

## PHOTODETECTING FIBER WEBS

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### Sponsors

DARPA, ARO, ONR, AFOSR HEL-MURI, US DOE, ISN, the Materials Research Science and Engineering Center (MRSEC) program of the NSF with use of their Shared Experimental Facilities.

To date, a barrier has existed between the fabrication technologies used for producing electronic devices and those used for optical fibers. The former comprise a collection of elaborate wafer-based processes, while the latter rely on simpler perform thermal-drawing techniques. In a recent publication that breaks this barrier, we report on the first successful fabrication of functional optoelectronic devices using fiber drawing techniques. These fibers are made by arranging a low-melting temperature conductor (Sn), amorphous semiconductor ( $\text{As}_2\text{Se}_3$  or  $\text{As}_{40}\text{Se}_{50}\text{Te}_{10}\text{Sn}_5$ ), and high-glass transition thermoplastic insulator (polyethersulfone, PES, or polyetherimide, PEI) into a macroscopic preform which shares the final fiber geometry, but lacks functionality due to the absence of intimate contact and proper element dimensions. The preform (33-mm thick, Fig. 1a) consists of a cylindrical semiconductor chalcogenide glass ( $\text{As}_{40}\text{Se}_{50}\text{Te}_{10}\text{Sn}_5$ ) core, contacted by four Sn metal conduits that are encapsulated in a protective PES cladding, and is subsequently heated and drawn into a fiber (980- $\mu\text{m}$  thick, Fig. 1b). The fiber exhibits both electrical and optical functionalities that follow from the excellent contact, appropriate element dimensions, and the preservation of the preform geometry throughout the drawing process. Specifically, the electrical conductance of this fiber was found to increase dramatically (two orders of magnitude) upon illumination by white light (20 mW), as seen in the large slope of the linear I-V curve when compared to that recorded in dark conditions (Fig. 1c).

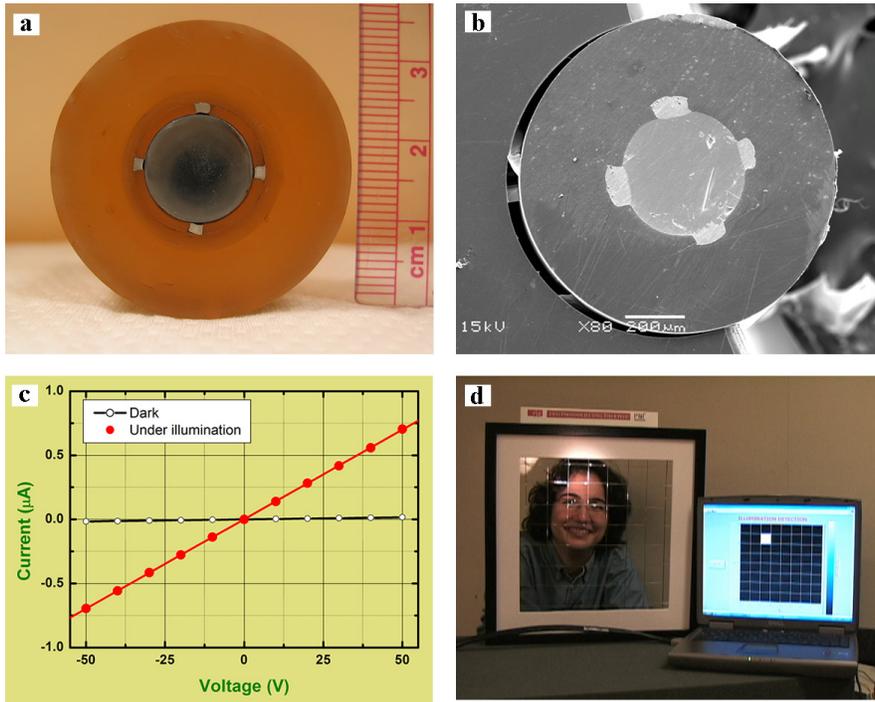
While the individual fiber behaves as a distributed photodetector, with sensitivity to visible and infrared light at every point along its entire length, it is the assembly of such fibers into 2D grids or *photodetector fiber webs* that enables the detection of an illumination point. Moreover this grid achieves  $N^2$  detection resolution with only a  $2N$  number of elements. An example of such a fiber web detector, that is used to measure the coordinates of an illumination point on a  $30 \times 30 \text{ cm}^2$  grid with 64-point resolution, is shown in Fig. 1d.

