A tunable dual-narrowband band-pass filter using plasma quantum well structure*

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A tunable dual-narrowband pass-band filter is designed. A one-dimensional photonic crystal (1D PC) is comprised of alternate dielectric layer and vacuum layer. Two quantum wells (QWs) as defects can be constructed by sandwiching two plasma slabs symmetrically in the 1D PC, and a dual-narrowband pass-band filter is formed. The conventional finite-difference time-domain (FDTD) method and piecewise linear current density recursive convolution (PLCDRC)–FDTD method are applied to the dielectric and plasma, respectively. The simulation results illustrate that the dual-narrowband frequencies can be tuned by changing the plasma frequency. The pass band interval and the half-power bandwidths (−3-dB band widths) are related to the space interval between two QWs.

Keywords: quantum well, dual-narrowband pass-band filter, plasma

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1. Introduction

Photonic crystals (PCs)[1,2] which are periodic dielectric structures fabricated artificially have aroused worldwide interest in the past two decades. They have many novel physical properties, which provide a good way to control the propagation of electromagnetic (EM) waves due to the existence of photonic band-gaps (PBGs). The PBG means that the propagation of EM waves is forbidden in a certain frequency range. When the working wavelength is located in a microwave range, the PCs can be called electromagnetic crystals or electromagnetic band-gap (EBG) structures.

Up to now, the PBG of most given PCs has been immutable. Namely, once the PCs have been fabricated, their PBGs keep unchanged. Several methods of tuning PCs were demonstrated recently. Tuning PCs have been developed by mechanical means, but they are focused on two-dimensional photonic crystals (2D PCs).[3,4] Thubtimthong and Chollet[5] designed a tunable PBG filter by applying a micro-actuator to compress a 1D PC along the propagation direction. It has been proposed that PCs constructed with ferroelectric or ferromagnetic materials could be tuned by an external electric or magnetic field.[6,7] Later, Velev *et al.*[8] proposed the PCs of the inverse opal type doped with a liquid crystal. The PCs made of semiconductor constituents[9] are suited to constitute tunable PCs. The idea of the former is based on liquid crystal dielectric's response in the external electric field, while the latter is mainly due to the variations of the concentration of free carriers within the semiconductor by changing the temperature or the density of dopants. Another possibility for tuning PCs with a superconductor constituent was described in Ref. [10]. The band gap of the PCs can be tuned by changing the external temperature. Hojo *et al.*[11] proposed plasma photonic crystals (PPCs), and its EBG can be adjusted by changing the parameters of plasma.[12] Mudachathi *et al.*[13] designed an electrostatically tunable optical channel drop filter based on 1D PC in silicon-on-insulator optical bench platform. Zhao *et al.*[14] designed a novel in-plane PC channel drop filter which was composed of a resonant cavity sandwiched by two parallel waveguides.

In analogy to the impurity levels of semiconductors, defect modes will be created within the photonic band gap if irregular regions are introduced into the perfect periodic structures.[15] Also much attention has been paid to PCs with defects. The property of the defect PC can be used as a single-channel or multi-channel filter. Fang *et al.*[16] reported on a high-Q filter-based 1D photonic crystal using single-negative permittivity materials. Chen *et al.*[17] proposed a two-channel filter in 1D photonic crystal with a single-negative material defect. However, little attention was paid to PC filters containing defects with tunable material.

In this paper, we design a tunable PC filter containing two plasma slabs as defects. The plasma defects are the so-called tunable quantum wells. This photonic quantum well structure

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can work as a double pass-band filter in the PBG. By changing the parameters of the plasma, the location of the narrow pass-band of EM wave can be tuned in a frequency region of the EBG.

