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Design of angle-tuned wedge narrowband thin film filter

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ABSTRACT

As a tunable optical filter, angle-tuned thin film narrowband filter is widely used in dense wavelength division multiplexing (DWDM) system. In oblique incidence, the transmitting facular broadens obviously, which will cause a decrease in transmissivity and rectangular degree of the filter. The transmitting spectrum characteristics and the transmitting facular broadening are also influenced by the non-parallel incident and emergent interfaces' wedge angle of the wedge filter. In the present paper, the transmitting intensity distribution in different incident angle of the wedge filter has been calculated, and the influences of the wedge angle to the transmissivity and the half bandwidth are also analyzed. The proper wedge angle and incident orientation will improve the characteristics of the transmitting spectrum. A 100 GHz DWDM angle-tuned wedge filter was fabricated which has a wedge angle of 0.8°. Compared with the parallel angle-tuned filter, the wedge filter can enhance the transmissivity and the rectangular degree in oblique incidence and its tunable wavelength range will increase 10 nm.

1. Introduction

Tunable optical filter is a key component for optical wavelength selection in the intelligent optical switching network [1]. With the low insertion loss, high rectangular degree and good temperature stability, the narrowband thin film filter in the DWDM system is widely used [2,3]. Traditional narrowband thin film filter only can be used in normal incidence due to its serious polarization sensitivity [4,5]. With the development of the technology of polarization insensitivity, more and more attentions have been paid to angle-tuned thin film filter for its good temperature stability and low cost [6–10]. As the incident angle is increasing, the transmitting facular broadens obviously, which will worsen the transmissivity and the rectangular degree of the transmitting spectrum, and the tunable range of the angle-tuned thin film filter will be greatly limited. In our previous research, we used beam shaping system and double filtering technology to enhance the transmitting characteristics [11]. However, it also causes high insertion loss and low integration degree. In this paper, we propose and fabricate one kind of angle-tuned wedge thin film filter which has a wedge angle of 0.8°. The simulation and experiments show that proper wedge angle and its orientation can restrain the broadening of the transmitting facular in oblique incidence, which will enhance the transmitting spectrum characteristics. Compared with the parallel angle-tuned thin film filter, the tunable wavelength range of the wedge angle-tuned thin film filter will broaden 10 nm.

2. Theoretical analysis

We have fabricated an angle-tuned thin-film filter with four cavities used in 100 GHz DWDM channel spacing according to stack (1) in the Filtech Corporation in China. In the stack (1), the high refractive index material H is Ta_2O_5 ($n_H = 2.05$) and the low refractive index material L is SiO_2 ($n_L = 1.456$), which are both quarter wavelength coatings and the reference wavelength is 1567 nm [12].

$$\begin{bmatrix} (HL)^7 2L3H4L3H2L(LH)^7 L(HL)^8 2L3H4L3H2L(LH)^8 L \\ (HL)^8 2L3H4L3H2L(LH)^8 L(HL)^7 2L3H4L3H2L(LH)^7 \end{bmatrix} \quad (1)$$

It has a stable angle-tuned transmission characteristics and it also eliminate the central wavelength separation phenomena of the two polarization modes by optimizing the spacer. This stack use both high and low index materials as the spacer to eliminate the polarization light central wavelength separation, so it has low polarization-sensitivity within tunable range. The theoretical angle tune range is from 0° to 20°, which wavelength tunable range can cover the whole C-band (from 1567 nm to 1528 nm). However, due to the serious transmitting facular broaden in oblique incidence, the transmissivity and the rectangular degree decrease obviously. So the practical incident angle range of the

