Chapter 4 Band Structure determined by Finite-Sized One-dimensional Photonic Crystal

4-1 Band structure calculated by transfer matrix method

As described in previous chapter, the numbers of ripples in transmission spectra are as many as the periods of 1-D PC, and they are mainly caused by the interference of the incident wave within the multi-layers. However, when we calculate the transmission as a function of incident angle, the ripples seems irregular. In order to analyze them, we calculate the transmission spectra with incident angles of θ=0°, θ=10°, θ=20°, θ=30°, θ=40°, θ=50°, θ=60°, θ=70°, θ=80°. Take the frequency values of all ripples' peaks in each transmission spectrum, and dot the diagram of *ω*-*K* relation with them as Fig. 4-1. Thus, we suppose that the curves should represent the positions of transmission peak value.

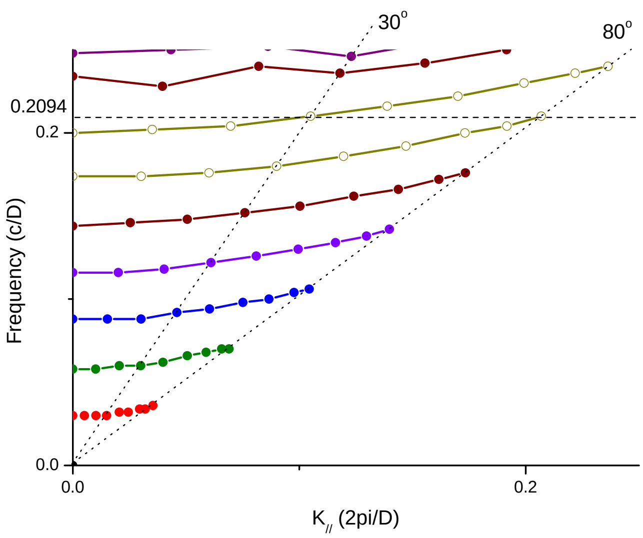


Fig. 4-1 The peaks of ripples taken from nine transmission spectra. Here is the first allowed band.

Therefore, when we calculate the transmission as a function of incident angle, the number of ripples will be equal to the number of crossing between the horizontal line and peak curve in *ω-K* relation diagram as Fig. 4-1. We take Ω=0.2094 for example. There are two crossing at $\theta=30^{o}$ and $\theta=80^{o}$, so there should be two ripples in diagram T (θ). We show it in Fig. 4-1-2 and see that's true.

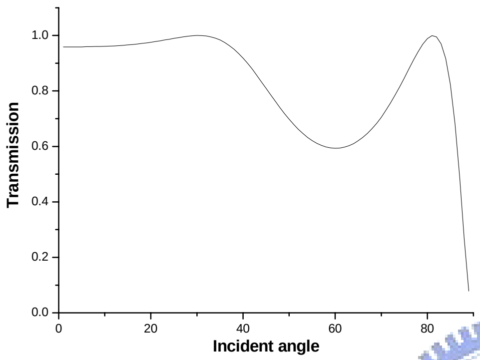


Fig. 4-1-2 The transmission diagram T (θ). There are two ripples and the peak is at $\theta=30^{o}$ and $\theta=80^{o}$.

In order to improve our tool, we wrote a program to calculate with higher resolution $\triangle\theta \le 1°$ (we use $\triangle\theta = 10°$ in Fig. 4-1) and plot all positions with transmission $T > 0.9$ in place of only the positions of peaks. The result is shown in Fig. 4-2 for the multilayer of finite periods (in Fig. 4-2, ten periods) with unit cell defined as $\left(\frac{1}{2}d_1, d_2, \frac{1}{2}d_1\right)$ [21]. The black regions show the "band" with transmission more than 0.9 (This limit surely can be adjusted as we need), and the transmission at the white regions is less than 0.9, i.e., 0.85 and 0.01 are both possible. Therefore, these bands are *digital*. This diagram looks similar to band structure calculated by plane wave expansion method; but the wave cannot be incident into the 1-D photonic crystal form $\theta \ge 90°$, so there are no data below the light line in Fig. 4-2. In this figure we can see that most of transmission in the fourth allowed band are high, this is the reason the optical switch designed in section 3-3.3 has no ripples.

