Photon-Level Tuning of Photonic Nanocavities

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Primary CNF Tools Used: JEOL 9500, AJA ion mill

Abstract:

We report an all-optical approach for extremely efficient tuning of a high-*Q* lithium niobate photonic crystal nanocavity, with a significant resonance tuning rate of 88.4 MHz/photon.

Summary of Research:

Controlling photonic functionalities by purely optical means is a long-term goal of nonlinear optics, which has been pursued for decades. Unfortunately, natural optical media generally exhibit fairly weak optical nonlinearities. Photonic crystal (PhC) nanocavities are able to strongly confine optical waves inside a small volume, thus particularly suitable for enhancing nonlinear optical interactions [1]. To date, PhC nanocavities have been applied on a variety of device platforms for optically tuning/switching the cavity properties [2-6]. However, it remains fairly challenging to achieve device control with only photon-level optical energy, which represents the ultimate efficiency of nonlinear optics. Here we report a lithium niobate (LN) PhC nanocavity that exhibits an optical *Q* as high as 1.41 million, more than one order of magnitude higher than previously reported [7-9]. With this device, we are able to demonstrate extremely efficient wavelength tuning of the device, with a resonance tuning rate as high as 88.4 MHz/photon, and nearly 100% preservation of the resonance quality.

Figure 1 shows the device, which was fabricated on a 300-nm-thick x-cut single-crystalline LN thin film, and patterned by JEOL 9500. We optimized the nanobeam width, layer thickness, lattice constant, and the shape of the elliptical holes to achieve a photonic bandgap of 26 THz covering optical frequency from 183 to 209 THz, for the transverse-electric-like (TE-like) polarization with the guided mode dominantly lying in the device plane. Simulations by the finite element method show that the cavity mode exhibits a radiation-limited optical *Q* of 1.23×10^8, with an effective mode volume as small as $0.78(\lambda/n)^3$.

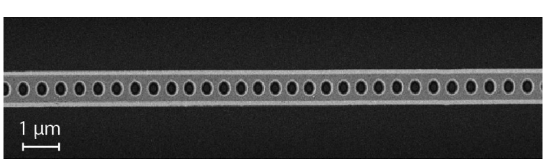

Figure 1: SEM image of a fabricated LN PhC nanobeam.

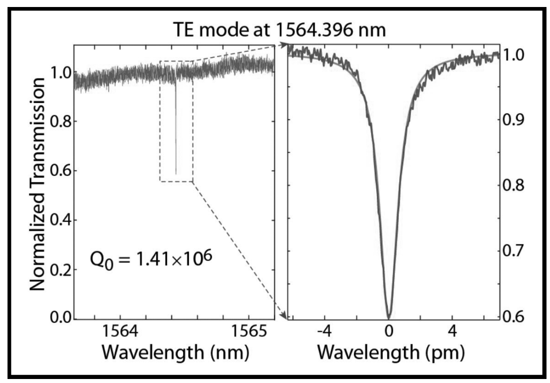

Figure 2: Laser-scanned transmission spectrum of a fabricated LN PhC nanobeam with the experimental data shown in blue and the theoretical fitting shown in red. (See pages vi-vii for full color version.)

Detailed experimental characterization of the fabricated device, as shown in Figure 2, shows that the device exhibits a high-quality cavity mode at 1564.396 nm in the telecom band, with an intrinsic optical *Q* factor as high as 1.41 million. This value is more than an order of magnitude larger than what was previously reported on LN nanophotonic devices [7-9]. To the best of our

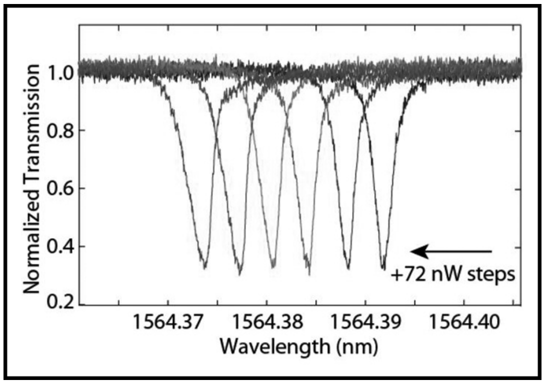

Figure 3: Measured transmission spectra of cavity exhibit strong resonant wavelength tuning with increasing intra-cavity power. (See pages vi-vii for full color version.)

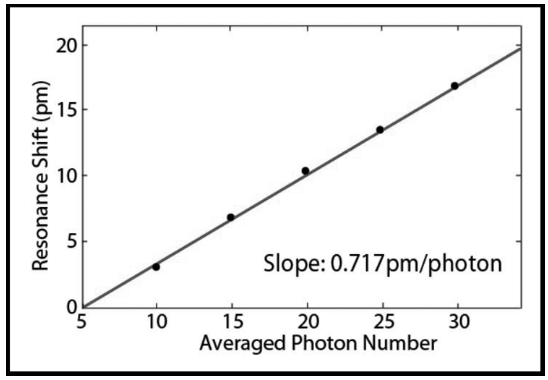

Figure 4: Linear resonant wavelength tuning as a function of intra-cavity power. The measured tuning efficiency is 88.4 MHz/photon, or equivalently 0.67 GHz/aJ.

knowledge, this is the second single-crystalline PhC nanocavity, other than silicon ones [10], that is able to exhibit an intrinsic optical Q above one million.

The extremely high optical Q, together with the tiny effective mode volume, of the device would result in dramatic enhancement of nonlinear optical interactions inside the cavity, thus allowing us to explore efficient nonlinear photonic functionalities. An intriguing nonlinear optical property of LN is the photorefractive effect [11], which manifests an intensity-dependent decrease of refractive index. We thus expect that the cavity resonance can be self-tuned by optical power launched into the device. To show this phenomenon, we maintain an external coupling efficiency of 65% (accordingly, loaded optical Q around 8.9×10^5). We continuously scanned the laser wavelength across the resonant wavelength back and forth and monitored the transmission of the device. As shown in Figure 3, when the input optical power increases from 72 nW to 432 nW, the cavity resonance wavelength continuously shifts towards blue.

As the laser wavelength was scanned back and forth in a periodic triangular fashion over a spectral range of 150 pm, the input power of 432 nW results in an averaged optical energy of about 3.96 aJ inside the cavity, which corresponds to an average of only 30 photons. Figure 4 shows the induced resonance shift as a function of average number of photons inside the cavity. It shows a clear linear dependence, with a tuning slope of 0.717 pm/photon, corresponding to 88.4 MHz/photon. Therefore, about 2.4 photons on average inside the cavity are able to shift the whole cavity resonance, clearly showing the extreme efficiency of the induced resonance tuning.

In summary, we demonstrated a LN photonic crystal nanobeam resonator with optical Q as high as 1.41 million. With this device, we were able to demonstrate efficient tuning of the cavity resonance, with a significant tuning rate of 88.4 MHz/photon and nearly 100% preservation of the resonance quality.

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