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Enhancement and extraction of spontaneous emission from 2-d thin film photonic crystals

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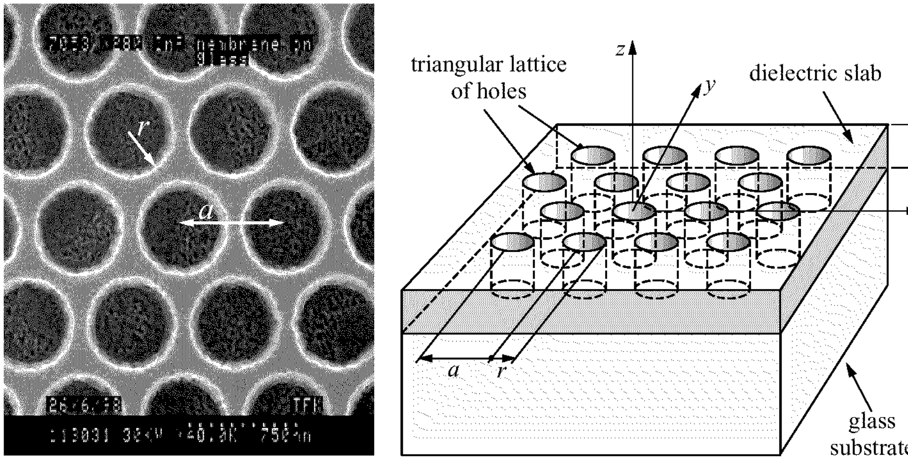
Abstract. The results of photoluminescence measurements on thin slab InGaAs/InP photonic crystals are presented, demonstrating a possibility of spontaneous emission engineering at room temperature using 2-d periodic thin film photonic crystals. The angle dependence of the PL spectral peaks is shown to track the photonic band dispersion. This revealed the band structure of the leaky conduction bands within the optical escape cone. Up to a 15-fold emission intensity enhancement was observed and explained in terms of a combination of Purcell enhancement, and Bragg extraction of high wave vector photons. Different design concepts for improving LED performance were demonstrated.

Introduction

Photonic crystals, artificially created, multi-dimensionally periodic structures are known for a forbidden electromagnetic bandgap. For that reason, they can be used to modify spontaneous emission. Initially, it was proposed to use photonic crystals to inhibit spontaneous emission [1], but they can be employed to enhance it as well, with significant implications for light-emitting diode structures. We show that thin slab 2-d photonic crystals can provide a spontaneous emission enhancement up to $F_p = 2.5$ and an overall extraction enhancement up of 15 times.

Spontaneous emission from photonic crystals

We used a thin-film InGaAs/InP 2-d photonic crystal at ambient temperature, but the results would apply equally to InGaN thin films for example. An MOCVD-grown $In_{0.47}Ga_{0.53}As$/InP single quantum well double hetero-structure was used for these experiments. Thin films for the photo-pumped LED's were fabricated using substrate removal, and bonded to a glass slide. A triangular array of holes is defined by electron-beam lithography, using a LEICA EBPG-5 Beamwriter. The semiconductor slab was etched through by reactive ion etching (RIE) using $SiCl_4$ at the elevated temperature of 200°C. The InP film thickness is 240 nm and the InGaAs quantum well active region thickness is 60 nm. Each sample had numerous triangular lattice structures spanning a photonic lattice constant range sufficient for optimization of the external efficiency. In our case of emission wavelength centered at vacuum wavelength $\lambda = 1650$ nm, the photonic crystal's lattice constant was made to vary from $a = 550$ nm to $a = 910$ nm. Correspondingly, the center of the photonic band gap varied from $\lambda = 1300$ nm to $\lambda = 1900$ nm. The thin-film LED photonic crystal structures are shown in Fig. 1.



(a) $r = 260$ nm $a = 720$ (b)

Fig. 1. (a) A triangular array of holes in the thin film on InGaAs/InP double hetero-structure; (b) Prospective view.

The LED emission was collected in a solid angle from normal up to 45° angle away from normal, in air. The calibrated photoluminescence signal versus photonic lattice spacing is shown in Fig. 2. As can be seen from the graph, the efficiency is optimized at a photonic lattice constant $a = 900$ nm, where conduction band modes match the InGaAs emission frequency. That gives the external efficiency for that LED structure 48%.

The angular resolved spontaneous emission allows for measurements of the dispersion diagram of a photonic crystal's leaky conduction band modes, that is modes with frequencies lying above the light cone in the glass substrate. We used the evolution of spontaneous emission spectral peaks versus angle to study the band structure of the photonic crystal. The dispersion diagram (solid lines in Fig. 3) is computed using the Finite Difference in Time Domain technique. Angular resolved spectra on thin film photonic crystals reveal some very sharp peaks in the spectrum compared to the reference emission linewidth of InGaAs. These are signatures of a new type of the Purcell enhancement [2], that can be realized in the spatially extended photonic bands, without a cavity [4].

