A non-polarization short-wave-pass thin film edge filter*

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(Received 10 April 2014)

Multilayer dielectric thin film edge filter has serious polarization sensitivity under oblique incidence. The cutoff-bands of the s-polarization and p-polarization light in conventional edge filter will separate obviously under 45° oblique incidence, which limits its application. Based on the two chosen materials TiO_2 and SiO_2, a novel stack structure is proposed to design the non-polarization short-wave-pass thin film edge filter. By using the (4*H* 4*L* 4*H*) as the matching layers, the polarization separation at 3 dB transmittance for the thin film edge filter cutoff-band is less than 1 nm at the incident angle of 45°. In this way, the non-polarization short-wave-pass edge filter is easily designed and fabricated.
Document code: A **Article ID:** 1673-1905(2014)04-0247-3
DOI 10.1007/s11801-014-4060-4

With low insertion loss, low cost and good temperature stability, the multilayer interference dielectric thin film edge filter is widely used in the intelligent optical networks and dense wavelength division multiplexing (DWDM) systems[1]. Under oblique incidence, the s-polarization and p-polarization light will have different transmittances due to the changes of phase thickness and optical admittance[2,3]. These phenomena will lead to the stop-band separation of the two polarized beams, which will cause serious polarization dependent losses[4,5].

In previous non-polarization thin film design works, Qi[6] provided a non-polarized thin film using the birefringence property of uniaxially anisotropic materials, Gu[7] designed a low-polarizing thin film bandpass filter using moderate refractive index materials as spacer, Yu[8] designed a non-polarization Fabry-Perot bandpass filter using three refractive index materials as mirror layers and spacer, and Thelen[9] designed a low-polarizing edge thin film filter at the Brewster angle by using three material combinations. No previous work involving non-polarization edge thin film filter using just high and low refractive index materials has been reported.

This paper proposes a novel stack structure to build a non-polarization edge thin film filter. In the Fabry-Perot thin film filter structure, both sides of the main passband will emerge several secondary peaks when their spacers use refractive index materials with higher orders. The polarization sensitivity of these secondary peaks is usually less than that of the main peak. In our former work, we designed a low polarization sensitivity bandpass thin film filter by using both high and low refractive index materials as the spacer[10]. So we can also use this kind of spacer structure to further reduce the separation of the secondary peaks of the two polarized beams. In this way, we get the non-polarization short-wave-pass edge thin film filter under 45° oblique incidence.

From the thin film optics theory, the typical stack of the short-wave-pass thin film edge filter is $(\frac{L}{2}H\frac{L}{2})^p$, where p is the number of cycles coatings, H and L represent the optical thicknesses of $\lambda_0/4$ of the high refractive index and low refractive index film layers[11], and λ_0 is the center wavelength under normal incidence.

Using the TiO_2 as the high refractive index material and the SiO_2 as the low refractive index material, we can get the appropriate cutoff-band at any wavelength when adjusting their film thicknesses. Fig.1 shows the simulation transmittance curves of the stack under normal incidence, where the reference center wavelength is 740 nm and p=12. From Fig.1 we can see that the transmittance curves of both s-polarization and p-polarization light are consistent due to they have the same admittance. The cutoff-band is from 635 nm to 645 nm. However, the cutoff-bands of the s-polarization and p-polarization light will separate obviously when the thin film edge filter is under oblique incidence. Fig.2 shows the simulation transmittance curves of the stack under 45° oblique incidence. Firstly, we can see from Fig.2 that the cutoff-bands of both s-polarization and p-polarization light shift to shorter wavelength due to the decrease of their optical thicknesses under oblique incidence. Secondly, the transmittance curves of the s-polarization and p-polarization light separate obviously due to the different optical ad-

* This work has been supported by the National Natural Science Foundation of China (No.61205062), the Natural Science Foundation of Hubei Province of China (No.2012FFB02701), the Scientific Research Project of Hubei Education Department (No.B2014246), and the Project of Hubei Province Universities Outstanding Youth Scientific Innovation Team (No. 201431).
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mittances, which causes serious polarization dependent loss of the average light. So the average light transmitting spectrum worsens in both transmittance and cutoff-band. The cutoff-band is from 570 nm to 608 nm, and the polarization light separation at 3 dB is more than 30 nm.

