# Silicon-based photonic crystals and templates

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Nanophotonics research at VTT is currently focused on silicon based photonic crystals in two and three dimensions. We have introduced a new geometry for two dimensional photonic crystals based on a triangular lattice of ring-shaped holes. We demonstrated theoretically that such photonic crystals show better reflectivity than conventional photonic crystals for air-fill factors smaller than 30%. We manufactured and characterized a waveguide consisting of a line defect inside a ring-hole photonic crystal. Besides that, we have developed the fabrication of patterned silicon, SOI and silica templates for the deposition of three dimensional opals as well as a method to measure the optical properties of single opal crystallites grown inside of micrometer-sized templates.

## 1. INTRODUCTION

Photonic crystals (PhCs) are materials with a periodic variation of the index of refraction. Photons interact with PhCs in a similar way to electrons with crystalline solids. The formation of dispersion band structure and optical band gap provides improvement in terms of emission control [1], guiding [2] and dispersion engineering [3]. Photonic crystals (PhCs) are thus expected to be an elementary building block in a future generation of opto-electronic devices with reduced size.

The high refractive index contrast and submicron feature sizes required in PhCs designed for optical wavelengths are easily addressed in two dimensions (2D). The most common 2D PhC consists in a triangular lattice of circular air holes patterned into a high refractive index material. We believe that low air-fill factor PhCs with ring-shaped holes (RPhCs) are more advantageous from the point of view of out-of-plane losses. We demonstrated in particular that such a PhC exhibits better optical properties than conventional PhCs.

Contrarily to 2D PhCs, fabrication of three-dimensional (3D) structures is still a technological challenge [4]. Artificial opals are 3D PhCs whose realization is based on self-assembly of monodisperse microspheres, usually polymer or silica. This method is relatively cost-efficient, and can be extended to the large scale required by mass production. Even though the refractive index of opals is too low for the formation of photonic band gap, they have direct applications in dispersion engineering. Further, they can be used as templates, and inverted after growth with a high refractive index material, like silicon or germanium, to form a full band gap photonic crystal. Our work in this area is focused on the growth of opals into pre-patterned deep structures that can be integrated into conventional photonic circuits.

## 2. 2D PHOTONIC CRYSTALS WITH RING-SHAPED HOLES IN A TRIANGULAR LATTICE

There are experimental proofs that smaller air-fill factors reduce out-of-plane radiation in PhCs etched in low index contrast planar waveguides [5,6]. The influence of the air-fill factor in high index contrast systems such as silicon-on-insulator has not been studied in detail. For example Monat et al. [7] observed experimentally that the air-fill factor had a quasi negligible influence on the quality factor of a single defect PhC cavity etched into a thin layer of InP on $SiO_2$. The authors explain this result by a larger density of fabrication imperfections in samples with lower air-fill factors. Another reason may as well be that the benefits of reduced of out-of-plane loss are cancelled by the decrease of the PhC's reflectivity at lower air-fill factors. One way to achieve higher reflectivity at low air-fill factors is to use non-conventional PhC lattice geometries. As an alternative to the conventional PhC we propose a PhC defined as a triangular lattice of ring-shape holes (Fig. 1, [8]). A similar structure was studied earlier in GaAs/AlGaAs and showed low-loss properties [6].

Using the 2D FDTD simulation method [9], we show that for air-fill factors smaller than 30%, an RPhC slab exhibits a larger reflectivity compared to conventional PhC in both the ΓK and the ΓM directions of the crystal lattice, provided that the radius R and the trench width w of the rings are optimized. For example, for a background index of 2.9, R=0.21a and w=0.165a (with a the period of the PhC), a 4-row RPhC slab reflects 93.3% and 75.8% of the light, in the ΓM and ΓK direction respectively. The corresponding reflectivities for a conventional 4-row PhC slab with the same air-fill factor are 91.4% and 69.3%.

