Extraction of light from sources located inside waveguide grating structures

H. Rigneault, F. Lemarchand, A. Sentenac, and H. Giovannini

Laboratoire d'Optique des Surfaces et des Couches Minces, Unité de Recherche Associée au Centre National de la Recherche Scientifique, Unité Propre de Recherche de l'Enseignement Supérieur A 6080, Microcavities and Light Scattering Groups, Ecole Nationale Supérieure de Physique de Marseille, Domaine Universitaire de St Jérôme, 13397 Marseille Cedex 20, France

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A crossed waveguide grating is presented that can extract the total guided-mode power emitted by a point-source dipole located in the structure. Results obtained with rigorous numerical simulations are compared with a simple graphic analysis to facilitate an understanding of the far-field radiation pattern of such a luminescent device.

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The problem of extracting the total electromagnetic power provided by a localized source located inside a solid-state microcavity structure has been addressed by many authors since Purcell[1] discussed the possibility of modifying the spontaneous-emission rate by tailoring the electromagnetic environment into which the source can radiate. Microcavities with different geometries have been considered, starting from the simple planar Fabry–Perot stack[2] to some more-advanced three-dimensional structures such as microspheres,[3] microdisks,[4] micropillars,[5] and photonic wires.[6] In the case of sources located inside planar microcavities it is now well established that although the extracted light can be directive the extraction coefficient is less than a few tens of percent (usually $<30\%$), with the remaining fraction of the total power trapped in the substrate or in guided modes.[7] The problem is somehow more complex for three-dimensional microcavities, which can have low extraction coefficients (usually associated with high-Q rotating modes) or broad-angle emission (owing to their small output surfaces). A source located inside a corrugated structure is a suitable alternative for extracting the electromagnetic power. Kitson *et al.* have shown that it is possible to scatter light from non-radiative modes by exciting dye molecules on a metallic grating.[8] These molecules can relax by generating surface plasmon polaritons. It is even possible to prohibit particular modes, causing a full photonic bandgap effect.[9,10]

In this Letter we present a solid-state device that can extract more than 80% of the total emitted light in specific directions. The structure [Fig. 1(b)] is a waveguide grating structure (WGS) with periodicity along two orthogonal directions (crossed grating).

Before reporting rigorous numerical results we describe the physical idea that led us to use grating structures to achieve strong extraction coefficients. Consider first a simple dielectric slab waveguide whose refractive index n_g is higher than the indices of the surrounding air n_a and the substrate n_s [Fig. 1(a)]. For simplicity we assume that this waveguide supports a single guided mode. It was shown[11] that when a luminescent source is introduced inside this slab most of the provided electromagnetic power is carried by the guided mode. Furthermore, this light is trapped for every polar ϕ direction in the film plane [Fig. 1(a)]. It is then natural to address the following question: Is it possible to extract 100% of the trapped light by use of a bidirectional corrugated surface?

The use of a grating to couple out guided light has been extensively treated,[12] including sources directly located under corrugated surfaces.[13] Nevertheless, only gratings with periodicity along one direction, which in fact are unable to extract the guided power for each ϕ direction, have been considered.[8] This result is quite easy to see if we consider plane vector $\mathbf{k}_p$, where $\mathbf{k}_p = k_x\mathbf{x} + k_y\mathbf{y}$ is the orthogonal projection of $\mathbf{k}$ in the (Oxy) plane. Figure 2(a) shows this plane for a slab waveguide supporting a single guided mode whose wave-vector modulus is k_g. For waves with wave-vector modulus $k < k_0$ (free-space range), where $k_0 = 2\pi/\lambda_0$, the light can emerge outside the structure [shaded area in Fig. 2(a)], whereas the guided mode solid circle with radius $k_g > k_0$ remains trapped in the slab. To couple the guided mode to the propagating waves running outside the guide it is interesting to use a shallow corrugated surface with periodicity dx along the x axis. In this case a specific running wave of planar wave vector $\mathbf{k}_p{}^0 = k_x{}^0\mathbf{x} + k_y{}^0\mathbf{y}$ is coupled through the grating

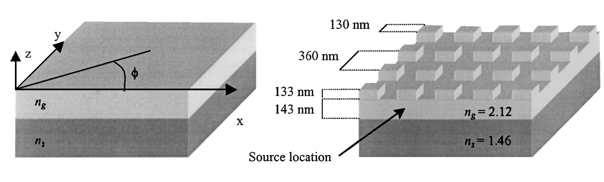

Fig. 1. (a) Planar slab and polar angle ϕ and (b) biperiodic WGS considered in the computation and source location.

