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Photonic Crystal Laser

Yong-Hee Lee and In-Kag Hwang

Department of physics, Korea Advanced Institute of Science and Technology
yhlee@kaist.ac.kr

Abstract

Recent progress toward wavelength-scale photonic crystal lasers is summarized. To realize the ultimate laser, one needs to have a wavelength-scale photonic crystal cavity that is lossless. As a candidate for this ultimate laser, the two-dimensional unit-cell photonic crystal laser compatible with current injection is proposed. Experimental demonstration of the low-threshold two-dimensional photonic crystal lasers in the triangular lattice and the square lattice will be discussed. The very high quality factor in excess of 1,000,000 is theoretically predicted from the wavelength-scale resonator supporting the whispering-gallery-like photonic crystal mode.

1. Introduction

Recently, the photonic crystal at optical regime has matured from a theoretical interest to realistic experimental problems, owing to the advancement of nanofabrication technologies. Generally, the lattice constant of a photonic crystal is about one-half of the wavelength of the light. In such a case, photons tend to interact very strongly with the periodically repeating structure through constructive or destructive interferences. Interestingly, the characteristics of this interaction can be artificially controlled by varying the lattice constant, the dielectric constant and the structure of the lattice. For example, one can create a novel optical material that has a 'photonic band gap', an energy region in which no electromagnetic wave can exist [1]. Remember that the 'electronic band gap' is the forbidden energy region for electrons in semiconductor 'electronic' crystals. However, unlike natural 'electronic' crystals, the 'photonic' counterpart can be designed, fabricated. In other words, the 'man-made' photonic crystal opens up the possibility of the photon control: it can be engineered to guide photons, to localize photons, or to modify the dispersion relation of photons. The concept of the photon confinement in multi-dimensions has attracted many scientists in search of the ultimate thresholdless laser. To realize the thresholdless laser, one needs to find a resonant cavity that satisfies two requirements. First of all, the cavity size should be extremely small on the order of a half wavelength. The fundamental limit of the mode volume that is allowed by nature is $(\lambda/2n)^3$. In addition, the cavity should be able to confine photons effectively with low optical loss: the cavity should have a high quality (Q) factor. The physical dimension of the cavity determines the number of photon modes available for a given cavity. It can be argued that the best choice is the cavity allowing just one single mode. Then, all the photons generated inside the cavity are forced to funnel through this single mode to come outside [2]. In fact, the larger quality factor encourages more efficient photon localization and, therefore, promotes stronger stimulated emission of photons from the excited atoms.

2. Nondegenerate Monopole Mode Unit-Cell PBG Laser

The smallest possible cavity configuration imaginable from the photonic crystal is the unit-cell resonator where only one lattice point is filled. Then around this imperfection in the middle of the photonic band gap, photons tend to be localized. However, even from this unit-cell cavity, several resonant modes are found and some the modes are doubly degenerate. Several ways to lift this degeneracy have been suggested and demonstrated. However, it is believed that utilizing the truly nondegenerate mode is generally more advantageous to funnel most of photons into one and only one resonant mode.

One way to lift the degeneracy is to use the cavity mode that is inherently nondegenerate. In this case, natural and efficient coupling with that sole mode is expected. One example of this genuine nondegenerate mode is the monopole mode. In the regular photonic crystal unit-cell cavities, this nondegenerate monopole mode is buried in the air band and cannot be found. However, if one decreases the size of the nearest air holes, the effective volume of the cavity is slightly enlarged as shown in Fig. 1(a) and this monopole mode can be pulled down into the middle of the photonic band gap where the photon confinement is stronger. The 2-D triangular PBG laser working in this monopole mode was realized with low threshold power of 0.3 mW [3]. It is interesting to note that this monopole mode has a node in the center of the cavity as shown in Fig. 1(b). Note that the monopole mode profile has good overlap with the central cavity region where optical gain is generated.