

Influence of two-dimensional magnetic photonic quantum wells on resonant tunneling spectral character

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Abstract The non-magnetic material closed photonic quantum well (PQW) and magnetic material PQW structures based on the non-magnetic material open PQW are proposed. The transmission spectra and the field distributions of these three PQW structures are calculated by finite-difference time-domain method, the quantized energy states are researched, and the feasibility of enhancing spectral intensity significantly by self-structure is disclosed. It is found that the optical transmittance of the magnetic PQW is close to 1, and the energy loss is less compared to non-magnetic PQW. Compared with the closed PQW structures, the device's volume can be reduced, the degree of free regulation of the energy band project can be increased, and more photon bound states can be obtained. The results show that the open PQW is the traveling wave well, and its capability of capturing photons is weak. However, the closed PQW and the magnetic PQW are standing wave wells. Their capabilities for capturing photons are strong, while the light field gradient of the material PQW is bigger.

Keywords magnetic quantum wells, spectral character, finite-difference time-domain method, resonant tunneling, transmissibility

1 Introduction

In recent years, the effect of resonant tunneling on semiconductor quantum well (QW) structures has received considerable attention for fundamental physics studies as well as for application in photonic devices. With the full boom of photon crystal (PC) [1,2] studies, analyzing their multitudinous resemblances between the

PC and the semiconductor, people were inspired to fabricate photonic QW (PQW) structures by imitating semiconductor QW structures. Many research findings have been obtained both theoretically and experimentally. Quantized levels similar to semiconductors have been observed from the tunneling spectra in one-dimensional (1-D) [3,4], two-dimensional (2-D) [5,6] and three-dimensional (3-D) [7] PCs. Thus, the PQW structures are realized.

Despite much profound studies of PC and manufacturing methods becoming more convenient, the future mainly focuses on non-magnetic materials. Thus, the applied range is limited, and the adjustable degree of energy level project is influenced to a certain extent. Some other materials such as magnetic materials [8,9] and the liquid crystal [10] were being used to manufacture PQW structures, but mainly concentrated on some specific cases. There has been no systematic and regular recognition. Since the magnetic material is an important component of the function material, it has possibly more applications than current use.

Many optical characteristics of PQW may be shown by an optical spectrum, which can be used to provide discrete energy levels of PQW structure with detailed information. Theoretically, the observable information of the spectrum contains frequency and intensity. Restricted by the complexity of the spectral intensity and the precision of data processing, majority of research on the spectrum is concentrated on frequency. However, improving experimental conditions, continuous optimization of algorithms, and the development of calculation conditions has made research on spectral intensity increasingly attractive. This is because in the PQW structure, spectral intensity increases with the increasing number of photons tunneling through the photonic wells. The larger the number, the higher the tunneling spectrum intensity, the more concentrated the light beam, and the higher the transmissivity. To obtain accurate values of spectral intensity, simple detection methods that can

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exhibit the spectral characteristics accurately [11,12] are continuously sought, and various factors which can enhance this intensity have been discussed [13,14].

Based on the simple research technique introduced, resonant tunneling characteristics of magnetic PQW structures are investigated. The discrepancy of tunneling spectra between the non-magnetic and the magnetic PQW structures is contrasted, the new measure for improving tunneling spectral intensity is proposed, and a train of new thought for increasing photonic confined states is offered. Their physical mechanisms are presented.

2 Physical models and theoretical method

Three types of PQW schematic diagrams are shown in Fig. 1. The building blocks (black circle) of all these PQW structures are formed in the square lattices, with lattice constant a in the air and constructed in the glass rods with radius $r = 0.25a$ and relative dielectric constant $\epsilon_1 = 4.55$. These rods are placed along the x direction, the $\pm y$ directions are called side directions of PQW structures, and the thickness is finite in the z direction. The potential well could be formed by removing multiple-line cylinders from the center of the two-dimension PC, and then filled up with proper media. The left and right sides of the potential well could be regarded as potential barriers. The light source is incident on the surface from the left in the case of normal incidence. Two detectors (P_1 and P_2) placed on each side of the PQW can be used to measure the incident power and the transmission power, respectively. Thus, transmissivity can be readily calculated as the ratio of transmitted power to incident power.

