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Study on superprism effect in the multilayer optical thin film stack

SUN Xue-zheng, GU Pei-fu, CHEN Hai-xing, JIN Bo, LI Hai-feng, LIU Xu

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

Abstract : Researches show that multilayer optical thin film stack can exhibit superprism effect due to their large abnormal dispersions. We investigated and simulated this effect numerically in a 1-D non-periodic film structure—Fabry-Perot filters (FPF), which possess drastic change in phase and large group delay around wavelength of peak transmittance, and fabricated this device to realize remarkable superprism effect. We tested experimentally with the maximum spatial separation shift up to $65\ \mu\text{m}$, and the experimental result is in good agreement with the theory. Compared with the traditional prism, the total thickness of our structure is only $3.3\ \mu\text{m}$, and our prism shows a stronger angular resolution of $1.89\ \text{nm}$.

Key words : multilayer optical thin film; photonic crystal; superprism effect; Fabry-Perot filter; group delay

1 Introduction

Superprism effect is a special phenomenon existing in photonic crystals (PCs)^[1-2]. Nowadays, many researches demonstrate that PCs possess anomalous dispersion and anisotropy properties near the bandgap, lead PCs achieve huge dispersion^[3-4]. For 1-D multilayer stacks, which own peculiar properties, can act as PCs, more and more people choose this structure to investigate superprism effect^[5-6]. We have used the simplest stacks-periodic high reflectance coatings arranged by only 20 layers to achieve $22\ \mu\text{m}$ of spatial dispersion before. We selected the non-periodic structure-FPF to get larger and more linear spatial shifts.

For conventional 1-D film stacks, we know the beam spatial separation caused by superprism effect is only proportional to the group delay accumulated throughout the structure, while it is independent of the wavelengths^[7]. As FPF structure have the largest group delay at peak

transmittance wavelength, we can get a large spatial separation around this wavelength when the beam with different wavelengths is incident obliquely. We designed and fabricated simple FPF structure in this paper, simulated the group delay and spatial dispersion curve numerically, and experimentally observed remarkable and linear spatial shifts, which is in excellent agreement with theory. Moreover, the device shows a stronger angular resolution, which goes up to $1.89\ \text{nm}$ than the conventional component.

2 Principle

A Fabry-Perot resonator consists of a cavity between two partial reflectors usually (but not necessarily) of equal reflectivity^[8], and is not a standard periodic structure, thus, the Bloch theory commonly used for calculating the band structure and the equi-frequency contour of the photonic crystal, is not appropriate for the present case. Nevertheless, Martina et al have presented other method to calculate the relationship

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between the spatial dispersion and the temporal dispersion^[7]. Now we operated the 1-D dielectric film stack as depicted in Fig. 1 to analyze this relation.

As shown in Fig. 1, the laser (s-polarization Gaussian beam) is incident obliquely on the glass substrate of the film stack, z-axis is the propagation direction while x is the direction perpendicular to the propagation direction. As the result of anomalous dispersion effect in PCs, the beams with different wavelengths propagate throughout the stack twice to accumulate different temporal dispersions and finally exit the dielectric stack at different positions along the x-direction.

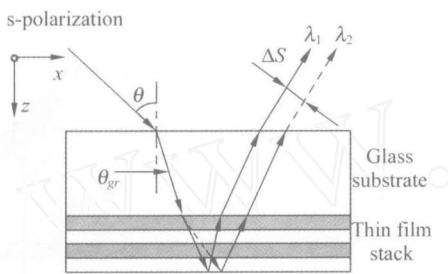


Fig. 1 Schematic diagram of superprism effect in thin film

Now, we suppose the total stack thickness is L , θ_{gr} is group propagation angle, and the components of group velocity along x and z coordinates are v_{gx} , v_{gz} respectively, the shifts in x -direction for different wavelength will be

$$S_x = 2L \tan(\theta_{gr}) = 2L \frac{v_{gx}}{v_{gz}} = v_{gx} \times t_g, \quad (1)$$

where the group delay

$$t_g = \frac{\partial \phi}{\partial \omega}, \quad (2)$$

Here ω is the frequency of light wave. Then we assume n_i as the refractive index of the i th layer, d_i as the physical thickness of the i th layer, k_x as the tangential component of wave vec-

tor, c as the light speed in vacuum. Now the phase change on transmittance could be expressed in WKB-type approximation as:

$$t_i(\omega, k_x) = t_i \left(\sqrt{\left(\frac{c}{n_i} \right)^2 - k_x^2} d_i \right), \quad (3)$$

$$v_{gx} = \sin(\theta) \times \frac{i \frac{(d_i / [n_i^2 - \sin(\theta)^2]^{1/2})}{(n_i^2 d_i / [n_i^2 - \sin(\theta)^2]^{1/2})}}{i}, \quad (4)$$