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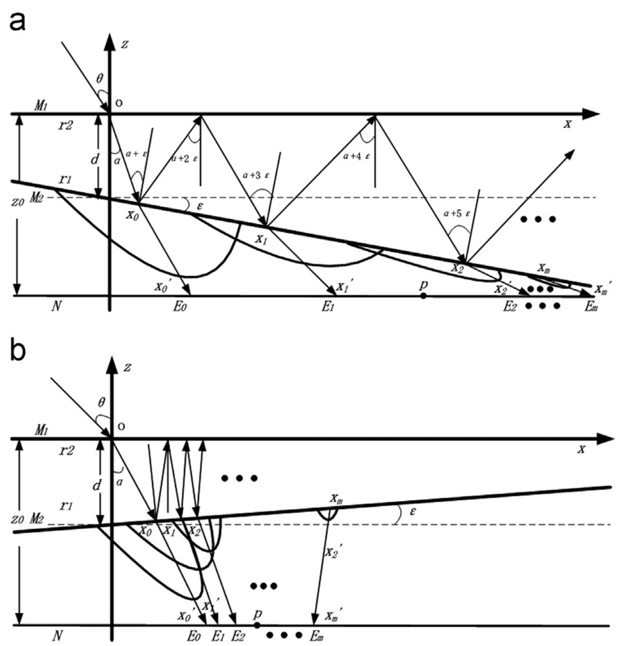

Fig. 1. The light transmitting through a wedge filter with a oblique Gaussian beam: (a) positive wedge angle ε and (b) negative wedge angle ε.

angle-tuned thin film filter is from 0° to 15°, which tunable central wavelength can only cover the range from 1567 nm to 1545 nm.

The symmetrical periods multiple layers can be simplied as a single equivalent coating by the method of effective interface [13], and the single equivalent coating has two effective interfaces. The equivalent refractive index of the stack (1) is $n_M = 1.82$ [14].

Fig. 1 describes a Gaussian beam which vibrating direction is vertical to the plane xz obliquely incidenting on the surface of a wedge thin film filter with an incident angle θ, where M_1 and M_2 are the two non-parallel effective interfaces of the wedge filter; r_1 and r_2 are the reflection coefficients of the interfaces; d is the distance of the wedge filter from the incident point to the first output point which can be confirmed as the average thickness of the stack; ε is the wedge angle of the non-parallel interfaces of the wedge filter; the surface N which is perpendicular to the axis z is the measuring surface; z_0 is the distance from the incident point to the measuring surface.

The wedge angle ε in Fig. 1(a) is in the same orientation to the incident angle θ, which can be described as a positive wedge angle, and the wedge angle ε in Fig. 1(b) is described as a negative wedge angle. As shown in the Fig. 1, the positive wedge angle will increase the reflected angle at the value ε between the two non-parallel interfaces in each reflection, and the negative wedge angle will decrease the reflecter angle at the value ε in each reflection. If the input beam is reflected back and forth in the two interfaces for m $(m = 1, 2, 3, \ldots)$ times and then transmitted, the output beam will be $(m+1)$th transmitted beam. The transfer axis joins the measuring surface N at x'_m. The electric field of the beam is E_m and the intensity of the beam is $E_m E_m^*$.

On the output surface M_2, Δx_m is the transverse walk-off of the mth round trip, and Δz_m is the distance traveled by the (m+1)th outgoing beam with reference to the incident point o. With a geometrical consideration, Δx_m and Δz_m can be derived in the analytic form

$$\Delta x_m = \sum_{i=1}^{m} \left\{ \frac{d \cos(\alpha+\varepsilon) \cos \alpha}{\cos(\alpha + 2i\varepsilon)} \{ \tan[\alpha + (2i-1)\varepsilon] + \tan[\alpha + (2i+1)]\varepsilon \} \right\} \tag{2}$$

$$\Delta z_m = \sum_{i=1}^{m} \left\{ \frac{d \cos(\alpha+\varepsilon) \cos \alpha}{\cos(\alpha+2i\varepsilon) \cos[\alpha+(2i-1)\varepsilon]} + \frac{d \cos(\alpha+\varepsilon) \cos \alpha}{\cos[\alpha+(2i+1)\varepsilon] \cos(\alpha+2i\varepsilon)} \right\} \tag{3}$$

On the measuring surface N, the transverse walk-off of the center of the (m+1)th outgoing beam is $\Delta x'_m$, and the distance traveled by the center of the beam with reference to incident o is $\Delta z'_m$. Using Eqs. (3) and (4) and the equivalent refractive index between the two surfaces, $\Delta x'_m$ and $\Delta z'_m$ can be expressed as

$$\Delta x'_m = \Delta x_m \cos(\alpha+\varepsilon) + [z_0 - d - \Delta x_m \sin(\alpha+\varepsilon)] \frac{1.82 \sin[(2m+1)\varepsilon]}{\sqrt{1 - \{[1.82 \sin[(2m+1)\varepsilon]\}^2}} \tag{4}$$

$$\Delta z'_m = \Delta z_m + [z_0 - d - \Delta x_m \sin(\alpha+\varepsilon)] / \sqrt{1 - [1.82\ \sin(2m+1)\varepsilon]^2} \tag{5}$$

