Tunable thin-film filter with low angle sensitivity*

YU Kan (俞侃)**, **BAO Jia-qi** (包佳祺), **and YIN Juan-juan** (尹娟娟)
Department of Information Science and Technology, Wenhua College, Huazhong University of Science and Technology, Wuhan 430074, China

(Received 4 July 2015)

Conventional angle-tuned thin-film filters have serious angle sensitivity for their low spacer effective refractive index, and it is difficult to fabricate their angle control system. In this 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 TiO_2 as the spacer, and its incident angle can be expanded to 25°. Compared with the traditional Ta_2O_5-SiO_2 thin-film filter stack, the novel stack has fewer layers. Using the polarization beam splitters and the half wave plates, the polarization sensitivity of the angle-tuned filter can also be suppressed. Simulation results and the experiments show that the thin-film filter with low angle sensitivity has an effective tuning range of 33 nm, which can cover the whole C-band, and its angle control system is easy to be fabricated.

Document code: A **Article ID:** 1673-1905(2015)05-0338-4
DOI 10.1007/s11801-015-5126-7

With low insertion loss, good temperature stability and high channel isolation degree, the narrowband multiple-cavity interference dielectric thin-film filter is widely used in the dense wavelength division multiplexing (DWDM) system and intelligent optical network[1]. As the incident angle of the thin-film filter is increased, the central wavelength will shift to shorter wavelength due to its effective optical thickness of spacer will decrease[2], and the central wavelength of the S-polarization will not coincide with that of the P-polarization[3]. With the development of thin-film non-polarization technique, more and more angle-tuning thin-film filters are emerging[4-6]. The former researches mainly focus on the non-polarization stack design, including the spacer layers[7] and the mirror layers[8].

However, the central wavelength shift velocity of the conventional angle-tuning thin-film filters is too high because their spacer effective refractive index is very low (usually less than 1.8)[9], which can cause the serious angle sensitivity. According to the international telecommunication union (ITU) protocol, the central wavelength positioning precision of 100 GHz channel spacing DWDM system should be less than ±8 pm. So the angle controlling precision of the conventional 100 GHz angle-tuning thin-film filter is very rigorous, especially in large angle oblique incidence, which will limit its tunable wavelength range and the incident angle range (usually less than 20°)[10].

In this paper, the relation of the central wavelength to the spacer stack effective refractive index and the incident angle is analyzed. Then we design and fabricate a novel 100 GHz channel spacing angle-tuning thin-film filter with low angle sensitivity by using the high refractive index TiO_2 as the spacer, where the incident angle can be enlarged to 25°. Based on the polarization beam splitters and the half wave plates, the polarization sensitivity of the angle-tuning thin-film filter can also be suppressed. The theoretical analyses and the experiments show that its wavelength tunable range is more than 33 nm and its angle controlling system is easy to be fabricated.

The variation of the performance of a Fabry-Perot thin-film filter with incident angle is a well known effect, and the central wavelength tuning equation of such a filter is given as[11]

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

where λ_0 is the central wavelength in normal incidence, λ is the central wavelength in oblique incidence, θ is the incident angle, and $n_{\rm eff}$ is the effective refractive index of the spacer, which is intermediate between the high and low refractive indices of the materials of the thin-film filter[12]. For the spacer with low refractive index, the effective refractive index is expressed as

$$n_{\rm eff} = n_{\rm L}\left[\frac{m-(m-1)(n_{\rm L}/n_{\rm H})}{m-m(n_{\rm L}/n_{\rm H})+(n_{\rm L}/n_{\rm H})^2}\right]^{1/2} , \quad (2)$$

