Highly directive light sources using two-dimensional photonic crystal slabs

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We have designed a microcavity with periodic microstructure that extracts nearly all the power emitted by a luminescent source and confines 80% of the energy radiated in the superstrate in a cone of half width 0.2° about the normal of the device.
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Generating light sources is a subject of intense activity. Several ways for improving these devices are explored: increasing the spontaneous emission rate, improving the conversion of emitted power into useful radiation, and controlling the angular directivity of the light. The latter requirement also proves useful in ameliorating the performances of biosensors, in which detectors usually see luminescent molecules under a limited solid angle. Many microcavities from Fabry–Pérot stacks to three-dimensional (3D) geometries such as microspheres, micropillars, and air bridges, have been studied to modify the emission rate by confining the light to small volumes.[1,2] 3D photonic crystals, namely photonic band-gap (PBG) materials, have also been suggested[3] for this purpose. Easier to fabricate, two-dimensional (2D) periodically patterned dielectric planar waveguides, i.e., mode band-gap (MBG) materials, which allow control of guided waves in two space directions and partially confine the light in the third direction with the total internal reflection process, are also under study.[4] In most light-emitting diodes (LEDs) the emitting part is a thin-film material whose index of refraction is quite larger than its surrounding media. A large fraction (close to 90%) of the emitted power is trapped in the structure through the guided waves and by total internal reflection. This problem is often resolved by introducing surface roughness on the LED, which scatters back in free space the nonradiative waves, so that over 30% of the light can escape from the semiconductor surface.[5] A better extraction efficiency combined with an increase of the spontaneous emission rate can be obtained by enclosing the emissive layer in a microcavity that forces the source to emit preferentially into modes that can couple to useful radiation. In planar microcavities such as Bragg reflecting mirrors based on a multilayer stack, up to 32% of the power is extracted while the remainder is carried mostly by the guided waves of the stack.[6] Prohibiting the propagation of lateral modes can overcome this limitation.[1,7] Another solution, using MBG-type structures, consists of favoring the coupling of the source to surface waves or guided waves and then Bragg scattering them in free space.[4,8–10] Experimental and numerical studies of these microcavities show a strong enhancement in the useful emission intensity due to a much better extraction rate and a higher spontaneous emission rate.[4] The issue of the directivity of the light source has received less attention. Indeed, it seems difficult to improve it with microcavities allowing a high confinement of the field since the lateral dimension of the emitting surfaces is usually of the order of the wavelength. On the other hand, extended cavities such as Fabry–Pérot stacks, while able to confine the radiated power into a cone of small aperture, are plagued with a relatively small extraction efficiency.[6] Last, the promising MBG-type cavities present a complicated radiation pattern that is not satisfactory as it stands.[9,11] In this letter, we design a MBG microcavity from which all the power provided by the source can be theoretically extracted, and that concentrates most of the radiated energy in an arbitrarily small solid angle about its normal.

To study the radiation pattern of the device, we use a well-proven model based on an entirely classical formalism in which the emitter is considered to be a forced electric dipole oscillating at frequency ω located in a complex structure.[12] The calculation of the emission, in the superstrate or substrate, of the active microcavity is performed by invoking the reciprocity theorem.[13] The latter states that, in the far field of the active device, the electric field at $\mathbf{R}=R\hat{\mathbf{u}}=R(\mathbf{u}_{\parallel}+u_z\hat{\mathbf{z}})$, $\mathbf{E}_1(\mathbf{R})=\mathbf{E}(\hat{\mathbf{u}})\exp(i\omega R/c)/R$, radiated by a dipole located at origin $\mathbf{O}$ [see Fig. 1(a)], can be obtained from field $\mathbf{E}_2(\mathbf{O})$ that exists when the same structure, without source, is illuminated by a plane wave with the incident wave vector directed along $(\mathbf{u}_{\parallel}-u_z\hat{\mathbf{z}})$. The radiated power in the direction of observation $\hat{\mathbf{u}}$ per unit solid angle, is proportional to $|\mathbf{E}(\hat{\mathbf{u}})|^2$. The reciprocity theorem is a powerful tool that allows one to interpret the radiation pattern of an active device by referring to the properties of the passive structure which have usually been more studied. All the numerical results were obtained with a 2D grating code, based on the scattering matrix approach and a Fourier modal method, as described in Ref. 14. The scattering matrix relates any incident