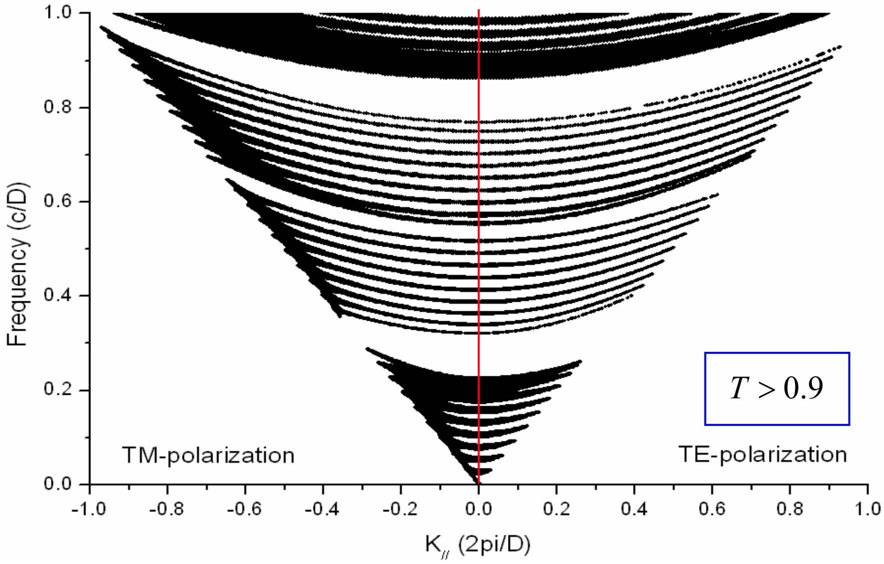


Fig. 4-2 The “digital” band structure (d_1/d_2=0.7) calculated from ten periods.

In fact, the information obtained by using transfer matrix method (TMM) is sufficient for us to form an “imitational” band structure, which is calculated from 1-D photonic crystal with *finite periods*. We briefly state the step below.

For a given incident angle, we can calculate the transmission at each frequency by TMM. The corresponding wavevector can be obtained by using the relation $K_{//} = \Omega \cdot \sin\theta$ (we take n=1). Thus, the band structure of finite-sized 1-D PC can be obtained in five minutes by using our program. We define the unit cell as $\left(\frac{1}{2}d_1, d_2, \frac{1}{2}d_1\right)$, where the thickness ratio d_1/d_2=0.7 and ten periods (note that in plane wave expansion method, the unit cell $\left(d_1, d_2\right)$ and $\left(\frac{1}{2}d_1, d_2, \frac{1}{2}d_1\right)$ are identical, but in TMM they are a little different). In Fig. 4-3, we show the contour plot of the band structure. The color scale on the right side displays the levels of transmission with different colors. We can see the transmission on the fourth allowed band is high and flat, and the second and the third allowed bands are filled with ripples. Therefore, we can calculate many different band structures by this method to search for better performance and fewer ripples, especially for optical switch proposed in section 3-3. In next section, we will improve our designs by using this band structure.

