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Evidence of Bloch wave propagation within photonic crystal waveguides

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ABSTRACT We report in this paper results obtained from characterizations of photonic band gap waveguide, using near field optical microscopy. We will show evidence of a Bloch wave propagating within our W1 photonic crystal waveguides (PCWs) structure, using a 2D Fourier transform approach. The processed image will then be compared to simulations obtained from plane wave method. This comparison exhibits that near-field measurements, using tapered optical fibers as probes, are mainly sensitive to the electric field propagating within the structure.

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1 Introduction

Photonic bandgap structures have drown a considerable interest since the pioneering work of E. Yablonovich [1] and S. John [2]. Their use to realize compact waveguide has been pointed out very early [3]. Since, photonic crystal waveguides (PCW) have been widely studied on InP membrane [4], thick waveguide on InP substrate [5, 6], SOI substrate [7–9] and GaAs waveguide [10]. Most of these studies rely on "classical" optical measurement where global information (transmission spectra, losses...) are obtained. Some recent work by Bozhevolnyi et al. [11] have shown nice near field optical characterizations on PCW and related bends. However if light guiding is evidenced in this paper, no clear image of the Bloch modes that compares to simulations is presented, mainly because of the speckle like background that smears out the sharp features. Revealing the Bloch modes that propagates in photonic crystal is important not only because it helps in a deeper understanding of PCWs with a direct comparison with the simulations, but also because the interaction between the SNOM tip and the electromagnetic field could be studied. Indeed, the electric and magnetic field of Bloch waves differ greatly in PCW because of the high difference in refractive index between the air holes and the semiconductor. As a consequence, the sensitivity of SNOM measurements to the electric or magnetic (or both) fields can be easily put forward and analyzed.

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2 Description of the sample and experimental set-up

Our PCWs are fabricated on a two-dimensional photonic crystal consisting of a triangular array of holes drilled vertically on an InP/GaInAsP/InP waveguide. The thicknesses of the InP upper layer and the GaInAsP confining layers are 0.2 μm and 0.5 μm respectively. The period of the photonic crystal is 0.36 μm and the hole diameter is 0.23 μm. These holes are etched by chemically assisted ion beam etching (CAIBE) using Ar/Cl2 chemistry [5]. The typical etched depth is larger than 3 μm for an air-filling factor $f = 40\%$. For the purpose of external source measurement, and for a reproducible coupling of the light in and out the photonic crystal (PC) section, the PCW is inserted in-between two monomode ridge access guides limited by cleaved facets [6]. For a proper width of the access ridges, the transmission from the ridge to the W3 PCW is above 90% on a very wide spectral range. The coupling to the W1 waveguide is insured by a taper section made by varying the hole radius [12]. The taper is partially visible on the bottom of Fig. 1a.

The experimental set-up consists of a collection mode SNOM with a tapered and metallized fiber tip used as a probe. Our apparatus, based on a commercial near-field optical microscope by Omicron™, has been modified for its specific use as a tool to investigate photonic waveguiding structures. For this purpose, a special piezoelectrically driven translation stage has been added which permits highly precise injection fiber positioning for an optimized fiber to device coupling. TE-polarized light (i.e., electric field is parallel to the multi-layer plane) is launched into the device via a lensed monomode fiber from a tunable laser source with wavelength set to 1510 nm in a high transmitting region of the waveguide. Both topographical and optical near-field images are then recorded simultaneously over the sample's surface.

3 Results and discussion

We have reported in Fig. 1a, the topographic view of the sample and the corresponding optical SNOM image in Fig. 1b. We can clearly see the details of the W1 waveguide

