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Suppression of spontaneous emission for two-dimensional GaAs photonic crystal microcavities

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JFA**8:00 am–10:00 am**
Rooms 327/329**Active Photonic Crystals and
Microstructures**TBA, *Presider***JFA1 (Invited)****8:00 am****Strong Purcell effect for quantum boxes
in micropillars and microdisks**J.M. Gérard, B. Gayral, B. Sermage, *France
Télécó/CNET/DTT/CDP, 196 av. H.
Ravera, F-92225 Bagneux Cedex, France;
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In a founding paper,¹ Purcell proposed to control the spontaneous emission (SE) rate of a dipole by using a cavity to tailor the dipole-field coupling. In spite of a major experimental effort motivated by the interest of this concept in optoelectronics, only minor SE rate enhancements could be observed in solid-state microcavities until recently.

Very severe requirements must be fulfilled by both the cavity and the emitter for observing this effect. According to Purcell, an emitter on resonance with a discrete cavity mode experiences a SE enhancement of the order of $3/4\pi^2 Q\lambda^3/V = F_p$, where V is the cavity mode volume, Q the cavity quality factor and λ the wavelength in the material, but this result is valid only as long as the emitter linewidth is narrower than the cavity mode. Usual solid-state emitters are quite broad spectrally, which puts a stringent upper limit on Q . Self-assembled InAs/GaAs quantum boxes (QBs) are thus very interesting in this context: isolated QBs display a single sharp (~ 50 μeV) emission line, which allows potentially to implement very high Q semiconductor cavities (up to $Q \sim 20000$).

Progress in microfabrication techniques has allowed a 3D engineering of the refraction index on the wavelength scale and a rich diversification of microcavity designs (micropillars, microdisks, photonic wires, microcavities based on photonic bandgap material...). When total internal reflection or waveguiding are used to confine light, the optical quality of small volume microcavities is extremely sensitive to the morphology of their sidewalls. The scattering by surface roughness provides an additional escape path to confined photons, which reduces their lifetime in the cavity and Q . We report the fabrication of both GaAs/AlAs micropillars and GaAs microdisks displaying an improved optical quality. By optimizing the reactive ion etching of micropillars, Q 's as high as 2000 for 1 μm diameter pillars could be obtained ($F_p = 32$). Microdisks have been defined through a novel process based on a two-step wet etching. Whispering gallery modes display then record high Q 's (12000 for 2 μm diameter disks instead of 1500 for the previous state of the art) which highlights a spectacular reduction of the microdisks edge roughness and corresponds to a very high F_p (~ 150).

By inserting QBs in such small volume/high Q microcavities, we could observe for the first time a very strong Purcell effect in the solid-state.² For GaAs/AlAs pillar microcavities, a (up to) five-fold shortening of the radiative lifetime is observed by time-resolved photoluminescence (PL) for the QBs which are on-resonance with a cavity mode, whereas it is essentially unmodified for off-resonance QBs. A simple model taking into account the spatial/spectral distribution of the QBs in the pillar and its Purcell factor F_p explains quantitatively the magnitude of this SE enhancement. Though our microdisks have not yet been studied by time-resolved PL, a clear signature of the Purcell effect could be observed in a simple c.w. experiment. In our structures, the number of QBs coupled to a given mode is not large enough to sustain lasing. When we raise the excitation power, the emission related to the fundamental optical transition of a QB thus saturates when we inject more than one electron-hole pair per lifetime. This behavior is observed for on-resonance as well as off-resonance QBs. However the onset of the saturation occurs for a much higher pumping power when QBs are resonantly coupled to a whispering gallery mode, which confirms that their radiative lifetime can be (up to) 20 times shorter due to the Purcell effect.

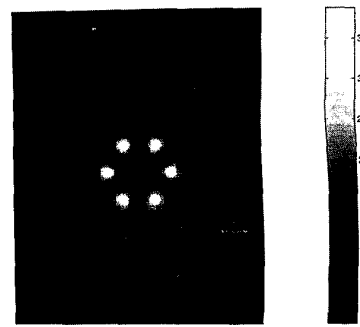
Beyond this result, InAs QBs will probably allow to witness other CQED effects in solid-state microcavities (e.g. the strong coupling regime for a single QB) and open unique opportunities for the development of single photon light emitters for applications such as quantum cryptography or metrology.