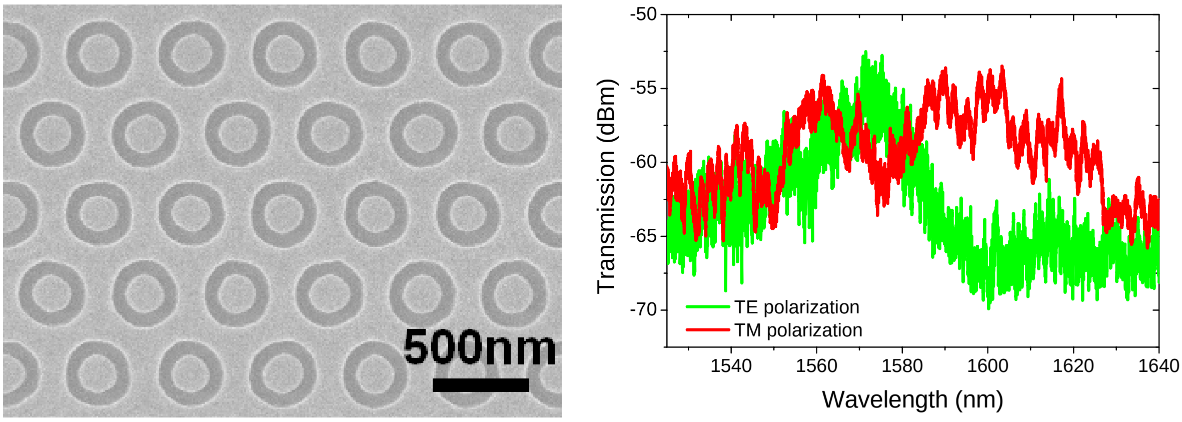

FIG. 1: (Left) Scanning electron micrograph of a ring photonic crystal patterned into SOI (silicon layer thickness: 240nm). The ring line width is only 70nm. (Right) Measured transmission spectrum of an RPhC waveguide.

The higher reflectivity of RPhC makes it a good candidate to realize high-Q cavities. We simulated a simple single defect cavity using 2D FDTD with silicon as background material. The resonant cavity is made by removing one hole from the crystal lattice. For an air-fill factor of 25%, we reached a quality factor of 1060 for RPhC. The corresponding value for a conventional PhC is only 580.

The large group velocity dispersion in PhC waveguides have raised a lot of interest lately for applications in dispersion management in photonic circuits [10,11]. In this context RPhC based single line defect waveguides (noted as W1) are particularly interesting, since they exhibit lower group velocities than in conventional PhC waveguides. Plane wave expansion calculations [12] show that group velocities as low as 0.005c can be achieved for a propagation constant $\beta$=0.44(2$\pi$/a) (c is the speed of light in vacuum). This corresponds to a group index $n_g$ of 200. This exceptionally large value is at least twice larger than in a conventional W1 waveguide according to our calculations. It is also larger than the values usually found in literature [10,11,13,14]. Observe that the air-fill factor of the RPhC is relatively low (f=32.5%), which is advantageous from the point of view of losses.

In order to validate our calculations we fabricated an RPhC waveguide into a SOI substrate using electron beam lithography and dry-etching. The manufactured RPhC is showed on scanning electron microscope picture in Fig. 1. Optical characterization is performed by polarization dependent fiber-to-fiber measurement. TM polarized light is guided by total internal reflection and it is transmitted over the whole measured wavelength range (Fig. 1). TE polarized light is transmitted only below 1580 nm. The decrease in transmission power from 1570 to 1585 nm is attributed to the decrease of the group velocity as one approaches the band edge. The measured transmission spectrum is consistent with our simulations.

## 3. 3D PHOTONIC CRYSTALS IN PATTERNED TEMPLATES

Integration of 3D photonic crystals with conventional photonic circuits requires alignment of the crystal with the circuit geometry. In integrated circuits based on thick silicon on insulator (SOI) or silica waveguides and components, the natural mounting is deeply etched well through the component layer, e.g., through the SOI film. If the attenuation length is assumed to be 2 unit cells, the thickness required for an fcc crystal with a buried defect is approximately 6 µm. An example of such a crystal, though without the defect, vertically deposited on patterned silicon substrate is represented in Fig. 2 [15].

