Transition of lasing modes in disordered active photonic crystals

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The transition from a photonic band-edge laser to a random laser in two-dimensional active photonic crystals is described. The lasing modes in the active photonic crystals shift from the edge of the photonic bandgap to the bulk of the gap when a certain amount of position and size disorder is introduced. The shift of lasing modes is determined with various gain profiles. The results show that the modulation of lasing modes is significant when the lasing transition wavelength overlaps the photonic bandgap. © 2007 Optical Society of America

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Laser action generated at frequencies just outside the photonic bandgap (PBG) is a peculiar optical phenomenon. Recently photonic band-edge lasers [1–3] have been realized in semiconductor [4,5] and organic materials [6–8]. In active periodic dielectric systems such as photonic crystals (PCs), the enhancement of light amplification is significant at the edge of the PBG, which is attributed to the coherent scattering from the periodic structures. Introduction of defects or disorders can lead to deformation [9–11], and eigenmodes can be created within the PBGs. If the degree of disorder is sufficiently high, the ordered structures will be transformed to random media, where light waves perform a random walk and multiple scattering processes occur. Under certain conditions, laserlike emission can be achieved in such random laser systems [12–15]. By varying the amounts of the disorder in an active PC, it is possible to acquire lasing emissions that are distinct from the photonic band-edge lasers. Since the origin of the transformation between photonic band-edge laser emission and random laser emission is not yet well understood, it is valuable to study the modulation of the lasing properties of the band-edge lasers and random lasers under the influence of disorder.

In this work, the modification of emission modes of the photonic band-edge lasers is investigated theoretically. We demonstrate the process in which the photonic band-edge lasers change to random lasers by assigning position or size disorder to two-dimensional (2D) active ordered PCs. Maxwell's equations coupled with rate equations for electronic population [16] are solved by the finite-difference time-domain (FDTD) method [17] to simulate the electromagnetic (EM) field distribution of the PC. EM fields obtained in the time domain are converted to the spectral domain by Fourier transformation to derive emission spectra of the system. The active medium is modeled as a four-level atomic system as described by Sebbah and Vanneste [18]. An array of infinitely long cylinders of circular cross section is embedded in an active medium, the cross sections of which are shown in the inset of Fig. 1(a). A perfectly matched layer is used to enclose the active medium to mimic an open system. The parameters of our FDTD simulation are shown in Table 1. The space and time increment are chosen as $\Delta x = \Delta y = 10$ nm and $\Delta t = 2.36 \times 10^{-17}$ s, respectively.

A position disorder is introduced into the PC so that the positions of each cylinder are randomized within a certain range from its lattice point and decided with a disorder parameter of d_{xy}. The coordinates of the cylinders can be expressed as $x = x_0$

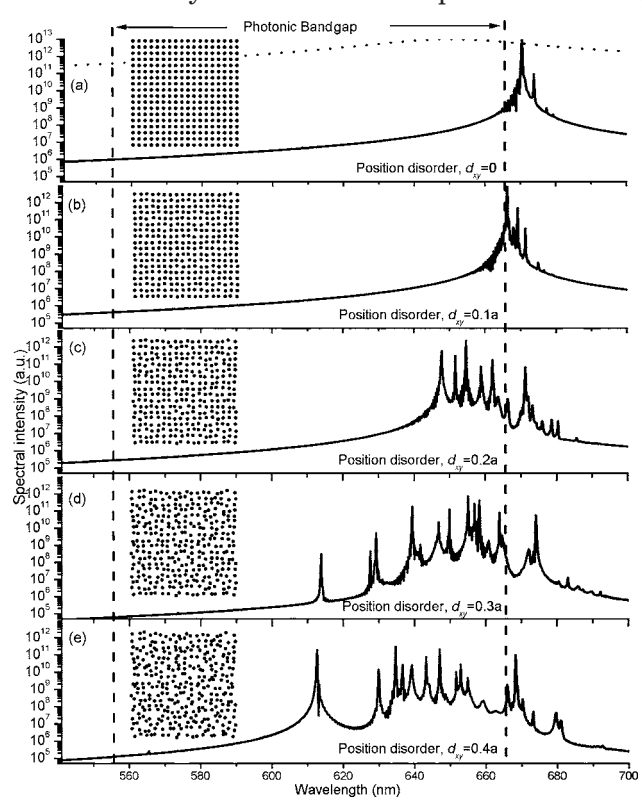

Fig. 1. Emission spectra of active disordered PCs: (a) $d_{xy} = 0$, (b) $d_{xy} = 0.1a$, (c) $d_{xy} = 0.2a$, (d) $d_{xy} = 0.3a$, (e) $d_{xy} = 0.4a$. (a) Inset, configuration of 2D PC. (b)–(e) Insets, particular configurations of disordered PCs with position disorder.

Table 1. Parameters of the 2D PC and the FDTD Simulation

Parameter	Value	Parameter	Value
System size	$4\ \mu m \times 4\ \mu m$	Collision time	$T_2 = 5\times10^{-14}$ s
Dielectric constant, matrix medium	1	Lifetime, energy state 2	$\tau_{21} = 5\times10^{-12}$ s
Dielectric constant, cylinders	7	Lifetime, energy state 3	$\tau_{32} = 1\times10^{-10}$ s
Radius of cylinders	60 nm	Lifetime, energy state 4	$\tau_{43} = 1\times10^{-13}$ s
Lattice constant	$a = 200$ nm	Total atomic density	$6.022\times10^{23}\ m^{-3}$
Filling fraction	23%	Pumping rate	$1\times10^{14}\ s^{-1}$

$+\gamma_x d_{xy}$, $y = y_0 + \gamma_y d_{xy}$, where x_0 and y_0 are the lattice point x and y coordinates of the cylinder, respectively. γ_x and γ_y are random variables. For the case of size disorder, the position of each cylinder is fixed in its lattice position, but the radius of the cylinder varies. The radius of each cylinder varies randomly within a distance d_r, that is, $r = R + \gamma_r d_r$, where γ_r is a random variable. γ_x, γ_y, and γ_r are uniformly distributed between −1 and 1; i.e., $\gamma_x, \gamma_y, \gamma_r \in [-1, 1]$. Particular configurations for position- and size-disordered systems are shown in the insets of Figs. 1(b) and 2(a), respectively.

A transverse magnetic (TM) bandgap of the PC is identified from $\lambda = 555$ nm to $\lambda = 665$ nm. The transition from the photonic band-edge laser to a random laser is illustrated with increasing disorder. In the numerical experiments, the lasing transition wavelength λ_t of the four-level atomic system is selected as 650 nm so that the gain profile overlaps the TM bandgap. The dotted line in Fig. 1(a) denotes the line shape of the gain curve.

The calculated emission spectra with various amounts of position and size disorder are shown in Figs. 1 and 2, respectively. When $t = 0$, a Gaussian pulse electric field (pulse duration 7×10^{-16} s) with arbitrary amplitude, parallel to the infinitely long cylinders, launches at the center of the system to excite the evolution of the EM wave. The emission spectra are determined from the field signals recorded in the time window $[487{,}500\Delta t, 650{,}000\Delta t]$. For each amount of disorder, 20 random configurations are computed. We observe that the characteristics of the spectral observations obtained from the configurations are universal. Multimode spectra are observed because the active medium is excited over a lasing threshold. The multipeaks corresponding to the lasing modes shift from the upper edge of the PBG to the center of the bandgap as the amount of position disorder increases from 0 to $0.4a$. In Figs. 1(a) and 1(b), the lasing modes pertaining to photonic band-edge lasers lie just outside the PBG. For the highly disordered system, the lasing modes shift inside the PBG and are randomly distributed, as shown in Figs. 1(c)–1(e). Lasing modes of highly disordered PCs emerge around the central wavelength of the gain curve because the stimulated emission occurs at the lasing transition wavelength ($\lambda_t = 650$ nm). For the size disorder, the transition occurs at relatively small amounts of disorder, as illustrated in Fig. 2. The shift of lasing modes is less sensitive for the position disorder. However, the emission profiles are similar in both position and size disorder, as the emission peaks of highly disordered systems are randomly formed and depend on the configuration of the scattering particles. The transition can be demonstrated in term of the field distribution patterns. Figure 3 shows the electric field of the active PC with various degrees of disorder, which is recorded in time step $\Delta t = 650{,}000$. Figure 3(a) shows a regular pattern that is a consequence of the Bragg-like diffraction arising from the periodic structure. When a disorder is introduced, the spatial symmetry of the periodic structure is dis-

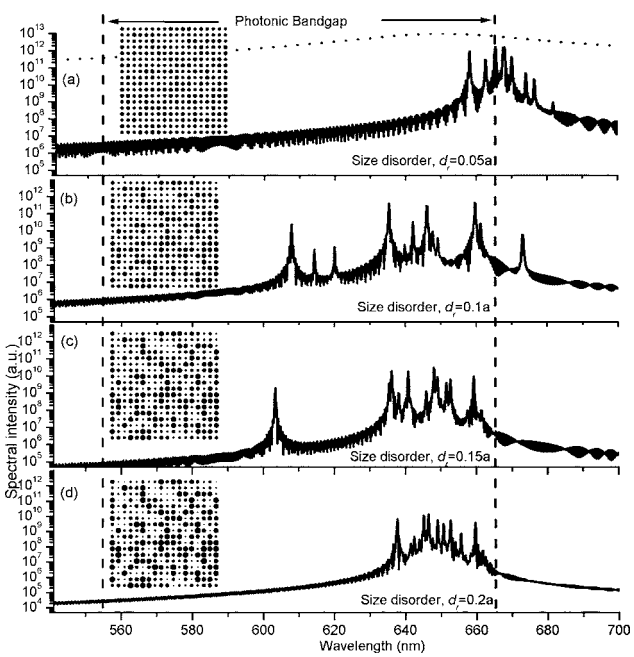

Fig. 2. Emission spectra of active disordered PCs: (a) $d_r = 0.05a$, (b) $d_r = 0.1a$, (c) $d_r = 0.15a$, (d) $d_r = 0.2a$. (a)–(d) Inset, particular configurations of disordered PCs with size disorder.

