Imaging of Spatial Modes of One Dimensional Photonic Band Gap Devices using Near-field Scanning Optical Microscopy

G. H. Vander Rhodes, J. M. Pomeroy, T. F. Krauss, M. S. Ünlü, and B. B. Goldberg

Abstract— **We have directly imaged the spatial modes inside a one-dimensional photonic band gap device using near-field scanning optical microscopy. Our results show large scattering at the transition between waveguide modes and lattice modes, as well as increased scattering for wavelengths within the stop band. Additionally, we present preliminary results on infrared imaging of the localized mode of a defect state at the center of the device. Eligible for Best Student Paper Award.**

Keywords— **photonic band gap, near-field scanning optical microscopy, spatial modes**

I. INTRODUCTION

THE photonic band gap (PBG) approach to periodic dielectric structures provides a framework to explore optoelectronic devices using techniques that are familiar to workers in condensed matter physics and engineering[1]. Much of the motivation for this approach was developed through work done in inhibited spontaneous emission[2], where it was experimentally verified that an excited atom has a much longer decay constant when placed in a cavity that does not support the emitted photon[3][4]. Results in one-dimension were extended to two- [5] and three-dimensions [6], where it became useful to start applying concepts such as Brillouin zones, reciprocal lattices, and Bloch waves, familiar from basic condensed matter physics.

Inhibited spontaneous emission has led to application of PBG concepts to optoelectronic devices. In many devices, spontaneous emission plays an important role in limiting the overall efficiency of a device, and by using PBG techniques to reduce it, increases in efficiency of LEDs[7], and lasers[8][9] has been possible. An obvious use of a photonic crystal is that of a wavelength specific optical filter. Since the PBG will not support photon modes within the stop-band, a PBG structure could be incorporated into a waveguide to create a band reject filter.

An important concept easily transfered from atomic lattices and the electronic waves they support to periodic dielectric structures and their photon modes is the concept of a defect. As in electron systems, a defect in a photonic lattice is a slight disruption in the periodicity of the material. This defect can be the removal of a unit cell structure, or it can be a local shift in the lattice spacing. Both of these defects will have an effect on the band structure and hence transmission spectra. If properly designed, a local shift in the lattice spacing, like a $\lambda/4$ phase slip, can open up a very narrow transmission window inside the stop-band. This could be used in the manufacture of a specialized notch filter, made especially useful through the design of structures with the same stop band with slightly different defect peak spectral positions. At the defect wavelength, a photon state within the PBG structure closely localized about the defect. The concept of localization has led to the design of structures that guide light on the nanometer scale with closely spaced defects[10].

II. DEVICES AND GROWTH

The devices studied were grown by molecular beam epitaxy (MBE), consisting of a 0.4 μm $Al_xGa_{1-x}As$ waveguide core ($x = 0.12$) cladded by an $Al_xGa_{1-x}As$ ($x = 0.35$) layer beneath and the air above. The one-dimensional waveguides and air gaps for the PBG structure were patterned using electron-beam lithography, and transferred into silica by dry etching with CHF_3. The silica pattern provided the template for reactive ion etching of the semiconductor waveguide with $SiCl_4$[11]. A scanning electron micrograph of a device with 10 air gaps and 460nm periodicity is shown in figure 1. A range of devices with between 3 and 10 air gaps, periodicities between 400nm and 480nm, and different defects were fabricated from the same wafer.

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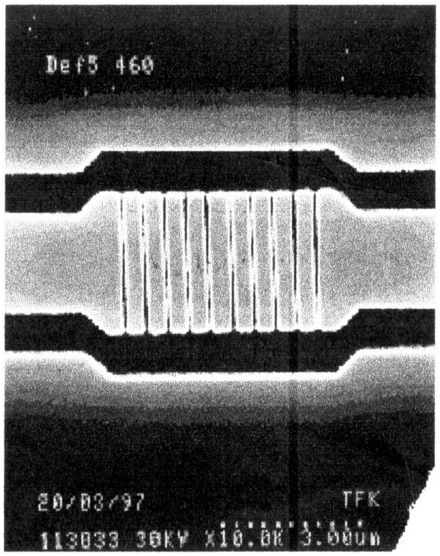


Fig. 1. Scanning electron micrograph of a device with 10 air gaps, 460 nm periodicity. Though indistinct in the micrograph, the spacing between the two central air gaps is 60 nm wider than the periodic spacing of 460 nm between all other air gaps.

