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Effect of Pump Area on Lasing Modes in Two Dimensional ZnO Nanorods Random Media

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Abstract: Based on the growth and photoluminescences experiment of Zinc Oxide (ZnO) nanorods, the structrue model of two-dimensional random media, in which the location and radius of ZnO nanorods are all disordered, was constructed. Using ZnO gain model, the spectrum characteristics and spatial distribution of optical field at some resonant peak in ZnO nanorods random media were simulated numerically by means of the finite difference time domain method, and the localized mode was found. The effect of pump area on stimulated radiation of the local mode in ZnO nanorods random media was studied from four aspects: changing the pump intensity, increasing the pump size every two columns from left to right, only pumping a zone of localized mode, and increasing the excitation area (the number of the ZnO nanorods) in localized area and nonlocal area respectively when the pump intensity is fixed. The results show: there exists a critical pump power; when the pump intensity is smaller than pump intensity at the lasing threshold, no localized mode can be excited with the size of the pump area; when the pump power reaches above the critical pump power, in the case of different pump powers, localized modes can be excited with different critical pump sizes; when the power size is fixed, the relative light intensity increases with the increasing of the pump intensity and the relative light intensity increases rapidly when the pump intensity exceeds the lasing threshold.

Key words: Random media; Localized mode; Pump sizes; Stimulated emission

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0 Introduction

In 1968, Letokhov predicted that the combination of multiple scattering and light amplification would lead to a form of laser action[1]. In random laser the cavity is "self formed", and multiple scattering between the highly disordered particles keeps the light trapped long enough for the amplification to form laser. ZnO is a strong scattering and high gain semiconductor with a wide-bandgap(E_g=3.37 eV) and a large exciton binding energy of 60 mev[2-3]. ZnO has attracted attention for its potential applications[4], and many forms of ZnO materials have been successively fabricated, such as ZnO semiconductor polycrystalline films[5-7], powder[8], clusters[9-10], nanorods[11-14]. Cao's group observed and extensively studied the lasing process in different forms of ZnO material[4-15]. The size of the excitation volume also affect the production of random laser[4,12]. If pump intensity is fixed, increasing the pump size is benefit for forming more closed-loop paths. When the excitation area is reduced to below a critical size, there is no laser can be found, because the closed-loop paths are too short, and the amplification can not offset the loss along closed-loop path. So the pump intensity at lasing threshold decreases with the increase of the excitation area. When pump size increases to a certain value, the pump intensity at lasing threshold nearly keeps unchanged. However, when pump sizes are the same, the transport mean

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free path decreases, so does the lasing threshold. Based on the growth mechanism and photoluminescence experiment of ZnO nanorods[12], we will further explore the dependence of random laser actions on pump area in ZnO nanorods.

1 Structural model and gain model

Based on ZnO nanorods' growth mechanism, we have established the structural model of ZnO nanorods random media whose spatial distribution shown in Fig. 1. The random media is formed by ZnO nanorods randomly distributed in uniform rectangular shape air medium. The size of random media is 5.2 μm × 5.2 μm, containing 900 ZnO nanorods. The location and radius of nanorods are all disordered, the diameters of nanorods are in the scope 45～55 nm.

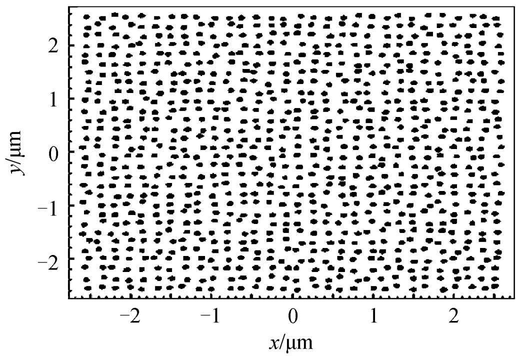


Fig. 1　Spatial distribution of ZnO nanorods random media

The permittivity of ZnO is expressed as[16]

$$\varepsilon_A(\lambda)=\varepsilon_A^{'}-i\varepsilon_A^{''}(\lambda) \tag{1}$$

Where the imagine part indicates amplifying by stimulated emission for $\varepsilon_A^{''}(\lambda)>0$. $\varepsilon_A^{''}(\lambda)$ can be expressed by

$$\varepsilon_A^{''}(\lambda)=c_0\exp\left[-\frac{(\lambda-\lambda_g)^2}{2w_g^2}\right] \tag{2}$$

Where c_0 is a parameter related to pump light intensity. For active dielectric media, the refraction index of ZnO is expressed as

$$n_{A-\mathrm{eff}}(\lambda)=\sqrt{n_A^2-i\varepsilon_A^{''}(\lambda)-i\gamma_A} \tag{3}$$

Where γ_A is the loss coefficient.

