High-Quality Factor Suspended-Wire 1D Photonic Crystal Micro-cavity in Silicon-on-Insulator

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Abstract. *We present a comparison of high Q-factor tapered membrane-type one-dimensional photonic crystal micro-cavities embedded in photonic wire waveguides based on silicon-on-insulator (SOI). Q-factor values as large as 24,000 have been measured, together with normalized transmission of 67%: an improvement in the Q-factor value in comparison with previous results obtained on structures with silicon cores supported by a silica buffer layer. Simulation using a 3D FDTD approach shows close agreement with measurements.*

Introduction

High quality factor waveguide micro-cavity structures have been a topic of research interest for several years. Hole-based one-dimensional photonic crystal (PhC) micro-cavities embedded in photonic wire waveguides, with a Q-factor value of around 500, were described in [1]. We now report achievement of an experimental Q-factor value as large as 24,000 in an air-suspended photonic-wire waveguide micro-cavity structure - a value that is, to our knowledge, the highest achieved in this particular format.

High Q-factor values have been reported for several different device designs [2,3], but the requirement of achieving high Q-factor values, together with large optical transmission and small modal volumes, has become increasingly important [4]. Recent work based on photonic-wires combined with 1D PhC micro-cavities having silicon waveguide cores supported by a silica buffer layer has achieved Q-factor values in excess of 100,000. Air-suspended membrane-type photonic crystal structures [5], including micro-cavities, have been successfully fabricated and have demonstrated very high cavity Q-factor values, but there are still issues of mechanical stability, robustness and fabrication complexity. The motivation of our work on designing and producing suspended-membrane PhC/PhW waveguide microcavities has been to investigate the impact of increased optical confinement within the waveguides, as well as the effect of possible reductions in the propagation losses.

Design considerations and FDTD simulation approach

Planar one-dimensional photonic crystal micro-cavities embedded in 500 nm wide photonic wire waveguides have been realized recently with Q-factor values of approximately 18,500 - and normalized transmission of nearly 85% [4]. This performance combination was achieved in structures in which the silicon guiding layer was supported by a silica lower cladding or buffer layer. The devices produced are useful for telecommunications applications such as dense wavelength division multiplexing (DWDM) and optical signal processing more generally. Detailed descriptions of the devices can be found in reference [4]. Figure 1 shows an SEM image of a particular device in which the silica cladding underneath the silicon core has been removed - creating an air-bridge type of structure (see the inset in Fig. 1).

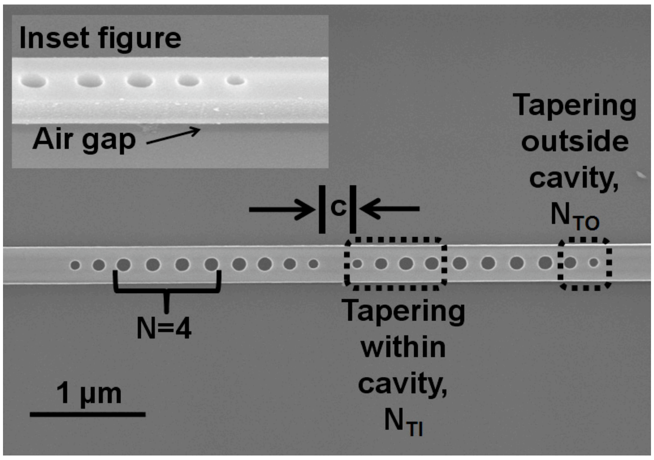

Figure 1: SEM image of an air bridge type of tapered single-row PhC/PhW waveguide with cavity length, c, four hole tapers within the cavity - and two hole tapers outside the cavity. Inset is a bird's eye view (angle ~ 25°) of the suspended PhC/PhW micro-cavities.

The structure consists of two mirrors with four period hole structures separated by a micro-cavity spacer section. Four-hole and two-hole aperiodic tapered structures were inserted within and outside the cavity on each mirror to reduce the modal mismatch between the un-patterned photonic-wire sections and the periodic hole mirror sections. 3D FDTD simulations have been carried out on similar device structures in reference [4] - but with the silica buffer layer having been removed. This device has an N = 4 periodic mirror with hole diameters of 182 nm and periodic spacing between the holes of 350 nm.

