Enhanced emission with angular confinement from photonic crystals

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We consider the emission of dipoles embedded in a photonic crystal. We demonstrate that it is possible to obtain an angular confinement of the emission (i.e., a large coherence area) together with an enhancement of the emitted power. A simple geometrical construction gives us a very comprehensive guideline. We illustrate the developed ideas with a structure working at the band edge of an expanded cubic photonic crystal and we take advantage of the large value of the density of states at these wavelengths. Then, it is shown that both directivity and total emitted power can be improved simultaneously without requiring defect modes. © *2002 American Institute of Physics.*
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The first prediction, in 1946, of the modification of the spontaneous emission by the electromagnetic environment has motivated numerous studies.[1] Experimental investigations of controlling spontaneous emission have been reported using various structures such as metallic planar cavities,[2] micropillars,[3] etc. In the optical range the losses of metals make their use questionable, particularly to inhibit spontaneous emission. Thus, it is necessary to employ dielectric structures. Unfortunately, the simplest structures such as planar Bragg reflectors are unable to provide a full three-dimensional (3D) inhibition, mostly because of the guided modes inside the structure.[4]

Photonic crystals were proposed at the end of the 1980s as a candidate to control the spontaneous emission of light[5] as well as for observation of strong localization of photons.[6] However, among the numerous publications on photonic crystals, relatively few deal with the emission (e.g., Refs. 7 and 8). Recently, experiments have been conducted with dye incorporated in colloids, which showed a clear stop gap in the fluorescence spectrum.[9]

Mainly, two features in the control of atomic spontaneous emission are of interest: the first one is to enhance the emitted power whatever the direction of emission, and the second one is to restrict the direction of the emitted light in a small angular region. We propose a solution in order to combine both by using a 3D photonic crystal at the band edge of a full band gap. It has been shown that the so-called density of states is increased near the band edges:[10,11] this phenomenon brings us the solution for the first problem. Moreover, we will show how to choose the proper characteristics of the photonic crystal in order to confine the emission outside the photonic crystal in a small angular region determined by the dispersion relation of the Bloch modes inside the crystal.

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Now, we will show how to shape the dispersion relation to obtain the desired directivity. Let us consider a dipole embedded in a slab (a slice) of photonic crystal. The question is: how will the dispersion relation of the Bloch modes inside an infinite photonic crystal help us to choose the parameters? The guidelines we will explain are based on the assumption that only the propagating waves in the crystal determine his behavior, and not the evanescent ones. Let us assume that the desired direction of emission is the direction of the z axis and that the output face of the crystal is in the xOy plane. First, the tangential components of the Bloch wave vector k_x and k_y are conserved at the interface delimiting the crystal and the surrounding homogeneous media if the output surface is infinite.[12] Indeed, the resulting structure is periodic along two directions defining the plane interface Ox and Oy, i.e., the resulting structure is invariant under the group of spatial translations associated with its periodicity. Moreover, for a given Bloch wave vector and frequency two situations can occur: if no solution (Bloch mode) exists then the emitted power is close to zero (null in an infinite crystal); however, if a solution exists then light can be emitted in the corresponding Bloch mode. Combining these two points gives us the conclusion that the projection on the tangential plane of the ''constant frequency dispersion diagram'' must be included in the tangential components region given by the desired angular region of emission. It is worth noticing that the energy will flow in the whole crystal as the direction of the energy flow is given by the normal to the constant frequency dispersion diagram.[12]

The next step is to find a structure having suitable properties. Our aim is to find a structure as simple as possible with a realization in the optical telecommunication domain (a wavelength close to 1.5 μm). The two leading techniques are sedimentation[13] (artificial opals) and advanced semiconductor processing. The second suits our goal perfectly as the

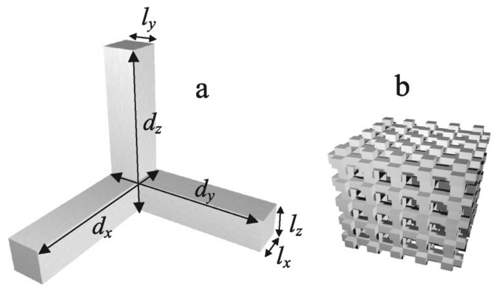

FIG. 1. a: Elementary cell of a simple cubic photonic crystal. Unexpanded photonic crystal: $d_x = d_y = d_z = 3.2\ \mu$m and $l_x = l_y = l_z = 0.8\ \mu$m. Expanded photonic crystal: same dimensions except $d_z = 3.41\ \mu$m and $l_z = 0.85\ \mu$m. The optical index of the dielectric is $n = 3.6$ and the embedding medium is vacuum. (b) Example of a $5\times5\times5$ cell simple cubic photonic crystal.

symmetries can be easily modified to shape the dispersion relation. So, we concentrate on the simplest one: the simple cubic crystal similar to those realized and recently reported by the Sandia National Laboratories group[14] (Fig. 1).

