# Design and Fabrication of High Quality-Factor 1-D Photonic Crystal/Photonic Wire Extended Microcavities

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***Abstract*—We have successfully demonstrated experimentally the fabrication and measurement of high quality-factor one-dimensional photonic crystal/photonic wire extended cavities based on silicon-on-insulator. The cavities that we have investigated ranged from 3 to 8 $\mu$m in length. A quality-factor of nearly 74 000 was measured at a cavity length of 5 $\mu$m through the use of tapering both within and outside the cavity, showing good agreement with the finite-difference time-domain simulation approach used.**

***Index Terms*—Integrated optics, photonic crystals (PhCs), photonic wires (PhWs), silicon-on-insulator (SOI).**

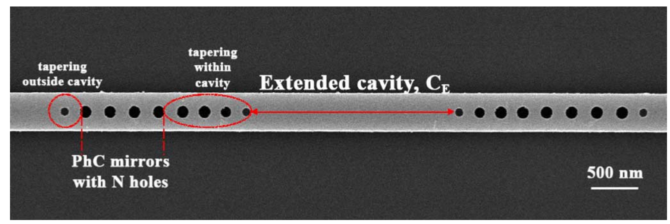


Fig. 1. Scanning electron micrograph (SEM) image of a 1-D PhC/PhC with extended cavity, $C_E$ covering from 2 to 8 $\mu$m with periodic mirrors, $N = 4$ and tapering hole outside and within cavity of $N_{\rm TI} = 4$ and $N_{\rm TO} = 1$.

## I. Introduction

PHOTONIC crystals (PhCs) are periodic structures that are known to be capable of controlling the propagation of light through a medium [1], [2]. They have became a promising platform for realizing photonic integrated circuits (PICs), reducing the size and power requirements of the optical components—with the aim of achieving monolithic integration on a single chips becoming the main target. Photonic wires (PhWs) based on high index contrast material such as silicon-on-insulator (SOI) can also provide high optical confinement. Two-dimensional (2-D) PhC devices have been demonstrated in applications such as beam-splitters, couplers, lenses, and power dividers [3], [4]. One-dimensional (1-D) PhC/PhW structures can provide useful characteristics in the design of devices with smaller size and higher $Q$-factor [5]–[9]. High $Q$-factor values have been achieved through careful design of the details of the microcavity design. But designing devices with longer spacer sections—such as extended cavities and multiple microcavities—gives desirable additional freedom in choosing the resonance wavelength of interest through the multiple resonances excited within the stop-band. Tapering with holes of different diameters and spacing may be used to reduce the modal mismatch between the unpatterned wire waveguide and the periodic mirror sections both within and outside the microcavity structure. Useful performance can be achieved through the use of 1-D PhC/PhW extended cavity structures where the microcavities that have been reported are further extended by several micrometers in cavity length—covering, in the present work, the range from 2 to 9 $\mu$m. Multiple resonances have been excited within the transmission band-gap. These multiple resonances can be controlled through variation of parameters such as the cavity length and hole dimensions. This design has considerable potential for practical applications such as wavelength-division multiplexing (WDM) in telecom applications. A waveguide with a Fabry–Pérot (FP) cavity formed by a several-micrometer-long spacer section between two mirrors has been realized in 2-D PhC structures [10], [11]—where one of several longitudinal (axial) modes of the cavity can be selected to match the operating wavelength required, i.e., to fall within the range of 1520–1580 nm required for typical WDM applications, switching purposes, and nonlinear optics. The large free spectral range (FSR) between the resonances excited means that such structures have the capability of tuning the resonances through thermo-optical effects where, for example, heating the silicon waveguide to approximately 300 °C should be sufficient to scan the resonance across the whole wavelength available within that range. In addition, through the use of the correct choice of tapering both within and outside cavity, it can be expected that enhancement of the $Q$-factor value—together with obtaining large optical transmission—will be possible, implying that viable scanning channel-drop filter devices could be produced.

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## II. Design Considerations and FDTD Approach

The proposed design, which consists of a single row of PhC holes embedded in a narrow (500 nm wide) PhW waveguide based on SOI material, is shown in Fig. 1. The waveguide devices were formed in a 260-nm-thick silicon core layer supported by a 1-$\mu$m-thick silica cladding as a buffer layer. In order

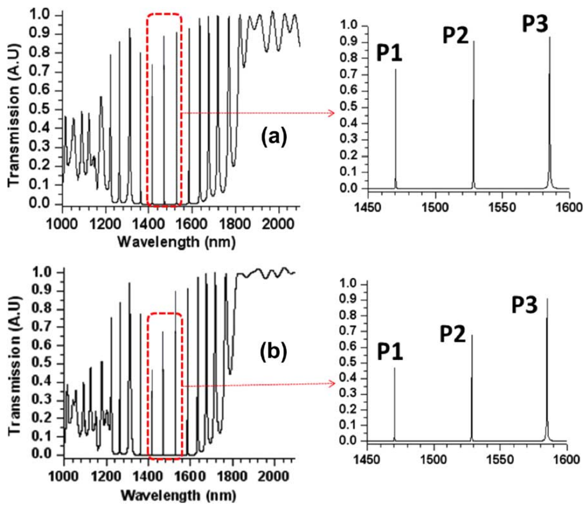


Fig. 2. 2-D FDTD simulation approach for 5-$\mu$m-long extended cavity with tapering within the cavity and (a) with tapering outside the cavity, (b) without tapering outside the cavity.