In Fig. 1 for any point p on the measuring surface N, if the distance between p and the direct transmitting point x'_0 is x', then the distance between p and the transfer axis of the (m+1)th outgoing beam will be X_m, which can be given by

$$X_m = |(x' - \Delta x'_m) \sqrt{1 - (1.82)^2 \sin^2[(2m+1)\varepsilon]}| \tag{6}$$

Accordingly, the travel distance of the transmitting axis of the outgoing beam to z is given by

$$Z_m = \Delta x'_m + 1.82 \bullet (x' - \Delta x'_m) \sin[(2m+1)\varepsilon] \tag{7}$$

The equation which describes the propagation of the Gaussian beam along the z direction in free space can be expressed as [15]

$$E(x,y,z) = A \frac{\omega 0}{\omega(z)} \exp\left[-\frac{x^2+y^2}{\omega^2(z)} \right] \cdot \exp\left\{ -i\left[\beta z - \arctan\left(\frac{z}{f}\right) \right] \right\} \exp\left[-i \frac{\beta(x^2+y^2)}{2R(z)} \right] \tag{8}$$

where A is the field amplitude of the beam waist and ω_0 is the beam waist, $R(z)$ is the radius of curvature of the wave front, $\omega(z)$ is the spot size equal to the distance in the transverse direction at which field amplitude decays to $1/e$ of its maximum value, and the f is the light frequency in vacuum.

Using the equation of the Gaussian beam, the electric field of the $(m+1)$th outgoing beam can be given by

$$E_m(X_m, y, Z_m) = k(r_1 r_2)^m \frac{\omega_0}{\omega(Z_m)} \exp\left[-\frac{{X_m}^2 + y^2}{\omega^2(Z_m)} \right] \exp\left\{ -i\left[\beta Z_m - \arctan(\frac{Z_m}{f}) \right] \right\} \times \exp\left\{ -i \frac{\beta[{X_m}^2 + y^2]}{2R(Z_m)} \right\} \tag{9}$$

where $k = \sqrt{1-r_1^2} \times \sqrt{1-r_2^2}$ and the total electric field at p of all the outgoing beam can be given by

$$E_t = \sum_{m=0}^{N} E_m(X_m, y, Z_m) \tag{10}$$

As shown in Fig. 1(a), if the mth reflected angle$\alpha + (2m+1)\varepsilon \geq \pi/2$, it will not go out from the output surface M_2, which will escape from the flank of the cavity. Hence, the overlay coefficient N can be expressed as

$$N = \left[\frac{\pi}{4\varepsilon} - \frac{\alpha}{2\varepsilon} - \frac{1}{2} \right] \tag{11}$$

So the intensity of the total output beams at p can be derived as

$$I = E_t E_t^* = k^2 \sum_{n=0}^{N} \sum_{m=0}^{N} (r_1 r_2)^{m+n} \frac{\omega_0^2}{\omega(Z_m)\omega(Z_n)} \exp\left[-\frac{X_m^2+y^2}{\omega^2(Z_m)} \right] \exp\left[-\frac{X_n^2+y^2}{\omega^2(Z_n)} \right] \times \cos\left\{ \beta(Z_n - Z_m) + \arctan\left(\frac{Z_m}{f}\right) - \arctan\left(\frac{Z_n}{f}\right) + \frac{\beta}{2}\left[\frac{X_n^2+y^2}{R(Z_n)} - \frac{X_m^2+y^2}{R(Z_m)} \right] \right\} \tag{12}$$

