Coupled photonic crystal nanobeam cavities

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We describe the design, fabrication, and spectroscopy of coupled, high quality (Q) factor silicon nanobeam photonic crystal cavities. We show that the single nanobeam cavity modes are coupled into even and odd superposition modes, and we simulate the frequency and Q factor as a function of nanobeam spacing, demonstrating that a differential wavelength shift of 70 nm between the two modes is possible while maintaining Q factors greater than 10^6. For both on substrate and freestanding nanobeams, we experimentally monitor the response of the even mode as the gap is varied, and measure Q factors as high as 2×10^5. © *2009 American Institute of Physics*.
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Photonic crystal (PhC) cavities have been of great interest in recent years for their ability to strongly confine light in wavelength-scale volumes.[1–3] The high quality (Q) factors and small mode volumes of these structures have enabled a wealth of applications in areas as diverse as low-threshold lasers,[4,5] optical switching,[6] low power nonlinear optics,[7] cavity quantum electrodynamics,[8,9] and chemical sensing.[10–12]

Single PhC cavities have now been optimized to a point where they can be treated as fundamental photonic components. To realize different functionality, it is essential to leverage the natural scalability of PhC cavities. For example, PhC cavities can be integrated into coupled resonator optical waveguides[13] to realize heterostructures capable of slowing light.[14] There is also much recent excitement about the possibility of entangling optical and mechanical degrees of freedom in waveguides[15] and double-cavity devices.[16–19] To achieve optomechanical coupling, the cavities require a small mass and a flexible platform. These two properties are inherent to PhC nanobeam cavities, which have been the subject of much recent investigation.[16,20–24] In addition, double nanobeam cavity structures could facilitate adiabatic wavelength conversion in a similar manner to that predicted for a double-layer PhC slab cavity, for which it was shown that broad bandwidth dynamic resonance tuning could be realized while maintaining the high Q factor of the cavity mode.[25] Here, we show the static tuning of double cavity modes by varying the cavity separation, thereby demonstrating a proof-of-principle of this effect.

In this work, we study coupled PhC nanobeam cavities consisting of two parallel suspended beams separated by a small gap, each patterned with a one-dimensional line of holes, as shown in Fig. 1(a). Similar silicon nitride structures were studied theoretically in Ref. 16 and were used as the basis for an optomechanical cavity in Ref. 17. Here, we present an experimental exploration of the resonances in coupled nanobeam silicon structures as the coupling strength is varied via the nanobeam separation. We investigate both on substrate and freestanding devices and employ a free-space optical probe technique, which does not perturb the cavities. The starting point for our double nanobeam design is our previously reported single PhC nanobeam cavity.[22,23] To briefly summarize the approach, we start with a 220 nm thick and 500 nm wide freestanding Si waveguide (nanobeam) which supports only a single transverse electric mode. The nanobeam is patterned with a linear array of air holes to introduce a stop-band in the guided mode bandstructure around 1550 nm. Near the middle of the beam, the hole size and spacing are tapered to introduce a defect potential capable of strongly localizing light. Optimization of the adiabatic five-hole taper design leads to simulated Q-factors greater than 10^7, and we have experimentally measured $Q=7.5\times10^5$ in these single beam structures.[23] We then created double cavity structures by positioning two such cavities side-by-side and varying the air gap between them. As expected from the physics of coupled harmonic oscillators, coupling generates modes which are symmetric and antisymmetric superpositions of the single cavity basis states, as shown in Fig. 2.[16] The frequency splitting between the modes is dependent on the strength of the coupling, which in this case is determined by the size of the gap.

The mode profiles, Q factors, and resonant wavelengths are shown in Fig. 2 as a function of the gap, d, between the nanobeams. The data were simulated with a three-dimensional, finite-difference, time-domain code (Lumerical

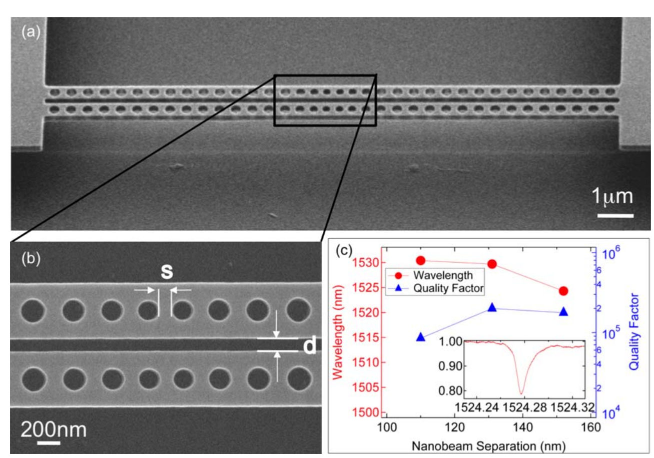

FIG. 1. (Color online) [(a) and (b)] Double nanobeam cavity, showing the separation $d=100$ nm and cavity length $s=146$ nm. (c) Mode wavelength and quality factor for different nanobeam separations. The resonant scattering spectrum for the 150 nm double cavity is shown in the inset.

