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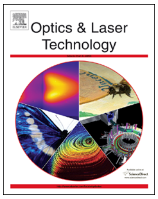

A novel angle-tuned thin film filter with low angle sensitivity

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ABSTRACT

An angle-tuned thin film narrowband filter is widely used in the dense wavelength division multiplexing (DWDM) system. With increase of incident angle of the thin film filter, the central wavelengths of both S-polarization and P-polarization will separate obviously and shift to short wavelength much faster, which will cause serious polarization sensitivity and angle sensitivity. In conventional angle-tuned thin film filters, the research works usually focus on the polarization sensitivity. However, their angle sensitivity is very high because the effective refractive indexes of their spacer are very low. Their precision of the angle controlling system is very rigorous (less than 0.005°) and their incident angles are usually less than 20°, which will limit their wavelength tuning range. In the present paper, we propose and fabricate a novel 100 GHz angle-tuned thin film filter stack with low angle sensitivity which uses the high refractive index material $\alpha-$Si as the spacer and its incident angle can be expanded to 32°. Using the polarization beam-splitters and the half wave plates, this angle-tuned thin film filter can also eliminate the polarization sensitivity. The simulation results and the experiments show that the angle-tuned thin film filter with low angle sensitivity has a effective tuning range of 40 nm, which can cover the whole C-band and its precision of the angle control is relatively easy (more than 0.05°).

1. Introduction

With low insertion loss, high adjacent channel isolation and good temperature stability, the multiple-cavity narrowband thin film filter is widely used in the DWDM system [1]. When thin film filter is used in oblique incidence, the spacer effective optical thickness will decrease and the central wavelength will shift to short wavelength, and the central wavelength of P-polarization will not coincide with that of S-polarization [2], which will cause serious polarization sensitivity [3]. With the rapid development of thin film de-polarization technique, more and more angle-tuned thin film filters are emerging [4–7]. For conventional dielectric angle-tuned thin film filter, the central wavelength shift velocity is too high in large incident angle because its spacer effective refractive index is relatively low (usually less than 1.8), which will cause the serious angle sensitivity, and it will cause the high cost and difficult precision of its the angle controlling system.

According to the ITU protocol, the central wavelength positioning precision of current 100 GHz channel spacing DWDM system should be less than ±8 pm. So the angle controlling precision of the conventional 100 GHz angle-tuned thin film filter is very rigorous, especially in the large angle oblique incidence, even less than 0.005° [8]. It will cause serious angle sensitivity and high cost of the angle controlling systems, which will limit its tunable wavelength range and the incident angle range (usually less than 20°).

In this paper, we design and fabricate a novel 100 GHz channel spacing angle-tuned thin film filter with low angle sensitivity by using the high refractive index material $\alpha-$Si as its spacer, which incident angle can be enlarged to 32°. Based on the polarization beam-splitters and the half wave plates, the polarization sensitivity of the angle-tuned thin film filter can also be eliminated. The theoretical analysis and the experimental results indicate that its tunable range is more than 40 nm and its easy precision of the angle controlling system is more than 0.05°.

2. Theoretical analysis

2.1. Angle sensitivity

The variation of the performances of a dielectric Fabry–Perot thin film filter with incident angle is a well known effect, which has been widely studied and often used by manufactures to ease a little some too tight production tolerances. The tuning equation of such a filter is given by [9]:

$$\lambda=\lambda_0\sqrt{1-(\sin^2\theta/n_{eff}^2)} \tag{1}$$

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where λ_0 is the central wavelength in normal incidence, λ is the central wavelength in oblique incidence, θ is the incident angle of the collimated light beam and n_{eff} is the effective refractive index of the spacer.

