A photonic crystal nanocavity laser in an optically very thick slab

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A photonic crystal (PhC) nanocavity formed in an optically very thick slab can support reasonably high-Q modes for lasing. Experimentally, we demonstrate room-temperature pulsed lasing operation from the PhC dipole mode emitting at 1.3 μm, which is fabricated in an InGaAsP slab with thickness (T) of 606 nm. Numerical simulation reveals that, when T ≥ 800 nm, over 90 % of the laser output power couples to the PhC slab modes, suggesting a new route towards an efficient in-plane laser for photonic integrated circuits. © 2011 Optical Society of America

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An optically thin dielectric slab with photonic crystal (PhC) air-holes has been a versatile platform for designing various high-Q cavities. [1] Thickness (T) of the PhC slab is often chosen to maximize the size of the photonic band gap (PBG), [2] which is approximately equal to half effective wavelength of the cavity resonance. For designing a PhC slab laser emitting at 1.3 μm, this thickness consideration requires that T should be about 250 nm.

In this letter, we show that even a very thick slab can support sufficiently high-Q cavity modes for lasing. Once we are free from the thickness constraint, design of a current-injection type laser becomes more feasible; we can employ a vertically varying p-i-n structure along with a current confinement aperture as has been done for vertical-cavity surface-emitting lasers. [3] Furthermore, as will be shown below, we can build an efficient in-plane emitting laser, where most of the laser emission couples to the two-dimensional (2D) Bloch modes [2] in the PhC slab.

We begin with numerical simulations using the finite-difference time-domain (FDTD) method. We adopt the widely-used modified single-cell cavity design, [4] and investigate the PhC dipole mode as shown in Fig. 1. We assume T and the lattice constant (a) are 2,000 nm and 305 nm, respectively. The refractive index of the slab is assumed to be 3.4. Other structural parameters are as follows: [4] the background hole radius (R) = 0.35a, the modified hole radius (Rm) = 0.25a, and the hole radius perturbation (Rp) = 0.05a. It should be noted that the in-plane PBG [2] is completely closed at T ≈ 1.5a for a PhC slab with R = 0.35a. However, it is interesting that we can still find several resonant modes that seem to be well confined within the defect region as shown in Fig. 1(b),(c). In fact, these modes have the same transverse mode profile while the number of intensity lobes along the z direction varies from 1 to 3. Therefore, these modes originate from the slab resonance between the top and bottom surfaces, which can act as reflectors due to the relatively high refractive index of the slab. We summarize various optical characteristics of the dipole modes in a slab with T = 2,000 nm including Q, emission wavelength λ, and mode volume V, in Table 1. [4] In particular, Q_{tot} [5] of the fundamental mode is over 5,000. It should be noted that a similar thick slab design was proposed by Tandaechanurat et al. with a special focus on a PhC cavity in a T = 1.4a slab. [6]

To gain further insight into the loss mechanism, in Fig. 2, we calculate Q_{tot}, Q_{vert}, and Q_{horz} [1, 5] as a function of T, where a is varied to keep the emission wavelength at 1.3 μm. First, let us focus on Q_{vert}. In the case of a thin slab PhC cavity, Q_{vert} depends strongly on \( Rm \) and \( Rp \) [7] and \( Q_{vert} \) of the dipole mode can be as high as \( \sim 15,000 \). [4] Indeed, when \( T \leq 400 \) nm, \( Q_{vert} \) is in the range of 10,000. However, when \( T \geq 500 \) nm, \( Q_{vert} \) increases almost exponentially as \( T \) increases. We obtain a surprisingly high \( Q_{vert} \) of \( 6 \times 10^{5} \) at \( T = 2,000 \) nm, im-

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Fig. 1. (a) Design of the modified dipole cavity. (b,c) FDTD simulations for the dipole mode in a PhC slab with \( T = 2,000 \) nm. (b) Top-down view of the electric-field intensity \(|E|^2\) profile and (c) cross-sectional views of \(|E|^2\) of the fundamental, first-order, and second-order slab modes.
we show intersection points between the dispersion curve and the three normalized frequencies \( \omega_{\alpha} = a/\lambda \) of the resonant modes. We find that these points are almost equally arranged in the \( k \) space, where \( \Delta k_z \) indeed satisfies the Fabry-Pérot resonance condition, \( \Delta k_z = \pi/T; \Delta k_z/(2\pi/a) = a/(2T) \approx 0.076 \). [9] Note that the group velocity \( (V_g \equiv d\omega/dk) \) of the fundamental dipole mode will approach zero as \( T \to \infty \) and \( k_z \to 0 \) [See Fig 3(b)].

