SAND2007-0548C

Selective Enhancement of Mid-IR Quantum Dot Electroluminescent Emissions Using Defect Mode Photonic Crystal Cavities

Mehmet F. Su*(1), Ihab F. El-Kady (1,2), Eric A. Shaner(2), and Christos G. Christodoulou(1)
(1) Electrical and Computer Engineering Dept., University of New Mexico, Albuquerque, NM, USA
(2) Sandia National Laboratories, Albuquerque, NM, USA
E-mail: mfatihsu@ece.unm.edu

Introduction

Photonic crystals are artificially fabricated crystals with a well-defined periodicity. When fabricated at nano scale, these structures have the ability of controlling light propagation. Photonic crystals control light by imposing a "photonic band gap", which essentially forbids propagation of light at a certain frequency range. The gap is intimately tied to the structural parameters of the photonic crystal; hence it is possible to adjust the gap position. However, one can obtain localized propagating modes inside the forbidden gap frequency region by introducing defects into the photonic crystal. Photonic crystals made of metals have been shown to possess the remarkable ability to recycle energy in the forbidden gap region to be emitted from a region near the forbidden band edge. These ideas have been used in several applications, including highly sensitive, tunable sensors [1] and highly efficient light sources [2].

This paper concentrates on another application of photonic crystals: We show photonic crystals can be used to selectively enhance and modify the light spectra of InAs Self Assembled Quantum Dot (SAQD) emissions in Mid-IR wavelengths. Quantum Dots, when used as light sources, offer unique advantages. For instance, quantum dots are able to emit light normal to the growth surface, whereas light produced by a quantum well is always parallel to the growth surface. It is therefore possible to develop new devices based solely on this property of SAQD based light sources. Before SAQD light sources could be used, however, improvements must be made on their emission spectra, which is rather broad (approximately 24 THz in our case) due to inhomogeneous broadening in SAQD energy levels. Our purpose in this work is to theoretically investigate interactions between a photonic crystal and a light source placed into a central defect cavity. The photonic crystal serves to confine lateral propagation of light, which in turn interacts strongly with the central cavity and modifies emission characteristics of the light source.

The paper is arranged as follows: In the next section we give simulation details. In the third section we present results, thus showing how photonic crystal cavity devices might be used to enhance SAQD emissions.

Simulation Details

There are several computational methods suitable for solving Maxwell's equations. In this work we use the Finite Difference Time Domain (FDTD) method due to its ability to simulate the underlying physics in a piece-by-piece manner. Additionally, FDTD allows us to obtain time evolution of electromagnetic fields as well as cavity quality factors, emission properties and other useful information.

The simulation case of interest in our case is similar to the optically thin photonic crystal cavity structure discussed by Vuckovic et al. [3] In this structure, there are holes (r/a=0.3, air filled) drilled into a dielectric slab (ε=11.56, thickness 0.6a) conforming to a hexagonal lattice with lattice constant a. This photonic crystal has a gap in lateral directions for TE polarized modes. The central hole in which the quantum dot source is placed is filled with a different material (ε=5.76), forming a cavity. UPML absorbers with air buffers are placed on all sides of the photonic crystal except for the bottom side. A Perfect Magnetic Conductor (PMC) boundary terminates the bottom side instead. This arrangement helps eliminating TM modes and reduces the simulation space size by one half. Including UPML boundaries, the size of the simulation space is 396x386x128 grid points (a=14 grid points). Using an OpenMP parallelized simulation program tuned for the machine **Error! Reference source not found.**, the simulation for 8000 time steps takes approximately 24 hours on an Origin 2000 system with 8 MIPS R12000 processors running at 350 MHz. Results from a detection point located 6 grid points above the source are saved and transformed to frequency domain using FFT. The system is set up so as to capture the enhancement effects of the photonic crystal cavity structure for emissions close to the surface normal. We set up the excitation source with a sine modulated Gaussian pulse,

$$f(t) = \exp\left(-\left(\frac{t-5\tau}{\tau}\right)^2\right)\sin\left(2\pi f_0\left(t-5\tau\right)\right)$$

where τ adjusts the width of the Gaussian pulse and f_0 is the frequency for modulation. In Figures 2-5, the center frequency for free space cases is approximately 39.5 THz, whereas the full width half maximum (FWHM) spans 26.5 THz-52.5 THz.

Results and Discussion

To better see the enhancement effects we set up several simulation cases. In Figures 4 and 5, results from the structure illustrated in Figure 1 are presented. For Figure 3, all air filled holes are removed from the structure with 3.5 micron-lattice constant, effectively leaving the source in a slab with a defect rod forming a cavity. For Figure 2, the defect is also removed, leaving the source in the dielectric slab.

Several points are evident from these cases: Firstly, Figure 3 shows the effects of placing the source into a defect cavity, which does not favor normal emission modes over modes emitted parallel to the slab surface. Second, comparison of Figure 3, which indicates the cavity modes of the defect, to Figure 4, clearly shows the enhancement effects of the photonic crystal to the cavity modes, observable in the form of sharp peaks. As expected, addition of the photonic crystal to the system inhibits the lateral emissions, enhancing normal modes. It is also possible to make some adjustments by changing the cavity dimensions and the photonic crystal lattice constant: In Figure 5, the lattice constant *a* is increased to 5 microns. This change causes a shift in both photonic band gap frequencies and cavity resonance frequencies. The enhanced cavity modes in this case cover almost all of the emission range of the source.

To sum up, in this work we have shown how a photonic crystal cavity structure can enhance the emission modes of a quantum dot source. The enhancement effects are primarily due to the features of the photonic crystal structure.

