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

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Spontaneous emission represents a loss mechanism that fundamentally limits the performance of semiconductor lasers. The rate of spontaneous emission may, however, be controlled within 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, a simple-to-fabricate two-dimensional (2-D) periodic structure may also introduce a large suppression of spontaneous emission.

By introducing a defect in a photonic crystal, a microcavity may be formed that 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 cw experiment.

Beyond this result, InAs QBs will probably allow to witness other QED 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).

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.

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. 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 cw experiment. In our structures, the number of QBs coupled to a given mode is not large enough to sustain lasing. When we increase the excitation power, the emission related to the fundamental transition of a QB thus saturates when we inject more than one electron-hole pair per lifetime. This behavior is observed 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 QED 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.

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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-dependent density-of-states only.

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 homogenous GaAs is also shown. For the normalized frequency 0.373 corresponding to the mode shown in Fig. 1 (wavelength = 815 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


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

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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. Another class of photonic lattices relies on the analogy of the bound photon states in arrays of microcavities to electrons states in a lattice of atoms. Recently, this inspired the realization of photonic molecules and photonic lattices constructed using arrays of coupled microcavities. Such periodic arrangements of bound photon modes have been used to realize disorder and—lately—strained photonic lattices. Experimentally, our photonic lattices are defined by metal–pattering highly uniform VCSEL-wafers. Excellent lateral uniformity, required for large coupled cavities, 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 (Rb) 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. As an example, consider the series of photonic lattices incorporating alternating shear strain shown in Fig. 1. These strained structures are made by shifting every other row of a 10 × 10 coupled-array by 6, as illustrated by the amplified spontaneous emission (ASE) patterns measured below threshold. Above threshold, we find that the near-field (NF) patterns virtually lock to the unstrained lattice patterns up to a critical displacement S ≈ 1 μm, 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 S ≈ 1.1 μm for a background reflectivity Rb = 0.985.

The switching behavior of the lasing mode is further illustrated in Fig. 3, which compares the measured and calculated 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 Rb (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 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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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).