

## LARGE-SCALE OPTICAL-FIELD MEASUREMENTS WITH GEOMETRIC FIBRE CONSTRUCTS

### Academic and Research Staff

Ayman F. Abouraddy, Ofer Shapira, Mehmet Bayindir, Jerimy Arnold, Fabien Sorin, Dursen S. Hinczewski, John D. Joannopoulos, and Yoel Fink

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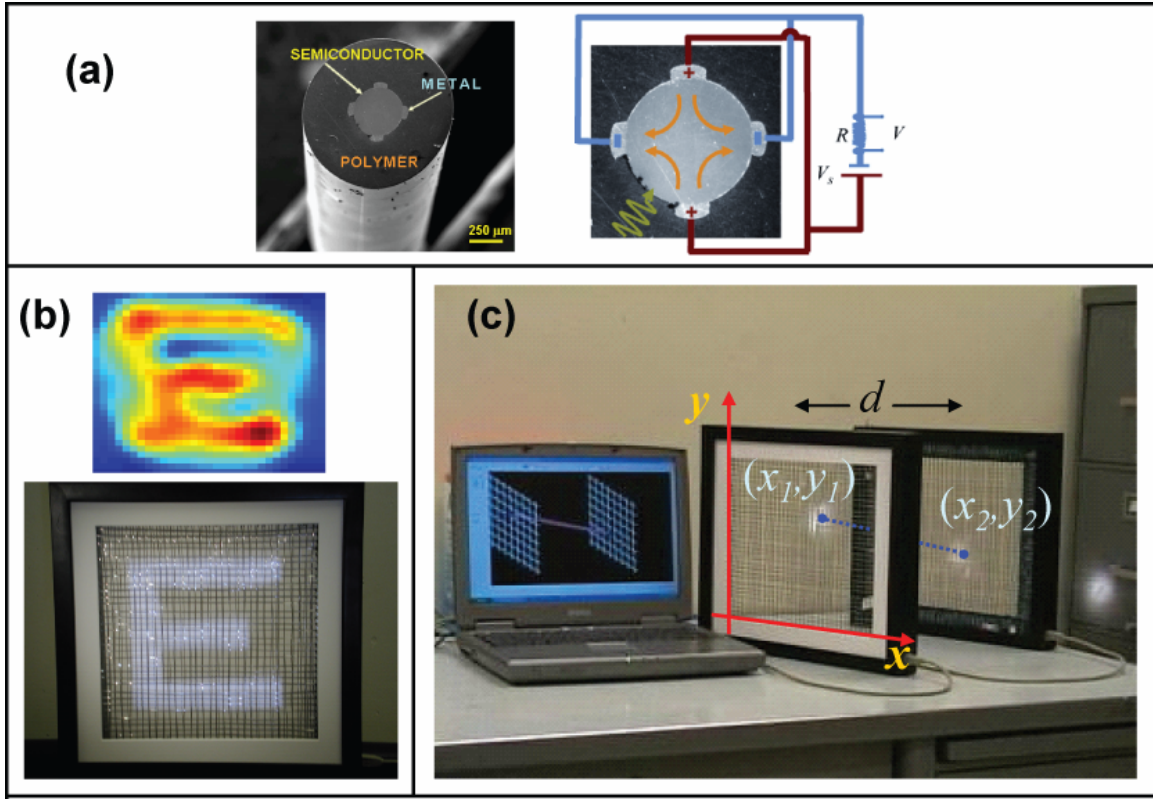
While textile fabric has provided essential protection from the environment for millennia, it has not been the realm of optical functionality. In a recent paper [1] we demonstrated that light-weight, flexible, photosensitive polymeric fibers woven into arrays can ‘see’ and can potentially allow for optical functionality to inhere in fabrics.

The fibers, produced by a thermal drawing procedure, have a photosensitive core (an amorphous semiconducting chalcogenide glass) contacted with four metal electrodes that extend the full length of the fiber and surrounded with a transparent polymer (Fig. 1a) [2]. Since such a fiber will produce an electrical signal that is proportional to the line integral of the intensity of an incident optical field, a 2D array constructed of these fibers can reconstruct the amplitude of an arbitrary incident intensity distribution from rotated versions of the distribution using the Radon transform (Fig. 1b) [1,3].