2 Numerical simulation

We have calculated the spectrum characteristic of ZnO random media without no gain and loss (i. e $\gamma_A=\gamma_B=0$, $C_0=0$) in ZnO gain range by means of finite difference time domain method (FDTD). Fig. 2 is the transmission spectrum of observation point (0.433, 0.048 6) in ZnO random media. x axis presents wavelength, y axis presents the transmission coefficient. Notice that there are four typical resonant peaks in the wavelength range of 375.0 nm to 395.0 nm, their wavelengths are denoted by λ_1, λ_2, λ_3 and λ_4 respectively. Here we take $\lambda_1=377.8$ nm, $\lambda_2=381.8$ nm, $\lambda_3=387.6$ nm, $\lambda_4=390.1$ nm. Fig. 3 is distribution of emitted light under 387.6 nm optical excitation, local characteristics are found in the distribution of emitted light.

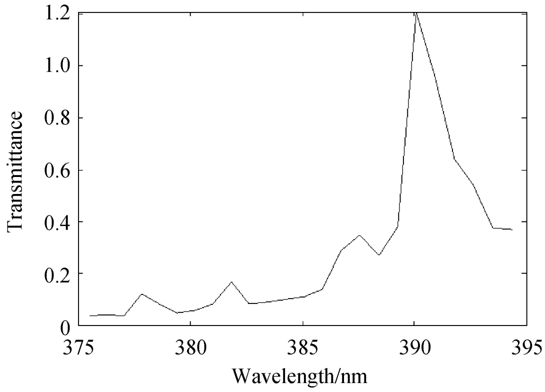


Fig. 2　Transmission spectrum of observation point (0.433, 0.048 6) in ZnO random media

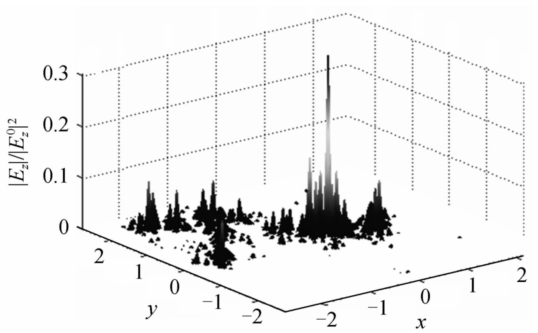


Fig. 3　Spatial distribution of emitted field in ZnO two-dimensional random media under 387.6 nm optical excitation

The following we will investigate the dependence of stimulated emission of local mode corresponding to 387.6 nm wavelength on pump area from four aspects. The pump light corresponding to 387.6nm wavelength was focused to a stripe on the surface of the random media in Fig. 3 with normal incidence, the part of random media is pumped called pump region, the others is called non-pump region. We consider the random media with the gain and loss, in this letter the loss coefficient of the ZnO nanorods and air is set as $\gamma_A=-0.005$ and $\gamma_B=0$ respectively, gain coefficient of the ZnO nanorods in non-pump region and air are all set $C_0=0$, gain coefficient of the ZnO nanorods in pump region is related to the pump intensity.

Firstly, the gain coefficient of the ZnO nanorods in pump region is set as $C_0=0.025$, 0.035, 0.038, 0.040, 0.042 separately, increasing the pump area, every time increasing two columns of nanorods from left to right, Fig. 4 is the dependence of relative light intensity′ logarithm on pump area in the random media. As one can see from Fig. 4, when the pump intensity is smaller than pump intensity at the lasing threshold, there is no localized mode can be excited no matter how much the pump area. For different pump power, localized modes can be lasing need different critical pump sizes.

