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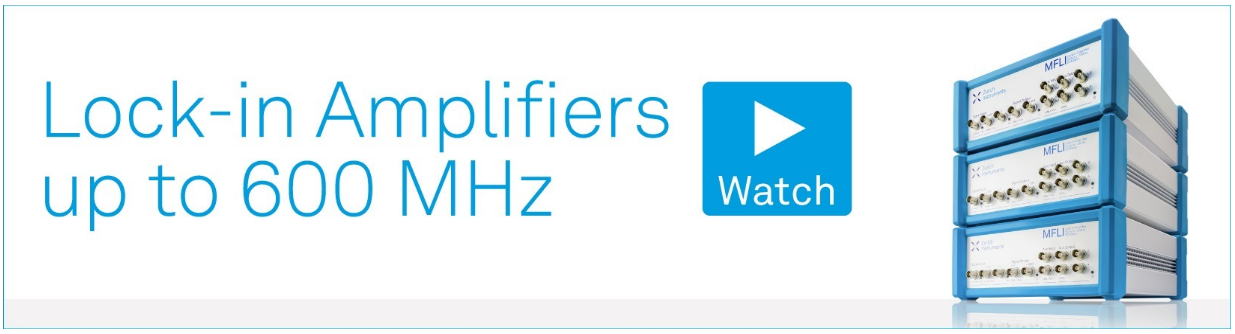

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Parabolic tapered photonic crystal cavity in silicon

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We demonstrate the design, fabrication, transmission spectrum measurement, and near-field characterization of a parabolic tapered one-dimensional photonic crystal cavity in silicon. The results shows a relatively high quality factor (~43 000), together with a small modal volume of $\sim 1.1(\lambda/n)^3$. Moreover, the design allows repeatable device fabrication, as evident by the similar characteristics obtained for several tens of devices that were fabricated and tested. These demonstrated 1D PhC cavities may be used as a building block in integrated photonic circuits for optical on-chip interconnects and sensing applications. © *2012 American Institute of Physics*. [doi:10.1063/1.3679659]

One dimensional (1D) photonic crystal (PhC) cavities play an important role in on-chip optical technology owing to their attractive properties such as confining light in a small volume, small footprint, and wavelength selectivity, as well as their relative ease of fabrication. If properly designed, these cavities can provide both small mode volume (V) and a relatively high quality factor (Q). This promising combination allows the enhancement of light-matter interactions. Over the recent years 1D PhC cavities has been proposed and demonstrated for various applications, e.g., optomechanics,[1] non-linear optics,[2] quantum optics,[3] light modulators,[4] sensors,[5] lasers,[6] and optical trapping.[7] A substantial effort was devoted to approaches for designing high-Q PhC. A major challenge towards obtaining a high-Q PhC cavity is to decrease the out-of-plane radiation loss as much as possible. This can be achieved in several ways, e.g., by designing a precise shift of the position of individual holes and/or modifying their radius.[8–11] Often, a very large computational power is required for precisely designing the required holes parameters. A different approach for the design of high-Q 1D PhC cavity based on a modulated Bragg mirrors with linearly increased modulation strength by controlling the holes size was proposed and demonstrated.[12–14] The approach requires relatively low computational effort compared with previous demonstrations. Due to the nanoscale dimensions required for the construction of PhC devices in the visible and the near infrared spectral regime, many of the PhC samples are being fabricated by an electron beam (e-beam) lithography as a nano patterning tool. While providing the required high resolution, it is very challenging to control the dimensions of each hole at the nanometer level using e-beam lithography, e.g., because of the proximity effect caused by an electron scattering in the e-beam resist.[15] Another way for modulating the Bragg mirror, not relying on modifying the holes periodicity and/or size, is by an adiabatic parabolic tapering of the width of the PhC waveguide. This concept was used to demonstrate an on-chip laser in a InGaAsP slab.[16] In this letter we show and experimentally demonstrated a simple yet efficient method for the design and the fabrication of high-Q 1D photonic crystal cavities in silicon based on the concept of parabolic tapering of the waveguide width with silicon dioxide cladding on both sides. The cavities were designed with symmetric oxide cladding to increase the mechanical stability and thermal isolation and to avoid contamination. We have tested the robustness of this approach by fabricating and testing several tens of identical samples, all showed very similar performances.