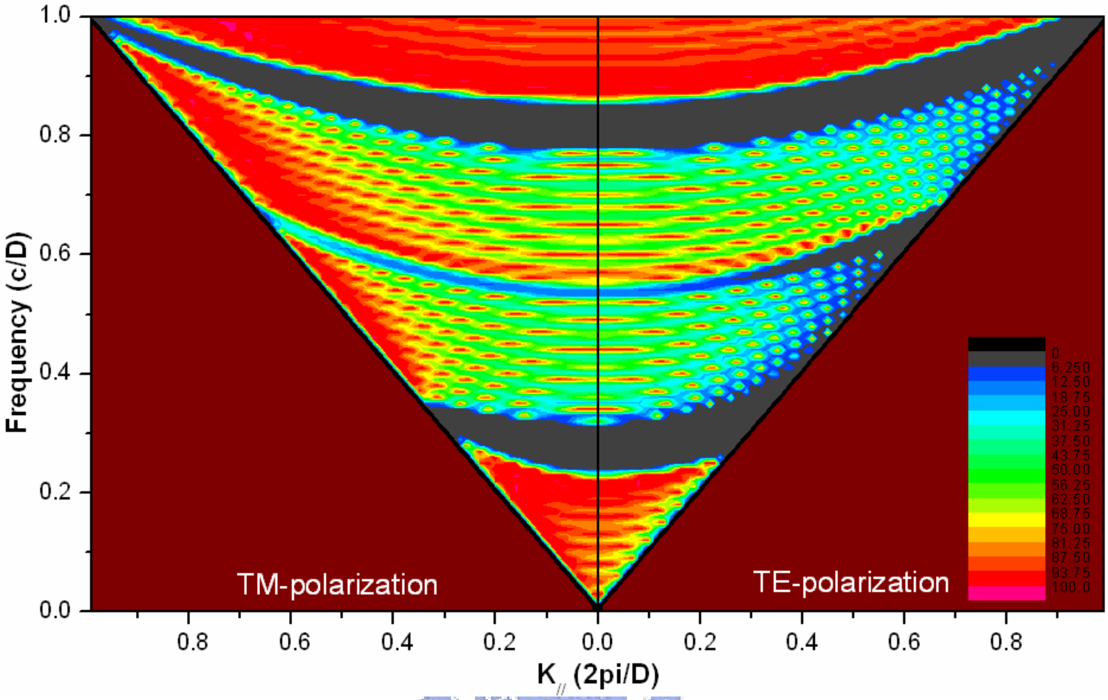


Fig. 4-3 The band structure of finite-sized PC calculated by TMM. This is a contour plot. The unit cell is $\left(\frac{1}{2}d_1, d_2, \frac{1}{2}d_1\right)$, where d_1/d_2=0.7, and duplicated ten periods.

4-2 Ripple-reduced design and applications

We calculate band structures mentioned in section 4-1 with unit cell of $\left(\frac{1}{2}d_1, d_2, \frac{1}{2}d_1\right)$ and index ratio d_1/d_2=0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1, 1.2, 1.5, 2, 2.5, 3, 4, 5, 10, and quarter-wave stack. By observing these band structures, we are able to design the devices with better performance, i.e., few ripples.

4-2.1 Angular tuning optical switch

It's convenient for us to search ripple-reduced design by using these band structures. Including considering the similarity between two transmission curves of TE and TM waves, all of the best performances are shown in Fig. 4-5.

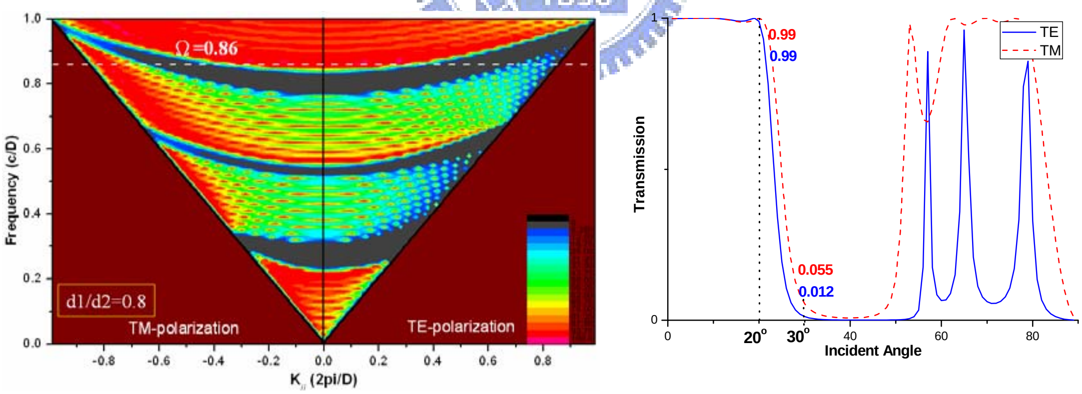


Fig. 4-5-1 Finite-sized PC band structure of d_1/d_2=0.8 and corresponding transmission diagram (Ω=0.86). Notice that the transmission curve behaves in response to the dash line in band structure. From θ=20° to θ=30°, the transmission from both 0.99 decay to 0.055 (TM) and 0.012 (TE).