III. EXPERIMENT

A schematic diagram of the experimental setup is shown in figure 2. The devices were measured using a tunable Ti:Sapphire laser launched into a single mode fiber whose end had been tapered slightly to a diameter of $\sim 30.0\mu$m using a CO_2 laser and micropipette puller. Optical fields present at the surface of the device were detected using Near-field Scanning Optical Microscopy (NSOM)[12]. The NSOM probe consisted of a single mode fiber tapered to a diameter of $\sim 0.1\mu$m and shadow coated with Al[13]. During scanning, the NSOM probe was held at a constant height of 10nm above the waveguide surface using the tuning fork shear-force feedback method[14]. Light collected by the NSOM probe was detected by an avalanche photodiode in single photon counting mode. An objective lens imaged the waveguide exit facet, and coupled with a pin-hole aperture was used to measure the transmitted light. In the input path, a 2x2 fiber coupler was used to simultaneously monitor the power incident on the sample.

IV. BAND EDGE IMAGING

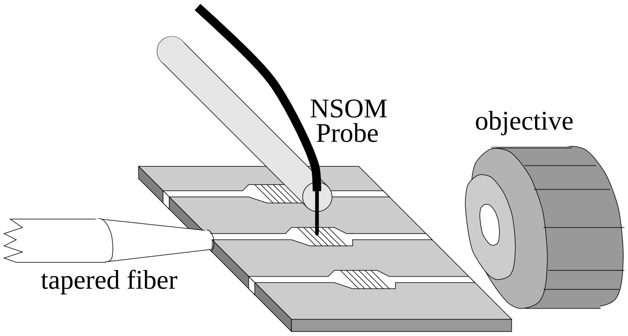
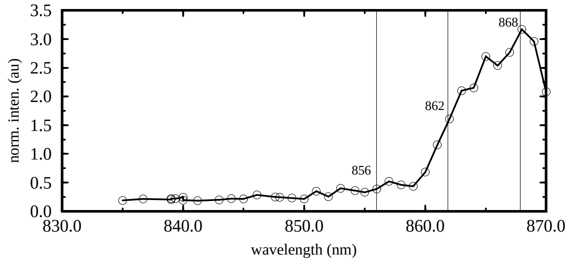


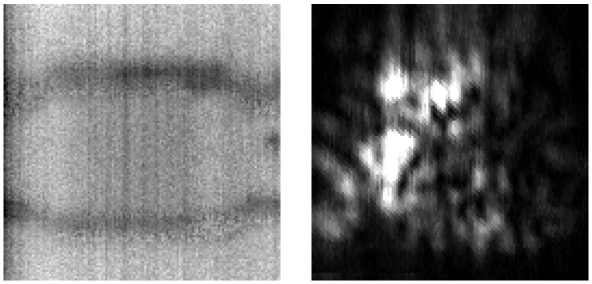
Fig. 2. A schematic diagram of the experimental setup used to measure the waveguides. Shown are the tapered fiber used to launch into the device, the NSOM probe used to collect the near-surface light, and the objective used to image the exit facet of the waveguide (not to scale). Not shown is the nanopositioning equipment used in scanning the tip over the sample.

The stop-band transmission widths of the samples are broader than the tuning range of the Ti:Sapphire laser, so complete transmission curves for a single device could not be obtained. The 400nm periodicity sample was initially chosen since its low-energy band-edge is within our laser window, and we could study the changes in spatial modes between incident wavelengths within and outside of the stop-band. The sample consisted of 4 air gaps on each side of a central defect with a 400nm periodicity to the air gaps.

The transmission as a function of wavelength is displayed in the top of figure 3, showing the long wavelength band-edge and the three wavelengths for the near-field images below. The topographic shear-force image, taken simultaneously with the 856nm data set, is used to correlate the spatial modes to the PBG structure. While the air gaps are not visible in this reproduction, they are resolved in the shear-force data.

