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. © 2012 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 ~200 nm for an operational wavelength of ~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 \(\omega_c \approx 0.38\), which agrees with earlier work by Johnson, et al. [1]. Also note that there exists a broad region \{r, T\} that gives a wide gap-to-midgap ratio [1] \(\frac{\Delta \omega}{\omega} > 30\%\). This is why r and T are often chosen to be \(~0.35a\) and \(0.5a\), respectively. We also find that a tiny PBG (usually \(\Delta \omega \sim 1\%\)) exists up to \(T \sim 1.25a\).

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 \(\sim 1.3 \mu m\) 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 1.25a. 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 \(\eta_{vert} = (1/Q_{vert})/(1/Q_{horz} + 1/Q_{vert}) = \)
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 $\tilde{\Delta}\omega \equiv \Delta\omega/\omega_c$, 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(λ/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(λ/n_{slab})^3] oscillating at $\lambda = 1365$ nm with $a = 500$ nm. Both modes are formed in a slab with $T = 606$ nm.

$(1/Q_{vert})/(1/Q_{tot})$ [5]. We find that $\eta_{vert}$ of ‘2h’ shown in Fig. 1(c) is 0.954 ($Q_{horz} = 3.3 \times 10^5$) with the same number of air-hole barriers shown in Fig. 2(b). We believe this $\eta_{vert}$ (or $Q_{horz}$) 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, $\tilde{\Delta}\omega$ 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 $\tilde{\Delta}\omega$ 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. Air-hole

![Figure 2](image2.png)

Fig. 2. (a) A schematic diagram shows how we finely tune air-hole sizes and locations to optimize $Q$. (b) An electric-field intensity distribution ($|E|^2$) of the highest-$Q$ mode (case II in Table 1).

Table 1. Examples of the second-order hexapole mode in a $T = 606$ nm slab.

<table>
<thead>
<tr>
<th>case</th>
<th>$R(a)$</th>
<th>$R_{bg}(a)$</th>
<th>$Q_{tot}$</th>
<th>$Q_{vert}$</th>
<th>$\eta_{vert}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>0.45</td>
<td>0.45</td>
<td>55,400</td>
<td>58,500</td>
<td>0.947</td>
</tr>
<tr>
<td>II</td>
<td>0.45</td>
<td>0.38</td>
<td>105,100</td>
<td>146,200</td>
<td>0.719</td>
</tr>
<tr>
<td>III</td>
<td>0.44</td>
<td>0.38</td>
<td>50,400</td>
<td>63,900</td>
<td>0.789</td>
</tr>
<tr>
<td>IV</td>
<td>0.43</td>
<td>0.38</td>
<td>27,900</td>
<td>34,400</td>
<td>0.811</td>
</tr>
<tr>
<td>V</td>
<td>0.42</td>
<td>0.38</td>
<td>17,800</td>
<td>21,800</td>
<td>0.813</td>
</tr>
<tr>
<td>VI</td>
<td>0.41</td>
<td>0.38</td>
<td>12,400</td>
<td>15,300</td>
<td>0.807</td>
</tr>
</tbody>
</table>
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


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.