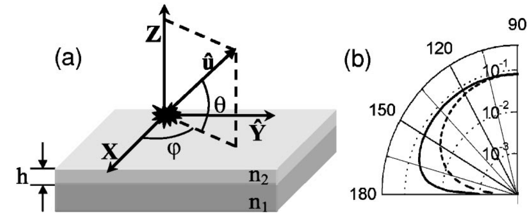

FIG. 1. (a) Geometry of the planar cavity. The thickness of the film is $h=0.06\,\lambda_0$, where λ_0 is the wavelength of radiation of the source in vacuum. Index of refraction of the film $n_2=3.5$, of the substrate $n_1=1.5$, and of the superstrate $n=1$. (b) Power radiated in the superstrate by a dipole directed along the $0X$ axis located on the film: in the plane $\varphi=0°$ (solid line), $\varphi=90°$ (dash line).

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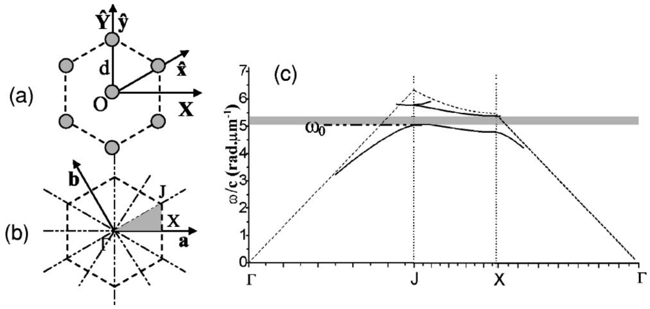

FIG. 2. (a) Hexagonal cell of air holes etched in the film of the planar microcavity of Fig. 1(a). The lattice constant is $d=0.35\lambda_0$. The holes are hexagonal and inscribed in a disk of diameter $d/\sqrt{3}$. (b) Reciprocal lattice of the periodically patterned thin film (i.e., mode band-gap material) and the reduced Brillouin zone. (c) Dispersion relation of the TE-like mode in the MBG. The cutoff frequency for the TM-like modes is well above the gap. The frequency ω_0, at the lower boundary of the gap, is the frequency of the source.

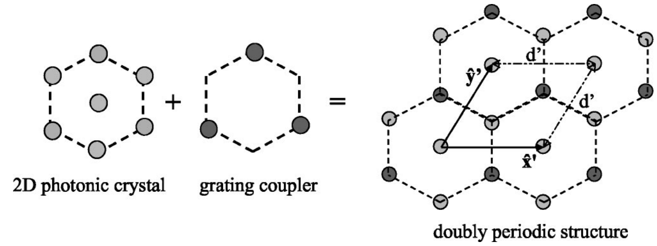

FIG. 3. Schematic top view in real space of the MBG of Fig. 2(a) and of the grating coupler that outcouples the guided waves in free space along the normal to the device. The microcavity is a combination of these two structures, it is periodic with period $d'=d\sqrt{3}$. The disks represent hexagonal holes that are drilled through the guiding layer. The black holes are 20% smaller than the gray ones.

plane wave impinging on the structure (from the substrate and the superstrate) to the outgoing diffracted plane waves. It permits the calculation of the field inside the structure, the dispersion relation of modes,[15] and the efficiencies of gratings.

We start from the simple multilayer system, depicted in Fig. 1(a), consisting of a semi-infinite substrate of refractive index $n_1=1.5$ covered by a layer of dielectric material with a high refractive index, $n_2=3.5$ (typically, a semiconductor such as GaAs). The superstrate is vacuum with index 1. We now place a luminescent source on the film. To model quantum-well sources, we consider solely dipole moments lying in the *XY* plane.[7] The emitted light is distributed among the radiative continuum that gets out of the structure (above and below) and the nonradiative part, including the guided modes, that remains trapped in the layer. The angular distribution of the intensity emitted in the superstrate is shown in Fig. 1(b). The lobe is strongly divergent for both planes of observation. The total radiated power in free space, obtained by integrating the emission over 4π strad is two times smaller than that obtained with a source located in free space. This is due to the loss of power carried by the guided modes and also by the inhibition of the spontaneous emission induced by the destructive interferences between the reflected fields that drive the emitter.[12]

