

Photonic Crystal Nanocavities for Efficient Light Confinement and Emission

Axel SCHERER,* T. YOSHIE, M. LONČAR, J. VUČKOVIĆ and K. OKAMOTO
Caltech, Pasadena CA 91125-3600, U.S.A.

D. DEPPE
University of Texas at Austin, Austin Tx 78712-1084, U.S.A

When combined with high index contrast slabs in which light can be efficiently guided, microfabricated two-dimensional photonic crystals provide us with the geometries needed to confine and concentrate light into extremely small volumes and to obtain very high field intensities. Fabrication of optical structures has now evolved to a precision which allows us to control light within such etched nanostructures. Sub-wavelength nano-optic cavities can be designed for efficient and flexible control over both emission wavelength and frequency, and nanofabricated optical waveguides can be used for efficient coupling of light between devices. The substantial reduction of the size of optical components leads to their integration in large numbers and the possibility to combine different functionalities on a single chip, much in the same way as electronic components have been integrated for improved multi-functionality of microchips. Here we describe the use of microfabricated periodic structures, photonic crystals, to define functional nano-optic cavities for efficient confinement and emission of light, which leads to the desire for miniaturization of optical devices.

PACS numbers: 78.66.Fd

Keywords: Two-dimensional photonic crystals, Nanocavity

I. DESIGN OF NANOCAVITIES

When we generate light in optical cavities with very small volumes (Figure 1), we can substantially decrease the number of modes for that emitted light to couple to. This effect was first recognized by Purcell, and leads to the conclusion that, if the emission spectrum is narrower than the cavity resonance peak, the spontaneous emission rate of light into one of the supported modes can be enhanced. Thus, spontaneously emitted light can be more efficiently coupled into an extracted mode. This lead to the desire for efficient light emitters, which are based on nanocavities with very small mode volumes and high Q values. We have developed new optical cavity designs based on photonic crystal [1,2] mirrors with single defects, which include carefully designed asymmetries (Figure 2), in which the out of plane losses from the photonic crystal cavity are significantly reduced.

Since the Q values of two-dimensional optical nanocavities are typically dominated by these out of plane losses, our new approaches have allowed us to design optical nanocavities with Q values in excess of 10,000. We have used these new device designs to fabricate low-threshold lasers in InGaAsP quantum well material, and have observed 0.2 mW threshold power and highly localized lasing modes. These cavities can also be optimized to con-

tain voids in the center of the two-dimensional Fabry-Perot structure. In this case, the optical field intensity overlaps with the material inside of the void, which can later be backfilled with low-index material of choice. For example, it is possible to use laser nanocavities as chemical sensors, in which the threshold current of the laser is strongly dependent on the amount and type of absorbing material contained within the central hole. Figure 3 shows the design and the field intensity distribution of one of these special nanocavities. Nonlinear material can also be introduced into such optical cavities to permit precise spectral tuning of the cavity resonance peak in

