Local tuning of the optical response of two dimensional photonic crystals

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Abstract. *Local tuning of the optical response of GaAs-based two dimensional photonic crystals (PhCs) is reported. A selective polymer infiltration technique was developed. Scanning electron microscopy and optical measurements were used to characterize the filled PhC structures.*

Over the past decade, photonic crystals (PhCs) have been intensively studied as a new platform for the realization of integrated optical devices such as waveguides, filters and switches [1]. On one hand, these devices are classically fabricated by omitting, modifying the size or the position of the air holes [2]. On the other hand, several theoretical studies suggested that selective filling of photonic crystal holes can provide a novel platform for ultracompact photonic integrated circuits and open the way up to create components such as single mode waveguides, broadband low-reflection waveguide bends, crossings, splitters [3] and ultrahigh-*Q* cavities [4]. Therefore PhC infiltration with organic materials [5-8] has a great potential for the realization of PhC devices provided that a selective filling procedure is achieved. For instance, F. Intonti *et al.* have demonstrated local microinfiltration of liquids via hollow submicron size pipettes [9], and C. Smith et *al.* have used a similar technique to create a PhC double heterostructure [10]. Moreover, D. Erickson et *al.* have used nanofluidic targeting to infiltrate a single row of holes within a planar PhC using fluids with different refractive indices [11].

In this communication, we present a selective polymer infiltration technique to trim the optical properties of GaAs-based planar PhC membranes. Our technique has several advantages with respect to micro-/nano- pipetting and nanofluidic procedures: it is fast, simple, easily reproducible and enables the control of the size of infiltrated PhC region (from 1 to 10 μm) [12].

Experiment

The sample, grown by molecular beam epitaxy, consists of a 320-nm-thick GaAs membrane on top of a 1.5 μm $Al_{0.7}Ga_{0.3}As$ sacrificial layer. A single layer of self-assembled InAs quantum dots (QDs) (high aerial density:100-150 dots/μm^2) emitting at 1.3 μm is embedded in the middle of the membrane. PhC nanocavities were fabricated using e-beam lithography and CHF_3 plasma etching of a hard SiO_2 layer which eventually serves as a mask for the pattern transfer onto the GaAs layer by $SiCl_4/O_2/Ar$ reactive ion etching [13]. The sacrificial layer is then selectively etched in a diluted HF solution to release the GaAs membrane. As a result, a PhC structure is obtained at the center of a 12 µm diameter suspended membrane. A L3 defect cavity was formed by omitting three holes along the ΓK direction at the center of the PhC triangular slab. The lattice constant and the holes diameter are a=330 nm and d~193nm, respectively [Fig. 1(a)]. This provides an air filling factor of 0.31 that corresponds to a photonic bandgap for the TE polarization at wavelengths around 1.3 µm. For the selective infiltration experiments we used a polymer with a refractive index n=1.502±0.005 at λ=1.3 µm. Details on the filling procedure are given in reference 12.

Results

Scanning electron microscopy (SEM) top view images of (a) empty and (b)-(c) locally infiltrated L3 cavities are shown in Figure 1, respectively. The size of the infiltrated PhC region can be controlled at the micrometer scale (i.e. corresponding to tens of air holes): e.g. 5.2 µm and 1.2 µm in figures 1(b) and 1(c) respectively.

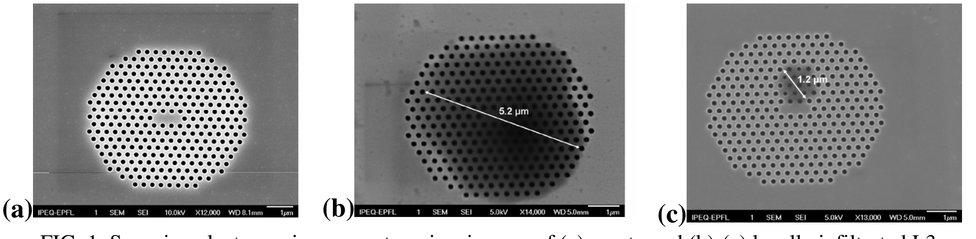

FIG. 1. Scanning electron microscopy top view images of (a) empty and (b)-(c) locally infiltrated L3 cavities. The dark regions are the polymer-filled areas.

Optical measurements were performed with an internal light source technique with frontal collection [14]. A helium-neon laser at 632.8 nm was used to excite the QD luminescence in the membrane. The frontal emitted signal is collected through the same objective and then coupled to a multimode fiber which is connected to a spectrometer providing a spectral resolution of 0.1 nm. The results are shown in Figures 2 (a) and (b). When the empty cavity is excited, a resonance peak appears at λ~1248 nm that corresponds to a cavity mode of the L3 cavity. Fitting the measured resonance wavelength with a two-dimensional plane wave expansion (2D-PWE) calculation, a filling factor value of 0.31±0.01 is obtained, which agrees with SEM measurements. The full width at half maximum of the peak resonance yields a quality factor Q ≈ 435.

Once the cavity boundaries are globally infiltrated [Fig. 1(b)], the resonance peak red-shifts due to the reduced refractive index difference between the holes and the substrate (Δλ=44 nm) [Fig. 2(a)]. The 2D-PWE fit of this energy peak provides the refractive index value of the infiltrated holes that is consistent with the polymer refractive index measured by ellipsometry. After the infiltration, the cavity quality factor decreases due to the reduced reflectivity of the PhC boundaries (Q' ≈ 199).

