k-Space Spectroscopy of Photonic Crystal Slabs

M. Galli[1], M. Belotti[1], M. Patrini[1], D. Gerace[1], L.C. Andreani[1], Y.Chen[2]
[1]*Dipartimento di Fisica "A. Volta", Università di Pavia, via Bassi 6, 27100 Pavia, Italy*
[2]*Département de Chimie, Ecole Normale Supérieure, 24 Rue Lhomond, 75231 Paris Cedex 05, France and Laboratoire de Photonique et de Nanostructures, CNRS, Route de Nozay, 91460 Marcoussis, France*

ABSTRACT
In this work we show how the dispersion relation of slab-type PhCs can be directly determined both in the radiative and guided mode regimes by means of k-space spectroscopy. Angle-resolved reflectance, attenuated total reflectance and micro-photoluminescence spectroscopy are used to determine several important characteristics like band-edge dispersion, slow-light propagation or far-field intensity distribution in passive as well as in active PhC devices. The results are successfully compared to theoretical calculations based on scattering matrix and guided mode expansion methods.

1. INTRODUCTION

Waveguide-based photonic crystals (PhC) have become a popular choice to realize highly advanced functional devices, ranging from low-threshold nanolasers to ultra compact slow-light devices [1-5]. This is due to their peculiar optical properties, which allows one to modify and to engineer the dispersion relation for photons at optical frequencies. For instance, nanoscale waveguides can be realized by introducing linear defects in a periodic structure. On the other hand, very high quality factor optical cavities with a modal volume of the order of a cubed wavelength may be obtained by simply removing one or few holes in the PhC lattice. When designing a PhC device for a particular application one has to face with the so called light-line problem. In fact, the $\omega(k)$ dispersion of the defect- and bulk- photonic modes lies partly above and partly below the dispersion line of light in air. As in conventional dielectric slabs, the former modes can couple with external radiation being quasi-guided modes with intrinsic finite linewidths, while the latter are truly guided modes with very low propagation losses which are more suitable for photonic applications. In this view, experimental methods which are able to gather information in the frequency-wavevector space, i.e. the photonic band dispersion, and to compare them with theoretical calculations are of fundamental interest.

2. EXPERIMENTAL

2.1 Sample Fabrication

One- and two-dimensional photonic crystal structures were patterned in Silicon on Insulator (SOI) wafers (SOITEC) by means of Electron Beam Lithography (EBL) followed by Reactive Ion Etching (RIE). EBL was performed on PMMA resist using a JEOL JBX5D2U vector scan generator at 50 keV energy. After developing the PMMA, pattern transfer to the waveguide core was realized through three-layer process: a 500 nm-thick S18 bottom layer, a 50 nm-thick Ge middle layer and a 150 nm-thick PMMA top layer. The top and middle layer were etched by standard RIE techniques, while the silicon top layer is etched by RIE using a SF6 and CHF3 gas mixture. The RIE parameters were optimised to obtain steep sidewalls in silicon [6]. One-dimensional structures consisting of linear arrays of air grooves were realized with the following parameters: slab thickness $d = 260$ nm, lattice constant $a = 650$ nm, air fraction $f = 0.18$. Membrane type two-dimensional PhCs realized in the triangular lattice of air holes and containing W1 single line defects (obtained by removing a single line of holes) were fabricated with parameters $d = 220$ nm, $a = 500$ nm, $r/a = 0.3$. Suspended membrane structures 20 m wide by 200 m long were obtained by selectively removing the SiO_2 cladding in an HF solution.

2.2 k-space spectroscopy techniques

2.2.1 Angle resolved reflectance and attenuated total reflectance

Optical spectroscopy in the k-space, i.e. mapping of the energy-momentum dispersion relation for both radiative and guided photonic modes, can be performed by means of angle-resolved reflectance and attenuated total reflectance (ATR) techniques, and have been applied to different slab type PhCs based on silicon or III-V semiconductors [7,9]. These techniques rely on the parallel momentum conservation for light incident and reflected off the PhC surface. When the energy and the wave vector of the incoming

