# Multiple flat-top transmission peaks of photonic crystals with super-lattice structures

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The formation of multiple transmission peaks with *flat-top* shapes in photonic crystals with a super-lattice structure is presented. By reducing the confinement strength from the barriers, the photon quantized states within each mini-bands of super-lattice structures can be coupled to each other, and multiple transmission peaks with flat-top shapes are formed. The performance of these flat-top transmission peaks is investigated in detail, and the formula to determine the frequency locations of these peaks is presented. These results may facilitate the potential applications of multiple channeled filtering based on photonic hetero-structures.

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## 1. Introduction

Photonic crystal hetero-structures [1], introduced following the concept of semiconductor hetero-structures, are made by combining at least two kinds of photonic crystals that have distinct photonic band structures. Similar to their semiconductor counterpart, there are many new and interesting phenomena in such structures, which have attracted attention [2-11].

One of the simplest photonic crystal hetero-structures is photonic quantum well structure [5,6], which is constructed by inserting one photonic crystal into another. The photonic band structures of two crystals are aligned properly to provide a frequency range which locates at pass bands of the inner crystal (called *well*), while falls inside band gaps of the outer crystals (called *barriers*). Photons with frequency falling into this range are confined to the well region and consequently, only those states at certain resonant frequencies can tunneling through the barriers, showing some sharp peaks in the transmission spectra of the whole system. This property is suggested to be potential in the design of multi-channeled filters [5,6]. However, the shapes of those transmission peaks of photonic quantum well structures are cusp-like. There are many limitations in the applications of such cusp-like peaks. For example, a little change of the location of these peaks, which may be caused by small errors of structural parameters, will lead to a dramatic decrease of transmittance.

Practically, flat-top transmission peaks are preferable due to their lots of advantages, as illustrated in many literatures [12], such as their higher error tolerance, more efficient in the rejection rate and so on. Here we present that the multiple transmission peaks with flat-top shapes can be obtained by extending the quantum well structure to another kinds of photonic hetero-structures: the super-lattice structures, which is introduced also following those of semiconductors [1]. They are constructed by periodically altering several photonic crystals. Certainly, the band structures of each component photonic crystals should be different. In fact, a photonic super-lattice structure can be obtained by repeating a quantum well structure a number of times [1]. So the photonic super-lattice structures usually contain several well regions, which is different with the quantum well structures. The existence of many well regions may cause the splitting of the original resonant modes, giving rise to a new set of allowed and forbidden mini-bands [1]. By properly designing the component photonic crystals, the split modes in each mini-bands could be coupled effectively, then the shapes of those multiple transmission peaks can be changed to be flat-top. In this letter, we show this idea based on a symmetric quantum-well structure we presented recently [2], and the final photonic hetero-structures also provide a wide high reflectance range due to the overlap of the band gaps of component photonic crystals, as we have investigated in detail [3,4].

## 2. Model

For the sake of simplicity, we will show our idea based on one-dimensional systems. The results can also be extended to two- and three-dimensional systems. Although there are several excellent methods for analyzing photonic super-lattice structures [1], the transfer matrix method [12] is the most convenient for one-dimensional systems. In the framework of the transfer matrix method, the fields at two places are related via a transfer matrix, which can be obtained by solving Maxwell equations under some boundary conditions. The reflectance, transmittance as well as field distribution can be obtained from this method.

Let's start with a photonic quantum well structure made of two different photonic crystals, since this system is well known to possess the property of multiple channeled filtering phenomenon [5,6], and by repeating them we can obtain a photonic super-lattice directly. We denote the component photonic crystal corresponding to the well by $PC_w$, and that to the barrier by $PC_b$. For convenience, both crystals are assumed to be multilayer structures composed of two alternating layers A and B with refractive index $n_A$ and $n_B$, respectively. The only difference between two crystals lies on their period constant: the constant of $PC_w$ is just twice of that of $PC_b$. Then, for a finite structure, $PC_w$ and $PC_b$ can be denoted by $(2A2B)^m$ and $(AB)^n$, respectively, where m and n are integers, and 2A (2B) means a twice thickness of A(B). In the following calculations, the refractive indices of two materials are chosen to be $n_A$ =1.45 and $n_B$ =3.5, closed to those of $SiO_2$ and Si in the near infrared region, respectively. The layer thicknesses $d_A$ and $d_B$ are assumed to satisfy the condition of equal optical path, i.e., $n_A d_A = n_B d_B$. We have calculated the photonic band structures of $PC_w$ and $PC_b$, and found that the $2^{nd}$ and 3rd pass band of $PC_w$ locate into the first gap of $PC_b$, which is required for the photon confinement.