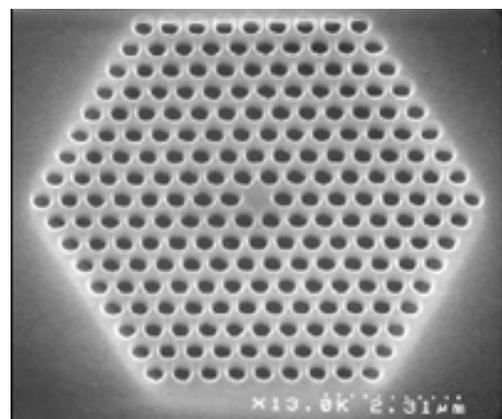


Fig. 1. PBG Nanocavity

*E-mail: etcher@caltech.edu

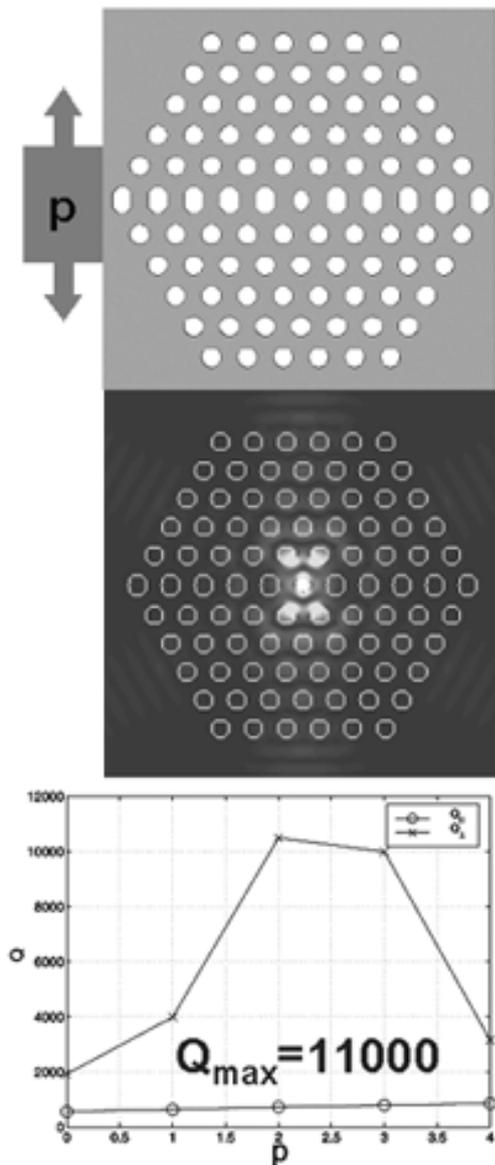


Fig. 2. High Q PBG resonator design

materials such as silicon. In this paper, we will describe the opportunities of using high-Q optical nanocavities to efficiently confine light, to generate ultra-small lasers, to route light and to extract it into desired modes. In the past, we have defined high Q partial edge dislocation cavities in InGaAsP for laser emission at 1500nm and in InGaAs quantum dots for laser emission at 1300nm, and in silicon for filtering light and waveguiding on silicon on insulator (SOI) chips.

II. HIGH Q PHOTONIC CRYSTAL CAVITIES

Figure 4 is a schematic of a 2D photonic crystal nanocavity, which can be fabricated using electron beam

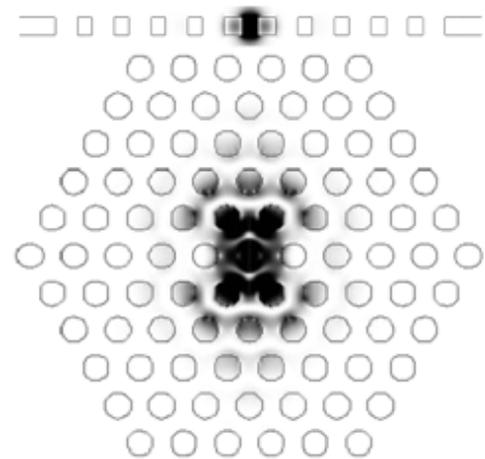


Fig. 3. Crossectional view and plan view of a high-Q cavity showing optical field intensity distribution

lithography and reactive-ion-etching to form the holes that lead to Bragg scattering within the 2D waveguide and result in the 2D photonic bandgap. A critical feature of this cavity is that it enables optical confinement to a mode volume of $\sim 2.5(\lambda_0/2n)^3$, where λ_0/n is the wavelength in the semiconductor. We have already demonstrated room temperature lasing in the smallest optical cavities, with mode volumes down to $2.5(10/2n_{slab})^3$, or $0.03 \mu\text{m}^3$ in InGaAsP emitting at $\lambda_0 = 1.55 \mu\text{m}$ [3]. We have also been able to tune the emission wavelength of these lasers from 1450 to 1620 nm within a 10×10 laser array in an area of $100 \mu\text{m} \times 100 \mu\text{m}$ by local lithographic modification of the cavity lengths. As the mode volumes of nanocavities are decreased, the coupling effi-

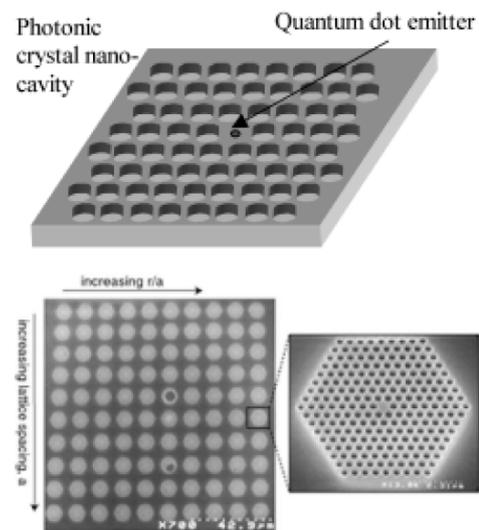


Fig. 4. Photonic crystal nanocavity with an active region containing self-organized quantum dots. Also shown is a typical array of nanocavities that allows the lithographic coarse tuning of the resonance peak.