1. E.M. Purcell, *Phys. Rev.* **69**, 681 (1946).
2. J.M. Gérard *et al.*, *Phys. Rev. Lett.* **81**, 1110 (1998).

JFA2**8:30 am****Suppression of spontaneous emission
for two-dimensional GaAs photonic
crystal microcavities**Thomas Søndergaard, Jes Broeng,
Anders Bjarklev, *Department of
Electromagnetic Systems Technical University
of Denmark, Building 348, DK-2800 Lyngby,
Denmark*

Spontaneous emission represents a loss mechanism that fundamentally limits the performance of semiconductor lasers. The rate of spontaneous emission may, however, be controlled by a new class of periodic dielectric structures known as photonic crystals. Although a three-dimensional periodic structure may rigorously forbid spontaneous emission within a frequency interval,¹ a simpler-to-fabricate two-dimensional (2-D) periodic structure may also introduce a large suppression of spontaneous emission.²

By introducing a defect in a photonic crystal, a microcavity may be formed with one or more modes strongly localized. These modes are of high interest for realization of low-threshold lasers.³ Such a photonic crystal microcavity is shown in Fig. 1, where the dotted circles represent holes in a GaAs substrate. A microcavity has been introduced by decreasing



JFA2 Fig. 1. The dotted circles arranged on a triangular lattice represent holes in a GaAs substrate. A defect has been introduced by decreasing the size of an air-hole. The amplitude of the electric field squared is shown for a mode localized to the defect. The center-to-center hole spacing relative to the free-space wavelength is 0.373.

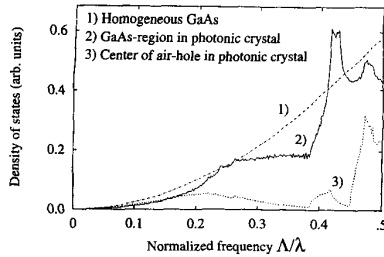
the size of a single air-hole in the otherwise perfect periodic structure. The amplitude of the electric field squared is also shown for a strongly localized mode. The figures in this text have all been calculated using a plane-wave method.⁴

Using a semiclassical approach, the change in the rate of spontaneous emission introduced by a photonic crystal is modelled through the concept of the position-dependent density-of-states. The emitters are modelled as electric dipoles. Spontaneous emission is modelled as emission stimulated by vacuum fluctuations in the classically treated electromagnetic modes.

The density-of-states at a given frequency is essentially obtained by counting modes within a narrow frequency interval and normalizing. Position dependence is introduced by further weighting the contribution from each mode with the amplitude of the electric field squared, where the amplitude has been normalized so that the total energy of the mode is unity. This leads to a more correct model for the rate of spontaneous emission compared to using the position-independent density-of-states only.²

The position-dependent density-of-states has been calculated for the full periodic structure shown in Fig. 1 with no defect. To the best of our knowledge this is the first calculation of the position-dependent density-of-states for 2-D photonic crystals.

The result is shown in Fig. 2 for a GaAs region mid between two air-holes and in the center of an air-hole in the full periodic photonic crystal (two extremes chosen to illustrate strong position dependence). A similar calculation for homogeneous GaAs is also shown. For the normalized frequency 0.373 corresponding to the mode shown in Fig. 1 (wavelength = 800 nm and center-to-center hole spacing = 300 nm) the curves for homogeneous GaAs and GaAs in the photonic crystal differ by a factor of 1.8. This factor corresponds to a possible 45 percent suppression of spontaneous emission in the GaAs photonic crystal structure. This leads to the conclusion that strong suppression of spontaneous emission in 2-D photonic crystals is feasible, having major implications on future realization of low-threshold lasers. Further analysis of the



JFA2 Fig. 2. The three-dimensional position-dependent density-of-states is shown for homogeneous GaAs as curve 1) along with the corresponding calculation for two positions in the full periodic photonic crystal characterized by holes having a filling fraction of 0.67 in a GaAs-substrate. Curve 2) represents a GaAs region mid between two air-holes in the photonic crystal, whereas curve 3) represents the center of an air-hole in the photonic crystal. Δ is the center-to-center hole spacing and λ is the free-space wavelength.

photonic crystal microcavity will be presented at the conference.

1. E. Yablonovitch. Inhibited spontaneous emission in solid-state physics and electronics. *Physical Review Letters*, 58(20), 2059–62, May 1987.
2. T. Søndergaard, J. Broeng, A. Bjarklev, K. Dridi, and S.E. Barkou. Suppression of spontaneous emission for a two-dimensional honeycomb photonic band gap structure estimated using a new effective-index model. *IEEE Journal of Quantum Electronics*. 34(12), Dec. 1998.
3. O. Painter, J. Vuckovic, and A. Scherer. Defect modes of a two-dimensional photonic crystal in an optically thin dielectric slab. *Journal of the Optical Society of America B*, 1999. In press.
4. R.D. Meade, A.M. Rappe, K.D. Brommer, J.D. Joannopoulos, and O.L. Alerhand. Accurate theoretical analysis of photonic band-gap materials. *Physical Review B*, 48(11), 8434–7 Sept. 1993.

