Probing the dispersion properties of 1D nanophotonic waveguides with far-field Fourier optics

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Abstract. *We present an advanced Fourier space imaging technique to probe guided light in nanophotonic structures with an effective numerical aperture of 2.5. This superresolution technique allows us to successfully investigate the dispersive properties of 1D nanowaveguides such as photonic crystal W1 waveguides, photonic wire, slot waveguides, and couplers.*

Introduction

The propagation of light in photonic structures is governed by the dispersion curve $\omega(k)$ relating the frequency ω to the spatial wave vector k. Engineering the slope of $\omega(k)$ allows the implementation of innovative concepts such as slow light in photonic crystal (PhC) waveguides [1] and ultra-fast wavelength conversion in silicon waveguide [2] where the achievement of the phase matching condition between pump and Stokes beams is crucial. Therefore, the experimental investigation of $\omega(k)$ is very important to understand the properties of propagation in such integrated photonic devices.

Some important regions of the dispersion curves lie outside of the light cone, implying that the associated modes do not radiate into free space and as a result propagate with minimal optical losses. Far-field optical techniques are at first view relevant only for the characterization of radiating modes, i.e. inside the light cone, and scanning near-field optical microscopy (SNOM) is currently used to characterize such nanophotonic structures. To retrieve $\omega(k)$, the required phase is determined via heterodyne techniques, which complicate the already cumbersome SNOM technique.

In this paper, we show that far-field optical experiments can be used to accurately extract the dispersion curve of modes propagating below the light cone.

Description of the Fourier space imaging technique

We have combined an end-fire set-up working in the 1.5μm range, generally used to measure the transmission through the waveguide, with a high numerical aperture Fourier space imaging set-up [3]. A single point in the Fourier space that is located in the back focal plane of the collecting lens corresponds to an unique direction of the light scattered from the sample. The continuity of the parallel component of the mode wave-vector at the sample surface implies that a unique in-plane wave-vector of the propagating field is associated with a single measured point in the Fourier space. Therefore, the measurement of the scattered field in the Fourier space for different excitation wavelengths permits, in principle, the retrieval of the dispersion curve of a mode propagating in a photonic waveguide. As the far field characterization of infinite photonic structures cannot record information carried by modes whose wave vector lies below the light line, we used an integrated linear probe grating (LPG) to fold the dispersion curve of truly guided mode into the light cone [4] as shown in Fig.1. Such a LPG acts as a local probe that scatters the transverse evanescent tail of the propagating mode with minimal disturbance if the LPG is far enough from the waveguide. In the present case the chosen lattice constant Λ of the LPG allows us to collect 2 scattered orders, which appears as straight lines in the pupil of the collecting objective (the red circle in Fig.1-center). The variation of the position of the observed lines in the Fourier space versus the different excitation wavelengths mimics the dispersion of the guided mode and can be unfolded back with the knowledge of Λ.

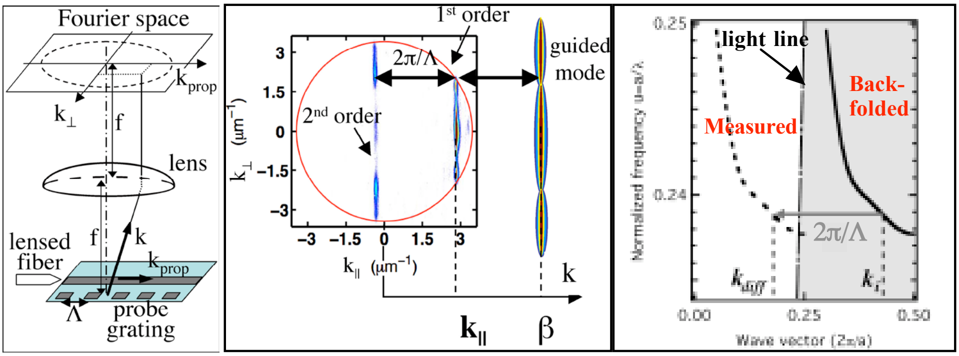

Fig. 1 Left: Schematic of the Fourier-space imaging principle. Center: Optical Fourier space images of a photonic waveguide. The wave vector of the guided mode lies far below the light cone. The first and second orders scattered at the linear probe gratings are however collected in the pupil of the imaging lens (red circle). Right: Illustration of the folding of a theoretical dispersion curve (dark line) into the light cone (dash line). Gray region: region below the light cone.

Dispersion curve of photonic wires and slot waveguides

We investigated rectangular silicon-on-insulator (SOI) waveguides of 300 and 400-nm-width (labelled as R300 and R400, respectively), as well as two different slot waveguides [5]. Waveguide patterns were defined by electron-beam lithography (EBL) using hydrogen silsesquioxane as a resist and transferred to the silicon layer by reactive-ion etching. The lateral profiles of the slot waveguides, S70 and S130, consist of two 180-nm-wide silicon sections spaced by an air trench of 70 and 130 nm, respectively. As shown in Fig.2-left, LPGs have been etched on both sides of the waveguides at the separation distance of Y=1µm or Y=3µm. The comparison of the experimental dispersion curves with simulations (empty circles) based on the Film Mode Matching method reveals a very good agreement. In Fig.2-right, the first order dispersion coefficients are deduced from the experimental dispersion data obtained in Fig.2-center. The observed anomalous first order dispersion results from the effect of the sub-wavelength waveguide geometry that dominates the material dispersion. These data confirm that not only properly designed rectangular wire waveguides but also slot waveguides allow wavelength separated laser beams to be phase-matched around 1.55 µm for nonlinear interactions. Based on the intrinsic fine spectral analysis of this technique we also succeeded to determine the coupling length of SOI wire couplers for different wire widths and relative waveguide separation distances [6].

