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Theodore Stedmark

Portland State University, stenmark@pdx.edu

Rolf Könenkamp

Portland State University, rkoe@pdx.edu

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Photoemission electron microscopy to characterize slow light in a photonic crystal line defect

Theodore Stenmark* and Rolf Könenkamp

Department of Physics, Portland State University, P.O. Box 751, Portland, 97207, Oregon, USA

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Using femtosecond nonlinear photoemission electron microscopy (PEEM) we provide a detailed characterization of slow light in a small-size asymmetric photonic crystal structure. We show that PEEM is capable of providing a unique description of the light propagation in such structures by direct imaging of the guided mode. This noninvasive characterization technique allows modal properties such as effective index, phase velocities, and group velocities to be determined. Combining experimental results with finite element method simulation calculations, we study slow light phenomena in a photonic crystal defect mode, and we produce a comprehensive picture of the mechanisms behind it. Our results illustrate the usefulness of electron microscopy in exploring nano-optical applications.

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I. INTRODUCTION

Photonic wave guiding structures exhibiting a strong dispersion relation have attracted considerable attention for applications in integrated optics, communications, and sensing devices [1–3]. Line defects in a photonic crystal (PC) slab offer a highly efficient way to create light with group velocities much smaller than is achievable in uniform materials. Slow light is needed for numerous device applications involving nonlinearity in absorption, transmission and reflection, and optical buffers. Propagation velocities in PC waveguide structures are typically measured with interferometric methods involving the outcoupling of the slow light into an optical fiber and comparing its phase delay to a reference light wave. Direct imaging of the modes in the defect, however, is more challenging. Approaches using scanning near-field optical microscopy have been reported [4]. Here we present an approach for direct mode imaging based on photoemission electron microscopy (PEEM), a high resolution [5,6] microscopy technique that collects photoemitted electrons from the sample surface to form an image. PEEM offers a nonscanning imaging method with a spatial resolution in the range of 5–100 nm by combining the advantages of light excitation and electron imaging. We have previously analyzed the photonic response of thin film slab waveguides [7–9] and experimentally determined dispersion relations [10]. We show here how this technique can be extended to slow light propagation in a PC defect channel that can directly be evaluated from PEEM images.

Our method allows us to characterize even a comparably small photonic crystal consisting of ~ 250 air holes in a ~ 270 -nm thick indium tin oxide (ITO) film on a glass substrate. In this paper we demonstrate the approach by comparing experimental results to a detailed finite element method simulation of the experiment in COMSOL-Multiphysics. The combined approaches enable us to determine accurate

experimental parameters that can then be used in a band structure calculation such that a complete optical picture can be inferred. We use an aberration-corrected PEEM [5] with a spatial resolution of ~ 20 nm in this application. Nonlinear two-photon photoemission with pulsed light in the wavelength interval $390 \text{ nm} < \lambda < 420 \text{ nm}$ is used.

The wavelength is varied to obtain the group velocity in a specific k -vector region near the Brillouin zone edge in the $\Gamma \rightarrow K$ direction of a hexagonal photonic crystal.

II. EXPERIMENT

A. Experimental details and evaluation

ITO-coated borosilicate glass substrates were purchased from SPI Supplies Inc. The ITO films had a specified sheet conductance of 10Ω and a thickness of $280 \text{ nm} \pm 20 \text{ nm}$. We found that the lateral absorption coefficient in these films is $< 10^3 \text{ cm}^{-1}$ at the operation wavelength of 400 nm, such that absorption losses remain small on the micrometer scale, while the conductance is sufficient to prevent charge-up in the microscopy work. A $\sim 1\text{-}\mu\text{m}$ wide trench was milled into the ITO layer with a FEI Strata 273 focused ion beam providing a mechanism for light to couple into the ITO layer via diffraction from the trench edge. Within a distance of $1 \mu\text{m}$ a hexagonal lattice of air holes was milled with a periodicity of $a = 180 \text{ nm}$ and holes of $\sim 95 \text{ nm}$ in diameter, as illustrated in Fig. 1. A typical cross-sectional profile of the hole lattice can be seen in Fig. 2. In this lattice a single row of holes was omitted in the nearest-neighbor direction of the lattice creating a line defect perpendicular to the trench as shown in more detail in Fig. 1.

