Low-Loss Two-Dimensional Pillar Photonic Crystals Filled with Dielectrics

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Abstract—**Optimization of two-dimensional pillar photonic crystals is presented. In the interpillar spaces, three-layer stacks of dielectrics were introduced. The simulation predicts the lowest coupling loss for such structures reported so far and lower etching depths for the pillar fabrication than in previous studies.**

Keywords-pillar photonic crystal; low loss; ; filling with dielectrics; high refractive index contrast.

I. Introduction

The concept of photonic integrated circuits (PIC's) is drawing a body of attention from academic as well as industrial prospects. A unique offer given by PIC's resides in monolithic integration of discrete optical components onto a single chip. Such a circumstance enables drastic reduction in size and power consumption of PIC-based devices. Several issues, however, have to be solved for achieving decent performance of PIC's. Control of polarization represents one of those since polarization dependence of PIC components produces an additional source of loss. Two-dimensional (2D) pillar photonic crystals (PhC's) showed substantial potential for dealing with the issue [1]. Further reduction in loss requires vertical confinement in the interpillar space. A vertical waveguide layer stack (VWLS) made of a material layer with high refractive index enclosed by two low-index layers was proved workable for the case of polymers theoretically and experimentally [2]. Low contrast between refractive indices of the polymers yielded appropriate loss for the pillars higher than 3 μm.

The present paper is aimed at demonstrating that introduction of a VWLS composed of materials with higher contrast in refractive index n allows: i) obtaining the lowest coupling loss among pillar PhC's reported so far and ii) lowering the pillar heights to 2-2.5 μm which leads to dramatic mitigation of the fabrication process.

II. Description of Simulation

Transverse magnetic (TM) photonic band gap width $\Delta\omega$ and coupling loss were simulated for 2D pillar PhC's. An illustration of the top view of the crystals is given in Fig. 1a. The PhC designs differed in radius r while their lattice constants a's were kept the same (see Fig. 1b). The pillars

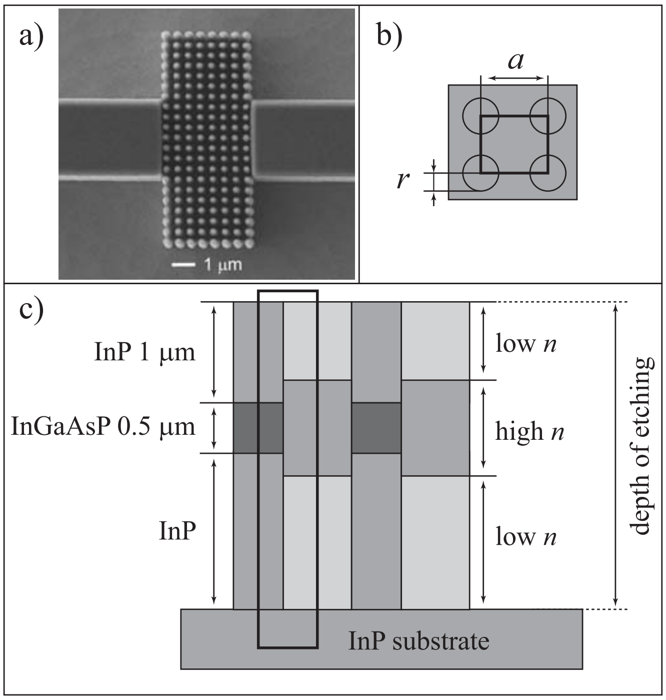

Figure 1. a) Top view of 2D pillar photonic crystal; b) Unit cell (by black square) of 2D photonic crystal used for band gap calculation; c) Cross section of photonic crystal: pillar composition (in darker colours): 1-μm-high InP part, 0.5-μm-high InGaAsP part and InP one of varying height depending on depth of etching, followed by InP substrate; composition of vertical waveguide layer stack: low n/ high n/ low n layers all with varying thicknesses. Black rectangle in bold denotes calculation window for simulation of coupling loss. n stands for refractive index, r, pillar radius, a, lattice constant of photonic crystal. The structure is periodic in the horizontal

were made to ensure compatibility with the generic integration technology. In the interpillar space, a VWLS was introduced (see Fig. 1c). Being designed for an operational wavelength of 1.55 μm, the PhC's yielded: i) propagation control of the TM-polarized mode and ii) minimal coupling loss of light on its advance through a PhC interface.

All the simulations employed the CrystalWave software of Photon Design. The band solver of CrystalWave was used to calculate $\Delta\omega$ as a function of effective refractive index n_{eff} and normalized pillar radius r/a. A 2D unit cell depicted by the

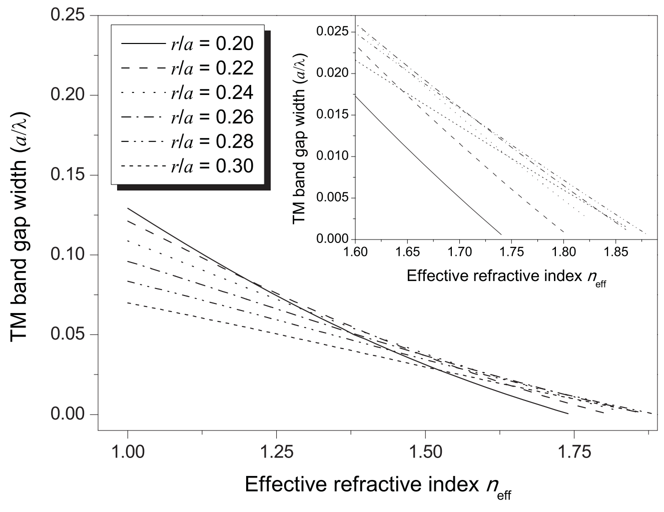

Figure 2. TM band gap width as a function of effective refractive index of the mode in vertical waveguide layer stack and normalized pillar radius *r*/*a* for 2D pillar photonic crystals. *r* denotes pillar radius, *a*, photonic crystal lattice constant, λ, wavelength.

