

Spontaneous emission in a high-contrast one-dimensional photonic crystal

P. Halevi, Adán S. Sánchez *

Instituto Nacional de Astrofísica, Óptica y Electrónica, Apdo Postal 51, Puebla, Puebla 72000, México

Received 28 December 2004; accepted 18 February 2005

Abstract

In a high-contrast one-dimensional photonic crystal (PC) spontaneous emission (SE) can resonantly excite evanescent modes that are guided by the high-index layers. Giant acceleration of SE takes place – as high as 76 (50) times the free-space value for a single atom (gas). Analogous SE in two-dimensional PCs, that resonantly excites waves guided by the dielectric cylinders, could lead to improvement of PC lasers. The radiative modes can have exotic radiation patterns and can be totally suppressed for TE polarization in certain spectral ranges. The SE rate is extremely sensitive to the atom's position at the interfaces, with possible applications in surface science.

© 2005 Elsevier B.V. All rights reserved.

PACS: 42.70.Qs

Keywords: Spontaneous emission; Photonic crystal

Ever since Purcell's pioneering paper [1], it has been understood that the rate of spontaneous emission (SE) by an atom depends on the density of available states for the emitted light, that is, on the material environment. The advent of photonic crystals (PCs) [2,3] has rekindled interest in this topic, for the radiation by an atom, embedded

in the PC, can be totally or partially suppressed within a photonic band (PB) gap. Among other applications, this has led to the realization of a PC laser [4]. Many theoretical and experimental papers were published on one-, two-, and three-dimensional (1D, 2D, and 3D) structures; they are too numerous to list, and we will only quote a representative sampling. While SE in 3D PCs [5–9] can be totally inhibited, in 2D PCs [10] the SE can still take place in the direction parallel to the cylinders. Turning to plane-parallel dielectric structures, publications are available for atoms in

* Corresponding author. Tel.: +52 222 2663100; fax: +52 222 2470517.

E-mail address: asanchez@inaoep.mx (A.S. Sánchez).

the environment of a single interface [11–13], a slab [14–18], and multilayers, including 1D PCs with a defect (cavity) [19–24]. Surprisingly, there are very few papers on SE in a perfect 1D PC – a superlattice (SL). In this category the SL was modeled as an infinite [25,26] or finite [27] array of plane scatterers (“Dirac Comb” SL). Unfortunately, while this extreme model gives, semiquantitatively, reasonable results for TE polarization of the emitted light, it fails for TM polarization. In this communication, we report for the first time, on SE in a realistically modeled, perfect 1D PC. We find that this, relatively simple structure exhibits a surprising number of new, significant features. We consider a monolithic SL made up of alternating layers of dielectric and air. We choose a large dielectric contrast: $\epsilon_1 = 1$ for the air and $\epsilon_2 = 16$ for the dielectric, corresponding to Ge. The radiating atom can be located either in the air or in the dielectric. In most situations encountered in practice, the radiating atom is weakly coupled to the light. Then the Weisskopf–Wigner approximation [28] is applicable, Rabi oscillations do not occur, and the decay is exponential. In fact, a quantum theory of radiation in a non-uniform dielectric medium [29] and a classical theory, with the atom replaced by an oscillating dipole [30] yield the same result for the emission rate. Our calculation is based on the latter theory [30] and are generalizations of [25,26]; the detailed calculation will be given elsewhere [31]. The rate of emission is expressed in terms of the eigenvalues $\omega_{\mathbf{k}}$ and eigenvectors $\mathbf{a}_{\mathbf{k}}(\mathbf{r})$ of the SL in the absence of the dipole [32]; these, of course, depend on the polarization (TE or TM). The decay rate Γ , normalized to the free-space value $\Gamma_0 (= \mu^2 \omega_0^3 / 3c^3 \hbar)$, where $\boldsymbol{\mu} = \mu \hat{\boldsymbol{\mu}}$ is the dipole moment and $\hbar \omega_0$ is the photon’s energy), is [30]

$$\Gamma/\Gamma_0 = (3\pi^2 c^3 / \omega_0^2) \int d^3 k |\mathbf{a}_{\mathbf{k}}(\mathbf{r}_0) \cdot \hat{\boldsymbol{\mu}}|^2 \delta(\omega_{\mathbf{k}} - \omega_0). \quad (1)$$

The wavevector $\mathbf{k}$ has a component $k_{\parallel}$ in the plane of the interfaces. The eigenvectors $\mathbf{a}_{\mathbf{k}}(\mathbf{r})$ represent a complete set of orthonormal functions that can be expressed in terms of the electric or magnetic field (for TE or TM polariza-

tion). Note that the $\mathbf{a}_{\mathbf{k}}(\mathbf{r})$ must be evaluated at the position $\mathbf{r}_0$ of the atom. The Dirac delta function takes care of energy conservation.

It is important to observe that the normal modes of the SL must include both radiative and non-radiative modes. The latter are characterized by $k_{\parallel} > \omega/c$ and therefore decay exponentially in the air, away from the surfaces of the dielectric layers. The non-radiative modes are guided by these layers. Unlike the radiative modes, they cannot be directly observed; nevertheless they can be coupled out by means of some conversion device. For example, it was demonstrated [23] that, by means of a coupling prism, the evanescent modes can be converted to radiative modes. Further, because a 1D PC, strictly speaking, has a PB gap only for axial propagation, the total emission rate never vanishes. Nevertheless, the TE radiative component of the radiation may vanish if, in a certain frequency range, only non-radiative ($k_{\parallel} > \omega/c$) modes exist. This was suggested in [33] and demonstrated (for a finite SL) by means of mode density calculations [34]. Such behavior is confirmed by our calculation of the SE in Fig. 1 for TE polarization, the dipoles being parallel to the interfaces ($\psi = 0$). The PB structure is shown in the upper part; the lower part is the emission spectrum, Eq. (1), for an atom located in the middle of one of the air regions. The spectrum closely follows the PB structure; the normalized frequencies $\omega d/c$ (d is the period of the SL) at which sharp discontinuities of the derivative occur coincide, in fact, with the lower PB gap edges for $k_{\parallel} = 0$. In the spectral regions, where the radiative component vanishes resonant emission into guided modes occurs. Note that the radiative maxima (kinks) coincide with the frequencies at which the light line cuts the lower band edges; hence radiation will occur in all directions in space. As ω or d decreases and approaches the band edge for on-axis propagation, $k_{\parallel}$ for the radiative modes becomes limited to values below a certain $k_{\max}(\omega)$; see horizontal arrow. This means that the radiation is restricted to a cone, around the SL axis, of angle $\sin^{-1}[k_{\max}(\omega)c/\omega]$. This angle and the radiative SE rate both approach zero for $k_{\parallel}$ coinciding with the on-axis PB edge. For narrow dielectric layers, separated by wide air gaps, the PB gaps for radiative TE modes become much

Download English Version:

<https://daneshyari.com/en/article/9785796>

Download Persian Version:

<https://daneshyari.com/article/9785796>

[Daneshyari.com](https://daneshyari.com)