The higher refractive index of the ITO ($n = 2.1$) [11], compared to the glass substrate ($n = 1.5$) below and the vacuum above the ITO allows for light to be confined vertically within the ITO layer forming a slab waveguide. At a wavelength of 400 nm the ITO work function of 4.2 eV [12] requires a two-photon process to induce photoemission. The yield of the photoemission is nonlinear for multiphoton processes and is given by, $Y_{PE} \propto |E|^{2n}$, where E is the electric field and

*stenmark@pdx.edu

FIG. 1. (a) Schematic showing a view of the sample configuration. (b) Side view illustrating the coupling of incident light into the ITO layer. Incident light diffracts off the trench edge into the thin ITO layer where the waveguide selects for allowed modes. The guided modes interfere with the incident light to create a stationary interference pattern at the ITO surface that is recorded in PEEM.

n represents the number of photons required to overcome the work function. A Spectra-Physics Mai Tai Ti:sapphire laser with ~ 60 -fs pulse duration tunable from 780–840 nm was used as a photon source and a Del Mar second harmonic generator to up-convert to a wavelength range of 390–420 nm.

The second harmonic pulses show a spectral spread of ~ 4 nm and a central wavelength precision of ± 1.2 nm. The laser illuminates the sample at an incident angle of $\sim 60^\circ$

FIG. 2. (a) PEEM image of photonic crystal structure taken with continuous wave illumination at 244 nm. (b) Scanning electron microscopy image of a cross section of a typical hole array milled and exposed by focused-ion beam milling.

with the sample plane normal and in a direction such that the coupling trench is perpendicular to the incoming light within ± 2 degrees. A series of images was taken with central wavelengths from 390 to 410 nm in 0.5–1 nm steps using transverse electric (TE) polarization.

B. Simulation of experimental data

We use COMSOL-Multiphysics which provides an iterative solver to evaluate Maxwell's equations over a finite geometry. We model the experimental photonic crystal waveguide using the same material properties, optical data, and geometry as in the experiment, and apply the same procedure for the measurement and characterization as in the experiment. This procedure allows a detailed consistency check with the experiment. In order to keep the model tractable and reduce the memory requirements, the distance between the light coupling trench and the photonic crystal is set somewhat smaller than in the experimental case. This leads to an offset of the interference pattern in the channel, but as the periodicity of the interference pattern is unchanged, the calculated mode and group velocities are not affected.

C. Photonic crystal calculation

Based on the geometric data determined from simulation and experiment we carry out a PC band structure calculation using MEEP [13]. First a two-dimensional (2D) MEEP calculation is set up to obtain an overview of the main features of the band structure. Subsequently, a 3D calculation is used to fully account for the finite layer height of the photonic crystal and the asymmetric substrate/air configuration. The obtained 3D band structure then allows us to place the experimental and simulated values for the effective index, N_{eff} , as a function of the wave vector, k , into the PC band structure and thereby connect waveguide and PC data.

III. THEORY

In isotropic media the group velocity of a wave packet is given by

$$v_g = \frac{d\omega}{dk}, \quad (1)$$

where ω is the angular frequency and k is the wave number. With a change of variables this may be expressed as

$$v_g = \frac{c}{n - \pi \frac{an}{a\pi}}, \quad (2)$$

where λ is the free space wavelength and n is the material refractive index. In terms of a group index we obtain

$$n_g = \frac{c}{v_g} = n - \lambda \frac{dn}{d\lambda}. \quad (3)$$

The in-plane component of the wave vector, k_{mode} , can be defined in terms of an effective index, N_{eff} , of the waveguide mode as

$$k_{\text{mode}} = \frac{N_{\text{eff}} 2\pi}{\lambda}. \quad (4)$$

The group velocity in the waveguide then becomes

$$v_{gWG} = \frac{d\omega}{dk_{\text{mode}}}, \quad (5)$$

and the group index of the waveguide is

$$n_{gWG} = N_{\text{eff}} - \lambda \frac{dN_{\text{eff}}}{d\lambda}. \quad (6)$$

A large group index indicates a low group velocity. A large group index can be achieved if $dN_{\text{eff}}/d\lambda \ll 0$. Slow light propagation can then be obtained, i.e., the speed at which a wave form or information can travel can be dramatically reduced.

