Photonic Crystal Nanocavities for Solid State Quantum Optics

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Abstract:
The radiative properties of an atom can be dramatically modified when it is coupled to an optical cavity [1]. Implementing such quantum optical effects in solid-state is essential for the realization of integrated quantum optical devices, including those relevant to quantum information science [2, 3]. The success relies on the fabrication of state-of-the-art artificial atoms and nanocavities. Our artificial atoms are InAs/GaAs self-assembled quantum dots (QDs) grown by molecular beam epitaxy. Our nanocavities are formed by defects in two-dimensional photonic crystal slabs. Here we report on the fabrication of a key building block for future photonic quantum technologies: the integrated coupling of photonic crystal cavities and waveguides.

Summary of Research:
Optical cavities are characterized by two main quantities: the mode volume, that is, the spatial extent of the electromagnetic confinement, and the quality factor (Q), which is proportional to the photon cavity lifetime. When trapped for long time (high-Q) in small volumes, photons strongly interact with the host material and create significant nonlinear effects. Photonic crystal nanocavities (PCNs) with ultra-high-Q and mode volume close to the diffraction limit ((λ/n)^3) have been achieved by several research groups [2, 4].

High-Qs are made possible by suppression of the electric field Fourier components within the light zone. But this comes at a price: High-Q PCNs are poorly coupled to the vertical direction (i.e. orthogonal to the slab). In this report we show the fabrication of L3 PCNs side-coupled to waveguides and optimized for highest Q and for highest far-field vertical collection [5].

The fabrication consists of the following steps: (i) we start with a molecular beam epitaxy (MBE) grown GaAs substrate. (ii) after defining the PCN pattern on the resist (ZEP 520A) by electron beam lithography, (iii) we transfer the pattern into the semiconductor by chlorine-based inductively coupled plasma reactive ion etching (ICP-RIE). Finally, (iv) the Al_xGa_1-xAs (x ≈ 0.7) sacrificial layer is removed by selective HF wet etching.

Figure 1 shows the scanning electron microscope images of the fabricated PCNs. Figure 1(a) shows the high-Q L3 PCN formed by three missing air holes in the hexagonal lattice of holes patterned in a λ/n thick slab. The marked holes were shifted and shrunk to maximize the Q. Figure 1(b) shows the L3 PCN optimized for far-field vertical collection. Starting from the former design, Figure 1(a), the marked holes were enlarged. Figure 2 shows the photoluminescence spectra of our PCNs. The photo-luminescence spectrum was measured by the cross-polarization resonant scattering. Emission peaks are well fitted by Lorentzian curves.

The typical Qs for high-Q L3 PCN were resolution limited, Q ≈ 7 × 10^4 (Figure 2a). As expected, a lower Q ≈ 3 × 10^4 (Figure 2b) was measured in L3 PCNs optimized for far-field, but a remarkable enhancement of light intensity was detected in the vertical direction.

When integrating the L3 PCNs optimized for far-field together with side coupled waveguides (Figure 3), we were able to observe the light in the waveguides and extracted from the center PCN even by naked eyes (Figure 3 inset). We note that the PCNs optimized for far-field can also act like a grating coupler that can gather the light from vertical direction. This allows us to scale up the device more easily compared to the edge-coupling and the fiber taper techniques.

Light confinement in nanocavities relying only on index guiding is well understood, while current PCN understanding is much less mature because of the hybrid character of the confinement. (Photons are confined vertically by total internal reflection and laterally by Bragg reflection.) Our PCNs demonstrate that we can model and fabricate PCNs in GaAs with specific functionalities. Together with the QDs, we can implement designs [2, 5] that are suitable for applications where light extraction is key such as single photon emitters [6].
References:


