Inhibited–Enhanced Spontaneous Emission in 2D Photonic Crystal Waveguides

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Abstract

Spontaneous emission of an atom embedded in a two–dimensional photonic crystal waveguide is studied both under the quantum and the classical point of view. It is shown that, whenever one of the sides of the photonic crystal waveguide is closed by a lattice that has a band–gap at the field frequency, spontaneous emission depends on the distance between the emitter and the closed waveguide end, and it may be either reduced to zero or enhanced.

1 Introduction

Since the pioneering work by Purcell [1], spontaneous emission has been known not to be an immutable property of the coupling between matter and space, but rather an effect that may be controlled, and even inhibited, if the radiation field is modified in a proper manner. The topic has recently attracted a renewed interest because of the developement of *photonic crystals* [2, 3, 4, 5, 6, 7, 8].

In this work, we consider the case of an emitter located within a *photonic crystal waveguide*, and we show that spontaneous emission *into a guided mode* may be inhibited or enhanced depending on the emitter location inside the waveguide. This fact might become relevant in view of the realization of active integrated photonic circuits where, in reason of their reduced threshold current densities and temperature sensitivity, *quantum dots* might be the eligible emitter structures. As we will show below, proper location of the dot is essential to obtain efficient emission.

To keep the treatment as simple as possible, we consider the case of the waveguide schematized in Fig.(1.a). We take a 2D photonic crystal waveguide (PCW) formed by a straight defect in a square lattice of high–index dielectric pillars in air. One of the waveguide ends is closed by the defect–free lattice. The other end extends to infinity. We assume that the PCW is singlemode, and that a single atom is located in the middle of the waveguide, at the distance L from the closed waveguide end. We first give the quantum description of the guided field–atom interaction in the

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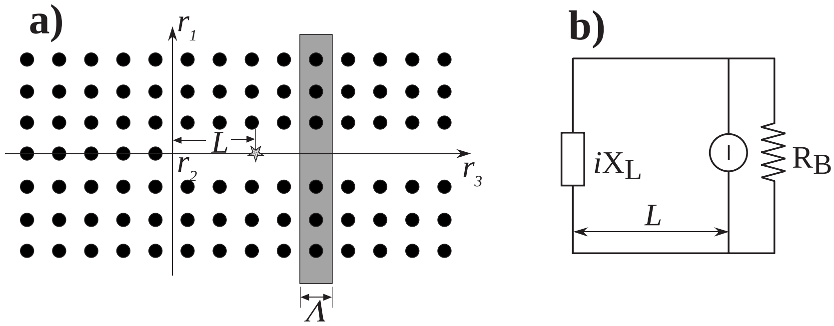

Figure 1: a) Top view of the photonic crystal waveguide. The star inside the waveguide represents the emitting atom. The dashed region is the elementary cell that, once repeated along the $\hat{r_3}$ axis, makes up the photonic crystal waveguide. Λ is the lattice pitch. b) Equivalent electric circuit for the waveguide of panel a). The closed waveguide end behaves as a reactive lumped element, placed at the distance L from the emitter, that is modeled by an ideal current generator. The open waveguide at the right hand side of the emitter behaves as a resistive load R_B.

PCW, and provide the explicit dependence of Einstein's coefficient on the atom position inside the waveguide. Then, by resorting to an equivalent electric model, we will give a simple classical interpretation of the suppressed–enahnced emission.

2 The quantum description

Let us suppose that a quantum dot interacts with the only guided mode that is supported by the waveguide of Fig.(1). It may be proved that, if we denote as $|i, 0_\mathrm{g}\rangle$ the initial state of the excited dot, with no photons in the guided mode g, and as $|f, 1_\mathrm{g}\rangle$ the final state in which the photon has been released, under the approximation of electric dipole the coefficient for the stimulated emission *into the guided mode* g is

$$B \propto \left|\left\langle f, 1_\mathrm{g}|\hat{\mathcal{H}}_{ED}|i, 0_\mathrm{g}\right\rangle\right|^2 \quad , \tag{1}$$

with $\hat{\mathcal{H}}_{ED}$ the quantum electric–dipole interaction hamiltonian, given by

$$\hat{\mathcal{H}}_{ED} = q\sum_j \mathbf{r}_j \cdot \hat{\mathbf{E}}(\mathbf{r}, t) = -q\sum_j \mathbf{r}_j \cdot \frac{\partial \hat{\mathbf{A}}(\mathbf{r}, t)}{\partial t} \quad . \tag{2}$$

The effect of the waveguide on the stimulated emission coefficient (hence on the stimulated absorption and spontaneous emission too) is purely classical: it only enters through the space and time dependence of the magnetic vector potential $\mathbf{A}$, which in turn depends on the dielectric arrangement that surrounds the dot.

