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Coupling strength control in photonic crystal/photonic wire multiple cavity devices

A.R.Md Zain, N.P. Johnson, M. Sorel and R.M.De La Rue

Resonance splitting has been demonstrated for two coupled micro-cavities with control of the free spectral range between the resonance peaks, together with a normalised transmission level of approximately 60%. Coupled micro-cavity-based structures that were separated by two closely spaced in-line coupler sections between the two micro-cavities have also been successfully fabricated and measured. The coupling strength of the two cavities was controlled via the use of hole tapering in the middle section between the two cavities. 2D finite-difference time-domain simulation shows close agreement with the results of measurements.

Introduction: There is considerable current interest in the realisation of compact and complex photonic integrated circuits (PICs) based on silicon-on-insulator (SOI). The high refractive index contrast of the combination of a silicon core with a surrounding cladding of silica and/or air provides strong optical confinement, leading to compact structures and small device volumes [1, 2].

Designing one-dimensional (1D) photonic-crystal/photonic-wire (PhC/PhW) micro-cavities with high-quality-factor performance into this kind of structure is useful for telecoms applications such as all-optical (nonlinear) switching and dense wavelength division multiplexing (DWDM). In addition, coupled micro-cavity structures can provide a useful platform for DWDM applications, where two or more micro-cavities can be coupled together and used to split the single cavity resonance into a number of resonances that depends directly on the number of micro-cavities used. This type of device is also potentially useful for filter function synthesis in telecommunication applications, for nonlinear optical functionality and in obtaining slow-light propagation [3–5]. Such structures consist of two or more cavities coupled through periodically spaced hole mirrors. The multiple coupled-cavity combinations produced split the selected single cavity resonance frequency into a number of resonances that depends on the number of cavities used in the design [5]. Tapering of the PhC hole structures within and outside photonic crystal/photonic wire micro-cavities has also been shown to yield a substantial improvement in the quality factor and optical transmission at the resonance frequencies [6, 7]. For applications that require a filter response with a nearly level passband and steeper skirts at the edges of the passband, the coupling strength between cavities must be carefully controlled, and additional cavities may be required to optimise the response [8].

This Letter proposes that the coupling strength of the two micro-cavities separated by several holes with different diameters and hole spacings can be substantially influenced by the tapered hole combination used in the separation region between the micro-cavities.

Design considerations and FDTD simulation approach: Planar 1D PhC/PhW micro-cavity structures were designed with a single row of holes embedded in 500 nm-wide photonic wire waveguides. This photonic wire has a dimension of 260 nm in thickness, which was supported by a silica buffer layer to provide optical isolation from the bulk silicon substrate. In this Letter, the PhC mirrors consist of a combination of mirrors formed by N periodic hole PhCs with diameters of 182 nm and periodic spacing of 350 nm. Two such micro-cavities – with spacer sections, c_1 and c_2, both 450 nm long – were coupled to form a double-cavity structure, as illustrated in Fig. 1.

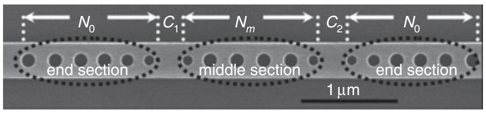

Fig. 1 *SEM image of two micro-cavities between three periodic mirrors with cavity lengths c_1 and c_2 (edge-to-edge distance between two hole at micro-cavity), number of holes on each side of the micro-cavities, N_0, and number of holes between two micro-cavities, N_m*

The two coupled micro-cavities each have a cavity spacer length of $c_1 = c_2 = 450$ nm. This structure was divided into three sections, consisting of two end sections, N_0 and a middle section, N_m. To reduce the modal mismatch for light entering from unpatterned wire waveguides into the mirror region, a tapered structure consisting of a combination of several aperiodically located holes and different diameters was used.

The four-hole tapered structures used in our design have diameters of 170, 180, 166 and 131 nm sequentially, together with centre-to-centre hole distances of 342, 304, 310 and 290 nm, respectively. On the other hand, the two-hole tapered structures used outside the cavity had diameters of 166 and 131 nm, with centre-to-centre hole distances of 310 and 290 nm. Both end sections, N_0, have two identical PhC holes, forming periodic mirrors, together with four aperiodically located holes forming tapers within the cavity. The tapered hole structures within the cavity have the same dimensions as were used previously in the single micro-cavity structure, for both end sections. At this point, a different number of holes was used in the tapered part of the middle section, N_m, by keeping the total number of periodic and aperiodic holes to six, for device simplicity, and to facilitate a consistent analysis. Fig. 2 shows the transmission spectra for a 6-6-6 (N_0-N_m-N_0) hole arrangement using different numbers of holes in the tapered part of the middle section, computed using a 2D-finite-difference time-domain (FDTD) numerical approach. As the number of holes in the tapered part of the middle section is increased from one to three holes, a clear resonance splitting is predicted, implying stronger optical coupling between the two cavities. The free spectral range (FSR) values calculated in the successive cases are 9.90, 17.65 and 26.74 nm, respectively.