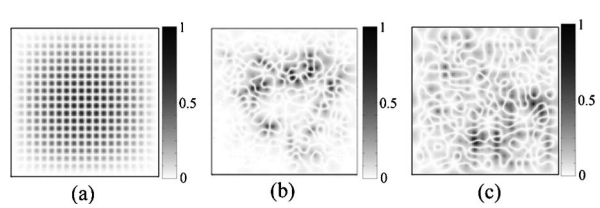

Fig. 3. Spatial distribution of the electric field of an active disordered PC recorded at time step $t = 650{,}000\Delta t$: (a) $d_{xy} = d_r = 0$, (b) $d_{xy} = 0.4a$, (c) $d_r = 0.2a$.

turbed. As the amount of the disorder increases, some high-intensity spots are formed as shown in Figs. 3(b) and 3(c). This phenomenon is attributed to the confinement of EM waves in the localized modes. By computing over 20 random configurations, we confirm that the localized modes are easier to create in size-disordered PCs than position-disordered ones. This is consistent with the results of others [11,19] that size disorder is more destructive to periodic structures than position randomness. The localized field pattern gives clear evidence for the localized modes.

Second, we vary the lasing transition wavelength λ_t but keep all other parameters unchanged. For each gain profile, we calculate the emission spectra and then determine the highest-intensity lasing modes as shown in Fig. 4. Each data point represents the highest emission peak of one configuration, except those for $\lambda_t = 590$ nm, where the mean values of 20 configurations and error bars with 95% confidence level are presented. For $\lambda_t = 530$ nm and $\lambda_t = 550$ nm, the peaks emerge around their lasing transition wavelengths, which are outside the PBG. Even when the disorder is large, i.e., $d_{xy} = 0.4a$, the shifts of the lasing modes are insignificant. The results reveal that excitation of the lasing modes depends on the lasing transition wavelength rather than the amount of disorder if the lasing transition wavelength is outside of PBG. For $\lambda_t = 580$ nm to $\lambda_t = 620$ nm, the shifts of lasing modes are clearly demonstrated. Except for $\lambda_t = 650$ nm, the lasing modes emerge in the lower band edge because the central wavelength of the gain curve is located in the shorter-wavelength range when $d_{xy} = 0$. The highest intensity modes gradually move toward the bandgap with increasing position disorder. The influence of size disorder is similar to that of the position disorder. For $d_{xy} = 0.4a$ and $d_r = 0.2a$, the electronic fields of 20 random configurations are analyzed in which the localized modes dominate the lasing emission, implying that in the highly disordered systems the lasing modes pertain to the random laser rather the band edge laser even when the emission peaks still stay outside the PBG.

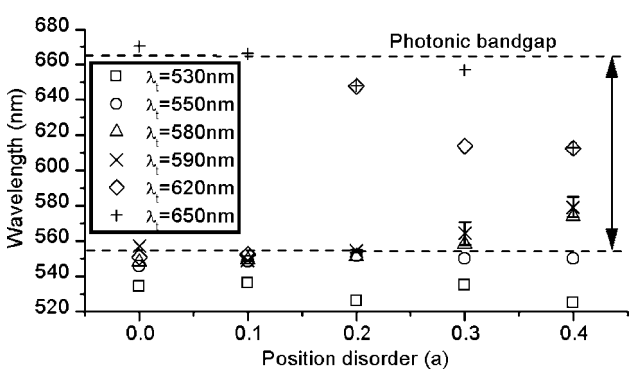

Fig. 4. Plot of the highest-intensity emission peak of active disordered photonic crystals.

We have investigated the lasing emission in active 2D PCs deformed by position or size disorder, demonstrating the shift of the lasing modes from the edge to the bulk of the PBG. However, the shifts of lasing modes are insignificant in the case where the lasing transition wavelength is outside the PBGs. The transition from the photonic band-edge laser to the random laser occurs at a relatively smaller disorder, while a higher amount of position disorder is required. The field distributions provide evidence for the domination of localized modes in highly disordered systems. The strength of disorder is one of the crucial factors for modulating the lasing modes of the photonic band-edge laser.

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