* This work has been supported by the Scientific Research Project of Hubei Education Department (No.B2014246), the National Natural Science Foundation of China (No.61205062), the Natural Science Foundation of Hubei Province in China (No.2012FFB02701), and the Project of Hubei Province Universities Outstanding Youth Scientific Innovation Team (No.T201431).
** E-mail: onlyfish@126.com

and for the spacer with high refractive index, the effective refractive index is expressed as

$$n_{\mathrm{eff}} = n_{\mathrm{H}} \left[\frac{m-(m-1)(n_{\mathrm{L}}/n_{\mathrm{H}})}{(m-1)-(m-1)(n_{\mathrm{L}}/n_{\mathrm{H}})+(n_{\mathrm{H}}/n_{\mathrm{L}})} \right]^{1/2}, \quad (3)$$

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. From Eq.(1), we can see that the central wavelength of the thin-film filter will shift to shorter wavelength when the incident angle increases.

Due to the high adhesion of the multilayer film and the good optical stability, Ta_2O_5 and SiO_2 are usually used as high and low refractive index materials to build a narrowband thin-film filter stack. According to the 100 GHz channel spacing DWDM system protocol, the passband (at −0.5 dB) of the thin-film filter should be larger than 0.3 nm, and the stopband (at −25 dB) should be less than 1.3 nm. In our former work, we designed a four-cavity angle-tuning thin-film filter stack, which is given by

$$\begin{bmatrix} (\mathrm{HL})^7 8\mathrm{L}(\mathrm{LH})^7 \mathrm{L}(\mathrm{HL})^8 8\mathrm{L}(\mathrm{LH})^8 \mathrm{L} \\ (\mathrm{HL})^8 8\mathrm{L}(\mathrm{LH})^8 \mathrm{L}(\mathrm{HL})^7 8\mathrm{L}(\mathrm{LH})^7 \end{bmatrix}, \quad (4)$$

where H is the high refractive index material Ta_2O_5 with n_{H}=2.05, and L is the low refractive index material SiO_2 with n_{L}=1.456[13], which are both quarter wavelength coatings[14]. The reference wavelength λ_0 is 1 565 nm in normal incidence. According to Eq.(2), the spacer effective refractive index of the four-cavity stack expressed as Eq.(4) is 1.54. This spacer effective refractive index value is very low, which can cause serious angle sensitivity and limit the oblique incident angle range of the angle-tuning thin-film filter. Due to the angle controlling precision of the device can only achieve 0.05°, the thin-film filter should be used within 16° oblique incidence. While the incident angle is larger than 16°, its central wavelength shift velocity is so high that the angle controlling system can not achieve the ITU wavelength positioning precision.

In order to reduce the angle sensitivity of the angle-tuning thin-film filter, we should use the material with higher refractive index to build the stack, especially the spacer stack. Due to the refractive index of TiO_2 is higher than that of Ta_2O_5, we can choose TiO_2 and SiO_2 as the materials with high and low refractive indices to build the thin-film filter stack. According to the thin-film filter genetic optimization algorithm[15], we get the three-cavity 100 GHz channel spacing thin-film filter stack as

$$\begin{bmatrix} (\mathrm{HL})^6 6\mathrm{H}(\mathrm{LH})^6 \mathrm{L}(\mathrm{HL})^6 6\mathrm{H}(\mathrm{LH})^6 \mathrm{L} \\ (\mathrm{HL})^6 6\mathrm{H}(\mathrm{LH})^6 \mathrm{L} \end{bmatrix}, \quad (5)$$

where H is the high refractive index material TiO_2 with n_{H}=2.32, and L is the low refractive index material SiO_2 with n_{L}=1.456. The reference wavelength λ_0 is also 1 565 nm.

As the difference between the relative refractive indices of TiO_2 and SiO_2 is higher than that of Ta_2O_5 and SiO_2, the three-cavity stack expressed as Eq.(5) can have less coatings than the four-cavity stack expressed as Eq.(4) and have higher rectangle degree. Fig.1 shows the simulated transmittance curve of the three-cavity stack expressed as Eq.(5) in normal incidence. From Fig.1 we can see that its passband at −0.5 dB is more than 0.4 nm, and its stopband at −25 dB is less than 1.1 nm.