The first issue is to control the guided modes that carry an important fraction of the emitted power,[6] and thus diminish the device efficiency. It is well known that a periodic perturbation of the planar waveguide, namely, a Bragg grating, may impede the propagation of guided waves in a given direction. Yet, blocking all the modes, whatever their direction, in the frequency domain *W* of the luminescent source, is more difficult. It is achieved in Ref. 7 with a triangular lattice of air holes in a symmetrical dielectric slab. Here, we consider an asymmetrical planar waveguide that supports only one TE mode in *W* described by its dispersion relation $k_g(\omega)$. We pattern the guiding layer with a triangular lattice of hexagonal dips. More precisely, the structure is periodic with period d along two vectors $\hat{\mathbf{x}}$, $\hat{\mathbf{y}}$ of the *XY* plane that verify $\hat{\mathbf{x}}\cdot\hat{\mathbf{y}}=\cos(\pi/3)$, as depicted in Fig. 2(a). Then, the electric field of the TE-like mode can be cast in the form

$$\mathbf{E}(\mathbf{r},z,t)=\exp(i\mathbf{r}\cdot\mathbf{K}_m-i\omega t)\sum_{\mathbf{K}\in\Sigma}\mathbf{E}_{\mathbf{K}}(z)\exp(\mathbf{r}\cdot\mathbf{K}), \qquad (1)$$

where $\mathbf{K_m}$ is the mode wave vector that is limited to the Brillouin zone; $\mathbf{r}$ is the in-plane component of the observation point $\mathbf{r}=x\hat{\mathbf{x}}+y\hat{\mathbf{y}}$; and $\mathbf{K}=(2\pi/d)(n\mathbf{a}+m\mathbf{b})$, with (n,m) relative integers, is a vector of reciprocal space Σ whose basis $(\mathbf{a},\mathbf{b})$ satisfies $\mathbf{a}\cdot\hat{\mathbf{x}}=1$, $\mathbf{a}\cdot\hat{\mathbf{y}}=0$, $\mathbf{b}\cdot\hat{\mathbf{x}}=0$, $\mathbf{b}\cdot\hat{\mathbf{y}}=1$. For small corrugations, the dispersion relation $\mathbf{K_m}(\omega)$ follows that of the unperturbed waveguide except at the edge of the Brillouin zone, i.e., when one can find $\mathbf{K}$ so that $|\mathbf{K_m}+\mathbf{K}|$ is close to $|\mathbf{K_m}|$ [this occurs at frequencies ω when $k_g(\omega)$ reaches π/d]. Indeed, in this region, the grating triggers the excitation of several guided waves propagating along different directions. The coupling between these degenerate modes introduces a frequency band gap corresponding to a change in the energy associated to each mode. In Fig. 2 we plot the dispersion relation $\mathbf{K_m}(\omega)$ when the extremity of $\mathbf{K_m}$ follows the reduced Brillouin-zone boundary $\Gamma JX\Gamma$, described by $\Gamma X=\pi\mathbf{a}/d$, $\Gamma J=2\pi(\mathbf{b}/3+2\mathbf{a}/3)/d$, which accounts for the symmetry of the crystal. To obtain a total band gap for the TE-like mode, it has been necessary to etch hexagonal air holes, inscribed in a disk of diameter $\phi=d/\sqrt{3}$, throughout the film down to the substrate. If the frequency of the source lies in the gap, no emitted power can be lost in the guided modes and the extraction rate is strongly enhanced.[7] On the other hand, the angular distribution of emitted light is not controlled and the directivity of the source is not improved.

Rather than blocking the modes, it has been suggested in Refs. 8–10 to recover them. Studies have shown that the field associated to guided waves in a multilayer[6] or to guided Bloch waves in a MBG,[16] can be very important as compared to that of the continuum spectrum. Hence, the emitter may couple to them preferentially. To recover the power trapped in the guided waves, one can use a hemispherical dome with a higher permittivity than the film. A similar result can be obtained, with a more repeatable and cheaper technology, thanks to a cross-grating coupler that scatters back in free space the guided waves and the continuum of the nonradiative plane waves provided by the source. The period of the cross grating is chosen so that whatever wave vector k in the *OXY* plane, there exists at least one reciprocal lattice vector $\mathbf{K}$, which satisfies, $|\mathbf{k}+\mathbf{K}|\leqslant\omega/c$. The power carried by the now leaky, guided modes escapes the device in free space along the directions (θ,φ) given by[9]

