Study of photonic quantum well structures containing negative-index materials

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Abstract

The properties of photonic quantum well structures composed of the photonic crystals containing positive/negative-index materials and the defect of negative-index materials are experimentally studied. Photonic quantum well structures are experimentally fabricated by transmission lines loaded with series capacitor and shunt inductor. It is found that the number of the tunneling modes can be tuned by adjusting the thickness of negative-index materials in the well. Simultaneously, we also analyze the variance of the frequency for tunneling modes when the capacitance and inductance of negative-index materials are changed.

1. Introduction

In 1970, Esaki and Tsu first presented the structures of semiconductors quantum well structures (SQWS) [1]. In it the wave functions of electrons are considerably modified due to the quantum confinement effects, and the electronic energies are quantized. Simultaneously, the quantum confinement leads to many new physical phenomena that do not exist in the usual semiconductors. Similarly, the photonic quantum wells structures (PQWS) can also be constructed provided that the band gaps of the constituent photonic crystals are aligned properly [2-7]. For example, Qiao et al proposed a PQWS composed of different photonic crystals with positive-index materials. It is found that the number of the tunneling modes can be tuned by adjusting the period number of the photonic crystal in the well region, leading to the phenomena of multiple channelled filtering [4]. Xiang and Chen investigated the hetero-structure composed of containing single-negative materials for multiple channelled filtering. Their simulation results show that when the average permittivity and average permeability of the whole structure are equal to zero, there will be a quantity of tunneling modes appeared which are insensitive to incident angles. But the number of tunneling modes in these structures cannot be accurately controlled by adjusting the periods of photonic crystals, and the tunneling modes usually appear in pairs [5,6]. Recently, PQWS containing negative-index materials and positive-index materials have been proposed in reference [7]. Moreover, simulation results have also been given that the number of these tunneling modes is the same as the periods of photonic crystals in the well and these modes are insensitive to the incident angle.

In this paper, we propose a type of PQWS composed of the photonic crystals containing positive/negative-index materials and the defect of negative-index materials.

2. Photonic quantum well structures

We consider the PQWS with the form of $(AB)^M(D)^N(AB)^M$. Where $(AB)^M$ denotes photonic barriers, $(D)^N$ acts as a defect, A and D are negative-index materials, B is positive-index materials. M and N are the corresponding number of periods. The thickness of A, B and D are expressed as d_a, d_b and d_d, respectively. If the average index of A and B is equal to zero, a special band gap appears in specific frequency range, called zero-average-index gap (zero-$\bar{n}$ gap). Suppose that negative-index materials $(D)^N$ defect into the zero-average-index photonic crystals the defect mode appeared which is

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insensitive to the incident angles [8]. Then the PQWS be fabricated. The schematic representation of the PQWS is shown in Fig.1.

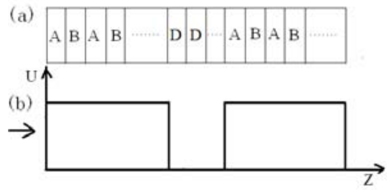

Fig.1: Schematic representation of the photonic quantum well structures. a. Fabricated with photonic crystal and defect. b. Energy band structure of the quantum well.

Negative/positive-index materials are assembled by LC-loaded transmission lines [9]. According to the method of transfer matrix [10], one can calculate the transmission coefficient of the wave passing through this structure.

