

Magnetic Imaging in Photonic Crystal Microcavities

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We demonstrate the *nonresonant* magnetic interaction at optical frequencies between a photonic crystal microcavity and a metallized near-field microscopy probe. This interaction can be used to map and control the magnetic component of the microcavity modes. The metal coated tip acts as a microscopic conductive ring, which induces a magnetic response opposite to the inducing magnetic field. The resulting shift in resonance frequency can be used to measure the distribution of the magnetic field intensity of the photonic structure and fine-tune its optical response via the magnetic field components.

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The interaction between light and matter lies at the basis of a large number of optical phenomena and its understanding is crucial for the development of new optical materials and devices. Control over the electric polarizability of materials, for instance by creating periodic structures, has allowed us to modify the radiative decay rate of electric dipoles [1–3]. The Maxwell equations, in principle, also allow for a magnetic optical response which is, however, much less understood and only recently has been considered for optical wavelengths. Tuning of the magnetic response via the realization of (nanostructured) metamaterials [4–6] is currently being investigated for the possible realization of perfect lenses and optical cloaking [7,8]. In that respect techniques that allow us to measure and control the magnetic response of photonic materials would be extremely useful.

Measurements of the electrical response of materials can be conveniently performed by using near-field scanning optical microscopy (NSOM). This technique can be used to map with a subwavelength spatial resolution the electric field in the proximity of photonic structures and to fine-tune their resonances [9,10]. To improve the spatial resolution of scanning near-field microscopes, in certain cases a metal coating is applied to the fiber tip. Interestingly, it turns out that the same metal coating creates several unexpected effects, amongst which the formation of plasmonic resonances in the tip. Lalouat *et al.*, reported that the metallic tip (without aperture) produces a redshift of the photonic modes due to the metallic dielectric perturbation, while the magnetic perturbation is negligible [11]. Devaux *et al.* found that with a proper design of the fiber aperture, the tip plasmon may be resonantly excited by the magnetic field only for certain structures, radiating light into the fiber and obtaining a magnetic image pattern [12].

Within this context, in a recent paper Burrese *et al.* showed that, by fabricating a metallic split ring resonator at the apex of a near-field probe, it is possible to convert the magnetic field to an electric field and this can be used to map the magnetic field [13].

In this Letter we show that it is possible to probe the magnetic field intensity of the near-field emission from semiconductor quantum dots embedded in a photonic crystal microcavity (PCMC) using a standard commercial metallic coated NSOM tip. The magnetic interaction is not mediated by any resonances of the tip, as previously reported [12,13], but is based on a very different physical mechanism. The aluminum that coats the tip aperture acts as a conductive ring in which an electric current is induced via the Faraday-Newmann law [see Fig. 1]. This conductive ring creates a magnetic moment that is opposite to the inducing magnetic field. The resulting perturbation of the magnetic environment of the photonic structure produces a sizeable high frequency shift of the photonic eigenmodes, which can be measured and used to map accurately the

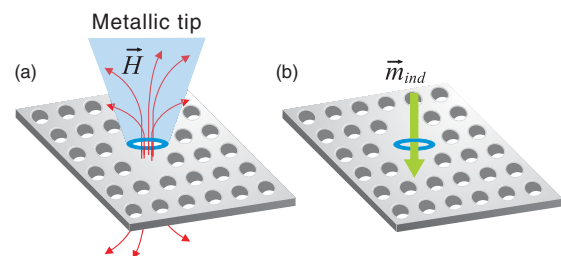


FIG. 1 (color online). Scheme of the magnetic perturbation induced by the nanometric metallic tip. (a) The tip is positioned on the sample surface and the magnetic field lines enter the tip aperture. (b) The magnetic flux throughout the metallic ring of the tip aperture induces a magnetic moments.

spatial distribution of the magnetic field normal to the plane of the microcavity.

By constructing near-field maps of this shift one obtains an experimental determination, with high resolution, of the spatial distribution of the magnetic field normal to the plane of the microcavity. The experimental data are found to be in very good agreement with theoretical predictions.

The investigated PCMC is fabricated on a suspended 320 nm-thick GaAs membrane, that is grown on top of a 1500 nm-thick $\text{Al}_{0.7}\text{Ga}_{0.3}\text{As}$ sacrificial layer and incorporates three layers of high-density InAs quantum dots grown by molecular beam epitaxy [14]. The photonic structure consists of a two-dimensional triangular lattice of air holes with lattice parameter $a = 301$ nm and filling fraction $f = 35\%$, where the cavity, denominated $D2$, is formed by four missing holes organized in a diamondlike geometry [see inset of Fig. 2].

