

PURE PHOTONIC CRYSTAL WAVEGUIDING FOR SIGNAL PROCESSING AT OPTICAL JUNCTIONS

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ABSTRACT

This paper describes a photonic crystal (PhC) waveguide of two-dimensional (2D) photonic bandgap lattice structure. Typically, PhC waveguides demonstrated have line defects of high index material placed in an otherwise periodic lattice structure, which serves to prohibit the propagation of light radiation within; such technique makes use of PhC waveguiding in the lateral axis and index confinement in the vertical axis. Here, pure 2D PhC waveguiding at 1550 nm without index guiding assistance was achieved instead, through successful fabrication of high aspect ratio pillar-type PhC lattices with intersecting orthogonal line defects and tunneling cavities. The experiment results were found to coincide with first principle simulation results of different tunneling cavity dimensions. These optical junctions therefore can be used for effective control of optical signal levels (via the phenomenon of drude absorption) to achieve ultrafast optical switching by means of high power 200 fs laser pulses as control signals.

Keywords: Photonic crystal, Optical crossing, Waveguiding intersection.

INTRODUCTION

The increasing pervasiveness of the internet in the twentieth century has affirmed the importance of global optical communication networking and hence ensured continual worldwide focus onto its future technological development. Particularly, integrated optical devices [1] are often touted to be the next generation breakthrough for its potential in high-speed broadband applications. Photonic bandgap [2] crystal (PhC) especially has been identified to be an important enabling technology for this purpose, as its inherent ability to control the propagation of optical radiation [3] cannot be found in existing simple material systems. Therefore, the properties of PhC and many of its optical device applications have been under

intensive research [4-6] since its discovery. Of them, two-dimensional (2D) PhC has been widely studied for its direct relevance to state-of-the-art semiconductor fabrication technology, which is a layered process [7-8].

In this paper, we report demonstration of light guiding in air without index assistance at 1550 nm wavelength, in 2D PhC waveguides. Based on intersecting [9] orthogonal waveguides with C_{4v} -symmetry tunneling cavity at intersecting junction as shown in Fig. 1, high transmission together with low crosstalk was achieved. These tunneling optical junctions therefore would allow effective control of optical signal levels via photonic absorption mechanisms, enabling ultrafast, optically induced control for silicon lightwave circuits.

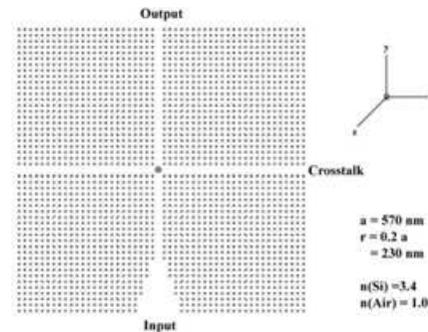


Fig. 1. Schematic of intersecting orthogonal 2D PhC waveguides with C_{4v} -symmetry tunneling cavity at the junction

In this device, the 2D PhC lattice of high aspect ratio pillars have waveguides formed by removal of two orthogonal rows of pillars. Figure 1 shows how input light radiation is confined to areas without bulk PhC lattice, propagation of light is prohibited since optical states are not available for the wavelengths within the bandgap frequencies. At the same time, diffraction effect at the very narrow

intersection, typically leading to high crosstalk and low transmission is effectively suppressed, through the use of designed tunneling cavity at the intersection of the device.

Here, unlike previous experiments with such symmetry-breaking backgrounds - whereby guided modes are insufficiently localized within the slab [10] causing PhC properties to be ostensibly lost - background effects can become small perturbations beyond a critical aspect ratio for the 2D PhC. Without other waveguiding mechanisms such as reflecting planes or materials with higher refractive index for index confinement, optical transmission collected at the output of such waveguides can be attributed purely to the action of the 2D PhC lattice.

