Front. Optoelectron. China 2008, 1(3–4): 210–214
DOI 10.1007/s12200-008-0067-4

RESEARCH ARTICLE

Micro Fabry Perot light modulator for flat panel display

Jiyong SUN (✉), Shanglian HUANG, Jie ZHANG, Yi QIN, Xuming SUN

The Key Laboratory for Optoelectronic Technology and System, Education Ministry of China, Optoelectronic Engineering Department, Chongqing University, Chongqing 400044, China

Abstract A new type of Fabry Perot light modulator for displays based on micro-electro-mechanical system technology is proposed. Multiple beam interference theory is used to design the modulator and analyze its characteristics. If Fabry Perot cavity length is one-quarter of the incident wavelength, the transmitted light is blocked by the modulator, and the modulator, which is illuminated from its backside, appears black. If the Fabry Perot cavity length is 0 or one-half of the incident wavelength, light may transmit the Fabry Perot modulator from its backside, and the modulator appears bright. Hence, the modulator may be used for flat panel displays. In this paper one Fabry Perot light modulator based on surface micromachining technology is introduced. The designed modulator has a contrast ratio of 150 and can theoretically be driven by a voltage of 2.4 V.

Keywords optical micro-electro-mechanical system (optical MEMS), Fabry Perot light modulator, interference, display

1 Introduction

Optical micro-electro-mechanical system (optical MEMS or MOEMS) technology has experienced rapid improvement in recent decades. MEMS-based light modulators for displays have become a key research focus [1–5]. The digital micro-mirror device (DMD) [6] developed by Texas Instruments, which consists of an array of moveable micro-mirrors, is a representative example based on optical MEMS for displays. Actuating voltage controls the mirror's tilt angle electro-statically in a binary fashion. The incident light is reflected and modulated by the tilt mirror. Another optical MEMS-based light modulator designed for display is the grating light valve (GLV) [7] which is proposed by a Stanford group led by Bloom D M. GLV is composed of an array of phase gratings with an initial phase difference of 0. When the grating is controlled by an actuating voltage, the phase difference becomes π. Hence, the GLV may diffract light from 0 diffraction order to the first diffraction order electro-statically. One type of MEMS-based grating light modulator for projection display is proposed by Chongqing University [8,9]. However, reflected light is used and the display function light system is not very compact in these light modulators, which limits their applications in flat panel displays, and they are all designed for projection displays. A new type of Fabry Perot light modulator based on MEMS technology for flat panel displays is proposed in this paper. For this modulator, transmitted light is used, which reduces the complexity of those display function light systems based on reflected light and makes it a promising application in flat panel displays.

2 Optical principle of Fabry Perot light modulator for display

When a beam of light is incident on the Fabry Perot light modulator (shown by Fig. 1), there are multiple reflections on the two plane parallel mirrors of the modulator. Multiple beam interference takes place. Intensity of the transmitted light is [10]

$$I^{\mathrm{t}}(\lambda)=\frac{(1-R)^2}{(1-R)^2+4R\sin^2\dfrac{2\pi nh}{\lambda}}I^{\mathrm{i}}(\lambda), \tag{1}$$

where R is the reflectivity of the mirror; h is Fabry Perot cavity length; $I^{\mathrm{i}}(\lambda)$ is the incident light intensity; and n represents the refraction index of the medium between the two mirrors. If the medium is air and $n=1$, Eq. (1) can be rewritten as

$$I^{\mathrm{t}}(\lambda)=\frac{(1-R)^2}{(1-R)^2+4R\sin^2\dfrac{2\pi h}{\lambda}}I^{\mathrm{i}}(\lambda). \tag{2}$$

Translated and revised from *Acta Optica Sinica*, 2007, 27(12): 2240–2244 [译自: 光学学报]

E-mail: stoiker@163.com

The distribution of the transmitted light is the function of R and h. It can be seen that there are minima when h is $(2k+1)\lambda/4$, and there are maxima when h is $k\lambda/2$. k is the interference order. Figure 2 illustrates the distribution of the transmitted light when the cavity length is 1 μm and the Fabry Perot is illuminated by unit amplitude light, which has a uniform spectrum distribution.

