# Ultra high quality factor one dimensional photonic crystal/photonic wire micro-cavities in silicon-on-insulator (SOI)

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**Abstract:** We present experimental results on photonic crystal/photonic wire micro-cavity structures that demonstrate further enhancement of the quality-factor (Q-factor) - up to approximately 149,000 - in the fibre telecommunications wavelength range. The Q-values and the useful transmission levels achieved are due, in particular, to the combination of both tapering within and outside the micro-cavity, with carefully designed hole diameters and non-periodic hole placement within the tapered section. Our 2D Finite Difference Time Domain (FDTD) simulation approach shows good agreement with the experimental results.



**OCIS codes:** (130.0130) Integrated optics; (250.5300) Photonic integrated circuits; (230.5298) Photonic crystal;

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#95897 - $15.00 USD Received 7 May 2008; revised 21 Jul 2008; accepted 21 Jul 2008; published 28 Jul 2008

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## 1. Introduction

It has been of major interest in recent research to produce faster optical processing for many telecommunications applications and other applications of high performance optoelectronics. The combination of one-dimensional photonic crystal structures (PhC) in narrow photonic wire (PhC) waveguides in high refractive-index contrast materials such as silicon-on-insulator (SOI) is one of the main contenders for provision of many compact devices on a single chip. This development is due to the ability of silicon technology to support monolithic integration of optical interconnects and form fully functional photonic devices incorporated into CMOS chips. The high index contrast of the combination of a silicon core with a surrounding cladding of silica and/or air provides strong optical confinement, leading to the realization of more compact structures, small device volumes, sharp bends, abrupt Y-junctions and Mach Zehnder structures [1-6]. On the other hand, the manipulation of the refractive index of silicon by means of the thermo-optic effect and 'electro optic' effects for compact modulators has also been demonstrated in both PhW- and PhC-silicon based devices [7, 8]. The large thermo-optic coefficient of silicon is a key point for the design of optical modulators that exploit the thermo-optic effect. In order to obtain a wide range of device functionality, the reduction of propagation losses in narrow wires is equally important, although there are still performance limitations determined by fabrication processes [9]. Recently losses as low as 0.92 dB/cm for a very narrow wire have been reported [10] through the use of hydrogen silsesquioxane (HSQ) resist and a reduction, through stage-tilt compensation techniques, of stitching errors produced during the electron-beam lithographic patterning process [11]. Compact single-row PhC structures embedded in PhW waveguide micro-cavities are essential components for wavelength selective devices, especially for possible application in WDM systems. The high quality factor and confinement of light in small volume, V, are important for optical signal processing and filtering purposes, implying large Purcell factor values. Early work by Foresi et.al [12] demonstrated micro-cavity operation with two identical periodic hole mirrors embedded in a suspended photonic wire type waveguide - and a quality-factor (Q-factor) value of 500 was obtained. Since then, large increases in Q-factor have been obtained by tapering carefully within the cavity, thereby reducing modal mis-match effects at the interfaces between the PhC mirrors and the cavity space section [13, 14]. At the same time, it has been shown that the length of the cavity spacer section must be adjusted precisely to obtain the best results. A growing interest in designing high-Q, photonic crystal and photonic wire embedded photonic crystal micro-cavities has therefore emerged [15-17], although only moderately high Q-factor values, such as ~18,700, together with sufficiently large transmission, approximately 85% in our case [18], are sufficient for possible applications such as Dense Wavelength Division Multiplexing (DWDM) - and non-linear optical functionality such as all-optical switching.

In this report, we demonstrate the enhancement of the Quality factor value through the combination of tapering within the cavity and also outside the cavity. For specific cavity design parameters, we have then demonstrated that a usefully large optical transmission level can be obtained. In one case, we have made a comparison of using different numbers of holes in the tapered sections on the outsides of the cavity. The Q- factor value, and the transmission level have also been estimated using a 2D FDTD computational approach.

#95897 - $15.00 USD Received 7 May 2008; revised 21 Jul 2008; accepted 21 Jul 2008; published 28 Jul 2008

## 2. Design optimizations and 2D FDTD approach

We have realized planar 1D PhC/PhW micro-cavity structures consisting of a single row of PhC holes embedded in 500 nm wide photonic wire waveguides based on SOI The waveguides were formed in a 260 nm thick silicon core layer supported by a 1µm-thick silica buffer layer that provided adequate optical isolation of the waveguide core from the silicon substrate. These devices were designed for TE polarization. In order to obtain the required high performance in this device, the correct choice of cavity length, the hole diameters and the combination of periodic and aperiodic hole spacing is necessary.