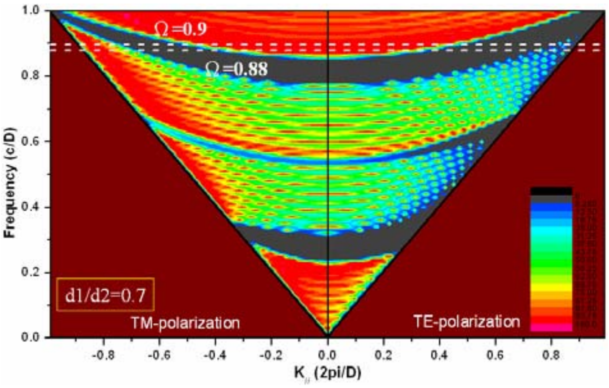
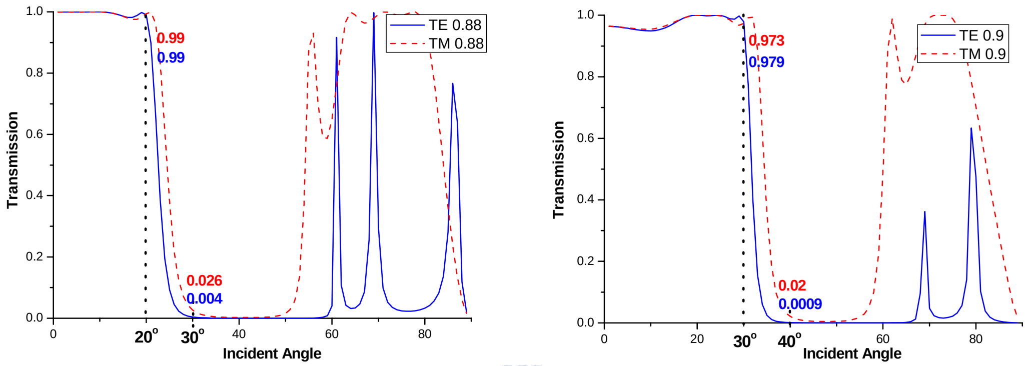


Fig. 4-5-2 Finite-sized PC band structure (d_1/d_2=0.7) and corresponding transmission diagram (Ω=0.88 and 0.9).



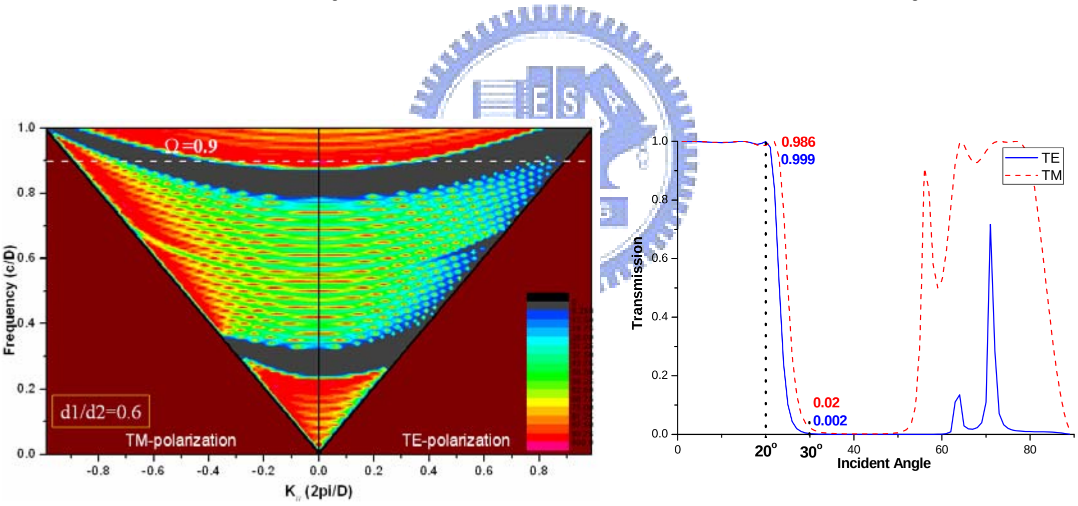


Fig. 4-5-3 Finite-sized PC band structure (d_1/d_2=0.6) and transmission diagram (Ω=0.9)