2. Physical modes and methods

In this paper, the structural configuration can be expressed as $(\mathrm{DV})^m\mathrm{DP}(\mathrm{DV})^n\mathrm{DP}(\mathrm{DV})^m\mathrm{D}$, where D and V denote the dielectric layer and vacuum layer respectively, P represents the plasma slab, and m and n refer to the numbers of the DV layers in the above structure. In this work, ceramic material is chosen to serve as the dielectric layer and its dielectric constant and thickness are $\varepsilon_{\mathrm{D}} = 9$, and $d_{\mathrm{D}} = 0.25a$ respectively. The dielectric constant and thickness of the vacuum layer are $\varepsilon_{\mathrm{V}} = 1$, and $d_{\mathrm{V}} = 0.75a$ respectively, where parameter a is the lattice constant or the space period of 1D PC, and the value of a equals the working wavelength of PC. We consider that this quantum well structure works in the L band of the microwave region, and the value of a is set to be $a = 6$ cm. The plasma slab is dispersive and a loss medium and its effective dielectric constant can be written as

$$\varepsilon = \varepsilon_0 \left(1 - \frac{\omega_{\mathrm{p}}^2}{\omega(\omega - \mathrm{j}\gamma)}\right), \tag{1}$$

where ε_0 is the permittivity of a vacuum, ω is the frequency of the incident EM wave, ω_{p} is the plasma frequency, and γ is the collision frequency of plasma. The value of γ determines the loss of EM wave in the plasma, which is not expected in this system, so a small value $\gamma = 10$ MHz is chosen. Because of $\varepsilon < \varepsilon_0$ in formula (1), we set the thickness of plasma slab $d_{\mathrm{P}} = 1.5a$. In terms of these notations, the structure can be intuitively illustrated in Fig. 1.

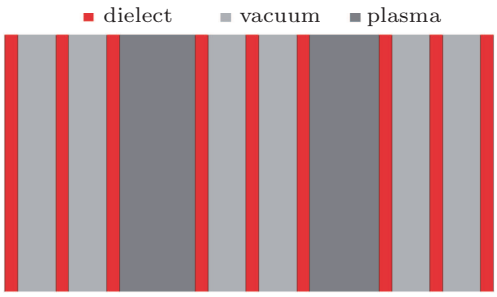


Fig. 1. (color online) 1D plasma QW structure.

The numerical simulation is based on the finite-difference time-domain (FDTD) technique with perfectly matched layer absorbing boundary condition. Although the transfer-matrix method (TMM) is a conventional and efficient method of analyzing 1D PC, it does not take into account the out-of-plane loss, which is the key parameter in a PC cavity. The FDTD method has been proved to be an accurate numerical method of simulating EM wave propagation. In this paper, the conventional FDTD method and the piecewise linear current density recursive convolution (PLCDRC) finite-difference time-domain method[18] are applied to the dielectric and plasma, respectively. In the 1D case, the following PLCDRC–FDTD electric field formulas are used in the program:

$$\begin{aligned} E_x^{n+1}(k) = {} & \frac{2\varepsilon_0}{2\varepsilon_0 + \Delta t\,(\sigma^0 - \zeta^0)} \left[\left(1 - \frac{\Delta t}{2\varepsilon_0}\zeta^0\right) E_x^n(k) \right. \\ & - \frac{\Delta t}{\varepsilon_0} \left(\frac{H_y^{n+0.5}(k+0.5) - H_y^{n+0.5}(k-0.5)}{\Delta z} \right) \\ & \left. - \frac{\Delta t}{2\varepsilon_0}\psi_x^n(k) \right], \end{aligned} \tag{2}$$

$$\begin{aligned} \psi_x^n(k) = {} & (\sigma^0 + \sigma^1 - \zeta^0 - \zeta^1)E_x^n(k) + (\zeta^0 + \zeta^1)E_x^{n-1}(k) \\ & + \mathrm{e}^{-\nu\Delta t}\psi_x^{n-1}(k), \end{aligned} \tag{3}$$

where k denotes the position of the grid in the z direction, n denotes the discrete time step, ε_0 denotes the dielectric constant of a vacuum, Δt denotes the time increment, and Δz is the spatial increment at the neighboring grid point. The other parameters can be seen in Ref. [18]. Magnetic field formulas are the same as those in the conventional FDTD method.

Only the normal incidence case is discussed here. In this case, the TM and the TE polarizations are degenerate. Therefore, TM and TE wave are in the same situation and we select the TEM wave as the incident EM wave source, and it is given by

$$E_x(t) = A(t - t_0)\exp\left(-\frac{(t - t_0)^2}{T^2}\right). \tag{4}$$

It is a differential Gaussian pulse in the time domain, where t_0 is the center position of the Gaussian pulse and T is a time constant. The smaller the constant T, the narrower the pulse width is and the wider the spectrum width is. In this paper, we choose $t_0 = 200\Delta t$ and $T = 40\Delta t$. The constant A in Eq. (4) is related to the amplitude of the incident wave. This incident EM wave source is a wideband source that can be used to analyze the forbidden band and the localization characteristic of PC.