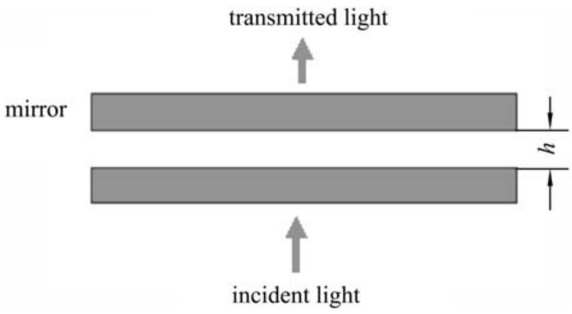


Fig. 1 Fabry Perot light modulator

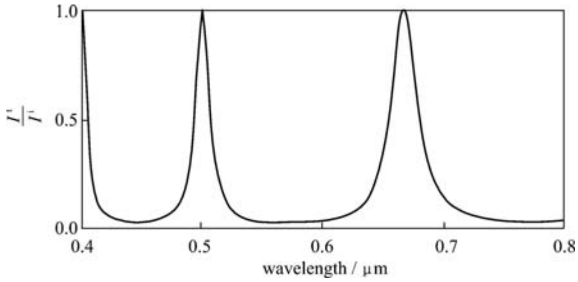


Fig. 2 Intensity distribution of transmitted light

The two neighboring maxima have the relation

$$h = \frac{k+1}{2}\lambda_1, \tag{3}$$

$$h = \frac{k}{2}\lambda_2. \tag{4}$$

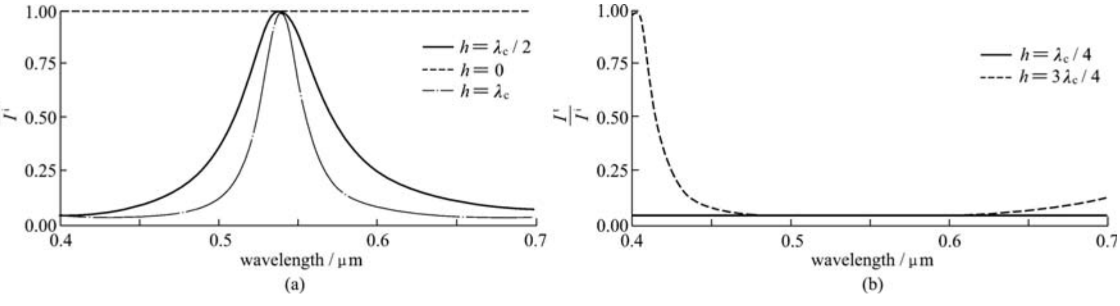
λ_1, λ_2 are the wavelengths of the neighboring maxima. Suppose that λ_s is the shortest wavelength of the incident light, $\lambda_s \leqslant \lambda$. Substitute λ_s into Eq. (3), with Eq. (4) we can have

$$\lambda_2 = \frac{k+1}{k}\lambda_s. \tag{5}$$

Considering $\lambda_s < \lambda_2 < \lambda_l$ (λ_l is the longest wavelength of the incident light), the minimum interference order k_0 can be solved with Eq. (5). If the interference order is larger than k_0, more than two interference maxima will take place. The corresponding cavity length h_0 may be calculated by substituting k_0 and λ_s into Eq. (3). There is only one wavelength that satisfies the condition $h = k\lambda_c/2$ if the modulator's cavity length h is shorter that h_0, and among incident lights only light of this wavelength can transmit the modulator. This light is blocked when the cavity length is $(2k+1)\lambda_c/4$.

If the modulator's cavity length is 0, the equation $h = k\lambda/2$ is satisfied by all wavelengths. All of the incident light will transmit the modulator. If we use red, green and blue LEDs as the light source spectrum between 0.4 and 0.7 μm, the maximum cavity length calculated by Eqs. (3) and (5) is 0.6 μm, with the condition that there is only one interference maximum. The corresponding interference order is 2. Figure 3 gives the distribution of the transmitted light when the incident wavelength is 0.54 μm. Figure 3(a) is the calculated result when cavity length is $k\lambda_c/2$ ($k = 0, 1, 2$). Figure 3(b) is the calculated result when cavity length is $(2k+1)\lambda_c/4$ ($k = 0, 1$). It can be seen from Fig. 3(b) that when cavity length satisfies the equation $h = \lambda_c/4$ ($\lambda_c = 0.54$ μm), not only the light λ_c but also all of the incident light is blocked by the modulator. Thus, the Fabry Perot can be used for the display by controlling its cavity length. When the cavity length is one quarter of the central wavelength of incident, the light modulator is at an "off" state and shows a black image. When the cavity length is $k\lambda_c/2$ ($k = 0, 1, 2$), the modulator is at an "on" state and shows bright, in which λ_c is the central wavelength of the color that the modulator will show. For the modulator that shows green, λ_c is 0.54 μm. At this time, the cavity length of the "on" state modulator may be 0, 0.27 and 0.54 μm, and the cavity length of the "off" state modulator is 0.135 μm.