From Eq. (1) we can see that the central wavelength of the thin film filter will shift to short wavelength while the incident angle is increasing. The wavelength shift velocity is determined by the spacer effective refractive index n_{eff}, which is intermediate between the high and low refractive index materials of the thin film filter [10,11]:

$$n_{eff} = n_L \left[\frac{m-(m-1)(n_L/n_H)}{m-m(n_L/n_H)+(n_L/n_H)^2} \right]^{1/2} \quad \text{for a low-index spacers} \tag{2}$$

$$n_{eff} = n_H \left[\frac{m-(m-1)(n_L/n_H)}{(m-1)-(m-1)(n_L/n_H)+(n_H/n_L)} \right]^{1/2} \quad \text{for a high-index spacers} \tag{3}$$

where n_H is the refractive index of the high refractive index material, n_L is the refractive index of the low refractive index material and m is the order number of the spacer.

Conventional narrowband thin film filter usually use the Ta_2O_5/TiO_2 and SiO_2 as its high and low refractive index materials. According to the 100 GHz channel spacing DWDM system protocol, the passband (@ −0.5 dB) of the thin film filter should be large than 0.3 nm and the stopband (@ −25 dB) should be less than 1.3 nm. Two typical 100 GHz three-cavity narrowband thin film filter stacks which use only the low or high refractive index materials as the spacer are given by:

$$G/[(HL)^8 6L(LH)^8 L]^3/A \tag{4}$$

$$G/[(HL)^8 4H(LH)^8 L]^3/A \tag{5}$$

where G and A denote glass and air, respectively. Low index material L is SiO_2 ($n_L = 1.46$) and high index material H is Ta_2O_5 ($n_H = 2.05$), which are both quarter wavelength coatings [12]. Given $n_G = 1.523$ and reference wavelength $\lambda_0 = 1565$ nm in normal incidence.

In oblique incidence, the refractive of S-polarization is $n_s = n \cos\theta$ and the refractive of P-polarization is $n_p = n/\cos\theta$, where n is the refractive index in normal incidence. Hence, the central wavelengths of both the S-polarization and P-polarization light will separate while the incident angle is increasing. The theoretical central wavelengths (of all the average light, S-polarization and P-polarization light) of the stack (4) and stack (5) vary with the angle of incidence are shown in Fig. 1, respectively. From Fig. 1 we can see that the central wavelength of the average light shift to short wavelength is much faster while the incident angle is increasing and the wavelength shift velocity of the high refractive index spacer is much slower than that of low refractive index spacer. For a 100 GHz DWDM system, the adjacent channel spacing should be 0.8 nm, so the angle controlling system precision in large angle incidence is much higher than that of in small angle incidence. The high angle sensitivity in large incident angle of the thin film filter will limit the wavelength tunable range and the wavelength positioning precision. So conventional angle-tuned thin film filter usually used within 20° oblique incidence and it should have high-cost rigorous angle controlling system.

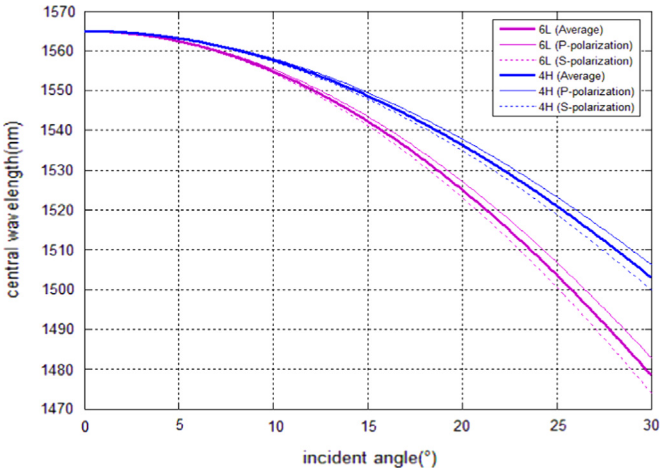

Fig. 1. Shift of central wavelength with angle of incidence.

