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Control of Radiation Characteristics of a Micro Random-laser

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Abstract: To control the radiation characteristics of random laser effectively, the random medium nano-cluster was put in a photonic crystal (PC). The finite difference time domain (FDTD) method was used to simulate its radiation characteristics after it was placed in the air and in the PC. The results show that if the cluster is put in the air, the radiation energy decreases gradually after being excited, and its emission spectra take on spontaneous emission characteristics. However, when the cluster is introduced into a PC, some spontaneous emission spectral peaks will drop off, one of which will leave and grow in intensity rapidly. Finally, it becomes the strongest single spectral peak. Therefore, if a random gain system is able to be put into a matching ordered system, the light can be confined and the spontaneous emission can be forbidden.

Key words: Finite Difference Time Domain Method (FDTD); Photonic crystal; Amorphous cluster; Radiation characteristics

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0 Introduction

In the last two decades, several types of micro-laser were developed. The key issue for a micro-laser is to confine light in a small volume with dimensions in the order of optical wavelength. In the vertical cavity surface emitting laser, light is confined by two distributed Bragg reflectors[1-2]. The micro-disc laser utilizes total internal reflection at the edge of a high-index disc to form whispering-gallery modes[3-4]. In the 2D photonic band-gap defect mode laser, light confinement is realized through Bragg scattering in a periodic structure[5-6]. However, the fabrication of these conventional micro-lasers requires expensive crystal growth and nanofabrication facilities.

In 2000, Cao′s group first observed lasing action in a micrometer-sized ZnO cluster which was called micro random-laser[7]. The size of the cluster was about 1.7 μm. It contained roughly 20 000 ZnO nanoparticles. They demonstrated that the optical confinement in this cluster is not caused by light reflection at the surface but by scattering inside the cluster. The light can be localized in the cluster through the process of multiple scattering and wave interference. In other words, the Anderson localization of light provides a physical mechanism for optical confinement of the micro-laser. And its low cost, small size, flexible shape, and substrate compatibility can lead to many potential applications. It is expected to substitute the conventional micro-lasers generated by reflection in mirrored cavities[8-9].

However, the threshold of this type of micro random laser is very high. To reduce the threshold, Zacharakis explored the two-photon pumping method in 2002[10]. He thinks the weak two-photon absorption allows deeper penetration of the pump light into the random medium, and results in better confinement of the emitted light. And Cao′s group has put forward another scheme: incorporating some degree of order into an active random medium. They have numerically simulated the lasing in a random system with a variable degree of order. When disorder is introduced into a perfectly ordered system, the lasing threshold is reduced. The lasing threshold reaches a minimum

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at a certain degree of disorder[11]. There exists an optimum balance of order/disorder for lasing, where the lasing threshold is comparable to the threshold of a single-defect photonic band-gap laser.

Spontaneous emission is the most important phenomenon in laser materials. The energy loss caused by it is a limitation to the luminescence capability of laser devices[5,12-14]. Photonic crystals (PCs) can have effects on some optical characteristics, such as modulating the electromagnetic modes and decreasing light group velocity[15-18]. The low group velocity can cause some unique optical phenomena, such as generating sum-frequency light and enhancing the effective gain. The increase of the effective gain should reduce the lasing threshold. If PC can be introduced into random laser system, the spontaneous emission can be controlled and be led to the target frequency in the emission spectra[19].

From experiments we known there contains many ZnO crystallite nanoparticles in an amorphous ZnO cluster and the nanoparticles arrange disorderly. In this paper, radiation characteristics of an amorphous cluster in different background are numerically simulated by using the finite difference time domain (FDTD) method.

1 Physical model

We consider a 2D transverse magnetic (TM) field. The Maxwell's equations for passive media can be expressed as

$$\frac{\partial E_z}{\partial x}=\mu\frac{\partial H_y}{\partial t},\ \frac{\partial E_z}{\partial y}=\mu\frac{\partial H_x}{\partial t},\ \frac{\partial H_y}{\partial x}-\frac{\partial H_x}{\partial y}=\varepsilon(\lambda)\frac{\partial E_z}{\partial t} \tag{1}$$

Where ε and μ are the electric permittivity and the magnetic permeability of medium, respectively.