Figure 1(a) is a schematic of non-magnetic material PQW structures frequently reported in literature [9,10] (called “open PQW structure” in the following text, with relative permeability $\mu_1 = \mu_0$, where μ_0 is relative permeability of vacuum). The well thickness is $w = na$, where n is the line number of dielectric cylinders removed in the z direction; and barrier thickness is $v = ka$, where k is the line number of glass rods of barrier region in the z

direction. In the following discussion, we choose the fixed barrier thickness for $v = 4a$. It can be maintained that, limited by the device volume, the size of the open-cavity PQW structure in the y direction is not large enough. A large portion of the photons accumulated in the well will thus radiate and leak out because they are not restricted by any confinement effect, resulting in lower transmissivity. For this reason, a new PQW structure by adding periodic structures M_1 and M_2 to the open PQW's side directions can be proposed. It is shown in Fig. 1(b) and named the closed PQW structure. The size of the well region can be expressed as mn , where m is the number of cylinders removed from each line in the y direction and the geometric meaning of n is the same as that in Fig. 1(a). The periodic structures M_1 and M_2 are also PC structures with the same geometric and dielectric parameters as the potential barriers. Due to the effect of band gap of M_1 and M_2 , once photons are trapped in the closed-cavity well, it would be nearly impossible for them to escape. Thus, the total number of photons localized in the well would increase, leading to considerable transmissivity. But the cost of this improvement is to increase the device volume — a feature not suitable for the optical integration and miniaturization of optical equipment.

A magnetic PQW structure has been proposed in which the air well region shown in Fig. 1(a) is substituted by the magnetic material dielectric rods, and the size of the well region is mn , as can be seen in the rectangular window of Fig. 1(c). The geometric parameters and dielectric constant of the magnetic material dielectric rods are the same as those of non-magnetic dielectric rods, i.e., the radius $b_2 = 0.25a$ and $\epsilon_2 = \epsilon_1 = 4.55$. The relative permeability μ_2 is chosen according to our design requirements.

The finite-difference time-domain (FDTD) method [15] with the perfectly matched layer absorbing boundary condition is used to calculate transmission spectra and field distributions of these PQW structures. By using this technique, photon propagation problems can be formulated systematically in terms of the well-known Maxwell equations without using special mathematical knowledge. For the sake of brevity, only the TM mode is

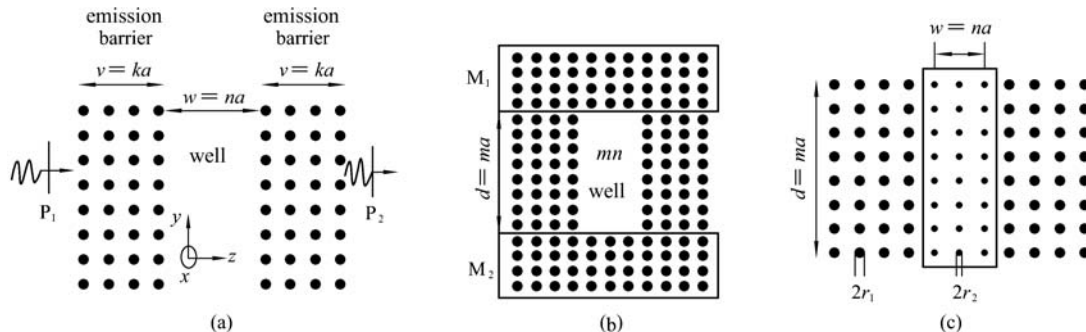


Fig. 1 Schematic structure. (a) Open PQW; (b) closed PQW; (c) magnetic PQW

investigated at normal incidence. The difference formulas used in programming are as follows:

$$\begin{aligned}
E_z^{N+1}(i,j) = & E_z^N(i,j) + \frac{\Delta t}{\varepsilon(i,j)\Delta x} \left[H_y^{N+1/2} \left(i + \frac{1}{2}, j \right) \right. \\
& \left. - H_y^{N+1/2} \left(i - \frac{1}{2}, j \right) \right] \\
& - \frac{\Delta t}{\varepsilon(i,j)\Delta y} \left[H_y^{N+1/2} \left(i, j + \frac{1}{2} \right) \right. \\
& \left. - H_y^{N+1/2} \left(i, j - \frac{1}{2} \right) \right], \quad (1)
\end{aligned}$$