Figure 2 shows a representation of the dispersion relation of the Bloch modes inside the infinite structure. The dispersion relation is obtained from the scattering matrix of a single grating layer, as reported in Refs. 12 and 15. The representation is quite unusual and must be commented on: the diagram shows if it exists (white) or not (gray) a Bloch mode for a given value of the frequency and of the two tangential components of the Bloch wave vector. Those tangential components are taken on the edges of the triangle ΓXM,[15] this triangle being the projection on the tangential plane of the reduced primitive cell of the reciprocal lattice. Consequently, the Γ point in Fig. 2 corresponds with the normal incidence, i.e., $k_x = k_y = 0$ (the $\Gamma - X$ path of the usual representation).[14] A more-detailed description of the method and the representation of the dispersion relation can be found in Ref. 15. Note that the present dispersion diagram is in agreement with the experimental transmission curves reported in Ref. 14. With the parameters of Lin's experiences a full band gap is found (Fig. 2, left). All the used parameters are given in the Fig. 2 caption and are those of the experiments in Ref. 14. Note that we have chosen to keep the same parameters as in the experiments rather than rescaling the structure to obtain an emitter working around 1.5 μm to allow easier comparisons with the experiments. Figure 2 shows that the upper limit of the band edge is for the Γ (and the X) point, i.e., for normal incidence. But, from the symmetries of the crystal six equivalent points exist: if one cuts a slice of this photonic crystal and if the emission is allowed in the direction of the normal (z) of the slice, it is also in the x and y directions in the plane of the slice. So the symmetries of the crystal must be reduced. The simplest solution is to change the periodicity along the z direction. Using an expanded crystal was first proposed using completely different arguments in Ref. 16 for a two-dimensional (2D) structure.

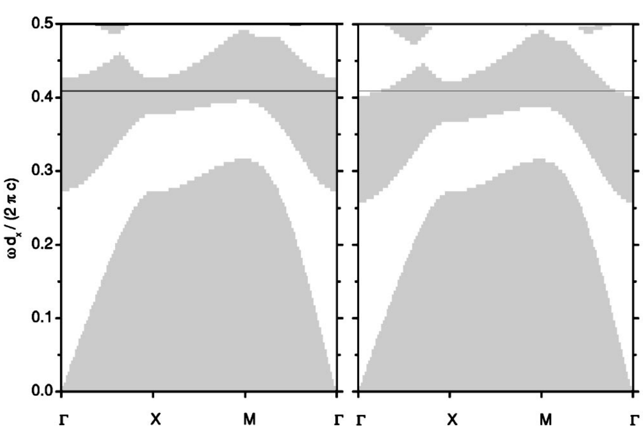

FIG. 2. Left: representation of the dispersion relation in the simple cubic photonic crystal. Right: dispersion relation in the expanded cubic photonic crystal. The gray regions are the regions where no solution exists. The black line is for $\omega d_x/(2\pi c) \approx 0.409$, corresponding to $\lambda \approx 7.83\ \mu$m.

Figure 2, right side, shows the same representation of the dispersion relation as in Fig. 2, left side, but for a crystal with an expanded periodicity in the z direction (the parameters are given in the Fig. 1 caption). The upper band edge is now for the normal direction (at Γ) but not for the orthogonal directions (at X). Then, if the frequency is chosen close to the band edge of this expanded crystal, the emitted light will be concentrated in narrow cones in the upper and the lower media. In order to concentrate the power only in the upper half space, one can use a structure composed of a slice of the expanded crystal lying above another slice of the unexpanded (simple cubic) crystal. The band-edge frequency of the expanded crystal is in the gap of the simple cubic one and then the emission will occur principally in the upper half space.

The emission of the source will be now considered using an entirely classical model of a dipole embedded in the photonic crystal since it is known that the effect of a cavity on emission rate is essentially classical.[17] The numerical method we use is presented in Ref. 18. This numerical method, which allows us to determine the emission of a dipole in a grating (thus assuming that the crystal is infinite along the x and y axes), is based on a Floquet–Bloch decomposition along x and y of the current source term (here, a dipole) $\mathbf{P}(t,\mathbf{r}) = \mathbf{P}_\omega(\mathbf{r})\exp(-i\omega t)$ with $\mathbf{P}_\omega(\mathbf{r}) = \mathbf{P}_0\,\delta(\mathbf{r}-\mathbf{r}_0)$, where δ is the Dirac function, $\mathbf{P}_0$ gives the orientation of the dipole, and $\mathbf{r}_0$ is the position of the dipole in the crystal. Then, using the scattering matrices of both structures above and below the source, a system is solved for each Floquet–Bloch component (or equivalently for each tangential component of the Bloch wave vector) that gives the radiated field for a given direction in the surrounding media.