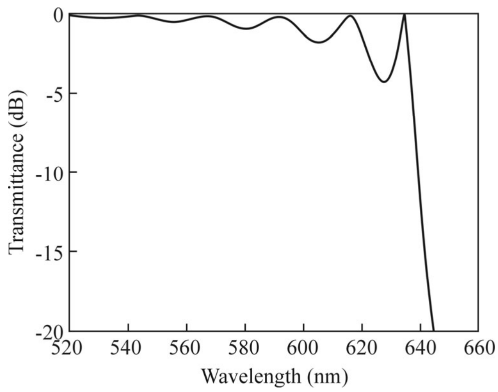

Fig.1 Transmittance curve of the original stack under normal incidence

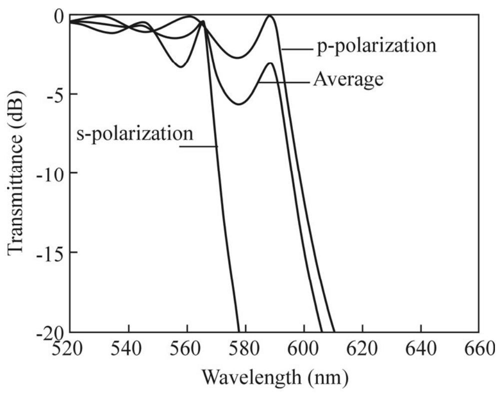

Fig.2 Transmittance curves of the original stack under 45° incidence

In our former research, we found that using both high and low refractive index materials as the spacer of the bandpass thin film filter can effectively decrease its polarization light central wavelength separation under oblique incidence. Under oblique incidence, the refractive index of s-polarization light is $n_s = n\cos\theta$ and that of p-polarization light is $n_p = n/\cos\theta$, where n is the refractive index under normal incidence. According to the theory of thin film matrix, we can calculate the cut-off-band central wavelengths at 3 dB of the two polarization light λ_s and λ_p. Hence, the cutoff-band wavelength separation degree CWL of the two polarization light can be expressed as:

$$CWL = \left|\lambda_s - \lambda_p\right| . \tag{1}$$

The polarization light cutoff-band separation can be eliminated by adjusting the stack structure. We propose an undetermined stack structure as $(\frac{L}{2} s_1 L s_2 H s_3 L \frac{L}{2})^p$, where the low refractive index material is SiO_2 (n_L=1.46), the high refractive index material is TiO_2 (n_H=2.3), and the reference wavelength is 680 nm. Therefore, the spectrum characteristics of the stack can be determined by the cycles coating parameter p and the interference grade order s_i of each refractive index material. So the characteristic parameter of the whole stack can be expressed as (p,s_1,s_2,s_3). As a quarter wavelength stack, the independent variables p and s_i are both positive integers, and their ranges are finite: $p \in (9-15)$ and $s_i \in (1-10)$. So we can get the appropriate results through optimizing the independent variables by the computer calculation. In the short-wave-pass edge thin film filter, the incident angle is 45°, the maximum cutoff-band width is σ=10 nm, and the maximum polarization separation is μ=1 nm. So the design index of the short-wave-pass edge thin film filter should contain the constraint condition as follows:

$$BW_{\text{cutoff}} \le \sigma,\ CWL \le \mu . \tag{2}$$

Under the constraint condition, the effective range of the convergence (p,s_1,s_2,s_3) is finite. Therefore, the optimization can be described as the minimization of the convergence (p,s_1,s_2,s_3), which contains the constraint condition. We also propose an evaluation function $\varphi(p,s_1,s_2,s_3)$ to evaluate the stack result which contains the constraint condition,

$$\varphi(p,s_1,s_2,s_3) = \varpi\sigma(10\sigma)^2 + \varpi\mu(10\mu)^2 , \tag{3}$$

where $\varpi\sigma$ and $\varpi\mu$ are the weighted factors of the cutoff-band width and the polarization wavelength separation degree. The values of the two weight factors both can be defined as 1. The initial parameter (p,s_1,s_2,s_3) is (9,1,1,1). Then computer can calculate all the appropriate stacks within the parameter range which contains the constraint condition. By tolerance optimizing analysis and comparing the evaluation function values of all the stacks, the best stack of the short-wave-pass edge thin film filter under 45° oblique incidence is $(\frac{L}{2} 4L4H4L \frac{L}{2})^{12}$.