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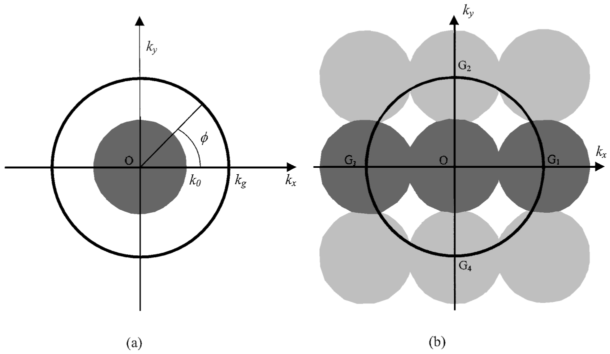

Fig. 2. Planar $\mathbf{k}_p$ space for (a) a slab and (b) a corrugated surface along the x axis (darker circles) and along the x and y axes (darker and lighter circles). The solid circle denotes the guided mode.

to all the waves of planar wave vectors $\mathbf{k}_p{}^m$ with $\mathbf{k}_p{}^m = \mathbf{k}_p{}^0 + mK_x\mathbf{x}$, where $K_x = 2\pi/\mathrm{d}x$. An alternative way to describe this phenomenon is as the periodic duplication of the free-space disk along the k_x axis. This situation is depicted in Fig. 2(b), where only the three darker circles along the k_x axis must be considered. In this case the guided-mode solid circle sections that overlap the darker circles can be extracted outside the slab because of the $m = +1$ and $m = -1$ first grating orders. On the other hand, the remaining guided-mode directions, which do not overlap the darker free-space circles, are still trapped in this Ox corrugated surface. To couple out the total guided mode outside the structure it is necessary to use a periodic surface along both the x and the y directions with periods dx and dy. In this case, as is schematically depicted in Fig. 2(b), where all the lighter and darker circles must now be considered, the guided-mode solid circle always intercepts the first-order free space circles. Furthermore, for this figure we have chosen $K_x = K_y = k_g$. Note that this condition ensures that dx and dy are smaller than λ and that the crossed WGS has a subwavelength scale. For the particular points G_i ($i = 1, 2, 3, 4$), waveguide vector $\mathbf{k}_g$ is coupled with the normally incident wave vector ($\mathbf{k}_p{}^0 = \mathbf{0}$). More generally, any planar wave vector $\mathbf{k}_p{}^0$ can be coupled through the grating to a $\mathbf{k}_p{}^{m,n}$ wave if $\mathbf{k}_p{}^{m,n} = \mathbf{k}_p{}^0 + mK_x\mathbf{x} + nK_y\mathbf{y}$.

We now consider a point-source dipole located at $\mathbf{r}_0 = x_0\mathbf{x} + y_0\mathbf{y} + z_0\mathbf{z}$ inside the WGS. This source emits free-space and trapped electromagnetic power for both polarization states. We know already from the simple previous analysis that the guided mode is totally extracted from the structure because the guided-mode solid circle is entirely intercepted by the free-space circles. Furthermore, we expect the guided light to escape from the structure following these intersections, giving rise to specific arc-shaped directions that concentrate the electromagnetic extracted power.

Aside from these qualitative considerations and to get some insight into this emission extraction process, it is interesting to model rigorously the emission from a dipole located in a WGS. In straightforward terms, our method is based on a Fourier description of the source, the structure, and the fields. More precisely, our point source is expressed in the Fourier plane as