In view of this waveguide model, \( Q_{\text{tot}} \) of the fundamental dipole mode can be written as the sum of waveguide propagation loss and scattering loss at the two mirror facets such that [9, 11]

\[
\frac{1}{Q_{\text{tot}}} = \frac{V_g}{\omega} \left[ \alpha + \frac{1}{T} \log \left( \frac{1}{r_0^2} \right) \right]. \tag{1}
\]

Here, \( \omega \) is the angular frequency of the resonant mode and \( \alpha \) is the waveguide propagation loss coefficient describing the imperfect horizontal photon confinement due to both the finite \( x-y \) domain size and coupling into the higher-order slab modes. [2] As shown in Fig. 3(b), \( \alpha \) varies as a function of \( k_z \); it tends to diverge as \( k_z \to 0 \) due to the presence of a zero group velocity at \( k_z = 0 \). [12] \( r_0 \) is a reflection coefficient and \( 1/(T) \log(1/r_0^2) \) describes the scattering loss at the two mirror facets. Thus, \( V_g \alpha/\omega \) and \( V_g \log(1/r_0^2)/(T\omega) \) can be rewritten as \( 1/Q_{\text{horz}} \) and \( 1/Q_{\text{vert}} \), respectively. [5] Now it is straightforward to show that \( Q_{\text{vert}} \) of the fundamental slab mode will grow indefinitely as \( T \to \infty \) and \( V_g \to 0 \). The fact that the slow group velocity can enhance \( Q \) of a resonant mode has been emphasized by Kim et al., [9] who analyzed the ultra-high-\( Q \) mode in a PhC linear cavity, and by Ibanescu et al., [13] who used the anomalous zero group velocity point in an axially uniform waveguide to design a high-\( Q/V \) cavity on a dielectric substrate. However, \( Q_{\text{horz}} \) will be bound by a finite value as \( k_z \to 0 \); \( Q_{\text{horz}} \) will approach the \( Q \) of an ideal 2D dipole cavity (TE mode). Therefore, this simple analysis based on the waveguide dispersion can explain major features in \( Q \) behavior observed in Fig. 2.

In our experiment, PhC dipole mode cavities are fab-
ricated in an InGaAsP slab with $T = 606$ nm. Seven 60-Å-thick compressive-strained (1.0 \%) InGaAsP quantum wells emitting near 1.3 µm are embedded at the center of the slab, with 120-Å-thick tensile-strained (-0.3 \%) 1.12 µm InGaAsP barriers in between. 240-nm-thick unstrained 1.12 µm InGaAsP is on top and bottom of the active layer and serve as a cladding. We use standard nano-fabrication processes including e-beam lithography (using hydrogen silsesquioxane as the resist), dry-etching to drill the PhC air-holes, and selective wet-chemical etching to undercut the InP sacrificial layer. To define deep and vertical air-holes, we use high-temperature (190°C) Ar/Cl$_2$ chemically-assisted ion-beam etching (CAIBE). As shown in Fig. 4(a) and (b), our optimized CAIBE system produces very deep (>3 µm) and vertical sidewalls, which are requisites to experimentally realize the theoretical $Q_{\text{tot}}$ of 2,000 ~ 3,000. Fig. 4(b) and (c) show scanning electron microscope (SEM) images of fabricated laser devices.

The fabricated lasers are photo-pumped at room-temperature with a 830 nm laser diode. The repetition rate of the pump laser is 1 MHz with a duty cycle of 2 \%. We use a 100× objective lens to focus the pump laser on to the cavity region. The same objective lens is used to collect the emitted laser light, which is fed into an optical spectrum analyzer. In Fig. 4(d), we present a light-in versus light-out (L-L) curve and a lasing spectrum for one example laser device. We confirm that the laser emission indeed comes from one of the degeneracy-split dipole modes [1] by comparing the emission wavelength (1323.7 nm) with that obtained by FDTD simulation. Assuming that about 20% of actual incident pump power is absorbed in the slab, the effective threshold peak pump power is estimated to be 78 µW.

Though the present work merely demonstrates an optically-pumped device, it is our hope that the thick-slab PhC cavity design will provide versatile routes toward a current-injection PhC laser. One feasible plan is to place the whole PhC slab cavity onto a metal substrate, where the metal may serve as both an electrical current pathway and a heat sink. [14] An alternative is to take advantage of the increased slab thickness, which enables more flexible design of the $p-i-n$ doped layers and a current aperture structure.

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