Photonic crystal nanobeam lasers

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Abstract: Photonic crystal lasers operating at room temperature based on high Q/V nanobeam cavities have been demonstrated. We report a large spontaneous emission factor (β-0.97) by fitting the L-L curve with the rate equations.

Photonic crystal lasers,1 with small mode volumes (V) and high Quality (Q) factors, have enhanced photon emission below threshold via Purcell effect,2-4 and can operate with high modulation speeds.5,6 Moreover, threshold-less lasing has been predicted in photonic crystal cavities, with necessary but not sufficient condition that the spontaneous emission factor (β) amounts to unity.7,8 Most photonic crystal lasers so far have been demonstrated based on two-dimensional (2D) photonic crystal slabs. Recently nanobeam structures attracted extensive interests because of their capability to achieve ultra-high Q/V factors in much smaller footprint.9-11 We emphasize a small mode volume of these resonators, close to the diffraction limit [(λ/2n)²], that is crucial for realization of large Purcell factor in solid-state emitters with a considerable homogeneous broadening (e.g. bulk semiconductors, semiconductor quantum wells at room temperature). In addition, nanobeam cavities do not have mode degeneracy12-15 and therefore can support a single cavity mode over a broad spectrum. This single-mode nature is important for a large β factor and reduction of lasing threshold.8 In this work we report the experimental demonstration of photonic crystal nanobeam lasers operating at room temperature.

The nanobeam cavities are designed using the same approach as our previous work.9 The cavity is designed, using three dimensional finite-difference time-domain (3D-FDTD) modeling, to support a fundamental TE-like mode at 1.59μm, polarized predominantly along x-axis. Field components of the fundamental mode are shown in Fig. 1(a). The electric field density is concentrated in the dielectric region, leading to a large confinement factor needed for a lasing action. The mode volume of this mode is 0.28(λ/n)³, which is close to the diffraction limit, and its passive Q factor is larger than 8,000,000. In addition, the cavity supports another mode at a longer wavelength (1.72μm). This is an extended mode, with a node in the center of the structure and a larger mode volume of 0.67(λ/n)³.

![Image](image1.png)

FIG. 1 (a) The lasing mode profile (Eₓ and Eᵧ components) that resonates at 1.59μm. The higher-order mode profile (Eᵧ component) that resonates at a higher wavelength of 1.72μm. (b)(c) Scanning electron micrograph image (side-view) of the final fabricated nanobeam structures with low and high magnification.

Our cavities are fabricated in a 330nm thick, MOCVD grown, In₀.₅₃(Al₀.₄₇)Ga₀.₅₃As slab that contains four compressively strained In₀.₆₅Ga₀.₃₅As quantum wells placed at the center of the slab. Active layer’s emission is maximized at wavelength of 1.59μm, and is transverse-electric (TE) polarized due to the strain. The slab is grown
on top of a 1 µm thick sacrificial InP layer. Top-down fabrication sequence, based on e-beam lithography (using negative Foxx resist) followed by ICP reactive ion etching (BCl3/HBr chemistry) is used to realize the structures. The remaining mask layer is then removed in HF, and nanobeams are released in 3:1 HCl:H2O solution at 11ºC. The final fabricated structures are shown in Fig. 1(b). The pattern consists of 10 nanobeam supported by the two pads located aside.

The samples are photo-pumped at room temperature with a 660nm pulsed laser diode. The pulse width and repetition rate are 9ns and 300kHz respectively, corresponding to a duty cycle of 0.27%. The pump beam is focused to a ~4µm diameter spot via a 100X objective lens, and the emitted light is collected via the same objective lens and analyzed using optical spectrum analyzer (OSA), infrared camera, and IR detector.

In Fig. 2(a), we show the output power as a function of the peak pump power (L-L curve) incident onto the nanobeam for one of the cavities. Soft turn-on of the laser, without pronounced threshold, is indication of a large β factor. In order to unambiguously attribute the lasing action to the localized defect mode, we used NIR camera to image the mode profiles at different pump levels (Fig. 2(a)). It can be seen that the emission spot is well localized to the center of the beam. In addition, by scanning the sample in x-z plane using a piezo-actuated stage with a spatial resolution of 6nm, we checked the dependence of the output power on the pump beam position [Fig. 2(b)]. As the pump beam is moved away from the center of the cavity, the beam intensity decreases rapidly and finally vanishes. This is further confirmation of emission from localized mode of the cavity, and not extended band-edge emission. Here, the slightly elongated shape along x-axis of the emission profile is due to the elliptical shape of the pump beam used in the experiment: the waist of pump beam is larger in x-direction, and it is much larger than the width of the nanobeam. This also allows us to evaluate the effective pump power, that is, the overlap of the pump beam with the nanobeam. This effective pump power is reported in Fig. 2(a). We evaluate an effective threshold of 84µW for our nanobeam laser. We note, however, that the threshold is even smaller, since not all the pump power incident onto the nanobeam is absorbed by the cavity. Finally, in Fig. 2(c) we show the polarization dependence of the emission beam. The laser is polarized in x-axis and exhibits a large polarization ratio of ~10, which is another signature of the highly polarized cavity mode.

The carrier and photon behaviors of the photonic crystal lasers can be analyzed using the following rate equations:\textsuperscript{16},

![FIG. 2](image-url)
We also show in Fig. 3 the theoretical behavior of the Purcell factor as it approaches infinity. In this scenario, there is no...
clear kink as the lasing action is built up. However, we point out that the lasing threshold in this limit is still finite, and is determined by $\alpha$. In fact, we note that the threshold power is independent of Purcell factor. The threshold photon density flux can be expressed as $\tilde{F}_{ph,th} = AN_s + \alpha BN_s^2 + CN_s^3$, where $N_s$ satisfies $G(N_s) = \frac{c}{\lambda_s^3}$. Some previous works have drawn similar conclusions. To reduce the lasing threshold or moreover achieve threshold-less behavior, it is necessary to engineer the cavity with small $\alpha$ factor (and thereby a high $\beta$ factor) and low surface recombination. This will be direction taken in our future work.

In conclusion, we have experimentally demonstrated photonic crystal nanobeam lasers operation at room temperature. The small cavity mode volume results in large Purcell factor. This effect, alongside with the single-mode coupling within the electron transition spectrum, leads to a high spontaneous emission factor ~0.97. These results present a promising candidate for low-threshold high-speed nanoscale lasers.

Acknowledgments

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