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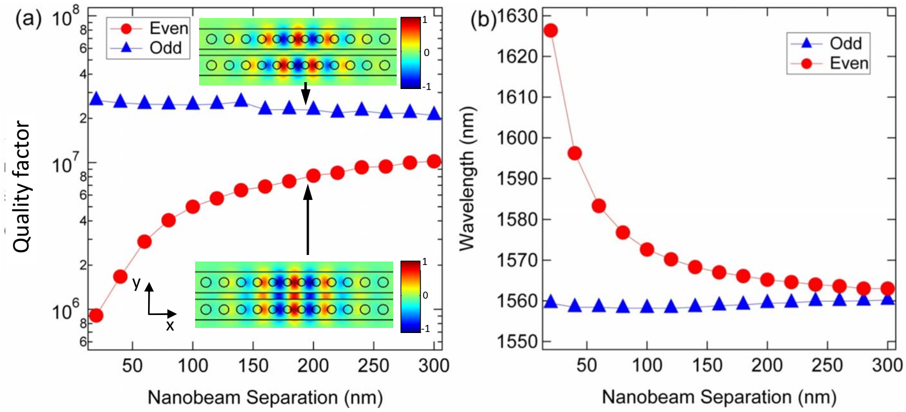

FIG. 2. (Color online) (a) Q factors of even and odd coupled nanobeam modes. Insets show E_y components of the modes. (b) Mode wavelengths as a function of separation, showing large dispersion of the even mode.

Solutions). For small d, there is a strong coupling between the cavities. This leads to a large wavelength splitting between the modes, with the even mode at longer wavelength, which is typical of coupled resonators. The wavelength of the odd mode changes little with d, whereas the even mode disperses rapidly to longer wavelength as d decreases. This asymmetry indicates the presence of second-order cross- and self-coupling effects between the coupled resonators in addition to the first-order effects of the index perturbation.[26] As d shrinks below 100 nm, the field intensity of the gap antinode grows and becomes the dominant feature in the mode, much like an air-slot cavity.[11,12,27,28] At the same time, the Q factor declines, since the PhC tapering is not optimized for the significant redistribution of the mode energy into the slot between the nanobeams. These factors imply that the even mode would be a sensitive probe of the interbeam distance, and thus useful for optomechanical applications.[16,17] It would also be useful in biosensing and chemical-sensing, as the gap antinode would be highly sensitive to perturbations in the external environment.

In contrast to the significant alterations of the even mode, the odd mode is similar in profile to a superposition of two *uncoupled* single cavity modes. The relatively flat odd-mode dispersion is likely due to the opposing effects of the first- and second-order coupling terms.[26] The Q factor, however, is substantially higher than that of the even mode and in

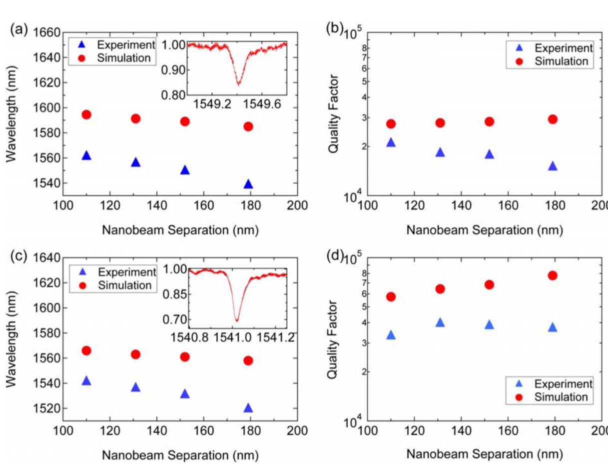

FIG. 3. (Color online) Wavelength and Q factor as a function of measured separation for on substrate [(a) and (b)] and freestanding [(c) and (d)] double nanobeam cavities. The insets show typical spectra normalized by reference spectra taken away from the cavity. The simulations in [(a) and (b)] do not include the residual ~40 nm FOx resist layer, which has a negligible effect on the Q factor and shifts the wavelength by only a few nanometers.