A commercial NSOM (Twinsnom, OMICRON) is used in an illumination-collection geometry. In this geometry, the sample is excited with light from a diode laser (780 nm) coupled into the tip that is raster scanned at a constant height, smaller than 10 nm, on the sample surface. In a previous work we used a dielectric tip for mapping the electric field local density of states [10]. Here we use an aluminum coated tip with a nominal aperture of 200 nm and a metal thickness of about 100 nm. Photoluminescence (PL) spectra from the sample were collected at each tip position through the same probe and the PL, dispersed by a spectrometer, was detected by a cooled InGaAs array, with a spectral resolution of 0.5 nm. The excitation conditions used in the experiments provide the quantum dot population of both the ground and first excited states, with an emission spectrum in the wavelength range between 1200 nm and 1320 nm. A typical PL spectrum collected by the near-field probe is reported in Fig. 2, where two main peaks are clearly recognizable, labeled M1 and M2.

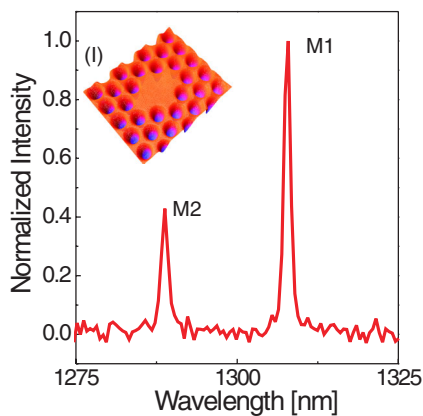


FIG. 2 (color online). Photoluminescence spectrum collected by the near-field probe during the scan. We label as M1 and M2 the two main modes of the cavity. In the inset a three-dimensional visualization of a scanning electron microscopy image of the investigated sample is reported.

The PL intensity maps associated to M1 and M2 are reported in Figs. 3(a) and 3(b). In these images the experimental spatial resolution (defined as the full width at half maximum of the smallest spatial structures that can be resolved) extracted from the PL intensity map is of the order of 100 nm, which gives also an upper value for estimating the dimension of the tip aperture. Comparing these results with the PL maps obtained by uncoated near-field fiber probe [10,15], we observed, as expected, that the improved spatial resolution offered by metallic tips has the drawback of the reduction of the detected signal by more than 3 orders of magnitude. Figures 3(c) and 3(d) show the three-dimensional (3D) finite-difference time domain calculated maps of the electric field intensity distributions (i.e. the electric local density of states) for the modes M1 and M2, respectively. The good agreement between theory and experiment indicates that the PL intensity maps collected by a metallic tip nicely reproduce the electric field local density of states.

Analyzing the PL spectrum at different spatial points of the tip scan on the PCMC surface, we noticed that the frequency of the cavity modes depends on the tip position. Figure 4(a) reports the PL spectra collected by a metallic coated near-field probe for the mode M2 in four different points on the sample surface (as indicated by the different colored symbols) separated by few hundred nanometers. For comparison, in Fig. 4(b) are reported the spectra collected in the same sample but using a dielectric tip.

In the case of a dielectric near-field probe [Fig. 4(b)], the spectra collected inside the cavity region are always redshifted with respect to the spectrum collected outside [stars (green curve)], unless the case in which the spectrum is collected in a minimum of the electric field intensity [triangles (yellow curve)]. In the case of a metallic coated near-field probe [Fig. 4(a)], instead, we do not observe redshifted spectra in the cavity region with respect to the spectrum collected outside. But we notice that in corre-

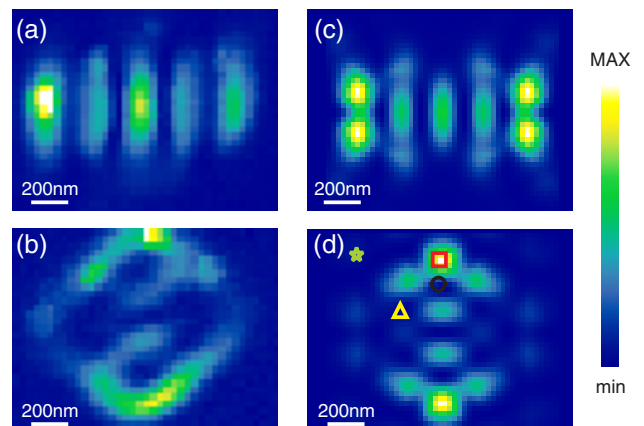


FIG. 3 (color online). (a),(b) Spatial distribution of the photoluminescence signal associated to the mode M1 and M2, respectively. (c),(d) Calculated electric field intensity associated to the mode M1 and M2, respectively. The different symbols indicate the position where the spectra in Fig. 4 are collected.