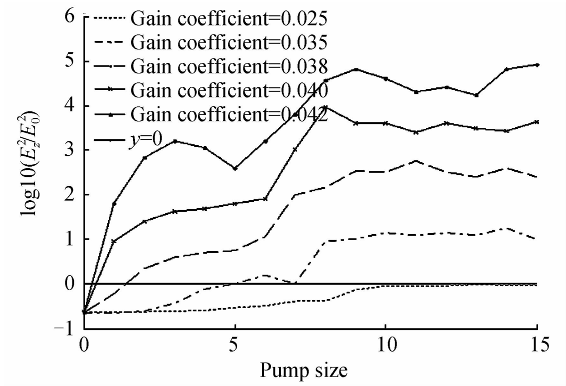


Fig. 4 The dependence of relative light intensity′ Logarithm on pump area in the random media

Secondly, Fig. 5 is spatial distribution of emitted field in ZnO two-dimensional random media under 387.6 nm optical excitation in xy planar projection, bright tiny spots appear in the image of emitted light distribution in the random media. Next we study one local region and one nonlocal region, and labeled them as A region and B region separately in Fig. 6. Now we pump the whole A region in Fig. 6, gain coefficient of the ZnO nanorods in A region is set as $C_0=0.025$,

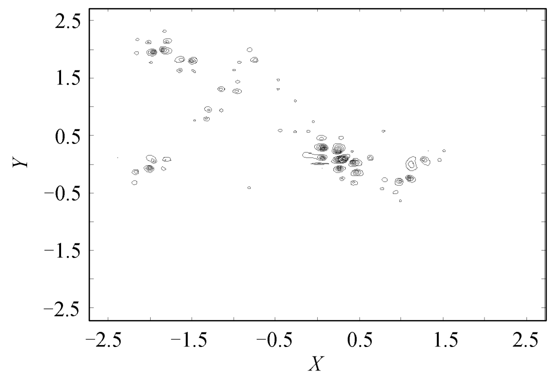


Fig. 5 Spatial distribution of emitted field in ZnO two-dimensional random media under 387.6 nm optical excitation in xy planar projection

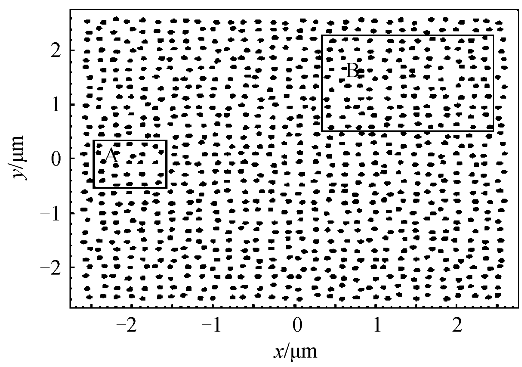


Fig. 6 The spatial distribution of ZnO nanorods random media (A: one local region, B: one nonlocal region)

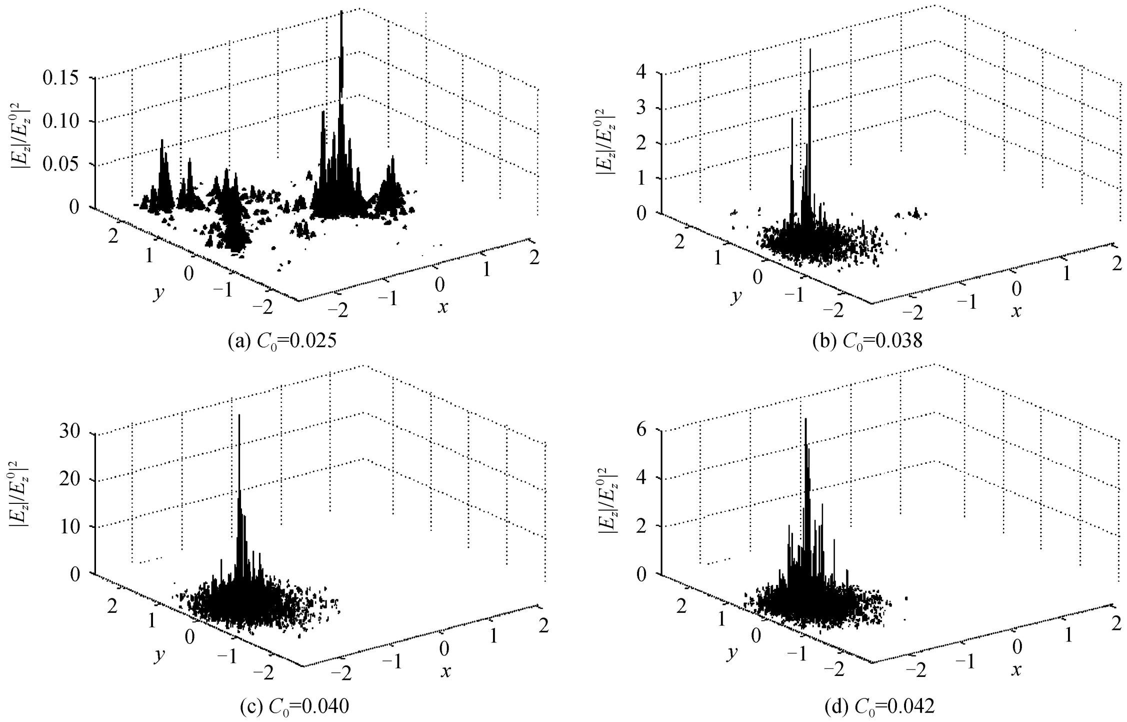
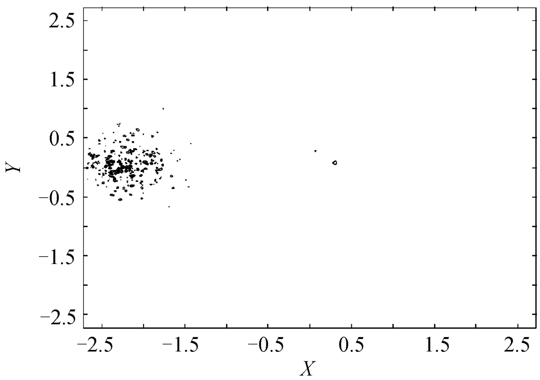