2.2. Low angle sensitivity stack design

In oblique incidence, the central wavelength shift for the S-polarization in a low-index-spacer filter is larger than that for a P-polarization; the central wavelength shift for S-polarization in a high-index-spacer filter is less than that for P-polarization [13], which will cause serious polarization sensitivity and the polarization dependent loss. In our former work, we found that the central wavelengths of the S-polarization and P-polarization light will coincide by using both high and low refractive index materials (Ta_2O_5 and SiO_2) as the spacer. In this way, a four-cavity 100 GHz narrowband de-polarization angle-tuned thin film filter is designed and fabricated, which stack structure is as follows [8]:

$$G/\Big[(HL)^7 2L3H4L3H2L(LH)^7 L(HL)^8 2L3H4L3H2L(LH)^8 L \\ (HL)^8 2L3H4L3H2L(LH)^8 L(HL)^7 2L3H4L3H2L(LH)^7\Big]/A \tag{6}$$

The stack (6) has a tunable wavelength range from 1561 nm to 1528 nm. However, the angle sensitivity of the stack (6) is very high because its spacer effective refractive index is very low ($n_{eff} = 1.65$), which can only be used within 20° oblique incidence. According to the ITU protocol, the central wavelength positioning precision of the 100 GHz channel spacing DWDM system should be less than ± 8 pm, so that its angle controlling precision should be less than 0.005°. In its angle controlling system we had to use the high-precision Faulhaber motor, related reducer and encoder to get the rigorous angle controlling precision so that the cost of this device is very high.

In order to decrease the cost of the angle controlling system, the spacer effective refractive index should be increased, which will decrease the wavelength shift velocity and increase the incident angle range. Compared with the conventional high refractive index materials TiO_2 ($n = 2.25$) and Ta_2O_5 ($n = 2.05$), the material $\alpha-Si$ has higher refractive index. So we can use $\alpha-Si$ and SiO_2 to construct a novel narrowband angle-tuned thin film filter stack with low angle sensitivity, especially use the high refractive index material $\alpha-Si$ as the spacer of the thin film filter. Using the ion-beam-sputtering technology, the $\alpha-Si$ film can be fabricated in the Leybold Helios sputtering system, which its material refractive index is 3.2 and its extinction coefficient K is 1.45×10^{-5}. Using the global optimization algorithm [8], we designed a novel $\alpha-Si$ spacer three-cavity angle-tuned thin film filter stack as follows:

$$G/[(HL)^4 4H(LH)^4 L]^3 1.83H0.6L/A \tag{7}$$

where low index material L is SiO_2, high index material H is $\alpha-Si$ ($n_H = 3.2$, $K = 1.45 \times 10^{-5}$) and reference wavelength $\lambda_0 = 1565$ nm. The double layer coating $1.83H0.6L$ in the stack (7) is the anti-reflection film. The stack (7) has fewer layers than that of the stack (4) to stack (6) due to its larger refractive index difference between the high and low refractive index materials used in the stack.

The theoretical central wavelengths (of all the average light, S-polarization and P-polarization light) of the stack (6) and stack (7) vary with the angle of incidence are shown in Fig. 2,

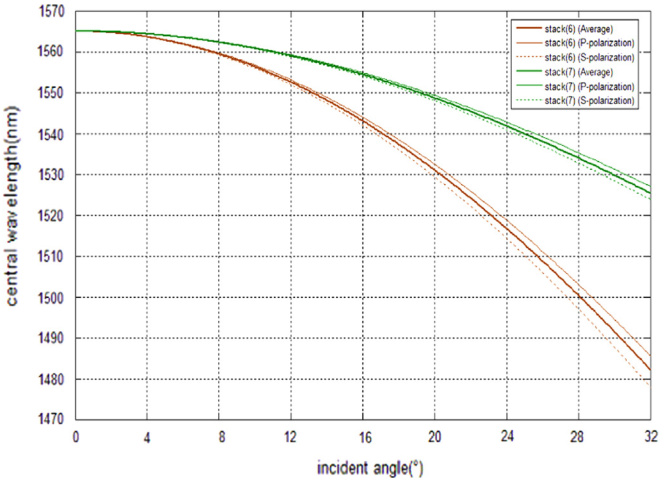

Fig. 2. Shift of central wavelength with angle of incidence.

