, $h_3=235$ nm, $n_1=2.4$, $n_2=1.49$, $T=408$ nm, $d_2=102$ nm. It can be concluded from Fig. 9 that the efficiency is inversely proportional to d_1 in the chosen wavelength region, and it is over 10% at 900nm when d_1 is below 36 nm. Therefore, we choose 36.7 nm as the width of wire grating, whose peak efficiency is nearly 90% and transmission intensity is approximately 10% at 900 nm.

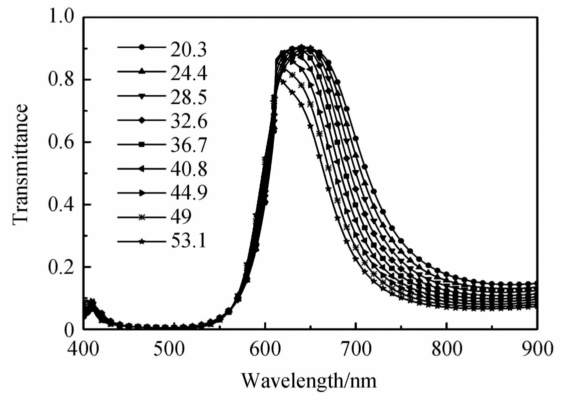

Fig. 9 Transmission efficiencies with different values of d_1

2.6 Defined length d_2

To get perfect transmission characteristics, we analyze the spectrums under the defined length d_2 varying from 85.6 nm to 118.4 nm with the step of 4.1 nm (approximately 0.01 of T). The values of structural parameters are $f=0.39$, $h_1=25$ nm, $h_2=70$ nm, $h_3=235$ nm, $n_1=2.4$, $n_2=1.49$, $T=408$ nm, $d_1=36.7$ nm. Fig. 10 shows that the transmission efficiency is proportional to d_2 in the left part of spectrum approximately, meanwhile, PTEs are very close when d_2 is over 100nm. So we choose 102 nm as the value of d_2 for catering to the wide-band filter, whose transmittance of left boundary band is below 10%.

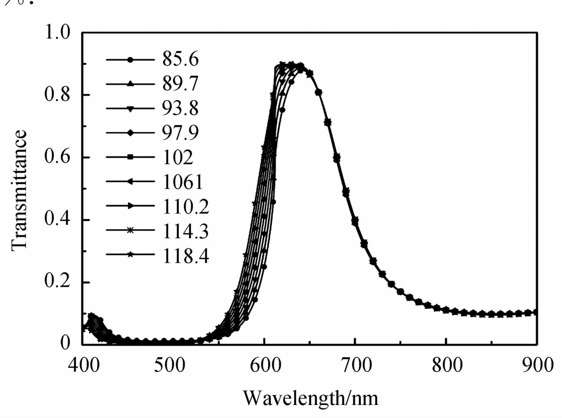

Fig. 10 Transmission efficiencies with different values of d_2

3 Conclusion

In this article, we presented a wide-band filter in the visible range based on GMR device with a metal wire grating. Transmission spectrum can be obtained with this structure, which is different from reflection spectrum of the GMR device without the metal wire grating. Furthermore, it causes that the FWHM increases ~10nm and the peak efficiency is nearly 90%, meanwhile, the resonant wavelength moves over 30nm in the short wave direction. The existence of Rayleigh anomaly furtherly broaden the bandwidth of the peaks.

According to the discussion and optimization of structural parameters, the impacts of refractive index of dielectric grating (n_1), heights of wire grating (h_2) and dielectric grating (h_3) are obviously stronger than other analyzed parameters. The influences on transmissions which three indexes caused should be precisely controlled when fabricating this kind of structure. Researchers can set the values of structure parameters flexibly catering to their specific requirements such as the filtering band or the resonant wavelength.

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