High Extraction Efficiency of Spontaneous Emission from Slabs of Photonic Crystals

Shanhui Fan, Pierre R. Villeneuve, and J. D. Joannopoulos
Department of Physics, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, Massachusetts 02139

E. F. Schubert
Center for Photonics Research, Department of Electrical and Computer Engineering, Boston University, 44 Cummington Street, Boston, Massachusetts 02215
(Received 16 October 1996)

A thin slab of two-dimensional photonic crystal is shown to alter drastically the radiation pattern of spontaneous emission. More specifically, by eliminating all guided modes at the transition frequencies, spontaneous emission can be coupled entirely to free space modes, resulting in a greatly enhanced extraction efficiency. Such structures might provide a solution to the long-standing problem of poor light extraction from high refractive-index semiconductors in light-emitting diodes. [S0031-9007(97)03094-9]

PACS numbers: 42.70.Qs, 41.20.Jb

Spontaneous emission arises from the intricate interplay between a radiating system and its surrounding environment [1,2]. A prominent example of this interplay can be seen in a photonic crystal, where spontaneous emission can be enhanced, attenuated, or even suppressed by changing the density of electromagnetic states at the transition frequency [3–6], or by changing the orbital angular momentum of the emitted photon [7]. The ability to control spontaneous emission could have profound consequences on many optoelectronics devices [8].

One device that could potentially benefit from this control is the light-emitting diode (LED), which spontaneously emits radiation from a p-n junction. In the past thirty years, various approaches have been proposed to enhance the extraction efficiency of LED's [9–12]. Many of these approaches rely on clever geometrical optical designs to either enlarge the escape cone of photons using a hemispherical dome [9], or to enable multiple entry of photons into the escape cone using photon recycling [10] or surface roughness [11]. These approaches, however, do not alter directly the spontaneous emission properties of the devices. The first attempt to increase LED efficiency by direct modification of spontaneous emission was made using a Fabry-Perot type microcavity [12]. However, these resonant cavity LED's could not provide enhancement over the entire emission spectrum, but rather only when at resonance. In this Letter, we present a different approach to the modification of spontaneous emission which leads to significant enhancement over a very wide range of frequencies. Furthermore, as no resonance or photon recycling is involved, the photon lifetime is shorter, which has the effect of reducing the absorption loss and increasing the response speed. In particular, we study the effect of a two-dimensional photonic-crystal slab on the spatial distribution of spontaneous emission from a dipole moment. We show that nearly *all* the emitted light can be extracted from such a dielectric geometry.

We begin by using a simple model for the LED which consists of placing a point dipole source inside a uniform high-index dielectric slab. For concreteness, we choose a slab of thickness $0.5a$, where a is an arbitrary length unit to be defined later, and a refractive index of 3.5, typical for high-index semiconducting materials, such as GaAs, at a wavelength of 1.55 μm. The schematic diagram of the setup is shown in Fig. 1(a). The emitted radiation from the dipole source will either couple to the guided modes of the dielectric slab or to radiation modes.

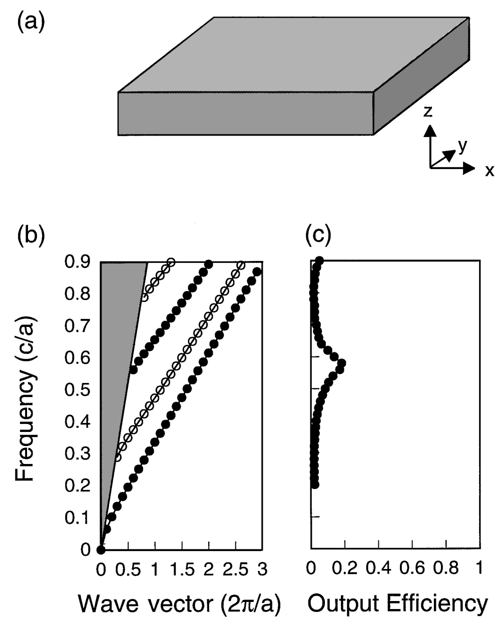

FIG. 1. (a) Schematic diagram of a uniform dielectric slab. (b) Dispersion relation of the structure shown in (a) for TE-like guided modes. The gray area corresponds to the continuum of extended (nonguided) modes. The solid circles correspond to TE guided modes with even symmetry with respect to the x-y symmetry plane, while the open circles correspond to TE guided modes with odd symmetry. (c) Output efficiency along the z direction as a function of frequency.