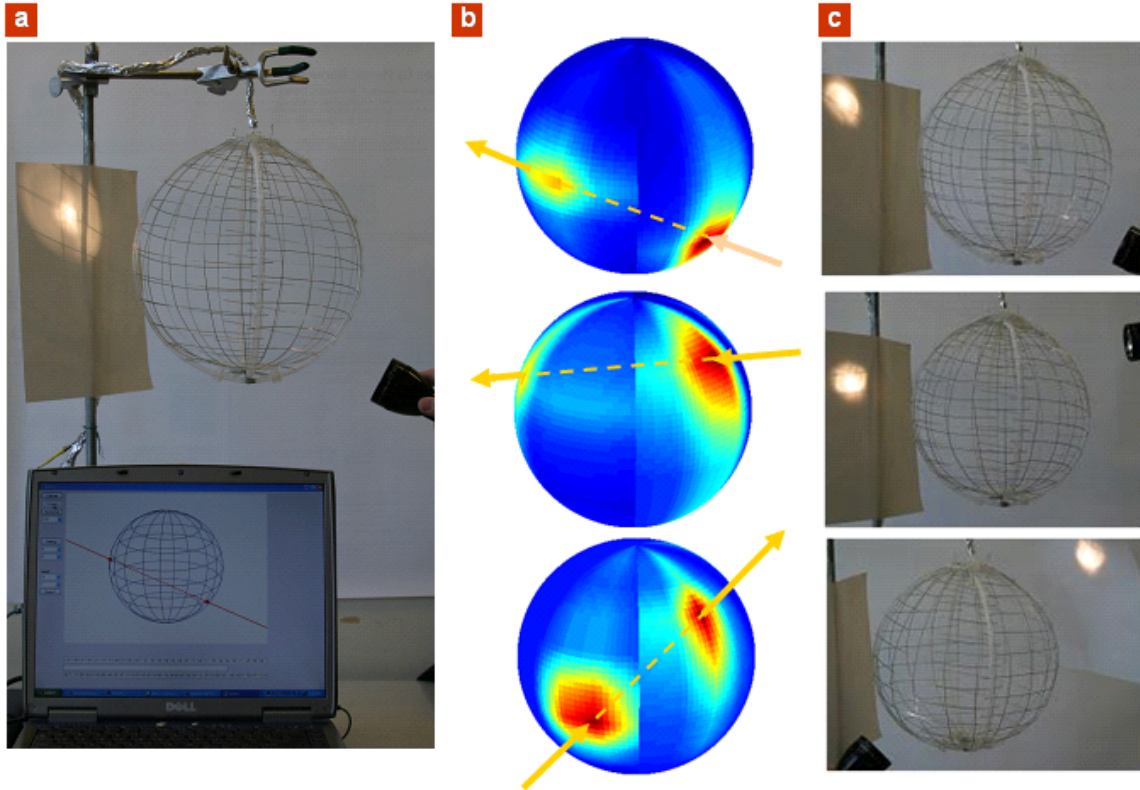
Furthermore, such an array is essentially transparent and one may stack cascaded arrays to extend the optical functionalities. An example is shown in Fig. 1c where two planar arrays separated by a distance  $d$  detect the position *and* direction of an optical beam. The flexibility of the fibers also allows us to construct novel array topologies such as that of a closed sphere (Fig. 2) that detects the path of a beam of light over the full  $4\pi$  steradians of the ambient environment [1]. Finally, two planar arrays that detect the intensity distributions in two planes can reconstruct both the amplitude and the phase of an incident wave front using the phase retrieval algorithm [1,4]. We demonstrate the feasibility of this approach by a lensless imaging experiment where we propagate the reconstructed complex field distribution backwards to estimate the illuminated object (Fig. 3).

