Higher-order defect mode laser in an optically thick photonic crystal slab

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The use of an optically thick slab may provide versatile solutions for the realization of a current injection type laser using photonic crystals. Here, we show that a transversely higher-order defect mode can be designed to be confined by a photonic band gap in such a thick slab. Using simulations, we show that a high-Q of $>10^5$ is possible from a finely tuned second-order hexapole mode. Experimentally, we achieve optically pumped pulsed lasing at 1347 nm from the second-order hexapole mode with a peak threshold pump power of 88 µW. © 2014 Optical Society of America

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Two-dimensional (2-D) photonic crystal (PhC) slab structures have, so far, been in the form of a thin dielectric slab, whose thickness $T$ is often chosen to be $\sim$200 nm for an operational wavelength of $\sim$1.3 µm. This thickness consideration is to maximize the size of the photonic bandgap (PBG) in the in-plane direction ($x$-$y$ plane) [1], which has unfortunately placed a severe constraint on the design of a current-injection type laser. Pulsed lasing operation has been demonstrated using a vertically-varying $p$-$i$-$n$ doping structure within the thin PhC slab, for which a sub-micron size dielectric post placed directly underneath the laser cavity serves as a current path [2]. Recent efforts have moved towards a laterally-varying $p$-$i$-$n$ structure and a few successful results were already reported by groups in both Stanford [3] and NTT [4]. However, there are still favorable reasons for using a vertically-varying doped structure, because such a design allows a monolithic growth of all of the epitaxial layers that are almost free of crystal defects.

Recently, we have shown that even a very thick slab can support sufficiently high-Q (few thousands) cavity modes for lasing. [5] In our previous result, however, the dipole mode formed in a triangular lattice air-hole PhC slab was emitting more photons into the in-plane directions rather than into the vertical direction ($z$) for efficient photon emission and collection. Moreover, $Q$ could not exceed 3,000 with $T = 606$ nm. It would seem, at first, that we have no other options for further improvement in $Q$, since the poor horizontal confinement appears inevitable due to the absence of a PBG. It is our purpose in this Letter to rebut this first intuition and show that the thick slab can be used to achieve an efficient vertical emitter with a surprisingly high $Q$ of over $10^5$.

To start, we perform numerical simulations both using the plane-wave-expansion method (PWE) [6] and the finite-difference time-domain method (FDTD) to investigate how a PBG evolves as we change the air-hole radius ($r$) and the slab thickness ($T$) [Fig. 1(a)]. Note that $r$ and $T$ are represented in the unit of the lattice constant ($a$). In the case of a triangular lattice air-hole PhC, $\{r = 0.40a, T = 0.6a\}$ gives the widest gap centered at $\omega_a \approx 0.38$, which agrees with earlier work by Johnson, et al. [1]. Also note that there exists a broad region of $\{r, T\}$ that gives a wide gap-to-midgap ratio [1] $\tilde{\Delta} \omega > 30\%$. This is why $r$ and $T$ are often chosen to be $\sim 0.35a$ and 0.5$a$, respectively. We also find that a tiny PBG (usually $\tilde{\Delta} \omega \sim 1\%$) exists up to $T = 1.25a$.

The dipole mode discussed in our previous work [5] $(T = 1.86a)$ is marked as ‘1d’ in the gap map. Now, we pose the question of whether we can design a certain resonant mode emitting at $\sim$1.3 µm that is confined by a PBG in a slab with $T = 606$ nm. From the gap map diagram, the only possibility appears to be increasing $a$ in order to bring down $T(a)$ below 1.25$a$. However, keeping the same ‘1d’ mode, larger $a$ usually results in the longer $\lambda$, because $\omega = a/\lambda$ is rather fixed by the in-plane modal structure of a resonant mode [7]. Therefore, we should look instead into other resonant modes that do not resemble the dipole mode.