3. Results

The PQWS were physically fabricated by means of LPKE-H100 circuit board plotter machine. The properties of the transmission spectra are measured by an Agilent N5320C PNA vector network analyzer. The positive-index materials are assembled by traditional transmission lines with width w=2.945mm and thickness d_b=6mm [11]. For the parameters of the negative -index materials A and D are L_a=5.6nH, C_a=1pF, d_a=6mm, L_d=1.2nH, C_d=1pF and d_d=12mm. The transmission response is given by the scattering parameter S_{21} when M=3 and N=1 or 3, as shown in Fig.2. In Fig.2 (a) one can see that the tunneling mode appear in the frequency f=1.608 GH. Corresponding, experimental data show that the frequency of tunneling mode is f=1.825GHz. The frequency shift is mainly caused by the dispersion characteristics of the real materials and loaded elements. And the loss of the materials leads to the lower transmissivity. While the periods of the layer D increased, we find that the numbers of tunneling modes are enlarged. And it equal to N, as shown in Fig.2 (b). One can see that the numbers of tunneling modes is 3 when N=3, whose corresponding frequency is 1.347, 1.551 and 1.848 GHz, respectively.

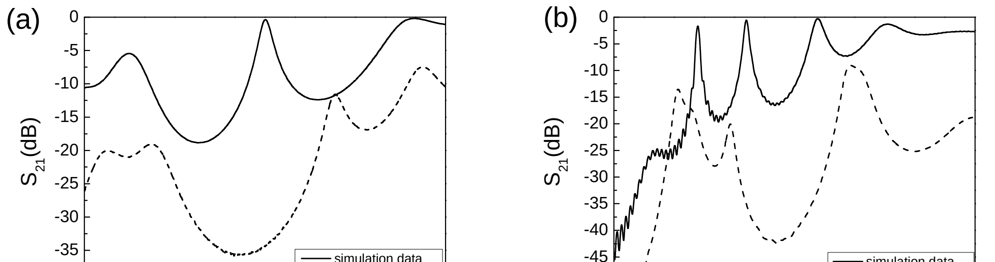

Fig.2: Transmission spectra S_{21} for $(AB)^3(D)^N(AB)^3$ PQW. (a) N=1;(b)N=3.The solid curves correspond to simulation data and the dashed curves correspond to experimental data.

Finally, we discuss the frequency variance of the tunneling modes as the effective relative permeability and effective relative permittivity of the layer D. The variances of the frequency for tunneling modes are shown in Fig.3. The results show that the frequency of tunneling modes reduces with the increase of the loaded series-capacitance and shunt-inductance. The detail explanation is as follows: (a) The effective relative permeability and effective relative permittivity increased while increasing the loaded series-capacitance and shunt-inductance; (b) The absolute value of effective index reduced because of the negative effective relative permeability and effective relative permittivity. (c) For the same optical path length, the frequency will reduce due to match the tunneling modes.

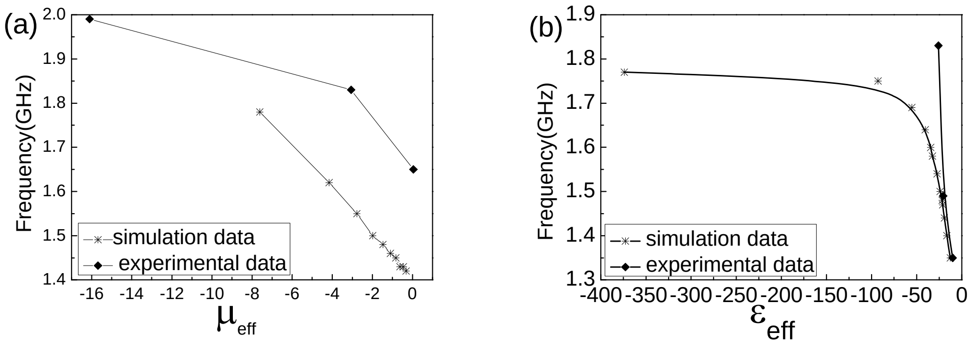

Fig.3: Variance of the frequency of the tunneling modes with permeability and permittivity.

4. Conclusion

In summary, we experimentally investigated the properties of photonic quantum well structures composed of the photonic crystals containing positive/negative-index materials and the defect of negative-index materials. We found that the number of the tunneling modes is the same as the periods of the negative-index materials D in well. The frequency of tunneling modes reduced with the increase of the loaded series- capacitance and shunt-inductance.

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