978-1-4244-2626-3/08/$25.00 ©2008 IEEE

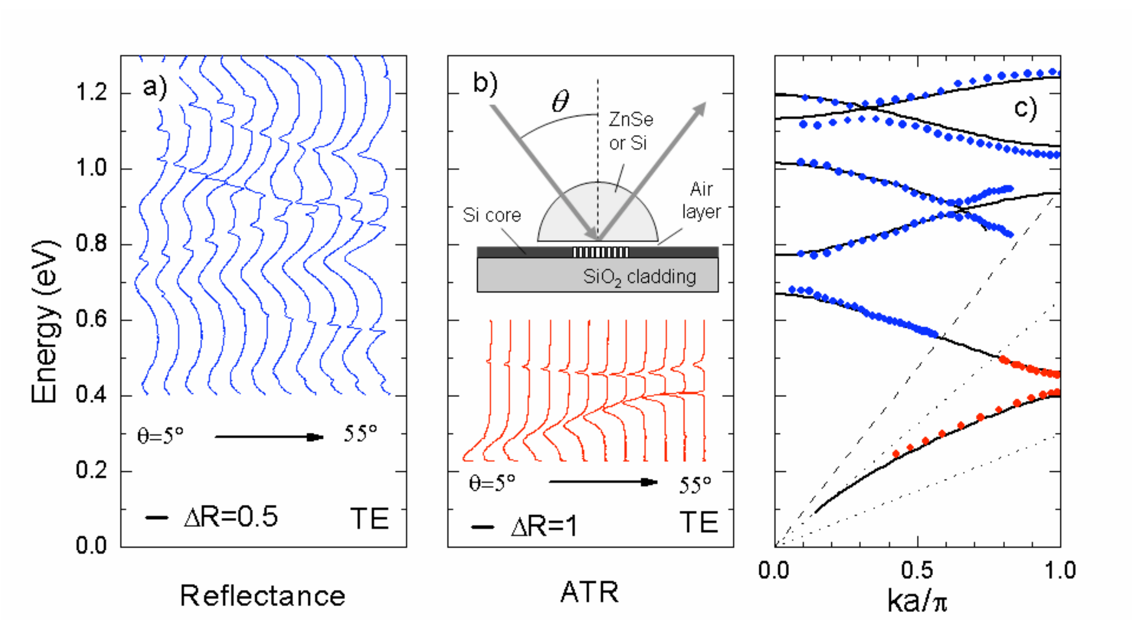

Figure 1. Experimental reflectance (a) and ATR (b) spectra for the 1D SOI PhC sample measured for TE polarization (curves are shifted for clarity). (c) Dispersion of the photonic bands as derived from reflectance and ATR spectra, compared to calculated dispersion (lines). Dotted lines: light lines of air, SiO_2 and Si.

beam match those of a photonic mode of the PhC structure, a resonant feature appears in the reflectance spectrum which marks the excitation of the photonic mode. By varying the angle of incidence and energy of the incident light, the band structure of the sample can be experimentally measured. While simple reflectance allows one to map the photonic bands above the light line (radiative modes), the use of ATR greatly extends the available momentum for incident light, therefore enabling the mapping of truly guided modes, which lie below the light line, up to the Brillouin zone edge. Also in this case, by varying the angle of incidence and energy of the light, the band structure of the sample can be experimentally plotted in a large part of the Brillouin zone. In this latter case, the guided resonances are evanescently excited by means of a high-refractive index hemisphere which is placed and kept very close to the sample surface (at a distance ranging from 100 to 500 nm) and leaving a thin air-layer behind (see sketch in Fig. 1) [10,11].

In this work, angle-resolved specular reflectance and ATR from the sample surface are measured in the spectral range 0.3 – 1.8 eV, at a spectral resolution of 0.5 meV, by means of a micro-reflectometer coupled to a Fourier-transform spectrometer (Bruker IFS66s). The angle of incidence θ is varied in the range 4° – 75° with an angular resolution of 0.5° that is set by the very small but finite numerical aperture of the beam that is focused on the sample. Transverse-electric (TE) and transverse-magnetic (TM) polarizations with respect to the plane of incidence are selected by means of KRS5 wire-grid and calcite Glann-Taylor polarizers. ATR measurements were carried on with a ZnSe or Si hemispheres (refractive index 2.4 and 3.5, respectively) that was kept close to the sample surface by means of piezoelectric actuators.