In transmittance, when the Fabry Perot light modulator is "off", its cavity length is $\lambda_c/4$. When it "on", its cavity length can be 0, $\lambda_c/2$ and λ_c. If we use λ_c as the cavity length of the "on" state, when it is switched between the "off"



(a)

(b)

Fig. 3 Intensity distribution of transmitting Fabry Perot light modulator and "on" state, light modulator variation of the cavity length will be $3\lambda_c/4$. If we use 0 or $\lambda_c/2$ as the cavity length of the "on" state, variation of the cavity length is only $\lambda_c/4$. Thus, 0 and $\lambda_c/2$ are preferred to the cavity length of the "on" state. The study presumes that the modulator works at green color ($\lambda_c = 0.54$ μm), and then the performance of the Fabry Perot light modulator will be discussed.

3 Optical characteristics of Fabry Perot light modulator

3.1 Cavity length of "on" state modulator is 0

It has been proven that when the cavity length is 0, all of the incident light will transmit the modulator. When the light is "off", all wavelength is blocked. The modulator cannot pass one specific wavelength and block others. The modulator can only show black and white images, not color. To make such a Fabry Perot light modulator show color, an additional color filter is needed.

It can be seen from Eq. (2) that distribution of the light intensity is determined by the cavity length of the modulator. But the transmittance ratio (transmitted light intensity divided by the incident light intensity) is determined by the reflectivity of the Fabry Perot mirror. The relationship between the transmittance ratio and the reflectivity R can be obtained by using Eq. (2):

$$I = \int_{0.4}^{0.7} \frac{(1-R)^2}{(1-R)^2 + 4R\sin^2\dfrac{2\pi h}{\lambda}} I^{\mathrm{i}}(\lambda)\mathrm{d}\lambda, \tag{6}$$

when h is 0 and $\lambda_c/4$, the integration results correspond to I_{on}, intensity of the "on" state modulator, and I_{off}, intensity of the "off" state modulator, respectively. The contrast ratio of the modulator is defined as $v = I_{\mathrm{on}}/I_{\mathrm{off}}$. The contrast of the modulator, when the cavity length is 0 and $\lambda_c/4$ respectively, can be calculated with Eq. (6).

Figure 4 gives the calculated transmittance ratio and the contrast ratio of the modulator by using Eq. (6). The incident light is presumed to have unit light and uniform spectrum distribution. It can be found that light transmits the modulator without diminishing when modulator is at an "on" sate. If define light efficiency as the intensity ratio of transmitted light and the incident light, the light efficiency is 1 at this time. To the "off" state light modulator, the intensity of the transmitted light decreases when the reflectivity increases. When R is near 1, the transmitted light becomes 0 because there is no light traveling into the Fabry Perot cavity, and hence no interference occurs. Figure 4 shows that the contrast ratio of the modulator increases when the reflectivity increases. When R is 0.95 the contrast ratio rises up to 1200.

3.2 Cavity length of "on" state modulator is $\lambda_c/2$

If the cavity length of the "on" state modulator is $\lambda_c/2$, there is only one light of color that can transmit the modulator. The light can show one specific color. Three modulators can now be used to compose one unit to show one pixel of the image. The cavity lengths of the three modulators are one half of the wavelength of red, green and blue colors, respectively. Therefore, the pixel can show different colors.

Similarly, the light efficiency and contrast ratio can be calculated with the method used in the above section. Figure 5 illustrates the calculated result of the light efficiency and contrast ratio when we presume that the transmitted light is emitted from a green LED. It can be seen that the light efficiency decreases with increasing reflectivity. When R is 0.9, the light efficiency is 0.4, and the contrast ratio is 150.

4 Design of Fabry Perot light modulator

It has become known that the reflectivity and cavity length are the two key parameters to Fabry Perot light modulators. The reflectivity is determined by the mirror, and the cavity length is determined by the modulator's structure.