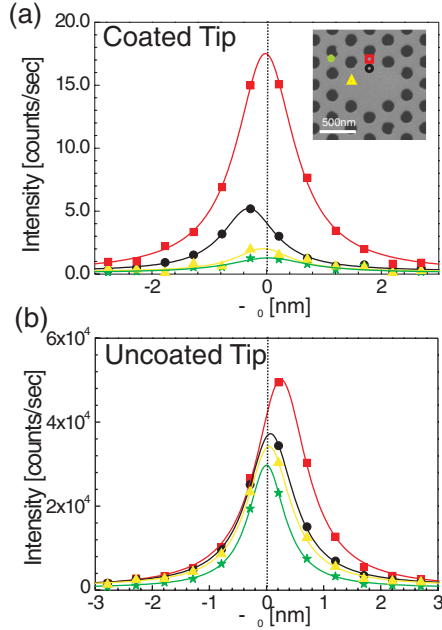


FIG. 4 (color online). (a),(b) Near-field spectra collected in different position of the cavity for the mode M2, with an aluminum coated tip (a) and an uncoated tip (b). The inset reports a scanning electron microscope image of the studied cavity, the symbols indicate the positions where the spectra are collected.

spondence of a minimum of the electric [circles (black curve)] the spectrum is blueshifted. It is important to stress that the dielectric perturbation of a metallic tip without aperture, despite the negative dielectric constant, would give a redshift of the photonic mode [11,16]. In Ref. [17], a redshift of the photonic modes for both dielectric and metallic tips has been reported; this last likely due to the dominance of the metallic dielectric perturbation.

The electromagnetic perturbation of a pure dielectric nanometric object in the proximity of the surface of the PCMC has already been studied in Refs. [9,11] and it provides that the frequency shift, $\Delta\omega_n$, of the n th mode is linear with the perturbation [16], $\delta\epsilon(\vec{r})$, as reported in Eq. (1):

$$\Delta\omega_n = -\frac{\omega_n}{2} \frac{\int d^3r \vec{E}_n^*(\vec{r}) \cdot [\delta\epsilon(\vec{r}) \vec{E}_n(\vec{r})]}{\int d^3r \vec{E}_n^*(\vec{r}) \cdot [\epsilon(\vec{r}) \vec{E}_n(\vec{r})]}, \quad (1)$$

where $\vec{E}_n(\vec{r})$ represents the unperturbed electric field.

The insertion of a dielectric tip provides an increase of the dielectric constant and consequently a redshift. Since the shift is proportional to the intensity of the electric field at the position of the nano-object, by spatially mapping the spectral shift as the NSOM tip scans the sample it is possible to reconstruct the electric field intensity distribution as it is demonstrated in [10,15].

However, in the case where the perturbation on the PCMC is due to a magnetic nano-object, we found that the frequency shift of the mode is given by a relationship analogous to the dielectric case, as shown in Eq. (2),

where the dielectric perturbation and the unperturbed electric field are changed with the magnetic perturbation, $\delta\mu(\vec{r})$, and the unperturbed magnetic field, $\vec{H}_n(\vec{r})$, respectively, [11,16]

$$\Delta\omega_n = -\frac{\omega_n}{2} \frac{\int d^3r \vec{H}_n^*(\vec{r}) \cdot [\delta\mu(\vec{r}) \vec{H}_n(\vec{r})]}{\int d^3r \vec{H}_n^*(\vec{r}) \cdot \vec{H}_n(\vec{r})}. \quad (2)$$

In our case the magnetic nano-object is the aperture of a metallic coated near-field probe that can be approximated as a conductive ring, where an electric current may be induced via the Faraday-Newmann law. The presence of the magnetic field of the PCMC normal to the ring plane (z axis) induces an electric current in the ring, that depends on the R - L characteristics of the ring itself. Since the real part of the induced magnetic field is antiparallel to the magnetic field of the PCMC along the z axis, the magnetic susceptibility of the ring is a tensor with only one diagonal component (zz), whose real part is negative. For these reasons the shift of the mode frequency is towards higher frequency and it is proportional to the intensity of the z component of the magnetic field. Assuming that the unperturbed field is constant over the small tip dimension, we have

$$\Delta\omega_n \sim \frac{\omega_n}{2} \frac{\delta\mu |H_{n,z}(\vec{r}_0)|^2}{\int d^3r \vec{H}_n^*(\vec{r}) \cdot \vec{H}_n(\vec{r})}, \quad (3)$$

where \vec{r}_0 is the tip position.