We expect that these metal, insulator, and semiconductor flexible fibers will pave the way for the future development of fibers, and even fabrics, with novel optical and electrical properties.

### References

- [1] M. Bayindir, *et al.*, "Metal-insulator-semiconductor optoelectronic fibres," *Nature*, **431**, 826-829 (2004).
- [2] Hart, S. D. *et al.* External reflection from omnidirectional dielectric mirror fibers, *Science* **296**, 510-513 (2002).

## Chapter 31. Photodetecting Fiber Webs



Fiber photodetectors. **(a)** A macroscopic preform consisting of a photoconductive core made of a chalcogenide glass (As-Se-Te-Sn), surrounded by a polymer (PES) cladding. The core is contacted by four metal (Sn) electrodes that run along the length of the preform. **(b)** An SEM micrograph of the fiber cross section demonstrating that the preform geometry has been preserved during the drawing process. **(c)** Measured current-voltage characteristics of a distributed metal-semiconductor-metal fiber photodetector in the dark and under illumination. **(d)** A two-dimensional web assembled out of photodetecting fibers detecting the location of a beam of light.

## UV HOLLOW PHOTONIC BANDGAP TRANSMISSION FIBERS

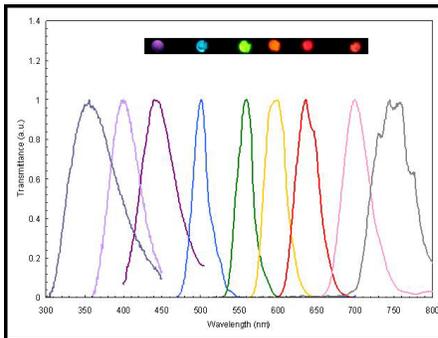
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AFOSR HEL-MURI, ISN

We have made significant progress on the design and fabrication of multilayer photonic bandgap fibers that confine light in a hollow core. These fibers have an all-solid meso-scale structure consisting of multiple alternating layers of high- and low-index materials surrounding a cylindrical hollow core. Hollow core guiding versions of these fibers have recently been successfully fabricated, with fundamental photonic bandgaps at 3 and 10.6  $\mu\text{m}$  wavelength. While those wavelengths may be used for high-energy laser delivery, it is also of interest to explore the usage of these fibers at near-infrared (IR) wavelengths where most modern solid-state lasers operate, enabling applications ranging from standard telecommunications to ultrafast physics and in particular to enable high energy laser transmission. In particular, those fibers that have a large refractive index contrast between the layer materials have been shown theoretically to allow great reductions in fiber losses and non-linearities as well as widely tunable dispersion and other interesting properties. The high refractive index contrast between the layer materials leads to large photonic bandgaps and makes the inner lining of the fiber analogous to an omnidirectional dielectric mirror. This structure should therefore have short electromagnetic penetration depths within the layer structure, minimizing the interaction of light with the layer materials. In a recent publication [1] we reported for the first time the fabrication of hollow-core guiding cylindrical photonic bandgap fibers at near-IR wavelengths, from 0.85 to 1.55  $\mu\text{m}$ . These fibers require a significant reduction in feature size from previous work; the photonic crystal lattice periods in the fibers fabricated were drawn down to 260 nm. We are very pleased to report a further breakthrough whereby the feature sizes in these fibers were reduced to below 40nm and have demonstrated 0.4MW peak power transmission at 355nm.