As a wedge thin film filter, the wedge angle ε is very important to the transmissivity of its transmitting spectrum. With a wegde angle ε, the peak transmissivity of the wedge thin film filter can be expressed as [16]

$$T' = \left[1 - \frac{1}{3}\left(\frac{\Delta\lambda}{\lambda_0}\right)\right]^{1/2} T_0 \tag{13}$$

where λ_0 is the reference central wavelength, T_0 is the peak transmissivity with ideal parallel incident and emergent surfaces, and $\Delta\lambda$ is the central wavelength shift of the filter caused by the wedge angle, whcih can be given as [16]

$$\Delta\lambda = 1.5 \times 10^{-4} \frac{\varepsilon^2}{n_M^2} \lambda_0 \tag{14}$$

As shown in Fig. 2, the transmissivity of the wedge thin film filter will decrease while the wedge angle is increasing. As the additional insert loss caused by the wedge angle is limited to 0.2 dB, the wedge angle should be less than 0.8°.

In Fig. 3, the transmitting intensity distribution in 15° oblique incidence has been derived with the Eq. (12) for (a) $\varepsilon = 0.8°$ and (b) $\varepsilon = -0.8°$. Other data used in the calculations are $A = 1$, $\omega_0 = 0.25$ mm, $d = 41$ μm, $r_1{}^2 = r_2{}^2 = 0.99$, and $z_0 = 10$ mm. As shown in Fig. 3, the transmitting intensity distribution with negative wedge angle will be much concentrated than that with positive wedge angle, which will improve the characteristics of interference order, transmissivity and bandwidth of the thin film filter in oblique incidence.

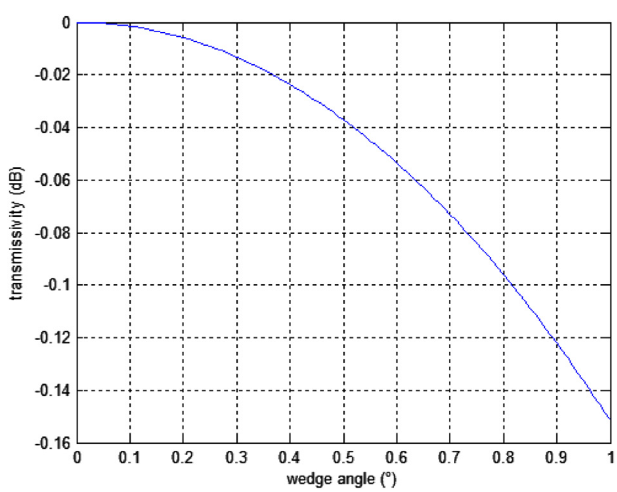

Fig. 2. Transmissivity with different wedge angle of the filter.

3. Experiments results and discussions

The transmitting beam field experiments are performed by the Beam-Master system, which is a beam profilers using two orthogonal knife-edges or slits to scan the beam profile. Fig. 4(a) and (b) shows the measured transmitting beam field distribution of the traditional parallel surfaces angle-tuned thin film filter at the incident angles of 0° and 15° respectively. As shown in the Fig. 4, the transmitting beam field is approximate circular symmetric at normal incidence and the center of the field has the maximum transmitting peak. At 15° oblique incidence, the transmitting beam field broadens along vertical axis, and the transmitting peak has a little vertical displacement, which causes the decreasing of the interference order and the transmissivity. The dimension of beam field distribution with 15° incidence is approximately 1.2 times of that with normal incidence.

According to the stack (1), the wedge angle-tuned thin film filter with the wedge angle 0.8° has also been fabricated. In Fig. 5, the transmitting beam field distribution in 15° oblique incidence has been measured for (a) $\varepsilon = 0.8°$ and (b) $\varepsilon = -0.8°$. As shown in the Fig. 5, the 15° oblique incidence transmitting beam field with 0.8° wedge angle broadens 1.5 times of that parallel surfaces filter in normal incidence, and the transmitting peak has more vertical displacement. However, the 15° oblique incidence transmitting beam field with −0.8° wedge angle will have less transmitting peak displacement and less broaden extent. So the filter with negative wedge should have higher interference order and transmissivity than that of the filter with positive wedge angle.

