Influence of random errors on the characteristics of typical 2D photonic crystal microcavity

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1 Introduction

Photonic crystals have been widely investigated due to their potential applications in photonic integrated circuits. One essential component of such integrated circuits is a low threshold photonic crystal laser that functions as a wavelength-scale coherent source. The characteristics and lasing actions of cavity modes localized by the photonic bandgap have been studied by many groups worldwide [1–5]. In order to fabricate the photonic crystal lasers that operate in near-infrared or optical wavelengths, the feature size of photonic crystals has to be some hundreds of nanometers. Fabrication of such fine structures inevitably generates random deviations from the perfectly ordered structures. The effects of disorder on the size of photonic band gaps have been investigated by Shanhui Fan using the supercell approximation [6]. In this method, the line defects (waveguide) and dot defects (cavity) are not considered. Further investigations of photonic crystal waveguide disorders have also been reported [7–9]. In these studies, several groups have presented a new photon Green-function-tensor formalism that provides clear physical insight into the phenomenon of extrinsic optical scattering loss in photonic crystal waveguides due to random fabrication imperfections [10, 11]. Recently, some researchers have undertaken numerical and experimental studies of structural disorder effects on the performance of photonic crystal band-edge lasers [12]. There have also been several theoretical investigations of the influence of disorder on photonic crystal microcavities [13], but they focus solely on the lifetimes and modal volumes and don’t consider statistical distributions and dependences on disorder strength.

In this paper, we undertake a study of the errors most likely to arise during fabrication, such as random errors of radius and position of the dielectric components. This is based on our previous work on the influence of random errors on the transmission properties of photonic crystals [14]. We are interested in the effects on these errors on the most fundamental properties of 2D photonic crystal microcavities such as the resonant frequency, resonant mode distributions and quality factor. For illustration purposes, we study the simplest microcavity – a single defect mode in a 2D square lattice.

2 Computational method

For concreteness, we focus on a two-dimensional (2D) photonic band-gap (PBG) system with a square lattice of dielectric rods in air, as shown in Fig. 1c and d, where the black and gray dielectric rods denote the perfect and disordered photonic crystal structures, respectively. The relative dielectric constants of the dielectric rods is 4.55. In the ideal case (black dielectric rods as shown in Fig. 1c and d), the cross-section radius \( r \) is chosen equal to \( 0.25a \), where \( a \) is the lattice constant. All results presented are for TE polarization with the electric field parallel to the rod axis and have been obtained with the 2D FDTD with perfectly matched layer boundary conditions. The simulations use \( 20 \times 20 \) grid points per unit cell.

In order to model the disordered structures caused by random errors of radius of the dielectric rods, we introduce a random variable \( \mu \). As shown in Fig. 1c, \( \mu \) is used to ran-
randomly vary the radius of the dielectric rods. We choose $\mu$ such that it follows a uniform distribution, $\mu \sim \text{Un}(-\delta r/2, \delta r/2)$, where $\delta r$ characterizes the disorder “strength”. To model the disordered structures caused by random errors of position of the dielectric rods, we introduce two random variables $\psi$ and $\xi$. As shown in Fig. 1d, $\psi$ and $\xi$ are used to describe the random errors of position of the dielectric rods. The variables $\psi$ and $\xi$ denote the angle and distance of position deviation from perfect photonic crystals, respectively. As above, $\psi$ is chosen so as to follow a uniform distribution $\text{Un}(0, 2\pi)$ and $\xi$ to follow a uniform distribution, $\xi \sim \text{Un}(0, \delta a)$, where $\delta a$ characterizes the disorder “strength”.

The actual strength of the disorder will depend on the precision of the lithographic technique used in the fabrication process and the mid-gap frequency for which the photonic crystal is designed. The lower the precision, the larger the ratio of disorder to minimum feature size for a given technique. A photonic crystal designed for 1.55 $\mu$m light will have a minimum feature size of about 0.1 $\mu$m. With state-of-the-art X-ray lithographic techniques, feature sizes as low as 0.05 $\mu$m can be obtained with a precision between 10% and 20%. Therefore, we have chosen 25% as the maximum disorder strength $\delta r$ and $\delta a$. The results of our calculations are presented below.

3 Results

We first study the influence of random errors of radius of the dielectric rods on the characteristics of photonic crystal microcavities formed by the removal of one dielectric rod as shown in Fig. 1a.

We set $\delta r$ to be 0.25$r$. We place a pulse source in the asymmetry position and record the fields at the monitor points positioned in different locations in the cavity. By using the fast Fourier transform (FFT) of the electric field at the monitor points we obtain the resonant frequency. Then the field is initialized by a dipole oscillation source with the angle frequency equivalent to the resonant frequency. After propagating the field in time, a mode is formed and the resonant mode distribution is obtained. After the mode is formed, we switch off the dipole oscillation and calculate the electromagnetic energy as a function of time. From the slope of the logarithm energy–time relation, $Q$ is calculated. We execute fifty simulations, each with a random seed for the random number generator. For each random simulation, the corresponding resonant frequency, quality factor and resonant mode distribution of the photonic crystal microcavity is obtained.

The influence of random errors of radius of the dielectric rods on the resonant frequency of photonic crystal microcavity will vary. We study their dependences on disorder strength $\delta r$ and $\delta a$. The results of our calculations are presented below.