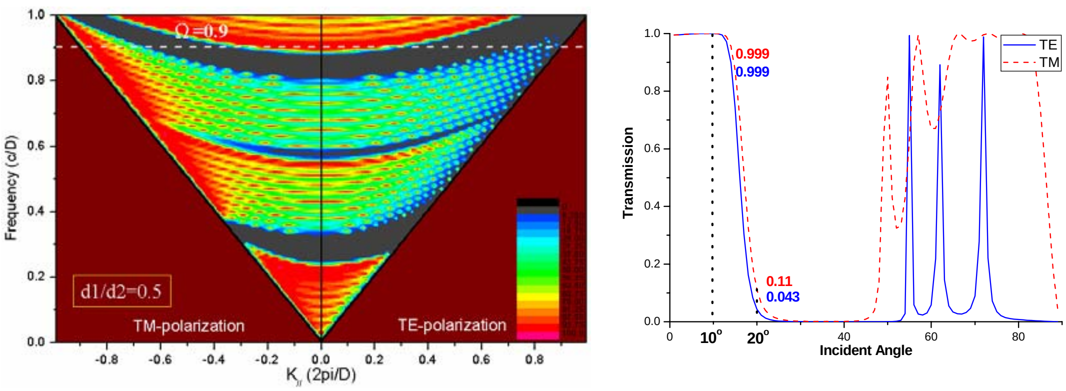


Fig. 4-5-4 Finite-sized PC band structure (d_1/d_2=0.5) and transmission diagram (Ω=0.9)

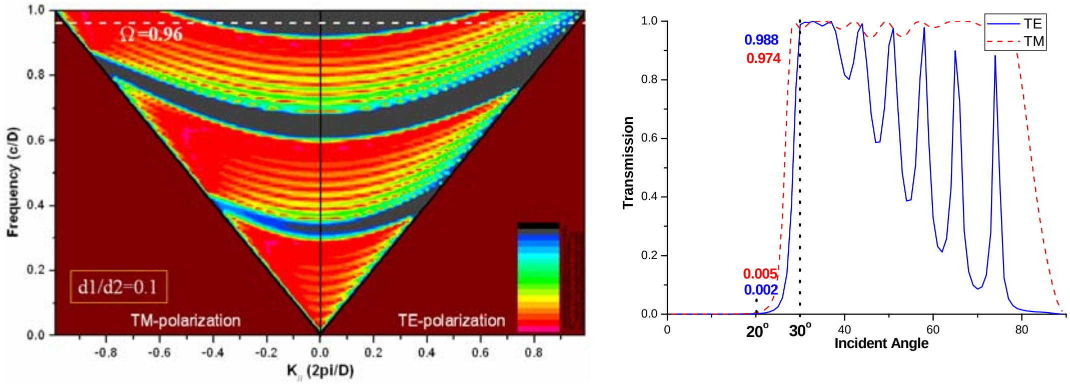


Fig. 4-5-5 Finite-sized PC band structure (d_1/d_2=0.1) and transmission diagram

Now, we consider the operation angle θ=45° in order to design the second case of optical switch mentioned in section 3-3.2. It's difficult to ensure not only similarity between TE and TM transmission but also flat of curve in the allowed band. In Fig. 4-6, we can see there are some ripples on allowed band, and the transmission of TM wave in bandgap isn't low enough. These results are obtained from ten-period PC. We could use more periods to achieve sharper transmission and to increase contrast. With these designs, the optical switch will switch from the ON state to the OFF state by only rotating the multilayer 7° or 8°.