Research described in this work has been funded by Sandia National Laboratories (SNL). Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

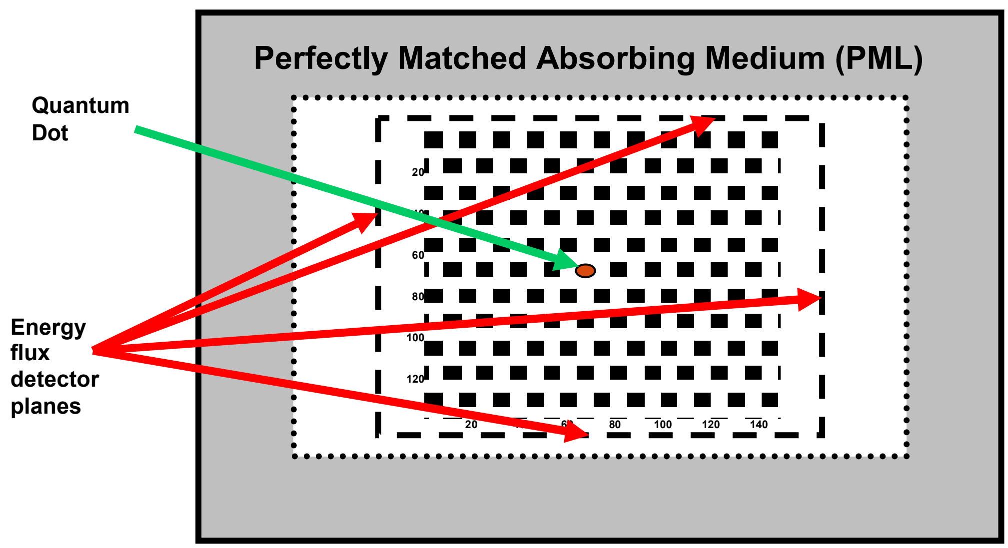

Figure 1 Cross sectional view of SAQD-Photonic crystal cavity simulation.

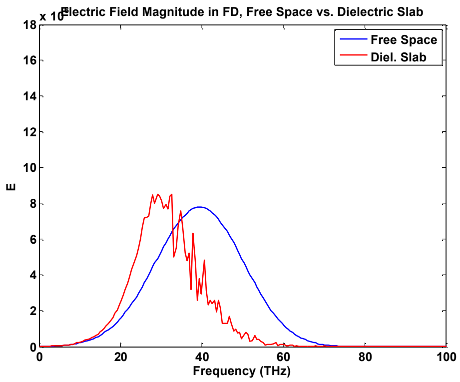

Figure 2 Fourier transformed results comparing free space emissions to emissions from a source in a dielectric slab. (To be compared to Figure 4.)

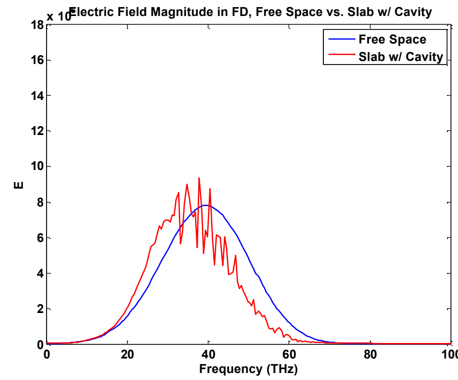

Figure 3 Fourier transformed results comparing free space emissions to emissions from a source in a cavity in a dielectric slab. (To be compared to Figure 4.)

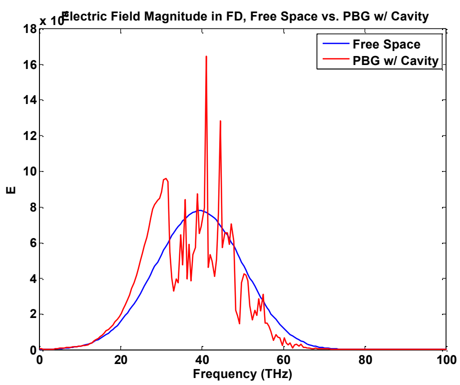

Figure 4 Fourier transformed results comparing free space emissions to emissions from a source in defect mode photonic crystal with cavity. The lattice constant is 3.5 microns.

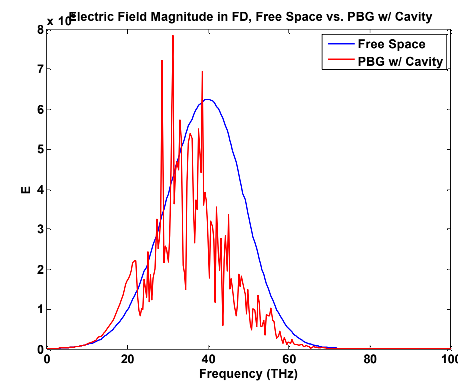

Figure 5 Fourier transformed results comparing free space emissions to emissions from a source in defect mode photonic crystal with cavity. The lattice constant is 5 microns.

References:

[1] I. El-Kady et al., "Tunable narrow-band infrared emitters from hexagonal lattices", *Photonics and Nanostructures-Fundamentals and Applications*, vol. 1, pp. 69-77, 2003.

[2] J. G. Fleming, I. El-Kady, S. Y. Lin, R. Biswas and K. M. Ho, "All metallic, absolute photonic band gap three-dimensional photonic-crystals for energy applications", *Nature*, vol. 417, p. 52, 2002.

[3] Jelena Vuckovic, Marko Loncar, Hideo Mabuchi, and Axel Scherer. "Design of photonic crystal microcavities for cavity QED", *Physical Review E,* vol. 65, p. 016608, 2001.

[4] M. F. Su, I. El-Kady, D. A. Bader, and S.-Y. Lin, "A novel FDTD application featuring OpenMP-MPI hybrid parallelization", *2004 International Conference on Parallel Processing (ICPP'04)*, pp. 373-379, 2004.