Localized modes in orientation-disordered one-dimensional media with uniaxial scatterers

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Localized modes in one-dimensional (1D) media with uniaxial scatterers that are assumed to be order in spatial location but disorder in spatial orientation of their optical axis are investigated. Based on the holistic effect model in random laser, i.e., the random laser is due to the interaction of the complex localized modes in active random media with local aperiodic quasi-structure with appropriate pump light, a physical model on this type of random media is found. Its disorder degree is defined by $D = n_o/n_e$. Then, the typical transmission spectrum through the random media and the light field intensity distribution corresponding to the defect modes in photonic band-gap are calculated numerically by means of the transfer matrix method, and the condition that the localized mode appears is discussed. Results show that the medium disorder plays an important role in determining the lightwave state. The localized state appears when the medium disorder is strong enough, and a new mechanism creating random laser phenomenon is brought forward.

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Letokhov predicted that the combination of multiple scattering and light amplification would lead to a form of laser action[1]. When excitation pump light intensity exceeded a threshold, Lawandy's group observed a narrowing of the spontaneous emission spectrum from a methanol solution of rhodamine 640 perchlorate dye and TiO_2 microparticles[2]. Wiersma's group reported the coherent backscattering measurements from amplifying random media using optically pumped Ti: sapphire powders[3]. Cao's group extensively studied the lasing process in disordered semiconductor polycrystalline films, powder, and clusters[4−9]. The localized mode is investigated in random media[10−12]. Over the past few years, this new type of laser received considerable attention due to not only its special physical mechanism and particular properties, but also its high potential for many practical applications[13]. The authors of this letter presented a new physical mechanism on lasing in active random media[14,15], i.e., the random laser is due to the interaction of the complex localized modes in active random media with local aperiodic quasi-structure with appropriate pump light.

So far, all the study on random laser action is relative to the isotropic scatterers, so the location disorder of scatterers is the unique factor to yield the localization of lightwave. A natural question to be presented is whether the disorder of spatial orientation of scatterers allows the lightwave localization if the scatterers are made of anisotropic material such as uniaxial crystals. In this letter, we investigate the transmission spectrum in a one-dimensional (1D) random medium with the uniaxial scatterers, which is order in spatial location but disorder in spatial orientation of their optical axes, by means of the transfer matrix method[16]. This study proposes a new mechanism for creating random laser phenomenon in disorder medium.

In random media, after light is scattered by scattering media and walks in gain media within scattering media for a random distance, it is scattered by scattering media again; Then, it walks for a random distance in gain media within scattering media, and scattered by scattering media once again, $\cdots$; Finally light may return to a scatterer from which it was scattered before or leaves the media. For the sake of further exploring the typical transmission through 1D medium with uniaxial scatterers that are assumed to be order in spatial location but disorder in spatial orientation of their optical axis, we simplify it to a 1D model with a configuration of binary dielectric layers. One layer simulates the uniaxial scatterers, while the other layer simulates the gain media. The structure is surrounded by air. We assume that it is made of alternating $L+1$ gain layers and L scattering media layers in the z-axial direction, i.e., total layer number is $2L+1$. In order to distinguish the effect of orientation disorder from location or size disorder, the location and thickness for each kind of layer are taken as orderly and the same, respectively. Lightwave will propagate along the z-axial direction.

It is quite complicated to analyze the effect of orientation disorder of the scatterers with an arbitrary spatial orientation even for the uniaxial and 1D cases. For simplification, we restrict the principal axis plane on the x-z plane, the angle between z axis and the optical axis is θ, and the orientation disorder can be realized by taking θ a random value for each scatterer. Let n_o and n_e be the refractive indexes of o-ray and e-ray, respectively, the value of the refraction index in the z-axial direction (denoted by n_2) presented by a uniaxial scatterer with an angle θ is randomly distributed in the range $[n_o, n_e]$ and is described as

$$n_2 = n_e\sqrt{\sin^2\theta + D^2\cos^2\theta}, \quad (1)$$

where $D = n_o/n_e$ and is called the disorder degree for the 1D random medium considered here with the uniaxial scatterers to be order in spatial location but disorder in spatial orientation. θ is a random variable and is assumed to be uniformly distributed in the range $[0, \pi]$, and

$$\theta = \pi * R, \tag{2}$$

where R is a random number distributed uniformly between 0.00 and 1.00.