### References

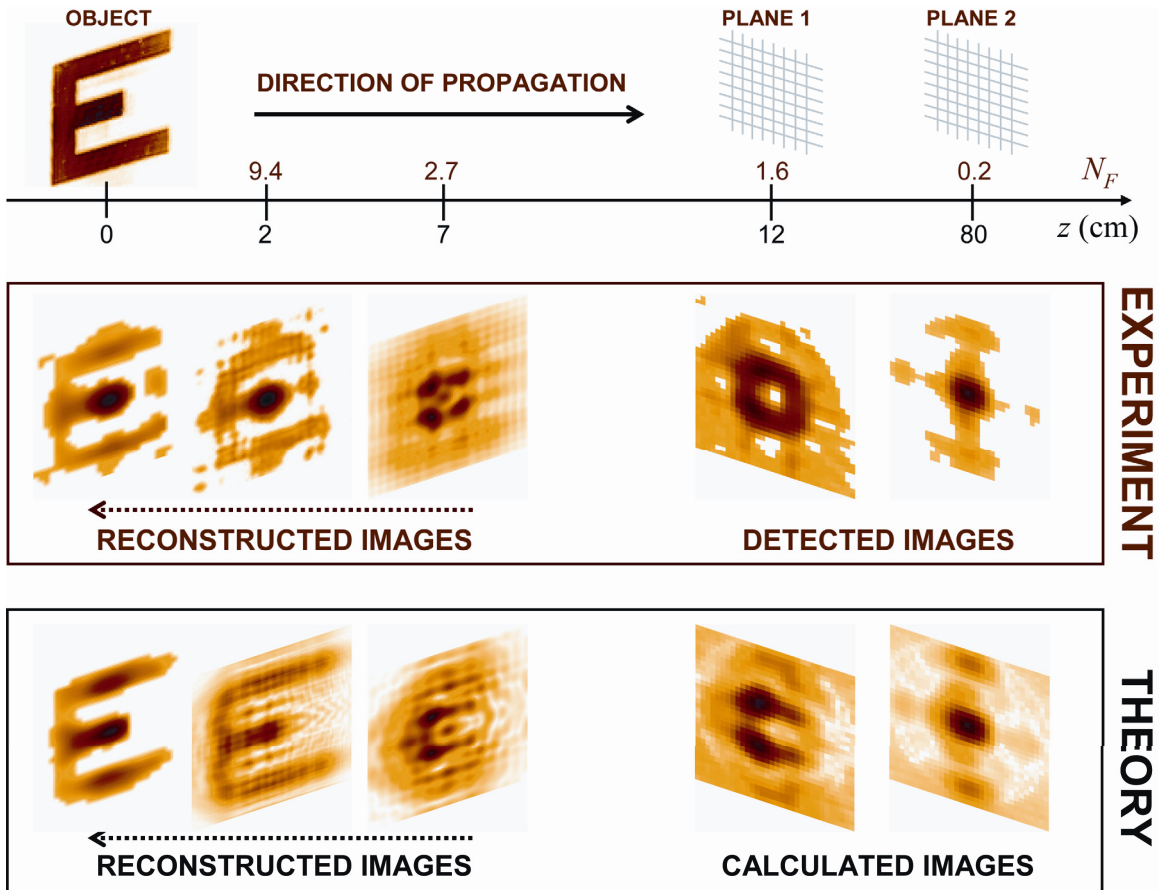
- [1] A. F. Abouraddy et al., “Large-scale optical-field measurements with geometric fibre constructs,” *Nature Materials* **5**, 532-6 (2006).
- [2] M. Bayindir et al., “Metal–insulator–semiconductor optoelectronic fibres,” *Nature* **431**, 826-9 (2004).
- [3] Kak, A. C. & Slaney, M. *Principles of Computerized Tomographic Imaging* (IEEE Press, New York, 1988)
- [4] J. R Fienup, “Phase retrieval algorithms: a comparison,” *Appl. Opt.* **21**, 2758–69 (1982).



**Figure 1** (a) Photosensitive fiber. The left panel shows an SEM micrograph of a fiber cross-section while the right panel shows the fiber electrodes connected to an external circuit and the associated electric field lines (yellow arrows). The scale bar is  $250 \mu\text{m}$ . (b) A  $32 \times 32$  fiber array (clear dimensions  $24 \times 24 \text{ cm}^2$ ) reconstructs the image of a letter 'E' formed using a white light source illuminating a transparency (the image of the letter 'E' seen in the lower panel is formed on a white sheet placed behind the transparent array). (c) Two planar fiber arrays can detect and reconstruct the path of a beam of light in 3D.



**Figure 2 Omnidirectional light detection.** **a**, A closed spherical fiber web is an omnidirectional photodetector which detects the direction of the beam throughout a solid angle of  $4\pi$ . The spherical web is sufficiently transparent to see through and for a beam of light to traverse unimpeded. **b**, The distribution of the electrical signals detected by the fibers for a light beam incident in three different directions. The arrows indicate the direction of the beams, and the dotted portion of each arrow corresponds to the beam's path inside the sphere. **c**, Photographs of the three beam trajectories that resulted in the signal distributions shown in **b**.