$$\begin{aligned}
& H_y^{N+1/2} \left(i + \frac{1}{2}, j \right) \\
= & H_y^{N-1/2} \left(i + \frac{1}{2}, j \right) + \frac{\Delta t}{\mu(i,j)\Delta x} [E_z^N(i+1,j) \\
& - E_z^N(i,j)], \quad (2)
\end{aligned}$$

$$\begin{aligned}
& H_x^{N+1/2} \left(i, j + \frac{1}{2} \right) \\
= & H_x^{N-1/2} \left(i, j + \frac{1}{2} \right) - \frac{\Delta t}{\mu(i,j)\Delta x} [E_z^N(i,j+1) \\
& - E_z^N(i,j)], \quad (3)
\end{aligned}$$

where the subscripts i and j indicate the position of the grid point in the z and y directions, respectively. N is the discrete time step, $E_z^{N+1}(i,j)$ represents the electric field E_z at the corresponding position (i,j) and time step $N+1$. The physical meaning of other field components can be analogized. $\varepsilon(i,j)$ and $\mu(i,j)$ are the position-dependent dielectric constant and magnetic conductivity of the material, respectively. Δt is the time increment, and $\Delta x = \Delta y = \Delta s$ is the spatial increment at neighboring grid points along the z and y directions. From the stability criterion, the duration of one time step should be satisfied with $\Delta t \leq \Delta s / (c\sqrt{2})$. These difference formulas are simple and easy to program. Some time-dependent problems such as pulse propagation and field distribution can be solved because the electro-magnetic fields are computed at each time step.

In the course of calculating the transmission spectra, the modulation Gaussian pulse is chosen as incident light source and is given by

$$E_z(t) = \cos(2\pi f_0 t) \exp \left[-4\pi \frac{(t-t_0)^2}{T^2} \right], \quad (4)$$

where f_0 is center frequency of fundamental wave $\cos(2\pi f_0 t)$, t_0 is center position of the Gaussian pulse, and T is a time constant. This incident light source is a

wideband source which can be used to analyze the forbidden band and the localization characteristics of PC conveniently. The smaller the time constant T , the narrower the pulse width and the wider the spectrum width. We can choose $t_0 = 20\Delta t$, $T = 2\Delta t$. In the calculated diagrammatic curves of transmission spectra, the frequencies described in X-coordinate are in reduced units which take $(\omega a / (2\pi c))$ as their units, c is the propagation speed of light in vacuum, and ω is the angular frequency. The Y-coordinate values can be calculated as the ratio of transmitted power to incident power.

In calculating the optical field distributions, the simple harmonic wave is chosen, which can be expressed by the following equation:

$$E_z(t) = \cos(2\pi f_m t), \quad (5)$$

where f_m is the frequency of the incident light source. With the increase in time step, the electromagnetic field distributions in the well regions reach steady state gradually.

3 Results and discussion

To ensure the accuracy and usefulness of our automated computer codes, we choose some structures which have been reported in the literatures [16,17]. With different algorithms but the same geometric parameters and refractive indices, those numerical results are in good agreement. Thus, the reliability and the accuracy of our computer codes are guaranteed, hence the reliable bases for subsequent research works are provided. The total field and the scattered field technology are used with absorbing boundary conditions for 2-D photonic crystal waveguides [18]. We first calculate the transmission spectrum of the perfect 2-D PC shown in Fig. 2(a). It shows that the first photonic band gap (PBG) is from 0.32 to 0.45, in which light possessing certain values of wave vector are not allowed to propagate. This result indicates that due to leaking, reflection and scattering, the loss of transmission still exists even in the conduction band regions, and thus transmissivity is slightly smaller than 1.

