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Free Spectral Range (FSR) control of a high quality factor - 1D Photonic Crystal (PhC) extended cavity

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Abstract

In this paper we report the consistency in controlling the Q-factor value ranging from 1000 to 80,000 together with good free spectral range (FSR) control between the resonance frequencies of between 30 nm to 62 nm of a long cavity based on SOI. The cavities that were considered in this paper ranged from 2 µm to 6 µm in length. The Q-factors for each resonance obtained for that particular extended cavity were measured in different occasion which has 5% variation in the Q-value over a period of times. We expect that the removal of Silica cladding underneath the silicon waveguide will enhance the Q-value due to better optical confinement within the waveguide.

1. Introduction

The PhC device is a periodic structure that capable to control light passing through the medium [1]. Thus it became one of the contenders as a platform in realizing the Photonic Integrated Circuits (PIC), which can reduce the power and size

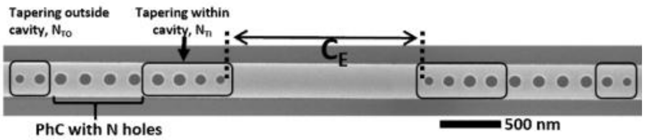

Fig. 1 SEM image of a long/extended cavity with the cavity length, C_E

requirement in the optical components. Among several applications, one of the capabilities that PhCs device can provide is through their selectively manage several wavelengths [2,3]. Reducing the modal mismatch between un-patterned wire waveguide and the periodic mirror section (N), both within and outside cavity (N_{TI} and N_{TO}) structure [4] is somewhat necessary by using holes of different diameters and spacing in order to enhance the device performance. One Dimensional PhC nano-beam device can offer extra freedom for designing a more complex device especially the one which has smaller footprint. Thus, 1D PhC extended cavity became a promising candidate where the multiple resonances were excited within the band-gap. It also shows that the device can be measured repeatedly and can be reproduced giving a consistent values of Q-factor together with the optical transmission.

2. FDTD simulation, Fabrications and Characterisations

A design of a 1D PhC/PhW with extended cavity were realized in 500 nm wide PhW waveguide with a cavity length of between 1 µm to 6 µm. At a particular choice of a cavity length and hole transition sections within and outside the cavity- high optical transmission and reasonably high resonance Q-values can be achieved as already reported in [2] as light entering or leaving the periodic sections. The design consists of two sections for each section consists of four tapering holes with aperiodically

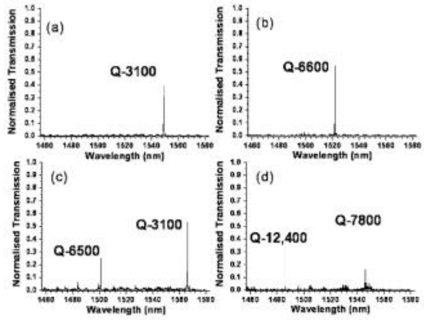

Fig. 2 Measurement result for extended cavity for (a) 2 µm (b) 2.5 µm (c) 3 µm (d) 3.5 µm

located within the cavity. The tapering hole within the cavity section have a hole with diameters of 170 nm, 180 nm, 166 nm and 131 nm – and centre-to-centre hole distances of 342 nm, 304 nm, 310 nm and 290 nm, respectively. On the other hand, a two aperiodic tapered hole were used in the tapering outside the cavity section with hole diameter of 166 nm and 130 nm- and centre-to-centre hole distances of 290 nm and 310 nm respectively. This design were generated and simulated using Finite Difference Time Domain (FDTD) approach showing good agreement with the measured results. The patterns were transferred into the silicon substrate using a VB6 Vistec precision electron-beam lithography (EBL) machine with negative tone HSQ resist as a mask. The PhW waveguides were etched using Inductively Coupled Plasma (ICP) dry etching to remove unwanted silicon areas. The devices were then measured using a tunable laser covering the wavelength range from 1.45 µm to 1.58 µm. 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.2** shows the measured results for extended cavities with lengths in the range 2 µm to 3.5 µm for the case where only tapering outside cavity were considered. The highest Q-value of approximately 12,400 was obtained with a cavity length of 3.5 µm situated at a resonance wavelength of 1485.62 nm- as shown in **Fig.2 (b)**. Free Spectral Range (FSR) of the resonances was measured as 65 nm whereas, at the cavity length of 3.5 nm, the FSR is reduced to approximately 61 nm. From our observation, multiple resonances within the mirror stop-band wavelength range are only obtained at cavity lengths longer than 3 µm. A Q-factor value of nearly 16,000 has been measured at a cavity length of 3.5 µm with a normalized transmission of around 55%. Initial works were carried out to produce high Q extended cavity device structure. The resonance Q-factor value ranging from 1,500 to 74,000 have been measured as shown in **Table 1** for the cavity length ranging from 4.0 µm to 6.0 µm. The resonance P_1, P_2, P_3 and P_4 were initially measured. After several months, second measurement were taken using different sample and the result were showed by P_1', $P_{2'}$', P_3' and P_4' showing some improvement in Quality factors. These results also show that the measured results that were obtained have good repeatability with consistent results. In addition, we have also shown that for the case of the extended cavity where the micro-cavity were extended to several microns ranging from 4 µm to 6 µm, the result can be repeated and reproduced while preserving the high Q-factor value. was also observed in the extended-cavity case as for the small spacer length micro-cavity structures described in [2].

