The Magnetic Control Tunable Characteristics of Localized Modes of One-dimensional Cantor Quasicrystal Structure Containing Nanoparticle Magnetic Fluid

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Abstract. The magnetic control tunable characteristics of localized modes of One-dimensional Cantor quasicrystal structure containing nanoparticle magnetic fluid is studied by using the transfer matrix method. First, the physical model of One-dimensional Cantor quasicrystal structure containing nanoparticle magnetic fluid is built. Then, the transmission spectrum of One-dimensional Cantor quasicrystals structure containing nanoparticle magnetic fluid is calculated by transfer matrix method. Finally, the magnetic control tunable characteristics of localized modes are discussed. The results show that the generation of One-dimensional Cantor quasicrystal structure containing nanoparticle magnetic fluid increased, the number of localized modes increased as well; the wavelength of localized modes shift to the long-wave direction with the refractive index of magnetic fluid increasing; the higher generation, the higher of the quality factor of the split localized modes; the wavelength drift variation decreases with the increasing of localized modes level at the same generation.

Introduction

In 1984, Shechtman and others published the report about the study of quasicrystal for the first time [1]. It has attracted the attention of researchers widely and become the research hotspot of materials science [2]. Quasicrystal structure belongs to aperiodic structure between periodic structure and disordered structure from the structural features. Compared to periodic structure, aperiodic structure has no translation symmetry; Compared to disordered structure, aperiodic structure is the ordered and certainty system. Quasiperiodic structure is a particular aperiodic structure such as Fibonacci, Cantor and Thue-Morse [2], etc.

Scientists are interested in Cantor quasiperiodic structure, because it is a typical quasiperiodic structure. The Cantor sequence can be given by the recursive rule: $S_n = S_{n-1}B_nS_{n-1}, B_n = 3^{n-1}B_1\left(n \geq 1, B_1 = B\right)$. Starting with S_0=A, the Cantor generations are S_0=A, S_1=ABA, S_2=ABAB^{3}ABA and S_3=ABAB^{3}ABAB^{9}ABAB^{3}ABA [2].

Photonic crystal containing nanoparticle magnetic fluid is a kind of tunable photonic crystal [3, 4]. The photonic crystal containing nanoparticle magnetic fluid has attractive application prospect on the new magnetron tunable photonic devices, causing the attention of scholars at home and abroad, and it has become a hot spot in the field of the new tunable photonic crystals because of the non-contact magnetic control adjustable features. The magnetic field control characteristics of photonic crystal fiber are studied by some scholars. The magnetic field sensor is made. For example, the research team of Nanyang technological university in Singapore fills the nanoparticle magnetic fluid of higher refractive index (>1.45) in the hollow of magnetic photonic crystal fiber, based on the band gap effect of the photonic crystal fiber with magnetic fluid which studies the magnetic fiber optic sensor [5]. The colloid ferrofluid as primitive materials of one-dimensional photonic crystals by the team of Ji-ping Huang at Fudan University, which the magnetic control of one-dimensional photonic crystals is studied based on colloid ferrofluid[6,7]. The temperature tunable characteristics of photonic crystal fiber which filled with Fe_3O_4 nano-particle is studied by the researcher of Nankai University [8]. The hollow photonic crystal fiber Fabry - Perot sensor based on magnetic fluid of measuring magnetic field and photonic crystal fiber Bragg grating sensor filled with the magnetic fluid are studied by the researcher of Northeastern University [9-11]. In 2014, Design of multichannel filters based on the use of periodic Cantor dielectric One-dimensionals is studied by Tzu-Chyang King and others [12]. Zero measure Cantor spectra for continuum one-dimensional quasicrystal is studied by Daniel Lenz at the same year [13].

However, there are few reports about the study of One-dimensional Cantor quasicrystal structure containing nanoparticle magnetic fluid. The magnetic control tunable characteristics of localized modes of One-dimensional Cantor quasicrystal structure containing nanoparticle magnetic fluid is studied in this paper. First, the physical model of One-dimensional Cantor quasicrystal structure containing nanoparticle magnetic fluid is built. Then, the transmission spectrum of One-dimensional Cantor quasicrystal structure containing nanoparticle magnetic fluid is calculated by transfer matrix method. Finally, the magnetic control tunable characteristics of localized modes is discussed, it has certain guiding significance for the photonic devices such as optical switch, filter in theory.