First, we designed the Bragg mirrors by simulating an infinite PhC structure using the plane wave expansion method. Figure 1 shows the dispersion diagrams for the transverse electric (TE) modes of a infinite silicon ($n_{Si} = 3.46$) PhC surrounded by a silicon dioxide ($n_{SiO_2} = 1.46$) cladding for different waveguide widths. The waveguide widths w_y were taken to be $1.29a$ and $1.43a$, the waveguide height was $w_h = 0.715a$, and the holes radius was $r = 0.325a$. As can be seen a complete band gap is obtained for the TE modes. The cut-off frequency of the lower dielectric band is increased with the decrease in the waveguide width. To operate around 1550 nm wavelength, we set the period to be $a = 350$ nm. In order to form mirrors with linearly increasing strength we modified the waveguide width in a parabolic fashion. As shown schematically in Figure 2(a), the width of the waveguide around the PhC section was decreased from $w_{\max}$ to $w_{\min}$ by using a parabolic tapering. The entire cavity consists

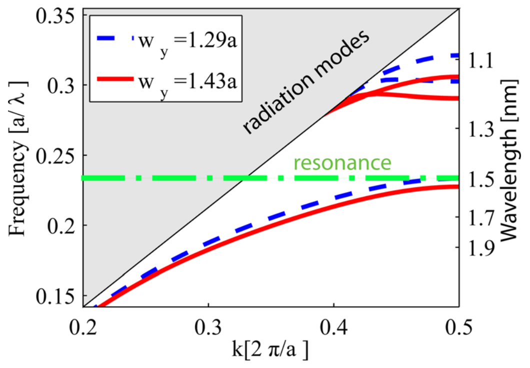

FIG. 1. (Color online) Dispersion diagram of the infinite PhC with $w_y = 1.29a$ and $w_h = 1.43a$ (the wavelength scale on the right side is corresponding to a periodicity of $a = 350$ nm).

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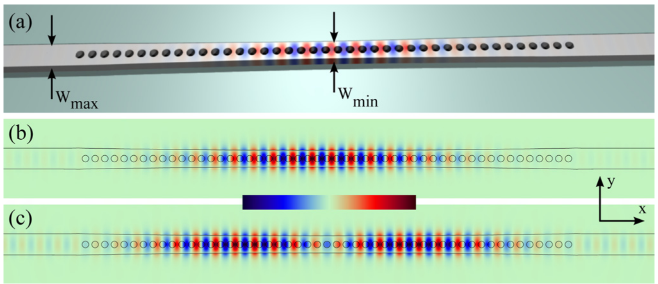

FIG. 2. (Color online) (a) 3D schematic of the parabolic PhC cavity with superimposed in-plane electric field distribution. (b) Simulated results of the in-plane electric field (E_y) for the first resonance mode of the parabolic PhC cavity. (c) Simulated result of the in-plane electric field (E_y) for the second resonance mode of the parabolic PhC cavity. A cross section at the middle height of the device is presented.

of 50 holes (25 holes for each mirror). To verify the usefulness of our design we performed a three dimensional (3D) finite-difference-time-domain (FDTD) simulation which allows the computation of the field distribution within the device for different wavelengths of operation. Figures 2(b) and 2(c) present the simulated electric field profile (E_y) of the first and the second cavity mode at the middle height of the device. From FDTD simulations we found that 15 holes for each mirror are sufficient for achieving a quality factor over a million. However, to be on a safe side we chose a higher value of 25 holes for each mirror. The simulated quality factor, mode volume, and the extinction ratio $\left(ER = \frac{P_{peak}}{P_{band\ gap}}\right)$ of the first cavity mode were found to be $Q = 2.1 \times 10^6$, $V = 1.1(\lambda_{res}/n_{Si})^3$, and $ER = 25\,dB$, respectively.

The PhC cavity device was fabricated using standard silicon on insulator (SOI) wafer with a 2 micron buried oxide and a 250 nm upper silicon device layer. The device pattern was defined by e-beam lithography (Raith 150 eLine) following by a coupled plasma reactive ion etching (Oxford Plasmalab 100) to transfer the pattern into the device layer. Finally the device was covered by silicon dioxide using a plasma-enhanced chemical vapor deposition (Oxford Plasmalab 100). To couple light into and out of the devices we used the inverse taper approach. Figure 3(a) shows a scanning electron microscope micrograph of the fabricated device before the deposition of the upper cladding oxide layer. In order to characterize our device we launch an in-plane TE polarized light from a tunable laser (Agilent 81680A) by using a polarization maintaining lensed fiber. Another lensed fiber was used for collecting the optical signal into the detector (Agilent 81634a). Figure 3(b) presents the measured resonance and the Lorentzian fit. From the fit we extract the loaded Q factor of the resonance to be 43 000 and the extinction ration to be 11 dB. The quality factor and the extinction ratio are smaller than the simulated values due to fabrication imperfections and material loss. We fabricated a few tens of PhC cavities in different chips with slightly different resonant wavelength and observed very similar values of Q factor (±10%) for all of them, providing an indication for the robustness of the proposed approach.