$$\begin{aligned}\mathbf{P}(x, y, z) &= \mathbf{P}_0\delta(x - x_0)\delta(y - y_0)\delta(z - z_0)\\ &= \int_{-\infty}^{+\infty}\mathrm{d}k_x\int_{-\infty}^{+\infty}\mathrm{d}k_y\,\frac{\mathbf{P}_0\delta(z - z_0)}{(2\pi)^2}\\ &\quad\times \exp i[k_x(x - x_0) + k_y(y - y_0)]\\ &= \int_0^{2\pi/\mathrm{d}x}\mathrm{d}k_x\int_0^{2\pi/\mathrm{d}y}\mathrm{d}k_y\,\frac{\mathbf{P}_0\delta(z - z_0)}{(2\pi)^2}\\ &\quad\times\sum_{n=-\infty}^{+\infty}\sum_{m=-\infty}^{+\infty}\exp i[(k_x + mK_x)(x - x_0)\\ &\quad + (k_y + nK_y)(y - y_0)]\,. \end{aligned} \tag{1}$$

The last term in Eq. (1) is a coherent superposition of periodic sources that have different phases but the same periodicity as the grating structure along both x and y axes. Because of the superposition principle in linear electromagnetic theory, the overall problem of a point source radiating inside a WGS reduces therefore to an infinite number of problems for periodic sources radiating inside the WGS. This problem is simpler because emitters, structure, and fields have the same periodicity, which allows us to solve the emission problem by the differential method[14] in which the source is treated as a field discontinuity in the numerical integration.[15] The outgoing wave's boundary conditions enable us to compute the total power radiated by the source at infinity by means of Poynting flux calculations through an Oxy parallel plane.

To confirm the simple physical picture given in Fig. 2 we now present the result of computations concerning a realistic structure in which a biperiodic grating is etched onto a homogeneous guiding layer [Fig. 1(b)]. We assume a deltalike emission at $\lambda = 650$ nm for a point-source dipole oriented along the x axis and located in the middle of the guiding layer. This location ensures good positioning of the source with regard to the fundamental guided modes of this WGS. More precisely, this structure supports two guided modes (one for each polarization state). The periods are chosen such that the TE guided mode satisfies the condition $k_g{}^{\mathrm{TE}} = K_x = K_y$ [configuration of Fig. 2(b)], whereas the TM mode with $k_g{}^{\mathrm{TM}} < k_g{}^{\mathrm{TE}}$ intercepts the free-space disks for every ϕ polar angle as well. This situation ensures the total extraction of the guided-mode's power for both polarization states.

Figure 3 shows in planar k_p space the result of computation for the Poynting flux power density per unit solid angle $\mathrm{d}P/\mathrm{d}\Omega$ in air [Fig. 3(a)] and in the substrate [Fig. 3(c)]. The darker curves are those of maximum power. As expected, light escapes from the structure in arc-shaped directions. These patterns

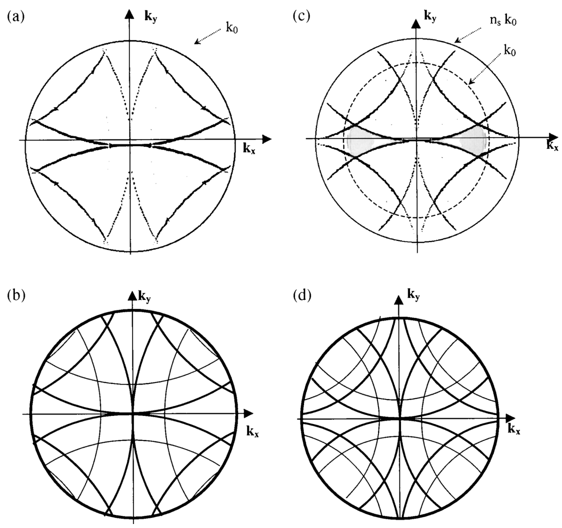

Fig. 3. Energy-density patterns from a biperiodic structure holding a point source. Computations are made for (a) air and (c) the substrate. The shapes of the arcs can be deduced from the guided modes TE_0 (broad solid curves) and TM_0 (thin solid curves) of the homogenous structure that intercept the free-space disks [(b) air and (d) substrate].

can be easily understood if we plot the intersections between the guided-mode solid circles and the free-space disks [Figs. 3(b) and 3(d)]. These intersections correspond to the guided-mode resonance directions of the structure without any source. It is interesting to mention that this simple analysis holds although the grating is not shallow (the groove depth is equal to half of the guiding layer thickness). Indeed, because of the strong refractive index of the homogeneous layer and the small effective index of the corrugated layer, the guide is weakly perturbed by the grating. Nevertheless, for a stronger corrugation of the guide, the guided mode k_g may depend on ϕ and the guided closed line may no longer be a circle. In the latter case, only rigorous computation can give the accurate radiation pattern at infinity.