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The dispersion relations of the guided modes are computed using a conjugate gradient plane-wave expansion method [13]. The first four TE guided mode bands are plotted in Fig. 1(b). These modes are characterized by an electric field lying within and parallel to the slab. The continuum of radiation modes is shown in gray above the light cone. We focus our attention on the TE guided modes since light emitted from a quantum well "sandwiched" between two dielectric layers would have a similar polarization. The first and third TE bands have even symmetry with respect to the mirror plane parallel to the slab [solid circles in Figs. 1(b) and 1(c)], while the other two have odd symmetry (empty circles).

We define the extraction efficiency as the fraction of emitted flux through the top and bottom surfaces of the slab to the total emitted flux. In general, we would expect the extraction efficiency to increase with the density of radiation modes, and decrease with the density of guided modes. To calculate the efficiency, we use a three-dimensional finite-difference time-domain method described in Ref. [14] with Mur's absorbing boundary conditions [15]. A point dipole source polarized in the x-y plane is inserted at the center of the dielectric slab, and is excited with a Gaussian profile in time. The extraction efficiency is shown in Fig. 1(c) as a function of frequency. The results are obtained by a discrete Fourier transform [16] which allows us to compute the efficiency at different frequencies in a single simulation run.

For the most part, the extraction efficiency is well below 10%. At low frequencies the density of radiation modes increases more rapidly than that of the single guided mode. Consequently the extraction efficiency initially increases with frequency, eventually reaching a maximum of 19% at $0.58c/a$. The drop in efficiency above $0.58c/a$ arises from the appearance of an additional guided mode which "traps" the emitted radiation and hinders light extraction from the slab. A similar drop is not observed at the cutoff frequency of the second band in Fig. 1(b) since the dipole source cannot couple to bands with odd symmetry.

The existence of guided modes in the slab impedes the extraction of light. In the case shown in Fig. 1(a) where the slab is surrounded by air, guided modes exist at every frequency [17]. By introducing a strong two-dimensional variation of the refractive index into the slab, we hope to create a frequency range for which no guided modes can exist. In this frequency range, all the spontaneously emitted power will couple to free space modes and will radiate out of the slab.

We choose to introduce an index variation by patterning a triangular lattice of air holes into the dielectric slab. The holes are chosen to have a diameter of $0.45a$, where a is the lattice constant of the triangular array. For the purpose of calculating the extraction efficiency, we choose a slab with a finite number of holes, as shown in Fig. 2(a). The triangular lattice is a natural choice since, in the case of a slab with *infinite* thickness,

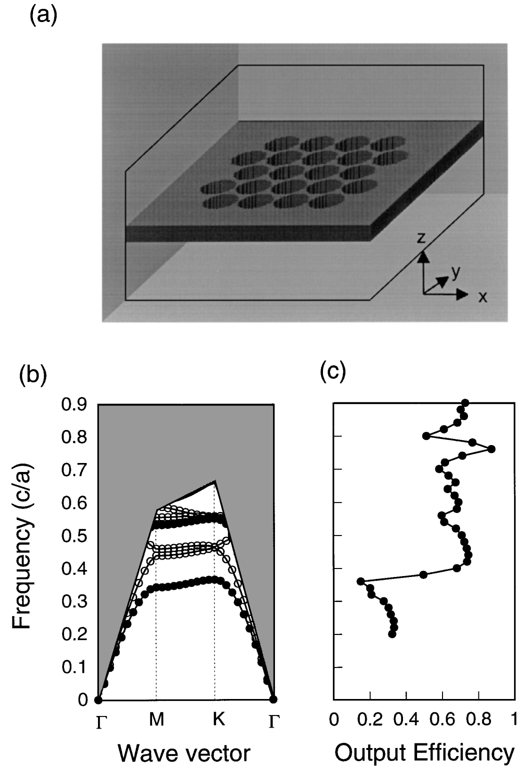

FIG. 2. (a) Schematic diagram of the computational cell containing a finite number of air holes inside a dielectric slab on a triangular lattice. (b) Dispersion relation of the structure shown in (a) for the case of an infinite number of air holes. The gray area corresponds to the continuum of extended (nonguided) modes. The solid circles correspond to TE-like guided modes, while the open circles correspond to TM-like guided modes. (c) Output efficiency as a function of frequency, for the case shown in (a).