Figure 2(b) and Fig. 2(c) are the transmission spectra for open and close PQW structures with the same well thickness $w = 5a$. The frequency region of Figs. 2(b) and 2(c) is compressed in comparison to Fig. 2(a). Only the range from 0.32 to 0.45 which corresponds to confined states is chosen, so as to distinguish the position-difference of the confined states clearly. It is seen that the number of resonant peaks of the closed PQW is equal to that of the open PQW, and their corresponding positions remain nearly unchanged. However, the outgoing light intensity of the closed PQW is obviously

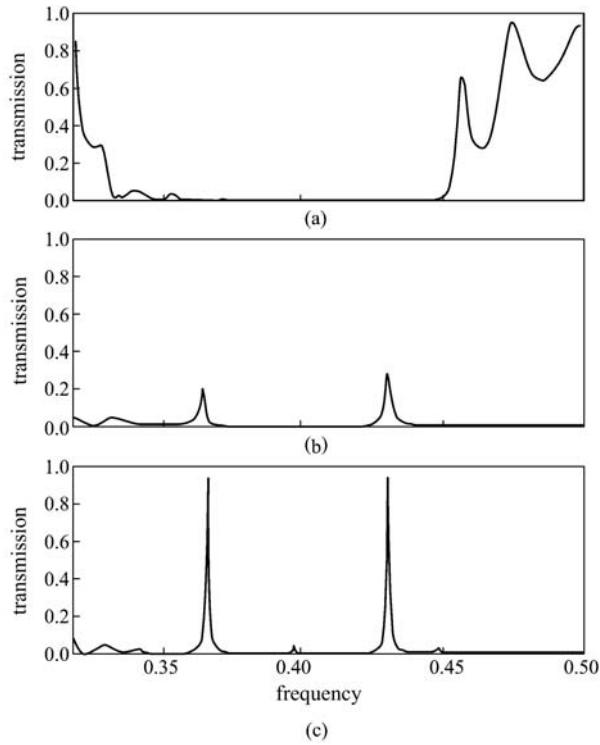


Fig. 2 Transmission spectra of PC and PQW structures with $w = 5a$. (a) Barrier PC; (b) open PQW; (c) closed PQW

stronger, its transmissivity is higher, the frequency selectivity is better, and the quality factor Q is larger. These features indicate that closed PQW could cause the stronger localization to photons and have more superior optical characteristics in comparison with the open PQW.

For the magnetic PQW structure shown in Fig. 1(c), it is easy to conjecture that if magnetic material in the well region has no effect on the photon motion, the transmission spectra would be the same as shown in Fig. 2(a). But if the magnetic material has an effect, the transmission spectra would change in comparison to Fig. 2(a). The transmission spectra of relative permeability $\mu_2 = 2, 3, 4$, and 12 for magnetic dielectric rods with well thickness $w = 3a$ are shown in Figs. 3(a)~3(d), respectively. Analyzing these four figures carefully, we can deduce that:

1) Compared to Fig. 2(a), the transmission spectra of magnetic PQW structures are changed, the photon motion is strongly restricted in the magnetic potential well, and the density of states is quantized. There are sharp peaks whose transmissivities are very close to 1 and whose formation embodies the new dispersion relation caused by spatially periodic arrangement of magnetic material. This phenomenon can be explained as the effect of resonant tunneling. Because of the narrower well thickness, the energy bands are quantized, and thus discrete energy levels are formed. When the energy of

incident photons is matched with the confined state of the PQW, the tunneling probability is accessible to 1. On the contrary, if none of them match, the tunneling probability is very close to 0. This implies that there are photon virtual states in the well, the movement of the photons is limited on these discrete energy levels, and the photonic bands are quantized.

2) The magnetic PQW structures exhibit much stronger confinement effects. Comparing Fig. 3 with Fig. 2(b), we can clearly see that the transmissivity of the open PQW structure is very low, and the transmission loss in energy is significant. However, the magnetic PQW structure's transmissivity is close to 1, similar to the closed PQW structures. This happens because for the open PQW structures with vacuum well region, photons are not restricted by any confinement effect at the side directions of the PQW. Therefore, they will radiate and leak out from the well, resulting in lower transmittance. For the dual complex materials, the propagation of waves is inhibited by the effect of both dielectric scattering and magnetic scattering which cause the formation of band gaps. These gaps, which are located at the side directions, block the paths for photons to radiate and leak out, bringing transmissivity to nearly 1.

