Near-Field spectroscopy of Photonic Crystal Cavities characterized by Fano Local Density of States

Francesca Intonti[1,2], Nicoletta Granchi[1,2], Matteo Ciardi[1], Dario Balestri[1,2], Daniele Pellegrino[3], Francesco Pagliano[3,4], Andrei Yu. Silov[3], Frank van Otten[3], Tong Wu[5], Kevin Vynck[5], Philippe Lalanne[5], Andrea Fiore[3] and Massimo Gurioli[1,2]

[1]Department of Physics, University of Florence, via Sansone 1, I-50019 Sesto Fiorentino (FI), Italy
[2]European Laboratory for Nonlinear Spectroscopy, via Nello Carrara 1, I-50019, Sesto Fiorentino (FI), Italy
[3]Department of Applied Physics and Institute for Photonic Integration, Eindhoven University of Technology, 5600 MB Eindhoven, Netherlands
[4]nanoPHAB, Groene Loper 19, P.O.Box 513, 5612 AP Eindhoven, The Netherlands
[5]LP2N, Institut d'Optique Graduate School, CNRS, Univ. Bordeaux, 33400 Talence, France
*corresponding author, E-mail: intonti@lens.unifi.it

Abstract

Microcavities and nanoresonators are characterized by their quality factors (Q) and mode volumes (V). While Q is unambiguously defined, there are questions on V and, in particular, on its complex-valued character, whose imaginary part is linked to the non-Hermitian nature of open systems. The complex modal volume implies a deep revision of the Purcell factor expression, with counterintuitive effects, such as non-Lorentzian local density of states. We experimentally demonstrate these predictions in coupled photonic crystal cavities with low optical losses.

1. Introduction

Optical resonators play an essential role in current developments in nanophotonics, such as integrated photonics, optical sensing, metamaterials and quantum electrodynamics. The interaction of light with electromagnetic resonators fundamentally relies on the resonant modes of the structure. With the recent advent of theoretical results on the normalization of leaky resonator modes, it becomes evident that cavity perturbation theory cannot rely on normalization based on energy but a quasinormal-mode (QNM) formalism is essential to account for the non-Hermitian character of the problem in the presence of non-negligible energy dissipation [1, 2]. QNMs are formal solution of differential equations with complex eigenvalues. Regrettably, the complex eigenvalues cause mathematical difficulties with QNM normalization. One approach to avoid the normalization problem imposes to consider energy dissipation as a perturbation of an ideal closed and non-absorbing system. With this approach the system is Hermitian and admits a complete set of discrete normal modes with real eigenvalue. The perturbation just results in a broadening of the eigenstates with a Lorentzian line shape, but not in a change of the resonance frequencies and field distributions. It has been showed that this phenomenological approach work properly for resonators with small energy dissipation (i.e., a high quality factor), but it becomes largely unsubstantiated for less confined resonances characterized by low quality factors. Non-Hermitian theories also predict that the complex nature of V leads to a strongly non-Lorentzian spectra profile of the local density of states (LDOS) in peculiar photonic and plasmonic systems [1,2]. In coupled resonators, the spectral dependence of the Purcell enhancement is predicted to be a generalized Fano profile with a dip in the spectral line shape [1]. Here, we experimentally demonstrate LDOS with strong non-Lorentzian line shapes in pairs of coupled, high-Q and small-V photonic crystals cavities (PhCCs). We show that the LDOS spectral line shape and spatial distribution can be measured by near-field hyperspectral imaging.

2. Material and Methods

We investigate two coupled L3 cavities in a GaAs slab with very different losses, see Fig. 1(a). Cavity #1, located near the border of the 2D photonic crystal, has $Q_1 \sim 400$, on the contrary cavity #2 has $Q_2 \sim 6000$. The diameter of the air holes circled in blue is tuned to control the losses of cavity #1, while the diameter of the air holes circled in red is tuned to reach a nominal detuning $\Delta = (\omega_1 - \omega_2)/|2g| \sim 0$, with g the coupling constant between the two uncoupled cavities and ω_1 and ω_2 their frequencies. In the middle of the GaAs membrane high-density InAs QDs are embedded. If properly excited, the InAs QDs show at room temperature bright photoluminescence (PL) which acts as an internal light source for the photonic structures. The measurements are performed with a scanning near-field optical microscope (SNOM) in illumination/collection geometry, was used. The spatially resolved images were recorded by scanning the probe tip over the sample at a fixed distance (few tens of nm).

The sample is excited by a laser diode at 780 nm, coupled into the tip. The emitted PL signal, collected by the tip, is coupled to a spectrometer and is finally detected by a liquid nitrogen cooled InGaAs array. At every tip position, the entire spectrum of the sample is collected with a spectral resolution of 0.1 nm.