The dielectric function of gain medium is expressed as

$$\varepsilon_A(\lambda) = \varepsilon'_A - i\varepsilon_A''(\lambda), \tag{3}$$

where the imaginary part indicates amplification by stimulated emission for $\varepsilon_A''(\lambda) > 0$ or absorption for $\varepsilon_A''(\lambda) < 0$. Based on the gain spectrum feature for gain medium, $\varepsilon_A''(\lambda)$ can be expressed by the following Gaussian function:

$$\varepsilon_A''(\lambda) = c_0 \exp\left[-\frac{(\lambda - \lambda_g)^2}{2w_g^2}\right], \tag{4}$$

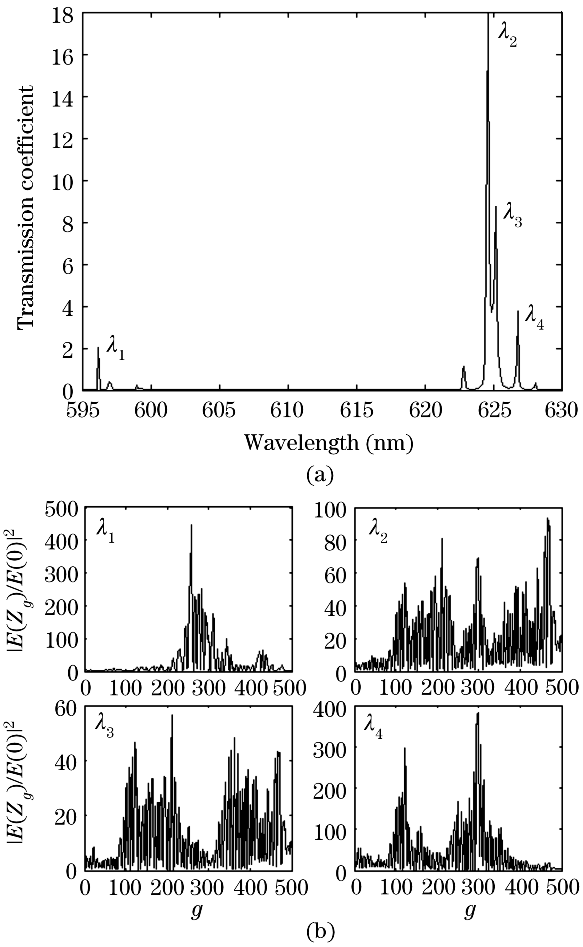

Fig. 1. For 1D medium with uniaxial scatterers that are assumed to be order in spatial location but disorder in spatial orientation of their optical axis and illuminated by a plane wave as $D = 1.26$. (a) Transmission coefficient versus wavelength; (b) the spatial relative light intensity distribution of a plane wave incident upon the sample for the four wavelengths, $\lambda_1 = 596.2$ nm, $\lambda_2 = 624.6$ nm, $\lambda_3 = 625.2$ nm, and $\lambda_4 = 626.8$ nm. g is the layer number inside the random medium.

where λ is the light wavelength, w_g is the half-width at half-maximum of gain spectrum, c_0 is a parameter related to the pump light intensity. We assume that the gain spectrum is centered around 613 nm with a width of ~ 12.0 nm (such as sulforhodamine 640), i.e., $\lambda_g = 613.0$ nm, $w_g = 6.0$ nm. For the gain media, we introduce the effective refractive index

$$n_{A-\mathrm{eff}}(\lambda) = \sqrt{n_1^2 - i\varepsilon_A''(\lambda)}. \tag{5}$$

As the width of gain media layer $a = 250.0$ nm, the width of uniaxial scatterers layer $b = 150.0$ nm, $n_1 = 1.0$, $n_e = 1.75$, $n_o = 2.20$, and $c_0 = 0.01$, we obtain $D = 1.26$ and use the transfer matrix method to calculate optical transmission through a 1D 499-layer random system[16]. In Fig. 1(a), we present the results of the transmission coefficient as a function of wavelength λ for a specific random structure illuminated by a plane wave in the gain region of gain media. There are some typical resonant peaks in the wavelength range of 595 – 630 nm, where $\lambda_1 = 596.2$ nm, $\lambda_2 = 624.6$ nm, $\lambda_3 = 625.2$ nm, and $\lambda_4 = 626.8$ nm. We also numerically calculate the spatial relative light intensity distribution $|E(Z_g)/E(0)|^2$ of a plane wave incident upon the sample for the four