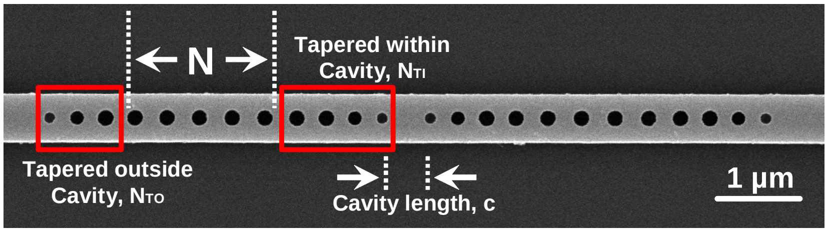


Fig. 1. Scanning electron micrograph (SEM) image of the tapered PhC micro cavities embedded in PhW waveguide with N number of periodic mirrors, cavity length, c (inside length of the two hole in the middle of the periodic mirrors) and aperiodic mirrors forming the tapered section where $N_{TI}$ is the number of hole for tapered within cavity section and $N_{TO}$ is the number of hole outside the cavity.

Tapering within and outside the cavity through the use of holes of different diameters and aperiodic spacing has been used to enhance the Q-factor, while simultaneously maintaining a useful optical transmission level – i.e. the tapered period and hole diameter transition sections, both outside and within the cavity, were designed to maximize the transmission for light entering or leaving the periodic mirror sections. Tapering outside cavity has an impact primarily to increase the optical transmission.

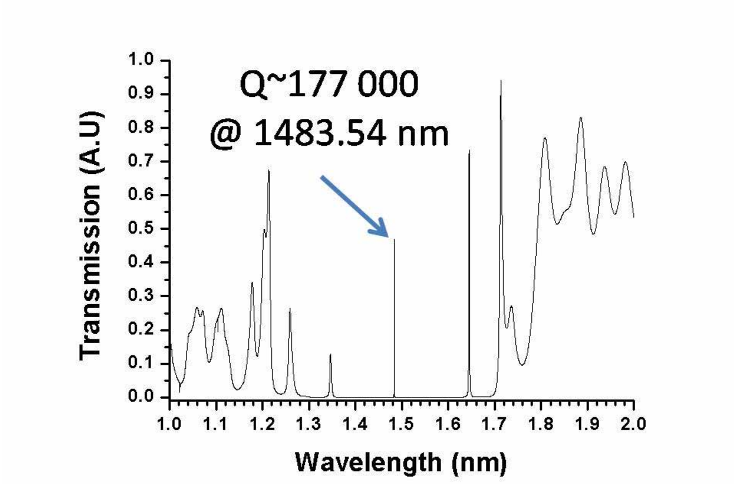


Fig. 2. Transmission spectra for N = 5 with $N_{TI}$ = 4 and $N_{TO}$= 3 using 2D FDTD approach with Q of approximately 177 000 at resonance frequency of 1483.54 nm at cavity length, c of 425 nm.

In this paper we report the use of mirrors having N = 5 periodically spaced holes with diameters of 182 nm and a periodic centre-to-centre spacing of 350 nm. A scanning electron micrograph (SEM) image of a typical cavity is presented in Fig. 1. The figure shows a 500 nm width photonic wire micro-cavity formed by two mirrors, each of which includes five periodically spaced PhC holes, N of same diameter. Gradually tapered hole arrangements are used, with different diameters and aperiodic spacing designed to produce a significantly enhanced Q-factor value through reductions in propagation losses and scattering that occur locally at transitions within and outside the cavity. Such tapered hole arrangements are made to reduce losses associated with abrupt changes in the modal distribution at the interfaces between the periodic mirror sections and the wire waveguide outside the micro-cavity region, as well as the spacer section within the cavity. Four-aperiodically located and tapered holes form the transition sections within the cavity - and have diameters of 170, 180, 166, and 131 nm respectively — with center-to-center hole distances of 342, 304, 310, and 290 nm respectively. - whereas the three-hole aperiodic tapered sections outside the cavity have hole diameters of 131, 166 and 185 nm respectively, with center-to-center distances of 275, 305 and 314 nm respectively. A 2D FDTD approach has been used to simulate the device. Figure 2 shows the transmission spectra for this design arrangement, computed using a 2D FDTD approach and assuming a cavity length of ~425 nm. A Q-factor of 177 000 was computed at a resonance wavelength of 1483.54 nm, with a transmission level of approximately 48% at this particular cavity length.