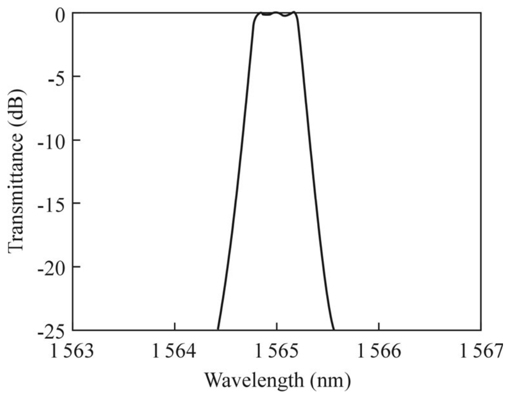

Fig.1 Transmittance curve of the three-cavity stack expressed as Eq.(5) in normal incidence

Fig.2 shows the central wavelength shifts with different incident angles of the four-cavity stack expressed as Eq.(4) and the three-cavity stack expressed as Eq.(5). From Fig.2 we can see that the central wavelength shift velocity of the stacks becomes faster and faster while the incident angle is increased. However, according to Eq.(3), the spacer effective refractive index of the three-cavity stack expressed as Eq.(5) can be enhanced to 2.06, which is much higher than that of the stack expressed as Eq.(4). So the central wavelength shift velocity to shorter wavelength of the three-cavity stack expressed as Eq.(5) is much slower than that of the stack expressed as Eq.(4). According to the ITU protocol, the wavelength positioning accuracy of the 100 GHz channel spacing DWDM system should be less than ±8 pm. Meanwhile, the precision of angle control system can only achieve 0.05°. So the stack expressed as Eq.(4) can only be used within 16° oblique incidence, in which the wavelength tunable range can only be 24 nm. However, the three-cavity stack expressed as Eq.(5) can be used in 25° oblique incidence, in which the central wavelength tunable range can be enlarged to 32 nm.

Using only high refractive index material TiO_2 as the spacer, the three-cavity stack expressed as Eq.(5) has lower angle sensitivity than the stack expressed as Eq.(4), and it has the advantages of large incident angle and easy angle controlling precision. However, the three-cavity stack expressed as Eq.(5) has serious polarization sensitivity due to its pacer structure has not any non-polarization design, which will cause high polarization dependent loss. The transmitting curves of different polarization waves in the 25° 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 separated obviously, and the wavelength separation of the two polarized light peaks is more than 0.8 nm. So we should use the polarization beam splitters and the half wave plates to suppress the polarization sensitivity of the angle-tuned thin-film filter based on the three-cavity stack expressed as Eq.(5).

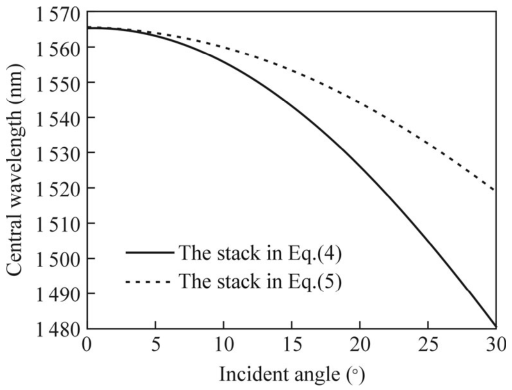

Fig.2 Central wavelength versus angle of incidence in the four-cavity stack expressed as Eq.(4) and the three-cavity stack expressed as Eq.(5)

