Shaping device for high rectangle factor tunable thin-film filter

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Abstract. The beam divergence angle of the incident collimator will change the transmitting characteristics of the angle-tuned thin-film filter, which insert loss will increase and passband will decrease. With the incident angle is increasing, the phenomena will be more and more obviously. According to the Lagrange-Helmholtz principle, the beam expander has been designed to compress the divergence angle of the incident beam. The double filtering technology has also been used to enhance the retangle factor of the thin-film filter. The experiment results show that the shaping system can effectively eliminate the influence of the divergence angle to the thin-film filter.

Keywords: thin-film filter; divergence angle; angle-tuned; collimator

1. Introduction
Optical filter is a key component in optical communication system¹. With the rapid development of the elimination polarization technology, more and more large tunable wavelength range angle-tuned thin-film filter are emerging²,³. With the low insert loss, high rectangle factor and good temperature stability, these tunable thin-film filters are widely used in the DWDM system. In their spatial coupling, the optical collimators are used to change the Gaussian beam to the approximately parallel beam. Due to the small divergence angle of the approximately parallel beam, the transmitting spectrum of the filter will worsen⁴. The insert loss will increase and the passband will decrease obviously, especially in the relatively large incident angle. In this paper we design and fabricate one kind of prisms to compress the divergence angle of the input beam. With a novel optical path structure the expanded beam can also revert to its original dimension. The theoretical analysis and experimental results show that the prisms can effectively compress the divergence angle, and it can greatly enhance the rectangle factor and passband stability of the transmitting spectrum.

2. Influence of the divergence angle
In our former work we design one kind of 100GHz channel spacing low-polarization four-cavity angle-tuned thin-film filter⁵. The stack of the thin-film filter is as follows:

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In the stack, the high index material $H$ is $Ta_2O_5$ and the low index material $L$ is $SiO_2$. They are both quarter wavelength coatings\(^6\). The central wavelength is 1563nm when the thin-film filter is in normal incidence, and the central wavelength shift to 1528nm at the angle of 20°. In the device, a pair of C-lens collimators are positioning on the both sides of the interference thin-film filter. The C-lens collimator is widely use in the optical communication for spatial coupling. It can divert the Gaussian beam to the expanded parallel beam. However, the expanded beam is not the strict parallel beam, it also has a very small divergence angle. The C-lens is fabricated by the Accelink corporation in China, its divergence angle is at about 0.34°.

To the approximately parallel beam with the small divergence angle, the transmitting spectrum will not change much in normal incidence. However, the overlapped spectrum will separate obviously in oblique incidence because of the divergence angle\(^6\). So the insert loss of the thin-film filter will increase and its passband will decrease. These phenomena will become more and more obviously while the incident angle is increasing. The figure 1 shows the simulation result of the stack in 20° oblique incidence with the 0.34° divergence angle.

![Figure 1. Transmittance curves of the stack(1) at the incident angle of 20° with the 0.34° divergence angle.](image1)

We can see from these simulation results that the central wavelength of the figure 1 is in 1528.5nm. With the divergence angle of 0.34°, the passband is at about 0.2nm, the stopband is 1.4nm and the insert loss is more than 2dB.

### 3. Divergence angle compression

Due to the influence of the divergence angle, the transmitting curve of the thin-film filter will distort. The figure 2 shows the simulation result of the transmitting curve of the filter with the divergence of 0.12°. As shown in the figure 2, the passband is 0.36nm, the stopband is 1.24nm and the insert loss is less than 0.2dB. From the figure 1 and figure 2 we also can know that if the divergence is decrease, the phenomena of passband decrease and insert loss increase will be restrained. As the strict parallel beam of the C-lens is impossible, so we can search the way to compress the divergence angle to one third.
From the Lagrange-Helmholtz principle we can know that the object dimension $y$, the aperture angle $u$ of the imaging beam and the medium refractive index $n$ is a constant. It calls the Lagrange-Helmholtz invariant, which is shown as follows:

$$nuy = n'u'y' = J$$

(2)

From the equation we can see that in the same refractive index medium, the divergence angle will compress to one third if the input beam will expand triple dimension.