Fig.3 shows the transmittance curves of the best stack under 45° oblique incidence. From Fig.3 we can see that the cutoff-band widths of both s-polarization and p-polarization light are 8 nm, which are much steeper than that of the stack mentioned above, even both the cycles coating parameter p=12. The cutoff-band wavelength separation degrees of the two polarization light beams at 3 dB are less than 2 nm, which are also much smaller than that of the former stack. So the proposed stack has the characteristics of non-polarization under large angle oblique incidence. However, the transmittance curves of both s-polarization and p-polarization light have large ripple near the cutoff-band, and they have great insert loss (more than 2 dB) ranging from 542 nm to 550 nm in passband, which will greatly limit the applications of the short-wave-pass edge thin film filter.

So we should further optimize the non-polarization stack to eliminate the ripple in cutoff-band and the high inert loss range in its passband. Using the needle method, the thickness of each layer in the later stack can be modified to get better result. In the TFcal thin film analysis software, we set the optimization target range, and it uses the needle method to work out the optimum design automatically by modifying the initial thickness of the later stack. Then we get the optimized transmittance curve, as shown in Fig.4. From Fig.4 we can see that the short-wave-pass edge thin film filter has stable passband, stop-band and cutoff-band, the ripple and the insert loss are very low, and the cutoff-band polarization light wavelength separation under oblique incidence is eliminated approximately. So it realizes the non-polarization edge thin film filter under 45° incidence.

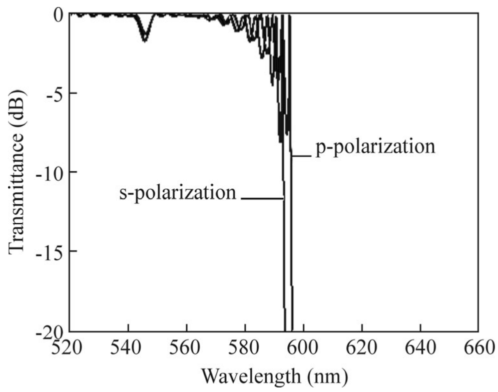

Fig.3 Transmittance curves of the best stack under 45° incidence

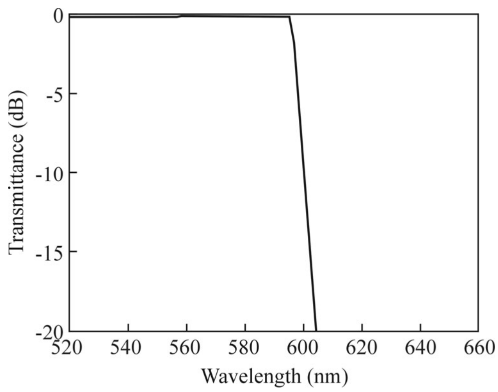

Fig.4 Transmittance curve of the later stack optimized by needle method under 45° incidence

In summary, a novel stack structure of the non-polarization short-wave-pass edge thin film filter is presented. According to the optimization algorithm and the proposed evaluation function, the computer can automatically calculate all the appropriate stacks within the parameter range which contains the constraint condition. Using the needle method designed, the non-polarization, low ripple, flat passband and steep cutoff-band edge thin film filter is obtained, which has the simple stack structure and can be fabricated easily. The results of design, evaluation and analysis are compared. Under 45° oblique incidence, it eliminates the phenomenon of polarization light wavelength separation. The edge thin film filter shows an average transmittance ratio more than 95% in wavelength region of 520—595 nm and less than 1% in 605—660 nm.

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