ciency between the spontaneous emission within the cavity and the lasing mode can be significantly improved. We have calculated coupling factors (β) above 85 % for optimized photonic crystal lasers constructed in active quantum well material. This spontaneous emission coupling efficiency can be even higher if the linewidth of the semiconductor emission is narrowed, as is the case when using quantum dot active material. Therefore, single defect photonic crystal lasers represent the ultimate evolution of VCSELs, as control over both vertical and lateral spontaneous emission is possible. With most of the spontaneous emission funneled into a single optical mode, the photonic crystal laser can be modulated at much higher frequencies even close to threshold. The photonic crystal provides us with the unique opportunity of coupling light emitted by one cavity, and using it to optically pump another with negligible diffraction losses. Photonic crystals provide us with the opportunity of constructing very compact laser sources with designed frequencies and polarization as well as wavelength and polarization sensitive detector arrays. Moreover, they can form very flexible platforms for connecting optical sources and waveguides in very compact microfabricated systems.

III. QUANTUM DOTS IN HIGH-Q NANOCAVITIES

The growth of quantum dots by epitaxial growth usually results in inhomogeneous broadening of the emission resulting from ensemble of InAs island sizes. For the ground state emission, the inhomogeneous broadening is typically as wide as 40meV and the lifetime is around 800 psec in bulk at room temperature. However, the ground state emission from single QD (SQD) is narrower than 150 μ eV at 60K or less in the low excitation regime as observed by spatially resolved photoluminescence (PL) or μ -PL. Microcavities are expected to modify radiation process and thereby enhance spontaneous emission dramatically.

Figure 5 shows luminescence spectra from quantum dot material before (dotted line) and after (solid line) the definition of a high-Q photonic crystal cavity [4]. The inset picture shows an enlarged image of the geometry of the photonic crystal nanocavity, which in this case contains approximately 500 self-assembled InAs quantum dots. Of this large number, only 3 or 4 match the Fabry-Perot resonance frequency, and contribute to the narrow but bright emission peak. Quantum dot material provides us with several important advantages when designing a photonic crystal laser. The first of these advantages is the opportunity to decrease the surface recombination of carriers, a particular problem in nanofabricated high surface area to volume devices. The second advantage of this materials system is the optical transparency compared with quantum well material, which enables a

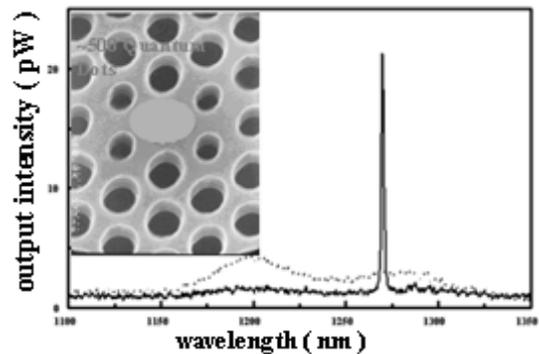


Fig. 5. Photoluminescence spectrum showing a sharp resonance peak measured from a nanocavity fabricated in

significant reduction of the re-absorption losses within the patterned mirror material surrounding the nanocavity. This problem results from our fabrication approach, in which the same material is used for both gain and as a two-dimensional mirror to confine the light. Finally, quantum dots are expected to allow a large reduction of the laser threshold power due to the smaller volume of active material, as well as the opportunity of taking advantage of the inherent narrow spectral width of single quantum dots.

Figure 6 shows the calculated Q values expected from our partial edge dislocation cavities as a function of the elongation parameter. As can be seen from the inset, we have tested the Q values of such planar two-dimensional photonic crystal nanocavities by fabricated within self-assembled InGaAs quantum dot material, and observe Q values between 2800 and 3500 for single 2-D Fabry-Perot nanocavities.

IV. QUANTUM DOT PHOTONIC CRYSTAL LASERS

Very high Q resonator designs [5] allow the localization of light and generate very high optical field intensities. These device designs have been discovered by high resolution, fully three-dimensional model calculations using finite difference time domain code. When we pump carefully designed high-Q cavities beyond the lasing threshold, we measure laser threshold powers of \sim 130 microWatts [6] (Figure 7). By taking into account the pump light absorption within the photonic crystal slab as well as the size of the diameter of the optical mode, an equivalent laser threshold of $<$ 25 microWatts for optical pumped devices, or $<$ 25 microAmperes for electrically pumped nanocavities can be calculated. Figure 7 shows a typical laser spectrum as well as the corresponding L-L curve of our first photonic crystal quantum dot laser.