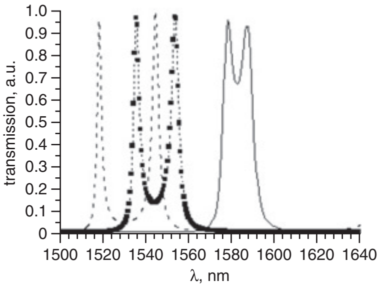

Fig. 2 *2D FDTD simulation for 6-6-6 (N_0-N_m-N_0) hole arrangement with different hole taper arrangement in middle section, N_m*

———— without hole taper
- - ■- - with one hole taper
- - - - - with three hole taper

Fabrication process and measured results: The devices were fabricated using a Vistec VB6 EBL machine and reactive ion etching. The device structures were finally characterised using a tunable laser that covered the wavelength range 1457–1580 nm. The light was end-fire coupled into the waveguides and detected using a germanium photodiode at the output end. The measured result is normalised against an unpatterned 500 nm-wide photonic wire without holes embedded in it. Fig. 3 shows measured results corresponding to the simulation results given in Fig. 2, with a normalised transmission of around 60% at resonance. Clear resonance splitting is observed with a three-hole tapered middle section. The values for the FSR between the split resonances measured for the successive cases are 2.74, 5.05 and 17.85 nm respectively. As the number of periodically arranged holes in the middle section is reduced (and they are replaced by tapered hole sections with different diameters and aperiodic spacing), the optical coupling through the middle section becomes stronger, and therefore the FSR between the two resonances increases. But multiple resonances with low transmission, of less than 5%, are also observed between the two clear resonances, in the latter two cases, and correspond to longer partial cavity structures formed between the middle mirror section and the outer ends of the outer cavity mirrors. Clearly the addition of suitable tapered hole structures at the input and output of the double cavity structure, as we have already demonstrated [6, 7] to be beneficial in the single cavity case, could well suppress such undesired features. As the number of periodic mirror holes in the middle section, N_m, is reduced to four (thereby becoming a 6-4-6 arrangement) for the situation with no tapered holes inserted in the middle section, a larger coupling strength is observed, with a clear resonance splitting (compare Fig. 3*a* with Fig. 4*b*). The value for the FSR between the two resonances has increased by 7 nm, from 2.74 to 9.74 nm. By inserting one reduced diameter hole into this particular design arrangement (maintaining four periodic holes in the middle section), the coupling strength between the two cavities is further reduced and is accompanied by a reduction in the measured transmission by approximately 20%. A reduction in the FSR value from 9.74 to 5.94 nm was obtained for this coupling condition, but a significant improvement in the *Q*-factor value from 400 to 1100 was also obtained.

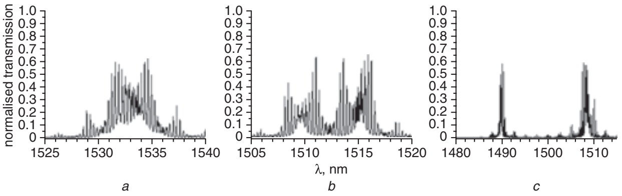

Fig. 3 *Measured results corresponding to 2D FDTD simulation result in Fig. 2*

a Without hole taper
b With one hole taper
c With three hole taper in middle section

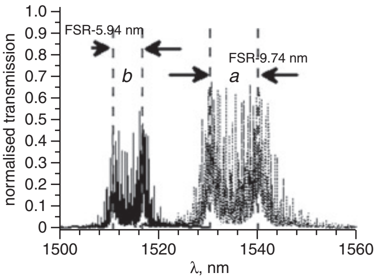

Fig. 4 *Measurement result for $N_m = 4$ with c = 450 nm*

a Without hole taper
b With one hole taper in middle section
——— with one hole taper
- - - - - - without hole taper

Conclusions: We have successfully demonstrated 1D PhC/PhW devices that use two coupled micro-cavities to split the cavity resonance in two, while retaining high optical transmission (of around 60%), which could also be useful for WDM applications. Control of the FSR of the combined resonance structures, through the use of different numbers of holes in periodic mirror holes and different numbers of holes in the aperiodic middle section between the cavities has also been demonstrated. For the case where a constant combination of tapered holes and periodic mirror holes was used, it was shown that, as the number of tapered holes in the middle section increases, there is an increase in the coupling strength, thus splitting the resonance more clearly, with an FSR of approximately 17.85 nm. In contrast, for the same number of mirror holes in the middle section, increasing the number of holes in the tapered section produces a reduction in the FSR between the two resonances. Our 2D FDTD simulations have shown reasonably close agreement with the measured results. Finally, the coupled cavity design in a two-cavity arrangement is potentially useful as a basic building block for designing multiple-cavity structures, with a series of cavities providing the required spectral response for WDM de-multiplexing applications.

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