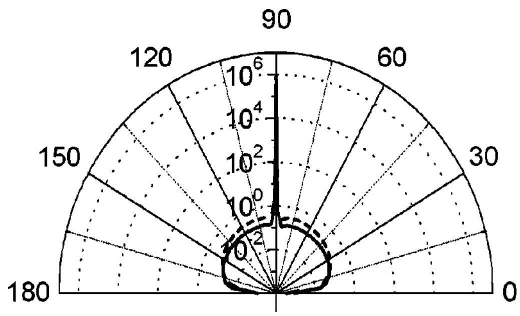

FIG. 4. Power radiated in the superstrate, in the plane $\varphi=0°$ by a source placed on the modified MBG presented in Fig. 3(b). The dipole moment is directed along the $0X$ axis (dash line) and $0Y$ axis (solid line). The radiated power is roughly isotropic.

$$\frac{\omega}{c}\sin\theta(\cos\varphi\hat{\mathbf{X}}+\sin\varphi\hat{\mathbf{Y}})=\mathbf{K_m}+\mathbf{K}. \quad (2)$$

The radiated pattern then presents peaks of emissivity along several arcs or portions of cones.[9,11] The height and filling factor of the grating influence the thickness (or angular divergence) of the arcs by increasing or diminishing the leakage of the modes.[9] These devices are interesting from an extraction point of view, but the angular distribution of the emitted light is still not satisfactory and it remains difficult to collect light from the arcs.

To concentrate the energy about the normal of the device while extracting 100% of the emitted power, we propose to improve this last technique by using the ability of 2D photonic crystal to modify the dispersion relation of the modes. Indeed, the presence of arcs in the spatial distribution of the emitted light is directly linked to the fact that the guided modes are excited by the source in any direction of the XY plane. If one is able to design a planar structure that supports guided modes in a small angular domain only, then, the grating coupler will be able to scatter back the light in a very directive manner. To impede the propagation of the guided waves in most directions, we can use a MBG that opens a total band gap for the modes. At frequencies close to the edge of the gap, the propagation of the modes is allowed only in certain directions of the reciprocal Brillouin zone. In the example presented in Fig. 2, when $\omega=\omega_0$, at the low edge of the gap, the periodic structure supports one mode in the reduced Brillouin zone, with wave vector $\mathbf{K_m}=\Gamma J$ (where ΓJ is a reciprocal space vector going from Γ to J), $|\mathbf{K_m}|=\pi/d$, and its five symmetrical partners in the complete representation shown in Fig. 3(a). Note that these guided modes are not leaky. To recover them in free space, we need to introduce a cross-grating coupler. We carefully chose its period and cell in such a way that the light trapped in the modes is scattered back in the normal direction to the device. Following Eq. (2), we see that the reciprocal lattice of the new periodic structure should include $\mathbf{K}'=\Gamma J$ and all its hexagonal symmetrical images. Hence, we alter the 2D hexagonal crystal with lattice constant d depicted in Fig. 2 so that it becomes periodic with period $d'=d\sqrt{3}$ and a $\pi/3$ rotated hexagonal cell. It amounts to changing slightly the shape of one hole over three, as shown in Fig. 3(b). The modification of this motif is responsible for the leakage of the modes, and thus for the spatial extent L of the electric field in the structure. It monitors the angular divergence $\delta\theta$ of the emitted light in free space with $\delta\theta\sim\lambda/L$, where λ is the wavelength of radiation. The typical length of the microcavity that is necessary to extract most of the power from the guided modes should be of the order of L. The bigger is the perturbation, the more divergent is the emitted beam and the lesser periods are needed to extract all the energy. The delicate interplay between light extraction and light absorption rates will limit, in practice, the angular resolution of the source (see Boroditsky *et al.* in Ref. 4).

In Fig. 4, we plot the angular distribution of the emitted light in the superstrate from a source placed in the altered MBG, depicted in Fig. 3(b), where one hexagonal hole over three is 20% smaller than the regular motif. The solid and dash lines correspond to dipole moments oriented along $\hat{\mathbf{X}}$ and $\hat{\mathbf{Y}}$, respectively. In both cases, we observe a very important peak of emissivity along the normal to the sample corresponding to the excitation of the mode. The average of the emitted intensity in the superstrate over all the orientations of the source shows that about 80% of the energy is now concentrated in a cone of half width 0.2°. The radiated power in the superstrate represents 25% of the total emitted intensity but it is nine times bigger than that obtained from the planar microcavity (while the total radiated power is 3.5 times that of the planar microcavity). Note that a larger emission enhancement could be expected with sources located in the middle of the film rather than at the upper boundary since the Bloch mode intensity is higher there.

By introducing periodical defects in a thin film of 2D photonic crystal, we have designed a very directive light source with high extraction rate that could be manufactured with the present nanotechnology.

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