Photonic crystal channel waveguides with complete bandgaps have been shown to exhibit slow light phenomena [14] with effective indexes on the order of a hundred. Typically, bandgap-guided and index-guided waveguides can be distinguished. In the index-guided waveguides the light only interacts within the first few rows of the holes in the waveguide periphery, and slow light occurs predominantly where light reflects coherently from the periodic structure, such that standing or slowly propagating waves are formed. In our case the waveguide belongs to this category. The propagation direction is in the nearest-neighbor direction in real space and in the $\Gamma \rightarrow K$ direction in the reciprocal lattice. For the hexagonal lattice the edge of the first Brillouin zone in the $\Gamma \rightarrow K$ direction lies at a normalized k vector of $ka/2\pi = 2/3$, where a is the periodicity of the lattice. The guided mode produced by the waveguide at $\lambda = 400$ nm, has a wave vector lying in the fourth Brillouin zone. When the k vector of the guided mode approaches the Brillouin zone edge, its dispersion becomes flat and $d\omega/dk \rightarrow 0$ resulting in a small group velocity as seen by Eq. (1).

In two-dimensional structures the guided modes can be categorized as transverse electric (TE) and transverse magnetic (TM), where TE modes have the electric field in the PC plane, while TM modes have the magnetic field in the PC plane. ITO is capable of supporting large TE band gaps in two-dimensional cases as illustrated in Fig. 3(a).

In our case of a thin film waveguide in which the light is confined in the vertical direction by total internal reflection, a full three-dimensional model is needed, and the modes can no longer be categorized as strictly TE or TM, but rather as TE-like and TM-like modes based on the dominant field directions [15]. In a symmetric situation where the ITO layer is embedded in air, TE-like modes as shown in Fig. 3(b) are found to exhibit a narrow bandgap, while no bandgap exists for TM-like modes. The introduction of a glass substrate creates an asymmetry that causes coupling of TE-like and TM-like modes and prevents the existence of a complete band gap [16]. This case is illustrated in Fig. 3(c).

Nonetheless, the asymmetric three-dimensional structure still exhibits interesting dispersion properties due to the geometrical and material properties even in the absence of a complete band gap [17]. In particular, a strong decrease of the group velocity can be obtained when the guided mode k vector approaches the defect channel Brillouin zone edge. The main difference to more ideal structures is, that coupling between

FIG. 3. Band diagrams generated with MEEP for (a) TE modes in a 2D hexagonal air-hole lattice in ITO, (b) TE-like modes in a thin-film ITO lattice with symmetric air cladding. The thick black line represents the light line. (c) All modes in a thin-film ITO lattice on a glass substrate. Note the disappearance of the band gap with the introduction of the asymmetric cladding. The experimental region for this work is indicated by a circle located near the K point.

TE and TM-like modes may occur and the complete bandgap disappears.

IV. RESULTS AND DISCUSSION

Figure 4 shows photoemission micrographs of the PC waveguide for 390, 395, and 400-nm illumination. The images reveal periodic patterns in the photonic crystal and in its channel region. The pattern in the photonic crystal region is based on contrast resulting from the PC holes with their

FIG. 4. (a)–(c) Colorized PEEM image and accompanying periodograms at laser wavelengths $\lambda = 390$, 395 , and 400 nm, respectively. (d)–(f) Fast Fourier transforms of the pixel intensity along the defect channel. The black dashed line represents a Gaussian fit to the experimental data.

variation of surface geometry and surface material composition. As the channelsurface region is plane and homogeneous, it is clear that the image pattern in the channel region involves a different contrast mechanism. It is light intensity contrast that results from the interference of the optical mode propagating in the channel with the laser light directed at the sample at 60° incidence; the photoemission yield is proportional to the square of the light intensity.

The channel patterns shown in Figs. 4(a)–4(c) are evaluated by Fourier transformation. Figures 4(d)–4(f) show the corresponding Fourier transforms of the laterally averaged intensity in the channel from which the wave vector of the guided mode is calculated. In all cases a single mode is observed in the PC defect channel, which changes with the wavelength of the illuminating light. In principle, more than one mode could be identified and characterized simultaneously [7] for a channel that supports multiple modes, but this is not the case here. From the k vector of the interference pattern and the known wave vector of the incident light a direct determination of the wave vector of the propagating channel mode, k_{mode} , is obtained from

$$|\vec{k}_{\text{ref}} - \vec{k}_{\text{mode}}| = k_{\text{int}}, \quad (7)$$

where k_{ref} is the laser light wave vector projected on to the sample surface plane and k_{int} is the wave number of the interference pattern observed in PEEM [18,8].

For the determination of the waveguide group index, n_{gWG} , we take a series of these images with wavelengths from 390 to 410 nm in 0.5–1 nm wavelength steps and then apply Eq. (6) to determine the group index in the channel region from the compiled data set of multiple wavelength sweeps.

