*Discussion:* The free-running SFDR of 84 dB/Hz$^{2/3}$ is the highest reported to date for free-running long wavelength VCSELs, which is further enhanced by injection locking. The relatively high RIN values observed are possibly due to reflections from the VCSEL-fibre coupling lenses [9], which is still under investigation. Reducing the optical reflections is expected to reduce the RIN and further increase the SFDR.

The enhancement in the fundamental power is attributed to the increase of photon density and possibly differential gain, which enhance the electrical-optical modulation efficiency. Similarly, with the increase of photon density and differential gain, the resonance frequency is increased. A larger offset between the modulation and resonance frequencies reduces the nonlinear distortion enhanced by the carrier-photon interaction, which in turn reduces the third-harmonic distortion.

*Conclusion:* We have demonstrated that injection locking improves the analogue performance of long wavelength VCSELs. We have found that injection locking can improve the modulation bandwidth by a factor of two and reduce modulation nonlinearities. The gain of the VCSEL RF link was improved due to an increase in modulation efficiency. Finally, the third-harmonic spur-free dynamic range was improved by 9 dB/Hz$^{2/3}$ to be 93 dB/Hz$^{2/3}$. This is the highest reported SFDR for a long wavelength VCSEL.

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*Electronics Letters Online No: 20020678*
*DOI: 10.1049/el:20020678*

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## References

1 LIU, J.M., CHEN, H.F., MENG, X.J., and SIMPSON, T.B.: 'Modulation bandwidth, noise, and stability of a semiconductor laser subject to strong injection locking', *IEEE Photonics Technol. Lett.*, 1997, **9**, (10), pp. 1325–1327

2 ANNOVAZZI-LODI, V., SCIRE, A., SOREL, M., and DONATI, S.: 'Dynamic behavior and locking of a semiconductor laser subjected to external injection', *IEEE J. Quantum Electron.*, 1998, **34**, (12), pp. 2350–2357

3 CHEN, J., RAM, R.J., and HELKEY, R.: 'Linearity and third-order intermodulation distortion in DFB semiconductor lasers', *IEEE J. Quantum Electron.*, 1999, **35**, (8), pp. 1231–1237

4 PAPPERT, S., SUN, C., ORAZI, R., and WEINER, T.: 'Microwave fiber optic links for shipboard antenna applications'. Proc 2000 IEEE Int. Conf. Phased Array Systems and Technology, Dana Point, CA, USA, pp. 345–348

5 LEE, H.L.T., DALAL, R.V., RAM, R.J., and CHOQUETTE, K.D.: 'Dynamic range of vertical-cavity surface-emitting lasers in multimode links', *IEEE Photonics Technol. Lett.*, 1999, **11**, (11), pp. 1473–1475

6 PIPREK, J., TAKIGUCHI, K., BLACK, K.A., HU, E.L., and BOWERS, J.E.: 'Harmonic distortion in 1.55 μm vertical-cavity lasers', *IEEE Photonics Technol. Lett.*, 2000, **12**, (12), pp. 1686–1688

7 MENG, X.J., CHAU, T., and WU, M.C.: 'Improved intrinsic dynamic distortions in directly modulated semiconductor lasers by optical injection locking', *IEEE Trans. Microw. Theory Tech.*, 1999, **47**, (7), pp. 1172–1176

8 YUEN, W., *et al.*: 'High-performance 1.6 μm single-epitaxy top-emitting VCSEL', *Electron. Lett.*, 2000, **36**, (13), pp. 1121–1123

9 WAY, W.I., LIN, C., ZAH, C.E., CURTIS, L., SPICER, R., and YOUNG, W.C.: 'Multiple-reflection-induced intensity noise studies in a lightwave system for multichannel AM-VSB television signal distribution', *IEEE Photonics Technol. Lett.*, 1990, **2**, (5), pp. 360–362

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# Quantum dot photonic crystal lasers

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D.G. Deppe and A. Scherer

Coupled cavity designs on two-dimensional square lattice photonic crystal slabs were used to demonstrate optically pumped indium arsenide quantum dot photonic crystal lasers at room temperature. Threshold pump powers of 120 and 370 μW were observed for coupled cavities including two and four defect cavities defined in optimised photonic crystals.