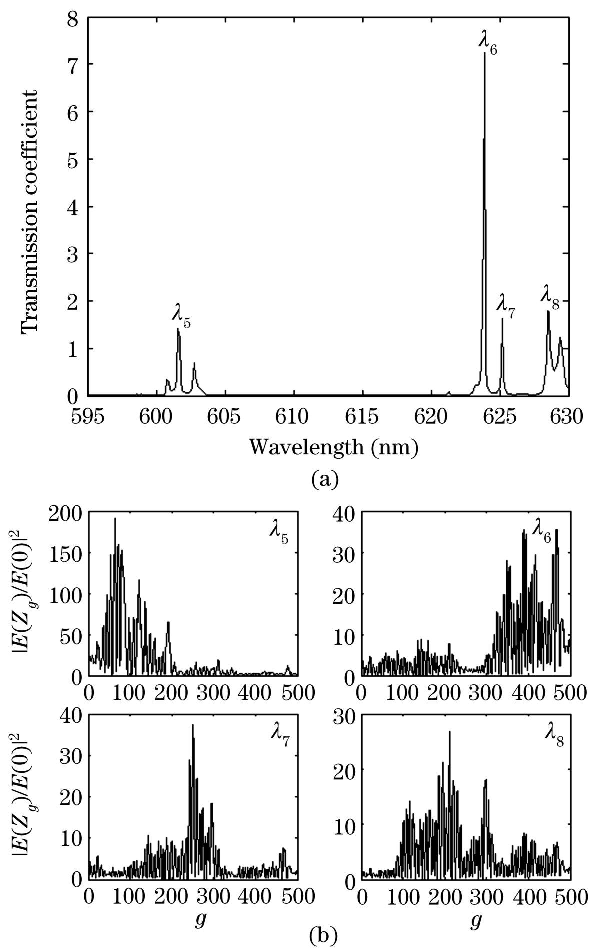

Fig. 2. As $n_o = 2.20$, $n_e = 1.80$, i.e., $D = 1.22$, the other parameters and the random realization are taken the same as those in Fig. 1. (a) Transmission coefficient versus wavelength; (b) the spatial relative light intensity distribution of a plane wave incident upon the sample for the four wavelengths, $\lambda_5 = 601.6$ nm, $\lambda_6 = 623.9$nm, $\lambda_7 = 625.2$ nm, and $\lambda_8 = 628.6$ nm.

wavelengths indicated in Fig. 1(a). The result is shown in Fig. 1(b), where the position is expressed by the layer number g inside the random medium. One can observe several features from Fig. 1(b). Firstly, some photon localized modes occur inside the random medium. The localized intensity is different for different localized mode wavelength. Secondly, there are several localized centers, i.e., there are several lasing regions.

As $n_o = 2.20$, $n_e = 1.80$, i.e., $D = 1.22$, and the other parameters and the random realization remain the same as those in Fig. 1, we calculate the transmission coefficient shown in Fig. 2(a) and the spatial relative light intensity distribution shown in Fig. 2(b), where $\lambda_5 = 601.6$ nm, $\lambda_6 = 623.9$ nm, $\lambda_7 = 625.2$ nm, and $\lambda_8 = 628.6$ nm. Figure 2(b) shows that the highest localized intensity reaches about 190 times of incidence intensity for the localized mode wavelength λ_5.

As $n_o = 2.20$, $n_e = 2.20$, i.e., $D = 1.00$, the medium considered here is a completely order one, there exist stretched states shown in Fig. 3 and localized states do not occur. Thus, the disorder degree of the medium D plays an important role in determining the lightwave state. The higher the disorder degree D is, the stronger the localized mode intensity is.

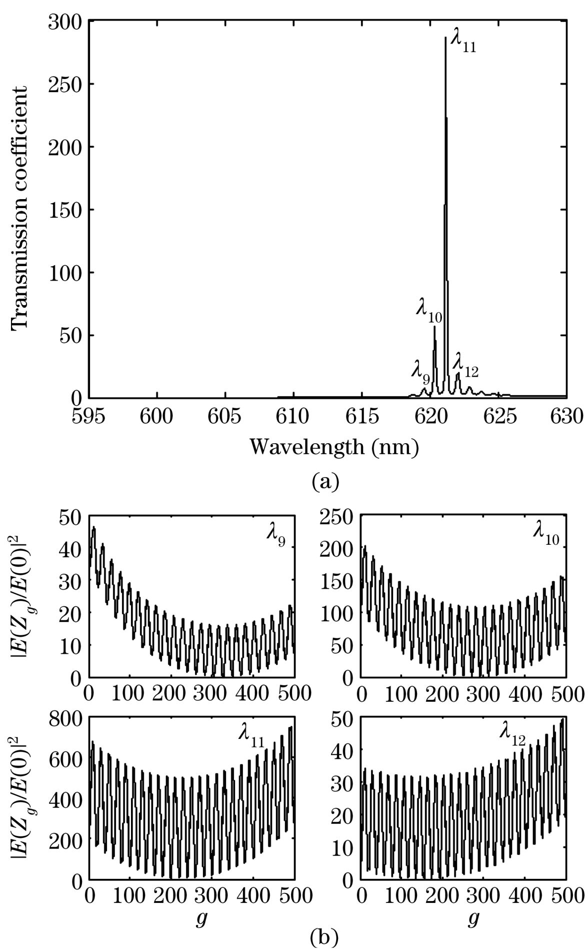

Fig. 3. As $n_o = 2.20$, $n_e = 2.20$, i.e., $D = 1.00$, the other parameters and the random realization are taken the same as those in Fig. 1. (a) Transmission coefficient versus wavelength; (b) the spatial relative light intensity distribution of a plane wave incident upon the sample for the four wavelengths indicated in Fig. 3(a).

In summary, the localized mode in a 1D random medium with the uniaxial scatterers being order in spatial location but disorder in spatial orientation of optical axis is investigated by means of the transfer matrix method. The disorder degree of the medium can be described by the ratio between the refractive indexes at two principal axes. The disorder degree of the medium D plays an important role in determining the lightwave state. As the disorder is strong enough, the disorder in spatial orientation can allow the Anderson localization of lightwave to occur, a new mechanism creating random laser phenomenon is revealed. It should be pointed out that our result is only one of the special structures in random media and θ is assumed to be a uniformly distributed. In general, there exist different results for other random structures. The result can give us some information about lasing in active random media, but it is so simple and crude that there still exist many basic problems that deserve further study.

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