3. Results

The near-field PL spectra collected in cavities 1 and 2 are reported in Figs. 1(b) and 1(c), respectively. As predicted by the QNM model, we observe that the LDOS in cavity 1 has an evident non-Lorentzian shape. Data are well described by the QNM formalism as the sum of two Fano profiles [blue and red lines are fits from the theory and the dark yellow and green lines are the mode decomposition in Fano profiles]. The fits in Figs. 1(b)–1(c) reproduce well the data and unveil the possibility for resonances to have negative contributions to the LDOS. To our knowledge, this constitutes the first experimental demonstration of strong non-Lorentzian LDOS of individual photonic resonances [3].

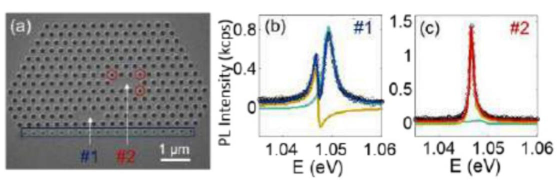

Figure 1: (a) SEM image of the sample. Cavities #1 and #2 are labeled with color code (blue and red) which is used also in the fits. (b)-(c) Experimental SNOM-PL spectra (open circles) in the center of cavities #1 and #2 with best fits (blue and red lines) with the two Fano QNM contributions (dark yellow and green full lines).

The observed Fano-like lineshape represents a distinctive hallmark that allows to directly relate the spectrum locally collected by the SNOM tip to the electric LDOS of the investigated system. In Fig. 2 are reported finite difference time domain (FDTD) simulations of the coupled system. The LDOS spectrum can be obtained as the flux of the Poynting vector (S) through a box that contains the exciting dipole, or through the calculation of the imaginary part of the Green's function, which are reported with dashed lines and open circles, respectively, for three different tip positions on the sample. The relevant aspect in Fig. 2 is that the lineshape of the LDOS strongly vary over spatial distances below the diffraction limit, calling for the use of near-field techniques for LDOS mapping. In order to benchmark this prediction, one has to consider the SNOM physical mechanism that converts the near field into the far field. With dielectric tip, it is possible to argue that the scattering in the far-field is due to the induced macroscopic polarization of the glass forming the apex of the tip. The induced dipoles inside the tip, which produce the detected light scattering in the far-field, are proportional to the

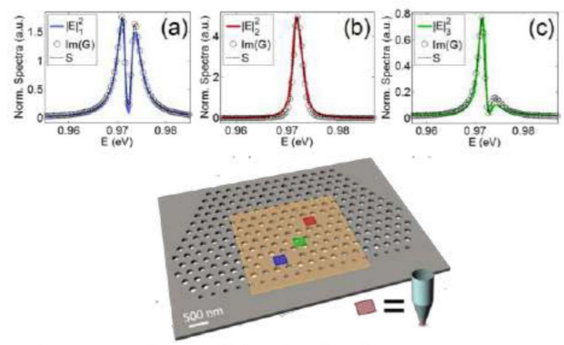

Figure 2: Scheme of the simulated system. (a)-(c) LDOS calculated by the Green's function (black circles) and by the net flux of S (black dashed lines). The red (blue, green) line is the spectrum of $|E|^2$ in the red (blue, green) sensor.

inducing electric near-field of the PL emission at the position of the tip. This means that the signal collected by the SNOM tip is proportional to PL electric field intensity $|E|^2$ and averaged over the spatial extension of the tip. Therefore, in the three graphs is also reported the electric field intensity on the small square sensors, that reproduce three different tip positions. The very good agreement of the spectra of $|E|^2$ with the LDOS confirms that SNOM spectroscopy is able to direct image the LDOS with a deep-subwavelength resolution of the order of 100 nm.

4. Conclusions

We provide experimental evidence of the existence of Fano LDOS in coupled system composed by two PhCCs with unbalanced loss, where one of the two PhCC has a relatively high nominal Q of 6000. We also prove that Near-field hyperspectral imaging of quantum dot photoluminescence is a direct tool for measuring the line shape of the LDOS.

Acknowledgements

F.I. acknowledges funding from NARCISO (EU-H2020, ID:828890).

References

[1] C. Sauvan, J. P. Hugonin, I. S. Maksymov, P. Lalanne, Theory of the Spontaneous Optical Emission of Nanosize Photonic and Plasmon Resonators, *Phys. Rev. Lett.* 110, 237401, 2013.

[2] P. Lalanne, W. Yan, K. Vynck, C. Sauvan, and J.-P. Hugonin, Light Interaction with Photonic and Plasmonic Resonances *Laser Photonics Rev.* 12, 1700113, 2018.

[3] D. Pellegrino, D. Balestri, N. Granchi, M. Ciardi, F. Intonti, F. Pagliano, A.Yu. Silov, F. W. Otten, T. Wu, K. Vynck, P. Lalanne, A. Fiore, M. Gurioli, Non-Lorentzian Local Density of States in Coupled Photonic Crystal Cavities Probed by Near- and Far-Field Emission, *Phys. Rev. Lett.* 124, 123902, 2020.