3. Results and discussion

Considering the QW structure, firstly we choose $m = 2$ and $n = 2$. The structure is just as shown in Fig. 1. The reason why we choose $m = 2$ is that it is sufficient to form an EBG structure. The first EBG ranges from 1.17 GHz to 2.15 GHz, and its central frequency is 1.66 GHz. When the plasma frequency is equal to zero, the situation of QW structure is the same as the vacuum case. Figure 2(a) shows the transmission coefficient of the above photonic QW structure versus EM wave frequency. Two sharp peaks can be seen in the figure. Being similar to the case of semiconductor QW structure, the $(\mathrm{DV})^m\mathrm{PC}$ plays a role of barrier, and the P slab can be regarded as a well. We can name these sharp peaks "confined states", which can

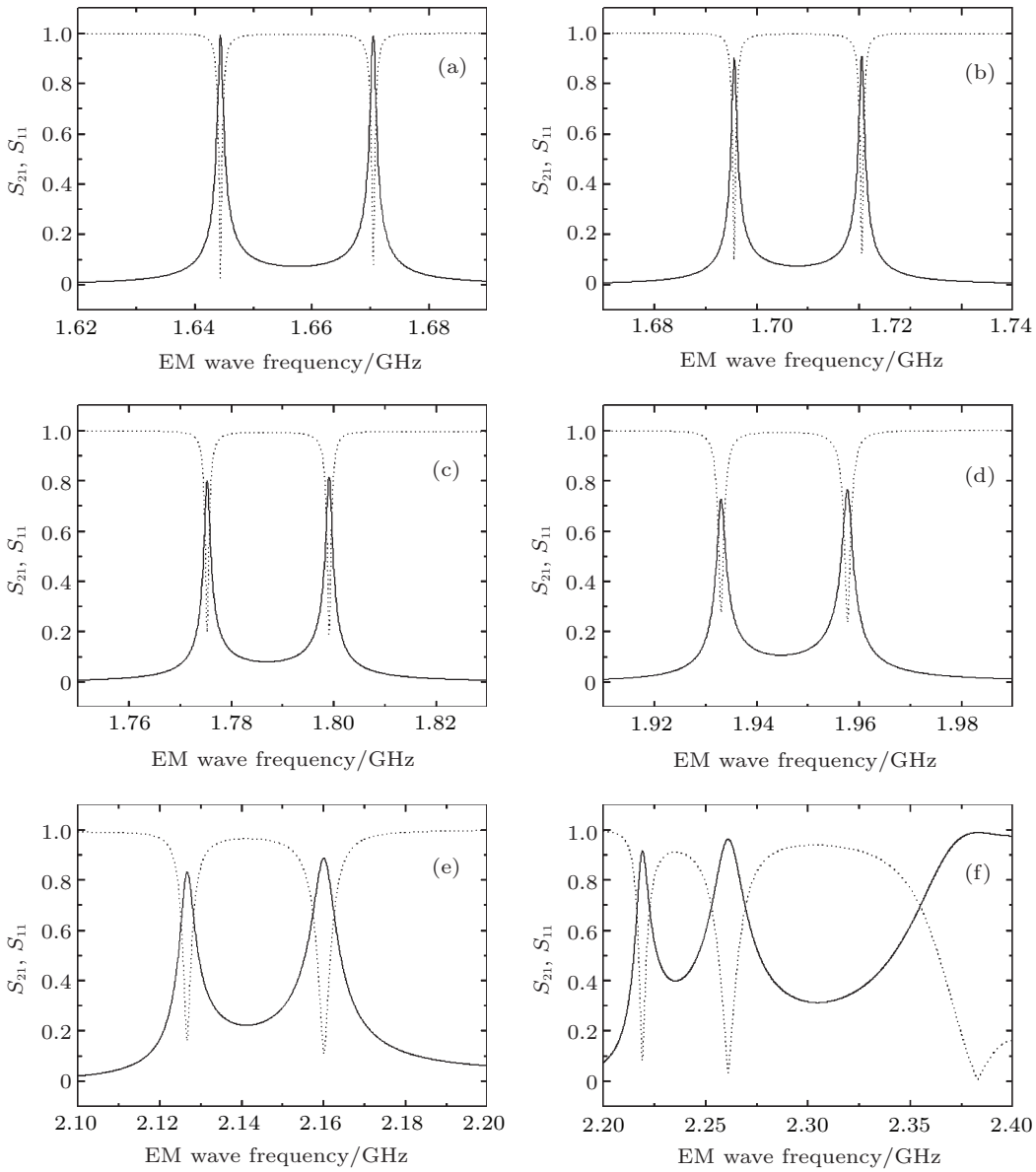


Fig. 2. Reflection/transmission coefficients for $\omega_p = 0$ (a), 0.5 (b), 0.8 (c), 1.2 (d), 1.6 (e), and 1.8 GHz (f) respectively.

be used as a dual-narrowband pass-band filter in the L band of the microwave spectra region. It is interesting to point out that the transmittances of the two confined states are 0.9921 and 0.9914 (close to 1.0) and both of the half-power bandwidths (-3-dB band widths) are 0.001 GHz. The interval between the two peaks of the pass band is about 0.0262 GHz. The two plasma slabs can be seen as a QW system and the confined states can completely transmit through the QW system, because they pass through the structure by resonant tunneling. When the energy of the incident EM wave is in accordance with the confined state of the QW system, the tunneling probability is accessible to 1. On the other hand, the tunneling decreases rapidly to 0 if both of them do not match.

In what follows, when this QW structure is not changed, we increase the plasma frequency by an external electric method. The confined states of the QW system can shift. Figures 2(b)–2(f) show the transmission coefficients versus EM wave frequency for the plasma frequency $\omega_p = 0.5$ GHz, 0.8 GHz, 1.2 GHz, 1.6 GHz, and 1.8 GHz respectively. It can be clearly seen