Tapered Photonic Crystal Microcavities Embedded in Photonic Wire Waveguides With Large Resonance Quality-Factor and High Transmission

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***Abstract*—We present the design, fabrication, and characterization of a microcavity that exhibits simultaneously high transmission and large resonance quality-factor (Q-factor). This microcavity is formed by a single-row photonic crystal (PhC) embedded in a 500-nm-wide photonic wire waveguide—and is based on silicon-on-insulator. A normalized transmission of 85%, together with a Q-factor of 18 500, have been achieved experimentally through the use of carefully designed tapering on both sides of each of the hole-type PhC mirrors that form the microcavity. We have also demonstrated reasonably accurate control of the cavity resonance frequency. Simulation of the device using a three-dimensional finite-difference time-domain approach shows good agreement with the experimental results.**

***Index Terms*—Microcavities, photonic crystal (PhC), photonic wires (PhWs), quality-factor (Q-factor), silicon-on-insulator (SOI).**

I. Introduction

MUCH research has been carried out with the aim of providing faster optical communication and data processing, whether for entertainment, route-switching, or computational purposes. Photonic crystal (PhC) structures are possible contenders for the provision of highly compact devices on a single chip that will allow the realization of complex subsystems. However, reduction of the propagation losses is a major concern for full device functionality—and there are still performance limitations determined by fabrication processes [1], [2]. On the other hand, photonic wire (PhW) waveguides based on silicon-on-insulator (SOI) can also provide strong optical confinement due to the large refractive index contrast between the waveguide core and its surrounding cladding, leading also to small device volumes and compact structures [3]. The manipulation of the refractive index of silicon by means of the thermooptic effect and "electrooptic" effects for compact modulators has been demonstrated in both PhW- and PhC-based devices [4]–[7]. For wavelength-selective devices, single-row PhC structures embedded in PhWs can be employed [8]–[10], with increased transmission being obtained by means of tapering outside the cavity. Compact microcavity optical filters can be produced by inserting a short spacer section between PhC mirrors. Moderately high resonance quality-factor (Q-factor) values are needed for possible applications such as wavelength demultiplexing, nonlinear behavior [11], and all-optical switching [12]. The very high Q-factor values achieved in some recent work [13] are not necessarily useful in practical situations such as dense wavelength-division-multiplexing telecommunications where the channel separation (e.g., 50 GHz) is typically much larger than the full-width at half-maximum (FWHM) of approximately 200 MHz that corresponds to a Q-factor of one million. Recently, Q-factor values as high as 8900 have been obtained for the type of device structure considered in the present letter—by tapering the PhC mirrors inside the cavity, as reported in [14]. This is the highest reported Q for this kind of structure. But the total optical throughput obtained for this resonance condition was not large. Tapering of the hole diameters both outside and within the cavity formed by two PhC mirrors embedded in a PhW can lead to the desirable combination of increased transmission at resonance and enhanced Q-factor, as will be described in this letter. The performance enhancement obtained is partly due to reductions in modal mismatch effects at the interfaces between the unpatterned PhW and the PhC cavity region, as mentioned in [15], [16].

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II. Device Descriptions and Simulations

Planar waveguide microcavities have been realized by means of single rows of PhC holes embedded in 500-nm-wide PhW waveguides based on SOI. The waveguides were formed in a silicon core layer supported by a 1-μm-thick silica buffer layer that provided adequate optical isolation of the waveguide core from the silicon substrate. In order to obtain the high performance required for this particular device, the correct choice of cavity length, hole diameter, and spacing between holes is required. In certain limited ranges of cavity length, a combination of these parameters with the hole transition section designed for maximum transmission for light entering or leaving the periodic section—i.e., with transitions both outside and within the cavity, high transmission on-resonance and high resonance Q-factor can be obtained. The tapered hole sections outside and within the cavity introduced in this letter have two and four aperiodic holes of various diameters and center-to-center

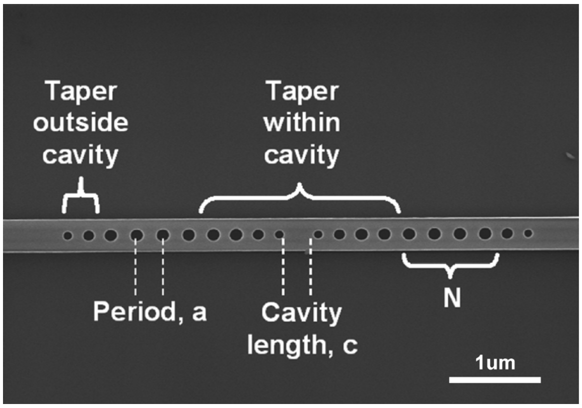

Fig. 1. Scanning electron microscope image of the tapered PhC microcavity embedded on the PhW waveguide with period, a (center-to-center hole distance), cavity length, c (inside length between two hole in the middle of the periodic mirrors), and taper region with a number of aperiodic hole.

