Journal of Zhejiang University SCIENCE A
ISSN 1009-3095 (Print); ISSN 1862-1775 (Online)
www.zju.edu.cn/jzus; www.springerlink.com
E-mail: jzus@zju.edu.cn

Design of non-polarizing thin film edge filters*

GU Pei-fu†, ZHENG Zhen-rong

(*State Key Laboratory of Modern Optical Instrumentation, Zhejiang University, Hangzhou 310027, China*)

†E-mail: gupeifu@zju.edu.cn

Received June 28, 2005; revision accepted Jan. 4, 2006

Abstract: The separation between s- and p-polarization components invariably affects thin film edge filters used for tilted incidence and is a difficult problem for many applications, especially for optical communication. This paper presents a novel design method to obtain edge filters with non-polarization at incidence angle of 45°. The polarization separation at 50% transmittance for a long-wave-pass filter and a short-wave-pass filter is 0.3 nm and 0.1 nm respectively. The design method is based on a broadband Fabry-Perot thin-film interference filter in which the higher or lower interference band at both sides of the main transmittance peak can be used for initial design of long-wave-pass filter or short-wave-pass filter and then can be refined to reduce the transmittance ripples. The spacer $2H2L2H$ or $2L2H2L$ of the filter is usually taken. Moreover, the method for expanding the bandwidth of rejection and transmission is explained. The bandwidth of 200 nm for both rejection region and transmission band is obtained at wavelength 1550 nm. In this way, the long-wave-pass and short-wave-pass edge filters with zero separation between two polarization components can easily be fabricated.

Key words: Thin film optics, Interference edge filters, Non-polarization design
doi:10.1631/jzus.2006.A1037 **Document code:** A **CLC number:** O484.4

INTRODUCTION

The design of tilted edge filters which avoid the polarization problems is a much more difficult task than that of polarizer design and there is no completely effective method (Macleod, 2001). Edge filters are divided into two main groups, long-wave-pass and short-wave-pass. They are widely used for various optical purposes, especially in wavelength division multiplexers (WDM) (Nosu *et al*., 1979) and multimedia color projection display (Zhang *et al*., 1999). Unfortunately, the separation between s- and p-polarization components is an invariable effect in such interference thin film edge filters at non-normal light incidence. This effect causes not only polarization separation, but also a limited sharpness of thin film edge filters.

Several methods for designing non-polarization edge filters have been reported (Thelen, 1980; 1981). The first method is to select an intermediate index layer in the basic period to suppress the high-reflectance band in both planes of polarization. The second one is to detune the spacer layers in a multiple half-wave filter to shift the reflectance characteristic in one plane of polarization and to bring two polarization edges into coincidence.

A new design method is put forward in this paper reporting that edge filters with non-polarization at incidence angle of 45° have been designed. The design principle is based on a broadband Fabry-Perot thin-film interference filter in which the higher or lower interference band at both sides of the main transmittance peak can be used for the initial design of long-wave-pass filter or short-wave-pass filter and then can be refined to reduce the transmittance ripples. The polarization separation at the edges of 50% transmittance for a long-wave-pass filter and a short-wave-pass filter is 0.3 nm and 0.1 nm respectively. The spacer of the interference pass-band filter is

* Project (No. 60078001) supported by the National Natural Science Foundation of China

usually $2H2L2H$ or $2L2H2L$. Moreover, the method for expanding the bandwidth of rejection and transmission is explained. Bandwidth of 200 nm for both rejection region and transmission band is obtained at wavelength 1550 nm. In this way, the long-wave-pass and short-wave-pass edge filters with zero separation between two polarization components can easily be fabricated and be widely used in non-polarizing applications, especially in WDM systems (Gu *et al.*, 2002). The sharper the edge of the filters, the more channels can be transmitted.