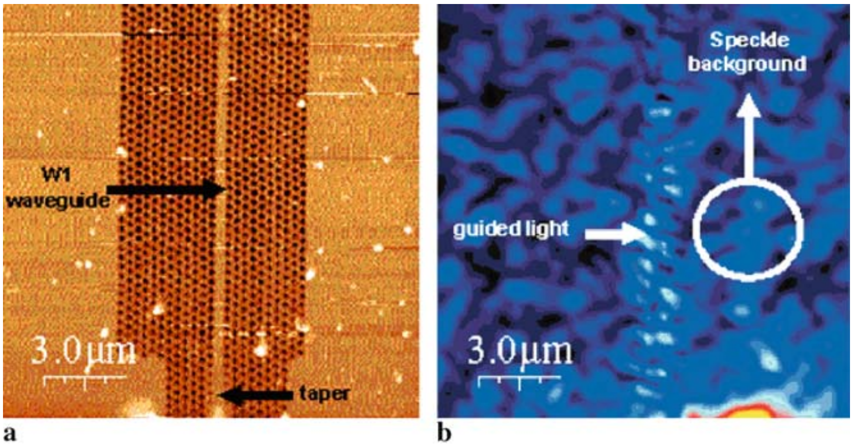

FIGURE 1 (**a**) Topographical and (**b**) Raw optical SNOM images of the sample

structure on the topographic view, starting from the taper at the input to the waveguide itself. On the SNOM image, we can observe three main components. First, one can clearly visualize the guided light in the W1 waveguide. Details as sharp as 100 nm give an estimate of our spatial resolution. At the bottom left, we can see an intense light spot that corresponds to out of plane scattering. We attribute this to coupling losses between the input waveguide and the taper. This feature is also observed in the far field view of the structure, indicating its non-evanescent character. Third, a "speckle" like background is observed on the entire image. This parasitic background prevents us to detail the guided light. We are sure that the detected guided light corresponds to an evanescent field because it is not seen in a far field view of the structure. Nevertheless, there are much more information in the collected data that the one that appears in the raw SNOM image. We thus need a way to subtract the speckle background and to enhance the contribution of the Bloch mode. A straightforward way to do this is based upon a 2D Fourier image analysis.

The 2D Fourier transform of the SNOM image is presented in Fig. 2. All the image processing presented here has been done thanks to the freely distributed software WSXM [13]. It should be noted that the scale is a logarithmic one, in order to visualize smaller contributions. Three main contributions appear in the Fourier space :

1- An intense central spot (depicted as a dashed circle in the figure) that represents the major contribution to the real space image

2- Three vertical lines that extends over all the Fourier space that corresponds to out of plane diffracted light

3- Horizontal equally spaced lines. These lines are exactly what one would expect as a signature of a propagating Bloch wave within a PCW.

Indeed, a wave propagating in an infinite PCW along the z propagation axis satisfies the following relationship:

$$\Psi(z+a) = \Psi(z)\exp(\mathrm{i}k - za) \tag{1}$$

where Ψ stands for the electric or magnetic field, a represents the period along the propagation direction, and k_z the propagation constant. The recorded SNOM signal is not sensitive to the phase of the electromagnetic waves, only to its amplitude i.e. $|\Psi|$. Therefore, the signal is periodic along the z direction with a period a. Its 2D Fourier transform should be discrete along the z direction corresponding to $k_z = n2\pi/a$, where n is an integer. Bloch modes should thus appear as equally spaced horizontal lines with an interval that corresponds to the period a. This signature is clearly observed in Fig. 2. The spacing between the Bragg lines corresponds to a period of 0.36 µm, i.e. exactly the period of the PCW.

In order to show evidence of the propagating Bloch wave, a circular cut filter was applied to the intense central spot in order to get rid of the speckle background and have a closer look on the contribution given by the horizontal lines. The filtered image is shown on Fig. 3. On this image was superimposed a drawing representing the position of the crystal. One can then clearly observe the apparition of a wave propagating within the PCW. This wave having, as expected, the same period as the crystal's can be identified with a Bloch wave.

Since we experimentally obtained the Bloch mode, we can now compare our results to numerical simulations. We calculated the Bloch modes using a 2D plane wave approach in

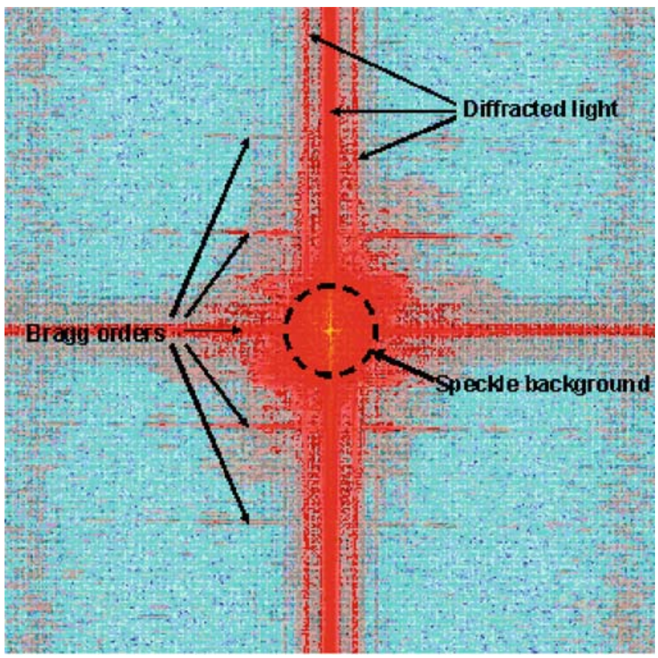

FIGURE 2 2D FFT of the optical SNOM image presented in Fig. 1 (logarithmic scale)

conjunction with the effective index method [14] in TE polarization (i.e. that contains only H_y, E_x and the E_z components of the electromagnetic field where the xz-plane corresponds to the propagation plane). The calculated dispersion curve of the W1 waveguide shows that for the $u = 0.238$ reduced frequency domain investigated here, the structure is monomode and that the guided mode is below the air light line. In this case, the losses occur only in the substrate. This means that most of the SNOM signal detected above the PCW is evanescent (except for the scattering at the input).