The structure under consideration consists of a slice of six periods of the expanded crystal above a slice of three periods of the simple cubic one. In addition, the upper period has been completed in order to end the crystal by holes rather than pillars. The position of the dipole has a great influence on the emitted power and must be chosen to benefit the largest value of the local density of states associated with the finite-thickness structure. A numerical study of this location gives us the optimal position of the dipole inside the expanded photonic crystal. Figure 3 shows the emission diagram of the dipole in the studied structure. The curves have been normalized in such a way that the maximum of the diagram is scaled to unity when the dipole is placed in the vacuum. The emitted power in the normal direction is about 74 000 times higher than the maximum emitted power by the dipole lying in vacuum (about 48.7 in the dB scale). Clearly,

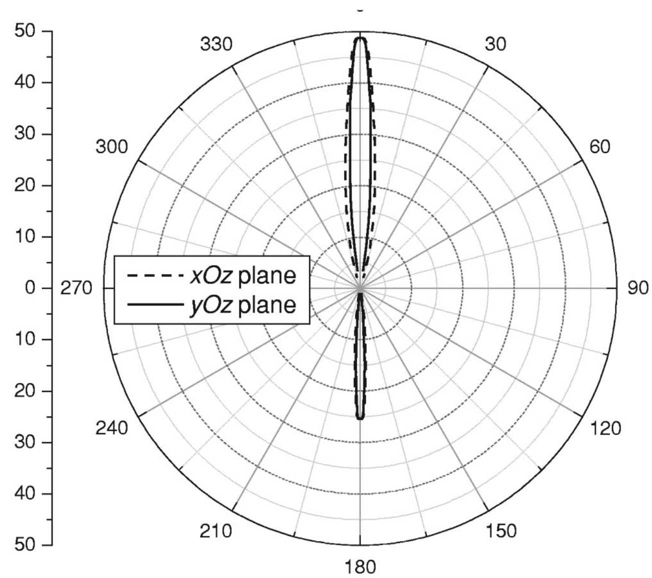

FIG. 3. Normalized emitted power in the dB scale by a dipole in the *yOz* (solid line) and *xOz* planes (dashed line). The oscillating dipole at $\lambda = 7.83\ \mu$m is directed along *Oy* and located at the middle of the expanded crystal, more precisely in the center and at the top of a vertical dielectric rod between the third and fourth layers of the expanded crystal.

the emission is concentrated in a narrow lobe when the dipole is embedded in the expanded photonic crystal. The beamwidth of this lobe is about 4° and can be lowered by adding a few expanded periods. The total emitted power can be evaluated using the classical formulas in antenna theory:[19] $P \approx U \Delta\theta_1 \Delta\theta_2$, where U is the power radiated per unit solid angle in the direction of the maximum of the lobe and $\Delta\theta_1$ and $\Delta\theta_2$ are the angular half-power beamwidths in the two principal planes. The result is that the emitted power is about 34 times higher when the dipole is in the crystal than in vacuum. From models such as the perturbation model it corresponds to a lifetime of the embedded atom divided by the same factor. Note that the maximum emitted power in the lower half space (the side of the unexpanded photonic crystal) is 220 times lower than in the upper direction with only three periods of unexpanded photonic crystal and can be easily lowered by adding a few unexpanded periods.

Even if our model assumes an infinite structure along the *x* and *y* axes, the results are representative of the behavior of a limited structure as long as the characteristic lateral size *d* is greater than $\lambda/\Delta\theta$ (with the parameters of the given example only about 120 μm) since all the Bloch wave vector values, except those close to the normal incidence, belong to the band gap. Note that all the energy emitted by the dipole is outcoupled from the photonic crystal, contrary to what happens when the dipole is in a homogeneous dielectric slab.

In conclusion, we have shown in this letter how using a simple structure without any cavity will enhance the spontaneous emission and canalize it inside a small solid angle around the normal of a photonic crystal slice: an enhancement of the total emitted power of 34 has been numerically demonstrated and the emission occurs in a lobe with about 4° half-power beamwidth. Moreover, it seems probable that advanced semiconductor processing techniques will allow the realization of such a structure operating at optical telecommunication wavelengths in the next few years. From this point of view the simplification generated by the absence of any microcavity will probably be an advantage. Maybe the more important point is that both improvement of the directivity and enhancement of the emitted power are achieved together and, in theory, the closer the operating wavelength is from the band edge, the narrower is the emission lobe, and higher the emitted power. Of course, technical limitations such as absorption or imperfections exist and will be studied and reported in a future paper, as well as the influence of the spectral width of the emitting source.

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