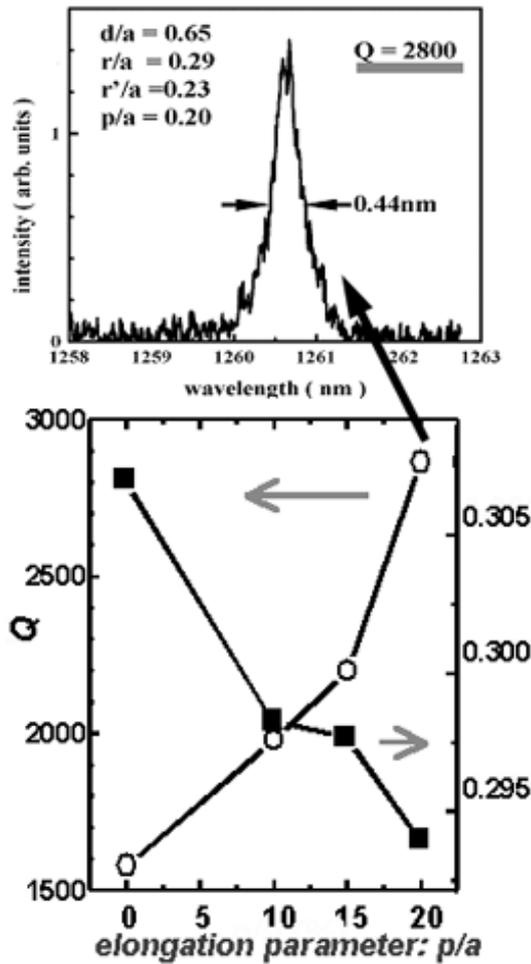


Fig. 6. Cavity Q versus the elongation parameter p/a of the partial edge dislocation. Spectrum of the luminescence from a high- Q structure showing Q of 2800.

V. NEAR FIELD OPTICAL PROBING

We have developed near field scanning optical microscopy (NSOM) imaging methods to measure spatial resolved photoluminescence (PL) and to compare modeled prediction of optical field intensity distributions with accurate measurements. The NSOM tip can be used to detect light generated by quantum dots in the photonic crystal in collection mode, or to excite single quantum dot (SQD) locally in the illumination mode. The combination of an ultrafast laser system with a NSOM is more informative than conventional micro-PL since the NSOM can obtain near-field information with as high resolution as 100nm or less while micro-PL has only micrometer resolution and generates only quasi-far field information (Figure 8). The combination of spatial and temporal resolution provides us with information of SQD emission process such as field distribution of mode, modal volume, emission lifetime and coupling efficiency of emission to the mode. The NSOM tip is scanned as collection mode