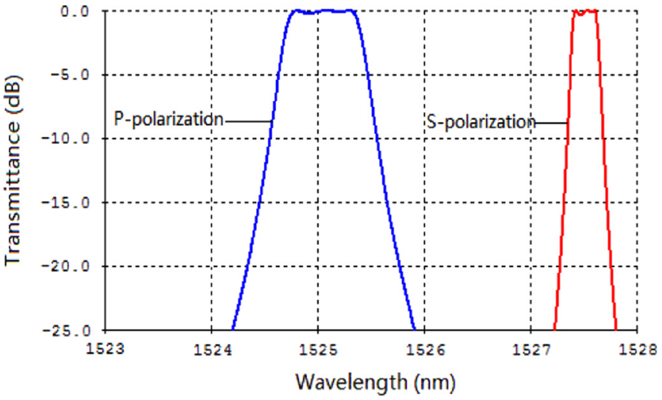

Fig. 3. Transmitting curve of the stack (7) in 32° oblique incidence.

respectively. From Fig. 2 we can see that the stack (6) will have the wavelength tunable range (1525–1565 nm) when the incident angle range is from 0° to 22°, while the stack (7) will have the same wavelength tunable range when the incident angle range is from 0° to 32°. The central wavelength shift to short wavelength of the stack (7) is much slower than that of the stack (6), because the spacer effective refractive index of the stack (7) ($n_{eff}=2.41$) is larger than that of the stack (6) ($n_{eff}=1.65$). According to the 100 GHz DWDM central wavelength positioning precision (± 8 pm), the angle controlling precision should be 0.05° in 32° oblique incidence, which is much higher than that of the stack (6) (less than 0.005°).

2.3. De-polarization design

Using only high refractive index material $\alpha-\mathrm{Si}$ as the spacer, the stack (7) has lower angle sensitivity than that of the stack (6), and it has the advantages of the large incident angle and the easy angle controlling precision. However, the stack (7) has serious polarization sensitivity due to its spacer structure that has not do any de-polarization design, which will cause high polarization dependent loss. The transmitting curves of different polarization light in the 32° oblique incidence are shown in Fig. 3. From Fig. 3 we can see that the central wavelengths of the P-polarization and S-polarization are separating obviously, which the wavelength separation of the two polarization light peaks is more than 2.5 nm. So we should use the polarization beam-splitters and the half wave plates to eliminate the polarization sensitivity of the angle-tuned thin film filter based on the stack (7).

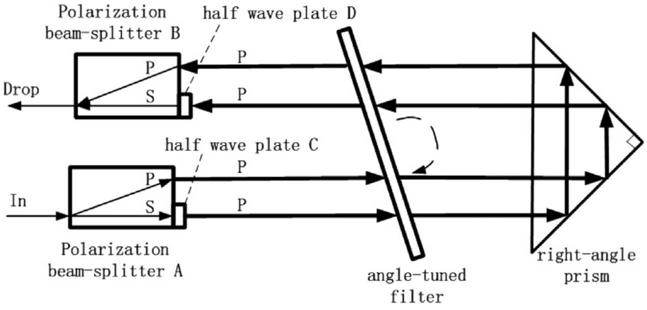

Fig. 4. De-polarization light path structure.

As shown in the Fig. 3, both the bandwidths of passband (@ −0.5 dB) and stopband (@ −25 dB) in S-polarization are less than the requirements of the 100 GHz channel spacing DWDM system. In order to get larger tuning range, we can use the polarization beam-splitters and half wave plates to transmit only P-polarization light. The de-polarization angle-tuned thin film filter light path structure is shown in Fig. 4.

This de-polarization angle-tuned thin film filter with low angle sensitivity including: an angle-tuned interference thin film filter based on the stack (7); a pair of polarization beam-splitters A and B which position on the same side of the filter; a pair of half wave plate C and D; a right-angle prism which position on the other side of the filter. The polarization beam-splitter A divides the input multiple wavelengths into two parallel light paths in P-polarization and the S-polarization modes. The half wave plate C at the S-polarization light path rotates the S-polarization light into the P-polarization light. Then the P-polarization light in both input paths arrive the angle-tuned thin film filter. Filter transmits λ_i from the multiple wavelengths to the right-angle prism. Using the right-angle prism the filter beam can be reflected to the angle-tuned thin film filter again, so it will have double filtering. After the first filtering, the transmissivity beyond the passband has been reduced obviously. So the double filtering can greatly decrease the bandwidth of the stopband, which has little change to the bandwidth of the passband. Hence the rectangle factor of the thin film filter will be increased. The half wave plate D at another P-polarization light path rotates the P-polarization light into the S-polarization light. The polarization beam-splitter B then converges the P-polarization and the S-polarization light into a random polarization light to the drop port. It will choose another wavelength when the oblique angle of the filter is changed.