PRINCIPLES

The basic type of interference edge filter is the quarter-wave stack with an-eighth-wave layers at each end. The design $G[(H/2)L(H/2)]^pA$ and $G[(L/2)H(L/2)]^pA$ are well known as long-wave-pass and shout-wave-pass edge filters respectively, where H and L are respectively quarter-wave thickness of high index layer and low index layer, and p is period number. The principal effect of operating such edge filters at oblique incidence is the splitting between the two planes of polarization. Fig.1 shows the transmittance curves of a long-wave-pass $G[(H/2)L(H/2)]^{15}A$ and a short-wave-pass $G[(L/2)H(L/2)]^{15}A$ filter made from TiO_2 (n_H=2.28) and SiO_2 (n_L=1.425) on a glass substrate (n_G=1.5) at operating wavelength 1550 nm and incidence angle of 45° in the air. It is clear from Fig.1a and Fig.1b that the polarization separation at the edges of 50% transmittance for a long-wave-pass filter and a short-wave-pass filter is 96 nm and 67 nm respectively. This limits the edge steepness which can be achieved for unpolarized edge filters.

Edge filters can be constructed from wide bandpass filters. Fig.2 shows transmittance curves of s- and p-polarization components of an initial filter: $G(HLH2L2H2LHLHL)^9A$ with reference wavelength 1530 nm at 45° incidence. The principal characteristic of the optical transmission curve plotted as a function of wavelength is a series of high-reflection zones separated by regions of high transmission. It can be seen that some edges appear to have no separation between the two planes of polarization. This means that the initial non-polarization edge filters can be obtained by choosing band with high or low interference order. And then, it is necessary to optimize

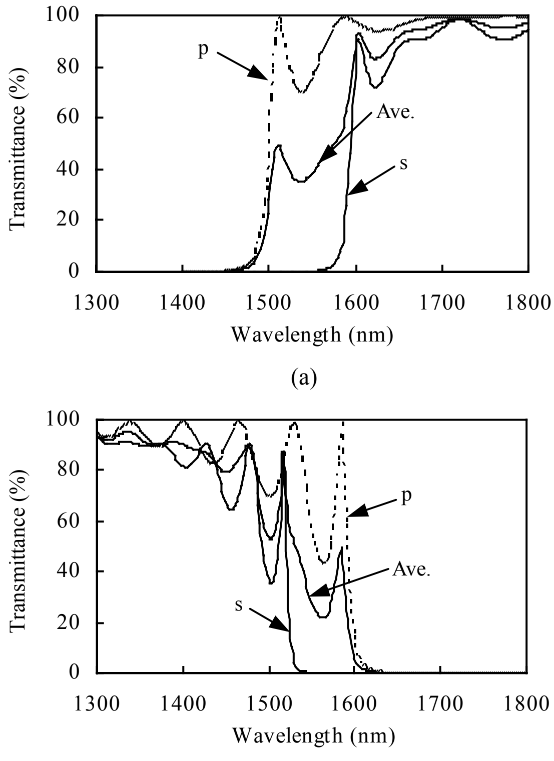


Fig.1 Transmittance curves of (a) long-wave-pass $G[(H/2)L(H/2)]^{15}A$ and (b) short-wave-pass $G[(L/2)H(L/2)]^{15}A$

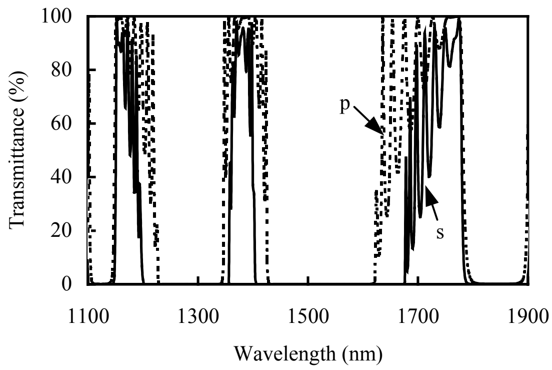


Fig.2 Transmittance curves of s- and p-polarization components of $G(HLH2L2H2LHLHL)^9A$ at 45° incidence

the layer thicknesses to reduce the ripples in the transmittance band.