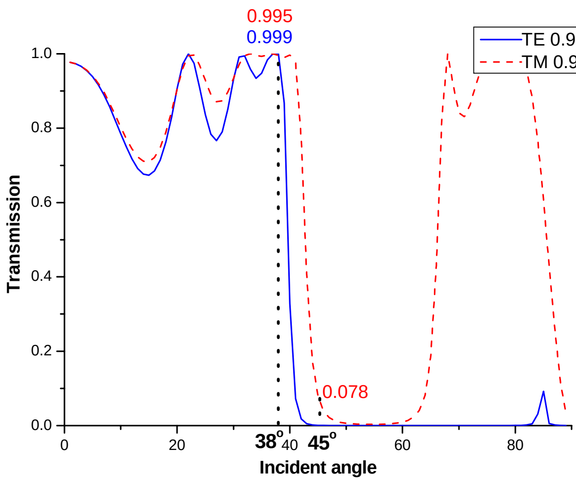


Fig. 4-6-1 The optical switch operate at θ=45°. The parameters $d_1/d_2=0.5$, and normalized frequency $\Omega=0.9641$.

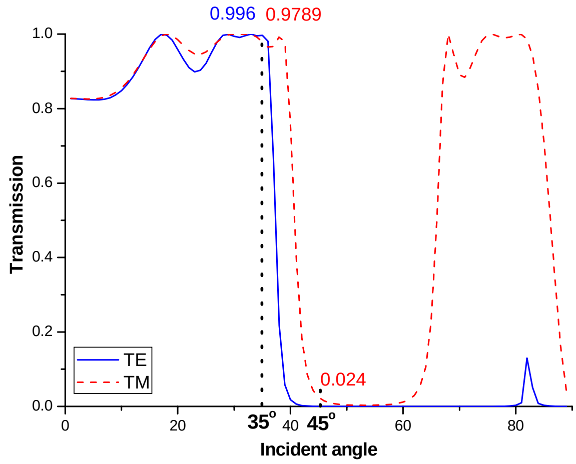


Fig. 4-6-2 The optical switch operate at θ=45°. The parameters $d_1/d_2 = 0.6$, and normalized frequency $\Omega = 0.938$.

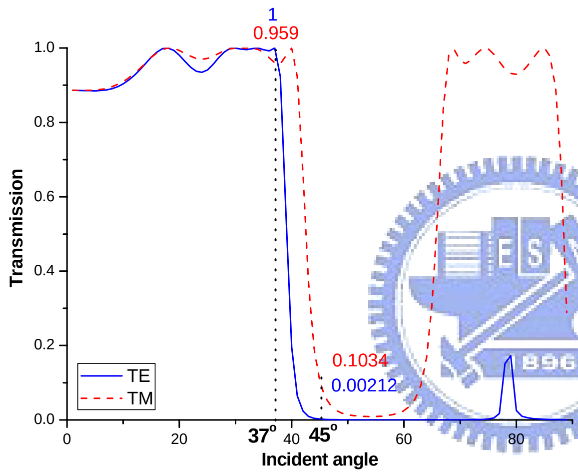


Fig. 4-6-3 The optical switch operate at θ=45°. The parameters $d_1/d_2 = 0.7$, and normalized frequency $\Omega = 0.927$.

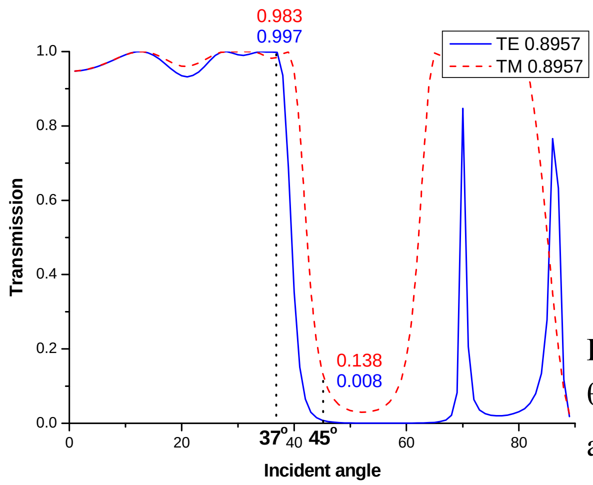


Fig. 4-6-4 The optical switch operate at θ=45°. The parameters $d_1/d_2 = 0.8$, and normalized frequency $\Omega = 0.8957$.