With a perfectly matched layer (PML) absorbing condition in order to model the open system, it can be listed as the follows

$$H_x^{n+1/2}(i,j)=H_x^{n-1/2}(i,j)-\frac{\Delta t}{\mu}\frac{E_z^n(i,j+1/2)-E_z^n(i,j-1/2)}{\Delta y} \tag{2a}$$

$$H_y^{n+1/2}(i,j)=H_y^{n-1/2}(i,j)-\frac{\Delta t}{\mu}\frac{E_z^n(i+1/2,j)-E_z^n(i-1/2,j)}{\Delta x} \tag{2b}$$

$$E_z^{n+1}(i,j)=E_z^n(i,j)-\frac{\Delta t}{\varepsilon(i,j)}\left[\frac{H_x^{n+1/2}(i,j+1/2)-H_x^{n+1/2}(i,j-1/2)}{\Delta y}-\frac{H_y^{n+1/2}(i+1/2,j)-H_y^{n+1/2}(i-1/2,j)}{\Delta x}\right] \tag{2c}$$

Where Δx, Δy is the space increments in x, y directions and the Δt is the time increment.

We introduce complex dielectric constant to describe the optical gain and absorbance for media. The dielectric constant function can be expressed as $\varepsilon=\varepsilon_{\mathrm{real}}+\mathrm{i}\varepsilon_{\mathrm{im}}$, and where the real part $\varepsilon_{\mathrm{real}}$ is the ordinary dielectric constant and the imaginary part $\varepsilon_{\mathrm{im}}$ indicates amplification when $\varepsilon_{\mathrm{im}}(\lambda)<0$ or absorbance when $\varepsilon_{\mathrm{im}}(\lambda)>0$. The spectral gain profile of the medium can be expressed by the Gaussian function $\varepsilon_{\mathrm{im}}=c_0\exp\left[-\frac{(\lambda-\lambda_0)^2}{(2\Delta\lambda)^2}\right]$. Where λ represents the light wavelength, λ_0 is the gain-centered wavelength, $\Delta\lambda$ is the half-width at half maximum of gain spectrum, c_0 the parameter related with pump light intensity.

We introduce an arbitrary amplitude short pulse Gaussian light on the center of a random gain medium as a pumping source to excite the random medium. For its excitation, the stimulated emission appears and the light can be expressed as

$$E=\cos\omega t\exp\left[-\left(\frac{t-t_0}{\tau}\right)^2\right] \tag{3}$$

With the light scattering, stimulated emission happens wherever the pumping source has traveled. We simulate the real-time energy distribution by use of FDTD. Because the dielectric constant is correlated with wavelength λ, there are different energy distributions correspond to the different wavelength respectively. The total energy spatial distribution contains all the different energy distributions. In order to obtain the radiation spectrum, the output of energy in time-domain must be transformed into frequency-domain. We use the fast Fourier transform (FFT) to obtain the spectra.

2 Numerical simulation

We assume there is an amorphous cluster of which size is about 6 μm and in the cluster there contains many hexagon crystallite particles. The size of the crystalline particles is about 450 nm. Firstly we put the cluster in air. The configuration is shown in Fig. 1. The parameters of the cluster are considered as: the particle-filling fraction $\varphi_1=60\%$, the dielectric constant of the particles is expressed as

$$\varepsilon_a=\varepsilon_{a_1}+\mathrm{i}c_0\exp\left[-\frac{(\lambda-\lambda_0)^2}{(2\Delta\lambda)^2}\right] \tag{4}$$

Where $\varepsilon_{a1}=5.4$, $c_0=-0.03$, $\lambda_0=450.0$ nm, $\Delta\lambda=25.0$ nm, the dielectric constant of background medium in the cluster $\varepsilon_b=2.75$. And the dielectric