TABLE I
COMPARISON OF 2-D FDTD APPROACH SHOWING THE EFFECT OF TAPERING WITHIN AND OUTSIDE CAVITY IN THE $Q$-VALUE AND OPTICAL TRANSMISSION FOR $C_E = 5\ \mu$m

| | Q-factor w/o \| both \| w/TI | Optical Transmission (%) w/o \| both \| w/TI |
|---|---|---|
| P1 | 800 \| 97,000 \| 51,000 | 35.1 \| 72.9 \| 46.3 |
| P2 | 760 \| 25,300 \| 8,600 | 38.3 \| 91.1 \| 67.5 |
| P3 | 320 \| 8,000 \| 3,900 | 43.8 \| 92.7 \| 90.5 |

Note: w/o—without hole tapering, w/TI—with tapering within cavity, both—using both tapering within and outside cavity

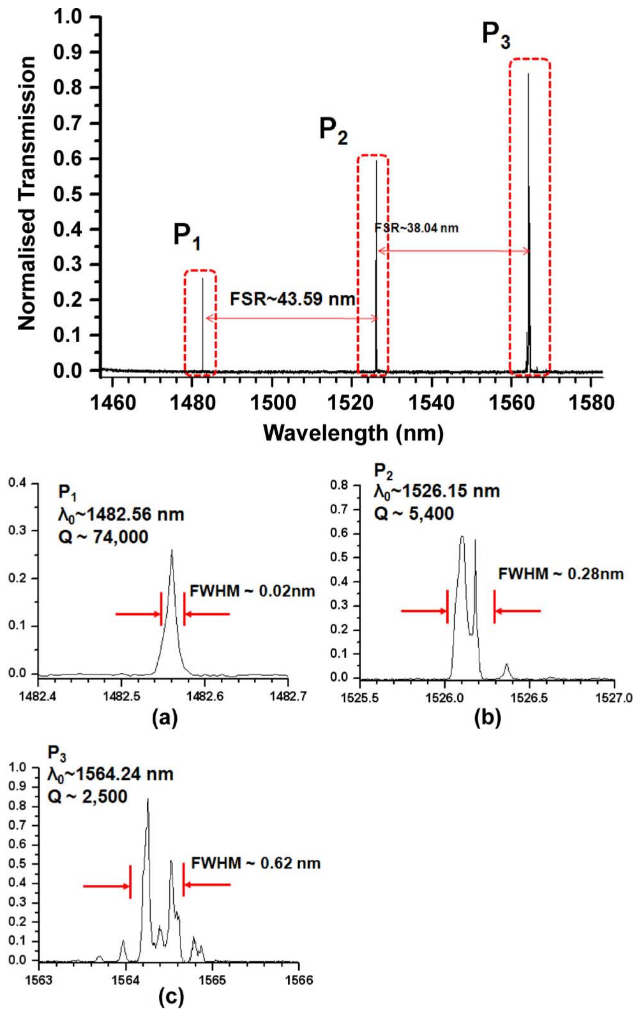


Fig. 3. Measurement result for ultrahigh $Q$ extended cavity of $c = 5.0\ \mu$m with resonance (a) $P_1$, (b) $P_2$, and (c) $P_3$.

to obtain a high-performance device, tapering of the hole patterns, both within and outside the cavity, have been used, as shown in Fig. 1. The tapered hole sections outside and within the cavity had one and four aperiodic holes, respectively, with different diameters and spacings. In this particular case, a 2-D finite-difference time-domain (FDTD) approach has been used to simulate the device, with the results shown in Fig. 2, where the highest predicted $Q$-factor value of approximately 97 000 and normalized optical transmission of 72.9% were obtained at a cavity length (defined by the inside hole edge-to-edge distance) of $C_E = 5\ \mu$m, using tapering both within and outside the combined cavity structure, as shown in Fig. 2. This predicted performance combination is the best so far reported, to our knowledge, for this particular design arrangement, where enhancement results, in particular, from using tapering both within and outside the cavity. Table I shows results obtained by using a 2-D FDTD approach to compare the $Q$-factor and optical transmission for our configuration—i.e., without a hole taper (w/o) and with only a single reduced size hole within the cavity (w/TI). The tabulated results show a substantial enhancement, especially in the $Q$-factor value, as aperiodic hole taper sections are introduced in order to match the Bloch modes of the periodic mirrors with the fundamental mode arriving from the unpatterned PhW waveguide [13–14].