a large in-plane band gap appears for both TE and TM polarizations [18,19].

The photonic band diagram for a corresponding slab with an infinite array of holes is plotted in Fig. 2(b). The gray region above the light line corresponds to the continuum of extended modes. Below the light line, we show the bands for every guided mode in the structure. The periodicity has a dual effect on the guided modes: it opens a gap, and also sets an upper frequency limit. A gap can be seen between the first and second TE-like bands, and between the second and third TM-like bands [20]. The first two TE-like bands are even with respect to the mirror plane parallel to the slab. The gap for the TE-like modes extends from $0.37c/a$ to $0.53c/a$ (size of 36%, which is defined as the gap width over the midgap frequency), while the gap for the TM-like modes extends from $0.47c/a$ to $0.56c/a$ (size of 17%). Above $0.66c/a$, all the modes are extended; the periodicity causes every mode above the cutoff to be Bragg scattered into the continuum.

We study the extraction efficiency for a dipole placed in the structure shown in Fig. 2(a). The dipole is located at the center of the slab, and is aligned along the y direction.

Again, only even TE-like modes will be able to couple to the emitted radiation. Results are shown in Fig. 2(c). At the band edge of the lowest band, the extraction efficiency jumps sharply from less than 15% to more than 70%. The efficiency remains close to 70% inside the entire gap region. A dip occurs around $0.55c/a$, which coincides with the upper edge of the gap. Above the second band, there are no TE-like guided modes. The efficiency oscillates around an average value of 70% with the occasional peak close to 90%.

We plot in Figs. 3(a) and 3(b) the power distribution of the electric field radiating from the dipole. The power is shown for two different frequencies, namely, $0.44c/a$ which lies inside the gap [Fig. 3(a)] and $0.76c/a$, which falls inside the continuum of extended modes [Fig. 3(b)]. In both cases, a large fraction of the power is radiated into free space, as expected.

Although both cases display large extraction efficiencies, the radiation patterns reveal important differences. In the case shown in Fig. 3(a), radiation appears to originate predominantly from the center of the array, while in Fig. 3(b) radiation appears to be more spread out. This difference is attributed to the nature of the eigenmodes in the absence of the dipole. Modes inside the gap do not propagate along the slab, thus emitted light goes directly into free space. On the other hand, modes above the light line possess large components in both the slab and free space. Emitted light, therefore, can propagate along the slab and then couple out, resulting in a more complex radiation pattern.

As we have shown in Fig. 2, light can be extracted from a dielectric slab with high efficiency using less than three periods of the triangular array in any direction around the dipole. Since only a finite number of holes is introduced into the slab, some radiation is able to escape along the slab. The radiation intensity decays away from the source, up to the edge of the array, and couples to guided modes and remains trapped inside the slab. By increasing the number of holes, one should be able to achieve even higher extraction efficiencies. One expects efficiencies approaching 100% in structures with a large number of holes.