Due to the prism has a characteristic to deviate the light to its bottom, so we can use double right-angle prisms to change the dimension of the input beam. If the vertical angle of the right-angle prism is $\alpha$ and the refractive index of the prism medium is 1.52, the amplification ratio $T$ of the prism is as follows:

$$T = \frac{1}{\cos \alpha \sqrt{1 - (1.52 \sin \alpha)^2}}$$

(3)

As we use the double right-angle prisms to expand the beam triple, so the compress ratio of each prism is 0.57. According to the equation 3, we can get the vertical angle of each prism is $32^\circ$. Figure 3 shows the double prisms expander system. The divergence angle will be compressed to one third while the beam expand to triple through the prisms.

4. The structure of the device

 Though the divergence angle can be compressed but the input beam dimension is also expanded. So the couple efficiency of the C-lens collimator on the other side of the thin-film filter is very low. We should also compress the expanded beam to its former dimension to the output collimator in the light path design. For the reason of device integration and low insert loss, we can reverse use the expand prisms to compress the beam dimension. Using a right-angle prism in the light path can solve the problem. Figure 4 shows the light path structure.
As shown in the figure 4, the expander prisms expand the beam triple from the input port and its divergence angle of the beam is compressed to one third. Due to the divergence angle of the beam is compressed, so the transmitting curve of the thin-film filter will be more stability. By using another right-angle prism the filter beam can be reflected to the thin-film filter again, the double transmitting beam with compress divergence angle will also pass the shaping prisms reversely. So at the drop port, the beam can be compress back to its former dimension and also its divergence angle will be triple. However, the relatively larger divergence will not influence the thin-film filter. In oblique incidence, the thickness of the thin-film filter will cause the light path displacement. However, the reverse double filtering can eliminate the light path displacement. So the collimator at the drop port can be fixed, which the tunable wavelength range and the angle modulation range will be greatly enlarged.

After the first filtering, the transmission degree beyond the passband has been decreased 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, while the only cost is the double insert loss of the thin-film filter. Figure 6 shows the simulation result of the single and double filtering of the stack.

As shown in the figure 5, in the double filtering the passband is 0.37nm, and the stopband is 0.82nm. It will have better rectangle factor. Due to the insert loss of the angle-tuned filter we fabricated is less than 0.4dB, so the whole insert loss of the double filtering is less than 1dB.
5. Experiments
We first test the transmitting spectrum of the angle-tuned thin-film filter without the shaping device. As shown in the figure 6, the measured transmitting spectrum is in the 20° incidence. At the incident angle of 20°, the passband is 0.22nm, the stopband is 1.36nm and the insert loss is 4dB. The indexes in oblique incidence can not content the design demand of 100GHz DWDM channel spacing. Figure 7 shows the measured transmitting of the filter with the divergence angle shaping device in 20° oblique incidence. As shown in the figure 7, the passband is 0.35nm, the stopband is 1.0nm and the insert loss is 1dB. So these indexes content the demand of the 100GHz DWDM optical communication system, and the rectangle factor has been greatly enhanced.

6. Conclusion
In oblique incidence, the divergence angle of the incident beam will greatly change the transmitting spectrum stability. Due to the collimator C-lens can only input an approximately parallel beam which has a small divergence angle, we design and fabricate a shaping device to compress the divergence angle to one third. In the optical path structure, we use the double filtering technology to resume the dimension of the output beam and eliminate the light path displacement in the thin-film filter. So both the collimators can be fixed, the coupling degree and the rectangle factor can be also enhanced greatly. The simulation results and the experiments show the validity of the shaping device. On all accounts, the design has a bright application for wide tunable range angle-tuned thin-film filter.

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