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# Design of de-polarization long-wave-pass thin film edge filter

K. YU*, J. J. YIN, J. Q. BAO

*Department of Information Science and Technology, Wenhua University, Wuhan 430074, P. R. China*

In conventional multilayer dielectric thin film edge filter stack structure, the P-polarization and S-polarization light will separate obviously in oblique incidence, which will cause the broadening of the cutoff-band and the serious polarization dependent loss. In 45° oblique incidence, the cutoff-band polarization separation at 3 dB transmittance for the conventional long-wave-pass thin film edge filter is more than 50 nm. Based on the $TiO_2$ and $SiO_2$ as the high and low refractive index materials, an algorithm and a novel stack structure is proposed to design the de-polarization long-wave-pass thin film edge filter. Using the $(4L2H4L)$ as the spacer layers, the cutoff-band polarization separation at -3 dB transmittance for the thin film edge filter is less than 2 nm at the incident angle of 45°. In this way, the de-polarization thin film edge filter can be easily designed and fabricated.

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*Keywords:* Edge filter, Long-wave-pass, Oblique incidence, De-polarization

## 1. Introduction

With low cost, good temperature stability and low insertion loss, the multilayer interference dielectric thin film edge filter is widely used in the optical communication and the solar power system [1]. In oblique incidence, the P-polarization and S-polarization light of the thin film filter will have different transmittance due to the different changes of their phase thickness and the optical admittance [2]. The phenomenon will cause the cutoff-bands of the two polarization light separate obviously, which will cause the serious polarization dependent loss and the broadening of the cutoff-band in average light [3,4]. In former de-polarization thin film stack design works, Wang calculated a theoretical de-polarization equivalent refractive index of the bandpass thin film filter [5], Gu designed a de-polarizing bandpass filter using a moderate refractive index material as the spacer [6], Qi provided a non-polarized thin film stack using the birefringence property of uniaxially anisotropic materials [7], Yu designed a de-polarization Fabry-Perot bandpass thin film filter stack by using three kinds of refractive index materials as both the mirror layers and the spacer [8,10], Thelen designed a low polarization sensitivity thin film edge filter at the Brewster angle by using three kinds of materials combination [9]. However, using the conventional high and low refractive index materials to fabricated de-polarization stack is still very difficult.

In this paper, a novel long-wave-pass thin film edge filter de-polarization stack structure is proposed which uses the $TiO_2$ and $SiO_2$ as the high and low refractive index materials. In the conventional thin film edge filter stack, the cutoff-band will emerge a secondary peak when the edge filter is in oblique incidence, which will cause the serious polarization sensitivity. This phenomenon is caused by the polarization light cutoff-bands separation, which will be more serious while the spacer uses only high or low refractive index materials. Using both high and low refractive index materials as the spacer, the de-polarization long-wave-pass edge thin film filter in 45° oblique incidence can be easily designed and fabricated.

## 2. De-polarization stack design

### 2.1. Polarization sensitivity

From the thin film optics theory, the conventional stack of the long-wave-pass thin film edge filter is as follows:

$$(\frac{H}{2}L\frac{H}{2})^m \quad (1)$$

In the stack (1), m is the numbers of cycles coating, $H$ is the high refractive index material and $L$ is the low refractive index material, which are both quarter wavelength coatings [11].

Using the $TiO_2$ ( $n_H = 2.3$ ) as the high refractive index material and the $SiO_2$ ( $n_L = 1.46$ ) as the low refractive index material [12], we can get the appropriate cutoff-band at any wavelength when changing their film thickness and layers. The Fig. 1 shows the simulation transmittance curve of the stack (1) in normal incidence, where the reference center wavelength is 840 nm and m=15. From the Fig. 1 we can see that the transmittance curve of both P-polarization and S-polarization light are coincide due to they have the same optical admittance. The cut-off-band is from 960 nm to 1010 nm and the stack (1) has great ripple from 1000 nm to 1040 nm. However, the cutoff-band of the average light will broaden obviously due to the P-polarization and S-polarization light will separate when the thin film edge filter is in oblique incidence. Fig. 2 shows the simulation transmittance curve of the stack (1) in 45° oblique incidence. Where the blue, red and black lines denote the transmittance curves of P-polarization, S-polarization and average light, respectively. Firstly, we can see from the Fig. 2 that the cutoff-bands of both P-polarization and S-polarization light shift to shorter wavelength due to the decreasing of their optical thickness in oblique incidence. Secondly, the transmittance curve of the P-polarization and S-polarization light are separating obviously due to the different optical admittance. So the average light emerges a secondary peak and it will worsen in both cutoff-band and transmittance. The whole cutoff-band of the average light is from 840 nm to 950 nm, which is much larger than that of in normal incidence. The polarization dependent loss of the average light is more than 4 dB and the polarization light cutoff-bands separation at -3 dB is more than 50 nm.