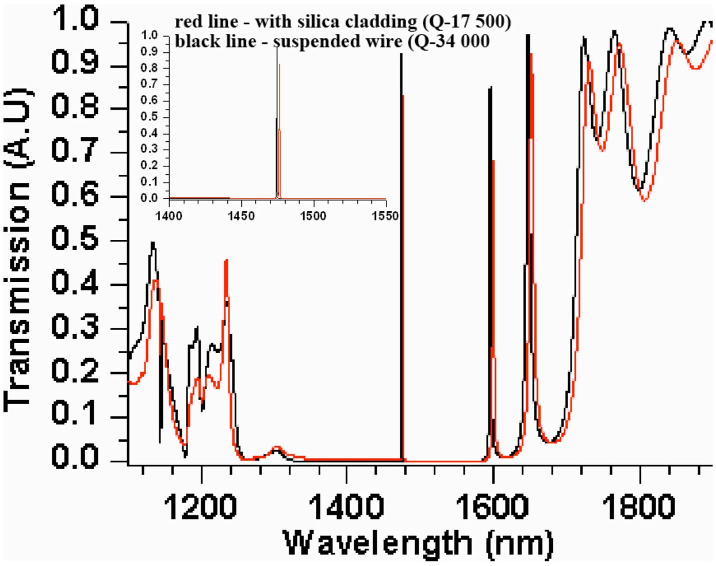

Figure 2: 3D FDTD computed for tapered one-dimensional PhC/PhW micro-cavities embedded in 500 nm photonic wire waveguides with cavity length, c ~ 425 nm for suspended wire (red line) and without removal of the silica buffer lower-cladding layer (black line).

Figure 2 shows a comparison of the transmission spectra for tapered photonic crystal micro-cavities embedded in 500 nm photonic wire waveguides obtained using the 3D finite-difference time-domain (FDTD) approach for both suspended wire structures and ones supported by a silica buffer layer. Our comparison is based on structures in which all of the parameters for the patterning of the silicon waveguide core are the same, i.e. wire width, hole diameters and spacings. The simulations show an increase in the Q-factor value from 17,500 to 34,000 for the suspended wire, in comparison with the value for the structure in which the silica buffer layer remains below the silicon guiding layer. A shift in the resonance frequency, in going from the supported structure to the suspended structure, by approximately -3 nm was also measured for this design arrangement - together with an increase in optical transmission by almost 10%. The shift is due, in particular, to a *reduction* in the effective refractive index of the guided light - thus shifting the resonance towards a shorter wavelength when the silica support layer is removed.

Experimental results

The devices were fabricated using direct-write electron-beam lithography on a Vistec VB6 machine, together with reactive ion-etching. They were characterized using a tunable laser covering the range from 1457 nm to 1580 nm. The TE polarized light was end-fire coupled into and out of the waveguides and was detected using a germanium photo-detector.