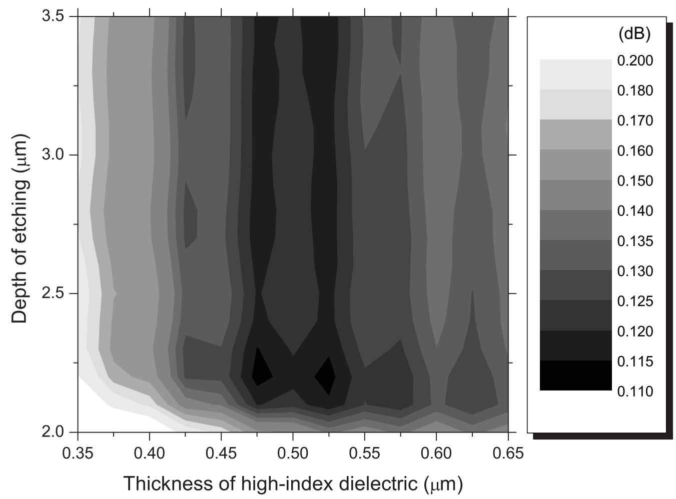

Figure 3. Coupling loss on advance through an interface of 2D pillar photonic crystal as a function of thickness of high refractive index material and depth of etching. Plot is limited by thickness of high refractive index material = 0.65 μm since larger values cause closure of photonic band gap.

black square in Fig. 1b was defined for that purpose. The pillar area was given n_{eff} = 3.26 while the n_{eff} of the interpillar region was varied. Normalized pillar radius varied between 0.20 and 0.30 with a step of 0.02.

The finite difference time domain engine computed loss as a function of etching depth and thickness of high *n* material in the VWLS. That necessitated definition of the calculation window (see Fig. 1c, black rectangle). Coupling loss of light on transition from the pillar into the VWLS is computed using the overlap integral of the mode profiles in the pillar and the VWLS. For the pillars, the InP area is given *n* = 3.17 and for InGaAsP *n* = 3.36. The low refractive index material in the VWLS has *n* = 1.45 corresponding to SiO_2 whereas its high-index counterpart was given *n* = 2.10 associated with Ta_2O_5.

III. RESULTS

A. TM Photonic Band Gap Width

TM photonic band gap widths as functions of n_{eff} for different *r/a* values were simulated for the PhC's to ensure rejection of the TM modes over all the C-band (1.53-1.57 μm). The modelling results are presented in Fig. 2. All of the curves follow the same trend: Δω becomes narrower with increasing n_{eff} leading to complete closure of photonic band gap. Larger *r/a* values yield a wider range of acceptable n_{eff} values. Rejection of all frequencies in the C-band (1.53-1.57 μm) requires the TM photonic band gap to be larger than 0.01 *a*/λ, with λ representing the wavelength, for all *r/a* values. The inset of Fig. 2 shows that such a condition is met at n_{eff} < 1.75 for the designs with *r/a* > 0.24.

B. Coupling Loss

An optimal etching depth and thickness of the high *n* material in the VWLS was found by the simulation of coupling loss. The results are given in Fig. 3. It is seen that an acceptable level of loss is already achieved at thicknesses of the high *n* layer from 0.45 μm to 0.6 μm. The preceding study [2] used a polymer stack with lower *n* contrast in comparison with ours. It reported a loss value of 0.2 dB per interface between the pillar and the VWLS for etching depths larger than 3 μm. In the current study, a value of 0.12 dB per pillar-VWLS interface was calculated for etching depths of 2-2.5 μm. This is the lowest value of coupling loss reported so far for pillar PhC's. Moreover, etching depths of 2-2.5 μm alleviate the pillar fabrication substantially.

IV. CONCLUSION

Two-dimensional pillar photonic crystals with a vertical waveguide layer stack of dielectrics in the interpillar space were investigated. Examination of the TM band gap width as a function of effective refractive index for different values of the normalized radii showed that safe rejection of frequencies from the C-band occurs for PhC designs with a normalized radius > 0.24. The study of loss vs depth of etching and thickness of high refractive index layer in the stack emanated coupling loss = 0.12 dB per pillar-VWLS interface for etching depths of 2-2.5 μm. This loss value was found to be the lowest reported so far for pillar photonic crystals. The said values of etching depths and coupling loss indicate substantial mitigation of the pillar fabrication process and the possibility of constructing a very low-loss pillar photonic crystal, compatible with standard photonic integrated circuits, using dielectrics such as SiO_2 and Ta_2O_5.

ACKNOWLEDGEMENT

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V. REFERENCES

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