Physical Model

The third generation, fourth generation and fifth generation structures of One-dimensional Cantor quasicrystal structure containing nanoparticle magnetic fluid are $S_2=ABAB^3ABA$, $S_3=ABAB^3ABAB^9ABAB^3ABA$ and $S_4=ABAB^3ABAB^9ABAB^3ABAB^{27}ABAB^3ABAB^9ABAB^3ABA$. A is Si dielectric layer that refractive index is $n_a = 3.42$, and B is dielectric layer of magnetic fluid.

The Results of Numerical Calculation

The Primitive materials of One-dimensional Cantor quasicrystal structure containing nanoparticle magnetic fluid are Si and water-based Fe_3O_4 magnetic fluids, the optical thickness is equal to it $n_a * d_a = \overline{n_b} * d_b = \lambda_0 / 4$, λ_0 is the center wavelength. The refractive index n_b of magnetic liquid is related to the distribution of magnetic particles of magnetic liquid closely. There are many factors that have influence on the distribution of the magnetic particles in magnetic fluids such as the magnetic dipole interaction between particles, the Brownian motion of particles which is closely related to the temperature, extra magnetic field, capture light, etc. When the room temperature is 20 °C, wavelength of light source is 1550 nm, density of water-based Fe_3O_4 magnetic fluids is 1.2 g/mL, the variation range of the extra magnetic field intensity is from 0 0e to 1661 0e, the refractive index n_b of magnetic liquid decreases from $n_{bh} = 1.447$ to $n_{bl} = 1.425$ with the increasing of magnetic field intensity. Here, water-based Fe_3O_4 magnetic fluid is selected as the primitive materials of photonic crystals.

The refractive index of dielectric layers A and B are n_a, n_b and its thickness are d_a, d_b respectively. Making the light wave to incident on the surface of One-dimensional Cantor quasicrystal structure containing nanoparticle magnetic fluid. The formulae which the light reflection coefficient and transmission coefficient are calculated by the transfer matrix method are[14]

$$t = \frac{2n_0}{n_0(m_{11} + n_{N+1}m_{12}) + (m_{21} + n_{N+1}m_{22})} \tag{1}$$

$$r = \frac{n_0(m_{11} + n_{N+1}m_{12}) - (m_{21} + n_{N+1}m_{22})}{n_0(m_{11} + n_{N+1}m_{12}) + (m_{21} + n_{N+1}m_{22})} \tag{2}$$

where m_{ij} is the matrix elements of M

$$M_b = \begin{pmatrix} \cos\delta_b & -\frac{i}{\eta_b}\sin\delta_b \\ -i\eta_b\sin\delta_b & \cos\delta_b \end{pmatrix} \tag{3}$$

The reflectance R and the transmittance T respectively are

$$R = |r|^2$$
$$T = |t|^2 \tag{4}$$

Taking the parameters $n_a = 3.42$, $n_{bl} = 1.425$, $n_{bh} = 1.447$, $\bar{n}_b = 1.4385$, $n_a * d_a = \bar{n}_b * d_b = \lambda_0 / 4$, the $\lambda_0 = 1550nm$ is the center wavelength. The third, fourth and fifth generation transmission spectrum of One-dimensional Cantor quasicrystal structure containing nanoparticle magnetic fluid are calculated by transfer matrix method when the refractive index of magnetic liquid changes with the intensity of magnetic field, results are shown in figure 1(a), figure1(b) and figure1(c).

The results of figure 1 show that: there are localized modes on the transmission spectrum of the third, fourth and fifth generation One-dimensional Cantor quasicrystal structure containing nanoparticle magnetic fluid in the band gap (from 1130nm to 2400nm), and the number of localized modes are 2, 4, and 8 respectively, the number of localized modes within a certain band gap increased with the generation of One-dimensional Cantor quasicrystal structure containing nanoparticle magnetic fluid increasing. From the transmission spectrum diagram of the third and fourth generation can be found that one localized mode is split out from both sides of each localized modes of the third generation respectively, and the localized mode also can be split out from the localized modes within the band gap respectively from the fourth generation to the fifth generation.