In the design of such a filter, three steps are involved:

(1) Select a wide band Fabry-Perot filter as the initial design with non-polarization edge in high or low order as well as sufficient bandwidth of reflectance band and transmittance band;

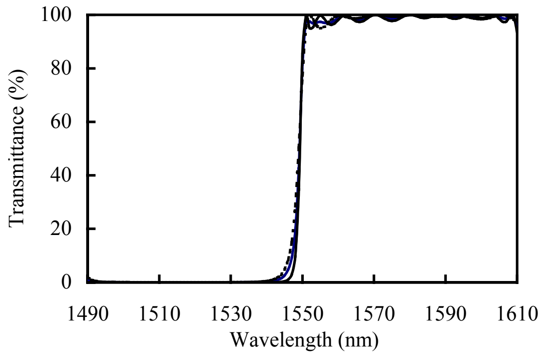
(2) Adjust the wavelength to the needed one;

(3) Optimize the layer thickness of the initial design to reduce the ripples in the transmittance region.

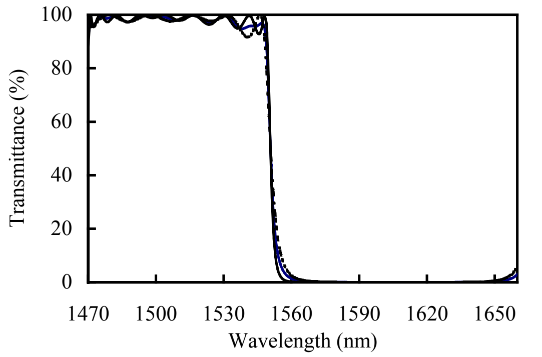
In this way, a non-polarization edge filter with excellent performance can be easily and rapidly achieved.

RESULTS

Fig.3 shows the transmittance curves of long-wave-pass and short-wave-pass edge filters from the initial design $G(HLH2L2H2LHLHL)^9A$ with monitoring wavelength of 2080 nm and 1340 nm at 45° incidence. It can be seen that the polarization separation at transition edges of 50% transmittance for a long-wave-pass filter and a short-wave-pass filter designed by this method is 0.3 nm and 0.1 nm respectively. Such an edge filter can be used to combine pump light 980 nm or 1480 nm and signal light 1550 nm in optical fiber amplifier systems, to combine or separate 1550 nm signal light with a 1510 nm supervisory channel, to combine or separate C-band with L-band signals and so on.



(a)



(b)

Fig.3 Transmittance curves of s- and p-polarization components for (a) long-wave-pass edge filter and (b) short-wave-pass edge filter from the initial design $G(HLH2L2H2LHLHL)^9A$ at 45° incidence

DISCUSSION

Edge filters can be constructed from wide band-pass filters with $2L2H2L$ or $2H2L2H$ spacer which can be used for displacing the pass bands of a band-pass filter to make one pair of edges coincide, resulting in an edge filter with very small polarization splitting. This technique is already being used to centre the p-polarization pass band of a tilted filter with s-polarization pass band (Gu *et al*., 2004). It is usually desirable to have narrowband filters without degradation in the transmittance peak when they are used at tilted incidence to collimated light, such as in the case of a low cost tunable WDM filter.

The rejection zone and the transmittance zone, shown in Fig.3, must somehow be extended for some applications, except C-band and L-band in DWDM systems. To do this, the rejection band in longer wavelength can be selected, which is efficiently used for short-pass edge filters. As Fig.4 shows, the initial design: $G(HLH2L2H2LHLHL)^9A$ is still taken, but the reference wavelength is 826 nm. The rejection zone and the transmittance zone with bandwidth of 200 nm can be achieved at incidence angle of 45°. In addition, at oblique incidence, the relative phase shift between s- and p-polarized light from the reflecting stacks can be adjusted by changing the index ratio or the layer number and selecting proper interference

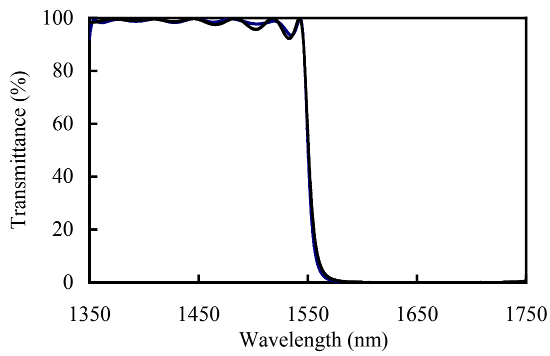


Fig.4 Transmittance curves of the two planes of polarization for a short-wave-pass non-polarization edge filter of the initial design $G(HLH2L2H2LHLHL)^9A$ with control wavelength 826 nm at 45° incidence

order of space. This alters the relative positions of the pass bands for the two planes of polarization and, if the adjustment is correctly made, it can make a pair of edges coincide. Table 1 lists the variation of bandwidth of rejection zone and the transmittance zone with the reflectance of the reflecting stacks and orders.