Leaky conduction band modes bring a two-fold advantage to LED's. First, by using them, we increase dramatically the light extraction efficiency, bringing it close to 100%. Second, we can speed up the radiative recombination to make it more competitive with the non-radiative recombination on exposed surfaces. Increase in recombination rates drives faster device operation as well.

Photonic crystals as passive outcouplers

Leaky photonic crystal modes can also be used as a passive out-coupling mechanism. These leaky modes are in the shaded area of Fig. 3 and have measured Q between 30 and 100. The periodic structure is in effect an efficient, coherent scatterer of light from the semiconductor film.

In other words, the proposed strategy is to separate the regions where the light is generated from those where the light is extracted. The two respective regions are the hexagonal area of unpatterned thin film for light generation, surrounded by a few periods of the pho-

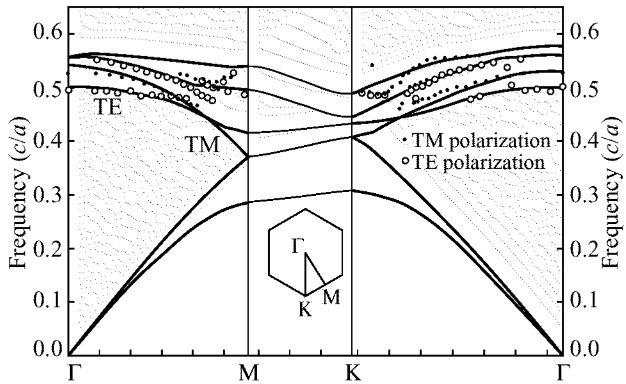


Fig. 2. Photoluminescence efficiency calibrated with respect to the reference sample, and corrected for the fractional sample absorption.

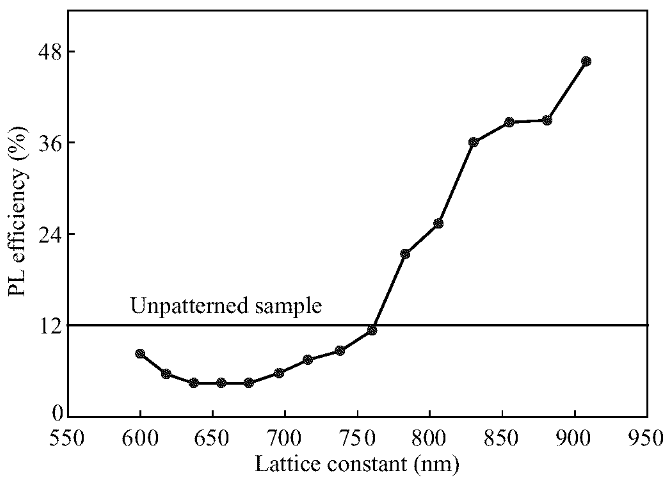


Fig. 3. Theoretical (lines) and experimental (circles) bands for the thin slab photonic crystal. The modes in the shaded area are leaky.

tonic crystal for light extraction. If the light is generated in the center region, a small $1/2n^2$ fraction corresponding to top and bottom escape cones is emitted directly from the central part of the unpatterned hexagonal area, and the rest is trapped in the thin film waveguide. When the guided light reaches the surrounding patterned region, it scatters or reflects at the interface, or couples to the leaky modes of the photonic crystal, and then scatters into the air or into the glass substrate.

In these experiments, we measured spontaneous emission from a 20 μm diameter unpatterned optically pumped region surrounded by a few rows of photonic crystal. The lattice spacing, a, of the photonic crystal was 600, 760 or 900 nm. According to our band structure calculations, in the $a = 600$ nm sample, only guided TM modes overlap with the emission band. For the $a = 760$ nm sample the spontaneous emission band overlaps with both guided TM and leaking conduction band modes of the photonic crystal. For the $a = 900$ nm sample all spontaneous emission should couple to the leaky modes, and thus to free space.

The photoluminescence acceptance angle was 0 to 45°C in the air. The spectrum of the $a = 600$ nm sample resembles that of an unetched thin film and has almost the same intensity. Indeed, even though the guided waves can couple to the guided TM modes inside the photonic crystal, there is no way for the light to escape. The integrated PL signal from the sample with $a = 760$ nm is about 4 times larger. The shape of the spectrum is also different, there are two distinct shoulders. Finally, the sample with the $a = 900$ nm hole spacing showed even higher overall efficiency, 6.25 times the efficiency of the unpatterned reference sample, which translates into more than 70% external quantum efficiency [3].

Summary

The results of photoluminescence measurements on thin slab InGaAs/InP photonic crystals were presented in this paper, demonstrating a possibility of spontaneous emission engineering at room temperature using 2-d periodic thin film photonic crystals. The angle dependence of the PL spectral peaks was shown to track the photonic band dispersion. This revealed the band structure of the leaky conduction bands within the optical escape cone. Up to a 15-fold emission intensity enhancement was observed and explained in terms of a combination of Purcell enhancement, and Bragg extraction of high wave vector photons. The Purcell enhancement factor was probably no more than 2 under our conditions, with most of the efficiency increase associated with Bragg extraction improvement. Different design concepts for improving LED performance were demonstrated.

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