Table 1. Comparison of a measured transmission spectra for extended cavities ranging from 4 µm to 6 µm for different measurement runs within a 6 months period using different samples with identical structures.

Cavity length, c/µm	Resonance Q-Factor		
	P_1/ P_1'	*P_2 P_2'*	*P_3 P_3'*
4.5	37,400 / 48,000	4000 / 11,000	-
5.0	74,000 / 68,,000	2400 / 7800	1500 / 3200
5.5	29,000 / 37,000	12,600 / 13,200	3,300 / 5200
6.0	36,500 / 41,500	18,700 / 21,100	4,000 / 7,000

4. Enhancing the Extended Cavities

Further enhancement of Q and the normalized transmission can be achieved through the removal of silica cladding underneath the silicon core as being reported in [5] for the case of 1D photonic crystal/photonic wire micro-cavity. In one occasion, at cavity length of 4.0 µm , we have successfully measured the extended wire cavity for the suspended wire. The Q-factor achieve at this cavity condition are 3900, 16 900 and 14 700 with respect to the resonance wavelength of approximately 1470.3 nm, 1525 nm and 1574.5 nm- as shown in **Fig.3 (a)**. Although somewhat surprisingly, we have found that the normalized optical transmission for the resonance at P_1 is significantly low at approximately 4% as compared to the resonances at position P_2 and P_3 of approximately 30% and 50%. Those resonances were measured to have 52 nm in Free Spectral Range (FSR). The normalized transmission of the resonance varies at which we believe that the Q-factor and optical transmission is optimum for a certain cavity condition. **Fig.3 (b)** shows the trend of the Q-factor value between the suspended PhC/PhW extended cavities and the one with the silica cladding underneath it. For each resonance conditions, the Q-factor dropped by approximately 15%, 32% and 35% for P_1, P_2 and P_3 respectively after the removal of Silica underneath it. The difficulties in achieving high transmission and high Q for the suspended wires for this particular device is due to the abrupt change of the mode traveling from the feeder waveguide with silica cladding into the wires region where the silica has been removed. Thus it produces higher propagation losses at the interface. But no attempt has yet been made as to measure the loss at that interface which we believe is the key toward enhancing the Q-value and optical transmission. More works on the fabrication process for a suspended wire is necessary at this point.

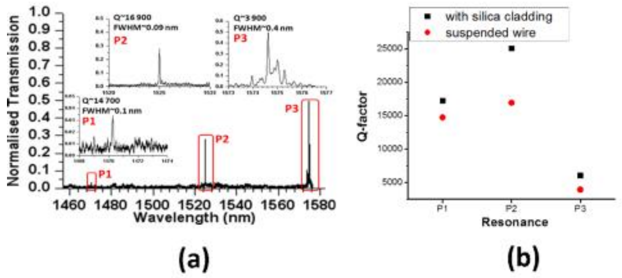

Fig. 3: *(a) Measurement result for ultra-high Q suspended wire with extended cavity of C_E=4 µm (b) Comparison of the resonance Q-factor value with the suspended wire waveguide*

5. Conclusions

We have successfully demonstrated experimentally the High Quality factors resonance with a good control of FSR value for extended cavities ranging from 2 µm to 6 µm. Different measurement cycles for each of the samples have also shown that consistent values in the Q-factor and resonance frequency were preserved. In addition, reproducing the high Q-factor values for different cycles of one design and completely different samples and designs would be required to determine the impact of environmental effects such as air pressure and humidity variation.

Acknowledgment

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