4-2.2 Dichroic Beam Splitter

In section 3-2, we present the method to design a dichroic BS which has good tolerance of incidence angle and finally employ the impedance-matching layer to eliminate the ripples. Now, we can use the band structure of finite-sized PC to search good performance with no ripples.

In fact, it's not as easy as we think. There is almost no such an "omnidirectional allowed band without ripples" exists at each normalized frequency. We can find that the TE-polarized wave always possesses lower transmission at large incidence angle. However, the good performance of the dichroic BS is presented by us in Fig. 4-7. Note that it is impossible to find such results by using plane wave expansion method.

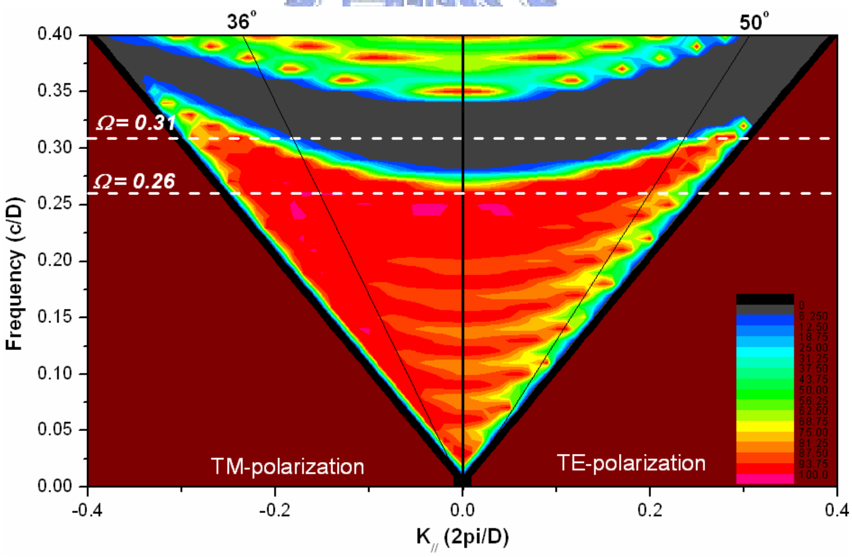


Fig. 4-7-1 Band structure of finite-sized PC (d_1/d_2=0.2). The dash line Ω=0.31 (Ω=0.26) represents the behavior of 1.3μm (1.55μm) wave. The 1.3μm TE (TM) wave will be transmitted after θ>50° (θ>36°).

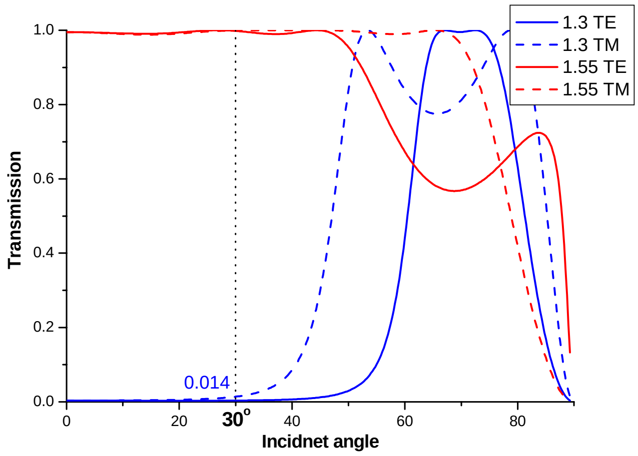


Fig. 4-7-2 (a) The transmission diagram of 10 periods PC. The lattice constant D=0.403μm.

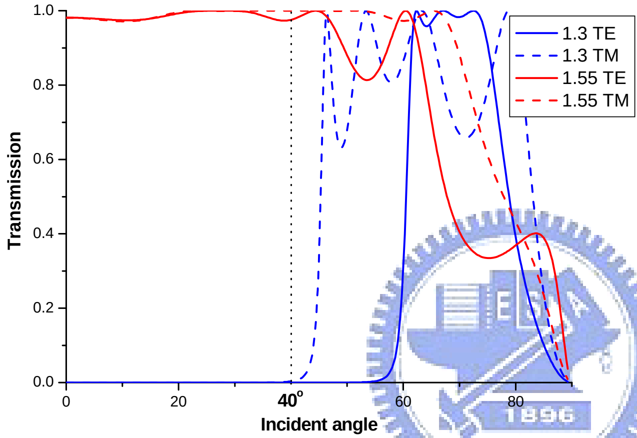


Fig. 4-7-2 (b) The transmission diagram of 20 periods PC. The lattice constant D=0.403μm.