The polarization beam-splitters are coupled with the single core fiber collimators at the input and drop port. Using a pair of polarization beam-splitters and the half wave plates, the polarization mode of the input light at the angle-tuned thin film filter will be changed to the P-polarization light, so the polarization light central wavelength separation and the polarization dependent loss of the transmission light will be greatly reduced. As the wavelength tuning range of the P-polarization light is larger than that of the S-polarization light, the wavelength tuning range can cover the whole C-band (from 1525 nm to 1565 nm). The incident angle range is from normal incidence to 32°. Fig. 5 and Fig. 6 show the simulation transmitting curve of the stack (7) after double filtering in normal incidence and in 32° oblique incidence. From Fig. 5 we can see that the central wavelength is at 1565 nm in normal incidence, the passband (@ −0.5 dB) is 0.33 nm and stopband (@ −25 dB) is 1.1 nm. As shown in the Fig. 6, the central wavelength shift to 1525 nm while the incident angle is 32°, its passband (@ −0.5 dB) is 0.42 nm and stopband (@ −25 dB) is 1.25 nm.

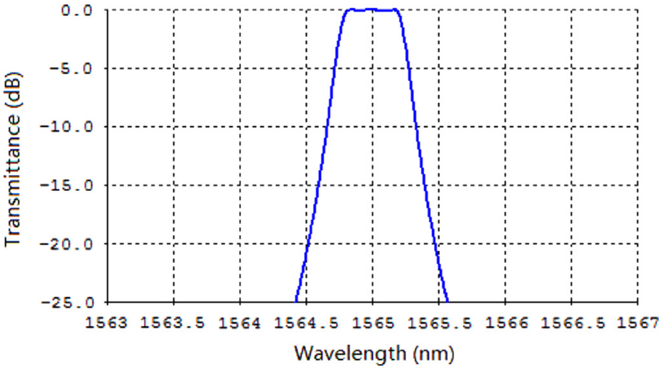

Fig. 5. Transmitting curve of the stack (7) in normal incidence after double filtering.

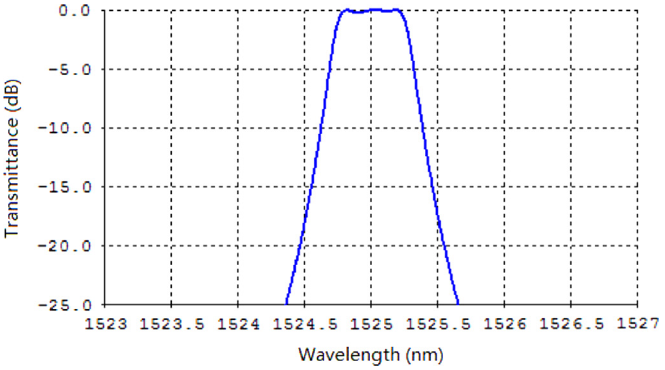

Fig. 6. Transmitting curve of the stack (7) in 32° oblique incidence after double filtering.

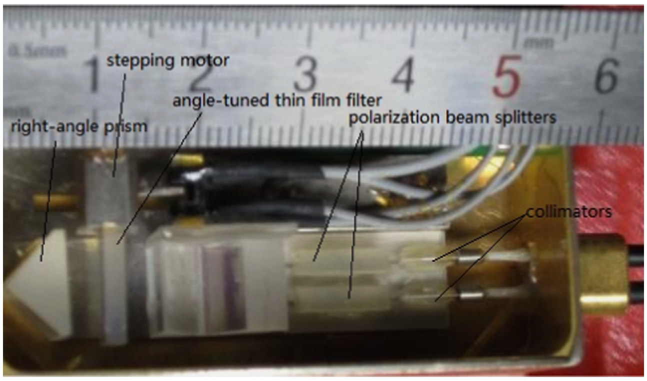

Fig. 7. Photograph of the fabricated angle-tuned thin film filter device.