Short wavelength transmission through hollow omniguide fibers

### References:

[1] Kuriki, K., Shapira, O., Hart, S., Benoit, G., Kuriki, Y., Viens, J. F., Bayindir, M., Joannopoulos, J. D., Fink, Y. "Cylindrical Photonic Bandgap Fibers for NIR Applications", *Optics Express*, **12**, No. 8, 1510-1517, April 2004.

## COMPLETE MODAL DECOMPOSITION IN PHOTONIC BANDGAP FIBERS

### Academic and Research Staff

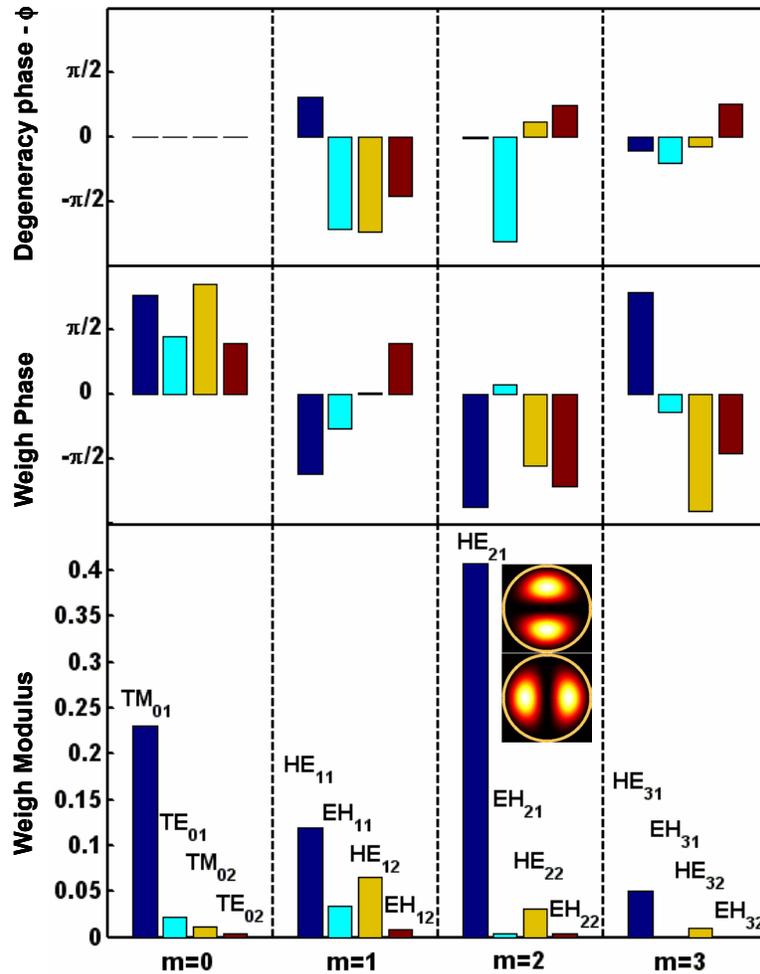
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AFOSR HEL-MURI, US DOE, ISN, the Materials Research Science and Engineering Center (MRSEC) program of the NSF with use of their Shared Experimental Facilities.

Modal decomposition in multimode optical waveguides plays an important role in the study of multimode wave propagation by providing insight to the nature of mode interactions due to structural perturbation. Nevertheless, to the best of our knowledge, *complete* mode decomposition (CMD), that also takes into consideration the vectorial aspect of the optical field and the degeneracy of the modes, has not yet been achieved. By CMD we mean analyzing the output optical field into a linear superposition of the waveguide eigenmodes, and determining the *amplitude and phase* of the complex coefficients in this superposition. The amplitudes and phases reveal information about modal losses and dispersion as was the aspire of many early efforts to model transmission in multimode waveguides, originally with Bell-Labs WT4 millimeter waveguide system, thereafter with step-index optical fiber, plastic optical fibers, and PBG fibers. Furthermore, CMD is of great importance in the analysis of mode-conversion due to induced scatterers such as fiber bends, tilted gratings, long period gratings, etc, with applications in dispersion management, variable attenuation, and enhanced transmission. While many experiments demonstrated mode conversion only few of them give a rigorous analysis based on a theoretical model. In this paper we present a novel theoretical approach to the CMD problem and then confirm the feasibility of this approach experimentally by applying it to the guided optical field in a photonic bandgap fiber. Our theoretical approach relies on adapting the phase retrieval algorithm to the waveguide problem.