FIG. 5. (a) Time-averaged E -field distribution at the ITO surface obtained from the numerical simulation for illumination at $\lambda = 400$ nm. (b) A comparison between the Fourier transforms from simulation (blue dashed line) and PEEM image (orange line). The peak at 180 nm in the simulation data results from the PC hole periodicity and is more prominent in the simulated data.

In the simulation the same approach is used to obtain k_{mode} , N_{eff} , and n_{gWG} . Figure 5 shows the calculated time-averaged electric field distribution at the sample surface and a comparison of the Fourier transforms for the experimental and the simulation results.

The simulation results are sensitive to a number of parameters such as the ITO layer thickness, the precise laser wavelength, precise shape of the air holes, and how far the holes extend into the glass substrate. Running a variety of these parameters allows us to separate out these dependences and characterize them. In this way we are able to match the experimental N_{eff} vs λ relationship well within experimental uncertainties. A comparison between experiment and two simulations with slightly different parameters is shown in Fig. 6, and Table I gives a summary of the underlying model parameters. For all reasonable parameters we find a significant increase in the effective index at wavelengths $\lambda \sim 395$ nm indicating a decreasing group velocity for that wavelength region. The group index that is equivalent to the slowdown factor is plotted in Fig. 6(b).

These results are explained in a band diagram obtained from the three-dimensional MEEP calculation shown in Fig. (7), where the parameters from simulation-2 were used to obtain the band structure of the photonic crystal in the $\Gamma \rightarrow K$ direction. In the figure the PC channel mode is projected into the PC band diagram. As the value for the k_{mode} is past the edge of the first Brillouin zone, a reduced k_{mode} is obtained for the folded zone scheme from

$$k_{\text{reduced}} = 2k_{\text{zone}} - k_{\text{mode}}, \quad (8)$$

TABLE I. Parameters varied between simulations.

	ITO thickness	Hole radius	Depth into glass
Simulation 1	280 nm	45 nm	0 nm
Simulation 2	260 nm	51 nm	90 nm

FIG. 6. (a) Experimental and calculated results for the effective index vs wavelength for the defect mode of the photonic waveguide. The difference in parameters between the two sets of calculated data are given in Table I. (b) Experimental and calculated group index vs wavelength obtained from Eq. (7) and a polynomial least-squares fit for the effective index data in part (a) of the figure. The parameters used for the two simulation models are listed in Table I.

where k_{zone} corresponds to the boundary of the first Brillouin zone of the photonic crystal.

Projecting the dispersion curve for k_{reduced} into the PC band diagram we then find that the dispersion curve for the channel mode flattens near $a/\lambda = 0.5$ as indicated in the

FIG. 7. Band diagram in the $\Gamma \rightarrow K$ direction calculated with MEEP for a PC with parameters corresponding to simulation-2. Only TE-like bands are shown. Yellow dots represent the experimentally determined k_{reduced} of the guided mode in the $\Gamma \rightarrow K$ direction projected on the first Brillouin zone. The dashed black line shows k_{reduced} obtained in simulation-2. A vertical line marks $a/\lambda = 0.5$, which corresponds to the projected Brillouin zone edge for the defect waveguide in the reduced zone scheme.

figure. This corresponds to the edge of the Brillouin zone for the line defect [19,20] and indicates that the observed slowdown is due to interaction with the periodic structure of the waveguide. Furthermore, we find that for decreasing k_{reduced} in Fig. 7 the dispersion curve of the line-defect mode closely approaches a TE-like band indicating a coupling to the PC band structure and a further decrease of $d\omega/dk$ as a consequence of avoided-level crossing. Both effects, the proximity to the line-defect Brillouin zone boundary as well as the approach of the line-defect dispersion curve towards a flat TE-like band in the photonic crystal may therefore give rise to the observed light slowdown.

V. CONCLUSIONS

Using electron microscopy we have examined a finite-size thin-film photonic crystal with an asymmetric stack geometry. This is a realistic photonic structure, but its characterization is challenging, as a clear separation of TE and TM modes is not possible. Through its direct imaging of the mode in the defect channel, PEEM permits a detailed characterization. High spatial resolution and strong image contrast in PEEM allow an accurate determination of guided photonic modes and resonances in the visible and infrared ranges [9,21]. A detailed and quantitative optical description in these structures is a prerequisite for a complete understanding of the mode distributions and power flow in a whole class of integrated photonic devices [22]. In future work a spatial evaluation of optical mode wave fronts appears possible in PEEM. When a pump probe methodology is employed, the time evolution of the modal structure may also become measurable.

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