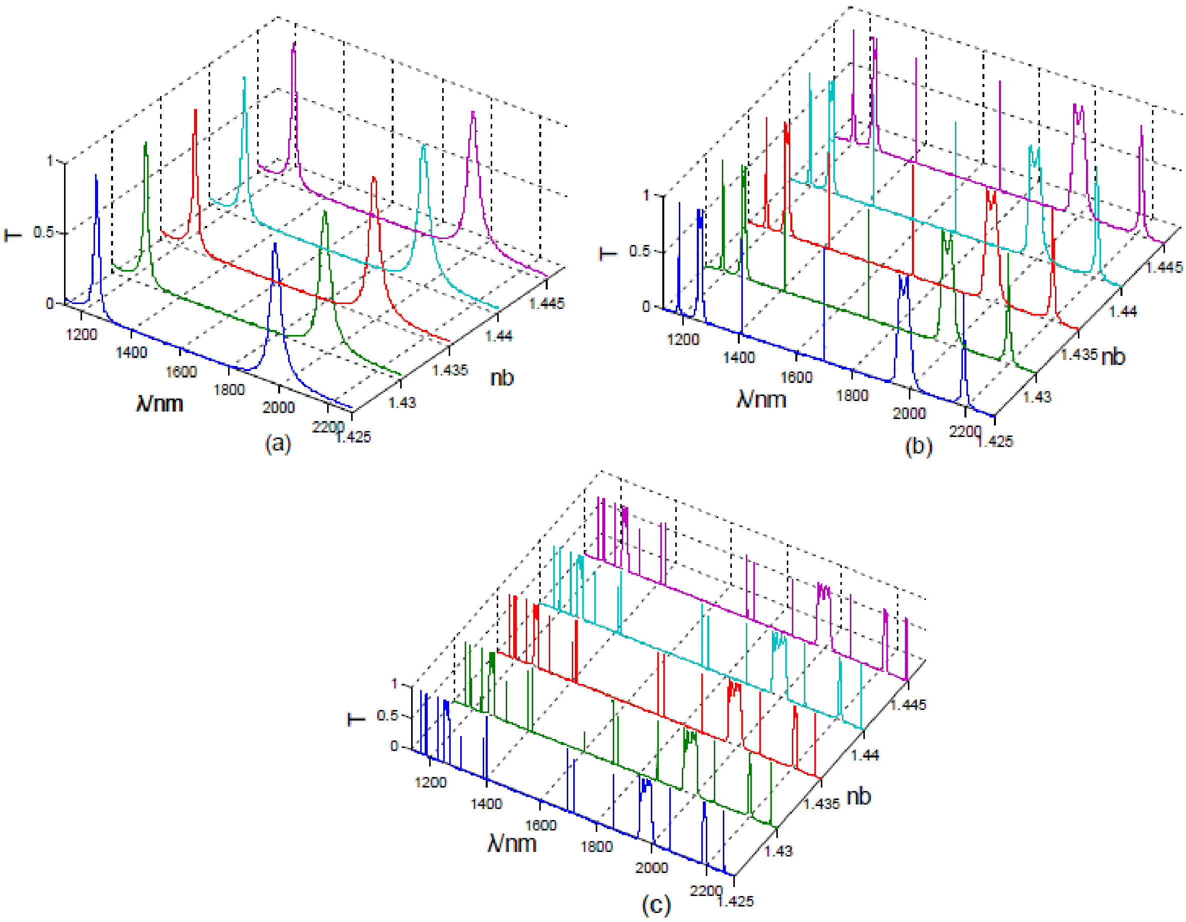

Figure1. The third, fourth and fifth generation transmission spectrum of One-dimensional Cantor quasicrystal structure containing nanoparticle magnetic fluid

The quality factor of localized modes is defined as $Q = \lambda / \Delta\lambda$, where λ is the center wavelength of localized modes, $\Delta\lambda$ is the bandwidth of the half peak. The quality factor of localized modes λ_1 and λ_2 (the localized modes in the middle)of fourth and fifth generation are calculated by the table 1 and table 2 which show that the higher generation of One-dimensional Cantor quasicrystal structure containing nanoparticle magnetic fluid, the higher of the quality factor of the split localized modes; the quality factor of localized modes decreases with the refractive index of magnetic fluid increasing at the same generation of One-dimensional Cantor quasicrystal structure containing nanoparticle magnetic fluid.

