Design of Super Narrowband DWDM Filters Based on the Effect of Spectral Splitting

C Q Huang 1, J Liu 2, P Tian 3, Z M Wan 2, Z M Luo 2 and M Chen 1

1 College of Physics & Electronics, Hunan Institute of Science and Technology, Yueyang 414006, China

2 College of Information & Communication Engineering, Hunan Institute of Science and Technology, Yueyang 414006, China

3 College of Optoelectronic Science and Engineering, Wuhan National Laboratory for Optoelectronics, Huazhong University of Science and Technology, Wuhan, 430074, China

E-mail: namecqh@yahoo.com.cn

Abstract. A novel approach is proposed to design super narrowband DWDM Filters consisting of multiple quantum wells (MQWs) by employing photonic crystals. Numerical investigations prove that the closed-cavity MQWs are more suitable for DWDM systems compared with the open-cavity MQWs. It is shown that different confined states could emerge from photonic band gap, which can be used as high-frequency carriers one-to-one. It is also found that these proposed MQWs could split the single spectral lines into multiples based on the effect of spectral splitting, and the number of the splitting is just equal to the number of the wells. In this way, the density of carriers can be increased multiplicatively in the same wave band, and thus the spectral efficiency can be improved multiplicatively. These results provide the prospects of channel density maximization and effective bandwidth optimization for optical communication.

1. Introduction

With rapid developments of computer and the global telecommunication market, especially the emergence of a series of new services such as the Internet, high-quality videoconference system and multimedia, the demand for bandwidth and capacity increases rapidly. Thus the spectral source is getting more and more lacked. The appearance of DWDM technology have avoided or relieved this situation to a certain extent.

In DWDM systems, MultiPlexers (MUX) and demultiPlexers (DEMUX) are key devices [1]. At the present time, thin film filter (TFF) and array waveguide grating (AWG) have been widely used as MUX/DEMUX devices in commercial DWDM systems due to their excellent temperature stability, low polarization dependent loss, high channel isolation and mature technology [2], etc.. However, they have also some drawbacks. For TFF, the insertion loss is big with non-uniform distribution; the price of its commercial application is shortening transmission distance, sacrificing communication quality, and reducing output power. For AWG, additional control devices and stable units are needed, leading to big volume of device, high trouble rate and maintaining difficulty [3]. In this case, it is urgent to explore new devices for satisfying the requirement of bandwidth and capacity with high quality and efficiency.

In this paper, we design the novel DWDM devices constructed by multiple-quantum-well (MQW) structures consisting of photonic crystal (PC), a series of new optical characteristics are discovered and analyzed. Because of the difficulty in fabricating the three dimensional PC, two dimension (2D) PC in reasonable arrangement is used as an alternative. The finite difference time domain method is used for numerical analysis.
2. Physical model and theoretical method

The most reported QW structure model composed by two-dimension PC in the literatures is shown in Figure 1 (a). Both potential barriers are consisted of the same two-dimension PC having a square lattice with a lattice constant \( a \). The lattice is made of dielectric rods on an air background. These rods are placed along the \( z \) direction. For each barrier thickness, it is determined by \( v = k \times a \), where \( k \) is the line number of rods in the \( x \) direction in the barrier region. The potential well is formed with air. It is obvious that the vacuum thickness in the \( \pm y \) directions is infinite, which are called the side directions of QW structures; but it is finite in the \( \pm x \) directions, which can be expressed as \( w = n \times a \), where \( n \) is the line number of the removed rods in the \( x \) direction. \( P_1 \) and \( P_2 \) are the same detectors placed at each side of the QW, which can be used to measure the incident power and the transmission power, respectively. Thus, the transmissivity can be calculated readily as the ratio of transmitted power to the incident power.

![Figure 1. The schematics of the SQW structures (a) open-cavity SQW (b) closed-cavity SQW.](image)

 Apparently, the well region structure of Figure 1 (a) is open, we call this schematic diagram as “open-cavity single quantum well (SQW)”. But we think that, the transmission efficiency of photon captured in the well region is impossible to be too high, it is because that the majority of them would radiate and leak out from the well as they are not restricted by any confinement effect in the \( \pm y \) directions, resulting in lower transmissivity. For this reason, we propose a new type of two-dimensional quantum well structure named as closed-cavity SQW, as shown in Figure 1 (b). The difference is that two periodic structures \( M_1 \) and \( M_2 \) is added in the side directions based on the Figure 1 (a). The geometric and dielectric parameters of \( M_1 \) and \( M_2 \) are the same of the case of potential barriers. The well region area is \( m \times n \), where \( m \) is the number of rods removed from each line in the \( \pm y \) directions, the lateral length of the well is \( d = m \times a \). We make a conjecture that, as the existence of band gaps caused by \( M_1 \) and \( M_2 \), the propagation of waves is also inhibited at the side directions, just like that at \( \pm y \) directions, so that the motion space of photons is reduced down. Once photons are trapped in the well, the probability for them to escape from the well would be very low, since the path of energy liberation is shut off, and the photon density and energy would be both increased, leading the transmissivity to nearly 1. The numerical calculation results have confirmed the correctness of our conjecture.