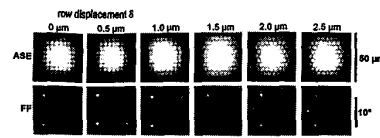
JFA3

8:45 am

Properties of photonic lattices created using arrays of coupled vertical cavity surface emitting lasers

Harald Pier, Claude-Albert Berseth, Eli Kapon, Michael Moser,* Tal Fishman,** Amos Hardy,** *Department of Physics, Swiss Federal Institute of Technology (EPFL), Lausanne, CH-1008 Switzerland; E-mail: pier@epfl.ch*

Structures with a periodically modulated refractive index are frequently discussed in the context of the possibility of forming a "photonic bandgap". These would be useful for many applications in optoelectronics, e.g. ultra-low threshold lasers, more efficient light emitting diodes or novel waveguides.¹ Another class of photonic lattices relies on the analogy of the bound photon states in arrays of microcavities to electronic states in a lattice of atoms. Recently, this inspired the realization of photonic molecules² and photonic lattices con-



JFA3 Fig. 1. Experimental data. By shifting adjacent rows, strained photonic lattices can be realized (amplified spontaneous emission patterns, ASE). Beyond a critical strain value, the mode undergoes a phase transition, resulting in an abrupt change of the far-field pattern (FF).

structed using arrays of coupled microcavities. Such periodic arrangements of bound photon modes have been used to realize disordered and—lately—strained photonic lattices.

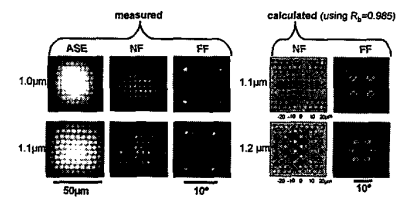
Experimentally, our photonic lattices are defined by metal-patterning highly uniform VCSEL-wafers. Excellent lateral uniformity, required for large coupled lattices, is demonstrated by the small (less than 0.2%) variations of the cavity resonance in the reflectivity spectrum measured across the wafer. Lasing only occurs at the locations of high-reflectivity gold pixels placed on a low-reflectivity (R_b) chromium-covered background. Using this approach, the design of the photonic lattices is extremely flexible and is limited only by the lithographic resolution. Typical pixel sizes are 4–5 μm , and spacings between pixels can be as small as 1 μm .

The lasing modes of these photonic modes are observed close to threshold. The structures are analyzed theoretically using a coupled resonator model employing the patterned reflectivity of the composite metal-dielectric mirror.³ As an example, consider the series of photonic lattices incorporating alternating shear strain shown in Fig. 1.⁴ These strained structures are made by shifting every other row of a 10×10 coupled-array by δ , as illustrated by the amplified spontaneous emission (ASE) patterns measured below threshold. Above threshold, we find that the near-field (NF) patterns virtually locks to the unstrained lattice patterns up to a critical displacement $\delta \approx 1.0 \mu\text{m}$, above which the lattice mode undergoes a phase transition to a hexagonal-like lattice mode. This abrupt switching is evidenced by the measured far-field (FF) of the corresponding lattices (see Fig. 1). The peculiar multi-lobed far-fields are a result of the out-of-phase coupling of adjacent cavities for the mode with the largest optical gain.

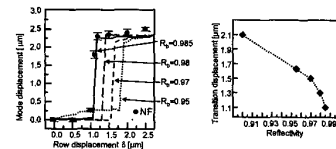
The model calculations well reproduce the observed features, as shown in Fig. 2. In particular, the phase transition is found to occur abruptly at $\delta \approx 1.1 \mu\text{m}$ for a background reflectivity $R_b = 0.985$.

The switching behavior of the lasing mode is further illustrated in Fig. 3, which compares the calculated and measured displacement in the peak at each pixel near the center of the lattice versus the row displacement δ . It can be seen that the phase transition point can be tuned by properly selecting R_b (Fig. 3, right plot).

Similar studies were carried out with tapered lattices, superlattice structures, and irregular lattices, varying the coupling and the position of the lattice points. Several interesting phenomena have been observed (and will



JFA3 Fig. 2. Amplified spontaneous emission pattern (ASE), near- (NF) and far-fields (FF) of lattices close to the transition point at 1.1 μm (left). Using the correct value for the reflectivity contrast, this situation can be modeled very accurately (right).



JFA3 Fig. 3. Left: In the experiment, the phase transition occurs between 1.0 and 1.1 μm shift (circles, NF). In the model, the background reflectivity R_b can be used to tune the switching point. The best fit to the experiment is obtained for $R_b = 0.985$, which is close to the actual value. Right: Calculated dependence of transition point on reflectivity.

be presented), ranging from decoupling of separated sublattices to injection-level dependent responses that could be useful for beam-switching applications. These studies provide insight into the photonic band structure of two-dimensional photonic crystals.

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2. M. Bayer *et al.*, *Phys. Rev. Lett.* 81, 2582–2585 (1998).
3. T. Fishman, A.A. Hardy, and E. Kapon, *IEEE Journal of Quantum Electronics* 33, 1756–1762 (1997).
4. H. Pier, E. Kapon, and M. Moser, *CLEO Europe*, Glasgow, Scotland, 1998, p. CTh11 (invited paper).

JFA4

9:00 am

Temperature dependence of lasing characteristics for 1.3 μm GaAs-based quantum dot lasers

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Recently ground-state 1.3 μm wavelength lasing has been demonstrated at room temperature from GaAs-based uncoated heterostructure lasers using an InGaAs quantum dot (QD)