Table 1 The quality factor of fourth generation localized modes

n_b	λ_1/nm	$\Delta\lambda$/nm	Q	λ_2/nm	$\Delta\lambda$/nm	Q
1.425	1407.27	0.36	3909.08	1699.20	0.51	3331.76
1.430	1411.82	0.37	3815.73	1704.36	0.53	3215.77
1.435	1416.37	0.38	3727.29	1709.50	0.55	3108.18
1.440	1420.91	0.39	3643.36	1714.63	0.57	3008.12
1.445	1425.46	0.40	3563.65	1719.76	0.60	2866.27

Table 2 The quality factor of fifth generation localized modes

n_b	λ_1/nm	$\Delta\lambda$/nm	Q	λ_2/nm	$\Delta\lambda$/nm	Q
1.425	1392.42	0.007	198917.14	1719.50	0.012	143291.67
1.430	1397.15	0.008	174643.75	1725.21	0.013	132708.46
1.435	1401.88	0.009	155764.44	1730.93	0.014	123637.86
1.440	1406.60	0.010	140660.00	1736.64	0.015	115776.00
1.445	1411.32	0.011	128301.82	1742.35	0.016	108896.88

When the refractive index n_b of magnetic liquid increases from 1.425 to 1.445 and the One-dimensional Cantor quasicrystal structure containing nanoparticle magnetic fluid within the band gap(from 1130nm to 2400nm) ,the wavelength of the third generation localized modes drift from 1260nm and 1986nm to 1274nm and 2003nm respectively, the drift variation of localized modes are 14nm and 17nm; the wavelength of the fourth generation localized modes drift from 1186nm, 1407nm,1699nm and 2194nm to 1201nm, 1425nm, 1720nm and 2219nm respectively, the drift variation of localized modes are 15nm, 18nm, 21nm and 25nm; the wavelength of the fifth generation localized modes drift from 1166nm, 1227nm,1313nm, 1392nm, 1719nm, 1858nm, 2066nm and 2265nm to 1181nm, 1243nm, 1331nm, 1411nm, 1742nm, 1882nm, 2092nm and 2294nm respectively, the drift variation of localized modes are 15nm, 16nm, 18nm, 19nm, 23nm, 24nm, 26nm and 29nm. Accordingly, the wavelength of localized modes shift to the long-wave direction with the refractive index of magnetic fluid increasing; the wavelength drift variation decreases with the increasing of the localized modes level at the same generation (the level of λ_1 > the level of λ_2).

Conclusion and Discussion

The transmission spectrum of One-dimensional Cantor quasicrystal structure containing nanoparticle magnetic fluid is calculated by transfer matrix method. The results show that the number of localized modes increases with the generation of One-dimensional Cantor quasicrystal structure containing nanoparticle magnetic fluid increasing; From the transmission spectrum diagram of the third and fourth generation can be found that one localized mode is split out from both sides of each localized modes of the third generation respectively, and the localized mode also can be split out from the fourth generation to the fifth generation; however, the localized modes of the third generation always can appear on the transmission spectrum of the fourth and the fifth generation, the new split localized modes is always based on the localized modes of previous generation, because all of them include the fixed structure of ABABBB; the quality factor of split localized modes gets higher when the generation of One-dimensional Cantor quasicrystal structure containing nanoparticle magnetic fluid increased, we can get that the next generation structure include the double structure of the previous generation from the recursive rule: $S_n = S_{n-1}B_nS_{n-1}, B_n = 3^{n-1}B_1(n \geq 1, B_1 = B)$, that makes the photon can have more time to accumulate and interaction in photonic crystals, so the quality factor gets higher; but the quality factor of localized modes decreases with the refractive index of magnetic fluid increasing at the same generation, because the refractive index of magnetic fluid is close to the refractive index of A dielectric layer with the refractive index of magnetic fluid increasing , the difference of refractive index between the two dielectric layers is smaller, so the quality factor gets lower; it has certain guiding significance for the photonic devices such as optical switch, filter in theory. The wavelength of the localized modes shift to the long-wave direction with the refractive index of magnetic fluid increasing, because the light can transmit stably in the crystal of quasiperiodic structure that must abide the standing-wave conditions $nd = k\lambda$, n is the refraction index of dielectric layer and d is the thickness, so the wavelength λ of localized modes increases with the refractive index n of defect layer increasing for the same level of localized modes (k is certain) when the thickness d is certain. The number of localized modes in fifth generation are more and the distribution are dense especially the localized modes on both sides of the band gap, the quality factor is high,that has certain guiding significance for making multi-channel filter in theory.

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