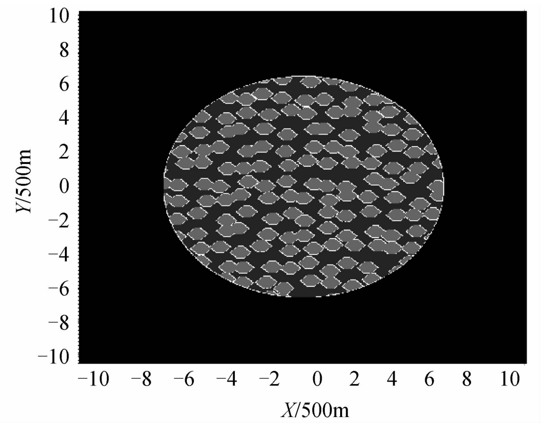
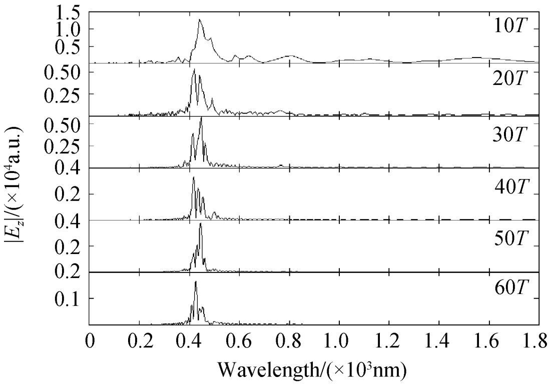


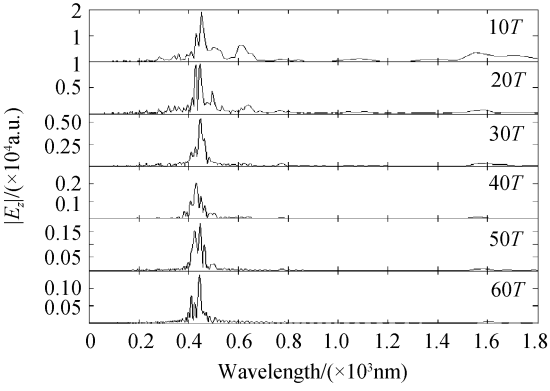
Fig. 1　The configuration of an amorphous ZnO cluster in air

constant of air $\varepsilon_c=1$.

The space and time increments are chosen to be $\Delta x=\Delta y=10$ nm, $\Delta t=2.357\times10^{-17}$ s, and the continual pumping time to be $T=500\Delta t$. We have probed the emission light in the center region and top region, and applied FFT to obtain the emission spectra. The results are displayed in Fig. 2, where Fig. 2(a) represents the spectra from the center region at $t=10T$, $20T$, $30T$, $40T$, $50T$ and $60T$ respectively and Fig. 2(b) represents those from the top region.



(a) The center region



(b) The top region

Fig. 2　The spectra from the center region and the top region of the system shown in Fig. 1

Comparing Fig. 2(a) with (b), the spectra of top region are slightly weaker than the center region. Anyhow, both the spectral peaks of the top region and center region are about 450 nm and the spectral configurations take on the characteristics of spontaneous emission. With increasing time, the spectral configurations do not change considerably, but the spectral intensity reduces slowly. So the laser action can be excited only when the stimulated source is strong enough, that is, a higher lasing threshold is required in this system.

To investigate the effect of an ordered system background, we put the cluster into a square PC, which is characterized by the particle-filling fraction $\varphi_2=50\%$, $\varepsilon_c=2.5$, and $\varepsilon_d=11.9$, where ε_c is its dielectric constant of columns, ε_d is the dielectric constant of background medium in the PC. The pattern is shown in Fig. 3.

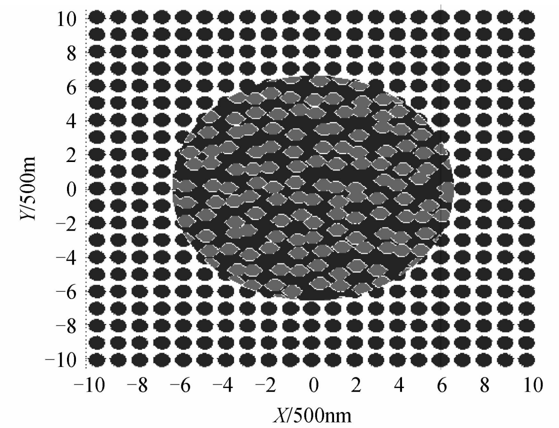
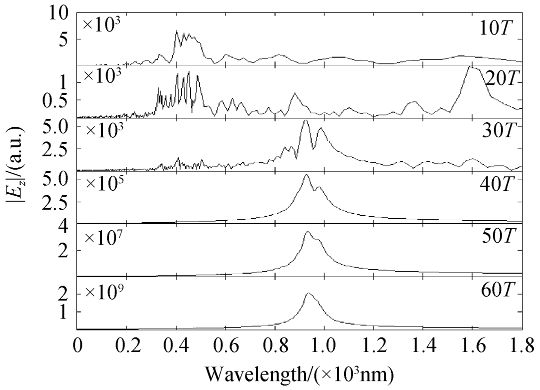