We are pleased to report on the development under the HEL-MRI of a novel modal decomposition algorithm, based on the phase retrieval approach, is applied to the measured optical field distribution at the output of a hollow-core photonic bandgap (PBG) fiber. Two intensity distribution measurements, near- and far-field, are performed, and the new algorithm is applied to these measurements to extract the complete modal content of the field. In contrast to the usual approach in phase retrieval problems, we do not employ direct minimization over the two-dimensional image space of intensity distributions. Instead, we make use of the knowledge of the (low-frequency) modes of the PBG fiber to map the problem into the one-dimensional abstract space of fiber eigenmodes, resulting in a considerable reduction of minimization variables. We used this algorithm to study the interaction of modes in the hollow-core fiber. Our approach is useful for mode analysis in any multimode waveguide, which serves as a diagnostic tool for wave propagation in the waveguide critical to the understanding of the loss mechanisms and output control of PBG based fiber lasers.



Complete reconstruction of modal content for PBG fiber. Lower panel depicts the weights modulus. The theoretical calculation of the most dominant mode,  $HE_{21}$ , is given in the inset for  $\phi=0$  as resulted from the decomposition (upper panel).

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- [1] Johnson, S., Ibanescu, M., Skorobogatiy, M.A., Weisberg, O., Engeness, T., Soljagic, M., Jacobs, S.A., Joannopoulos, J. D., Fink, Y., "Low Loss Asymptotically Single Mode Propagation in Large-Core Omniguide Fibers" *Optics Express* 9, 749-779, December 2001.
- [2] Temelkuran, B., Hart, S.D., Benoit, G., Joannopoulos, J.D., Fink, Y., "Wavelength Scalable Optical Fibers for CO<sub>2</sub> Laser Transmission", *Nature* 420, 650-653, December 2002.
- [3] Ibanescu, M., Johnson, S.G., Skorobogatiy, M.A., Weisberg, O., Engeness, T., Soljagic, M., Jacobs, S.A., Joannopoulos, J.D., Fink, Y., "Analysis of Mode Structure in Hollow Dielectric Waveguide Fibers", *Physical Review E*, 67, 046608, April 2003.