We obviously deduce from formula (2) that v_{gx} depends only on the incident angle and physical structure of the stack but not on the wavelength, it is approximately constant for certain incident angle and film stacks. Now, we can get the final spatial separation after exiting the stack. And t_g also can be easily calculated by the formula $t_g = \arctan \frac{\text{Im}(t)}{\text{Re}(t)}$ after transmittance coefficient t , is calculated by the characteristic matrix method^[9].

3 Design

We designed 1-D superprism structures based on the theory of thin film. The FPF structure consist of alternating layers of high index material ($n = 1.435$ at 850 nm) and low index material ($n = 2.06$ at 850 nm) on a quartz substrate ($n = 1.46$), and the stack is arranged as Airy (HL)⁵ H 4L H (LH)⁵ Sub. For this regular quarter-wave thin film stacks, spatial shift S_x can be easily calculated from the formula we presented before.

Calculation is performed when the incident laser is in s-polarization state and the incident angle is 23.5° on the glass-film stack interface. The reflectance and transmittance group delay of the device are got as shown in Fig. 2.

From the figure we can easily find the group delay increases when the reflectance reduces, in

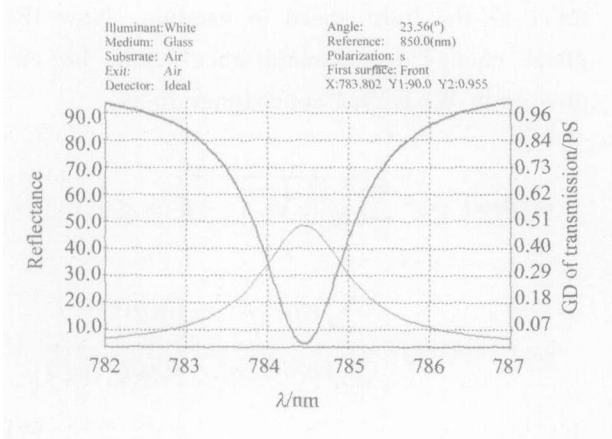


Fig. 2 Reflectance and group delay (GD/ps) on transmittance

other words, present the same variation trend as transmittance, and achieve its peak values at peak transmittance wavelength. The reason is when a maximum amount of energy is stored in the FPF cavity at its resonant wavelength, and when it moves away from the resonant wavelength, the amount of stored energy decreases rapidly. So the resonant wavelength, i. e. the wavelength of peak transmittance, executes the maximum number of roundtrips in FPF cavity. Therefore, the total time elapsed from entering the stack to exiting the stack (temporal group delay) at peak transmittance wavelength is longer than the others.

4 Fabrication and experiment

The sample of FPF was coated with e-beam in vacuum by two materials of TiO_2 and SiO_2 , the whole physical thickness of thin film stacks was about $3.3 \mu\text{m}$. The physical thickness for each layer was monitored by an optical method and the background vacuum was $3.0 \times 10^{-3} \text{ Pa}$, the partial pressure for oxygen was $1.8 \times 10^{-2} \text{ Pa}$, meanwhile, the heated temperature for the substrate was set to 300 .

The experimental setup for measurement of superprism effect in FPF is shown in Fig. 3. The beam from source (tunable laser) is first attenuated by the multi-reflection of the group of

prisms, and the attenuated light beam focused by lens is incident obliquely on our FPF, then computer processes the images obtained by CCD, that is used for recording the position information of the light spot after exiting the thin film stack with Gaussian fitting method. To achieved large beam spatial separation, the CCD is arranged at the same side as the incident beam, so the shift caused by superprism effect is twice of the design, for the beam propagates thin film stacks two times. The spectrum of tunable laser is 782 ~ 787 nm in our experiment, and detected images of the output spots at different wavelengths are shown in Fig. 4, and Fig. 5 gives the comparison of theoretically calculated and experimentally observed shift.