We report in Fig. 4 a zoom from Fig. 3 of the topographic and optical SNOM images and the corresponding simulations of the magnetic (H_y) and electric field (E_x) components of the Bloch mode at $u = 0.238$ reduced frequency. We can see that in the optical SNOM image that the signal is maximum in the holes surrounding the waveguide. We can also notice a modulation along the propagation direction with minima between the holes. The E_x component of the electric field has qualitative features that are very similar to those seen in the SNOM image. There is an appreciable field in the first row of holes surrounding the PCW and minima between the holes along the propagation direction. This confirms the fact that the signal detected in SNOM experiment is mainly related to the electric field. In fact, a PCW could be an interesting object to study the interaction between the SNOM tip and the evanescent field. The electric and magnetic field map differs a lot because of the high index contrast between the holes and the semiconductor. We are now performing FDTD simulations to study the tip sample interaction. Preliminary results on 2D structures confirm the fact that the obtained image echoes the electric field map. 3D modellings are on the way to go deeper in the interpretation of the SNOM images.

The last point we wish to discuss here is the influence of topography in our results. Indeed, when operating SNOM measurements on highly corrugated surfaces, which is our case here, optical measurements may be subjugated to topographical artifacts and therefore not reflect the real optical response of the sample. The observed optical signal above

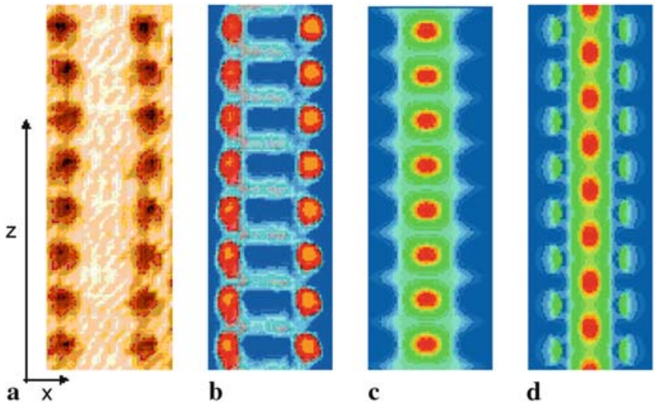

FIGURE 4 Comparison of (**a**) and (**b**) Optical SNOM images (zoomed from Fig. 3 within the white rectangle). (**c**) magnetic field amplitude (H_y) and (**d**) electric field amplitude (E_x) of the plane wave calculated Bloch mode

the PCW could then be related to the movement of the tip that goes in and out of the holes during scanning. One way to encounter this drawback is to perform constant height measurements, i.e. with feedback loop turned off. We were unfortunately unable to perform constant height measurements on those samples. However, results (to be published soon) recently obtained on other structures, namely bent and straight W1 PCWs on SOI, truly confirm that our measurements and Fourier 2D transform analysis clearly evidence the propagation of a Bloch wave within a W1 PCW.

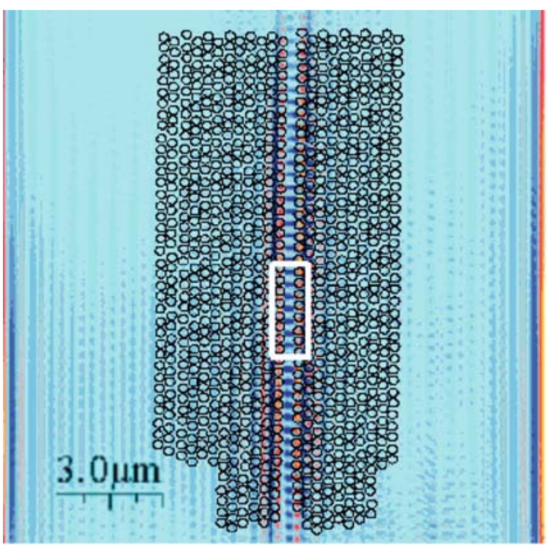

FIGURE 3 Image obtained after filtering Fig. 1b using a cut filter on the contribution marked with a *dashed circle* in Fig. 2

4 Conclusion

We have presented in this paper results of the near field optical characterization of a W1 photonic crystal waveguide. We have shown that we can evidence propagating Bloch modes using filtering in the Fourier space. The signature of the Bloch waves in the 2D Fourier transform appears as horizontal lines equally spaced with a period that corresponds to the PC ones. The obtained results demonstrate that obtained image reflects the electric field map. This sensitivity to the electric field of SNOM measurements, using tapered optical fibers as probes, illustrates that PCW could also be seen as an interesting tool to study the tip sample interaction. Indeed, due to the high index contrast in PCW, electric and magnetic fields have strongly different mappings. Therefore, the respective contribution of the electric or magnetic field can be easily isolated, hence permitting straightforward analysis of the influence of the probe on the measurements.

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