Tilted-potential Photonic Crystal Cavities for Integrated Quantum Photonics

(Student Paper)

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ABSTRACT

We demonstrate a novel, tailored-index photonic crystal cavity designed for optimal extraction and propagation of single photons in integrated quantum photonic chips. The structure consists in a line-defect photonic crystal waveguide with linear effective-index profile supporting Airy-function photonic modes. The observed modes are analyzed theoretically and experimentally using site-controlled quantum dot systems. Selective excitation of Airy-modes by properly positioned single quantum dots is demonstrated.

Keywords: photonic crystal cavities, tailored refractive index, optical disorder, single photon sources.

1. INTRODUCTION

Integration of semiconductor quantum dots (QDs) and photonic crystal (PhC) membrane cavities and waveguides is a promising platform for the realization of integrated quantum photonics circuits for generation and processing of single photons on-chip [1-2]. Basic functions in such systems are efficient extraction of photons from single QDs and their routing to specific destinations on the circuit. This can be accomplished using Purcell enhancement of the single photon emission in a photonic nano-cavity [3], which is optically coupled in an optimal way to waveguides [4] free of mode-localization effects [5]. We propose and demonstrate a novel PhC tailored-index cavity in which the characteristic Airy-function modes can fulfill both objectives.

2. CONCEPT

The tailored-index cavity consists of a PhC line-defect membrane-waveguide in which the two rows of border holes are shifted outwards by an amount s(x) proportional to their position, up to a maximum value of s_{max}. This yields an approximately linear variation of the effective index n_{eff} of the waveguide mode along its axis. A photonic cavity with a linear index variation is thus formed, in which several modes with characteristic resonance frequencies ω_l (and photon energy $E_l = \hbar\omega_l$) are confined, as shown in Fig. 1(a).

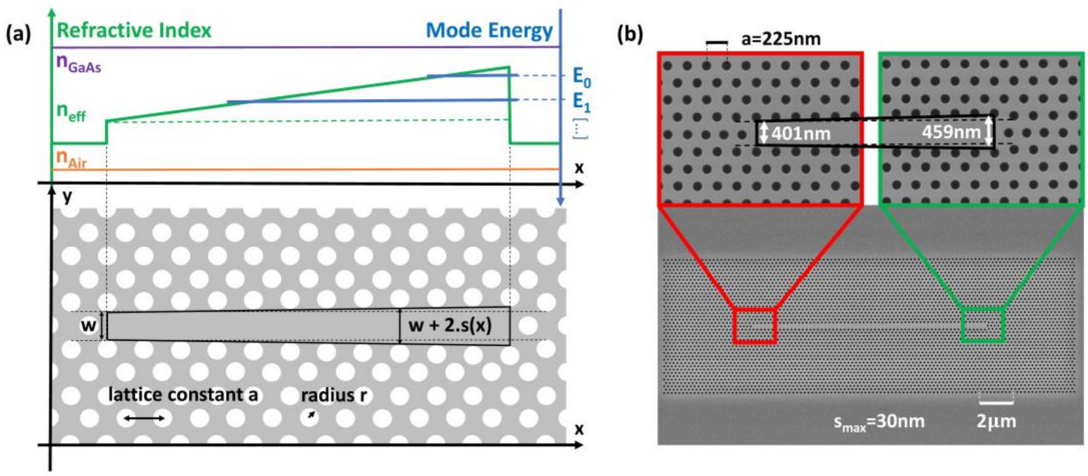

Figure 1. (a) Schematic illustration of the tilted-index cavity (bottom) and the effective index variation showing the resonant mode energies (top). (b) Scanning electron microscope images of a fabricated structure, with magnified view of the two cavity edges. Designed s_{max}=30nm.