In this article we developed a tunable filter, as shown in Fig. 6, which using the wedge angle-tuned thin film filter we designed above. This tunable filter include a wedge thin film filter and a pair of fiber collimators which position on the two sides of the filter. The broken line arrow shows the direction of rotation, which keeping the wedge angle of the filter is negative. The angle-tuned filter transmits only one wavelength λ_i from the multiple wavelengths to the drop port. It can choose another wavelength when the incident angle of the wedge filter is changed. The control of the filter is flexible for using a step motor to tune the incident angle.

Fig. 7 shows the transmitting spectrum of the wedge thin film filter at the incident angle of 0°. In normal incidence, the polarity of the 0.8° wedge angle has little influence to the transmissivity and the bandwidth, and transmitting spectrum with the positive wedge angle is coincide with the negative wedge angle. As shown in Fig. 7, the central wavelength is at 1567 nm, the half-bandwidth is 0.5 nm, the bandwidth at 0.5 dB is more than 0.4 nm, the

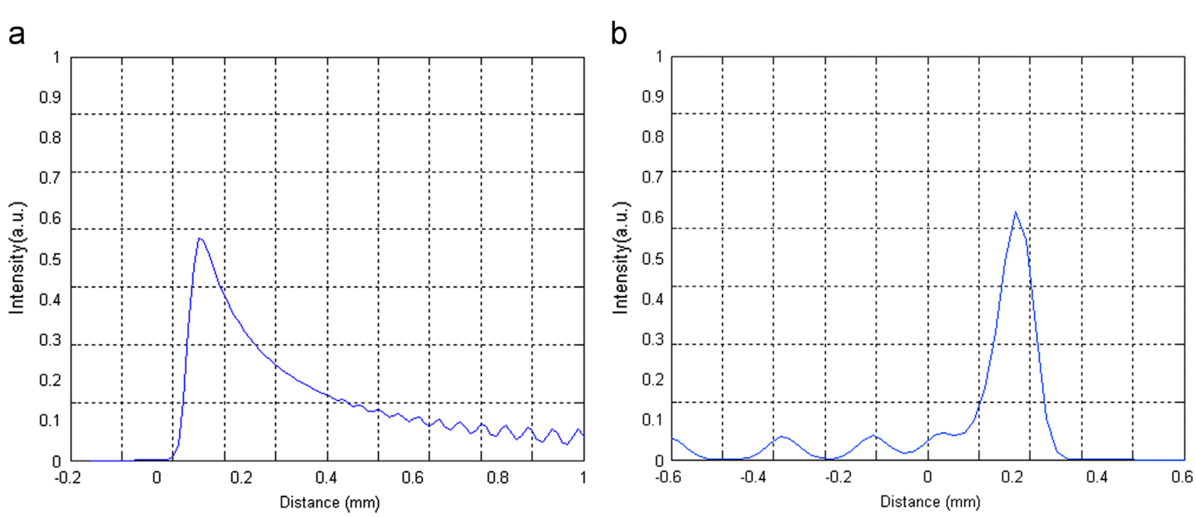

Fig. 3. The transmitting intensity distribution at the incident angle of 15°. (a) wedge angle $\varepsilon = 0.8°$ and (b) wedge angle $\varepsilon = -0.8°$.

