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Light extraction from optically pumped light-emitting diode by thin-slab photonic crystals

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We describe a promising thin-slab light-emitting diode (LED) design, which uses a highly efficient coherent external scattering of trapped light by a two-dimensional (2D) photonic crystal. The light generation region was an unpatterned heterostructure surrounded by the light extraction region, a thin film patterned as a 2D photonic crystal. A six-fold photoluminescence enhancement was observed compared to an unpatterned thin film LED. That corresponded to 70% external quantum efficiency. © *1999 American Institute of Physics.* [S0003-6951(99)01634-4]

There is a significant discrepancy between the high internal efficiency and poor external efficiency of light-emitting diodes (LEDs). A large fraction of the generated light is never emitted from the semiconductor, but is trapped by total internal reflection. Depending on the optical design, the efficiency ratio can be as poor as $1/4n^2 \approx 1/50$, (where $n = 3.5$ is the semiconductor refractive index). Accordingly, LED designs include features that would allow a greater fraction of the internal light to escape, such as surface roughening,[1,2] transparent substrates and superstrates,[3] and photon recycling.[1] Resonant-cavity LEDs use quantum electrodynamical enhancement of spontaneous emission in high-Q resonators.[4–6] All these methods allow up to 30% external efficiency LEDs.

A thin slab two-dimensional (2D) photonic crystal can produce a direct enhancement of the spontaneous emission process by quantum electrodynamic effects. These occur through the modification of the optical mode density, and the concentration of electric field fluctuations within the photonic crystal active region. These direct enhancement effects will be discussed in another letter. Here we will examine an unpatterned semiconductor film, in which there are no special quantum electrodynamic effects, and spontaneous emission proceeds normally. The edges of the thin film will be surrounded by a 2D photonic crystal, causing coherent scattering of the internally trapped light. Thus, in this case the photonic crystal serves not to increase the spontaneous emission[7] but merely to improve the extraction of existing spontaneous emission.

Our thin slab photonic crystals, shown in Fig. 1, consist of a perforated semiconductor film bonded to a glass slide. The semiconductor film is an InGaAs/InP double heterostructure. After separating the slab from its host substrate and bonding it to a glass carrier using an optical ultraviolet-curable epoxy, 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 using $SiCl_4$ at the elevated temperature of 200 °C, leaving hexagonal active regions surrounded by photonic crystal rows. The InGaAs/InP film thickness is 420 nm and the InGaAs quantum well active region thickness is 20 nm.

Figure 2 shows the dispersion diagram for in-plane propagation of electromagnetic waves in the photonic crystal regions calculated using the finite difference time domain method.[8] There is a band gap for the transverse electric (TE)-like modes. More importantly in our case, all guided modes of the photonic crystal lying above the light cone for escape into the glass substrate are leaky. These leaky modes are in the shaded area of Fig. 2 and have measured[9] Q between 30 and 100. The periodic structure is in effect an efficient, co-

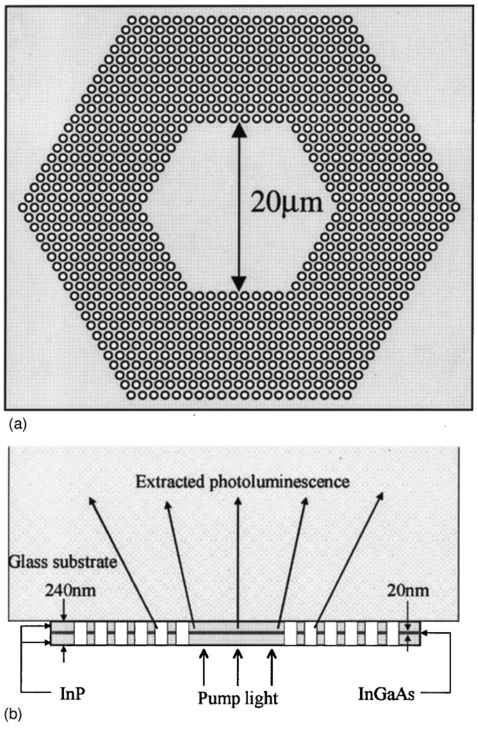

FIG. 1. (a) Top view of our proposed LED geometry. Spontaneous emission occurs on the central unpatterned area of a thin film, and is extracted by coherent scattering from the photonic crystal rows around the periphery. (b) Side view of our InGaAs/InP semiconductor thin film on a glass superstrate.