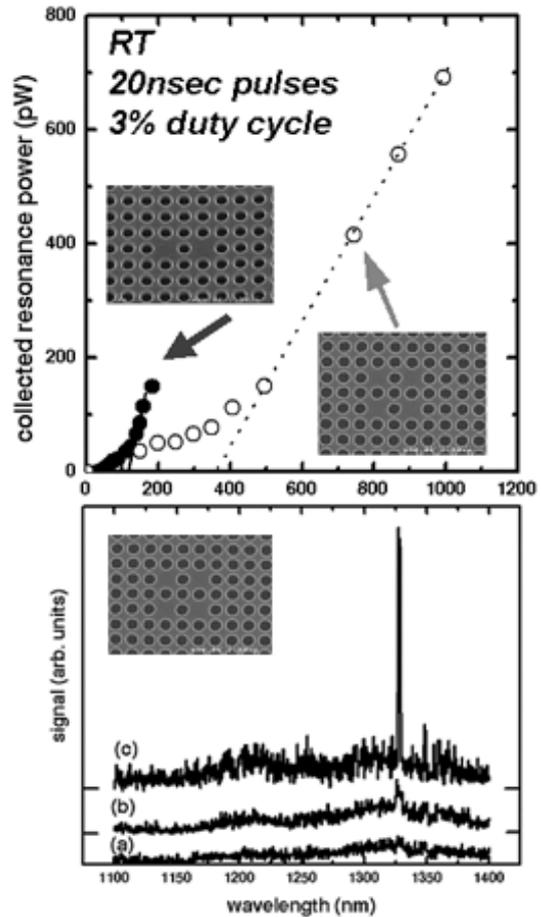


Fig. 7. Spectrum and L-L curve of a quantum dot photonic crystal laser

on the surface of cavity pumped by an ultrafast pump laser. On the other hand, the ultrafast laser can pump SQD on center of cavity through NSOM tip as illumination mode and objective lens picks up far field pattern as well. This combination with NSOM is used to confirm modified radiation resulting from resonant modes within the nanocavity.

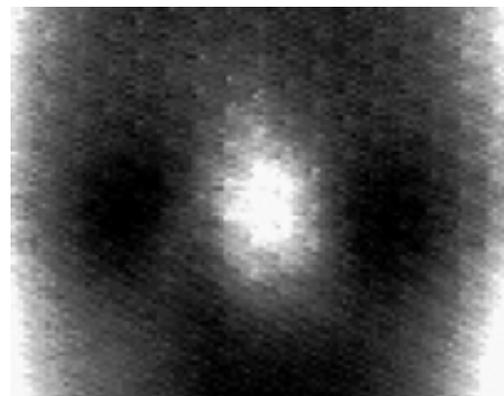


Fig. 8. NSOM image of PBG structures optical cavity.

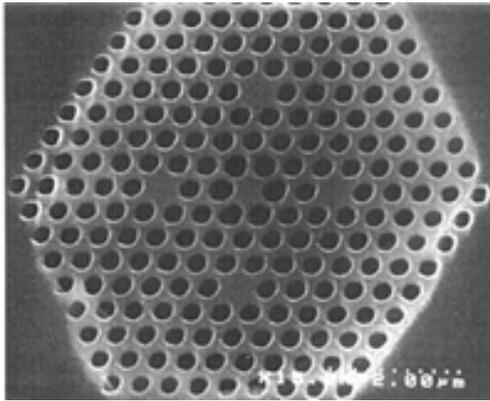


Fig. 9. Multiple optical nanocavities defined within a photonic crystal slab

VI. PHOTONIC CRYSTAL WAVEGUIDES AND SELF-COLLIMATING STRUCTURES

We have explored the fabrication of multi-cavity structures, and have developed methods for collimating light through the photonic crystal to optically interconnect these resonators. Figure 9 shows a multi-resonator structure, in which the resonators are coupled together through the photonic crystal. One of the key challenges of using such multi-resonator structures lies in fabricating the individual resonators with sufficient accuracy to allow spectral alignment and mode-matching of light from one cavity to another. This can be accomplished through the use of photonic crystal waveguides or by the use of self-collimating directions within the photonic crystal.

We have developed the design, fabrication and characterization tools to examine light propagation between optical cavities through photonic crystal waveguides. Waveguiding structures, which are analogous to “wires” for our nanophotonic circuits, have to be carefully designed to avoid the excitation of leaky modes and diffraction losses. We have developed several new designs of photonic crystal waveguides in order to optimize the single-mode performance needed for the proposed optical clock distribution system. Figure 9 shows three new geometries which we will investigate in this program to determine their suitability as optical interconnects. Another method for connecting multiple photonic crystal cavities together uses the self-collimation which is obtained in certain crystal directions due to the group velocity variation resulting from modifications in the shape of the band diagram as a result of patterning. Figure 10 provides an example of self-collimation in a photonic crystal in which the collimation direction is determined by the shape of the band diagram. We expect both of these geometric methods for connecting cavities to find applications in the development of all-optical clock distribution systems, and will investigate their performance

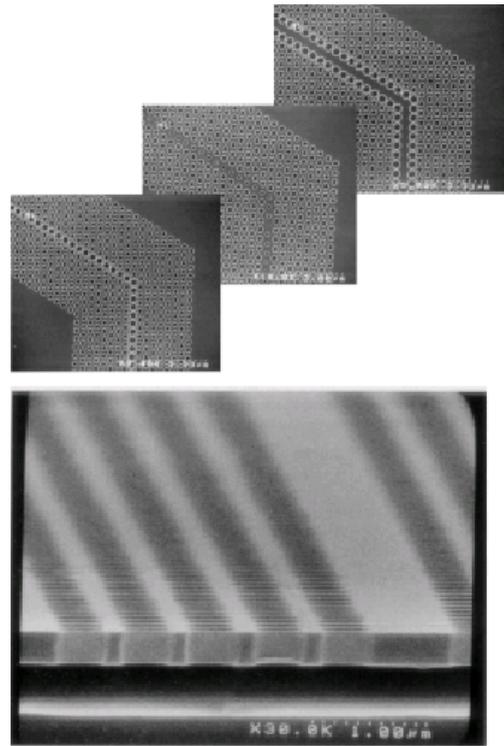


Fig. 10. Three geometries for single mode waveguides

in quantum dot material.