When the cavity is locally infiltrated [Fig. 1(c)], the resonance peak slightly red-shifts (Δλ=4 nm) [Fig. 2(b)]. This shift is consistent with the 2D-PWE calculation for the same polymer distribution as in Fig. 1(c). The cavity quality factor slightly decreases with respect to the empty state (Q' ≈ 360).

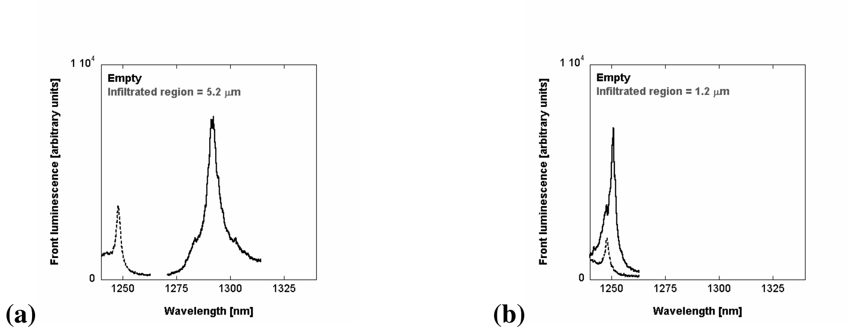

FIG. 2. Front luminescence spectra of the locally infiltrated L3 cavities shown in figure 1 (solid lines). The diameter of the polymer-filled region is (a) 5.2 μm and (b) 1.2 μm, respectively. The resonance peaks for the corresponding empty cavities are shown as reference (dashed lines).

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References

[1] K. Busch, S. Lölkes, R.B. Wehrspohn, and H. Föll, Photonic Crystals, Weinheim: Wiley-VCH, 2004.

[2] B-S. Song, S. Noda, T. Asano and Y. Akhane, "Ultra-high-*Q* photonic double-heterostructure nanocavity", Nature Materials, vol. 4, pp. 207-210, 2005.

[3] S. Mingaleev, M. Schillinger, D. Hermann and K. Busch, "Tunable photonic crystal circuits: concepts and designs based on single-pore infiltration", Optics Letters, vol. 29, pp. 2858-2860, 2004.

[4] S. Tomljenovic-Hanic, C. Martijn de Sterke and M.J. Steel, "Design of high-*Q* cavities in photonic crystal slab heterostructures by air-holes infiltration", Optics Express, vol. 14, pp.12451-12456, 2006.

[5] J. Martz, R. Ferrini, F. Nüesch, L. Zuppiroli, B. Wild, L.A. Dunbar, R. Houdré, M. Mulot and S. Anand, "Liquid crystal infiltration of InP-based planar photonic crystals", Journal of Applied Physics, vol. 99, 103105, 2006.

[6] R. Ferrini, J. Martz, L. Zuppiroli, B. Wild, V. Zabelin, L.A. Dunbar, R. Houdré, M. Mulot, and S. Anand, "Planar photonic crystals infiltrated with liquid crystals: tuning and optical characterization of molecule orientation", Optics Letters, vol. 31, pp. 1238-1240, 2006.

[7] P. El-Kallassi, R. Ferrini, L. Zuppiroli, N. Le Thomas, R. Houdré, A. Berrier, S. Anand, and A. Talneau, " Optical tuning of planar photonic crystals infiltrated with organic molecules," Journal of the Optical Society of America B, vol. 24, pp. 2165-2171, 2007.

[8] R. van der Heijden, C-F. Carlström, J. Snijders, R. W. van der Heijden, F. Karouta, R. Nötzel, H. Salemink, C. Kjellander, C. Bastiaansen, D. Broer, and E. van der Drift, "InP-based two dimensional photonic crystals filled with polymers," Applied Physics Letters, vol. 88, 161112, 2006.

[9] F. Intonti, S. Vignolini, V. Türck, M. Colocci, P. Bettotti, L. Pavesi, S.L. Schweizer, R. Wehrspohn and D. Wiersma, "Rewritable photonic circuits", Applied Physics Letters, vol. 89, 211117, 2006.

[10] C. L. C. Smith, D. K. C. Wu, M. W. Lee, C. Monat, S. Tomljenovic-Hanic, C. Grillet, J. Eggleton, D. Freeman, Y. Ruan, S. Madden, B. Luther-Davies, H. Giessen and Y-H. Lee, "Microfluidic photonic crystal double heterostructures", Applied Physics Letters, vol. 91, 121103, 2007.

[11] D. Erickson, T. Rockwood, T. Emery, A. Scherer and D. Psaltis, "Nanofluidic tuning of photonic crystal circuits", Optics Letters, vol. 31, pp. 59-61, 2006.

[12] P. El-Kallassi, S. Balog, L. Balet, L.H. Li, R. Ferrini, R. Houdré, A. Fiore and L. Zuppiroli, "Local tuning of the optical response of two-dimensional photonic crystals", Applied Physics Letters, submitted.
[13] A. Gerardino, M. Francardi, L. Balet, C. Monat, C. Zinoni, B. Alloing, L.H. Li, N. Le Thomas, R. Houdré and A. Fiore, "Fabrication and characterization of point defect photonic crystal nanocavities at telecom wavelength", Microelectronic Engineering, vol. 84, pp. 1480-1483, 2007.
[14] R. Ferrini, D. Leuenberger, M. Mulot, M. Qiu, J. Moosburger, M. Kamp, A. Forchel, S. Anand, and R. Houdré, "Optical study of two-dimensional InP-based photonic crystals by internal light source technique", IEEE Journal of Quantum Electronics, vol. 38, pp. 786-799, 2002.