Advancing the Performance of One-Dimensional Photonic Crystal/Photonic Wire Micro-cavities in Silicon-on-Insulator

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Abstract: We present new results that demonstrate advances in the performance achievable in photonic crystal/photonic wire micro-cavities. In one example, a quality-factor value as high as 147,000 has been achieved experimentally at a useful transmission level.
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1. Introduction

The combination of narrow (photonic wire) optical waveguides and one-dimensionally periodic photonic crystal structures in high refractive index semiconductors such as silicon, in the form of silicon-on-insulator (SOI) and epitaxial structures based on the III-V semiconductors, has been a topic of interest for a number of years [1-4].

Recent work has led to demonstrations of quality-factor (Q-factor) values approaching 60,000 [2] and the combination of a Q-factor value approaching 20,000 together with a normalised transmission coefficient of nearly 90% [3]. Observations using various versions of scanning near-field optical microscopy (SNOM) have also verified that such structures can exhibit optical confinement in very small volumes, resulting in extremely large Purcell-factor values (5). Key factors in achieving such high values of Q-factor and normalised transmission are the incorporation of hole diameter tapering, careful displacement of hole position in transition sections (both within and outside the cavity) and careful adjustment of the length of the cavity spacer section, aided by numerical modelling.

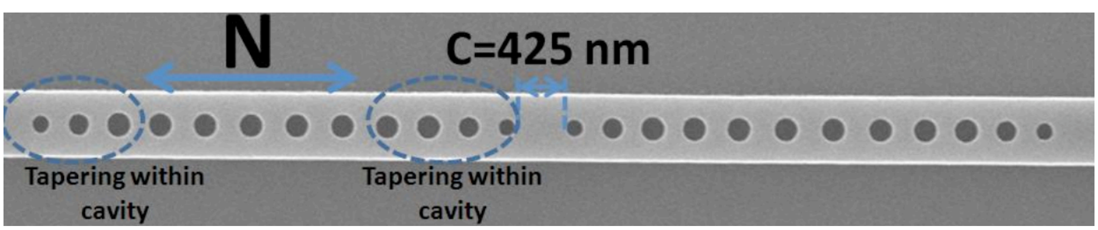

Fig. 1:Scanning electron micrograph of typical microcavity structure using 5-hole periodic Bragg mirrors and tapered hole input and output structures, both within and outside the cavity.

2. Device Design, Fabrication and Measurement

In this presentation we shall describe new results for the combined photonic wire/photonic crystal micro-cavity structure that include achievement of resonance quality-factor (Q-factor) values of well over 100,000, in combination with usefully large transmission factors. Substantially higher transmission coefficient values have been achieved, in conjunction with somewhat smaller (c. 80,000) Q-factor values. A scanning electron micrograph of a typical cavity is presented in Fig.1. It shows a photonic wire microcavity that has a wire width of 500 nm, three-hole tapers at the input and output of the cavity – and four-hole tapers for the mirrors within the cavity. The periodic parts of the mirrors are formed by five holes. The hole diameters and spacings chosen for the structure shown in Fig. 1 are similar to those quoted in reference [3]. Although we have also looked at the use of extended cavities with longer spacer sections, the present design retains the use of a short cavity having a spacer section length that is somewhat less than the optical wavelength in the medium - and is the configuration that can maximise the Purcell factor of the micro-cavity. The value of the Q-factor achievable is strongly dependent on the length of the cavity space section. Operation is always in (quasi-) TE polarization, i.e. with the predominant electric-field vector component being in-plane.

As described previously, the pattern generation for our devices was carried out by direct-write electron-beam lithography (EBL) in a Vistec VB6 machine. A one-stage dry-etch transfer process, with minimal writing time, was used in conjunction with a layer of hydrogen silsesquioxane (HSQ) negative resist to transfer the written pattern, with high precision and small edge-roughness [6], into the silicon waveguide layer.