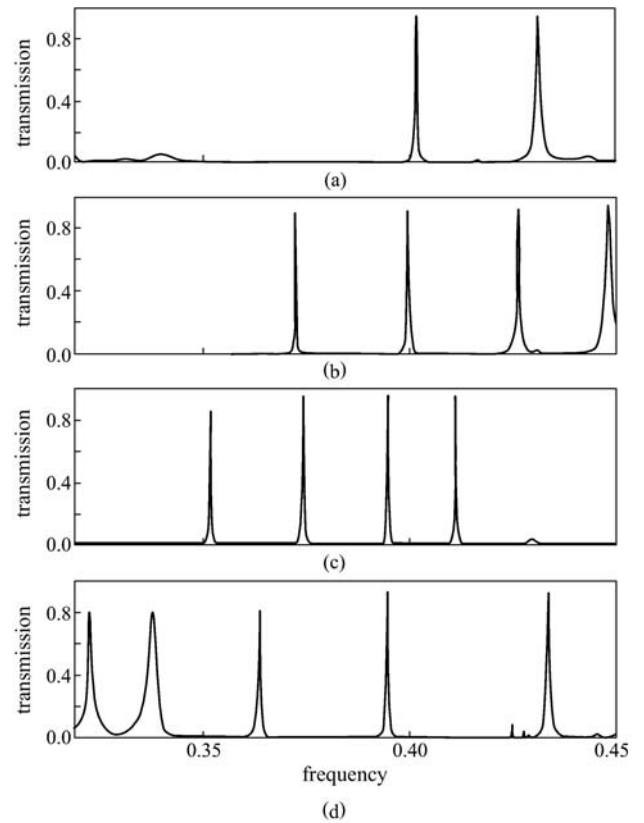


Fig. 3 Transmission spectra of different permeability with $w = 3a$ for different permeabilities. (a) $\mu_2 = 2$; (b) $\mu_2 = 3$; (c) $\mu_2 = 4$; (d) $\mu_2 = 12$

3) With increasing magnetic conductivity, the number of the resonant peaks increases gradually, but they are not proportional. The center frequencies of new resonant peaks shift to lower frequency regions. Up to one limit, frequency spacing in the adjacent resonant peaks becomes narrower, but more resonance peaks appear over a certain energy range. The goal of realizing tunable filtering is reached, probably as the magnetic permeability rises, the stronger the non-homogeneity of the system, and the more intensive the scattering process of light. In this case, the condition of producing new quantized states is created. This indicates that we can generate more resonant peaks simply by adjusting the electromagnetic parameters as much as desired, leading to multiple channeled filtering.

4) The optical frequencies corresponding to the resonant peaks may be lower than the PBG of the perfect barrier PC. In this case, the adjustable range of the frequency is enlarged.

5) Compared to the open PQW structure, the magnetic PQW structure's resonant peak is sharper, the transmissivity is larger, the quality factor Q is higher, the peak width at half-height is narrower, and the frequency selectivity is better.

6) A series of resonant peaks may be obtained by selecting the different well thicknesses of PQW structures properly. In case of the same magnetic permeability, the narrower the well thickness is, the higher the frequencies of the resonant peaks. This phenomenon indicates that luminous wavelength can be changed by adjusting the PQW structures. Thus, a new train of thought has been provided for the tunable wavelength. In this way, not only is the adjustable degree of energy level project increased, but the electrical and optical properties are also improved.

It is worth mentioning that magnetic materials belong to dual complex materials with several parameters, such as dielectric constant, dielectric dissipation, magnetic permeability and magnetic dissipation. For the sake of simplicity, dielectric dissipation and magnetic dissipation are not considered.