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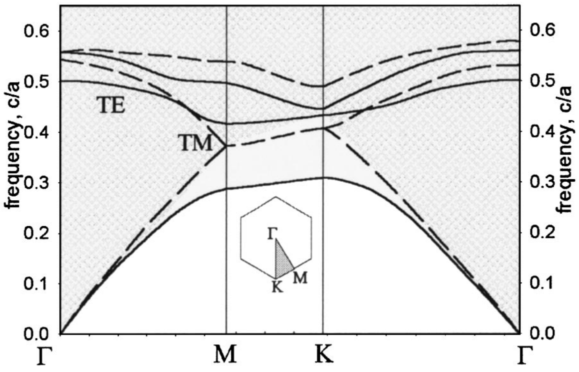

FIG. 2. Dispersion diagram of TE-like modes of the infinite photonic crystal shown in Fig. 1. To set the horizontal wave vector scale, $\Gamma M = 2\pi/\sqrt{3}a$, where a is the hole spacing. All modes in the shaded area are leaky.

herent scatterer of light from the semiconductor into the glass substrate, from which it can escape externally.

In other words, our strategy is to separate the regions where the light is generated from those where the light is extracted. The two respective regions of Fig. 1(a) are the hexagonal area of unpatterned thin film for light generation, surrounded by a few periods of the photonic 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,[10] or couples to the leaky modes of the photonic crystal, and then scatters into the air or into the glass substrate. A suitable design of such a LED structure should therefore satisfy the following common sense requirements:

(1) The size of the unpatterned light generation region has to be not larger than the re-absorption length of the guided light. It is straightforward to estimate an average re-absorption length of the guided light inactive region. Assuming a 10% overlap of the guided modes with the 20-nm-thick active layer, and an average absorption coefficient of $\alpha = 5 \times 10^3\,\text{cm}^{-1}$, we obtain an average re-absorption length of about 20 μm. In high-quality materials, this length is even larger due to photon recycling.

(2) Another requirement is that the photonic crystal dimensions have to be chosen so that the spontaneous emission band of the active region overlap with the frequency of the leaky modes of the photonic band, above the light line. This requirement is fulfilled by the conduction band modes, i.e., the modes that are placed above the band gap in Fig. 2.

(3) Finally, the leakage length of the guided modes inside surrounding photonic crystal has to be shorter than the re-absorption length inside the photonic crystal. The leakage length, L, of the light from the photonic crystal can be estimated from the modal Q: $L = c/n \times Q/\omega = \lambda Q/2\pi n$, where $n \sim 3.5$ is the semiconductor refractive index, and λ and ω are, correspondingly, the spontaneous emission wavelength and frequency. For the measured values of $Q \sim 30...100$ this gives a leakage length $L \sim 6...20\,\mu$m. Voids in the InGaAs/InP film reduce the effective re-absorption so that the re-absorption length in the photonic crystal is even larger than the 20 μm in the unpatterned thin film established earlier.