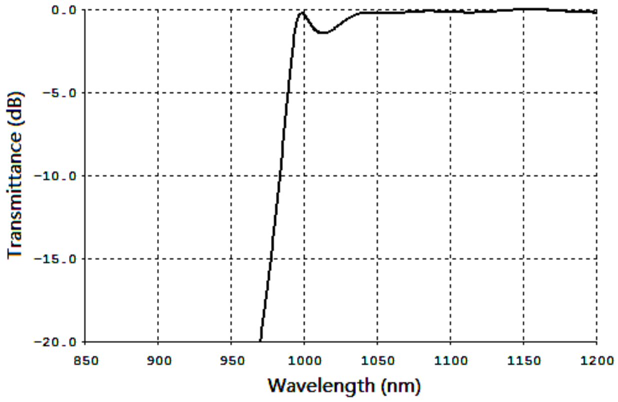

*Fig. 1. Transmittance curve of the stack (1) at normal incidence*

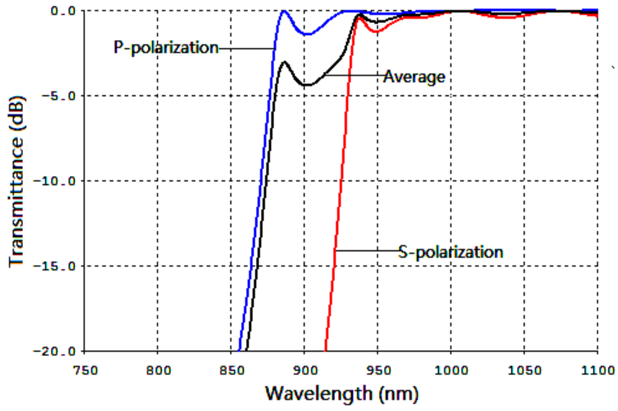

*Fig. 2. Transmittance curve of the stack (1) in 45° oblique incidence*

## 2.2. Optimization algorithm

The wavelength shift for the P-polarization in a low refractive index spacer is smaller than that for the S-polarization, but it is larger in a high refractive index spacer, which cause the phenomenon of polarization light central wavelength separation in oblique incidence [13]. Therefore the central wavelengths of both P-polarization and S-polarization will coincide when use a moderate middle refractive index as the spacer, which refractive index is between the high and low refractive index materials. Hence, we can use both high and low refractive index materials as the spacer to obtain the moderate middle refractive index which can effectively decrease the polarization light central wavelength separation. In oblique incidence, the refractive of the P-polarization is $n_p = n/\cos\theta$ and the refractive of the S-polarization is $n_s = n\cos\theta$, where $n$ is the refractive index in normal incidence. According to the theory of thin film matrix, we can calculate each cutoff-bands wavelength at 3 dB of the two polarization light $\lambda_s$ and $\lambda_p$. Hence, the two polarization light cutoff-bands wavelength separation degree $CWL$ can be expressed as:

$$CWL = \left|\lambda_s - \lambda_p\right| \tag{2}$$

The polarization light cutoff-bands separation can be eliminated by adjusting the spacer stack structure. We proposed an undetermined stack structure as follows:

$$\left(\frac{H}{2} s_1 L s_2 H s_3 L \frac{H}{2}\right)^m \tag{3}$$

In the stack (3), the low refractive index material $L$ is $SiO_2$ and the high refractive index material $H$ is $TiO_2$, the reference wavelength is 720 nm. Therefore, the transmittance characteristics of the stack can be determined by the cycles coating parameter m, the interference grade order $s_i$ of each refractive index material. So the characteristic parameter of the whole stack can be expressed as $(m, s_1, s_2, s_3)$. As a quarter wavelength normalized stack, the independent variables m and $s_i$ are all positive integers, and their parameter range is finite: $m \in (10-16)$ and $s_i \in (1-10)$. So we can get the appropriate results through optimizing the independent variable by the computer calculation. In the long-wave-pass edge thin film filter stack initial conditions, the oblique incident angle is 45°, the maximum cutoff-band width is $\sigma$ =10 nm and the maximum polarization separation degree is $\mu$ =5 nm. So the design index of the long-wave-pass edge thin film filter should content the constraint condition as follows:

$$BW_{cutoff} \le \sigma, \quad CWL \le \mu \tag{4}$$

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

$$\varphi(m, s_1, s_2, s_3) = \varpi\sigma(10\sigma)^2 + \varpi\mu(10\mu)^2 \qquad (5)$$