that the confined states are very sensitive to the plasma frequency. In a detailed description, the confined states will shift towards the higher frequency region rapidly if the plasma frequency increases. Owing to this property, this QW structure is used as a tunable dual-narrowband pass-band filter system. But when the plasma frequency is equal to 1.8 GHz, the two peaks will move to the down-edge of the PBG and it is the limit of the tuning. With the increase of plasma frequency, the transmittances of the peaks will decrease, which may be due to the plasma absorption and reflection effect for incident waves, but the peaks still reach -3-dB band widths. The dual resonant channel within the EBG moves to the higher frequency due to the variable property of the double defects.

The higher the plasma frequency, the larger the effective refractive index of plasma and the longer the wavelength of the defect states. The effective refractive index of the plasma slabs is reduced by introducing the plasma frequency, then the optical thickness $\sqrt{\varepsilon}d_{\rm P}$ decreases and the wavelength of the confined wave shortens, which causes the confined states to shift towards a higher frequency. What is more, it can be clearly observed that the interval between the two peaks remains unchanged (about 0.026 GHz) because the frequency interval is determined by the space interval between the two QWs. In other words, the smaller the value of n, the larger the frequency interval. On the other hand, the offset of the double pass-bands is not proportional to the increase of plasma frequency. The reason is that the optical thickness value of the P slab varies nonlinearly with the plasma frequency.

The central frequency of the dual transmission peak only depends on the plasma frequency, so all the dual transmission channels in Fig. 3 are symmetrically located at both sides of the same central frequency due to the unchanged plasma frequency.

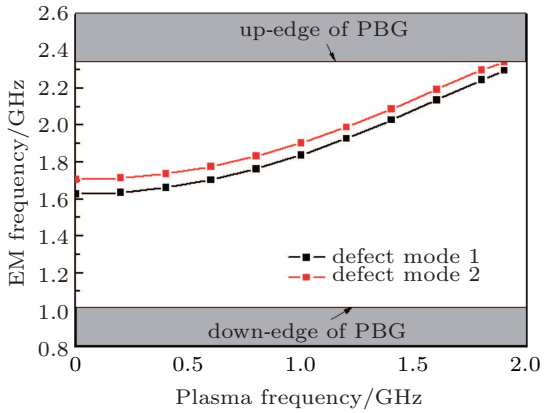


Fig. 3. (color online) Dependences of wave frequency peak on plasma frequency for two defect models.