Table 1 Width of rejection and transmittance region with different filter structures for a 1550 nm short-wave-pass edge filter

Design	Index ratio (n_H/n_L)	Width of rejection (nm)	Width of transmittance (nm)
$G(HLH10LHLHL)^pA$	2.28/1.425	115	47
$G(HL10HLHL)^pA$	2.28/1.425	81	83
$G(HL8HLHL)^pA$	2.28/1.425	74	113
$G(HL8HLHL)^pA$	2.28/1.56	63	140

It can be seen from Table 1 that the rejection bandwidth reduces and the transmittance bandwidth increases when the spacer order of Fabry-Perot filter decreases or the reflectance reduces. So that it can easily adjust the width of rejection or transmittance band by means of adjusting reflectance and interference orders.

This characteristic is usually for one angle of incidence only. As the angle of incidence moves away from the design value, the splitting will reappear (Macleod, 2001). However, the designs made by this method have large angle region where the edge split performance is not degraded obviously. As shown in Fig.5, the edge of two planes of polarization is still not split even at incidence angle of 60°, although the transition wavelength moves into shorter wavelength. And, of course, the performance becomes much better when the incidence angle decreases. This feature is important for application of cone light illumination.

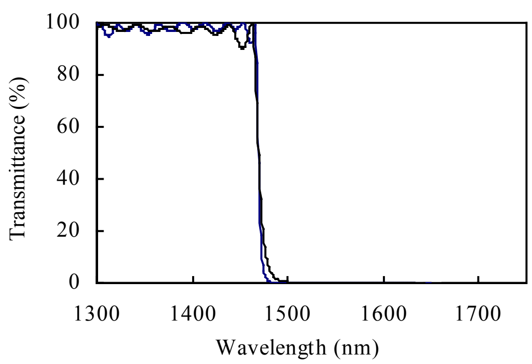


Fig.5 Transmittance curves of the two planes of polarization for the design shown in Fig.4 at incidence angle 60°

CONCLUSION

Based on higher or lower interference band of a broadband Fabry-Perot thin-film interference filter, a non-polarization edge filter can be easily constructed. Such an edge filter has the following features:

(1) Very easy to refine to get design with small ripples in transmittance band, with zero separation between two polarization components at transition edge and with broad transmittance band and rejection band.

(2) Small angle effect compared with other design methods.

(3) No quarter wave thickness design, but can be controlled by a modified turning point method.

The designs made by this method can be used for various optical purposes, especially in wavelength division multiplexers and multimedia color projection display.

References

Gu, P.F., Bai, S.Y., Li, H.F., Zhang, Y.G., Liu, X., 2002. Design of DWDM thin-film interference filters. *Acta Optica Sinica*, **22**(7):794-797 (in Chinese).

Gu, P.F., Chen, H.X., Zhang, Y.G., Li, H.F., Liu, X., 2004. Wavelength-division multiplexed thin film filters used in tilted incident angles of light. *Appl. Opt.*, **43**(10):2066-2070. [doi:10.1364/AO.43.002066]

Macleod, H.A., 2001. Thin-Film Optical Filters, 3rd Ed. Institute of Physics Publishing, Bristol and Philadelphia, p.368-377.

Nosu, K., Ishio, H., Hashimoto, K., 1979. Multireflection optical multi/demultiplexer using interference filters. *Electron. Lett.*, **15**:414-415.

Thelen, A., 1980. Avoidance or enhancement of polarization in multilayers. *J. Opt. Soc. Am.*, **70**(1):118-121.

Thelen, A., 1981. Nonpolarizing edge filters. *J. Opt. Soc. Am.*, **71**(3):309-314.

Zhang, Y.G., Gu, P.F., Liu, X., Tang, J.F., 1999. Color-separation multilayer systems used for thin film transistor-liquid crystal display. *Acta Optica Sinica*, **19**(6):791-794 (in Chinese).