Internal Spatial Modes of One Dimensional Photonic Band Gap Devices Imaged with Near-field Scanning Optical Microscopy

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Photonic band gap (PBG) devices[1] have been used to improve optoelectronic device performance through modification of spontaneous emission, and are currently of much interest due to the control of the photonic state which incorporated defects can provide. The concept of defect localized photon states has led to the design of structures that guide light on the nanometer scale[2].

Near-field scanning optical microscopy (NSOM) can image the optical emission and absorption properties of materials and devices at resolutions typically $< \lambda/10$. Near-field imaging relies on maintaining near-surface scanning and is thus ideally suited to collect evanescent optical fields which do not propagate into the far-field, and cannot be measured by conventional microscopy.

The devices studied were $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As}$ waveguides with microcavities defined by air gaps patterned using e-beam lithography[3]. A slightly tapered single mode fiber was used to launch a tunable Ti:Sapphire laser into the waveguide as shown in figure 1. Optical fields present at the surface of the device were detected in collection mode NSOM[4] with an Al-coated single mode fiber tapered to an aperture of $\sim 0.1\mu$m. During scanning, the NSOM probe was maintained in feedback at a constant height of 10nm above the waveguide surface. An objective lens imaged the waveguide exit facet to measure the transmitted light.

The long wavelength band-edge transmission spectra of a sample consisting of 4 air gaps on each side of a central defect with a 400nm periodicity is displayed in the top of figure 2. The topographic image, taken simultaneously with the 856nm data set, is used to correlate the spatial modes to the PBG structure. The three near-field images are taken within the stop band, on the band-edge, and within the transmission region – the wavelengths denoted by the vertical lines in the transmission spectra. The incident beam enters the waveguide from the left in each image.

The interference patterns observed are typical of periodic structures. Specifically, the brightest regions are at the transition between the one-dimensional waveguide mode and the photonic crystal mode. This is due to the impedance mismatch, 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. As the band-edge is approached, the device becomes more transparent, and the one-dimensional waveguide modes couple more efficiently into PBG modes and through the device, shown as a clear increase in penetration of the spatial modes.

Transmission spectroscopy scans found a possible defect candidate at 874nm in the 440nm period sample. A transmission graph and a spatial mode image is shown in figure 3. A large localization of light in the area of the defect is observed, which is quite different from the images taken at wavelengths about the band-edge in figure 2. The optical intensity detected in figure 3 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[5].

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 results are suggestive of a spatial map of a defect state.

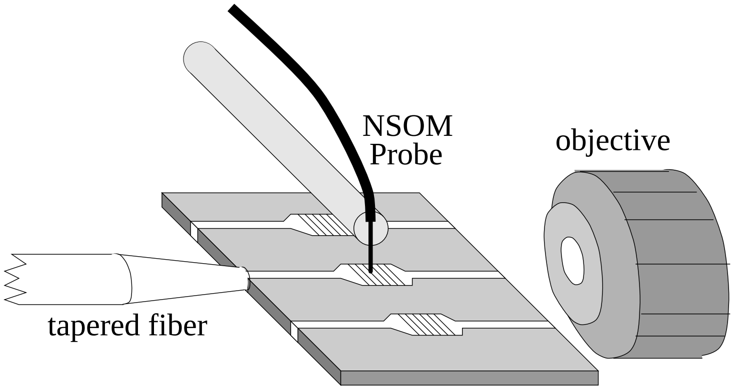
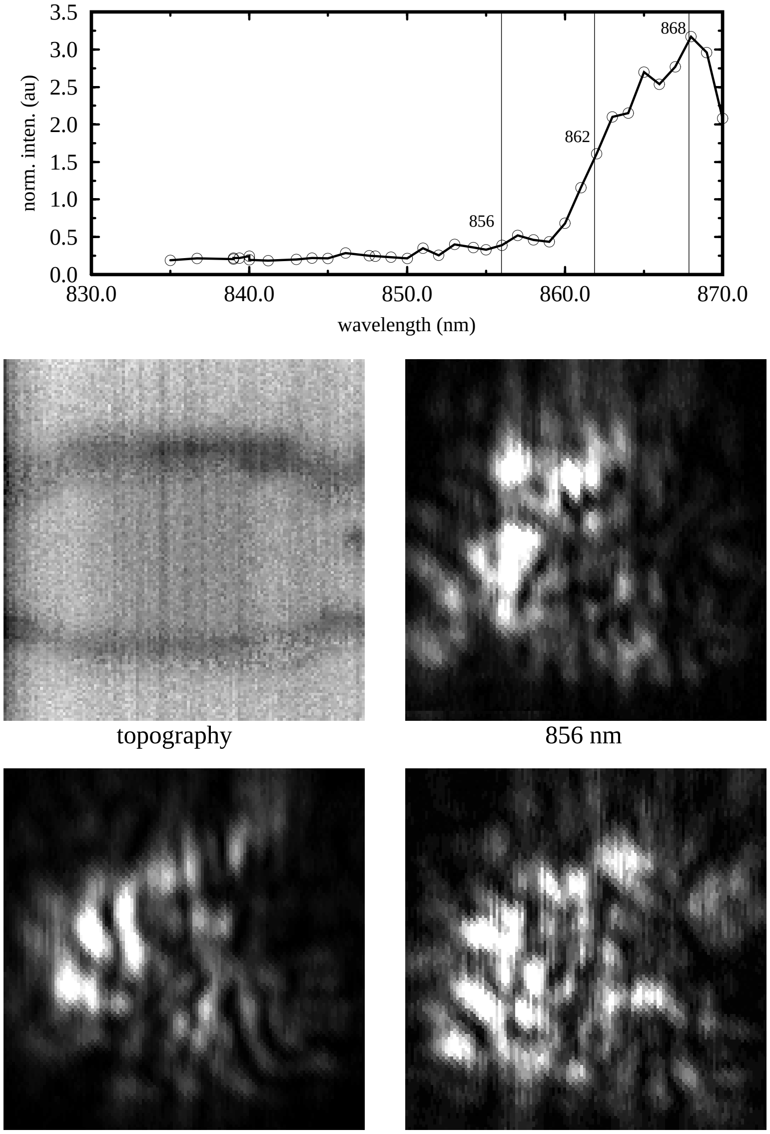