3. RESULTS AND DISCUSSION

3.1 SOI photonic crystal slabs

Fig.1a shows the experimental reflectance spectra taken on the 1D PhC sample for various angle of incidence. The curves display a prominent interference pattern due the multiple interference occurring at the core-cladding and cladding-substrate interfaces. Superimposed to the interference fringes, several sharp features are clearly visible, whose energy position varies with angle and polarization. We ascribe these structure to resonant coupling of the incident radiation to quasi-guided modes of the patterned waveguide, which lie above the light line and are therefore accessible via simple reflectance. On the other hand, Fig. 1b reports on the ATR spectra taken on the same sample. Here the excitation of guided mode lying below the light-line is clearly manifested through the strong absorption –like dips appearing in ATR spectra. From the measured reflectance and ATR spectra, the photonic band dispersion over the full Brillouin zone (BZ) can be extracted by plotting the energy position of the resonant structures versus the in-plane component of the wavevector of light, as shown in Fig. 1c. Notice the strong curvature of the photonic band dispersion as well as the opening of a band gap as k-vector of incident light approaches the zone edge. We stress here that the experimental mapping of photonic mode dispersion below the light line and up to the BZ edge represents the most direct observation of a photonic band gap in a PhC slab. The experimental data are compared to a full 3D calculation, as obtained by expanding the magnetic field on the basis of the guided modes of an unpatterned waveguide and assuming an average refractive index in each layer [12]. Very good agreement between theory and experiment is obtained for dispersion and energy of photonic bands both TE and TM polarizations (not shown in Fig 1).

3.2 Single line-defect waveguides on Silicon membranes

Angle-resolved ATR reveals as a powerful technique also in the optical characterization of sub-micrometer sized PhC structures [11]. Fig. 2a shows the ATR spectra taken for single W1 waveguides at several incidence angles and obtained employing a Si hemisphere as a high-index prism. Although the resonant structures corresponding to the excitation of the defect mode are now much weaker, the characteristic dispersion of the TE-polarized W1 mode can be readily measured up to the zone boundary and above. In fact, we notice that incident angles θ higher than about 40 degrees using a Si prism correspond to k-vectors falling in the second BZ of the 2D photonic lattice. This turns out to be very convenient for the excitation of the W1 mode close to the Si light-line, for which the dominant wavevector component falls in the second BZ. The experimental ATR spectra allows us to extract the W1 dispersion, which display a strong bending from very steep just below the light-line to almost flat (dispersionless) when approaching the zone edge (Fig. 2b). Such a sharp bending translates into extremely strong variation of the group velocity v_g of light propagating in the line defect [13]. Since $v_g = d\omega/dk$, experimental values for the mode's group velocity can be obtained simply by the differentiating the experimental mode dispersion, as shown in Fig. 2c. Here group velocity values as small as c/1000 are inferred from experimental data. Both mode dispersion and group velocity dispersion are very well accounted for by theoretical calculations based on guided mode expansion (Fig. 2b,c). Such low v_g values, although probably difficult to achieve in long (mm sized) devices due to increased scattering losses [14,15], are very promising in view of obtaining efficient slow-light devices for nanophotonics applications [16].

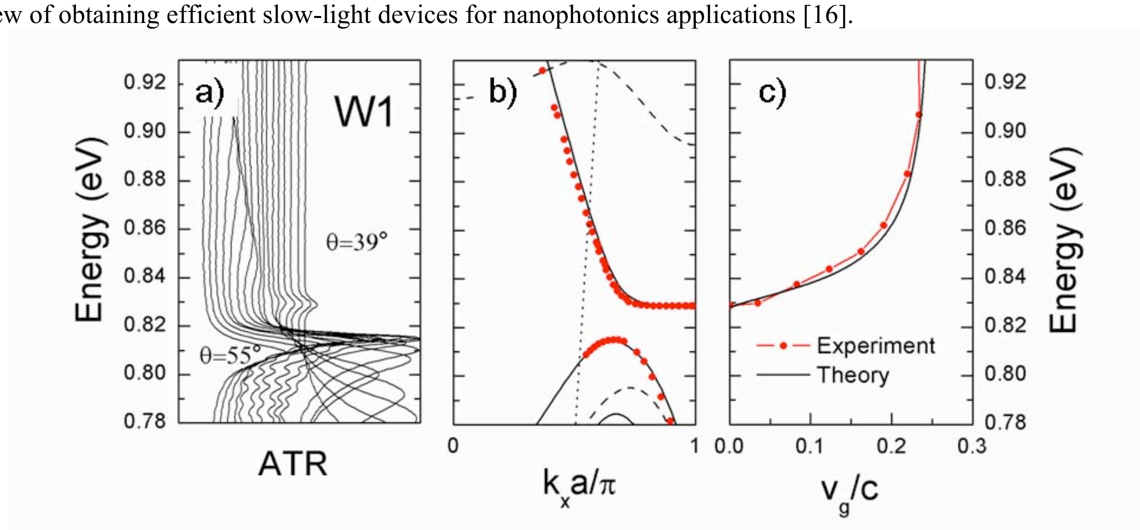

Figure 2. (a) Experimental ATR spectra measured on a single line-defect W1 waveguide, for TE polarization (curves are shifted for clarity). (b) Measured dispersion of the photonic bands as derived from ATR spectra (closed circles) compared to calculated dispersion (lines). (c) Experimental group velocity dispersion (closed circles) compared to calculated dispersion (line).