3. Experimental results

According to the stack (7), we use the ion-beam-sputtering technology fabricate the low angle sensitivity 100 GHz channel spacing de-polarization narrowband angle-tuned thin film filter with the polarization beam-splitters and the half plates, as shown in the Fig. 7. From Fig. 7 we can see this device is very smart, the input port and the drop port are at the same side. Then we test the transmitting spectrum of the filter in normal incidence and in the incident angle of 32°. Fig. 8 shows the measured transmitting spectrum in normal incidence, which insert loss is 2 dB, its passband is 0.3 nm and its stopband is 1.0 nm. Fig. 9 shows the measured transmitting spectrum in 32° oblique incidence. As shown in Fig. 9, the central wavelength shift to 1524.6 nm and the insert loss is 2.5 dB, its passband is 0.38 nm and stopband is 1.28 nm, which still confirm the requirements of the 100 GHz DWDM system.

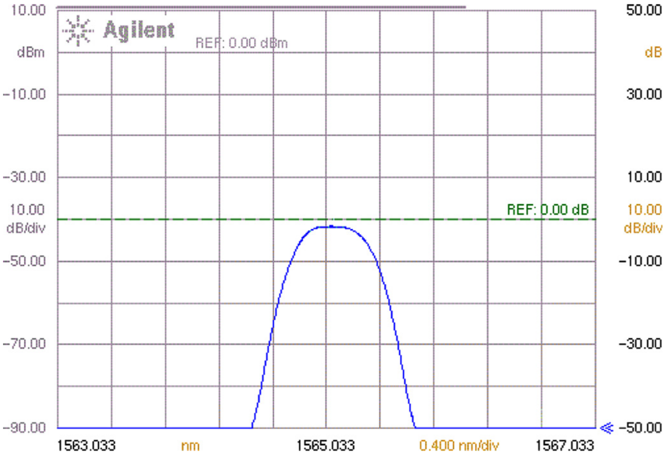

Fig. 8. Measured spectrum in normal incidence.

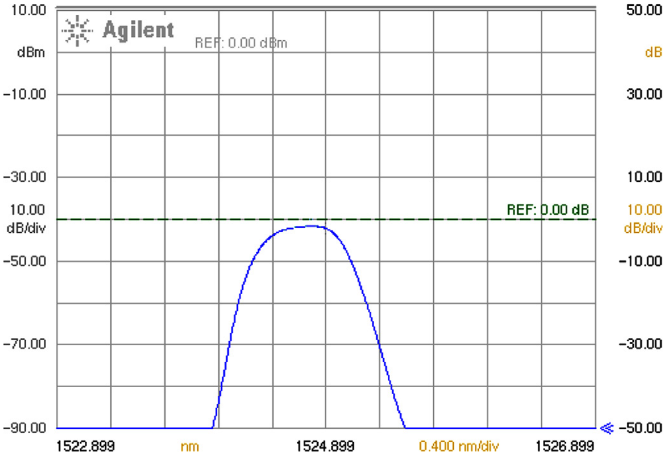

Fig. 9. Measured spectrum in 32° incidence.

4. Conclusion

Using the polarization beam-splitters and the high refractive index material $\alpha-\mathrm{Si}$ as the spacer, a novel 100 sGHz channel spacing de-polarization narrowband angle-tuned thin film filter with low angle sensitivity is designed and fabricated. It has the angle tuning range from normal incidence to 32° oblique incidence, which is much larger than that of the conventional angle-tuned thin film filter. The precision of the angle control of this device can be enhanced to 0.05°, which is easy to be fabricated. The simulation results and the experiments show that the angle-tuned thin film filter with low angle sensitivity has an effective tuning range of 40 nm, which can cover the whole C-band. It has a bright application opportunity for its flexibility, low cost and wide wavelength tuning range.

Acknowledgments

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