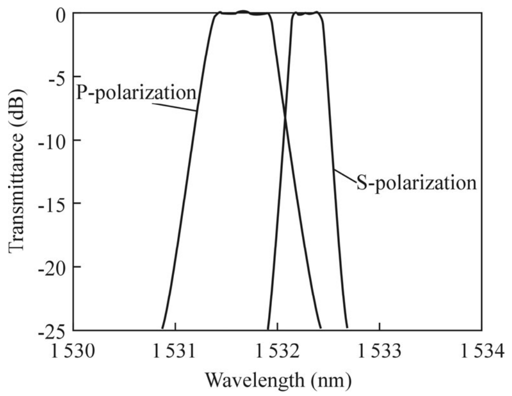

Fig.3 Transmittance curves of different polarization waves based on the three-cavity stack expressed as Eq.(5) at the incident angle of 25°

As shown in Fig.3, both the bandwidths of passband at −0.5 dB and stopband at −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 schematic diagram of the non-polarization angle-tuned thin-film filter light path structure is shown in Fig.4.

This non-polarization angle-tuned thin-film filter with low angle sensitivity includes an angle-tuned interference thin-film filter based on three-cavity stack expressed as Eq.(5), a pair of polarization beam splitters A and B which locate on the same side of the filter, a pair of half wave plates C and D, and a right-angle prism which locates 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 S-polarization modes, respectively. The half wave plate C in the S-polarization light path rotates the S-polarization light into the P-polarization light. Then the P-polarization light in both input paths arrives at the angle-tuned thin-film filter. Filter transmits the wavelength 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 can be reduced obviously. So the double-filtering can greatly decrease the bandwidth of the stopband, which has little influence on the bandwidth of the passband. Hence, the rectangle factor of the thin-film filter can be increased. The half wave plate D in the other P-polarization light path rotates the P-polarization light into the S-polarization light. The polarization beam splitter B then converges the P-polarization light and the S-polarization light into random polarization light to the drop port. It will choose another wavelength when the oblique angle of the filter is changed.

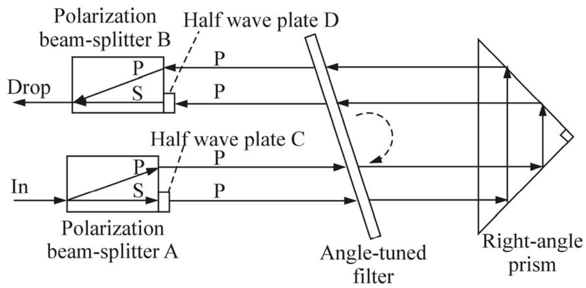

Fig.4 Schematic diagram of the non-polarization light path structure of the angle-tuned thin-film filter

The polarization beam splitters are coupled with the single core fiber collimators at the input and drop ports. 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 can be changed to the P-polarization, so the central wavelength separation between two polarization waves and the polarization dependent loss of the transmission light are 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 be from 1 532 nm to 1 565 nm, and the incident angle range is from normal incidence to 25° oblique incidence.

According to the three-cavity stack expressed as Eq.(5), we use the ion-beam-sputtering technology to fabricate the low angle sensitivity 100 GHz channel spacing non-polarization narrowband angle-tuned thin-film filter with the polarization beam splitters and the half plates. Then we test the transmittance spectra of the filter in normal incidence and in the incident angle of 25°. Fig.5 shows the measured transmittance spectrum in normal incidence, where the insertion loss is 2 dB, its passband is 0.3 nm, and its stopband is 1.0 nm. Fig.6 shows the measured transmittance spectrum in 25° oblique incidence. The central wavelength shifts to 1 532 nm, the insertion 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.