**Figure 3 Non-interferometric lensless imaging using two fiber webs.** An object (letter 'E') is illuminated with a laser beam (the image of the object is captured with a Vidicon camera) and the diffracted fields propagate to the planes of two  $32 \times 32$  planar fiber arrays at two different locations are obtained using the fiber webs. The Fresnel number  $N_F$  is also given. Two intensity distributions are measured. The phase retrieval algorithm is used to obtain back-propagated images in the direction receding from the webs towards the object (the object reconstruction is at at 0 cm, shown on the left). The reconstructed images are blurred, but an image is obtained at the location of the object. The second row shows the results of theoretical reconstructions with the phase retrieval algorithm when using the diffraction patterns that were obtained from the measured illuminated object distribution.

## **FLEXIBLE PIEZOELECTRIC FIBERS FOR ACOUSTO-SENSING AND ACTUATING DEVICES**

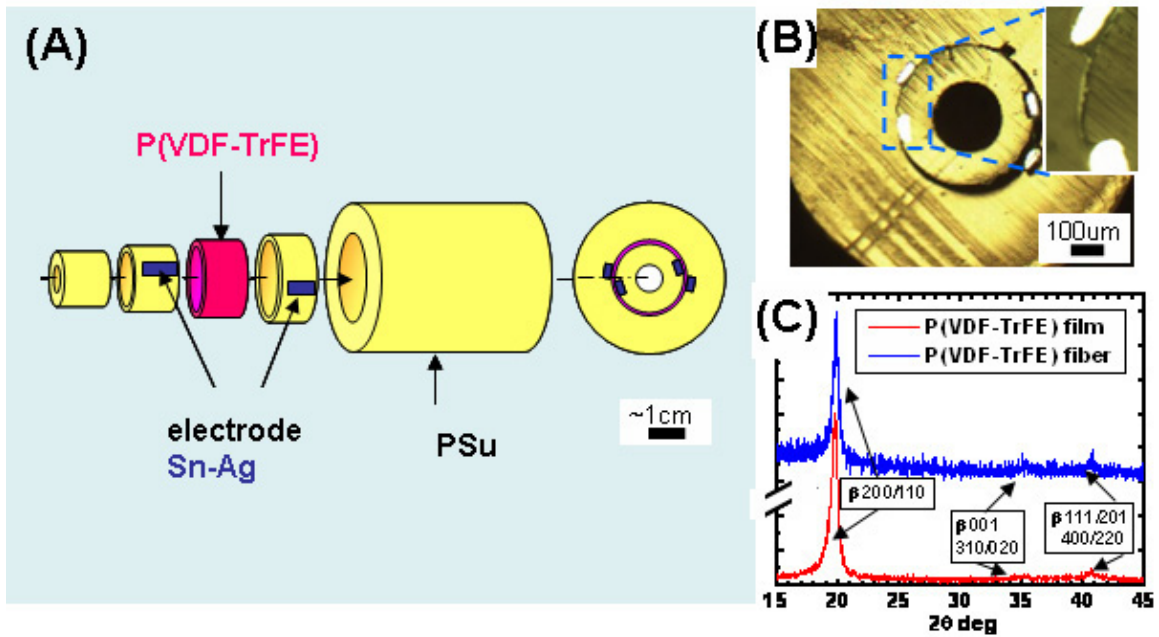
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Shunji Egusa, Dana Shemuly, John D. Joannopoulos, and Yoel Fink