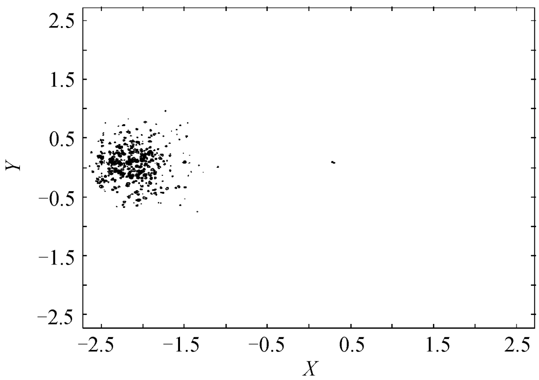
Fig. 7 The spatial relative light intensity distribution in the random media, the whole A region in Fig. 6 is the pump area

0. 038, 0. 040, 0. 042. Fig. 7 is the spatial relative light intensity distribution in the random media, (a), (b), (c), (d) are corresponding to the gain coefficient 0. 025, 0. 038, 0. 040, 0. 042. As one can see from Fig. 7, the pump size is fixed, the relative light intensity increases with a increase of the pump intensity, when the pump intensity exceed the lasing threshold, then the relative light intensity increases rapidly.

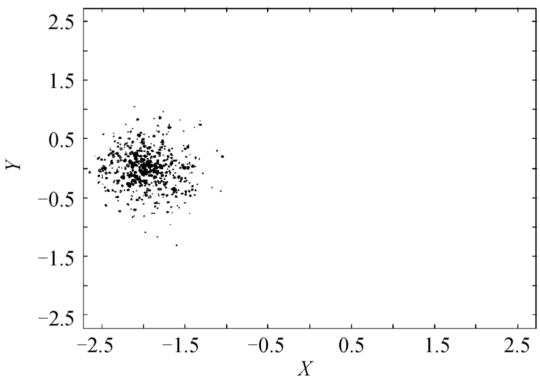
Thirdly, we pump the left four columns of A region in Fig. 6, gain coefficient of the ZnO nanorods are pumped is set as $C_0 = 0.040$. Fig. 8 is the spatial relative light intensity distribution in the random media in xy planar projection, (a), (b), (c), (d) are corresponding to pump left one, two, three, four columns of ZnO nanorods. The Fig. 8 shows, the pump intensity is constant, pump the local region, with a increase of the pump size, the position of the localized mode moves toward the direction of the increasing of pump area, simultaneously, relative light intensity is also increased.



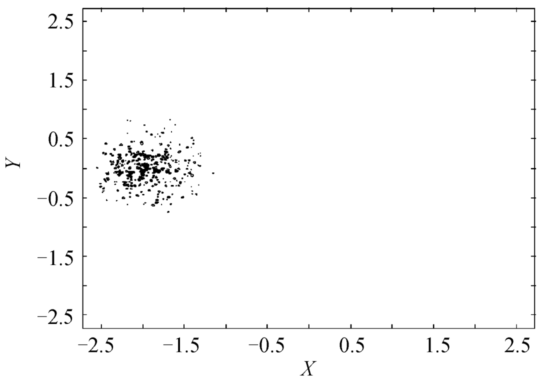
(a) Pump left one column of ZnO nanorode