## 3. Discussion

The reflection spectra of photonic quantum well structures $(AB)^2(2A2B)^4(2A)(BA)^2$ are shown in Fig.1(A), where $\omega_0=\pi c/2n_Ad_A$. We have added a layer of 2A and changed the order of A and B in the barrier crystal on the right to make the whole structure be symmetric, since the symmetry will facilitate the high transmittance of the whole system[12]. Only normal incidence is calculated here, and the structure is assumed to be stratified on a glass with refractive index $n_S$ = 1.5. It can be found that there are multiple transmittance peaks located symmetrically inside a wide high reflection range. The wide high reflection range is formed due to the overlap of band gaps of $PC_w$ and $PC_b$, which is also a feature of photonic hetero-structures [3,4]. The multiple sharp transmission peaks are the spectral results of confined resonant modes inside the well regions, which has been studied in detail [5, 6]. These multiple transmission peaks are suggested in the application of multiple channeled filters. However, we noticed that the shapes of these peaks are cusp-like, as shown in Fig. 1 (B).

To tailor the shapes of these transmission peaks, we expand the quantum well structure to a super-lattice one. As mentioned above, a super-lattice structure can be constructed by repeating a quantum well structure directly. We first consider the case with two well regions: $(AB)^2(2A2B)^4(2A)B(AB)^2(2A2B)^4(2A)(BA)^2$, which is just twice of the quantum well structure discussed above. Fig. 2*(a)* shows its reflection spectra, from which it is found that the original sharp peaks of quantum well structure are split into two small peaks. This splitting is caused by the interaction of confined resonate modes within the well regions [1]. The physics behind this phenomenon is similar to that of well known coupled cavities made by multiple defects. Adding more well regions will cause this splitting to a further step, resulting in the emergence of more small peaks around the position of original peaks, as shown in Fig. 2 *(b)*, which shows the spectra of structures with three well regions. Generally, the number of these small peaks is determined by the number of wells, while the width of each peak is affected by the degree of the confinement from the barriers. The ranges covering these small split peaks are regarded as mini-bands.

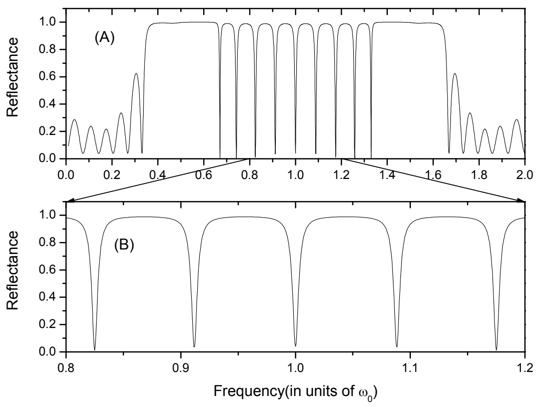


*Fig. 1. Reflective spectra for photonic quantum structure $(AB)^2((2A2B)^8(2A))(BA)^2$. (a) for the frequency range of $0\sim2\omega_0$, (b) for the frequency range of $0.8\omega_0\sim1.2\omega_0$.*

However, the existence of mini-bands does not mean the shapes of the transmission peaks be flat-top. In general, the states within the mini-bands are quantized, since only those modes satisfying the resonant conditions can exist in confined well regions and pass through the whole system. These quantized states lead to many small sharp transmission peaks and large fluctuations of transmittance within each mini-band region, which can be seen in Fig. 2. As mentioned above, the number of these states is determined by the number of the wells, while the width of each peak is affected by the degree of the confinement from the barriers. So, in order to merge these smaller peaks together to form a flat-top peak, the confinement should be weaken, at the same time, the number of wells should be increased.

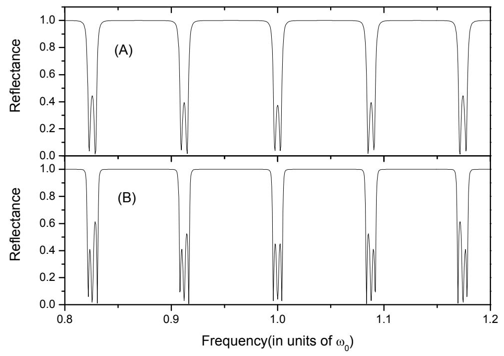


*Fig.2 . Reflective spectra for photonic super-lattice structures , showing the splitting within each mini-bands; (A) for the structure with two well regions, (B) for the structure with three well regions.*

There are several methods to weaken the confinement from the barrier. Reducing the period number of the $PC_B$ is one of the simplest ways in practice. Fig. 3 *(a)* shows the numerical results of the super-lattice structure: $AB(2A2B)^4 2ABAB(2A2B)^4 2ABAB(2A2B)^4 2ABA$. It can be found that the shapes of the transmission peaks have been improved significantly. Especially for those central peaks during the frequency range [0.8-1.2], as shown in Fig. 3 *(b)*, their transmittances are kept larger than 90% within each mini-band regions. However, by increasing the number of well regions cannot obtain a better result. The reason is that to increase the well regions, the number of barriers should be increased simultaneously. Since all the barriers in the whole super-lattice contribute the confinement to the photons, the width of the small transmission peaks within each mini-bands will decrease with the increase of barriers number, which will give a negative contribution to the form of flat-top transmission peak.

