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Numerical analysis of coupled photonic crystal cavities

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Abstract: We numerically investigate the interaction dynamics of coupled cavities in planar photonic crystal slabs in different configurations. The single cavity is optimized for a long lifetime of the fundamental mode, reaching a Q-factor of $\approx$43, 000 using the method of gentle confinement. For pairs of cavities we consider several configurations and present a setup with strongest coupling observable as a line splitting of about 30 nm. Based on this configuration, setups with three cavities are investigated.

Keywords: Photonic crystal cavities; Cavity–cavity interaction; Finite-difference time-domain method

1. Introduction and motivation

Progress in the field of photonic crystals in recent years has lead to the development of optical resonators with ultralong photon lifetimes (or equivalently, ultra-high Q-factors), and very small effective mode volumes [1]. These two quantities are important benchmarks for many applications, hence their optimization has been subject to many investigations. For integrated solid state systems planar photonic crystal cavities (PhCCs) are a promising approach and both high Q-factors and small mode volumes have been achieved [4]. For systems with embedded quantum dots as fermionic resonator, even normal mode splitting as indicator of the strong-coupling regime has been experimentally demonstrated [5,6]. This paves the way to quantum networks, where quantum resonators (like quantum dots) are interacting via the light field by embedding them into strongly interacting photonic cavities [7].

In this work we investigate the electromagnetic coupling in a variety of simple cavity networks consisting of PhCCs. This extends our previous work on coupled mikrodisks, which focused on asymmetric mode- and Q-splitting [8]. In literature, experiments with side-coupled L3-cavities showed strong cavity–cavity interaction with asymmetric splittings of 20 nm around the single cavity resonance at the closest center-to-center distance of $2\sqrt{3}a$ where a is the lattice constant [9]. The asymmetry in the splitting is explained with a tight-binding approach [10] and is well known from coupled optical resonator waveguides [11,12]. We use a rigorous numerical approach to study the strength of the electromagnetic coupling for various configurations of a pair of coupled cavities. We show that due to the radiation emission pattern and distance dependence a specific configuration is favorable. Also, we discuss several arrangements with three cavities, which couple optimal for linear orientation, as our calculations show.

This manuscript is structured as follows: first, we introduce the considered L3 photonic crystal cavity and discuss the optimization of the lifetime of the fundamental cavity mode using the method of gentle confinement. Then, we show numerical results for three configurations of coupled cavity pairs. Finally we demonstrate how the geometrical setup of three coupled cavities affects the mode spectrum.

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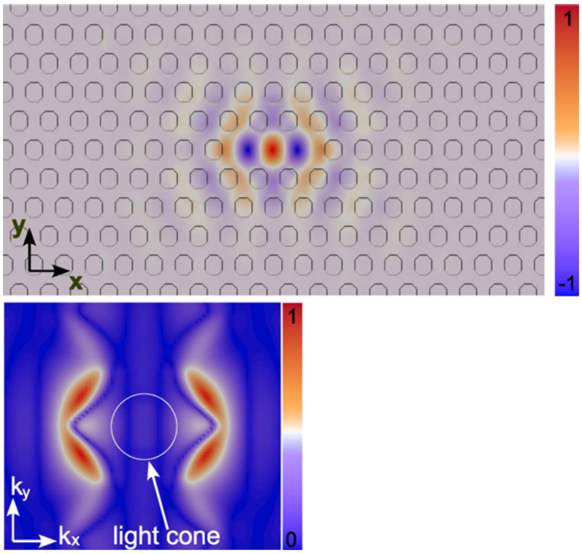

Fig. 1. Unmodified L3 cavity. Top: Photonic crystal structure (black outlines) and calculated normalized electric field pattern of the *y*-component of the fundamental mode in real space. Bottom: Normalized pattern of the absolute square of the electric field pattern Fourier transformed to k-space. The white circle indicates the light cone (leaky region) which contains some field contributions for this unmodified cavity.

2. Single cavity, lifetime optimization

For the numerical evaluation of the 3D-Maxwell equations we utilize an in-house finite-difference time-domain code (FDTD) [13] tightly linked to the filter diagonalization method Harmonic Inversion [14] to efficiently extract frequencies and lifetimes of resonances from the temporal response. We use parameters similar to [2] in order to obtain a 2D photonic bandgap for TE polarized light in the PhCC. The photonic crystal slab, shown in Fig. 1, has a lattice constant of $a = 300$ nm, a thickness $t = 0.6 \times a$, and a hole radius $r = 0.3 \times a$. An electric permittivity of $\epsilon = 10.595$, representing a GaAs slab at a temperature of $T = 4$ K, is used. The computational domain is set to $29 \times 14\sqrt{3} \times 2a^3$ with a spatial discretization of $a/16$ (18.75 nm), which is sufficient to gain converged results. Further spatial refinement only leads to corrections of the resonance in the GHz regime and of the Q-factor below 1%. A subpixel averaging method is used [15] to achieve this accuracy.

In this work we investigate L3 cavities, i.e. photonics crystals with three linearly aligned adjacent defects, i.e. missing air holes. First, we discuss the optimization of the Q-factor of such a L3 cavity following the method of gentle confinement as proposed in Ref. [2]. The main objective of this method is the reduction of the fraction of spectral components within light cone in k-space which is equivalent to a suppression of the propagating modes. This is achieved by modification of the cavity's environment. In our case, we shift the air holes (parameter s) left and right of the L3-cavity and reduce the radius of the holes (parameter r'), see Fig. 4 for illustration of the parameters. Without any modifications, a considerable fraction of spectral components is inside the light cone (propagating modes), see Fig. 1, bottom, consequently the Q-factor of the most long living mode located around the wavelength 1077 nm is only $Q \approx 4000$. Fig. 2 shows the change in lifetime of the photonic mode if the air holes left and right of the L3-cavity are systematically shifted from $s = 0$–$0.25a$. A maximum of $Q \approx 33,000$ is achieved for $s = 0.185a$. By adjusting the hole radius, the Q-factor can be further increased. We obtained an optimum for $r' = 0.2a$, reaching $Q \approx 43,000$, which corresponds to a FWHM of $\approx$0.025 nm. This is a result very similar to the structure presented in [2], however here the lower

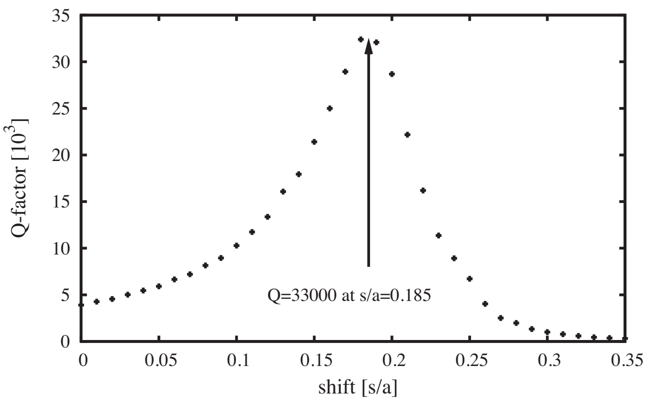

Fig. 2. Calculated Q-factor of the fundamental mode as a function of the shift s of the air holes left and right of the L3-cavity. For $s = 0.185a$ the maximum of $Q \approx 33,000$ is achieved. By additionally changing the hole size the lifetime can be increased to $Q \approx 43,000$ (not shown, see text).