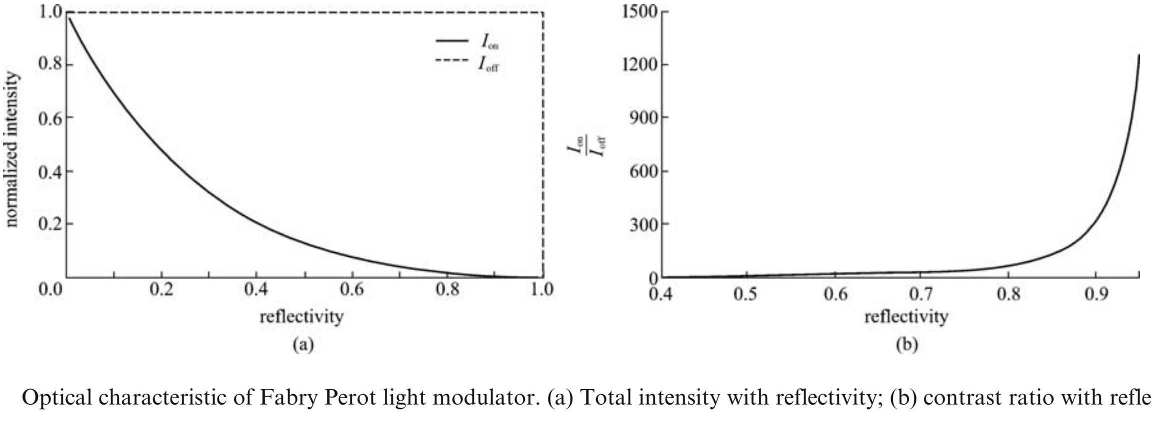


Fig. 4 Optical characteristic of Fabry Perot light modulator. (a) Total intensity with reflectivity; (b) contrast ratio with reflectivity

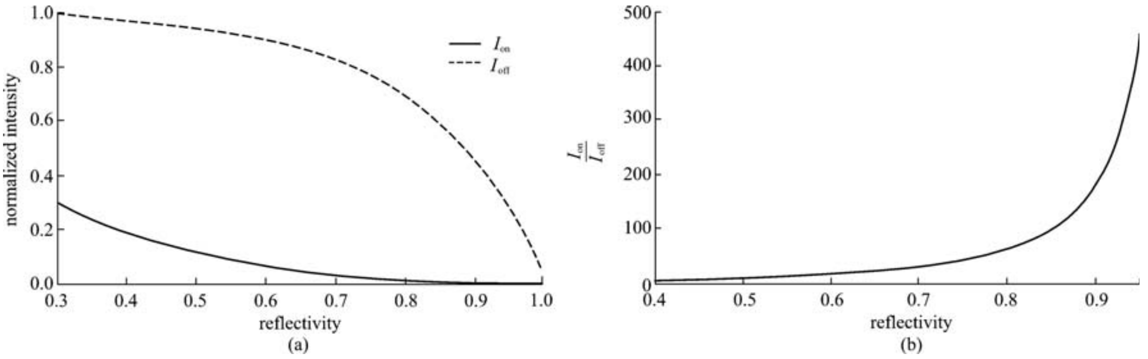


Fig. 5 Optical characteristics of Fabry Perot light modulator. (a) Transmitted intensity with reflectivity; (b) contrast ratio with reflectivity

4.1 Mirror's design

There are two types of mirrors: the metal mirror and the multidielectric mirror. A metal mirror is formed by sputtering or evaporating a thin film of Al, Ag or Au on the substrate. Their fabrication process is simple, and high reflectivity can be achieved. But the absorbance of the metal will reduce the light efficiency of the modulator.