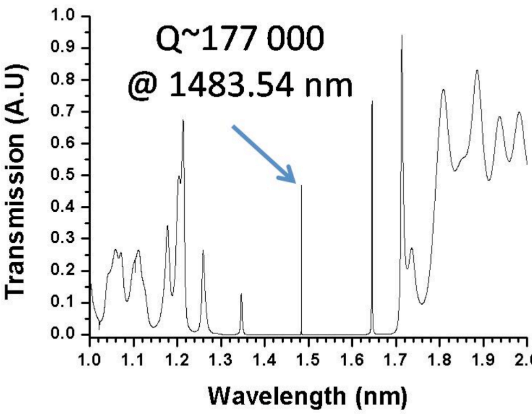

Fig. 2(a): Computed transmission spectrum for micro-cavity with 5-hole mirrors plus tapers

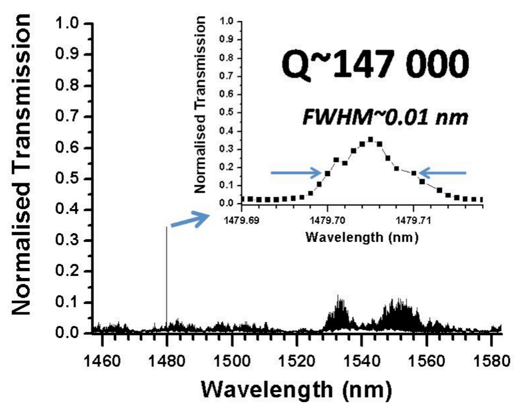

Fig. 2(b): Measured spectrum for the same micro-cavity, with expanded spectrum inset.

In our recent work, we have found it convenient to carry out computational modelling of the properties of different micro-cavity designs using a high-resolution calculation based on a two-dimensionally varying model of the refractive index distribution, together with an effective refractive index calculated for the planar silicon-on-insulator waveguide. The results of calculations that last on the order of a working day for their execution on a personal computer are shown in Fig. 2(a) and yield an estimated Q-factor value of 177,000, at a wavelength of 1483.54 nm. The corresponding measured transmission spectrum appears in Fig. 2(b) – and yields an estimated value of 147,000, at a wavelength of 1479.705 nm. We believe that the fact that the computation involves the effective index approximation, rather than a fully three-dimensional calculation, and the uncertainty in the specification of the actual dimensions of the fabricated device together imply a satisfactory level of agreement in the estimates of both Q-factor and resonance wavelength. We have addressed issues of reproducibility for photonic-wire based device structures produced using electron-beam lithography in reference [6], which indicates that careful attention to HSQ resist cycle life-time can significantly increase the accuracy with which a target wavelength can be approached. Achieving a specific wavelength with the accuracy implied by our ability to measure it, and by the line-width of the resonance, seems likely to require the addition of a tuning mechanism, e.g. electro-optic [7] or thermal tuning [8,9].

An important aspect of the structures that we have fabricated, as well as similar ones published by other workers, is that the silicon waveguide core is firmly anchored to the silicon substrate via the silica buffer (lower-cladding) layer. But we have also begun work on an air-bridge version of our micro-cavity device structure, using a suitably adjusted design. For the air-bridge structures, conventional ultra-violet (UV) photolithography has been used to define windows in the silicon waveguide layer, through which the silica lower cladding layer could be selectively removed using buffered hydrofluoric acid (HF). Air-bridge/membrane structures have been used to obtain the highest Q-factor values achieved in waveguide photonic crystal-based micro-cavities – and we are investigating the extent to which the modified geometry implied by surrounding the entire photonic wire waveguide with air affects the Q-factor values that are achievable. We shall report results obtained in the conference presentation.

3. Conclusions

The Q-factor and transmission coefficient combination achieved in this work are probably still some way from the best that can eventually be obtained. With sufficiently low propagation losses obtained through smooth side-walls - and micro-cavity designs based around a greater number of holes in the periodic parts of the cavity mirrors, substantially higher cavity resonance quality factors should be possible. Further attention to the design of the tapered sections will contribute both to increases in the Q-factor and to the transmission coefficient.

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4. References

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