### 3. Fabrication and optical characterization of the micro cavities

The waveguide patterns were defined using an approximately 200 nm thick layer of hydrogen silsesquioxane (HSQ) negative-tone resist. The devices were fabricated using single-step direct-write electron beam lithography in a Vistec VB6 machine at 100 keV electron energy, with proximity correction at a base dose of 1500 $\mu C/cm^2$. This VB6 beam writer has the capability of writing a 1.2 mm by 1.2 mm field at 1.25 nm resolution. In addition, extra care has to be taken to reduce the potentially significant impact of field stitching errors on the pattern produced - i.e. to ensure the flatness of the sample during the writing process. The patterns were finally transferred into the silicon guiding layer by using an inductively coupled plasma (ICP) reactive ion etching process. $SF_6/C_4F_8$ combined chemistry was used to etch the silicon layer, contributing to obtain silicon waveguides with smooth side-walls. The devices were characterized using a tunable laser that was capable of covering the wavelength range from 1.45 μm to 1.58 μm with the spectral resolution of 1 pm measurement step.

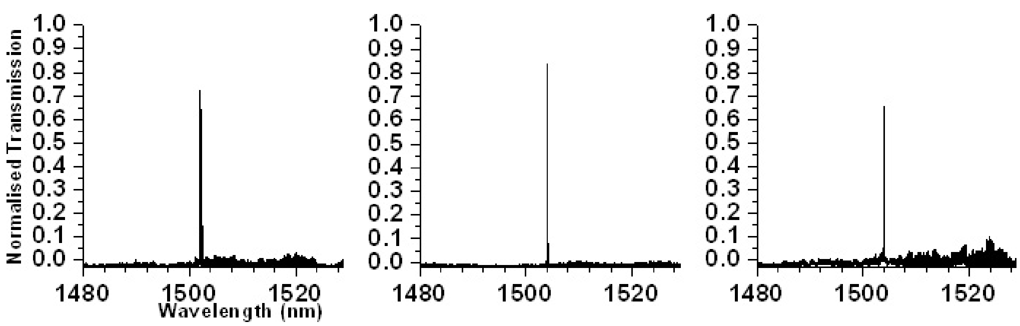


Fig. 3. Transmission spectra for N = 4 and $N_{TI}$ = 4 with (a) $N_{TO}$=1 (b) $N_{TO}$=2 (c) $N_{TO}$=3 – with a cavity length, c = 450 nm.

TE polarized light was end-fire coupled into and out of the device waveguide - and the optical signal was detected using a germanium photodiode. The experimental results were normalized with respect to an identical, but unstructured, 500 nm wide wire waveguide without any holes embedded in it. Figure 3 shows measured results for N=4, $N_{TI}$=4 with a different number of holes used in the tapered section outside the cavity. $N_{TO}$ varies from one to three while retaining a cavity spacer length, c, of 450 nm. The measured Q-factor values were 8000, 21500 and 19000 respectively, with normalized transmission values of 73%, 83% and 65% respectively. It shows that for N=4, the highest Q factor achieved was obtained with $N_{TO}$=2.

#95897 - $15.00 USD Received 7 May 2008; revised 21 Jul 2008; accepted 21 Jul 2008; published 28 Jul 2008