In the waveguide of Fig.(1.a), $\mathbf{A}$ may be proved to read as

$$\mathbf{A}(\mathbf{r},t) = \mathrm{Re}\left\{\left[\psi(\mathbf{r})\mathrm{e}^{-i\kappa_B r_3} + \Gamma_L \psi^*(\mathbf{r})\mathrm{e}^{i\kappa_B r_3}\right]\mathrm{e}^{i\omega t}\right\}\hat{r_2} =$$

$$= 2|\psi(\mathbf{r})|\cos\left(\kappa_B r_3 + \frac{\varphi_L}{2} + \alpha(\mathbf{r})\right)\cos\left(\omega t + \frac{\varphi_L}{2}\right)\hat{r_2}\,,$$

where $\psi(\mathbf{r}) = |\psi(\mathbf{r})|\, \mathrm{e}^{i\alpha(\mathbf{r})}$ is the envelope of the Bloch mode that propagates in the infinitely long guide.

According to eqs.(1,2), hence, spontaneous emission, which is proportional to the squared modulus of $\mathbf{A}$, changes periodically along the waveguide, with the period

$$\frac{\Delta r_3}{\Lambda} = \frac{\pi}{\kappa_B \Lambda} \tag{3}$$

3 The classical description

In order to numerically verify the above statements, we follow the approach proposed in ref.[9] by Xu *et al.*, where it was shown that the spontaneous emission rate of a quantum atom inside a cavity is proportional to the radiation energy which is emitted by a classical dipole located in the same cavity.

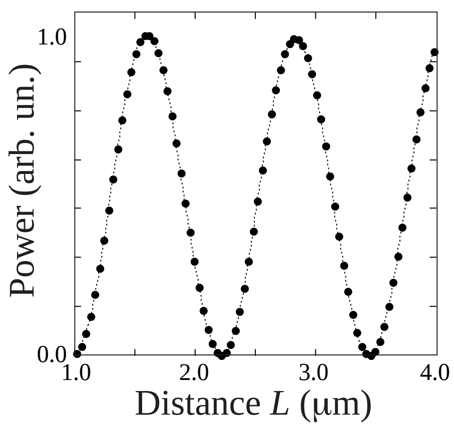

Figure 2: Amount of active power flowing through the guide when changing the location of the emitter.

Then, we perform a set of simulations in which an equivalent electric current density is placed in the middle of the waveguide at a distance L from its closed end, and we measure the active power that flows through any section at the right hand side of the source.

Fig.(2) shows the dependence of the amount of flowing power vs. the source location in the waveguide. The periodic behaviour of the emitted power that is predicted by the quantum approach can clearly be seen.

A simple classical interpretation of the phenomenon is provided by modelling the waveguide and the emitter as an equivalent electric circuit (see Fig.(1.b)). Indeed, by using the approach proposed in ref.[10], it may be shown that the infinite lattice at the right hand side of the emitter may be represented as an equivalent reactive lumped element, whose impedance is $Z_L = iX_L$. Whereas, the open photonic crystal waveguide at the right hand side of the emitter may be thought as a real impedance, that we denote as R_B, and the emitter as an ideal current generator.

Depending on the distance L between the emitter and the waveguide closed end, the equivalent reactive element Z_L may behave as a short circuit, an open circuit or a purely reactive load, which is placed in parallel to R_B. At those distances where the $Z_L = 0$, the current generator does not generate any real power. Whereas, whenever Z_L behaves as an open circuit, the emitted real power is maximum. As in common transmission lines, the distance between two consecutive locations of maximum emission is equal to half the propagating wavelength, in agreement with eq.(3) above.

4 Conclusions

The emission from an atom embedded in a two–dimensional photonic crystal waveguide has been studied both under the quantum and the classical point of view. It has been shown that, as soon as one of the waveguide ends is closed by a lattice that presents a band gap at the field frequency, the emission depends on the distance between the atom and the waveguide end, and it may either be suppressed or enhanced.

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