## NON-LINEAR MESOSTRUCTURED FIBERS FOR SPECTRAL CONTROL AND SWITCHING APPLICATIONS

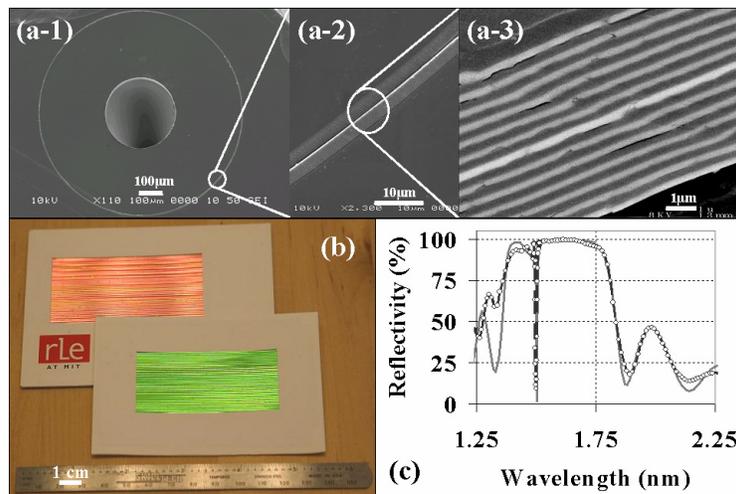
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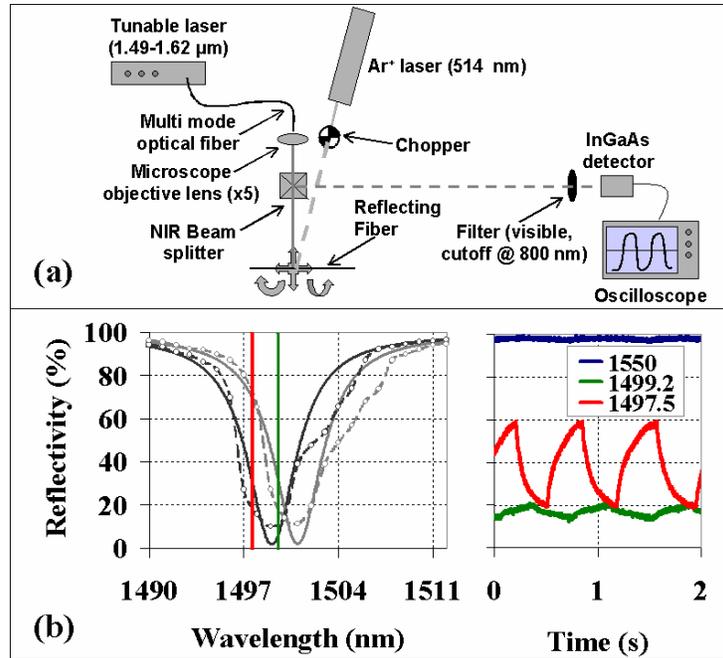
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ONR, ISN and the Materials Research Science and Engineering Center (MRSEC) program of the NSF with use of their Shared Experimental Facilities.

We have recently introduced a novel photonic bandgap fiber which operates in reflection called *mirror fibers* [1]. By introducing a half-wave layer in the middle of the multilayer structure, we have created reflection fibers with a Fabry-Perot resonator and demonstrated mechanical tuning of the corresponding resonant mode [2]. Incorporating a highly photorefractive chalcogenide glass into the cavity structure enabled the optical tuning of the resonant mode corresponding to the cavity length. We demonstrate a shift by 2 nm at 1.5 microns of a cavity resonant mode with quality factor equal to 225 under illumination at 514 nm. Dynamic optical tuning is also reported for frequencies up to 400 Hz. Experimental results are compared with simulations based on the amplitude and kinetics of the transient photodarkening effect measured in situ in thin films.



**(a-1,2,3)** SEM micrographies of the cross-section of a 910-micron diameter fiber showing the  $\text{As}_2\text{Se}_3$  cavity layer (bright grey in the middle of the layered structure), the  $\text{As}_2\text{S}_3$  mirror layers (intermediate grey) and the polymer layers (dark grey), **(b)** two arrays of fibers reflecting different colors in the visible due to the shift in the position of the 3<sup>rd</sup> order bandgap resulting from the difference in diameter and **(c)** measured (dashed black line with dots) and computed (continuous grey line) reflectivity spectra of the 910-micron diameter fiber. The measurement curve is the superposition of a FTIR measurement and a narrow band measurement.



Experimental set up for the optical tuning measurement. **(b) Left:** shift of the cavity resonant mode to higher wavelengths under  $530 \text{ mW/cm}^2$  illumination. Dashed lines with dots correspond to narrow-band measurements; continuous lines correspond to TMM simulations. **Right:** modulation at 1.5 Hz of the reflected power at three different probe wavelengths. 1497.5 and 1499.2 nm are indicated with a red and green line respectively on the narrow band reflectivity spectra.

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- [2] Benoit, G., Hart, S., Temelkuran, B., Joannopoulos, J. D., Fink, Y., "Static and Dynamic Properties of Optical Cavities in Photonic Bandgap Yarns" *Adv. Mater.*, 15, No. 24, 2053-2056, December 2003.