It seems that these flat-top transmission peaks might be fragile. We check this point by introducing some errors on thicknesses of each layer. Fig. 3 *(c)* shows the spectra of the case of error=1%. It can be found that the flat-top shapes of each transmission peaks are maintained, although there are some fluctuations on the tops of each peaks. At the same time, the widths of each peaks change to be a little wider. This result can be explained from the formation mechanism of the flat-top peaks. We have mentioned above that the flat-top transmission peaks are constructed from the mini-bands of super-lattice structure. These mini-bands are known to be formed due to the coupling of the modes between the wells. Disorder introduced into the barriers reduces their structural symmetry, which will weaken the degree of confinement to photons, thus provide a relative large range within which the modes can be coupled. So the widths of mini-bands are enlarged. However, disorder introduced into the wells would cause position variations of the flat-top transmission peaks, since the condition of mode resonance has been changed. These variations are random since the errors of layer thickness are taken randomly. As a result, the tops of the transmission peaks are fluctuated. As long as the error is not large enough, the center of the flat-top transmission peaks can be hold, as shown in Fig. 3 *(c)*.

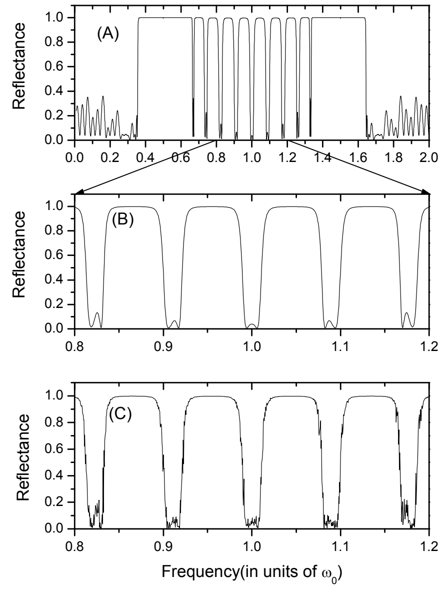


*Fig.3. Reflective spectra for photonic super-lattice structures $AB\ (2A2B)^4 2ABAB\ (2A2B)^4 2ABA\ B(2A2B)^4 2ABA$, showing flat-top transmission peaks. (a) for the frequency range of $0\sim2\omega_0$, (b) for the frequency range of $0.8\omega_0\sim1.2\omega_0$, (c) with 1% random error in each layer thickness.*

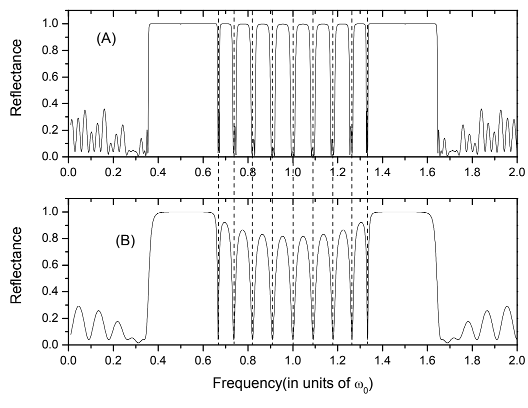


*Fig. 4. Reflective spectra (a) for structure $AB(2A2B)^4 2ABAB(2A2B)^4 2ABAB(2A2B)\ ^4 2ABA$, and (b) for structure $B(2A2B)^4(2A)B$, showing the same positions of the transmission peaks.*

There is a simple way to determine the frequency positions of these flat-top peaks. As mentioned above, the mini-bands are formed due to the mode coupling of the $PC_w$, so there should be some relationship between these mini-bands and the transmission peaks of pure $PC_w$. We found that the positions of each flat-top transmission peaks are almost the same with those of $B(2A2B)^4 2AB$, as shown in Fig. 4. The latter denotes the $PC_w$ with two B layers on both sides, and its transmission peaks can be calculated according to the equivalent method[12], as given in the following formula:

$$x = \frac{1}{\pi}\cos^{-1}\left[\pm\sqrt{\frac{\cos\left(\frac{k\pi}{p+1}\right)+\frac{1}{2}\left(\frac{n_B}{n_A}+\frac{n_A}{n_B}\right)}{1+\frac{1}{2}\left(\frac{n_B}{n_A}+\frac{n_A}{n_B}\right)}}\right]$$

where, 2p+1 is the total number of the peaks within the gap. For k=1, 2, …, p, the sign "±" takes "-"; while for k=p+2,p+3, …,2p+1, the sign "±" takes "+".

## Conclusions

In conclusion, we have studied the formation of multiple flat-top transmission peaks in photonic crystal super-lattice structures. By reducing the period numbers of the crystals in the barriers, the photon confinement within well regions is decreased, and the small peaks caused by the quantized states within each mini-band can merge to each other to form flat-top transmission peaks. The features of these peaks are discussed. The formula to determine the frequency position of these flat-top peaks is given. These results may facilitate the potential applications of multiple channeled filters by using photonic crystal heterostructures.

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