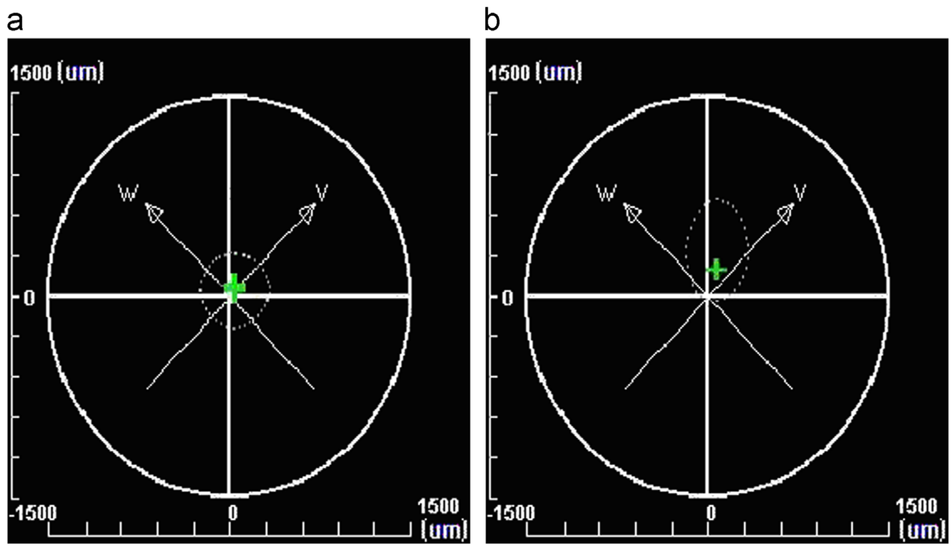

Fig. 4. The transmitting beam field distribution on the parallel surface thin film filter. (a) at normal incidence and (b) at the incident angle of 15°.

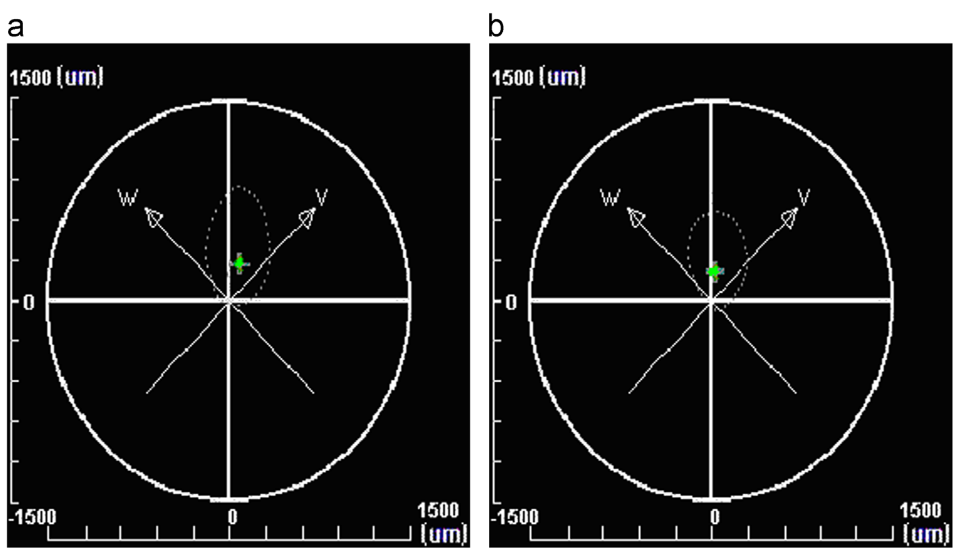

Fig. 5. The transmitting beam field distribution on the wedge thin film filter at the incident angle of 15°. (a) wedge angle $\varepsilon=0.8°$ and (b) wedge angle $\varepsilon=-0.8°$.

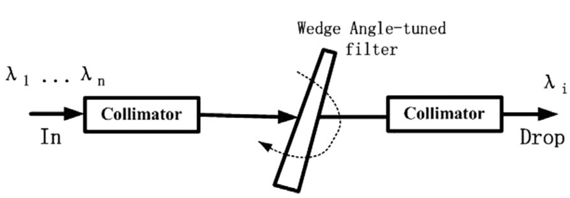

Fig. 6. Structure of the wedge angle-tuned filter.

bandwidth at 25 dB is less than 1 nm, the rectangular degree is 0.43, the insert loss is less than 2 dB and the passband of the transmitting spectrum is very flat.

Fig. 8(a) shows the transmitting spectrum of the wedge thin film filter at the incident angle of 15° with 0.8° wedge angle. As shown in Fig. 8(a), the central wavelength is at 1545.4 nm, the half-bandwidth is 0.8 nm, the bandwidth at 0.5 dB is less than 0.2 nm, the bandwidth at 25 dB is more than 1.6 nm, the