Not given by simple graphic considerations are the intensities and widths of the various arcs. Numerical integration in the planar k space of $dP/d\Omega$ shows that only the TE mode carries significant power, not the TM mode (thinner arcs in Figs. 3(b)–3(d)]. From the calculation we find that 65% of the total emitted light is contained in the arcs, whereas the remaining 35% is emitted in all directions and appears as a quasi-isotropic background. All in all, the light emission is divided into one third for air and two thirds for the substrate. From Fig. 3(c) it is possible to see the total reflection circle of unit diameter (dashed curve). For k greater than this circle's radius the light is trapped in the substrate. Although it is coupled out by the WGS, this trapped light is 30% of the total power emitted into the substrate.

In conclusion, we have presented a crossed WGS that is able to extract the total guided-mode power, whatever the polar direction ϕ is. We have presented a simple graphic analysis of the arc-shaped radiation pattern at infinity and compared it with a rigorous electromagnetic calculation of a point-source dipole emitting into the structure. Although 80% of the light escapes from the WGS through running waves through the two sides of the structure, some unwanted light still remains at a large angle and may be difficult to collect. Studies of cancellation of these arc-shaped light concentrations at large angles by use of strong corrugated gratings are in progress. This remaining problem a side, this type of structure is of potential interest for use in building high-extraction-coefficient luminescent devices.

H. Rigneault's e-mail address is herve.rigneault@enspm.u-3.mrs.fr.

References

1. E. M. Purcell, Phys. Rev. **69,** 681 (1946).
2. F. DeMartini, G. Innocenti, G. R. Jacobovitz, and P. Mataloni, Phys. Rev. Lett. **59,** 2955 (1987).
3. L. Collot, V. Lefèvre-Seguin, M. Brune, J. M. Raimond, and S. Haroche, Europhys. Lett. **23,** 327 (1993).
4. S. L. McCall, A. F. J. Levi, R. E. Slusher, S. J. Pearton, and R. A. Logan, Appl. Phys. Lett. **60,** 289 (1992).
5. J. M. Gérard, D. Barrier, J. Y. Marzin, R. Kuszelewicz, L. Manin, E. Costard, V. Thierry-Mieg, and T. Riviera, Appl. Phys. Lett. **69,** 449 (1996).
6. J. P. Zhang, D. Y. Chu, S. L. Wu, S. T. Ho, W. G. Bi, C. W. Tu, and R. C. Tiberio, Phys. Rev. Lett. **75,** 2678 (1995).
7. H. Rigneault, S. Robert, C. Begon, B. Jacquier, and P. Moretti, Phys. Rev. A **55,** 1497 (1997); H. Benisty, H. De Neve, and C. Weisbuch, IEEE J. Quantum. Electron. **34,** 1612, 1632 (1998).
8. S. C. Kitson, W. L. Barnes, and J. R. Sambles, Opt. Commun. **122,** 147 (1996).
9. S. C. Kitson, W. L. Barnes, and J. R. Sambles, Phys. Rev. B **52,** 11,441 (1995).
10. S. C. Kitson, W. L. Barnes, and J. R. Sambles, Phys. Rev. Lett. **77,** 2670 (1996).
11. C. Amra and S. Maure, J. Opt. Soc. Am. A **14,** 3102 (1997).
12. T. Tamir, in *Integrated Optics*, T. Tamir, ed. (Springer, New York, 1975), p. 83.
13. W. Lukosz, D. Clerc, Ph. M. Nellen, Ch. Stamm, and P. Weiss, Biosens. Bioelectron. **6,** 227 (1991); K. G. Sullivan, O. King, C. Sigg, and D. G. Hall, Appl. Opt. **33,** 2447 (1994).
14. P. Vincent, in *Electromagnetic Theory of Gratings*, R. Petit, ed. (Springer-Verlag, Berlin, 1980), p. 101.
15. J. E. Sipe, J. Opt. Soc. Am. B **4,** 481 (1987).