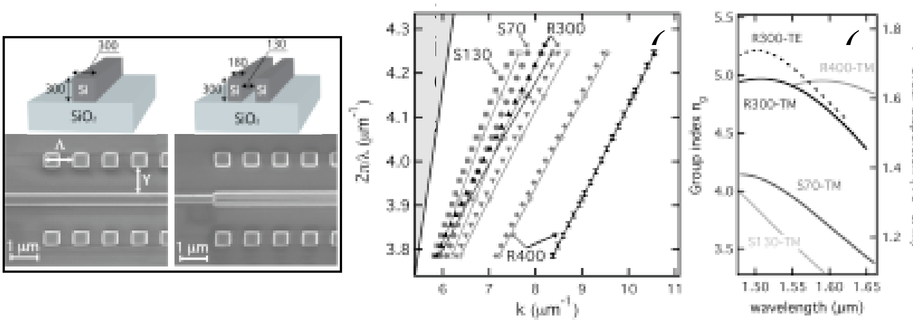

Fig. 2 Left: Perspective layout and top-view SEM images of rectangular R300 (left) and slot S130 (right) wire waveguides. The dimensions are given in nm. Center: Experimental (dots) and theoretical (dots and line) dispersion curves of the TE (dark) and TM (grey) modes propagating in the rectangular and slot nanowires. Right: Experimental group index dispersion curves.

Investigation of slow light modes in PhC waveguides

Figure 3 shows the dispersion curve of a specially designed W1 photonic crystal waveguide (SW1) as well as a standard W1 waveguides. The SW1 waveguide was engineered to operate in a slow-light regime over a large frequency bandwidth, by changing the diameter of the first and second row of holes near the line defect [1]. Two LPGs were etched outside of the PhC pattern in order to probe the dispersion properties of the W1 waveguide. The Fourier space image of the emitted light from the gratings exhibits sharp lines, labeled D1, D2 and Dr1 corresponding to the forward first-order, the forward second-order, and the backward-scattered first-order waves, respectively. The spacing between D1 and D2 is exactly equal to the modulus of the LPG reciprocal wave vector. Note that the phase wave vector of each component of the Bloch wave is unambiguously determined in the Fourier imaging space, which is not the case for a numerical Fourier transform of the real space image. The k_x-position of these lines varies according to the wavelength as plotted in Fig.3-left. This variation accelerates when the excitation wavelength enters the slow-light regime, i.e. for wavelengths λ longer than ~1.53µm. A 3D plane wave expansion calculation of the SW1 band structure is in very good agreement with the unfolded experimental data. In addition to the dispersion curves, the linewidths of the far-field spectra, which are not limited by the set-up resolution, provide a direct access to the modal losses. Note that wave vectors corresponding to group index higher than 150 could not be measured due to the disorder and the impedance mismatch at the input coupling between the PhC waveguide and the access ridge waveguide. This explains in particular why the dispersion curve of the W1 reference waveguide stops at k=0.39 (2π/a) whereas in the case of the SW1 even mode the limit is at k=0.45 (2π/a).

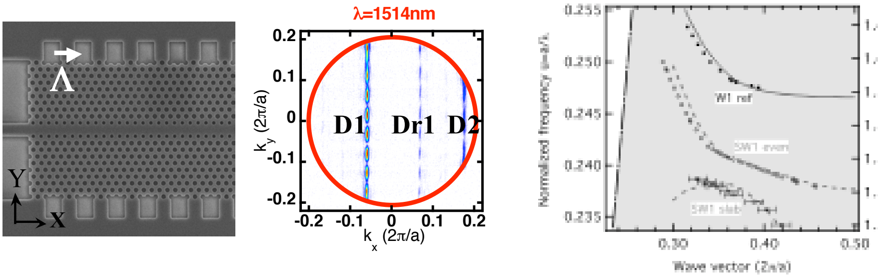

Fig. 3 Left: an electron microscopy image of a SW1 waveguide with the linear probe gratings at the waveguide boundaries (lattice constant *a*=370nm and Λ=4a). Center: a Fourier space far-field image of the Bloch wave mode propagating in the SW1 waveguide and scattered at the linear probe gratings. Right: experimental (dots) and theoretical (lines) dispersion curves.

Conclusion

An advanced Fourier space imaging technique has been successfully applied to retrieve important information about the optical properties of SOI nanophotonic waveguides. The ability to probe the wave vectors below the light cone, i.e. wave vectors of evanescent modes, has to be linked with the issue of the resolution of optical microscope. Here the largest wave vectors measured correspond to an effective numerical aperture of 2.5. In the present study the integrated optics and the optical microscopy fields merge naturally and both benefit from each other.

Acknowledgement

The authors would like to acknowledge support from the European projects ePIXnet (IST-004525), Funfox (IST-004582), the COST P11 action and the Swiss NCCR-Quantum Photonics. We would particularly like to stress that such a study strongly relied on the role played by the European network of excellence ePIXnet as a catalyst of advanced integrated European research.

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