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Published in:
2010 Conference on Lasers and Electro-Optics (CLEO) and Quantum Electronics and Laser Science Conference (QELS)

Publication date:
2010

Document Version
Publisher's PDF, also known as Version of record

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Abstract： We have measured the variation of the spontaneous emission rate with polarization for self-assembled single quantum dots in two-dimensional photonic crystal membranes, and obtained a maximum anisotropy factor of 6 between the decay rates of the two nondegenerate bright states.

OCIS codes: 160.5298 Photonic crystals, 270.0270 Quantum optics

It is well known that the spontaneous emission (SE) of a quantum emitter depends not only on the intrinsic properties of the emitter, but also on the density of vacuum fluctuations surrounding the emitter. Since the idea of making use of photonic crystals to control SE was put forward by Yablonovitch [1], it has attracted considerable interest. Recently, a strong orientation dependence of SE rates of emitters in any nanophotonic environment has been predicted [2]. However, so far, no experimental demonstration has been reported. By using a polarization sensitive time-resolved setup, we systematically measured the polarization dependent SE rates of self-assembled single quantum dots (QDs) embedded in photonic crystal membranes (PCMs). We observed a large anisotropy factor of decay rates between the two nondegenerate bright states, indicating a large anisotropy of the vacuum electromagnetic field inside PCMs.

When optically exciting a QD, choosing the sample growth direction [001] as the quantization axis (z) for angular momentum, one lifts an electron to the conduction band and leaves a hole in the valence band, forming four possible exciton states. These four exciton states can be further categorized into two groups according to the values of their total angular momentum: bright states and dark states. Among them, only the bright states are optically active. Due to the low symmetry of self-assembled quantum dots and anisotropic exchange interactions, the two bright states are separated in energy (typically 0-30 μeV and are usually denoted as X or Y states according to their dipole orientations ([110] or [1-10]). The X and Y states decay independently and each follows a bi-exponential function [3]. Moreover, the large anisotropy of the vacuum electromagnetic field, *i.e.* the substantially different projected local density of optical states (LDOS) inside PCMs can give rise to a strongly polarization dependent decay rate. Here we quantify the polarization dependence by defining the anisotropy factor as: $\eta_\gamma \equiv \gamma_X / \gamma_Y$, where γ_X (γ_Y) represents the decay rate of the X (Y) states.

In our experiment, the sample used is a GaAs PCM with a layer of self-assembled InAs QDs embedded in the center of the membrane, which is mounted in a closed-cycle cryostat keeping the temperature at 10 K. The density of QDs is about 250 μm^{-2} and the excitation intensity is below the saturation of the exciton state, so that only photon emission from the ground state is observed.

We investigated about 30 QDs positioned in 7 different PCMs, with the lattice parameters ranging from 260 nm to 320 nm. For the sake of exploiting a pronounced 2D photonic crystal bandgap effect, we chose QDs in the PCMs with r/a=0.30, where r is the radius of the air holes and a is the lattice constant. Besides, for comparison, we also measured 4 QDs outside the PCMs. For each QD, the photoluminescence was projected onto different polarizations.

Fig. 1 shows typical decay curves for QD A and QD B, where QD A lies inside the PCM and QD B outside the PCM. We display three decay curves for QD A, corresponding to 0° (H), 70° and 90° (V) polarizations individually. For reference, we also display two decay curves for QD B, each corresponding to H or V polarization. From Fig. 1, we find that the SE of the single QD has been substantially inhibited inside the PCM compared to QDs outside the PCMs, and the inhibition factors are quite different for different states. By comparing QD A with QD B, we get an inhibition factor of 15.8 for the X state and 6.5 for the Y state.

The photoluminescence intensity and decay rate for different polarizations for QD A are presented in Fig. 2, where each decay curve has been fitted with a bi-exponential function, and only the fast decay rate is presented. From Fig. 2, we find that we get a minimum decay rate at H polarization and a maximum decay rate at V polarization, because the two polarizations come from two orthogonally oriented dipoles (X and Y) respectively. Between them, the decay rate has contribution from both

978-1-55752-890-2/10/$26.00 ©2010 IEEE

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dipoles, thus yielding an intermediate decay rate and a higher deviation from bi-exponential decay. The PL intensity shows a maximum (minimum) value at H (V) polarization, which is opposite to the decay rate. This can be understood as a higher inhibition of decay rate in the X-Y plane resulting in a higher emission intensity in the Z direction due to energy redistribution.

To conclude, we have systematically measured the polarization dependent SE rate of self-assembled single QDs inside PCMs and obtained a maximum anisotropy factor of decay rate between the X and Y states of 6. Our measurement results on one hand prove the existence of two orthogonally oriented dipoles in self-assembled single QDs [3], and on the other hand demonstrate the large anisotropy of the vacuum electromagnetic field inside PCMs [2], which is a crucial condition for achieving quantum interference effects with two closely lying energy levels [4], potentially enabling many fascinating phenomena, such as coherent population trapping, spectral narrowing, phase-dependent line shapes, quantum beats *etc*. Therefore, our experiment is not only vital in realizing complete control of the SE of single QDs with PCs, but also important for fundamental studies in quantum optics, *e.g.* achieving quantum interference with practical systems.

Figures and tables:

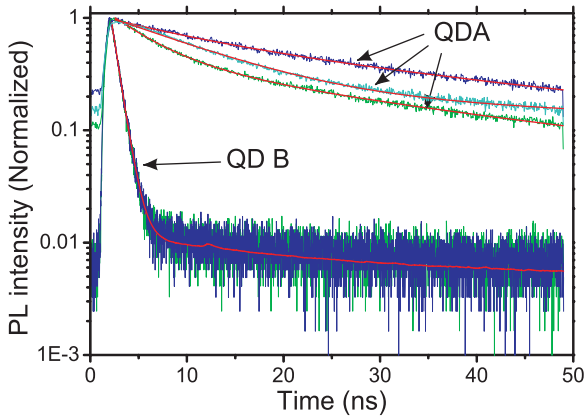

Fig. 1. Three decay curves for QD A (inside PCM) and two decay curves for QD B (outside PCM). In each decay curve, the red line is the result of a bi-exponential fit.

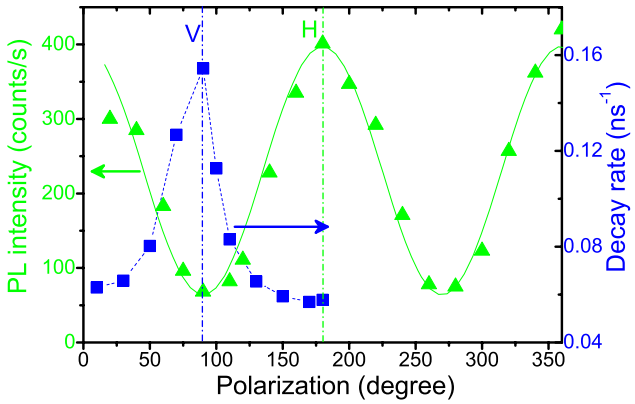

Fig. 2. Photoluminescence intensities and decay rates versus polarizations for QD A (inside PCM).

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