*Introduction:* Photonic crystal (PC) [1, 2] planar cavities are likely to form compact building blocks, which can be used in future integrated nanophotonic systems. One of the most notable characteristics of PC cavities is that the mode profile and the quality ($Q$) factors are geometrically controlled and can be designed. Using simple defect cavity designs, the first photonic crystal lasers were reported [3] on InGaAsP multi-quantum well (QW) structures several years ago. Quantum dot (QD)-PC lasers, however, have been more difficult devices to construct due to much lower available gain from QD material [4, 5]. The smaller gain results not only from a lower total volume of actively emitting material but also from variations in the spatial locality of QDs as well as inhomogeneous emission broadening. These effects result in a smaller number of QDs contributing to the gain in a resonance as the $Q$ factor is increased.

Our approach to address these issues is to use high $Q$ cavities with relatively larger mode volumes. In this Letter, we describe simple designs of coupled cavities in square lattice photonic crystals and demonstrate laser operation from such quantum dot photonic crystal (QD-PC) cavities.

*Designs:* We start by using square lattice defect cavities since their predicted mode volumes are generally larger due to the smaller bandgap. To increase the mode volume we analysed coupled two-defect cavity structures with a three-dimensional finite difference time domain (3D-FDTD) model. The analysed two-defect cavities were located two lattice constants ($a$) apart from each other to form one coupled cavity mode in a two-dimensional (2D) square lattice PC slab with 11 by 13 lattice periods surrounding the cavities. The modelled photonic crystal slab geometry had a thickness ($d$) of $0.45a$, hole radii ($r$) of $0.38a$ and a semiconductor refractive index of 3.4. Fig. 1 shows the amplitude profile of the electric field in the centre of the slab. Ryu *et al.* [6] previously classified the mode from such a defect cavity as a whispering gallery mode. The electric field is vertical to the hole cylinder axis in the middle of the slab. The calculated vertical and the lateral $Q$ factors ($Q_\perp$ and $Q_\parallel$) of the coupled cavity devices are 9800 and 24000, respectively, and the mode volume ($V = \int(\varepsilon E^2)/\max(\varepsilon E^2)\ dr^3$) is $1.13(\lambda/n)^3$. Single defect cavities with similar geometries exhibit values of 8500, 26600, and $0.78(\lambda/n)^3$, respectively. Two-defect coupled cavities therefore increase the mode volume by 50% with similar $Q$s.

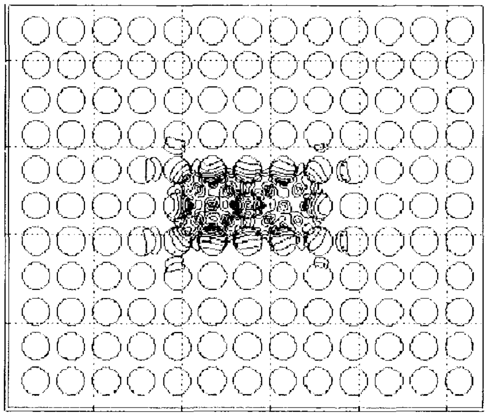

**Fig. 1** *Amplitude profile of electric field on middle of PC cavity slab of two-defect cavities*

Frequency $a/\lambda$, 0.315. Ratios of $d/a$ and $r/a$ are 0.45 and 0.38, respectively
Structure may be clear in Fig. 2*a*