The resulting perturbation of the magnetic susceptibility of the PCMC would produce a high frequency shift of the photonic modes. These considerations not only explain the blueshift of the mode but, like for the case of a pure dielectric tip, by mapping the shift induced by the magnetic nano-object it is possible to access to the magnetic field component of the PCMC modes. Note that we neglect the plasmonic resonances at the tip ring, which for a Al tip of 100–200 nm are expected to be in the uv to visible range [11]. This assumption is experimentally confirmed by the fact that our PL intensity maps with a metallic tip (not reported here) give an image pattern of the electric field intensity, while the ring plasmon would produce a magnetic imaging [12].

Figures 5(a) and 5(b) show the calculated distribution of the intensity of the magnetic field component along the z axis for the two cavity modes M1 and M2, respectively. Note that the electric and magnetic intensity maps are complementary: to a maximum of the electric field corresponds a minimum of the magnetic field (and vice versa). This property, which is a direct consequence of the Maxwell equations relating the electric (magnetic) field to the spatial derivative of the magnetic (electric) field, is extremely useful for assessing the nature of the perturbation of the metallic coated tip.

Figures 5(c) and 5(d) report the spectral position of the peak as a function of the spatial coordinate of the tip, in the case of a metallic coated tip, for the two cavity modes M1 and M2, respectively. These spectral shift maps, are obtained by fitting every emission spectrum with a Lorentzian

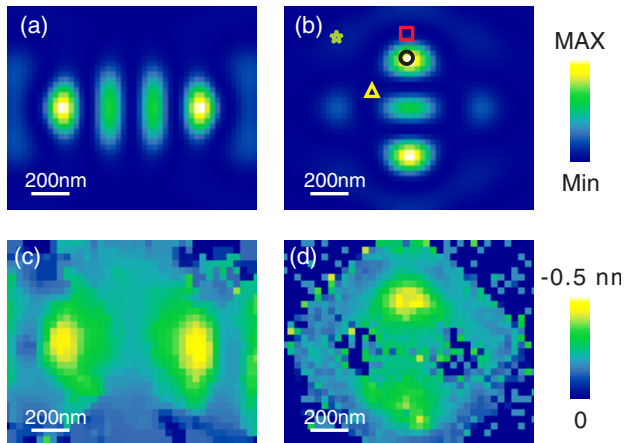


FIG. 5 (color online). (a),(b) Calculated intensity of the magnetic field component along the z axis for the mode M1 and M2, respectively. The color scale indicates the intensity of the field. (c),(d) Experimental spectral shift map associated to the mode M1 and M2, respectively. In this case the color scale indicates the spectral position of the cavity modes.

curve and reporting the central wavelength of the cavity resonance extracted from each fit curve as a function of the spatial position of the tip. An experimental problem, in obtaining the maps with the metallic tip, is that the detected signal is pretty low when the shift is large, not only because of the small collection efficiency, but also because the shift is maximum in points where the PL signal is minimum [18]. The sign of the PL shift and the spatial correlation with the mode maps, clearly demonstrated the magnetic interaction of the metallic coated tip with the PCMC optical mode. The comparison between the experimental data and the numerical calculations clearly indicates that the map of the spectral shift directly corresponds to the z magnetic field intensity associated with the resonance M1 and M2.

In conclusion, we have demonstrated a nonresonant method to image and tune the magnetic field component of the electromagnetic field at optical wavelengths. In particular, we have observed a reversible and local high frequency tuning of the modes of a photonic crystal microcavity at the insertion of a metallic coated NSOM tip on the sample surface. The sign of the mode shift is a clear fingerprint of the magnetic field interaction. We use the map of the wavelength shift induced by the tip to image the complete magnetic field distribution. Since the perturbation is based on a nonresonant effect it does not critically depend on the geometry or coating material of the tip. The possibility to tune and map the magnetic field component of (near) visible light opens up interesting possibilities. For instance, measuring the magnetic field component can provide very useful feedback for the design and realization of metamaterials, in which resonances in the magnetic re-

sponse of a material are used to create, e.g., negative refraction. The combination of using both the electric and magnetic field response of materials at optical frequencies is a new field of physics that researchers are just starting to explore and that is bound to lead to interesting surprises in the near-future. It is completely unknown, for instance, what kind of nonlinear “optics” can be developed when combining electric and magnetic fields. To have access to the magnetic field component and to be able to influence locally its response will most likely be of great value in that respect.

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Note added.—During finalization of the manuscript, the work of Burrese *et al.* [19] came to our attention.

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