The incident beam enters the waveguide from the left in each image. The three near-field images are taken within the stop-band at 856nm, on the band-edge at 862nm, and within the transmission region at 868nm. The overall impression is of interference patterns typical of periodic structures. On closer inspection, the brightest regions are at the transition between the one-dimensional waveguide mode and the photonic crystal mode. This is likely due to the impedance mismatch at such an interface, where power is not only reflected back along the waveguide, but intensity is also scattered into both evanescent and propagating modes which are collected by the near-field probe. Also significant in this data set is the clear increase in penetration of the spatial mode along the length of the photonic crystal region for increasing wavelengths. Note the large increase in intensity on the right-hand side of the 868nm image compared to the 862nm image. As the band-edge is approached, the device becomes more transparent, and the one-dimensional waveguide modes couple more efficiently into the PBG modes and through the device.





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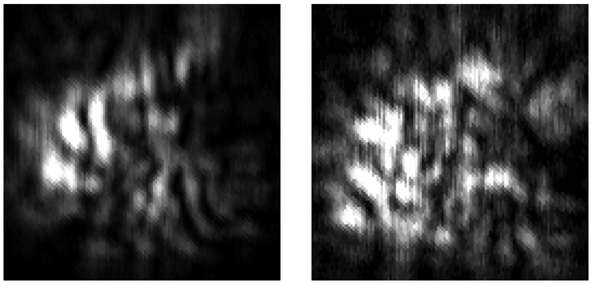

862 nm 868 nm

Fig. 3. Imaging of the band-edge modes. The top graph shows the transmission through the sample, clearly showing the position of the band-edge. The first image is that of the topography of the sample, obtained using the shear-force technique. The other three images are the spatial modes obtained using the NSOM probe and the avalanche photodiode, excited at the wavelengths as indicated on the transmission graph. Note the greater penetration into the device for longer wavelengths.

V. Defect Imaging

Of major interest in telecommunications and in the utilization of PBG devices for all optical switching and wavelength demultiplexing is the performance and characterization of defects deliberately introduced into PBG waveguide structures. Our intent with these devices is to simultaneously map the defect localized evanescent optical fields, and measure any changes in transmission through the structure caused by the presence of the additional dielectric of the NSOM probe. The results presented here are preliminary in nature.

Transfer matrix method (TMM) simulations of these devices indicated that there should not be a defect state in the stop-band of samples with the 400nm periodicity, while a defect should exist in the 440nm periodicity sample. Due to oxidation of the air gaps, however, it is difficult to precisely predict the wavelength of the defect state. Transmission spectroscopy scans found a possible candidate at 874nm in the 440nm period sample. Note that defect states, even in PBG structures with relatively few periods like these can be quite narrow. The TMM simulations estimated the defect width at $\sim$ 0.5nm. A transmission graph and a spatial mode image is shown in figure 4. We see a large localization of light in the area of the defect; quite different from the images taken at wavelengths about the band-edge in figure 3. The optical intensity detected in figure 4 appears to have a significant scattered component to it, indicating a propagating as well as evanescent mode. For a pure PBG crystal and defect, only an evanescent localized mode is expected[15]. We are in the process of additional measurements as well as improving our experimental setup to separate the scattered components from the localized ones.

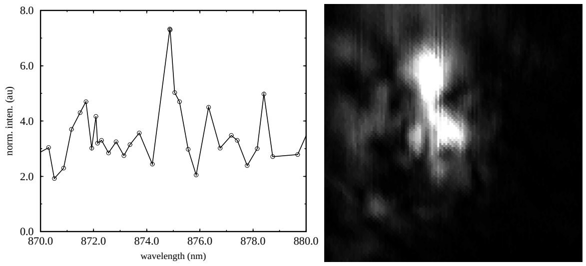

Fig. 4. Imaging of defect modes in the 440nm periodicity sample. The left graph shows a weak peak in the transmission spectra, about 0.5nm wide. The right image is a near-field scan taken at that peak in the transmission. The near-field scan for this launch wavelength is dramatically different than the scans taken about the band-edge in the 400nm sample. The lower of the two bright spots is within the local region of the defect. The upper spot is probably due to some slight roughness in the channel defining the waveguide, causing a great deal of scattered light to couple out of the structure.

VI. Conclusions

Using near-field scanning optical microscopy the spatial optical mode structure of a one-dimensional photonic band gap device operating in the near infrared has been measured for the first time. Clear indication of coupling to the transmitting modes of the PBG is evidenced by the greater penetration as the wavelength is tuned through the band-edge. Additional preliminary results are suggestive of a spatial map of a defect state. These measurements open up the possibility of directly determining the performance and efficiency of real PBG devices.

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