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ISN, DARPA, NSF

Piezoelectric materials are critically important for a wide range of technological applications, from various electromechanical sensors/actuators to acoustic and non-linear optical devices. A piezoelectric material undergoes a change in electrical polarization in response to mechanical stress, and vice versa. Piezoelectric ceramics, or perovskite-type metal oxides (e.g.  $\text{PbZr}_{1-x}\text{Ti}_x\text{O}_3$  or PZT,  $\text{BaTiO}_3$ ,  $\text{KNbO}_3$ ), are well known examples, however their applications are limited by brittleness, heavy weight, and difficulty in processing into desired shapes. Piezoelectric polymers, on the other hand, are flexible, light weight, non-toxic, and easy to process. Poly(vinylidene fluoride), abbreviated as PVDF, and some of its copolymers exhibit by far the strongest piezoelectricity of all known polymers. These are semi-crystalline polymers and upon achieving specific crystalline phase (beta-phase) and poling, their piezoelectricity is comparable to the ceramic materials. In this report, we present the design and fabrication of flexible piezoelectric micro-structured fibers, enabled by the use of these piezoelectric polymers. PVDF typically requires post-processing in order to achieve the beta-phase, whereas its copolymer with trifluoroethylene, P(VDF-TrFE) spontaneously anneals into the beta-phase, hence is more appropriate for our fabrication scheme. A multi-material perform is fabricated using P(VDF-TrFE) layer, sandwiched by sets of metal electrodes. Polysulfone (PSu) surrounds these structures to provide mechanical support (Fig. 1A). This perform is drawn into meters of flexible fiber, whose cross section is shown in Fig. 1B. Sets of metal electrodes apply the poling voltage across the P(VDF-TrFE) layer, and upon poling, they control the sensing/actuating of piezoelectric activities of the fiber. XRD peak assignments confirm that the P(VDF-TrFE) layer in the fiber is in beta-phase (Fig. 1C). Thus fabricated fibers find immediate applications as one-dimensional broadband acoustic and vibration/pressure sensing devices. Detailed characterizations of these fibers are in progress.



**Figure 1:** (A) Scheme of piezoelectric fiber preform fabrication. Piezoelectric layer, P(VDF-TrFE), 100 $\mu$ m thick, is sandwiched by two sets of metal (Sn<sub>96</sub>Ag<sub>4</sub> alloy) electrodes. Polysulfone (PSu) surrounds these structures to provide mechanical support. (B) Optical microscope image of a cross section of piezoelectric fiber, fabricated by drawing the multi-material preform. Thin layer of P(VDF-TrFE) between electrodes are shown in the inset. (C) XRD characterization of the crystalline phases of  $\beta$ -P(VDF-TrFE) film (red curve) and P(VDF-TrFE) layer extracted from a fabricated fiber (blue curve).

## **THIN FILM FIBER DEVICES**

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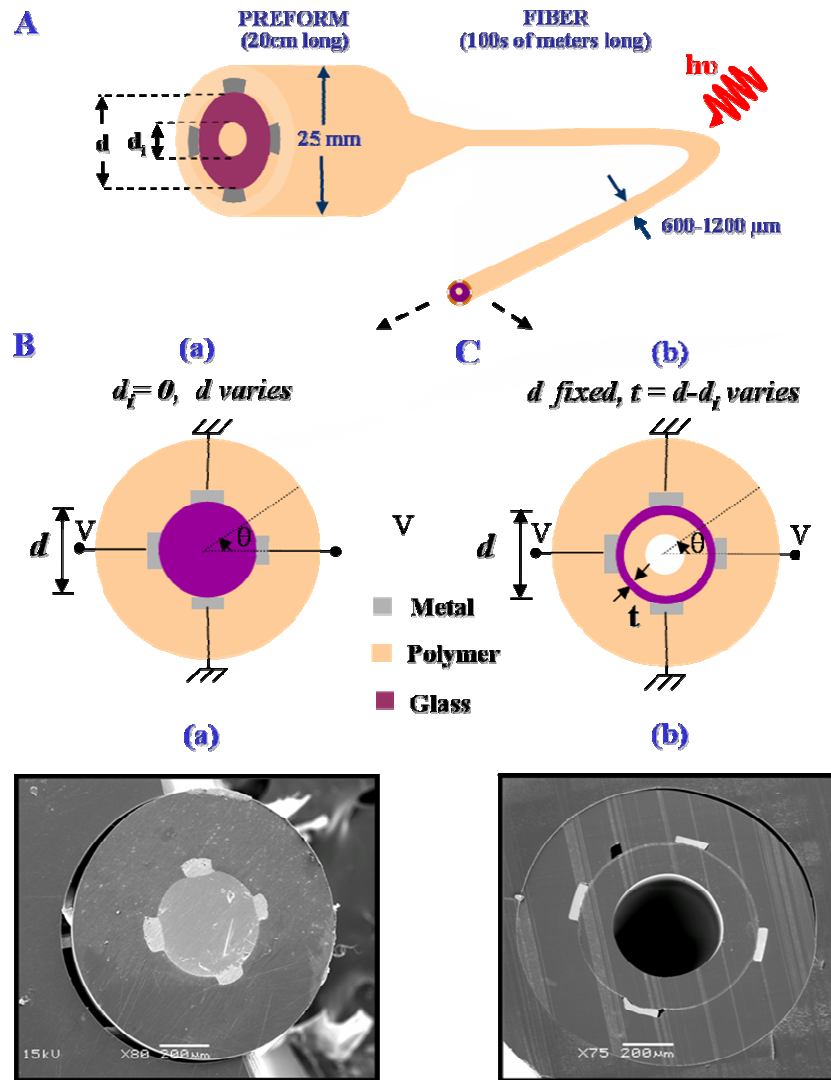
Fabien Sorin, Nick Orf, Ofer Shapira, Jeff Viens, Ayman F. Abouraddy, John D. Joannopoulos, and Yoel Fink