(b) Pump left two columns of ZnO nanorode



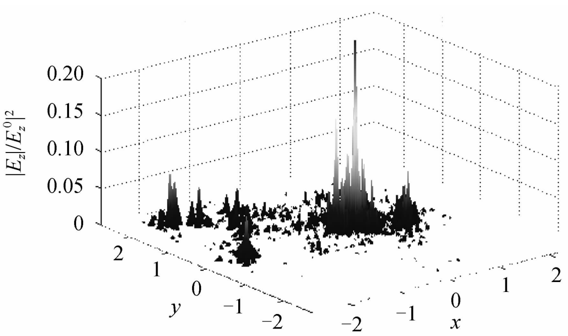
(c) Pump left three columns of ZnO nanorode



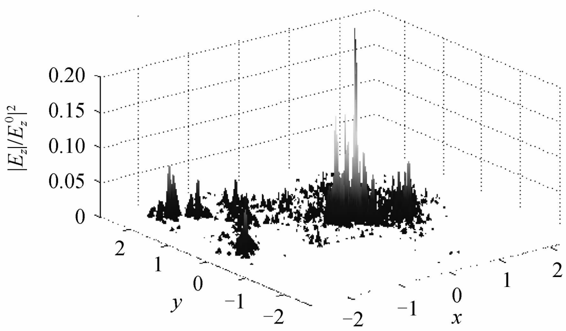
(d) Pump left four columns of ZnO nanorods

Fig. 8　The spatial relative light intensity distribution in the random media, the pump intensity is constant in A region

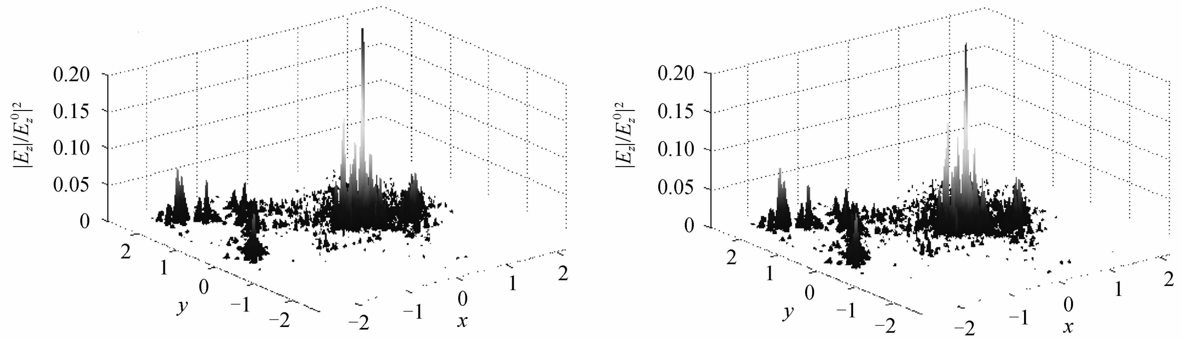
At last, we pump B region (nonlocal region) in Fig. 6, increasing the pump area, every time increasing three columns of nanorods from left to right, the gain coefficient of ZnO nanorods are pumped is set as $C_0 = 0.040$, Fig. 9 is the spatial relative light intensity distribution in the random media. (a), (b), (c), (d) are corresponding to pump left three, six, nine, twelve columns of ZnO nanorods in B region. Fig. 9 shows, the pump intensity is fixed, distribution and intensity of optical field does not vary with the change of the pump size in nonlocal region.



(a) Pump left three columns of ZnO nanorode



(b) Pump left six columns of ZnO nanorode



(c) Pump left nine columns of ZnO nanorode

(d) Pump left twelve columns of ZnO nanorode

Fig. 9 The spatial relative light intensity distribution in the random media, the pump intensity is constant in B region

3 Conclusions

Setting up the structural model of two-dimensional random media in which the center and radius of ZnO nanorods are all disordered and using a ZnO gain model, we mainly studied the effect of pump area on lasing modes corresponding to the resonant peak in ZnO nanorods random media from four aspects. The results show: When the pump intensity is smaller than pump intensity at the lasing threshold, there is no localized mode can be excited no matter how much the pump area, for different pump power, localized modes can be lasing for different critical pump sizes; the pump size is fixed, the relative light intensity increases with increase of the pump intensity, when the pump intensity exceed the lasing threshold, then the relative light intensity increases rapidly; pumping the local region with a constant pump intensity, let the pump size increase, we found that the position of the localized mode moves toward the direction of the increasing of pump area, simultaneously, relative light intensity is also increased; the pump intensity is fixed, distribution and intensity of optical field does not vary with the change of the pump size in nonlocal region.