where $\varpi\sigma$ and $\varpi\mu$ are the weighted factors of the cutoff-band width and the polarization wavelength separation degree at 3 dB. The value of the two weight factors both can be define as 1. The initial parameter $(m, s_1, s_2, s_3)$ is $(10,1,1,1)$. Then computer will calculate all the appropriate stacks within the parameter range which content the constraint conditions. By tolerance optimizing analysis and comparing the evaluation function values of all the possible stacks, the best stack of the long-wave-pass thin film edge filter in 45° oblique incidence is as follows:

$$\left(\frac{H}{2}4L2H4L\frac{H}{2}\right)^{15} \qquad (6)$$

Fig. 3 shows the transmittance curve of the stack (6) in 45° oblique incidence, where the blue and red lines denote the transmittance curves of P-polarization and S-polarization light, respectively. From the Fig. 3 we can see that the cutoff-band widths of both S-polarization and P-polarization light are less than 8 nm, which are much steeper than that of the stack (1). The cutoff-band wavelength separation degree of the two polarization light at 3 dB is less than 2 nm, which is also much smaller than that of the stack (1). The cutoff-band of the average light has no obvious secondary peak. So the stack (6) has the lower polarization dependent loss and higher cutoff degree than that of the stack (1) in 45° oblique incidence.

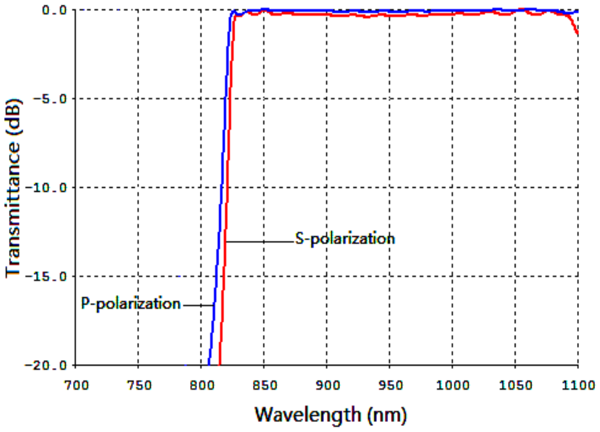

*Fig. 3. Transmittance curve of the stack (6) in 45° oblique incidence*

## 2.3. Needle algorithm optimization

However, the transmittance curves of both P-polarization and S-polarization light have some ripple near the cutoff-band and about 1100 nm in the passband (at about 2 dB), which will greatly limit the application of the long-wave-pass thin film edge filter. So we should further optimize the de-polarization stack (6) to eliminate the ripple in cutoff-band and its passband. Using the needle method, the thickness of each layer in the stack (6) can be revised to get the 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 revising the initial thickness of the stack (6). Then we get the optimized transmittance curve, as shown in the Fig.4, which is the average light in the incident angle of 45°. From the Fig. 4 we can see that the long-wave-pass thin film edge filter has the flat passband (820-1100 nm) and the steep cutoff-band (810-820 nm), the ripple and the insert loss is less than 0.5 dB, and the cutoff-band polarization light wavelength separation in oblique incidence has approximately been eliminated. So it realized the de-polarization thin film edge filter in 45° angle oblique incidence.

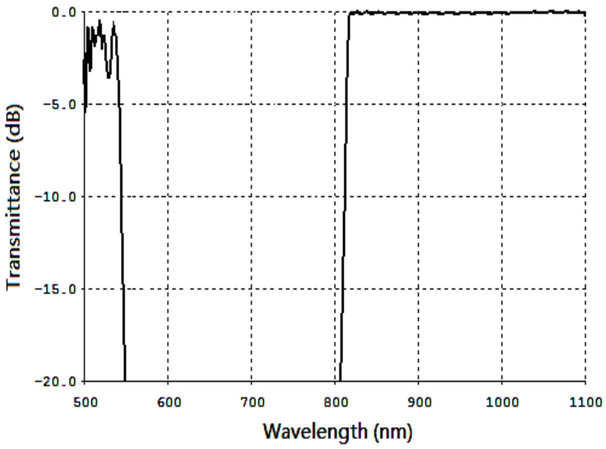

*Fig. 4. Transmittance curve of the stack (6) optimized by needle method in 45° oblique incidence*

## 3. Experimental analysis

The de-polarization long-wave-pass thin film edge filter is fabricated by the APS Leybold Vacuum coating machine, which is using the reflective monitoring to the coatings deposition. As shown in the Fig 5, the edge filter is measured by the Lambda 90 near infrared spectrophotometer in the incidence angle of 45° . The experimental result shows that the long-wave-pass edge filter eliminates the phenomenon of the polarization light separation, which has no obvious peak in the cutoff-band, and its passband transmittance is more than 92% from 850 nm to 1200 nm.