The effect of resonant tunneling is a kind of collective transport conduction for photons. In the well region with more photons, more sufficient energy for photons to penetrate through the PQW structure can be piled up. Thus, the transmissivity increases. To further explore the physical origin of the enhancement in tunneling spectral intensity of magnetic QW, in case of normal incidence with the simple harmonic plane wave, field distributions corresponding to normalized resonance frequencies 0.406, 0.406 and 0.430 for open, closed and magnetic PQW structures with well thickness $3a$ are calculated by using the FDTD method (Fig. 4) respectively. The y and the z axes take the lattice constant a as their unit cell, and E_x corresponds to optical field intensity, which takes $V \cdot m^{-1}$ as its unit cell. Figure 4(a) shows that the open PQW is the traveling wave well, in which the light field exhibits the Gaussian distribution and the gradient of potential field is smaller. Thus, the capability for the well to capture photons is weak. In this case, a portion of the photons accumulated in the well will radiate or leak out into free air. This is the main reason for open PQW in lower transmissivity. Figures 4(b) and 4(c) indicate that the closed PQW and the magnetic PQW are the standing wave wells, in which Gaussian wave envelopes have periodic variation in the wavelength dimension, and stable standing wave fields are formed in the well. A bigger light field gradient can be obtained because of the smaller space volume of the well. In addition, the effect of band gap around the well region leads to the strong confinement, i. e., the ability for the well region to restrict photons is very strong. Gaussian wave envelopes in one potential well cannot migrate to others. The paths for photons to escape from the well are blocked up, i. e., the photons would find it very difficult to escape from PC surroundings. This situation indicates that the confined photons are frozen at some discrete energy levels, raising the possibility that each level may get together more photons. By carefully analyzing Fig. 4(c), we can clearly see that light waves trend to propagate in a higher refractive index or magnetic permeability medium, and the transmission energy is

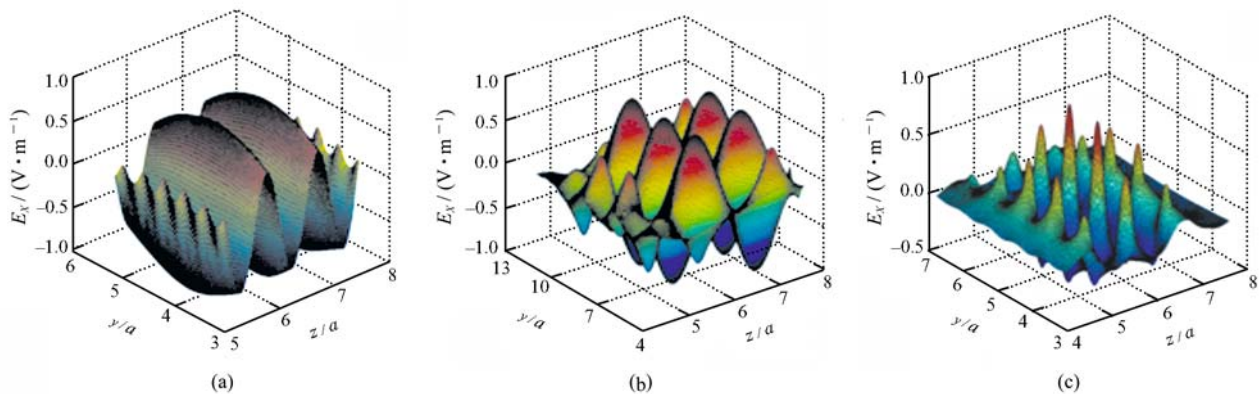


Fig. 4 Optical field distributions in PQW. (a) Open PQW; (b) closed PQW; (c) dielectric rod of magnetic material

mainly restricted in magnetic dielectric cylinders. Simultaneously, a strong focusing effect appears in the well region. Comparing with Fig. 4(b), the density of wave envelopes shown in Fig. 4(c) is much higher, and the volume of single wave envelopes is much smaller, enabling a much larger gradient of optical field. This enhancement in optical gradient originated from the redistribution of photon pattern density. It changes the characteristic and the efficiency of light-matter interaction and will have many applications in the field of photoelectronics.

4 Conclusions

The optical spectrum information is determined by the intrinsic properties of material, which cannot be explored by other means. The transmission spectra and the optical field distributions of the open and closed PQW and the magnetic PQW have been calculated by FDTD method. Researches show that the magnetic PQW are the standing wave wells, in which the quantized photon energy levels can be obtained, the energy loss is much less, and the transmittance is very close to 1. Compared to the non-magnetic closed PQW structure, the device volume of a magnetic PQW structure can be reduced and more photon bound states can be obtained. Thus, the adjustable degree of energy level project may be enhanced. The conclusions drawn by this work could provide theoretical guidelines for the design and production of optical communication devices such as the laser source, photoelectric detector, and optical switch. These research works have enormous application value in both integration and microminiaturization for optic devices.

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