A dielectric mirror is made up of interleaved high index material layers and low index material layers. Each layer has optical thickness equal to $\lambda/4$. The reflectivity of the dielectric mirror can be calculated with its character matrix by using the thin film interference theory when the incident light is normal to the Fabry Perot modulator [11]:

$$\begin{pmatrix} B \\ C \end{pmatrix} = \prod_{k=1}^{m} \begin{pmatrix} \cos\dfrac{2\pi\eta_k L_k}{\lambda} & \dfrac{\mathrm{i}}{\eta_k}\sin\dfrac{2\pi\eta_k L_k}{\lambda} \\ \mathrm{i}\eta_k \sin\dfrac{2\pi\eta_k L_k}{\lambda} & \cos\dfrac{2\pi\eta_k L_k}{\lambda} \end{pmatrix} \begin{pmatrix} 1 \\ \eta_\mathrm{s} \end{pmatrix}, \quad (7)$$

$$R = \left(\frac{\eta_0 B - C}{\eta_0 B + C}\right)\left(\frac{\eta_0 B - C}{\eta_0 B + C}\right)^*, \quad (8)$$

where η_s is the index of the substrate, and η_0 is the surrounding medium index.

Reflectivity can be designed with the above equation by choosing the appropriate material and the number of layers. Figure 6 gives a designed dielectric mirror based on the surface micromachining technology. It is composed of poly-Si, Si_3N_4, and SiO_2. The optical thickness of each layer is $\lambda_c/4$, where the λ_c is 0.54 μm.

4.2 Structure design

Figure 7(a) gives the proposed Fabry Perot light modulator, and Fig. 7(b) shows details of each layer. This modulator is designed to show green color ($\lambda_c = 0.54$ μm). The cavity length of the "off" state modulator is $\lambda_c/4$, and the cavity length of the "on" state modulator is 0. Figure 7 is the model of a single modulator. If this modulator is used to compose the 2D arrays, images can be displayed with the 2D modulator arrays. The modulator is composed of top moveable mirror, bottom mirror, and the substrate. The top mirror and the bottom mirror are described in Sect. 4.1. Its reflectivity is depicted in Fig. 6. The size of the top mirror is 50 μm × 50 μm, the Si_3N_4 layer of the top moveable mirror is also used as the supporter layer, and its outer parts form the supporter beam. To increase the beam's strength, the thickness of the Si_3N_4 layer is increased from one quarter of the wavelength to three quarters of the wavelength, i.e., its thickness is increased from 67 to 200 nm (presume that the index of Si_3N_4 is 2). The beam width is 4 μm. Poly-silicon layer of the two mirrors is also used as the top and bottom electrode. With no voltage applied, the cavity length is 0.135 μm, and the modulator is at an "off" state. Light is incident from the backside of the substrate. The top moveable mirror moves downward with the applied voltage, the cavity length becomes 0, and the modulator becomes "on". If the reflectivity of the mirror is described by Fig. 6, the transmittance ratio of the "on" state light modulator is 1. The transmittance ratio of the "off" state light modulator is 0.0067. The contrast ratio of the modulator is then 150. Figure 8 gives the actuating characteristic of the modulator. It can be seen that with a voltage of 2.4 V, the cavity can be switched from 0.135 μm to 0. This modulator has relatively low actuating voltage.

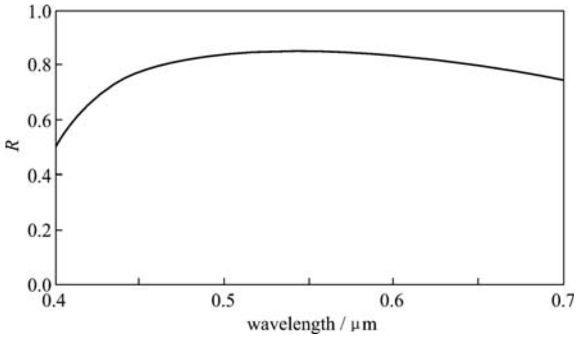


Fig. 6 Reflectivity of multiple thin films

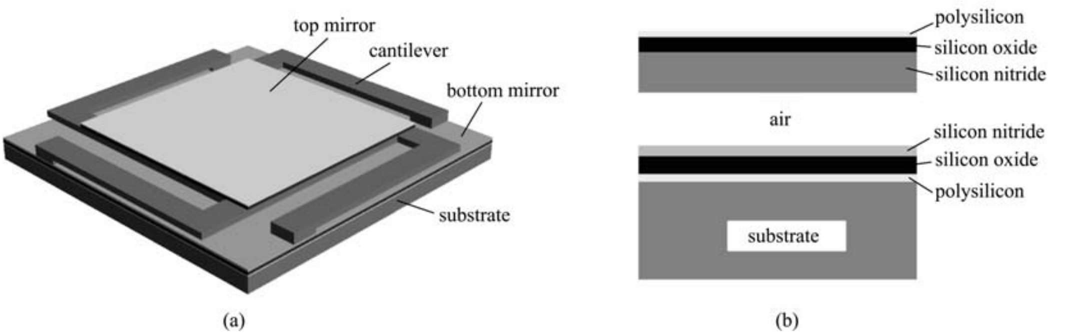


Fig. 7 Fabry Perot light modulator. (a) Schematic view of designed modulator; (b) layers of modulator