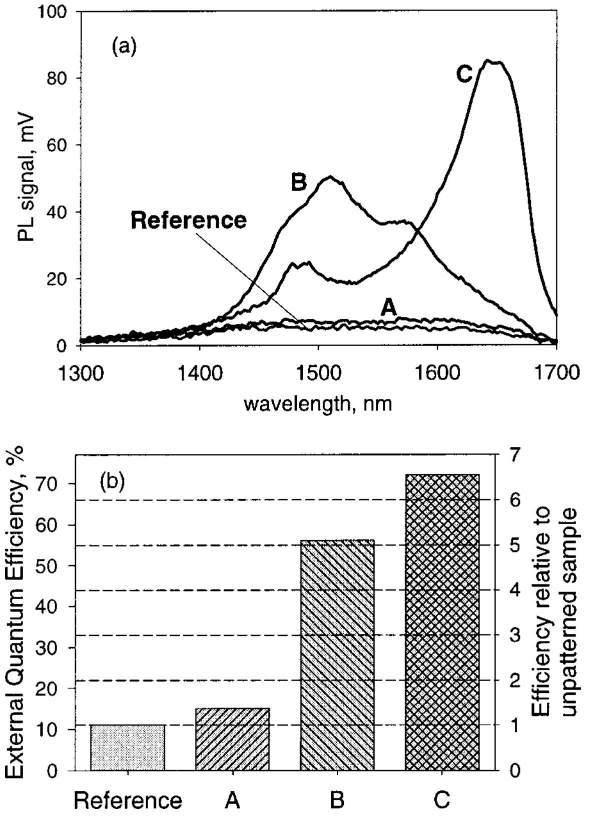

FIG. 3. (a) Angle-integrated PL spectra of our LED structure. Samples A, B, and C have lattice constants $a = 600$, $a = 760$, and $a = 900$ nm, respectively. The peak wavelength is redshifted for larger lattice constants, and follows the general shift of the photonic conduction band modes. (b) Comparison of PL efficiencies from LED structures with different lattice constants. Left axis: calibrated external efficiency; right axis: relative to an unpatterned reference sample.

In our experiments, we measured the spontaneous emission from a 20 μm diameter unpatterned optically pumped region surrounded by 15 rows of photonic crystal. The lattice spacing, a, of the photonic crystal samples A, B, and C was 600, 760, or 900 nm, respectively. According to our band structure calculations, in the $a = 600$ nm sample A, the spontaneous emission band overlaps with the band gap for TE modes, and only emission into guided transverse magnetic (TM) modes is allowed. For the $a = 760$ nm sample B, bands move to the lower frequencies and the spontaneous emission band overlaps with both the guided TM and the leaking conduction band modes of the photonic crystal. For the $a = 900$ nm sample C, the bands move to the lower frequencies, and all spontaneous emission goes into the leaky conduction band modes, and eventually to free space.

The photoluminescence (PL) spectra from these samples are shown in Fig. 3(a) along with the spectrum of an unpatterned reference sample. The PL acceptance angle in most cases was 0° to 45° in the air. The absolute PL was extrapolated to 2π steradians in glass by invoking a Lambertian distribution, that was checked by using a glass hemisphere for some samples. The spectrum of the sample A (with $a = 600$ nm) resembles that of an unetched thin film and has almost the same intensity. Apparently, even though the guided waves can couple into guided TM modes inside the photonic crystal, there is no efficient mechanism for the light to get out. The integrated PL signal from the sample B ($a = 760$ nm) is about 4 times larger. The shape of the spectrum is also different, there are two distinct shoulders. These are due to the angle averaging over the sharp spectral features that are associated with the wave vector and frequency matching to the bands of the photonic crystal. Such sharp spectral features will be discussed in a separate letter dedicated to the spontaneous emission that arises within photonic crystals. Finally, the sample C with the $a = 900$ nm hole spacing showed even higher overall efficiency, 6.25 times the efficiency of the unpatterned reference sample.

Only the unpatterned center area was pumped in this experiment, thus pumping conditions remained identical for all samples. The spectrally integrated PL signals are summarized in Fig. 3(b). More than a six-fold increase in light extraction was achieved using photonic crystal rows around the edges of an active semiconductor film. For comparison, an unpatterned thin film placed between two glass hemispheres has an optical escape probability, or extraction efficiency, of $2[1/4(n_s/n_g)^2] \sim 0.11$, where $n_s = 3.2$ and $n_g = 1.5$ are the refractive indices of the InGaAs/InP semiconductor film and the glass substrate, respectively. In our ultrathin films, the effective refractive index is probably slightly smaller than that of the bulk material. Also, the high internal efficiency of the InGaAs active layer, that we calibrated to be near unity, allows photon recycling to further boost the external efficiency of the unpatterned film. With all these benefits combined, we estimate that a thin film, when encapsulated in glass or epoxy, can have a double-sided external efficiency $\geqslant 11\%$. This sets an absolute extraction efficiency scale for the photonic crystal samples in Fig. 3(b), and translates into a more than 70% efficient LED structure.

One of the advantages of the described LED design is that, due to coherent scattering in the periodic photonic crystal, it provides a shorter light escape length. Therefore, it will be superior to random scatterers which are more subject to parasitic absorption.

In conclusion, we proposed and demonstrated a promising LED design that uses highly efficient coherent scattering of guided light by a photonic crystal as an outcoupling mechanism. More than a six-fold PL extraction efficiency enhancement was observed compared to the unpatterned thin film LED. This could produce $>70\%$ external quantum efficiency, and a corresponding wall-plug efficiency. Further far-reaching effects can be expected in LEDs where the light is generated inside the photonic crystal itself.

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