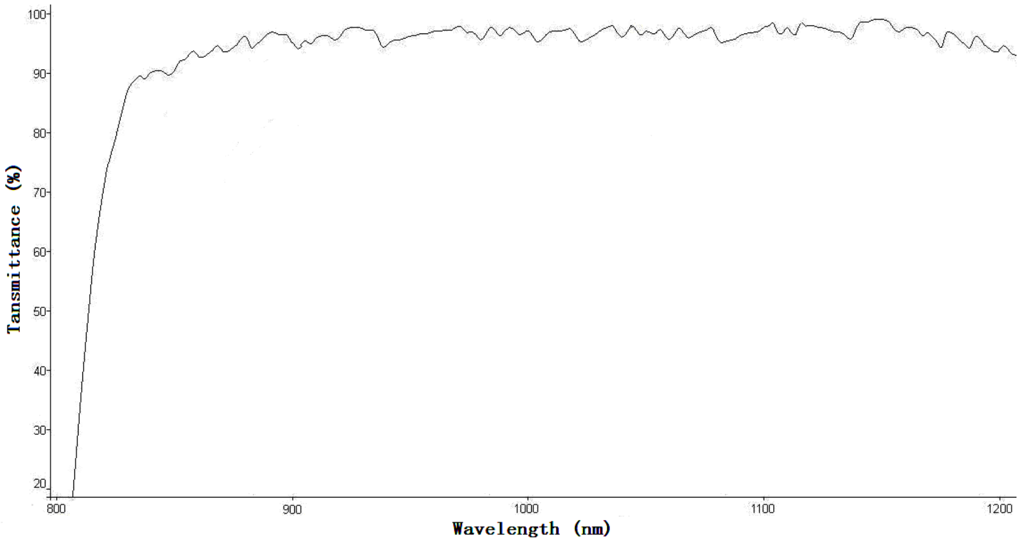

*Fig. 5. Measured spectrum of the edge filter in 45° oblique incidence*

## 4. Conclusions

In summary, a novel stack structure of the de-polarization long-wave-pass thin film edge filter stack is presented and fabricated According to the optimization algorithm and the proposed evaluation function, the computer can automatically calculate all the appropriate stacks within the parameter range which content the constraint conditions. After the needle method further designed, the de-polarization, low ripple, flat passband and steep cutoff-band long-wave-pass thin film edge filter is obtained, which has the simple stack structure and can easily be fabricated. Results of measurement, evaluation and analysis are compared. In 45° oblique incidence, it eliminates phenomenon of the polarization light wavelength separation. The thin film edge filter shows an average transmittance ratio is more than 92% at wavelength region 850-1200 nm and less than 1% at 550-800 nm.

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## References

[1] L. Domash, M. Wu, N. Nemchuk, J. Lightwave Technol. **22**(1), 126 (2004).
[2] J. E. Antonio, A. Castillo, D. A. May, Opt. Lett. **35**(3), 324 (2010).
[3] Y. Suemura, A. Tajima, N. Henmi, J. Lightwave Technol. **14**(6), 1048 (1996).
[4] K. Yu, W. Liu, D. X. Huang, Opt. Commun. **281**, 3709 (2008).
[5] C. Wang, B. Luo, W. Pan. Acta Optica Sinica **25**(5) 707 (2005).
[6] P. F. Gu, H. F. Li, Y. G. Zhang, Appl. Opt. **45**(10), 2066 (2004).
[7] H. J. QI, R. J. Hong, K. Yi, Appl. Opt. **44**(12), 2343 (2005).
[8] K. Yu, J. J. Yin, J. Q. Bao, Optik **125**, 397 (2014).
[9] A. Thelen, Appl. Opt. **23**(20), 3541 (1984).
[10] K. Yu, W. Liu, D. X. Huang, Microwave. Opt. Technol. Lett. **50**(8), 2163 (2008).
[11] D. Wang, Z. X. Fan, J. B. Huang, Chin. Opt .Lett. **4**(11), 675 (2006).
[12] X. M. Chen,J. X. Ma, Y. T. Yang, Appl. Opt. **49**(28), 5271 (2010).
[13] K. Yu. Y. Y. Liu, J. Q. Bao, Opt. Laser. Technol. **56**, 71 (2014).

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*Corresponding author: onlyfish@126.com