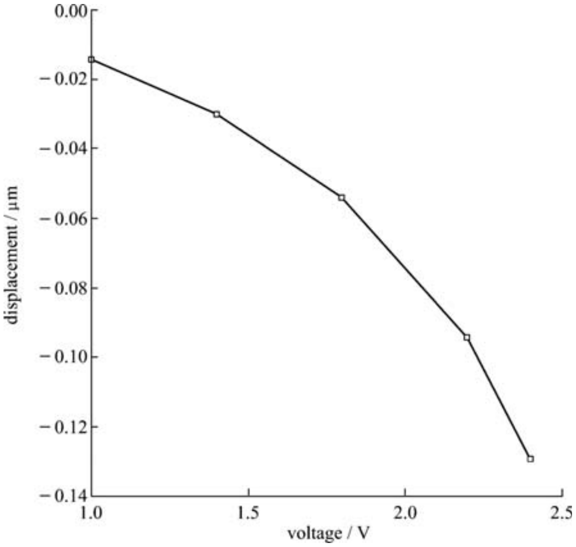


Fig. 8 Simulation result of electro-static actuation

5 Conclusion

This paper proposed a new type of MEMS-based Fabry Perot light modulator for displays. When the cavity length is 0, all wavelengths will transmit the modulator. When the cavity length is $\lambda_c/4$, almost all wavelengths will be blocked by the modulator. This property can be used for displays, and show black and white images. If the cavity of the "on" state modulator is designed to be $\lambda_c/2$, the modulator will show different colors. A color image can be displayed by using three (red, green and blue, respectively) modulators. The structure of the modulator has been designed based on MEMS technology. This modulator has the contrast ratio of 150. Its actuating voltage is simulated by using the Coventor software. The calculated result shows that the modulator can be switched with a voltage of 2.4 V. The modulator has promising applications in flat panel displays.

References

1. Taii Y, Higo A, Fujita H, et al. Electrostatically controlled transparent display pixels by PEN-films MEMS. In: Proceedings of IEEE/LEOS International Conference on Optical MEMS and Their Applications, 2005, 13–14
2. Wang K. Micro-optical components for a MEMS integrated display. Dissertation for the Doctoral Degree. Washington: University of Washington, 2004, 4–8
3. Tamada H, Taguchi A, Oniki K, et al. High contrast and efficient blazed grating light valve for full-HD 5,000 lumen laser projectors. In: Proceedings of International Conference on Consumer Electronics (ICCE 2006), Digest of Technical Papers, 2006, 133–134
4. Kim S, Barbastathis G, Tuller H L. MEMS for optical functionality. Journal of Electroceramics, 2004, 12(1–2): 133–144
5. Wu M C, Solgaard O, Ford J E. Optical MEMS for lightwave communication. Journal of Lightwave Technology, 2006, 24(12): 4433–4454
6. Hornbeck L J. Digital light processing for high brightness high-resolution applications. Proceedings of SPIE, 1997, 3013: 27–40
7. Bloom D M. Grating light valve: revolutionizing display technology. Proceedings of SPIE, 1997, 3013: 165–171
8. Zhang Jie, Huang Shanglian, Yan Xu, et al. Optimization and analysis for structural parameters of grating moving light modulator. Acta Optica Sinica, 2006, 26(8): 1121–1126 (in Chinese)
9. Zhang Jie, Huang Shanglian, Fu Hongqiao. Optical characteristics analysis and simulation of grating light valve. Acta Optica Sinica, 2005, 25(11): 1452–1456 (in Chinese)
10. Sun Jiyong, Chen Weimin, Zhu Yong, et al. Influence of optical source spectrum on optical fiber F-P strain sensor. Acta Optica Sinica, 2002, 22(5): 596–600 (in Chinese)
11. Tang Jinfa, Zhen Quan. Applied Film Optics. Shanghai: Shanghai Science and Technology Press, 1984, 50–52 (in Chinese)