It is well known that even a single defect resonator supports multiple resonances such as the quadrupole, the hexapole, and the monopole modes [8]. These higher-order modes are pulled down from the conduction band-edge of the photonic band structure [7]. Further tuning the defect region can get more higher-order modes pulled down into the gap. One possible route from the (first-order) dipole mode (‘1d’) to the second-order hexapole mode (‘2h’) is drawn by an arrow in the gap map diagram. The ‘2h’ is designed to be resonant at a wavelength close to that of ‘1d’ [9] even though it has quite a large $a$ of 500 nm (thus, $T \approx 1.21a$). As a quantitative measure showing how well the PhC layers work as a mirror, we calculate the vertical extraction efficiency $\eta_{vert}$ defined by $\eta_{vert} = (1/Q_{vert})/(1/Q_{horz} + 1/Q_{vert}) = \quad$
Fig. 1. (a) A 2-D map of a PBG for a triangular lattice air-hole (radius = r) PhC in a dielectric slab (n_{slab} = 3.4) with a thickness of T. The 2-D color scale map represents the size of the PBG in terms of the gap-midgap ratio defined by $\Delta \omega \equiv \Delta \omega / \omega_c$, where $\omega_c$ is the center frequency of a PBG. The contour lines of $\omega_c$ are overlaid on the 2-D map. Note that throughout the Letter, all frequencies are normalized by $2\pi c / a$, hence $\omega = a / \lambda$ (dimensionless). (b) The (first-order) dipole mode ($Q = 2,600$ and $V = 0.82(\lambda / n_{slab})^3$) oscillating at $\lambda = 1341$ nm with $a = 325$ nm and (c) the second-order hexapole mode ($Q = 15,200$ and $V = 2.23(\lambda / n_{slab})^3$) oscillating at $\lambda = 1365$ nm with $a = 500$ nm. Both modes are formed in a slab with $T = 606$ nm.

$(1 / Q_{\text{vert}}) / (1 / Q_{\text{tot}})$ [5]. We find that $\eta_{\text{vert}}$ of ‘2h’ shown in Fig. 1(c) is 0.954 ($Q_{\text{horz}} = 3.3 \times 10^5$) with the same number of air-hole barriers shown in Fig. 2(b). We believe this $\eta_{\text{vert}}$ (or $Q_{\text{horz}}$) has not yet been saturated due to the small gap size, expecting further improvement by increasing the number of barriers. Probably, in applying the idea of a higher-order resonant mode, $T$ of 606 nm would be the upper limit for $\lambda \sim 1300$ nm, as ‘2h’ can only be made barely located at the top-right corner of the gap map diagram. We would like to note that the same strategy can be applied more effectively to the case of an intermediate thickness range of $400 \text{ nm} < T < 600 \text{ nm}$. Imagine a first-order resonant mode (‘1x’) oscillating at $\omega \approx 0.26$ within a slab with $T = 1.1a$. At this region, $\Delta \omega$ is only about 5%. We can bring it down deep into the band gap by utilizing its second-order resonant mode (‘2x’). If ‘2x’ oscillates at $\omega \approx 0.33$, then, without altering $\lambda$, ‘2x’ can be formed in a slab with $T \approx 0.87a$, at which $\Delta \omega$ is as large as 20%.

Surrounding the ‘2h’ with the large air-holes of $R = 0.46a$ would give better spectral matching between the ‘2h’ resonance and the center of the tiny bandgap. However, such a large air-hole radius is not advantageous for the device’s mechanical robustness. Therefore, we proceed to study if the background air-hole radii ($R_{bg}$) can be substantially reduced without sacrificing $Q$ too much. Several representative cases of fine-tuned air-holes are shown in Fig. 2 and Table 1. $\omega$ and $Q$ are most sensitively dependent on the parameters near the center of the resonator: $R_1$, $K_1$, and $K_2$. These parameters have been determined in a manner to optimize $Q$. The outskirt region from $R_4$ is intended as a mirror.

![Fig. 2](image_url)

**Table 1.** Examples of the second-order hexapole mode in a $T = 606 \text{ nm}$ slab.

| case | $R(a)$ | $R_{bg}(a)$ | $Q_{tot}$ | $Q_{vert}$ | $\eta_{vert}$ |
|------|--------|-------------|----------|-----------|--------------|
| I    | 0.45   | 0.45        | 55,400   | 58,500    | 0.947        |
| II   | 0.45   | 0.38        | 105,100  | 146,200   | 0.719        |
| III  | 0.44   | 0.38        | 50,400   | 63,900    | 0.789        |
| IV   | 0.43   | 0.38        | 27,900   | 34,400    | 0.811        |
| V    | 0.42   | 0.38        | 17,800   | 21,800    | 0.813        |
| VI   | 0.41   | 0.38        | 12,400   | 15,300    | 0.807        |
radii before and after $R_4$ are designed to vary gradually to minimize unintentional scattering losses at the crystal dislocations. Since $R_1$, $K_1$, and $K_2$ are fixed, all the resonant wavelengths tend to stay near 1323 nm. $a = 450$ nm for all those cases, thus $T = 1.35a$ and there exists no PBG.