4. CONCLUSIONS

We have shown that angle-resolved reflectance and attenuated total reflectance can be successfully used as k-space spectroscopies to measure the photonic band dispersion over the whole Brillouin zone in one- and two-dimensional PhC slab. In particular, ATR spectroscopy allows the direct observation of important characteristics like the opening of photonic band gaps at zone edge, as well as the group velocity slowing down, occurring in the guided mode region below the light line. The high sensitivity of the technique reveals when measuring sub-micrometer sized PhC structures like, for instance, single line-defect waveguides. The experimental are found to be in very good agreement with full 3D calculations based on the expansion of the magnetic field on the guided modes.

REFERENCES

[1] P. St., J. Russell, D. M. Atkin, T. A. Birks, and P. J. Roberts, in *Microcavities and Photonic Band Gaps: Physics and Applications*, vol. 324 of NATO Advanced Study Institute, Series E: Applied Sciences, edited by J. Rarity and C. Weisbuch (Kluwer Academic Publishers, Dordrecht, The Netherlands, 1996), p. 203.

[2] T. F. Krauss, R. M. De La Rue, and S. Brand, *Nature* 383, 699 (1996).

[3] S. G. Johnson, S. Fan, P. R. Villeneuve, J. D. Joannopoulos, and L. A. Kolodziejski, *Phys. Rev. B* 60, 5751 (1999).
[4] A. Chutinan and S. Noda, *Phys. Rev. B* 62, 4488 (2000).
[5] S. G. Johnson, P. R. Villeneuve, S. Fan, and J. D. Joannopoulos, *Phys. Rev. B* 62, 8212 (2000).
[6] D. Peyrade, Y. Chen, A. Talneau, M. Patrini, M. Galli, F. Marabelli, M. Agio, L. C. Andreani, E. Silberstein, and P. Lalanne, *Microelectron. Eng*. 61-62, 529 (2002).
[7] V. N. Astratov, D. M. Whittaker, I. S. Culshaw, R. M. Stevenson, M. S. Skolnick, T. F. Krauss, and R. M. De La Rue, *Phys. Rev. B* 60, R16255 (1999).
[8] M. Patrini, M. Galli, F. Marabelli, M. Agio, L. C. Andreani, D. Peyrade, and Y. Chen, *IEEE J. Quantum Electron.* 38, 885 (2002).
[9] M. Galli, M. Agio, L.C. Andreani, L. Atzeni, D. Bajoni, G. Guizzetti, L. Businaro, E. Di Fabrizio, F. Romanato, A. Passaseo, *Eur. Phys. J. B* 27, 79-87 (2002).
[10] M. Galli, M. Belotti, D. Bajoni, M. Patrini, G. Guizzetti D. Gerace, M. Agio, L. C. Andreani, and Y. Chen, *Phys. Rev. B* 70, 081307(R) (2004).
[11] M. Galli, D. Bajoni, M. Patrini, G. Guizzetti D. Gerace, L. C. Andreani, M. Belotti and Y. Chen, *Phys. Rev. B* 72, 125322 (2005).
[12] L. C. Andreani and M. Agio, *IEEE J. Quantum Electron.* 38, 891 (2002).
[13] Notomi, K. Yamada, A. Shinya, J. Takahashi, C. Takahashi, and I. Yokohama, *Phys. Rev. Lett*. 87, 253902 (2001).
[14] D. Gerace and L. C. Andreani, *Opt. Lett.* 29, 1897 (2004).
[15] L. C. Andreani, D. Gerace, and M. Agio, *Photonics Nanostruct. Fundam. Appl*. 2, 103 (2004).
[16] Liam O'Faolain, T.P. White, D. O'Brien, X. Yuan, M.D. Settle, and T.F. Krauss, *Opt. Expr.* 15, 13129 (2007).