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## Subwavelength imaging of light confinement in high- $Q$ /small- $V$ photonic crystal nanocavity

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The optical near field of a high- $Q$  and ultrasmall volume photonic crystal nanocavity is visualized with a subwavelength resolution by using a scanning near-field optical microscope (SNOM) operating at the same time in *collection-scanning mode* and in *interaction-scanning mode*. It is shown that the nanocavity resonant mode is selectively visualized by using the SNOM interaction-scanning mode while the whole electromagnetic field surrounding the nanocavity is probed using the SNOM collection-scanning mode. The different optical near-field images are compared in light of a three-dimensional numerical analysis and we demonstrate an unexpected mode coupling at the cavity resonance. © 2008 American Institute of Physics. [DOI: 10.1063/1.2890051]

Semiconductor photonic crystal resonators have attracted much attention over the recent years. Their potential for high quality (high- $Q$ ) factor in small volume ( $V$ ) cavities opens innovative ways to control light, including the stopping and the trapping light,<sup>1</sup> quantum information processing,<sup>2,3</sup> and the enhancement of light-matter interactions.<sup>4</sup> This potential is expected to lead to a wide range of applications for integrated on-chip photonics.<sup>5–7</sup>

The methods most commonly used for examining the properties of such nanocavities are optical far-field techniques, which typically consist in analyzing (spectrally or temporally) the photons radiated into the far field. However, these methods provide only *indirect* insight in the light-matter interactions occurring in the cavity optical near-field, which are at the origin of the remarkable properties of these cavities. As a result, scanning near-field optical microscopy techniques (SNOM) are highly relevant to *directly* probe such nanostructures.<sup>8</sup> As reported in Refs. 9–11, the SNOM technique is a powerful method for localizing, both spatially and spectrally, the electromagnetic field confinement inside photonic crystal cavities. However, only low- $Q$  cavities have been studied so far and the very first attempts at probing small volume cavities have shown that the near-field probes [SNOM probes in Ref. 12 and atomic force microscopy (AFM) probes in Refs. 13 and 14] strongly alter—or even completely disrupt in the case of AFM probes—the light confinement mechanism inside the cavity. For these reasons, probing with a high resolution the optical near-field of the light confined inside a high- $Q$ /small- $V$  nanocavity is a challenging task.

In this study, we face this challenge and achieve experimentally high resolution SNOM pictures of the light confined inside a nanocavity exhibiting a  $Q$ -factor of 41 000 (40 times higher than our previous works in Ref. 12 and 80 times

higher than in Refs. 13 and 14) and a modal volume of  $5.5 \cdot 10^{-14} \text{ cm}^3$  (almost 15 times lower than in Ref. 13). The near-field images reported here are simultaneously recorded using the recently proposed SNOM *interaction-scanning mode*,<sup>12,13,15</sup> and the classical SNOM *collection-scanning mode*.<sup>8–11</sup> The differences between these two imaging methods are discussed in light of the recorded images by comparing them with three-dimensional (3D) calculations of the cavity mode.

The nanocavity considered in this work is a Fabry–Perot-like resonator integrated on a ridge waveguide, designed in such a way to suppress the radiation losses at the mirror termination.<sup>16</sup> Similar structures have been recently investigated by other group.<sup>17</sup> The cavity is fabricated by electron beam lithography and reactive ion etching on a silicon-on-insulator substrate. As shown in Fig. 1, for a transverse electrical (TE with the H-field is normal to the substrate plane) polarization of the light, the nanocavity<sup>18</sup> exhibits a single resonance at telecommunication wavelength ( $\lambda_0 \sim 1558 \text{ nm}$ ) with a  $Q$ -factor of 41 000.

The sample is then mounted on a SNOM coupled to a spectrally resolved optical bench. A TE polarized tunable laser source is coupled to the access waveguide by using a lensed fiber (Lovalite® Photonics Tip). The light transmitted through the cavity is collected using an achromatic metallic mirror objective and detected using an InGaAs photodiode. By accurately maintaining the optical alignments, an ultrasmall homemade near-field probe consisting in a chemically etched silica fiber with a 20 nm width apex is scanned at a 4 nm height above the cavity surface, while the probe-surface distance is controlled thanks to a shear-force feedback.<sup>19</sup>

As expected for a nanometric-sized dielectric probe,<sup>12,20</sup> the cavity resonance wavelength is slightly redshifted when the probe is introduced inside the cavity optical near-field. Remarkably, due to the extremely small size of the probe and