References

[1] LETOKHOV V S. Generation of light a scattering medium with negative resonance absorption[J]. *Soviet Physics JETP*, 1968, **26**(8): 835-840.

[2] SERVICE R F. Will UV lasers beat blues[J]. *Science*, 1997, **276**(5314): 895-897.

[3] ZHANG Guo-bin, SHI Chao-shu, HAN Zheng-fu, *et al*. Photolumi-nescence properties of ZnO films deposited on Si substrates[J]. *Journal of Luminescence*, 2001, **22**(2): 157-159.

[4] YANG J K, BORISKINA S V, NOH H, *et al*. Demonstration of laser action in a pseudorandom medium[J]. *Applied Physics Letters*, 2010, **97**(22): 223101.

[5] CAO H, ZHAO Y G, ONG H C, *et al*. Ultraviolet lasing in resonators formed by scattering in semiconductor polycrystalline films[J]. *Applied Physics Letters*, 1998, **73**(25): 3656-3658.

[6] CAO H, XU J Y, ZHANG D Z, *et al*. Spatial confinement of laser light in active random media[J]. *Physical Review Letters*, 2000, **84**(24): 5584-5587.

[7] CAO H, ZHAO Y G, ONG H C, *et al*. Far-field characteristics of random lasers[J]. *Physical Review B*, 1999, **59**(23): 15107-15111.

[8] CAO H, ZHAO Y G, HO S T, *et al*. Random laser action in semi-conductor power[J]. *Physical Review Letters*, 1999, **82**(11): 2278-2281.

[9] CAO H, LING Y, XU J Y, *et al*. Photon statistics of lasers with resonant feed back[J]. *Physical Review Letters*, 2001, **86**(20): 4524-4527.

[10] CAO H, XU J Y, SEELING E W, *et al*. Microlaser made of disorder media[J]. *Applied Physics Letters*, 2000, **76**(21): 2997-2999.

[11] CAO H. Random lasers-development, features and applications[J]. *Optics and Photonics News*, 2005, **16**(1): 24-29.

[12] LIU X, WU X H, CAO H, *et al*. Growth mechanism and properties of ZnO nanorods synthesized by plasma-enhanced chemical vapor deposition [J]. *Journal of Applied Physics*, 2004, **95**(6): 3141-3147.

[13] YU S F, CLEMENT Yuen, LAU S P, *et al*. Random laser action in ZnO nanorod arrays embedded in ZnO epilayers[J]. *Applied Physics Letters*, 2004, **84**(17): 3241-3243.

[14] SONG Q H, CAO H, Improving optical confinement in nanostructures via external mode coupling[J]. *Physical Review Letters*, 2010, **105**(5): 053902.

[15] CAO H. Review on latest developments in random lasers with coherent feedback [J]. *Journal of Physics A: Mathematical and General*, 2005, **38**(49): 10497-10535.

[16] XIE Ying-mao, LIU Zheng-dong. Effect of pump area on lasing in active random media[J]. *Chinese Physics Letters*, 2005, **22**(11): 2827-2830.

ZnO 纳米柱无序介质中泵浦面积对局域模发射的影响

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摘 要:基于 ZnO 纳米柱制备及发光实验,建立了 ZnO 纳米柱的位置和大小都是无序的二维介质结构模型.通过构建增益模型,用时域有限差分法数值模拟了无序介质中频谱特性以及 ZnO 增益频谱范围内的某一个共振峰对应的波源在无序介质中的光场分布情况,发现了局域模的存在.分四种情况讨论了此局域模的受激辐射与泵浦面积的关系:改变泵浦功率,从左到右依次增加两层 ZnO 纳米柱泵浦和单独泵浦一个局域区域;泵浦功率一定时,增加泵浦局域区域和非局域区域中 ZnO 纳米柱个数.结果表明:存在一个临界泵浦功率,当泵浦功率小于临界泵浦功率时,无论泵浦面积多大都不能激发局域模;当泵浦功率大于临界泵浦功率时,对于不同的泵浦功率,局域模被激发所需的临界泵浦面积不同;随着泵浦功率的增加,当泵浦面积一定时,光场相对强度呈递增趋势,当泵浦功率超过临界功率时,光场相对强度急剧上升.

关键词:无序介质;局域模;泵浦面积;受激辐射