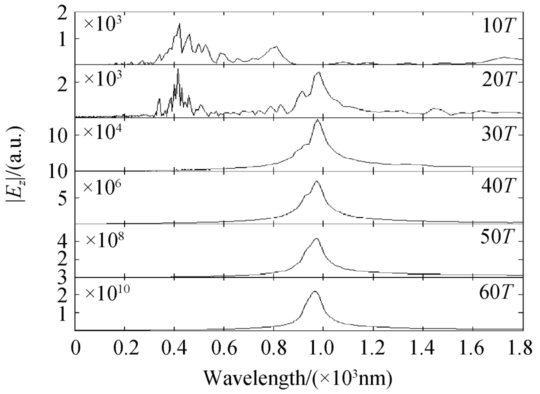
Fig. 3　The configuration of the amorphous cluster in PC

We use the aforementioned pumping source to excite this system, and simulate its spectra in the same way. The results are shown in Fig. 4. In Fig. 4(a), the spectral peak is near 450 nm and the intensity of peak is about 5000 a. u. at $10T$; but at a later time, another new spectral peak at 950nm emerges and increases rapidly. At $40T$ it has already evolved into a strong single spectral peak which intensity has been reached 5×10^5 a. u. Until $60T$ the intensity of this new peak has increased up to 2×10^9 a. u. Similarly, we can draw the same conclusion from Fig. 4(b). The nuance is that the spectra of top region increase little faster than those of the center region.

Briefly, the initial stages of the spectra configuration are similar to the spectra from the cluster in air. But with growing time, a new peak emerges and intensifies in intensity rapidly. Finally, it becomes a strong sole peak in contrast to spontaneous emission. Therefore, if a random gain medium has been put in a matching PC, the light can be trapped in the system, the interaction between the stimulate light and gain medium strengthened, and the spontaneous emission controlled. In a word, PC can not only modulate the lasing mode, but also improve the effective gain of system and reduce the lasing threshold.



(a) The center region



(b) The top region

Fig. 4 The spectra from the center region and the top region of the system shown in Fig. 3

3 Conclusion

In conclusion, the radiation characteristic of an amorphous ZnO cluster in air takes on properties of spontaneous emission. When the cluster is placed in PC, some primary spectral peaks drop off gradually and a new spectral peak emerges and grows rapidly. Consequently, if a random gain system could be put into a matching ordered system, the light can be confined, lasing modes can be modulated, the effective gain can be improved, and the lasing threshold can be reduced finally. The result of this study generates a new method in the manufacture of low threshold micro-lasers. And such micro-lasers are more cost-effective, easy to fabricate and could be imbedded in optical integrated circuit easily.

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微型随机激光辐射特性的控制

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摘　要：为了对随机激光输出特性进行有效地控制，将随机介质纳米团簇植入到光子晶体中，利用有限时域差分法进行模拟，比较了团簇置于空气中和光子晶体中的输出特性. 结果表明：当把团簇单纯地置于空气中，被激发后辐射光的能量会随时间慢慢减少，光谱呈自发辐射的特性；而当将这个团簇植入一光子晶体中，一些原始的自发辐射谱峰会逐渐消失，其中一个谱峰会快速上升，最后成为光谱中唯一的一个能量最强的谱峰. 因此如果一个无序的系统置于一个匹配的有序系统中，光能被有效地限制，自发辐射能被抑制，激发模式会被调制，系统的有效增益会被提高，激光阈值能被减少.

关键词：有限时域差分法；光子晶体；非晶纳米团簇；辐射特性