Figure 1. Vander Rhodes, *et al.*



topography

856 nm

862 nm

868 nm

Figure 2. Vander Rhodes, *et al.*

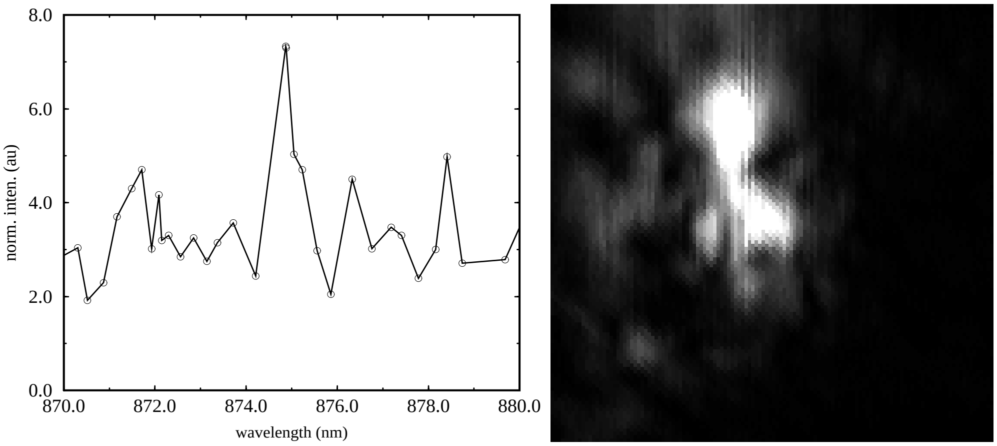


Figure 3. Vander Rhodes, *et al.*

Figure Captions

Fig. 1: 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).

Fig 2: 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.

Fig 3: 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.

REFERENCES

[1] E. Yablonovitch, "Photonic band-gap structures," *J. Opt. Soc. Am. B*, vol. 10, no. 2, pp. 283–295, Feb. 1993.

[2] Shanhui Fan, Joshua N. Winn, Adrian Devenyi, J. C. Chen, Robert Meade, and J. D. Joannopoulos, "Guided and defect modes in periodic dielectric waveguides," *J. Opt. Soc. Am. B*, vol. 12, no. 7, pp. 1267–1272, July 1995.

[3] T. F. Krauss, B. Vögele, C. R. Stanley, and R. M. De La Rue, "Waveguide microcavity based on photonic microstructures," *IEEE Photonics Tech. Lett.*, vol. 9, no. 2, pp. 176–178, Feb. 1997.

[4] B. B. Goldberg, M. S. Ünlü, W. D. Herzog, and E. Towe, "Near field optical microscopy and spectroscopy of heterostructures and laser diodes," *IEEE JSTQE*, vol. 1, pp. 1073–1081, 1995.

[5] D. R. Smith, R. Dalichaouch, N. Kroll, S. Schultz, S. L. McCall, and P. M. Platzman, "Photonic band structure and defects in one and two dimensions," *J. Opt. Soc. Am. B*, vol. 10, no. 2, pp. 314–321, Feb. 1993.