## III. FABRICATION AND LINEAR CHARACTERIZATION

The devices were fabricated using the direct-write approach in a Vistec VB6 electron beam lithography (EBL) tool. They were then etched using ICP dry etching technology. The pattern was transferred using a single layer of hydrogen silsesquioxane (HSQ) and etched using a combination of $CHF_3$ and $S_2F_8$. The devices were finally characterized using a tunable laser covering the range from 1457 to 1583 nm, with a central wavelength of around 1520 nm. TE polarized light was end-fire coupled into the 2-$\mu$m-wide feeder waveguide and adiabatically tapered into a 500-nm-wide PhW waveguide. At the other end, the optical signal was then detected using a germanium photodiode. The experimental results were normalized with respect to an identical but unstructured 500-nm wire without any PhC holes embedded in it. Fig. 3 shows an experimental result obtained corresponds to the simulation result shown in Fig. 2 with $C_E = 5\ \mu$m. By using tapering both within and outside the cavity, the measured resonance of approximately 74 000 at the resonance wavelength of 1482.56 nm and FWHM $\sim$ 0.02 nm have been obtained. In addition, the ambiguity in extracting the factors from direct experimental measurements is due to the presence of fine structure superimposed on the resonance of the

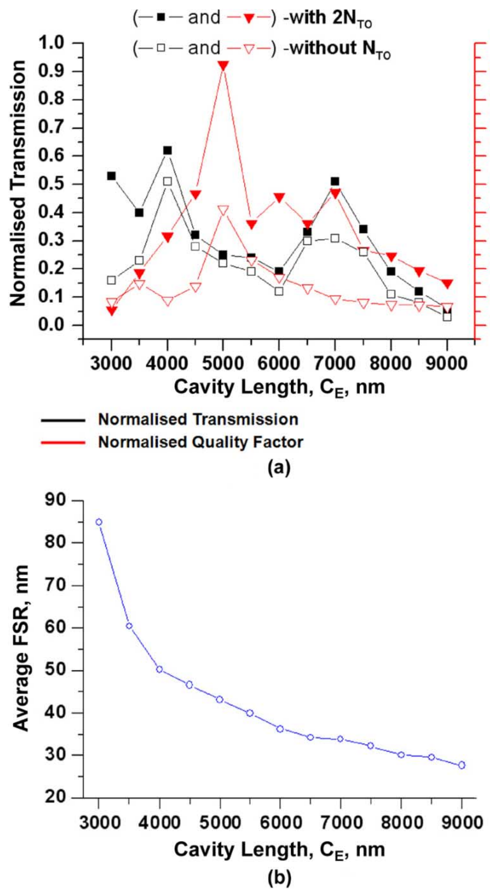


Fig. 4. (a) Comparison of $Q$-factor against normalized transmission of an extended cavity length $C_E$ ranging from 3 to 9 $\mu$m for different hole tapered arrangement for $N_{\rm TI} = 4$. (b) Graph showing the average FSR value at each cavity conditions.

isolated cavity. This fine structure is due to the FP cavity produced by the cleaved end-facets of the waveguides. The FSR between adjacent resonances was measured to be approximately 43.59 nm. Fig. 4 shows a comparison of the normalized transmission and $Q$-factor values for different cavity lengths ranging from 3 to 9 $\mu$m. Different configurations of the number of aperiodic holes used in the tapering outside the cavity have been investigated—mainly a two-hole taper structure with mirrors having four periodically spaced holes on each side of the cavity and $N_{\rm TI} = 4$—and compared with the results obtained without using any tapered hole structure outside the cavity. Fig. 4(a) shows that a combination of tapering within and outside the microcavity, together with the correct choice of hole diameters and spacing, has a significant impact on the objective of achieving large $Q$-factor values, together with high optical transmission, in the extended cavity arrangement. For easier understanding of its characteristics, the overall performance of this device is illustrated in Fig. 4(a)—which is based on the highest value obtained at resonance for each cavity condition. Most of the $Q$-factor and transmission values measured were located at wavelengths in the range from 1475 to 1510 nm, which correspond to the resonances of $P_1$ or $P_2$. For simplicity, only the highest resonance $Q$-factor value and normalized transmission value are considered for each cavity condition. On the other hand, the largest normalized experimental transmission value of more than 60% was measured at a cavity length of 4 $\mu$m, but the $Q$-factor at this resonance condition was smaller, at 45 000, for the case where tapering was used both within and outside the cavity ($N_{\rm TI} = 4$, $N_{\rm TO} = 2$). Above all, the use of both tapering outside and within the cavity has led to large improvements, as compared to results obtained without any hole tapering outside the cavity. In addition, the FSR between resonances for each cavity condition decreased inversely, as expected, as the cavity length was increased, as illustrated in Fig. 4(b).

## IV. Conclusion

We have successfully demonstrated experimentally important characteristics of 1-D PhC/PhW extended cavities, in particular for wavelength tuning purposes. Such devices could be useful for WDM applications, optical switching and nonlinear optics, where resonance at a particular wavelength is desired. In the present work, we have measured a $Q$-factor of approximately 74 000 at one of the cavity resonance conditions, together with a reasonably large optical transmission. This $Q$-factor value was achieved through the use of tapering both within and outside the cavity arrangement. A reduction in the FSR values is also observed at larger extended cavity lengths.

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