In order to demonstrate the high confinement of the optical field in the region of PhC cavity we performed a near field measurement of the cavity. For this propose we designed a cavity with an air upper cladding by using similar design rules as mention above, with hole periodicity of $a = 350\,\text{nm}$, hole radius of $r = 0.325a$, and waveguides width ranging from $w_{\min} = 1.43a$ to $w_{\max} = 1.57a$. The simulated and measured quality factors of the first cavity mode were found to be $Q_{sim} = 1 \times 10^6$ and $Q_{\text{measured}} = 35\,000$, respectively. Next, we scanned the PhC cavity by a near field scanning optical microscope (NSOM, Nanonics MultiView 4000) using a metal coated tip with an aperture of 250 nm diameter. Figure 4(a) shows a cartoon of the NSOM measurement. When the metallic coated NSOM tip is located near the PhC cavity, it is locally modifying the refractive index of the cladding, resulting in a shift in resonance wavelength[17] and practically

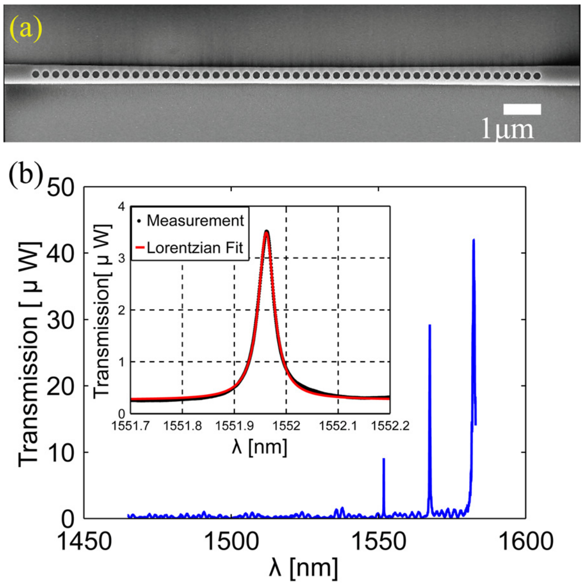

FIG. 3. (Color online) (a) SEM micrograph of the fabricated device. (b) Measured transmission spectrum. The inset shows a zoom on the resonance peak with the Lorentzian fit (Q = 43 000).

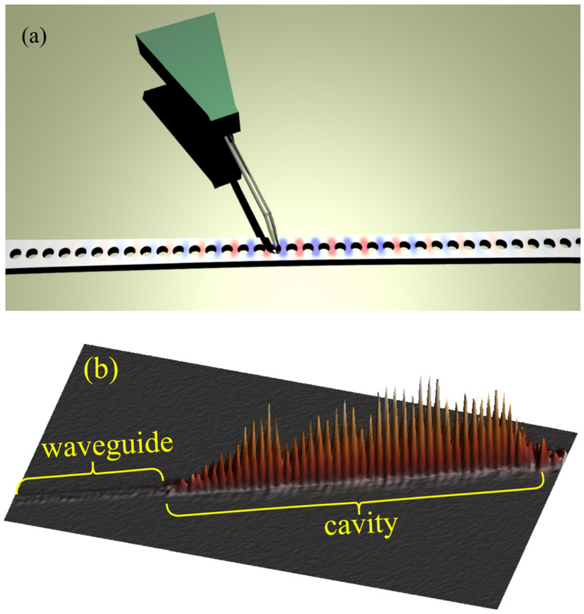

FIG. 4. (Color online) (a) 3D schematics of the NSOM measuring setup. (b) A 3D representation of the measured near field signal at resonance.

affecting the measurement. To compensate for this effect, the resonance wavelength was manually tracked during the NSOM scanning by using a transmission feedback. Figure 4(b) presents a near field optical intensity distribution in the cavity at the resonance wavelength. We can clearly observe the high intensity within the PhC cavity region as compared with the waveguide section. The mode analysis and scattering characterization[18] of these PhC cavities can be done using additional NSOM phase measurement[19–21] which is out of scope of this letter.

In summary, we demonstrated the design, fabrication, transmission spectrum measurement and near-field characterization of a parabolic tapered high-Q 1D PhC cavity in silicon. The design allows robust device fabrication, as evident by the similar characteristics obtained for several tens of devices that were fabricated and tested. Thus, these 1D PhC cavities may be used as a building block in integrated photonic circuits for optical on-chip interconnects applications. Additionally, our cavities can be designed with or without a layer of silicon dioxide as an upper cladding layer, which makes them promising candidates for active silicon photonics components, e.g., electro-optical modulators and detectors, as well as for the passive devices, e.g., sensors and filters.

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