For completeness, we also study the emission properties in an array of short dielectric posts. This configuration is analogous to the one described above, except that where there was dielectric now there is air, and vice versa. The posts have a radius of $0.15a$, a height of $0.5a$, a dielectric constant of 12.096, and are arranged on a honeycomb lattice. A schematic diagram of the structure is shown in

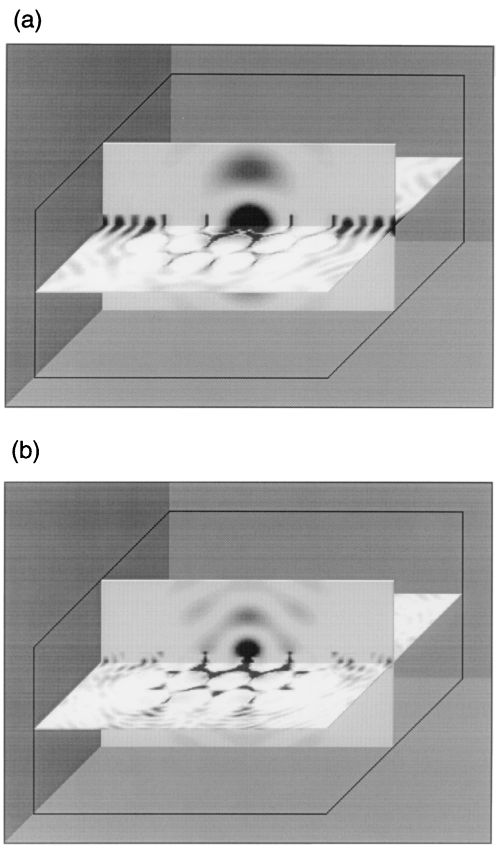

FIG. 3. Spatial distribution of the electric-field power density radiating from a dipole in the triangular lattice. The power density is shown for frequencies (a) $f = 0.44c/a$ and (b) $f = 0.76c/a$.

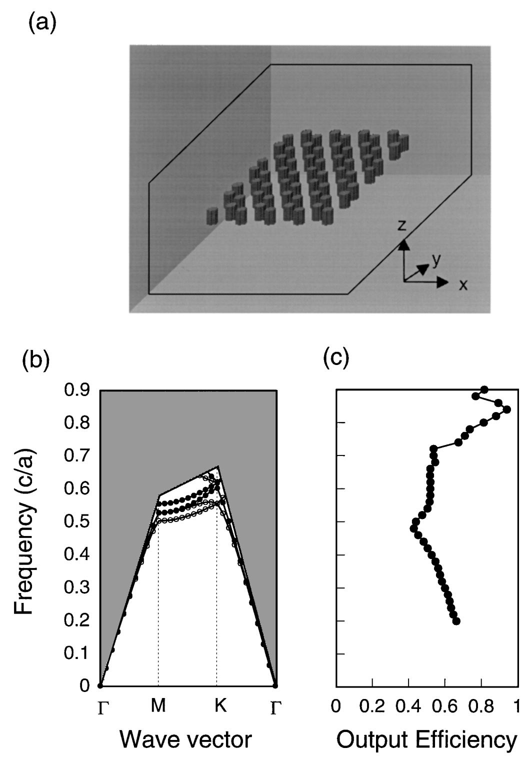

FIG. 4. (a) Schematic diagram of the computational cell containing a finite number of short dielectric posts on a honeycomb lattice. (b) Dispersion relation of the structure shown in (a) for the case of an infinite number of posts. The gray area corresponds to the continuum of extended (nonguided) modes. The solid circles correspond to TE-like guided modes, while the open circles correspond to TM-like guided modes. (c) Output efficiency as a function of frequency, for the case shown in (a).

Fig. 4(a). As was the case for the triangular lattice of air holes, the honeycomb lattice of dielectric posts generates a complete in-plane band gap for both polarizations when the posts have *infinite* length [5]. However, it turns out that the gap lies above the cutoff frequency for the guided modes (i.e., above the light line). The band structure is shown in Fig. 4(b) for the case of rods with finite length. There is no gap for the guided modes in this structure. The output efficiency is shown in Fig. 4(c). As expected, there is no spectral region with high extraction efficiency below the light cone. Above the light cone, however, the efficiency jumps above 80%, with a peak at 94%.

In conclusion, we demonstrate that efficient light extraction from a dielectric slab can be achieved with a two-dimensional photonic crystal. We present results for two different frequency regimes, namely, below and above the light cone where, in the former case, a gap is created between the guided modes. We also discuss the differences in the physical mechanisms and radiation patterns between these two regimes.

This work is supported by the MRSEC Program of the NSF under Award No. DMR-9400334.

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