In order to observe the resonant EM wave pass through the QW structure, we select the continuous wave as an incident source. Figures 4(a)–4(b) have given the tunneling wave and declining wave shape in the z direction for $\omega_{\rm p} = 0$ and $\omega_{\rm p} = 0.8$ GHz. Figure 5 shows the electric energy distribution in the QW structure with the continuous incident wave frequency $f = 1.6443$ GHz. It shows the resonant peak of the first pass-band when the quantum well is a vacuum (or the plasma frequency is zero). It can be seen that the QWs are confined in a very large electric energy and then the resonant wave jumps out of the QW system.

Next, in order to observe the interaction between the two plasma quantum wells, we reduce the space interval between the double QWs and set $n = 1$. Figure 6(a) shows the transmission and reflection coefficients versus the incident EM wave frequency when the plasma frequency is equal to zero, the transmittances of the resonant peaks are up to 0.99738 and 0.99716 and both of the −3-dB band widths are about 0.0008 GHz. The frequency interval is obviously larger than that of above modes (0.0262 GHz) and it is 0.0789 GHz. Figures 6(b)–6(d) show the transmission and reflection coefficients versus incident EM wave frequencies for $\omega_{\rm p} = 0$, 0.5, 1.2, and 1.6 GHz respectively. The resonant peaks can move to the higher frequency region for which the physical explanation is the same as that for the above structures. When the plasma frequency is equal to 1.6 GHz, the resonant peaks are close to the down-edge of the EBG.

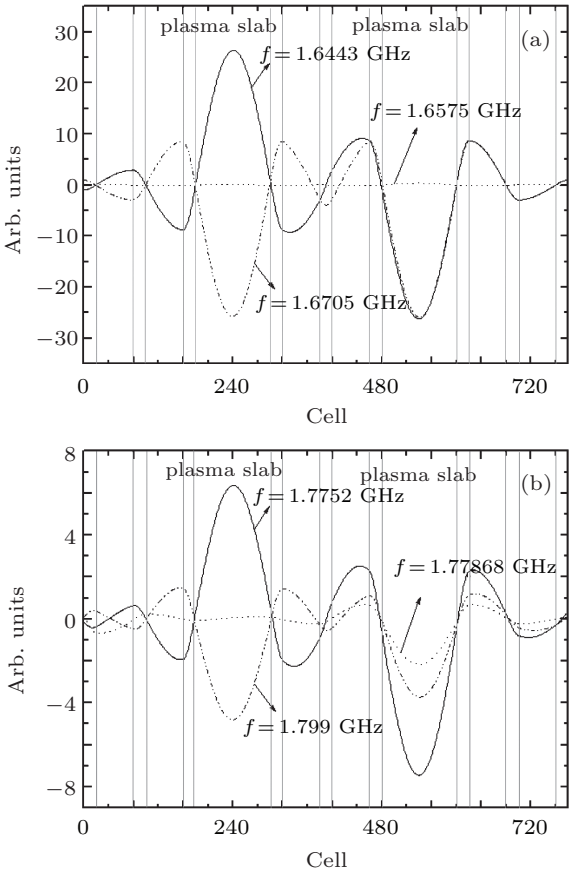


Fig. 4. Continuous wave shapes for (a) $\omega_{\rm p} = 0$ and (b) $\omega_{\rm p} = 0.8$ GHz.

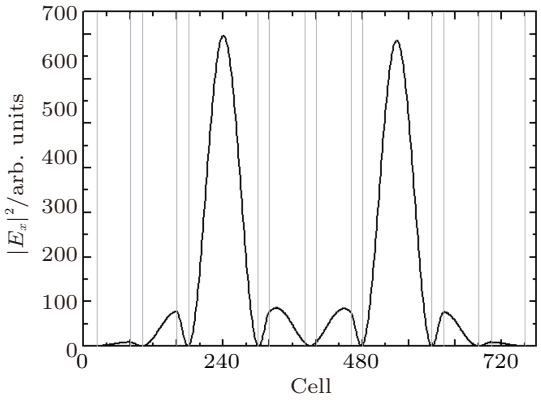


Fig. 5. Electric energy distribution ($f = 1.6443$ GHz).