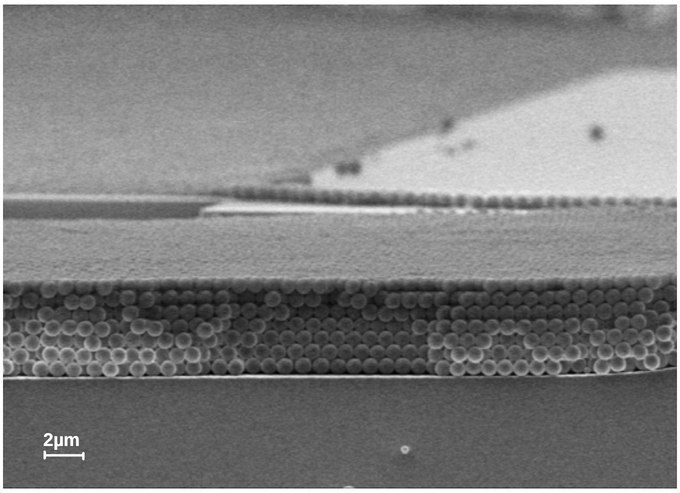

FIG. 2:. Face-centered cubic (111) opal grown from monodisperse silica spheres with diameter 980 nm by vertical deposition on patterned silicon substrate [15].

The small lateral size of the deep well allows a control over the crack positioning. These cracks are probably a consequence of strains induced by the shrinkage of the colloidal crystal during the drying procedure [16]. In the case of opal grown on an unpatterned substrate or in a large area well, these cracks are almost randomly distributed over the surface. Nevertheless, a typical size of crack-free domains can be empirically predicted, and for vertically deposited PMMA is on the order of 100 μm$^2$. The patterned substrate is in practice a rigid frame, which, for trenches smaller than the crack-free typical size, gives rise to large strains. This results in cracks appearing only at the opal–substrate interfaces. This gives a guarantee of a structure free of cracks, at least in volume [4].

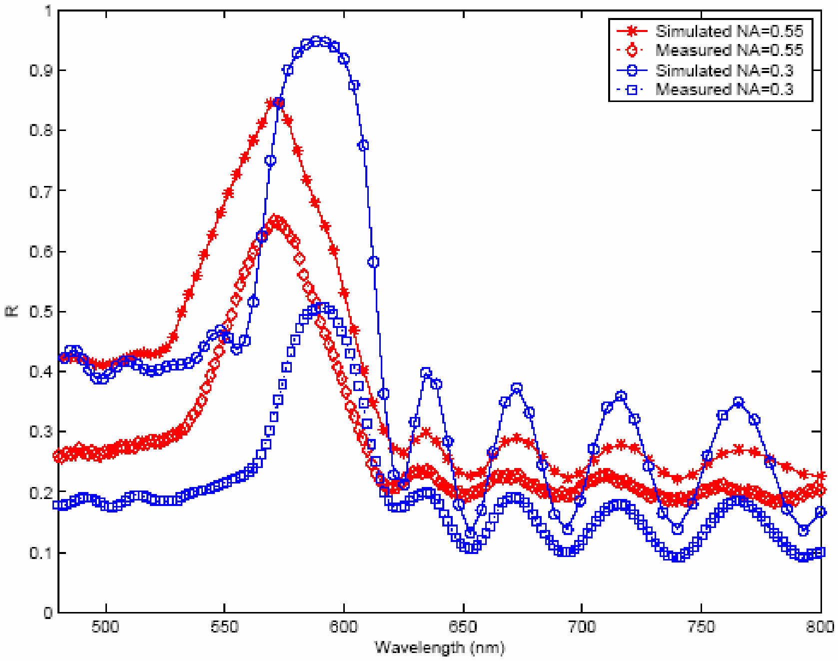

FIG. 3: Measured and simulated reflection spectra from a PMMA opal on silicon. Numerical apertures of 0.55 and 0.3 correspond to spot sizes of 3 μm and 15 μm on the sample, respectively [17].