FABRICATION PROCESSES

In the design of fabrication process, attention was paid to allow for independent manipulation of the lithographic and time-multiplex etch processes. This is due to the different requirements for optical patterning and etching needed to realize drastically different mask openings and etch depths, for deep sub-micrometer sized PhC array of pillars and for deep trenches required to couple standard single mode fibers of more than a hundred micrometers width. Therefore, an initial mask for the PhC structures of critical dimensions were first defined through a thin layer of hardmask. Photoresist strip followed by a refill of thick resist then allowed for patterning and etching of fiber grooves using a second recticle. When the required etch depth of the fiber grooves was achieved, photoresist strip then revealed the pre-patterned PhC structures for final device etch.

In lithography of these devices, a binary mask having no phase-shift features was used to pattern the dense cubic lattice of PhC pillars (diameters 230nm, spaced 340nm apart) at deep UV wavelength of 248nm. As the critical dimensions required was sub lithographic wavelength, patterning aberrations such as optical proximity errors (OPE) easily arise - especially near regions of designed PhC 'defect structures' - which had to be biased using derived proximity correction models (see Fig. 2).

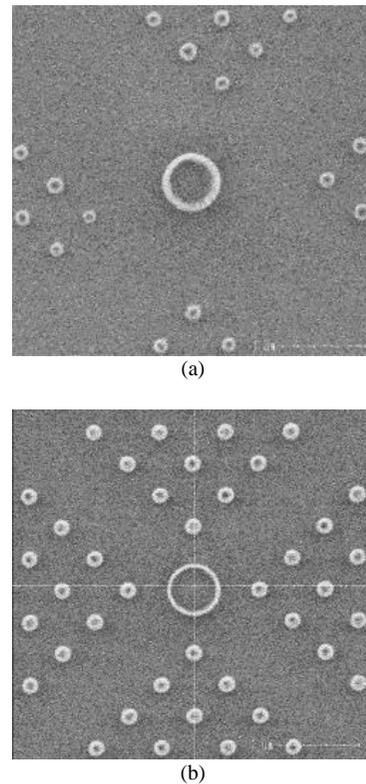


Fig. 2. Scanning electron micrographs (SEMs) of fabricated PhC device with tunneling cavity at intersecting waveguide junction (a) with and (b) without OPE.

Similarly the case for the etch process, catastrophic etch failures often result as a direct consequence of shrinkage in process-window bought about by drastic reduction in etch opening and critical dimension sizes. Harmonization between etch and passivation phases in the time multiplexed process using an STS deep reactive ion etcher, allowed successful realization of high aspect ratio (HAR) etch. At the same time, minimization of the inevitably formed time-multiplexed etch sidewall "scallops" in the form of wave-like surface undulations allowed for smooth, vertical PhC pillar sidewalls with scallop depths reduced to only 12nm from reported low values of 50-300nm as shown in Fig. 3.

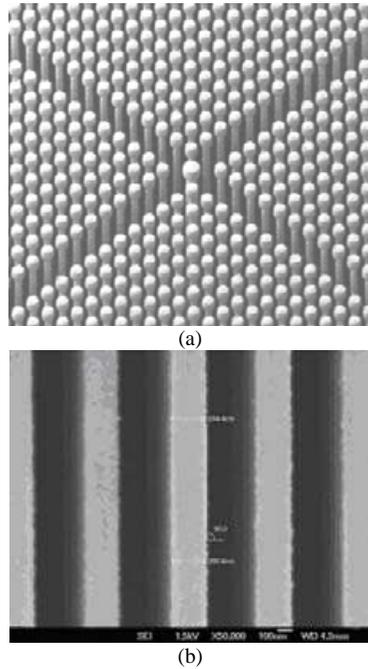


Fig. 3. SEM of fabricated PhC lattice of (a) bulk pillars with 115nm radii with single row defect waveguide and intersection tunneling cavity; (b) cross sectional view of minimized scallops on sidewalls of pillars.