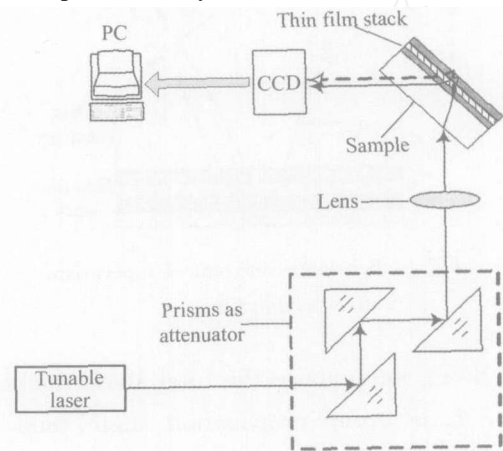


Fig. 3 Setup for the measurement of superprism effect

5 Discussion

As shown in Fig. 5, the spatial dispersive shift goes up to $65 \mu\text{m}$ at the wavelength of 784.54 nm, which is the wavelength of peak transmittance with maximum group delay as shown in Fig. 2, that is in excellent agreement with theoretically expected shift along the x -direction, and the shift decrease gradually as the wavelength moves away from the peak transmittance. Some difference between the experimental curve and the numerically simulated one, as depicted in Fig. 5, are caused by the unstableness

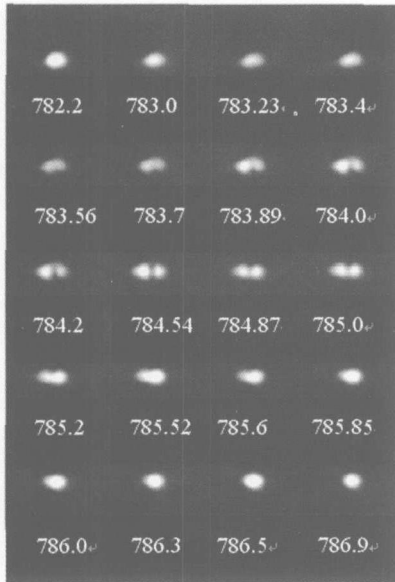


Fig. 4 Image detected by CCD arrays for the output light spots at different wavelengths(nm)

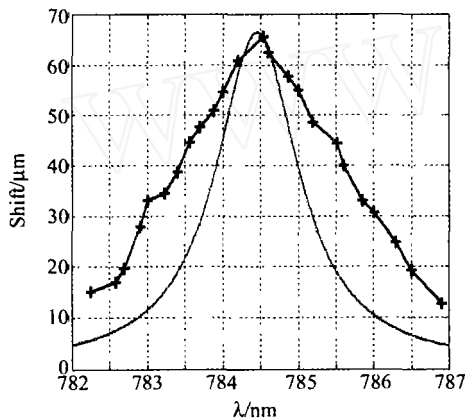


Fig. 5 Comparison between the measured shift curve (+) of exiting position for different wavelengths and the theoretically simulated curve

of the light density in the tuning process of the laser , which could introduce the error as the

center position of light spots was calculated using the Gaussian fitting method.

Also , we can get from Fig. 5 that in the band of 782 ~ 784.5 nm , together with 784.5 ~ 787 nm the shift of beam spatial separation is proportional to the wavelength , which means that this device can be used as demultiplexer. Meanwhile , the device has a higher spatial resolution than the conventional component , such as grating and prism. For example , from 784.54 nm to 786.5 nm , and it's easy to know the angular resolution can go up to 1.89 nm , which is two orders of magnitude stronger than that of the conventional component , such as grating and prism.

6 Conclusion

A simple multilayer optical thin film structure--FPF with remarkable superprism effect and linear spatial shift has been designed and fabricated ,and the maximum shift caused by superprism effect measures about 65 μm , which is in excellent agreement with the theory. And our design based on the optical thin film theory is more simple and effective since the structure is easier to design and fabricate than 2-D , 3-D photonic crystal structures. Besides , our discussion on superprism effect makes FPF possible to exploit new valuable applications in demultiplexer and other optical communication system ; it also lays foundation for investigating superprism effect in more complicated optical thin film stacks.

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Brief professional biography of the author :

SUN Xue-zheng was born in Anhui, China, on March 10, 1983. She received her B. S. degree from China Jiliang University, College of Information Engineering in 2003. Since then she has been studying for her Ph. D. degree at Zhejiang University, Dept. of Optical Engineering. Her research interests include superprism effect in the multilayer optical thin films.

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