The measurement of the optical quality of single opal crystallites and opals grown on small pre-defined areas can be easily accomplished by spectroscopic microscope. However, the small lateral dimension necessitates the use of high magnification, which usually indicates high numerical aperture (NA). This makes the interpretation of the results complicated due to the wide angular distribution of the light, which tends to broaden and blue shift the measured Bragg reflection peak. We have developed a robust method for computing the reflection of arbitrarily shaped and sized beams from finite thickness photonic crystals, and obtained consistent results from a large single crystallite with different magnifications [17]. Fig. 3 represents measured and simulated reflection spectra from a PMMA opal on patterned silicon substrate with two spot sizes on the sample - 3 μm with NA=0.55 and acceptance angle 33.4°, and 15 μm with NA=0.3 and acceptance angle 17.5°. This method allows for the direct and nondestructive measurement of the optical quality of a deposited singular opal, as with larger beams it is only possible to probe the overall quality of the opals on a larger area.

## 4. CONCLUSION

On the 2D photonic crystal side, we have showed theoretically that the performance of low air-fill factor PhCs can be improved by using ring-shaped holes rather than the traditional circular holes. We demonstrated experimentally band gap guiding in an RPhC waveguide. On the 3D photonic crystal side, we performed sedimentation of PMMA spheres into silicon templates and achieved large ordered and crack-free opals. Furthermore, we developed a model to estimate the local quality of a finite 3D photonic crystal from reflection spectra at various acceptance angles.

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[1] E. Yablonovitch, Phys. Rev. Lett. **58**, 2059 (1987).

[2] A. Mekis, J. C. Chen, I. Kurland, S. Fan, P. R. Villeneuve, and J. D. Joannopoulos, Phys. Rev. Lett. **77**, 3787 (1996).

[3] B. Gralak, S. Enoch, and G. Tayeb, J. Opt. Soc. Am. A **17**, 1012 (2000).

[4] P. Ferrand, M. J. Minty, M. Egen, J. Ahopelto, R. Zentel, S. G. Romanov, and C. M. Sotomayor Torres, Nanotechnology **14**, 323 (2003).

[5] A. Talneau, L. Le Gouezigou and N. Bouadma, Opt. Lett. **26**, 1259 (2001).

[6] M. Galli, M. Agio, L.C. Andreani, L. Atzeni, D. Bajoni, G. Guizzetti, L. Businaro, E. Di Fabrizio, F. Romanato, and A. Passaseo, Eur. Phys. J. B **27**, 79 (2002).

[7] C. Monat, C. Seassal, X. Letartre, P. Regreny, M. Gendry, P. Rojo Romeo, P. Viktorovitch, M. Le Vassor d'Yerville, D. Cassagne, J.P. Albert, E. Jalaguier, S. Pocas, and B. Aspar, J. Appl. Phys. **93**, 23 (2003).

[8] M. Mulot, A. Säynätjoki, S. Arpiainen, H. Lipsanen, and J. Ahopelto, proceedings of ICTON 2005 (Barcelona), vol. 1, p. 155.

[9] M. Qiu, F2P: Finite-difference time-domain 2D simulator for Photonic devices, http://www.imit.kth.se/info/FOFU/PC/F2P/.

[10] M. Notomi, A. Shinya, S. Mitsugi, E. Kuramochi, and H-Y. Ryu, Optics Express **12**, 1551 (2004).

[11] M. Notomi, K. Yamada, A. Shinya, J. Takahashi, C. Takahashi, and I. Yokohama, Phys. Rev. Lett. **25**, 253902-1 (2001).

[12] S. Johnson and J.D. Joannopoulos, Optics Express **8**, 173-190 (2001).

[13] X. Letartre, C. Seassal, C. Grillet, P. Rojo-Romeo, and P. Viktorovitch, M. Le Vassor d'Yerville, D. Cassagne, and C. Jouanin, Appl. Phys. Lett. 79, 2312 (2001).

[14] S. Hughes, L. Ramunno, J. F. Young and J. E. Sipe, Phys. Rev. Lett. **94**, 033903 (2005).

[15] J. Ye, R. Zentel, S. Arpiainen, J. Ahopelto, S. G. Romanov, and C. M. Sotomayor Torres, to be published.

[16] B. Griesebock, M. Egen, and R. Zentel, Chem. Mater. **14**, 4023 (2002).

[17] K. Varis, M. Mattila, S. Arpiainen, J. Ahopelto, F. Jonsson, C. M. Sotomayor Torres, M. Egen, and R. Zentel, Opt. Exp. **13**, 2653 (2005).