*Experiment:* Five stacked self-assembled InAs QD layers were grown by molecular beam epitaxy to form the active gain material. The QD density in our samples is $5 \times 10^{10}/\text{cm}^2$ and the QD layers were separated by 30 nm GaAs layers. $\text{Al}_{0.2}\text{Ga}_{0.8}\text{As}$ is used for cladding layers to form thin slab waveguides, which are deposited on an 800 nm $\text{Al}_{0.94}\text{Ga}_{0.04}\text{As}$ sacrificial layer on a top of GaAs substrate. To define 200 nm-thick 2D-PC slab cavities, electron-beam lithography, chemically assisted ion-beam etching, oxidation of $\text{Al}_{0.94}\text{Ga}_{0.04}\text{As}$ layer, and wet etching of $\text{AlO}_x$ layer were performed. The detailed fabrication steps can be found elsewhere [4, 5]. Many geometries of single-, two-, and four-defect coupled cavities were fabricated within photonic crystals with lattice sizes of 31 × 31, 31 × 33, and 33 × 33, respectively. Figs. 2*a* and *b* show typical scanning electron microscope images of two-coupled and four-coupled cavities, respectively.

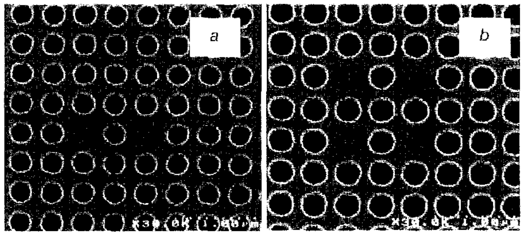

**Fig. 2** *Coupled cavities consisting of two- and four-defect cavities in two-dimensional square-lattice PCs*

*a* Two-defect cavities
*b* Four-defect cavities
Lattice spacing of each square lattice and *r*/*a* ratios are 400 nm and 0.34, and 420 nm and 0.38 for structures in Figs. 2*a* and *b*, respectively

Twenty nanosecond pumping pulses with 2.86% duty cycle from a 780 nm semiconductor laser were used to measure luminescence spectra and L (pump power)-L (collected resonance power) curve. The pumping beam diameter was varied up to 4 μm.

*Results:* Fig. 3 shows two L-L curves taken from two- and four-defect coupled cavities. Each of these cavities exhibits distinct threshold and linear increase in output power above threshold. Threshold pump powers of 120 and 370 μW are measured for two- and four-defect coupled cavities, respectively. Fig. 4 shows luminescence spectra from a four-defect coupled cavity. Below threshold (Fig. 4*a*), the resonance cannot be clearly observed. Close to threshold, nonlinear amplification of emission is seen (Fig. 4*b*). Above threshold, the resonance intensity increases significantly. The lasing wavelength of 1328 nm matches the ground state emission of the QDs. The photonic crystal geometry of $a/\lambda = 0.316$ in this laser also matches the analysed mode frequency of two-defect coupled cavities. Spectral line widths decreased from 1 to 2 nm (below threshold) to less than 0.2 nm (above threshold). The combination of distinct threshold in the L-L curves and line width narrowing both indicate that the cavities are indeed lasing. For two-defect coupled cavities, the resonance was measured at $a/\lambda = 0.3$, which is smaller than the simulated value since the experimental slab thickness is larger and the hole diameter is smaller than modelled. Single defect cavities did not lase in our experiments, probably due to a lack of sufficient gain from the QDs.