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Such structures were first studied numerically using a 2D finite-difference method (FDM), based on a 250nm-thick GaAs suspended membrane, a triangular PhC hole array of pitch a=225nm and various hole-radius to pitch (r/a) ratios. The tilted-index structures are variants of a uniform L_{61} line-defect cavity in which the hole shift s(x) is introduced (see Fig. 1). An example of the calculated modes for a cavity of total length of 62a=13.95µm and a maximum hole shift of s_{max}=10nm is shown in Fig. 2. The confined modes exhibit Airy-function envelopes similar to those of quantum mechanical particles confined in linearly-graded potential wells [6], superposed on the waveguide Bloch patterns. Each mode, of characteristic energy, consists of a main lobe systematically shifted in x according to the mode energy, to which an oscillating extended "tail" is attached. The main lobes of these wavefunctions can serve for efficient photon extraction from QDs placed there, together with controlled coupling to a distant location via the mode tail. Note that even a slight maximal shift (10nm) of the end holes produces a dramatic difference in mode structure with respect to the uniform-index L_{61} base cavities. The exact slope of the shifted holes determines the energy-position configuration of the spectrally-resolved near-field patterns.

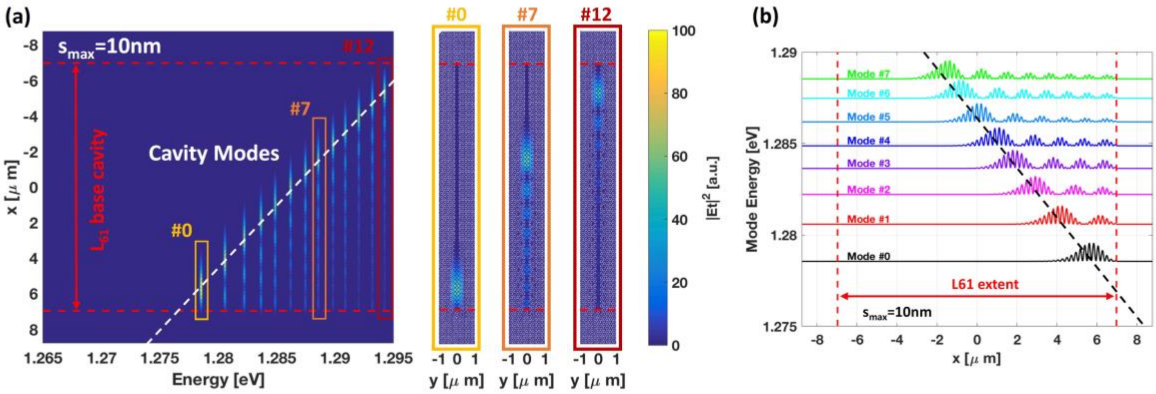

Figure 2. (a) Numerical simulation of in-plane electric field of the confined modes of a tilted-index cavity displayed in position-energy plane. Magnified view of three selected modes in x-y plane are shown. (b) Cross sections of the corresponding PhC Airy-modes. Parameters are s_{max}=10nm, pitch a=225nm, hole radii r=72.5nm, membrane thickness 250nm.

3. DEMONSTRATION

The tilted-index structures were produced on 250nm-GaAs suspended membranes in which the designed PhC hole patterns were fabricated using electron beam lithography. Site-controlled InGaAs/GaAs multiple QDs grown by metallorganic vapour phase epitaxy on substrates patterned with pyramid recesses served as internal light sources [7-8]. The structures were optically characterized by measuring their photoluminescence (PL) spectra and imaging their spectrally-resolved near field patterns at 10K [9]. Examples of the measured spectrally resolved (diffraction limited) near field patterns are shown in Fig. 3. Airy-mode patterns are clearly observed, with energy-position configurations closely matching the simulated results. Simulations and measurements of structures with different maximal hole shifts s_{max} indicate reduced effects of fabrication disorder with increasing effective-index slopes.