Contrary to the initial expectation, $Q$ can be made higher even in the absence of a rigorous PBG [10]. In Case II, we find that $Q_{\text{vert}}$ can be greatly improved by more than a factor of 10, thereby $Q_{\text{tot}}$ can reach over $10^5$. It is interesting to observe that, comparing I and II, air-holes located far from the mode’s energy ($R > 6$) can affect $Q_{\text{vert}}$. It should also be noted that just one layer of $R_4 = 0.45a$ effectively blocks the horizontal photon leakage. As we progressively reduce $R$, both $Q_{\text{vert}}$ and $Q_{\text{horz}}$ decrease somewhat. At the final stage of the tuning (VI), all air-hole sizes become reasonable for experimental realization and $Q$ remains well above what is required for lasing.

In experiment, we intend to fabricate structurally more robust design similar to VI rather than the $Q$-optimized design of II. We use the same InGaAsP wafer containing 7 InGaAsP quantum wells emitting near 1325 nm used in our previous work [5]. To define high-aspect ratio air-holes, we use chemically-assisted ion-beam etching with Ar and Cl$_2$ [5]. The fabricated devices are optically pumped at room-temperature with a 830 nm laser diode driven by a pulse generator at 1 MHz with a duty cycle of 2.5%. A 100× objective lens is used to focus the pump laser on the center of the resonator. The $L$-$L$ curve clearly shows a threshold, estimated to be 88 $\mu$W in terms of peak pump power, where we have assumed about 20% of actual incident pump power is absorbed by the slab. We verify single mode lasing operation over a wide spectral range (1300 nm~1400 nm) with a side-mode suppression ratio of $\sim 30$ dB. To confirm if the measured laser peak truly originates from the ‘2h’, we perform FDTD simulation using a contour input for actual fabricated air-holes from the SEM image. The FDTD expects that the designed ‘2h’ mode should locate at a wavelength of 1340 nm, which agrees very well with the experimental result.

In summary, we show that a PhC slab with optically thick $T = 606$ nm can be used to construct a PBG-confined resonant mode oscillating at a wavelength of $\sim 1300$ nm. We also show that a surprisingly high $Q$ of over $10^5$ can be obtained even in the absence of a rigorous PBG, and that the use of the higher-order resonant mode can be quite advantageous for making an efficient PhC laser with an optically thick slab.

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References

1. S. G. Johnson, S. Fan, P. R. Villeneuve, J. D. Joannopoulos, and L. A. Kolodziejski, “Guided modes in photonic crystal slabs,” Phys. Rev. B 60, 5751–5758 (1999).
2. H.-G. Park, S.-H. Kim, S.-H. Kwon, Y.-G. Ju, J.-K. Yang, J.-H. Baek, S.-B. Kim, and Y.-H. Lee, “Electrically driven single-cell photonic crystal laser,” Science 305, 1444–1447 (2004).
3. B. Ellis, M. A. Mayer, G. Shambat, T. Sarmiento, J. Harris, E. E. Haller, and J. Vuckovic, “Ultralow-threshold electrically pumped quantum-dot photonic-crystal nanocavity laser,” Nat. Photon. 5, 297–300 (2011).
4. S. Matsuo, K. Takeda, T. Sato, M. Notomi, A. Shinya, K. Nozaki, H. Taniyama, K. Hasebe, and T. Kakitsuka, “Room-temperature continuous-wave operation of lateral current injection wavelength-scale embedded active-region photonic-crystal laser,” Opt. Express 20, 3773–3780 (2012).
5. S.-H. Kim, J. Huang, and A. Scherer, “Photonic crystal nanocavity laser in an optically very thick slab,” Opt. Lett. 37, 488–490 (2012).
6. S. Johnson and J. Joannopoulos, “Block-iterative frequency-domain methods for maxwell’s equations in a planewave basis,” Opt. Express 8, 173–190 (2001).
7. J. D. Joannopoulos, S. G. Johnson, J. N. Winn, and R. D. Meade, Photonic Crystals: Molding the Flow of Light (Princeton University Press, Princeton, NJ, 2008), 2nd ed.
8. H.-G. Park, J.-K. Hwang, J. Huh, H.-Y. Ryu, S.-H. Kim, J.-S. Kim, and Y.-H. Lee, “Characteristics of modified
single-defect two-dimensional photonic crystal lasers,” Quantum Electronics, IEEE Journal of 38, 1353 – 1365 (2002).

9. Structural parameters for this 2nd hexapole mode are as follows: $K_1 = 1.07a$, $K_2 = 0.99a$, $R_1 = 0.28a$, $R_{bg} = 0.46a$, $R = 0.46a$. For definitions of these parameters, see Fig. 2.

10. S.-H. Kim, A. Homyk, S. Walavalkar, and A. Scherer, “High-Q impurity photon states bounded by a photonic-band-pseudogap in an optically-thick photonic-crystal slab,” http://arxiv.org/abs/1209.5726.