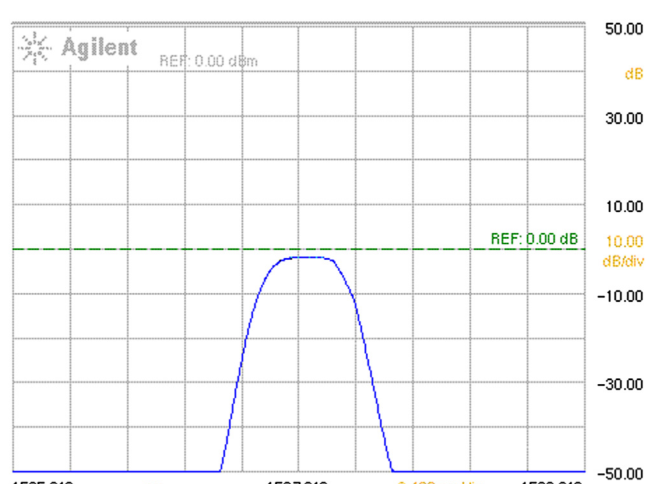

Fig. 7. Measured transmitting spectrum of the wedge filter at normal incidence.

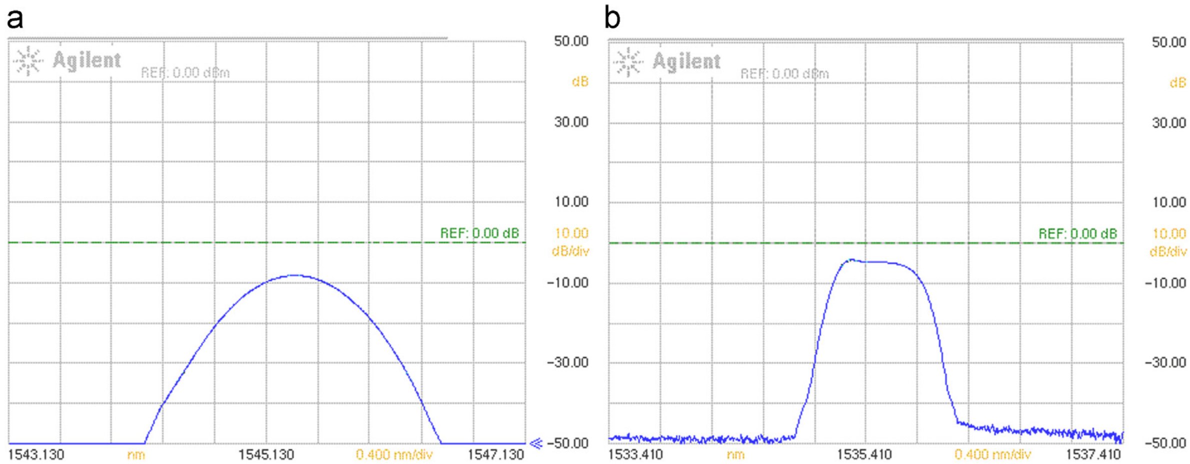

Fig. 8. Measured transmitting spectrum of the wedge filter. (a) incident angle of 15°, wedge angle $\varepsilon = 0.8°$ and (b) incident angle of 17.5°, wedge angle $\varepsilon = -0.8°$.

transmitting spectrum rectangular degree worsens to 0.12, and the insert loss is more than 5 dB.

Fig. 8(b) shows the transmitting spectrum of the wedge thin film filter at the incident angle of 17.5° with −0.8° wedge angle. As shown in Fig. 8(b), the half-bandwidth is 0.6 nm, the bandwidth at 0.5 dB is 0.3 nm, the bandwidth at 25 dB is 1.2 nm, and the rectangular degree is 0.25, which still confirm the requirements of the 100 GHz DWDM system. The insert loss is less than 4 dB, and the central wavelength is shift to 1535.4 nm, which stable wavelength tunable range is broadening approximate 10 nm than that of parallel angle-tuned thin film filter.

4. Conclusion

In this paper, the wedge filter's transmitting intensity distribution in oblique incidence with different wedge angle has been calculated. The transmitting intensity distribution with negative wedge angle will be much concentrated than that with positive wedge angle, so the proper wedge angle and incident orientation will improve the characteristics of its transmitting spectrum. A 100 GHz DWDM angle-tuned wedge thin film filter was fabricated with the wedge angle of 0.8°. Compared with the parallel angle-tuned filter, the wedge filter with the −0.8° wedge angle can enhance the transmissivity and the rectangular degree in oblique incidence and its tunable wavelength range will increase 10 nm.

Acknowledgments

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