Stimulated by the high transmissivity of closed-cavity SQW aforementioned discussions, we further design the closed-cavity MQW structures, as shown in Figure 2 (a) and Figure 2 (b). To our surprise, a series of excellent optical characteristics are found. For the sake of simplicity, we only introduce the closed-cavity double QW (DQW) structure and the closed-cavity triple QW (TQW) structure with narrow barrier thickness, the size of the well regions are all the same. It is obvious that MQW can be regard as the cascade connection of multiple SQW structures, and we can obtain the open-cavity multiple QW (MQW) structures by only removing the all dielectric rods at the side directions.
We use the finite-difference time-domain (FDTD) method [4] with PML [5] absorbing boundary conditions to truncate the computational region and minimize the reflections from the outer boundary as research tools. In the following discussion, we only consider the transverse-magnetic (TM) polarization since its omni-direction total reflection is always defined by the omni-directional photonic band gap (PBG). The difference formulas used in computational procedures are as follows

\[
E_z^{N+1}(i, j) = E_z^N (i, j) + \frac{\Delta t}{\varepsilon(i, j) \Delta x} [H_y^{N+1/2}(i + 1/2, j) - H_y^{N+1/2}(i - 1/2, j)]
\]

\[
H_y^{N+1/2}(i + 1/2, j) = H_y^{N-1/2}(i + 1/2, j) + \frac{\Delta t}{\mu(i, j) \Delta x} [E_z^N (i + 1, j) - E_z^N (i, j)]
\]

\[
H_x^{N+1/2}(i, j + 1/2) = H_x^{N-1/2}(i, j + 1/2) - \frac{\Delta t}{\mu(i, j) \Delta x} [E_z^N (i, j + 1) - E_z^N (i, j)]
\]

Where \(N\) indicates the discrete time step, the subscripts \(i\) and \(j\) indicate the position of the grid point in the \(x\) and \(y\) directions, respectively. \(E_z^{N+1}(i, j)\) represents the electric field \(E_z\) at the corresponding position \((i, j)\) for time step \(N+1\). \(\varepsilon(i, j)\) and \(\mu(i, j)\) are the position-dependent dielectric constant and magnetic permeability of the material, respectively. \(\Delta t\) is the time increment, and \(\Delta x = \Delta y = \Delta s\) is the spatial increment in neighboring grid points along the \(x\) and \(y\) directions.

The stability condition for the FDTD is determined by choosing a suitable \(\Delta t\) to ensure the solutions with purely real frequencies for all possible wave vectors \(k\). If the following condition is satisfied, the FDTD time stepping equations are stable numerically

\[
\Delta t \leq \frac{\Delta s}{c \sqrt{2}}
\]

Where \(c\) is the speed of light in vacuum.

For simplicity of analyses, we use modulation Gaussian pulse, which can be given by

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

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. In this letter, we choose \(t_0 = 20\Delta t\), \(T = 2\Delta t\). In favor of the observation, in the calculated diagrammatic curves of transmission spectra, the frequencies described in \(X\)-coordinate are in reduced units which take \((\omega / 2\pi c)\) as their units, and \(\omega\) is the angular frequency.
The $Y$-coordinate values which represent the transmission coefficients can be calculated as the ratio of transmitted power to the incident power.

These difference formulas are simple and easy to be programmed. The time-varying electric fields at the input and output ports can be recorded in digit groups. By taking the fast Fourier transform (FFT) of these recorded fields at a large range of frequencies[6], the transmission spectra can be obtained. From the above equations, we can see that for a fixed total number of time step the computational time is proportional to the number of discretization points in the computation domain, which means that the FDTD algorithm is one of order $N$ (where $N$ is also the number of computational nodes). Thus, the FDTD method reduces significantly both memory requirement and CPU time. That is the very reason why we use the FDTD method for our research tool.

3. Numerical results

In the model of the Figure 1 or Figure 2, the parameter choices are as follows: the barrier width $v = 5a$, the well width $w = 10a$, the lateral length of the well $d = 8a$ for the closed-cavity MQW structures, relative dielectric of dielectric rods $\varepsilon_r = 4.55$, and the radius of rods $r = 0.25a$. For simplicity of analyses, only the TM wave is analyzed, and the Gaussian pulse is in the case of normal incidence on the entrance face. The computational space have a spatial sampling rate of $(\lambda_0/40)$, where $\lambda_0$ is the wavelength of fundamental wave in vacuum.