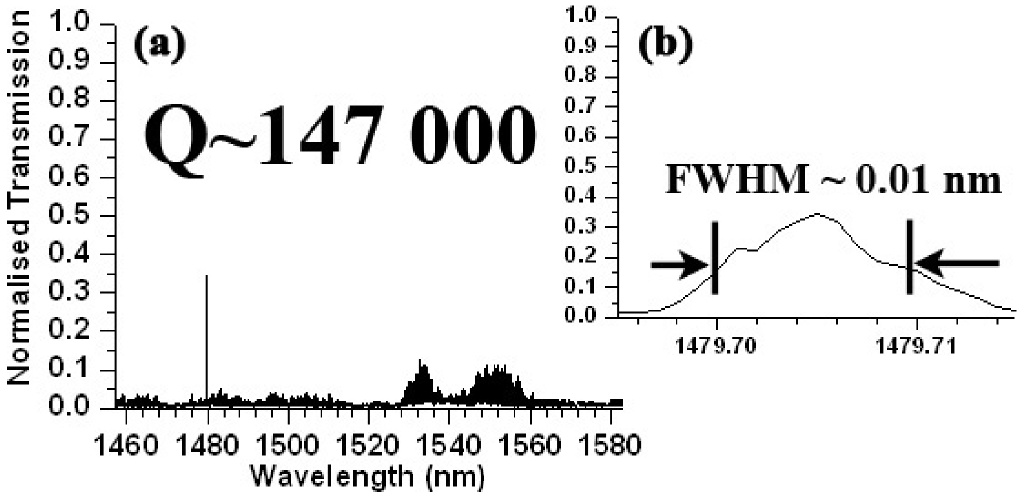


Fig. 4. Measured transmission spectra for N = 5 with $N_{TI}$ = 4 and $N_{TO}$= 3 corresponded to simulation result in Fig. 2 with Q of approximately 147 000 at resonance frequency of 1479.705 nm.

Further enhancement of the Q-factor value has been obtained through the use of N=5, together with three hole aperiodic tapering outside the cavity and $N_{TO}$ as shown in Fig. 1. Figure 4 shows the measured transmission spectrum of the device with a cavity length of 425 nm - corresponding to the simulation result in Fig. 2, with $N_{TO}$ = 3. The estimated experimental quality factor value of ~147 000 was at the resonance wavelength of 1479.705 nm, with full width half maximum (FWHM) of ~ 0.01 nm- see inset in Fig. 4(b). A normalized transmission of approximately 34% has been measured for this particular resonance. The effect of Fapy-Perot (FP) ripple in Fig. 4(b) is clearly small.

Table 1. Comparison of Simulated and Experimental value of different taper outside cavity, $N_{\mathbf{TO}}$ for N=5 and $N_{TI}$=4

| | Simulation | | Experimental | |
|---|---|---|---|---|
| $N_{\mathbf{TO}}$ | *Q* | *Tx* | *Q* | *T(N))* |
| 1 | 65000 | 0.72 | 51000 | 0.65 |
| 2 | 95000 | 0.69 | 79000 | 0.52 |
| 3 | 177000 | 0.48 | 147000 | 0.34 |
| 4 | 74000 | 0.35 | 62000 | 0.25 |

Substantially higher normalized transmission coefficient values have been measured, in conjunction with the somewhat smaller Q-factor value of 79 000 for the particular device with $N_{TO}$=2, as shown in Table 1. This table also shows a comparison of the simulation and measured results for N=5 and $N_{TI}$=4, using different numbers of holes in the tapered sections outside the cavity, $N_{TO}$. In this particular design, a reduction in optical transmission is observed with additional hole taper sections outside the micro-cavity, together with a significant enhancement in the Q-factor value. This result is probably due in part to the increase in the length of the device, including the aperiodic tapered hole sections that contribute to the increased propagation losses. Although we have also looked at more

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extended cavities that have longer spacer lengths, the present design retains the use of a short cavity that has a spacer section that is shorter than an optical wavelength in the medium. The Q-factor achievable is strongly dependent on the number of holes in the tapered sections outside the cavity, together with the length of the cavity spacer section. With a Q-factor of 147 000 and a modal volume of approximately 0.02 ($\lambda^3$), Purcell factor values greater than 10 000 are attainable with the present cavity. Such values are comparable with the highest values obtained in previous work. [19]

## 4. Conclusions and discussions

We have successfully demonstrated substantial further enhancement of the quality factor value achieved in one dimensional PhC/PhW micro-cavities based on silicon-on-insulator. A high Q-factor value (approaching 147 000), together with a useful transmission level of 34%, has been measured at a cavity spacer length of 425 nm. It should be noted that this performance has been obtained in structures with a supporting lower cladding. Further device enhancement is possible through more attention to the design of the tapered sections, together with the use of a larger number of holes in the periodic parts of the cavity mirrors. This combination will contribute increases in both the Q-factor and the transmission coefficient.

## Acknowledgements

The authors would like to acknowledge financial support through the ePIXnet European Community project and Universiti Teknologi Malaysia (UTM) Skudai, Johor, Malaysia.