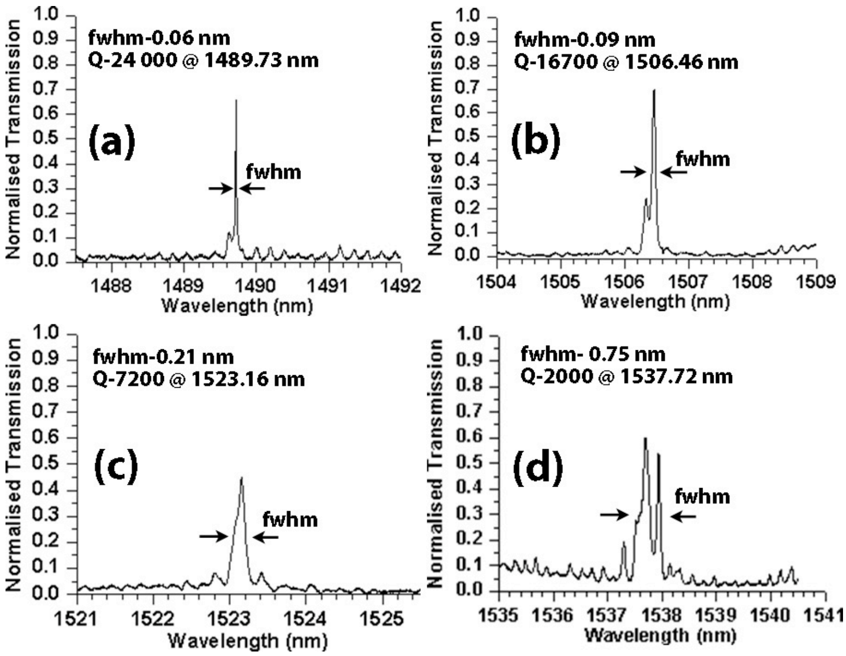

Fig 3:Measurement result for suspended PhC/PhW micro-cavities in a suspended wires with cavity lengths, c (a) 390 nm (b) 415 nm (c) 440 nm (d) 465 nm

Experimental results corresponding to the simulation results obtained using the 3D FDTD approach given in Fig. 2 are shown in Fig. 3.The best experimental Q-factor value - approximately 24 000 - was obtained for a cavity length, c, of 390 nm and at a normalized transmission level of 65%.

Cavity length, c/(nm)	With silica buffer cladding		Suspended wire waveguides	
	Q	*Normalized Transmission*	*Q*	*Normalized Transmission*
390	18 500	0.85	24 000	0.67
415	16 600	0.82	16 700	0.71
440	9 000	0.71	7 200	0.45
465	5 900	0.83	2 000	0.58

Table 1: Comparison of the measured results for the suspended wire waveguides and the one with silica cladding still exist underneath the wire waveguides

As the cavity length was increased from 390 nm to 465 nm, the Q-value decreased to 2000, together with a reduction in the normalized optical transmission level. Table 1 gives the results for the structures shown in Fig 1, in comparison with our previous results – obtained without removal of the silica buffer layer.

Conclusions

We have successfully demonstrated a further enhancement of the PhC/PhW cavity Q-factor value, from 18,500 to approximately 24,000, using the membrane type of structure - at a cavity length of 390 nm - for one of our design arrangements. This value is somewhat lower than the value of 34,000 predicted in the corresponding simulation. Discrepancies between simulation and measurement are probably attributable to imperfections in the fabrication processes. We believe that high Q-factor values, possibly up to more than 500,000, will be achievable if the correct combination of the number of periodic mirror holes, cavity length and aperiodic hole tapering within and outside the cavity is used. The enhancement in the Q-value in this particular design is due to the increase in the optical confinement – thus enhancing the field intensity of the mode confined within the micro-cavity. The effective refractive index changes due to the air gap underneath the silicon guiding layer have also produced a shift in the resonance frequency by approximately 3 nm. The 3D FDTD approach used to simulate the devices has shown reasonably close agreement with the measured results.

References

[1] J.S.Foresi, P.R.Villeneuve, J.Ferrera, E.R.Thoen, G.Steinmeyer, S.Fan, J.D.Jonnopoulos, L.C.Kimmering, H.I.Smith and E.P.Ippen,"Photonic-bandgap micro-cavities in optical waveguides",Nature 390, 143 (1997).

[2] T.Asano, B.S.Song, S.Noda," Analysis of the experimental *Q* factors (~1 million) of photonic crystal nanocavities", Optics Express **14**, 1996-2002 (2006)

[3] P. Velha, E. Picard, T. Charvolin, E. Hadji, J. C. Rodier, P. Lalanne and D. Peyrade, 'Ultra-High Q/V Fabry-Perot microcavity on SOI substrate', *Optics Express*, **15** (24), 16090-16096, 26th November (2007).

[4] Ahmad Rifqi Md Zain, Marco Gnan, Harold M. H. Chong, Marc Sorel and Richard M. De La Rue, "Tapered Photonic Crystal Microcavities Embedded in Photonic Wire Waveguides With Large Resonance Quality-Factor and High Transmission', *IEEE Photonics.Technology Letts*, **20**(1), 6 – 8, 1st January (2008).

[5] L.O.Faolain, X.Yuan, D.Mcintyre, S.Thoms, H.M.H.Chong, R.M. De La Rue and T.F.Krauss,"Low loss propagation in photonic crystal waveguides", Electronics Letters, 42 (25), December (2006).