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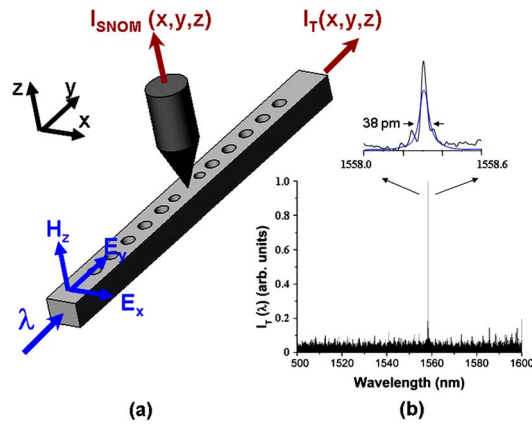


FIG. 1. (Color online) (a) Schematic of the experiment. A TE polarized tunable laser is coupled to the nanocavity. As the near-field probe is scanned over the cavity surface, the light collected by the probe ( $I_{\text{SNOM}}(x,y,z)$ ) and the light transmitted through the cavity ( $I_T(x,y,z)$ ) are collected at the same time. The first operating method,  $I_{\text{SNOM}}(x,y,z)$ , corresponds to the classical SNOM collection-scanning mode, while the second one,  $I_T(x,y,z)$ , is the interaction-scanning mode. (b) Typical nanocavity transmittance spectra. The experimental spectrum exhibits a Lorentzian-shaped peak at resonance.

to its relative small refractive index, the resonance wavelength is redshifted ( $\delta\lambda=0.2$  nm), while the cavity  $Q$ -factor is only lowered by a factor 2. Consequently, the near-field probe used here operates in a perturbation regime weak enough to avoid a drastic alteration of the light confinement inside the cavity.<sup>12,20</sup>

For SNOM measurements, we then develop an experimental setup allowing the simultaneous recording of the near-field maps of the nanocavity in collection-scanning mode<sup>8–11</sup> and interaction-scanning mode.<sup>12,13,21</sup> The first method is similar to the one used in classical aperture-SNOM measurements, and the probe is used to locally collect the electromagnetic field above the cavity [ $I_{\text{SNOM}}(x,y,z)$  in Fig. 1]. The second operating mode is based on the cavity transmittance-variations [ $I_T(x,y,z)$  in Fig. 1], which depend on the probe position above the nanocavity. Figure 2 shows typical near-field images recorded using the two operating modes at the cavity resonance wavelength modified by the presence of the probe ( $\lambda_0+\delta\lambda$ ). In addition, for the purpose of providing an insight in the spatial localization of the nanocavity on the optical near-field images, we present the shear-force feedback signal recorded during the optical scans in Fig. 2(b). Figure 2(a) additionally shows the scanning electron microscopy (SEM) image of the cavity.

Let us first analyze the image recorded in interaction-scanning mode. As explained in Refs. 12 and 21, the near-field map is proportional to the resonant electric field distribution inside the cavity. Thus, the positions of hot (or dark) spots are entirely determined by the position of the nodes (or antinodes) of the total electric field intensity. To allow for a direct comparison, we plotted in Fig. 3(a) the total electric field intensity, i.e.,  $\|\vec{E}_x\|^2 + \|\vec{E}_y\|^2 + \|\vec{E}_z\|^2$ , computed at a 4 nm height above the cavity surface by using a 3D fully vectorial frequency-domain modal method relying on Fourier expansion techniques.<sup>22</sup> A rapid glance at the two images reveals strong similarities between the numerical one in Fig. 3(a) and the experimental one in Fig. 2(c).

In contrast to the interaction-scanning mode which detects photons outcoupled from the cavity, the collection-scanning mode is directly related to the photons surrounding

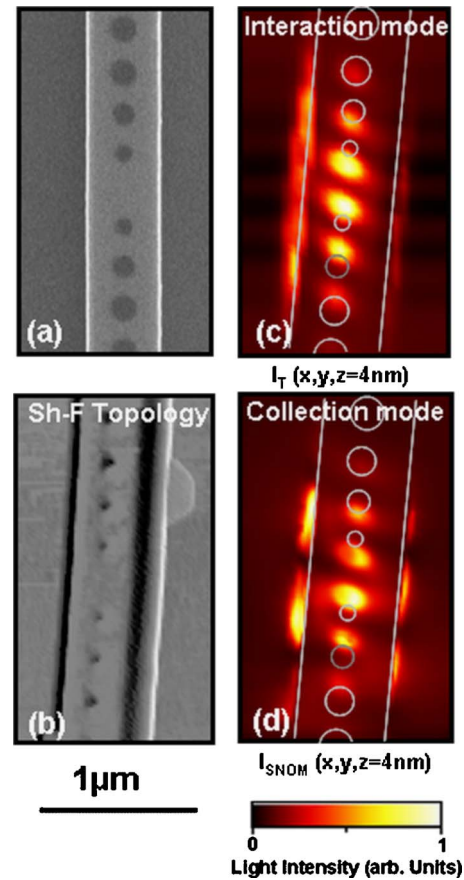


FIG. 2. (Color online) (a) SEM picture of cavity. (b) Shear-force feedback signal recorded during the probe scan above the structure. (c) Interaction-scanning mode map and (d) Collection-scanning mode map of the light confined at the cavity resonance.

the cavity optical near-field. As will be shown hereafter, the two imaging modes are complementary, and both of them must be taken into account in order to achieve a stringent analysis of the whole electromagnetic field surrounding the nanocavity at resonance.

A comparison between the maps recorded using the two operating modes [Figs. 2(c) and 2(d)] unambiguously shows their similarities and differences. The cavity resonant mode signature is clearly present in each of the two mapping modes, with hot and dark spots appearing at the position of the nodes and antinodes of the electric field. However, by contrast with the *interaction-mode* image, the *collection mode* image additionally exhibits a phase-shifted beating of

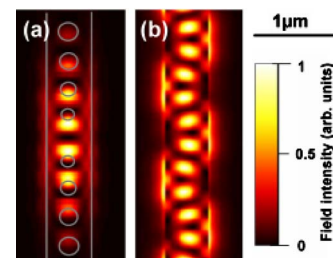


FIG. 3. (Color online) (a) 3D calculations of the resonant mode intensity at 4 nm above the nanocavity:  $\|\vec{E}\|^2 = \|\vec{E}_x\|^2 + \|\vec{E}_y\|^2 + \|\vec{E}_z\|^2$ . (b) Computed electric field intensity distribution above a SOI waveguide resulting from the propagation of the fundamental mode and the first order mode. The figure illustrates the phase-shifted beating pattern on the edge of the waveguide that can be observed in the SNOM collection mode measurements.

alternate hot and dark spots on the edge of the waveguide. We note that the contrast is maximal in the central part of the cavity and that it rapidly vanishes as one enters the mirrors. Additionally, we also note that the characteristic beating length is  $\sim 600$  nm, which surprisingly corresponds to twice the separation distance between the standing wave antinodes (or nodes) in the middle of the waveguide.

As the alternation of the hot and dark spots along the two edges of the waveguide does not respect its transversal symmetry, this implies that at least two modes with an opposite parity are coexisting inside the structure, leading to a phase-shifted beating pattern on the SNOM collection mode picture.<sup>23</sup> Such a phenomenon is generally attributed to the summation of the field amplitudes of the modes inside the SNOM probe. Moreover, as the silicon waveguide is bimodal, we believe that the observed beating results from the co-existence of the fundamental mode (with an even parity) bouncing between the two mirrors and the first order mode (with an odd parity) propagating along the waveguide. We computed the beating pattern expected for these two modes in the case of the silicon waveguide. The result is plotted in Fig. 3(b). It clearly exhibits a beating pattern similar to that one observed experimentally with a characteristic beating length close to the measured value.

Consequently, we believe that the SNOM collection mode picture results from the competition of the cavity resonant mode electric field distribution and of the beating pattern. At last, we underline that the beating is not observed elsewhere along the ridge waveguide except in the vicinity of the cavity resonant mode. Thus, we believe that the first order mode is not propagating along the whole waveguide but is rather excited inside the cavity by the resonant fundamental mode itself. The origin of this coupling, which is obviously indirect since the two modes are orthogonal, is currently under investigation.

In conclusion, we have presented optical near-field maps of the light confined within a high- $Q$ /small- $V$  photonic crystal nanocavity recorded in interaction-scanning mode and in collection-scanning mode. The differences between these two imaging methods have been analyzed and the comparison between the different pictures has been found to be supported by three dimensional field distribution calculations. The interaction-scanning mode is found to be selectively sensitive to the cavity resonant mode field distribution while the collection-scanning mode detects the whole electromagnetic field surrounding the nanocavity. In addition, the comparison between the two imaging methods has revealed unexpected mode coupling at the cavity resonance. Finally, since we were able to overcome the challenge of directly probing the optical near-field of the nanocavity without drastically altering its light confinement, we believe this study to a step towards the in situ mechanical nanomanipulation of confined electromagnetic fields<sup>24</sup> for the control of the quantum nature of strongly coupled cavity-atom systems of solid-state physics.

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