fact is approximately twice the Q factor of a single nanobeam cavity (1.4×10^7). Intuitively, this is consistent with the larger mode volume, $V\sim0.7(\lambda/n)^3$, which is about twice that of the single cavity; the more extended real-space distribution of the fields results in a more localized k-space distribution, and therefore a reduction in the radiative components within the light cone.[29]

The double nanobeam structures shown in Fig. 1 were fabricated on a silicon-on-insulator wafer (SOITEC, Inc.) consisting of a silicon device layer of 220 nm, a SiO_2 layer of 2 μm, and a thick silicon substrate. A negative e-beam resist, FOx-17 (Dow Corning) diluted in six parts of methyl isobutyl ketone, was spun onto the sample at 5000 rpm to give a layer 135 nm thick and patterns were defined using a 100 kV electron beam lithography system (Elionix). A negative resist simplifies the pattern writing, since the only exposed region is along the nanobeam, and FOx proved to be a robust etch mask for the Reactive Ion Etching (RIE) process. The resist was developed for 14 s in tetramethyl ammonium hydroxide (25% TMAH) followed by a thorough rinse in de-ionized water. The patterns were transferred to the silicon layer using reactive ion etching with a SF_6, C_4F_8, and H_2 plasma. The SiO_2 sacrificial layer was removed using a hydrofluoric acid vapor etching tool (AMMT).[23,30]

We experimentally probed our double nanobeam cavities using a cross-polarized resonant scattering technique.[9,31] A tunable cw laser (Agilent) was focused onto the cavity from normal incidence with a microscope objective (numerical aperture=0.5). The resonantly scattered reflected signal was analyzed in the cross polarization before being sent to an InGaAs detector. Recently, we used the same approach to measure Q factors as high as 7.5×10^5 in single nanobeam cavities.[23] Because the resonant excitation field drives the (E_y) fields in the coupled nanobeams *in phase*, this technique is primarily sensitive to the even mode. We note that in principle, the field gradient of the focused spot could be exploited to excite the odd mode, as could butt coupling or evanescent waveguide coupling techniques.[21,32,33] Figure 1(c) shows the resonant wavelength and Q factor of the even mode for three different nanobeam separations. The mode redshifts as d decreases, in agreement with our simulations (Fig. 2), although the data may reflect additional small contributions from e-beam proximity effects and fabrication imperfections. The Q factor varies between 1×10^5 and 2×10^5. Although this is more than an order of magnitude lower than predicted by simulations, this is a highly useful range for applications and we expect increases as the fabrication quality of our structures improves.

We also investigated the effect of the substrate on the cavity modes. As mentioned above, for small *d*, the even mode field intensity is concentrated in the space between the cavities. This slot mode could be useful for biosensing and chemical sensing, but to be robust in a liquid environment such a device would require the structural stability provided by a substrate. Due to the limited tuning range of our laser, these data were obtained from cavities with a spacing (*s*) of 136 nm, which is smaller than our optimal, high *Q* design of 146 nm [data shown in Fig. 1(c)]. In Figs. 3(a) and 3(b), we present the results of our resonant scattering spectroscopy for unreleased, on-substrate nanobeam cavities (i.e., supported by SiO_2). The FOx resist was not removed for these cavities, since any etch process would also remove the substrate. However, we estimate that the resist layer remaining on top of the silicon nanobeams has a thickness less than 40 nm. The resonant wavelength and *Q* factor of the even mode are plotted as a function of *d*. The resonance blueshifts with increasing *d* as the effective index of the cavity mode decreases. The experiment shows a larger dispersion than the simulation, likely reflecting the increasing role of e-beam lithography proximity effects for small gaps. The measured *Q* factors of $1.5-2.0\times 10^4$ are remarkably high for supported cavities,[21] considering that the designs were optimized for freestanding nanobeams. Given the robust structure, high *Q* factors, and field intensity in the gap, the supported double nanobeam cavity is a promising approach to scalable, on-chip sensing applications.

Figures 3(c) and 3(d) show the experimental data for the same cavities after the sacrificial SiO_2 substrate was removed. The modes are blueshifted compared to the results of Fig. 3(a), as expected from the decreased effective index of the air cladding compared to the oxide. The *Q* factors, however, are increased by a factor of ~2 due to the reduced leakage into the substrate.

In conclusion, by varying the spacing of two coupled nanobeam cavities, we experimentally demonstrated a resonant wavelength shift of 20 nm due to intercavity coupling in dual cavities while maintaining a relatively constant *Q* factor. This shows the same tuning principle that was predicted recently for double planar PhC cavities, and the effect would be magnified for coupled nanobeams with smaller separations. The ability to tune the resonant wavelength of a cavity without adverse effects on the *Q* factor opens up potential areas for research in optomechanics, adiabatic frequency conversion, and sensing.

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