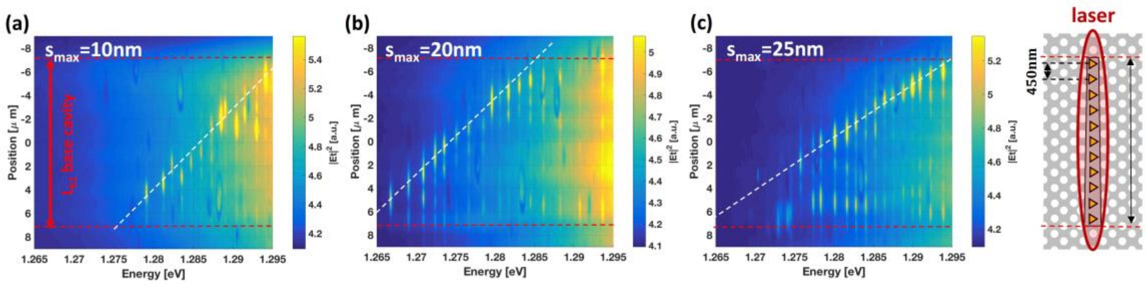

Figure 3. Experimental spectrally-resolved near-field patterns of tilted-index cavities for (a) s_{max}=10nm, (b) s_{max}=20nm and (c) s_{max}=25nm. Arrays of 450nm-spaced QDs serve to excite all cavity modes. Laser spot used for excitation depicted schematically.

In a second series of structures, single QDs were positioned at prescribed locations along the cavity, for matching the position of the main lobe of an Airy-mode of particular photon energy. In a specific configuration, two QDs, separated by ≈ 9.5µm, were positioned near the two edges of the cavities (see Fig. 4). Excitation of each QD separately was possible using a micro-PL setup with an excitation spot of 1-2µm-diameter. Thus, it was possible to excite the Airy-modes of the cavity with a point-like source (each QD is ~20nm wide), with a relatively broadband spectrum due to emission from the QD barriers at the high power levels (~1mW) of the exciting laser. As evident from the spectrally resolved near field patterns (Fig. 4), only the Airy modes with sufficient overlap with the point-like sources are excited. This demonstrates the possibility of coupling the emission of single QDs to selected Airy modes by proper positioning of the QD with respect to the spatial mode patterns.

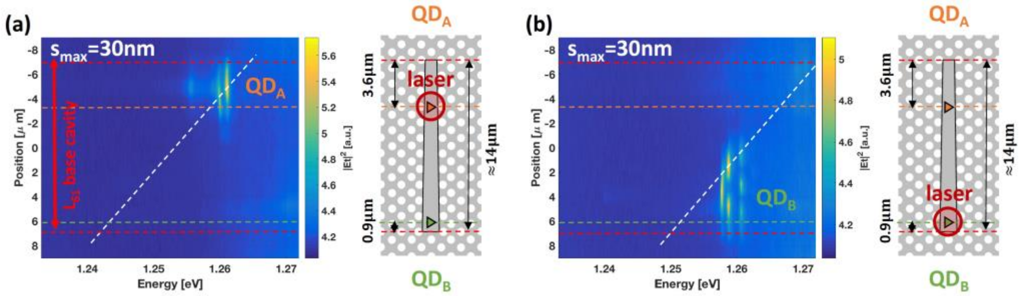

Figure 4. Experimental spectrally-resolved near-field patterns of tilted-index cavities with only 2 QDs located at specific positions at both ends, s_{max}=30nm: (a) excitation with QD_A; (b) excitation with QD_B. Laser spot used for excitation is depicted schematically.

4. CONCLUSIONS

By proper tailoring of the effective index in PhC membrane cavities, it is possible to shape the spatial mode envelope patterns in the form of Airy-functions. These mode shapes make possible the combination of efficient extraction of single photons and their guiding to remote on-chip destinations by precise placement of the QDs. Using site-controlled QDs, the feasibility of such QD-Airy function coupling (and subsequent extraction and guiding of single photons) was demonstrated.

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