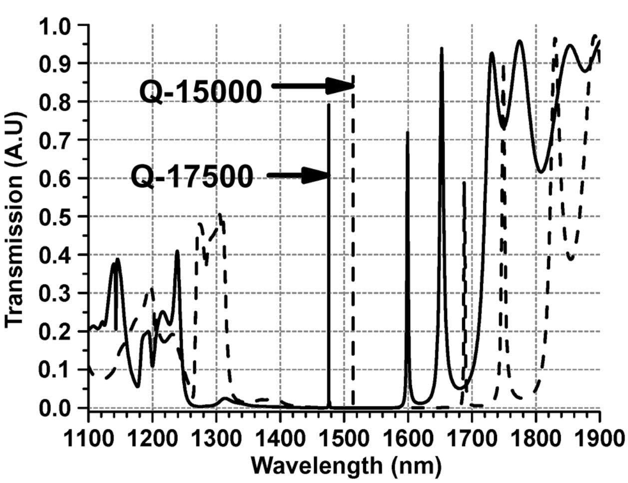

Fig. 2. Transmission spectra of the tapered periodic mirrors with cavity length, $c = 390$ nm (straight line—FWHM ~ 0.08) and $c = 415$ nm (dashed line—FWHM ~ 0.1) using the 3-D FDTD method.

hole distance respectively, as shown in Fig. 1. A three-dimensional (3-D) finite-difference time-domain (FDTD) modeling approach has been used to simulate the device. In this letter, PhC mirror structures consisting of four periods of holes with diameters d of 182 nm and periodicity a of 350 nm were embedded in a 500-nm-wide, rectangular cross-section, silicon PhW with a thickness of 260 nm. In Fig. 1, two sections, each using four aperiodically located and tapering holes within the cavity have been used, with respective hole diameters of 170, 180, 166, and 131 nm—with center-to-center hole distances of 342, 304, 310, and 290 nm, respectively. Although somewhat surprising, our limited observations and simulation have indicated that upwards and downwards variation in hole size, i.e., the use of 180-nm second hole diameter instead of, for example, 168 nm has given slightly larger Q-factor and transmission values. Whereas the two-hole aperiodic tapered sections outside the cavity have hole diameters of 160 and 130 nm, respectively, with center-to-center hole distances of 310 and 290 nm, respectively. Fig. 2 shows the transmission spectra for this design arrangement computed

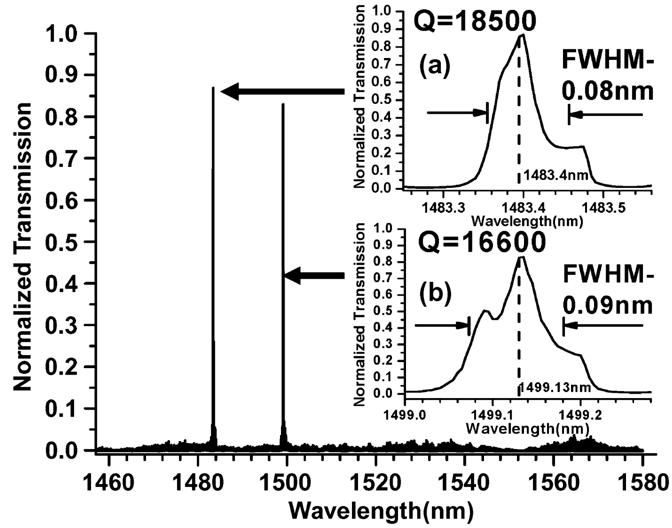

Fig. 3. Measurement result for (a) resonance frequency at $\lambda = 1483.4$ nm for $c = 390$ nm; (b) resonance frequency at $\lambda = 1499.13$ nm for $c = 415$ nm.

using the 3-D FDTD approach, together with cavity lengths, respectively, of $c = 390$ nm and $c = 415$ nm. A Q-factor of approximately 15 000 was calculated, with the impressive transmission value of nearly 90%, at a resonance peak wavelength of 1517 nm, for the $c = 415$ nm cavity. On the other hand, a Q-factor of nearly 17 500, with transmission of around 80% was observed for the $c = 390$ nm case. A shift in the resonance frequency by approximately 30 nm was thus obtained for a 25-nm difference in cavity length.