VII. DISCUSSION OF QUANTUM DOT PHOTONIC NANOCAVITIES FOR QUANTUM COMPUTATION

Through the fabrication of high-Q nanocavities and the growth of quantum dots, it is possible to mimic

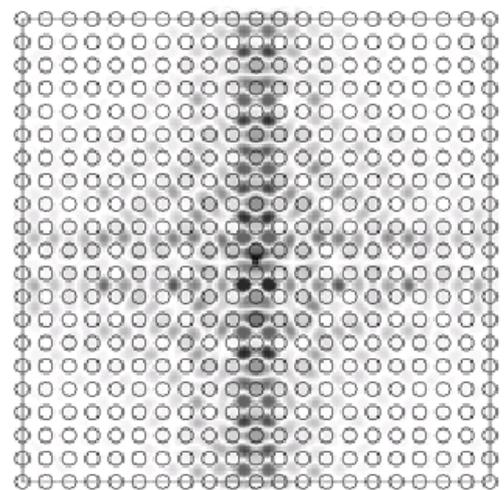


Fig. 11. Self-collimation in slab of PBG

the well-known vacuum Rabi oscillator, in which the Jaynes-Cumming-ladder spectral splitting (or oscillation frequency) depends directly on the photon number in the cavity (or excitation level). This type of cavity QED photon/exciton quantum entanglement could provide the key step for quantum computing. To achieve strong coupling with a single quantum dot, having an excited state lifetime τ , in a nanocavity with optical mode volume V , photon decay rate k , and quality factor Q , the splitting $2g_0$ needs to exceed κ . (Typically the dipole dephasing rate γ at low temperatures is smaller than κ , so this is not the main problem.) One can easily show that $2g_0/\kappa$ is proportional to Q divided by the square root of the product τV . Although strong coupling based on self-organized quantum dots has been considered before, the cavity volumes required for the strong coupling were prohibitively small for the $\tau \sim 1$ ns typical lifetime. Today, the nanocavities based on “point defects” within 2D photonic crystals demonstrated by our group can achieve the necessary mode volumes. Remarkably, V is 100 times smaller than that of previous native-oxide 2- μm -aperture nanocavities, while it is still possible to retain a Q of a few thousand. Possibilities which may result from including quantum dots into high Q nanocavities include the definition of two photon logic gates, as well as the possibility of using the cavity as a data bus or even as a short-term quantum-mechanical memory element.

VIII. CONCLUSIONS

High Q cavity designs have been developed by three-dimensional finite difference time domain calculations and are demonstrated to enable low-threshold lasing. These structures are also very interesting for quantum optics, with the opportunity for using the strong coupling between narrow linewidth emitters and high Q cavities.

ACKNOWLEDGMENTS

Support under DARPA contracts MDA972-00-1-0022 and MDA972-00-1-0019, as well as AFOSR contract QMTSYS F49620-01-1-0497 is gratefully acknowledged.

REFERENCES

- [1] E. Yablonovitch, *Phys. Rev. Lett.* **58**, 2059 (1987).
- [2] S. John. *Phys. Rev. Lett.* **58**, 2486 (1987).
- [3] O. Painter, R. Lee, A. Scherer, A. Yariv, J. O’Brien, P. Dapkus and I. Kim, *Science* **284**, 1819 (1999).
- [4] T. Yoshie, A. Scherer, H. Chen, D. Huffaker and D. Deppe, *Appl. Phys. Lett.* **79**, 114 (2001).
- [5] H. Ryu, S. Kim, H. Park, J. Hwang, Y. Lee and J. Kim, *Appl. Phys. Lett.* **80**, 3883 (2002).
- [6] T. Yoshie, J. Vuckovic, A. Scherer, H. Chen and D. Deppe, *Appl. Phys. Lett.* **79**, 4289 (2001).