RESULT AND DISCUSSION

Optical measurements of these PhC devices were carried out using an ANDO optical spectrum analyzer (OSA). The continuous wave source radiation used was coupled to the device using Melles Griot NanoMax-TS alignment stages. Input and output optical fibers positions are guided passively along deeply etched fiber grooves with accuracy of about $\pm 1 \mu\text{m}$. Probe needles with diameters of $2 \mu\text{m}$ were also used to achieve coupling in the vertical axis through application of downward pressure onto fibers for their lower alignment to the floor of the fiber grooves. Tilt of the fibers was also minimized through alignment to the designed device-facet wall, which has an optimized etch angle of 90 degrees. Figure 4 shows the schematic for experiment setup used to measure transmission and reflection from the waveguides of the PhC device.

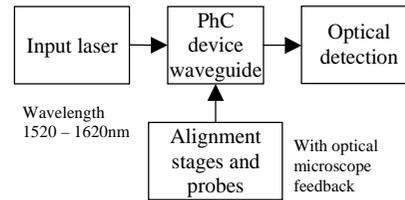
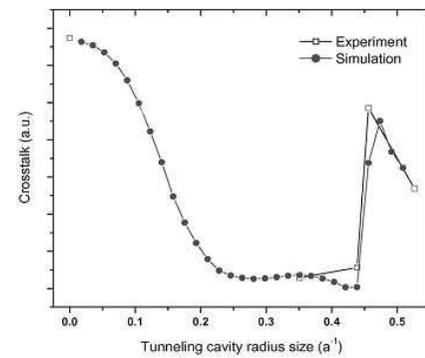
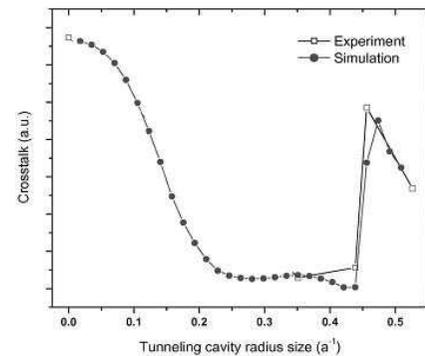


Fig. 4. Schematic of experimental setup.

With its orthogonal waveguide branches and circular tunneling cavity geometry, degenerate states at the optical junction can become sufficiently differentiated for varied cavity radii - becoming odd/ even for the through and crossing waveguide branch respectively.



(a)



(b)

Fig. 5. Experiment measurement (unfilled-symbols) and FDTD simulation results (filled-symbols) for (a) crosstalk, and (b) transmission.

For cavity radii as ratios to the lattice pitch of the PhC, crosstalk and transmission level measurements were made as unfilled symbols in Fig. 5 while the results of finite difference time domain (FDTD) simulations are marked by filled symbols. As expected, the measurements showed high levels of loss due to lack of waveguiding mechanism along the z direction. However, good agreement between the simulated and measured spectra was observed in spite of the fact that experiment readings for cavity radius between 0 to 0.35 times of pitch cannot be obtained since these structures are beyond current fabrication process capability. We have also studied the effect of 2D PhC pillar height on waveguiding with respect to radiation wavelengths. For pillar heights of multiples of the radiation wavelengths ranging from 0 to 10, 3D FDTD simulations was performed for the structure to determine the critical value required for depth of etching, which is five times that of the radiation wavelength. For a wavelength of 1.55 μm , this would correspond to PhC pillars with an aspect ratio of 35, which is the condition used to obtain the measurement results of Fig. 5.

CONCLUSION

Hence, it has been demonstrated that quasi-2D PhC device performance was obtained for PhC device fabricated using CMOS compatible, deep UV lithography and deep reactive ion etching technique. In the absence of other confinement mechanisms, pure PhC guiding of light at 1.55 μm wavelength in the intersecting waveguides, with varying tunneling defect sizes was demonstrated. The optical measurements also indicate the importance of vertical confinement to radiation losses in symmetry restricted and non-restricted orthogonal waveguide modes. New experiments for alternative control of cavity state by high power 200 fs pulsed laser is now undergoing, and are expected to yield similar transmission properties, dynamically such that ultrafast induction of optical modulation can be obtained.

Acknowledgments

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