III. Experimental Results

The devices were fabricated using direct-write electron-beam lithography in a Vistec VB6 machine, together with ICP dry-etching technology. Actual fabricated structures were measured to have ridge waveguides approximately 494 nm wide. The devices were measured using a tunable laser covering the wavelength range from 1.45 to 1.58 μm. TE polarized light was end-fire coupled into and out of the device waveguides—and the optical signal was then detected using a germanium photodiode. The experimental results were normalized with respect to an identical, but unstructured, nominally 500-nm-wide PhW waveguide without any holes embedded in it. Fig. 3 shows the measured transmission spectrum for a tapered PhC microcavity embedded in a PhW waveguide, with cavity lengths of 390 and 415 nm—corresponding to the simulation results given in Fig. 2. The estimated experimental Q-factor values were 18 500 and 16 600, with a measured transmission of around 85%—and these values were obtained at resonance central wavelengths of 1483.4 and 1499.13 nm, with FWHM values of ~0.08 and ~0.09 nm, respectively—see the insets in Fig. 3(a) and (b), which have expanded horizontal scales. The distance between the points of the arrows has been used to obtain, in a reasonably conservative manner, the estimates of the resonance quality factors, via the 3-dB points. The ambiguity in extracting the Q-factors from direct experimental measurements is due to the presence of fine structure superimposed on the resonance of the isolated microcavity. This fine structure is due to the

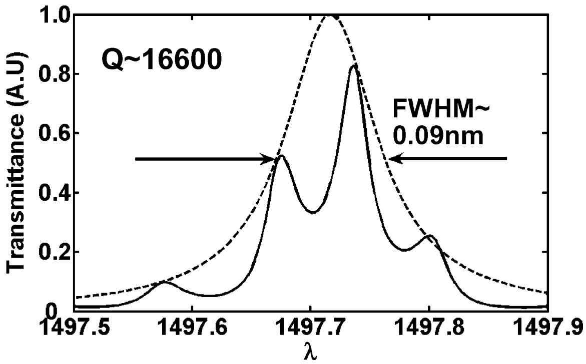

Fig. 4. Examples of transmittance of a microcavity calculated as "isolated" (dashed curves) and embedded in a full length waveguide that matches the experimental dimensions (continuous curves), obtained using a TMM model. The microcavity has the cavity length of $c = 415$ nm corresponding to the experimental result of Fig. 3(b).

Fabry–Pérot cavity produced by the cleaved end-facets of the waveguides. In order to retrieve the Q-factor of the microcavity, a model based on the transfer matrix method (TMM) was also investigated [15], [16]. We have found that a TMM model that matches the experimental dimensions yields a transmission spectrum that remains "enveloped" by the Lorentzian resonance of the microcavity, considered as an isolated device, over a range of plausible Q-factor values (see Fig. 4). Therefore, the determination of the Q-factor by the approach shown in Fig. 3 can be considered as an appropriate procedure.

IV. Conclusion

We have successfully demonstrated that hole diameter and position tapering outside and within the cavity significantly increase the optical transmission and enhance the resonance Q-factor of single-row PhC/PhW microcavities. We have fabricated device structures and shown experimentally that a microcavity formed by correctly spaced tapered PhC mirrors embedded in a PhW waveguide can exhibit a resonance Q-factor value as large as 18 500, together with transmission of more than 80%. The comparison of experimental results with 3-D FDTD simulations shows relatively good agreement, with predicted Q-factor values of between 15 000 and 17 500, together with transmission of more than 80%, at specific cavity lengths. The measured results also show that the resonance peak wavelength can be controlled accurately via the cavity length. We have sought to maximize the Q-factor and transmission of our PhC/PhW microcavities, but have not carried out a systematic optimization process. Given sufficient computational capability, we believe that an algorithmic approach to maximizing performance and obtaining a target resonance wavelength would be appropriate.

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