We first calculate the transmission spectrum of potential barriers (perfect 2D PC). We can clearly observe that the first PBG is from 0.325 to 0.465, in which light possessing certain values of wave vector is not allowed to propagate. In order to save the space of a whole page, we have not given the chart of transmission spectrum.

Figure 3 (a), 3 (b) and 3 (c) are the transmission spectra of open-cavity SQW, open-cavity DQW, and open-cavity TQW structures. Figure 4 (a), 4(b) and 4(c) are the transmission spectra of closed-cavity SQW, closed-cavity DQW, and closed-cavity TQW structures. It is clearly seen many defect modes (sharp peaks) with different frequencies emerge in the PBG. But for the open and closed QW structures, the amplitudes for transmission spectra of closed-cavity QW structures are bigger than that for open-cavity QW.

The formation of these sharp peaks embodies the new-fashioned dispersion relation which is caused by spatially defective arrangement of the well. While the energy of incident photons is matched with the confined state located in the well regions, they will fall into the potential wells and involve in the wells inescapably, just like falling into a deep water well. As long as the thickness of the potential barriers is not very thin, the moving photons will reflect basically after striking against the potential well walls. If the energy is not enough big, the photon can only limit in the wells level. Because of the quantum closeness of PBG, the effective state density of photons is concentrated in a certain specific narrow energy range, leading to narrow energy distribution. This is the sharpened phenomenon of the density of states. Based on the effect of the resonant tunneling, the tunneling probability of photons may achieve 1. On the contrary, if the energy of incident photons is matched with the confined state, the tunneling probability would be very close to 0.

The reason why the transmissibility of open-cavity MQW is that, for the open MQWs with vacuum well region, photons are not restricted by any confinement effect (not only the refractive index, but also the band gap) at the side directions of the MQWs. These photons cannot transmit effectively along the designed direction, and majority of them will radiate and leak out from the well, resulting in lower transmittance. While the closed-cavity MQW is just right opposite. This explanation just conforms to our conjecture above mentioned. That is the very reason we project the closed-cavity MQWs in this paper.

From Figure 3 and Figure 4, we can observe that, each sharp peak which appears in the SQW could split into two or three for DQW or TQW structures ·····. Further researches indicate that the number of sharp peaks is just equal to that of the wells in MQW structures. This phenomenon is called as spectral splitting. It is noted that, these sharp peaks can be assigned to the center wavelength of the DWDM filters or the guide waves one-to-one for optical communication system. In this way, the
number of the center wavelengths can be multiplied in a limited PBG. Thus the spectral efficiency can be improved multiplicatively in a fixed frequency band.

![Figure 3. Transmission spectra of (a) open-cavity SQW (b) open-cavity DQW (c) open-cavity.](image)

![Figure 4. Transmission spectra of (a) closed-cavity SQW (b) closed-cavity DQW (c) closed-cavity.](image)

In order to further improve the spectral utilization, we have been seeking for the new ways unceasingly. We find that, while the barrier thickness is changed, the frequency interval between two sharp peaks has a remarkable change. Figure 5 (a), (b) and (c) represent transmission spectra with the same well width w=10a but different barrier width v=3a, 5a, 7a, respectively. It can obvious that, the narrower the barrier thickness is, the bigger the distance between adjacent sharp peaks is. This phenomenon indicates that centre wavelength of the DWDM filters can be fine adjusted by only changing the thickness of the barriers. There are no intersection and overlapping but PBG between neighboring sharp peaks, so that the signal crosstalk is reduced, and the resource of spectrum is effectively used. In DWDM systems, as it is used as MUX, it combines optical signals of different wavelengths before transmitting them; as it is used as DEMUX, it separates the combined optical signals in the optical fiber and then sends them to different communication terminals. By using this kind of technology, the request of the wavelength interval for DWDM devices is reduced, and the transmission capacity of the DWDM system is improved.

4. Conclusion

In this paper, 2D open-cavity and closed-cavity MQW structures are designed, the differences of transmission spectra for these two kinds of QW structures are compared and analyzed. The research results indicate that there are some superiorities for closed-cavity MQW structures compared with open-cavity MQW structures. It is also found that different confined states could emerge from photonic band gap (PBG). These confined states can be used as high-frequency carriers one-to-one for optical communication systems. It is also found that the single spectral lines split into several equidistant lines separated by band gap, and the number of the splitting is just equal to the number of the wells. In this way, the density of carriers can be increased multiplicatively in the same wave band, and thus the spectral efficiency can be improved multiplicatively.
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Figure 5. Spectra of dual QW with $w=10a$ but different barrier widths (a) $v=3a$ (b) $v=5a$ (c) $v=7a$. 