The transmission curves of Fig. 4-7-2 (a) and (b) indicate that ripples are dramatically eliminated for $\theta<40^o$. If we want to extend the operation angle to 80^o, we have to follow the procedure of combining heterostructure in section 3-2. The other needful multilayer have to perfectly transmits 1.3μm wave, and isolates the 1.55μm wave for $\theta>40^o$. And then, the omnidirectional dichroic BS without transmission ripples is finished by using the heterostructure.

4-2.3 Display

The optical switch we mentioned above is designed as a lightvalve. Therefore, such device is able to be applied to display technology. In section 4-2.1, our lightvalve will be turned from the ON state to the OFF state by only rotating 8^o. However, we must consider the incident light RGB has a bandwidth, not single frequency. Thus, the multilayer has to rotate more to completely isolate or pass the incident light. Even though the difference maybe small, we present one method to reduce half of the rotation angle.

We found it is different to get better results than those in section 4-2.1. After thinking, we understand it is impossible to obtain sharper curve by introducing the heterostructure. It seems impossible to achieve our wish for the multilayer. We should solve the problem from the other way; if the multilayer is unchanging, we can change the incident beam. Thus, there is a simple physical concept to be applied. We show it in Fig. 4-8. When the mirror rotates θ^o, the reflected beam will rotate $2\theta^o$. By adding a mirror, we obtain half needed rotation angle, i.e., the response time will reduce half.

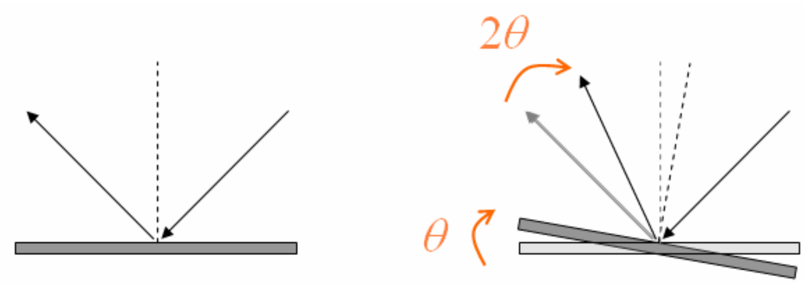


Fig. 4-8 The mirror rotates θ^o, reflected beam will rotate $2\theta^o$.

Therefore, one mirror and one multilayer can be associated to be a lightvalve, and we can turn the ON or OFF state by rotating at most 5^o.The rotation of mirror can be controlled by optical MEMS technology. Here we show one kind of lightvalve combined from the multilayer operating at $\theta=45^{o}$ in Fig. 4-9. The lightvalve is bounded by the light-absorbing layer.

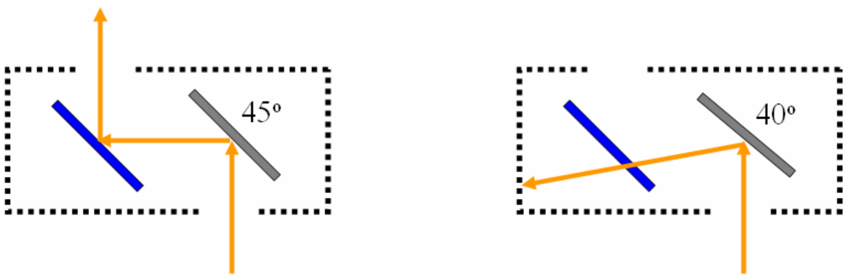


Fig. 4-9 The lightvalve combined with a multilayer and a mirror.
It is bounded by the light-absorbing layer.

Such a lightvalve may have the ability to substitute the LCD, LCOS, and DMD in a projector. Our advantage is that the response time is brief (because the rotation angle is small), and the two polarizations of incident light are both considered.