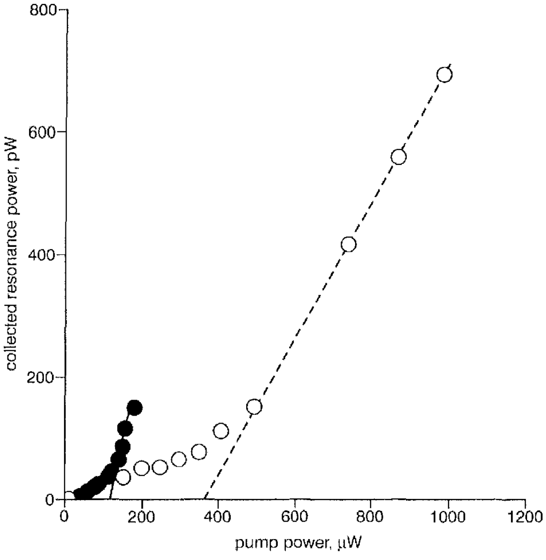

**Fig. 3** *Pump power dependence of collected resonance power from coupled PC cavities*

● PC cavity consisting of two-coupled defect cavities
○ PC cavity consisting of four-coupled defect cavities

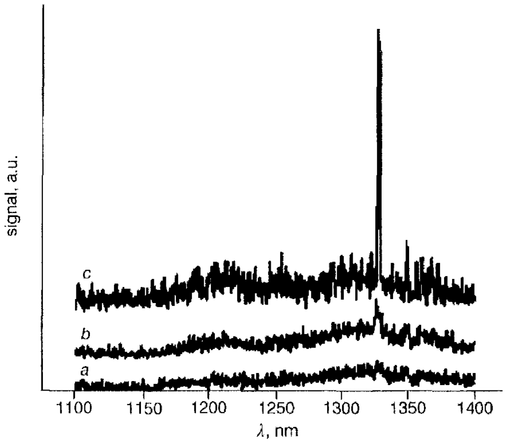

**Fig. 4** *Luminescence spectra taken from four-coupled PC cavity at room temperature by short optical pulse pumping*

(a) below threshold, pump power = 140 μW
(b) close to threshold, pump power = 250 μW
(c) above threshold, pump power = 990 μW

*Conclusion:* Lasing was demonstrated from self-assembled indium arsenide quantum dots included in photonic crystal coupled cavities. Two- and four-defect cavities, which were designed to control the available gain volume, were found to retain high quality factors. The cavity resonance showed clear threshold behaviour in the optically pumped L-L curves and line width narrowing was observed.

*Acknowledgments:* The authors greatly appreciate valuable discussions with and encouragement from M. Lončar and J. Vučković. This work was supported by the NSF under Grants ECS-9912039 and DMR-0103134, the AFOSR under F49620-01-1-0497, and by DARPA under MDA972-00-1-0019.

*11 June 2002*
*Electronics Letters Online No: 20020650*
*DOI: 10.1049/el:20020650*

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## References

1 YABLONOVITCH, E.: 'Inhibited spontaneous emission in solid-state physics and electronics', *Phys. Rev. Lett.*, 1987, **58**, pp. 2059–2062
2 JOHN, S.: 'Strong localization of photons in certain disordered dielectric superlattices', *Phys. Rev. Lett.*, 1987, **58**, pp. 2486–2489
3 PAINTER, O., LEE, R.K., SCHERER, A., YARIV, A., O'BRIEN, J.D., DAPKUS, P.D., and KIM, I.: 'Two-dimensional photonic band-gap defect mode laser', *Science*, 1999, **284**, pp. 1819–1821
4 YOSHIE, T., SCHERER, A., CHEN, H., HUFFAKER, D., and DEPPE, D.: 'Optical characterization of two-dimensional photonic crystal cavities with indium arsenide quantum dot emitters', *Appl. Phys. Lett.*, 2001, **79**, pp. 114–116
5 YOSHIE, T., VUČKOVIĆ, J., SCHERER, A., CHEN, H., and DEPPE, D.: 'High quality two-dimensional photonic crystal slab cavities', *Appl. Phys. Lett.*, 2001, **79**, pp. 4289–4291
6 RYU, H.Y., KIM, S.H., PARK, H.G., HWANG, J.K., LEE, Y.H., and KIM, J.S.: 'Square-lattice photonic band-gap single-cell laser operating in the lowest-order whispering gallery mode', *Appl. Phys. Lett.*, 2002, **80**, pp. 3883–3885