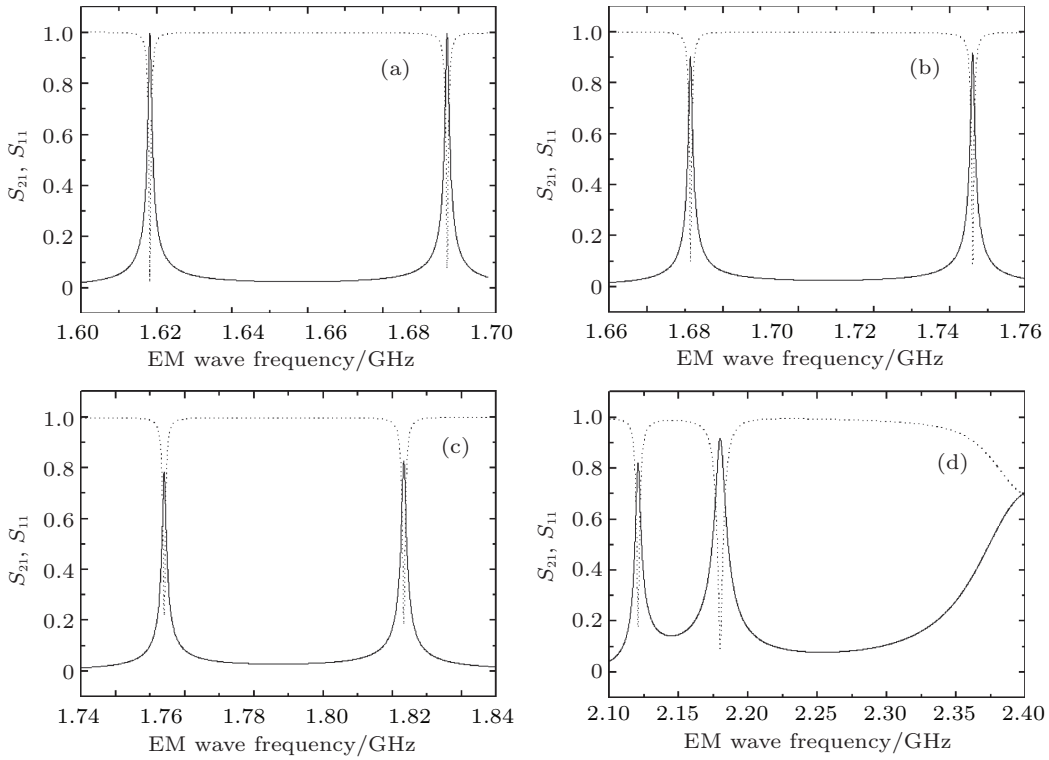


Fig. 6. Reflection/transmission coefficients versus EM wave frequency for $\omega_p = 0$ (a), 0.5 GHz (b), 0.8 GHz (c), and 1.6 GHz (d) respectively.

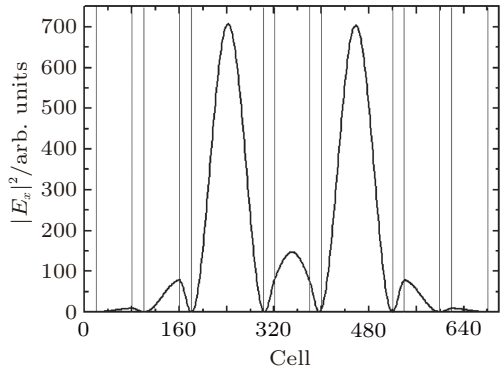


Fig. 7. Electric energy distribution ($f = 1.6181$ GHz).

4. Conclusion

In this paper, 1D photonic QW structures with alternatively stacked dielectric-vacuum layers and double plasma slabs as defects are suggested. By using FDTD simulation, the result shows two narrowband pass-bands in the EBG region. Thus, this QW structure can be used as a dual-narrowband pass-band filter in the L band of the microwave region. The pass-bands can be tuned by increasing the plasma frequency in the EBG under the condition of not changing the structure. In the other case, the pass-band interval and the −3-dB band width of pass-bands are related to the space interval between double plasma QWs.

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