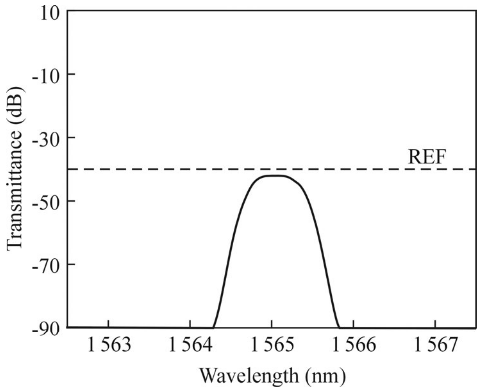

Fig.5 The measured transmittance spectrum in normal incidence

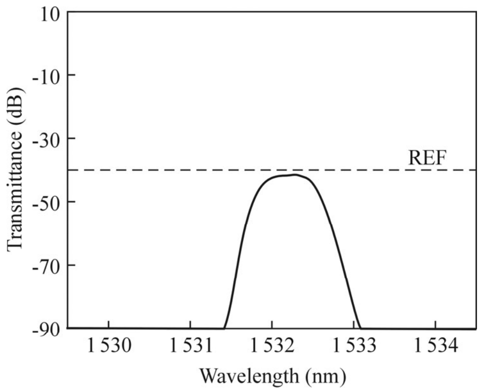

Fig.6 The measured transmittance spectrum in 25° oblique incidence

In summary, using the polarization beam splitters and the high refractive index material TiO_2 as the spacer, a novel 100 GHz channel spacing non-polarization narrow-band angle-tuned thin-film filter with low angle sensitivity is designed and fabricated. It has the angle tuning range from normal incidence to 25° oblique incidence, which is much larger than that of the conventional angle-tuned thin-film filter. The angle controlling precision of this device can be enhanced to 0.05°, and the angle control system 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 33 nm, which can cover the whole C-band. It has a potential application prospect for its flexibility, low cost and wide wavelength tuning range.

References

[1] MU Xin, FU Xiu-hua, ZHAO Yan and JIA Yan, Acta Photonica Sinica **40**, 259 (2011). (in Chinese)

[2] LI Wei, CHANG Sheng-jiang, WANG Xiang-hui, LIN Lie and BAI Jin-jun, Optoelectronics Letters **10**, 180 (2014).

[3] L. Domash, M. Wu and N. Nemchuk, Journal of Lightwave Technalogy **22**, 126 (2004).

[4] YU Kan, JI Zi-juan, HUANG De-xiu, BAO Jia-qi and YIN Juan-juan, Acta Photonica Sinica **39**, 1971 (2010). (in Chinese)

[5] YU Kan, LIU Wen and HUANG De-xiu, Acta Photonica Sinica **37**, 1175 (2008). (in Chinese)

[6] NIE Ming-ju and LIU De-ming, Acta Photonica Sinica **38**, 2015 (2009). (in Chinese)

[7] K. Yu, Y. Y. Liu, J. Q. Bao and D. X. Huang, Optics and Laser Technology **56**, 71 (2014).

[8] K. Yu, J. J. Yin, D. X. Haung and J. Q. Bao, Optik-International Journal for Light and Electron Optics **125**, 397 (2014).

[9] K. Yu, W. Liu, D. X. Huang and J. Chang, Optics Communications **281**, 3709 (2008).

[10] K. Yu, W. Liu, D. X. Huang and J. Chang, Micro-wave and Optical Technology Letters **50**, 2163 (2008).

[11] YU Kan, LIU Wen, HUANG De-xiu and HUANG Hua-mao, Chinese Journal of Lasers **34**, 1287 (2007). (in Chinese)

[12] Yu Kan, Huang Dexiu, Fan Ling, Bao Jiaqi and Wu Changfa, Acta Optics Sinica **30**, 214 (2010). (in Chinese)

[13] FU Chang-feng, CHEN Xi-ming, LI Lan, HAN Lian-fu and WU Xiao-guo, Optoelectronics Letters **6**, 37 (2010).

[14] ZHOU De-rang, DUAN Guo-ping, CHEN Jun-ling, HAN Jun-he and HUANG Ming-ju, Journal of Optoelectronics·Laser **24**, 1948 (2013). (in Chinese)

[15] YU Kan, ZHOU Xiao-yang, WANG Jia-qi, XU Jing-jing and YIN Juan-juan, Optoelectronics Letters **10**, 247 (2014).