### **Sponsors**

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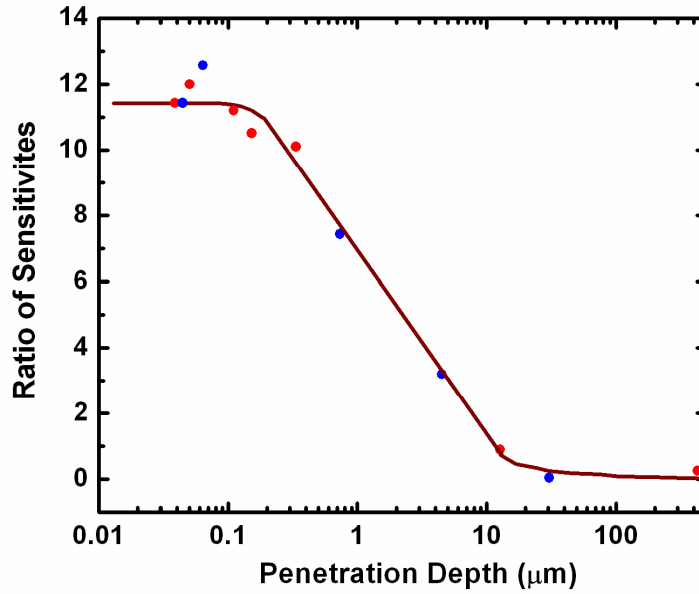
The recent fabrication of 1D distributed photoconducting fibers has brought an original approach to the technology of semiconductor devices in general and of light detection in particular, by enabling for the first time the delivery of optoelectronic functionalities at fiber optics length scales, uniformity and cost. The extension in length, the ease and low cost of production combined with the low weight and flexibility of these fibers have enabled the fabrication of large area 2D and 3D fiber webs that can capture light intensity distributions at scales and practicability unachieved so far. The reduction of diameter brings also the possibility of waving these fibers into smart fabrics with novel capabilities to be used in a myriad of applications. Depending on the application, the smart systems composed of fiber devices will require single elements with different sizes and level of performance as photo (or thermal) sensors. Since the increase of fiber length is coupled with an increase of the noise of the system, it is essential to come up with innovative structures to optimize the characteristics of the individual long fibers and of their large assembly. The strategy we envisioned is to replace the fiber core as the semiconducting active material by a sub-micrometer-thick semiconducting film running along the entire fiber length. The tremendous advantage of the new film structure compared to the core fibers relies in the drastic reduction of the dark current and hence of the device noise. For films of thickness much smaller than the fiber diameter but equal to a few penetration depths at a given wavelength of illumination, the dark current is drastically reduced while the amount of light absorbed, and so the photo-current, remain nearly unchanged. This leads to a drastic increase in sensitivity (signal-to-noise ratio) for a wide range of wavelengths. This new structure also comes with an increase in response speed and permits the production of thinner and more flexible fibers that weight up to 3 times less than the core structures. It also enables the integration of multiple and complex functionalities into a single fiber and opens up the possibility for smarter fibers capable of the most complex functionalities of semiconductor devices.

The integration of several thin films into a single fiber is a natural next step towards these goals. We have produced fibers with two thin films of arbitrary thickness and materials capable of unprecedented spatial as well as spectral resolution of the detected beam. Applications of this work are numerous in large area optical and thermal sensing systems, remote sensing of anlayses, solar energy and smart fabrics.

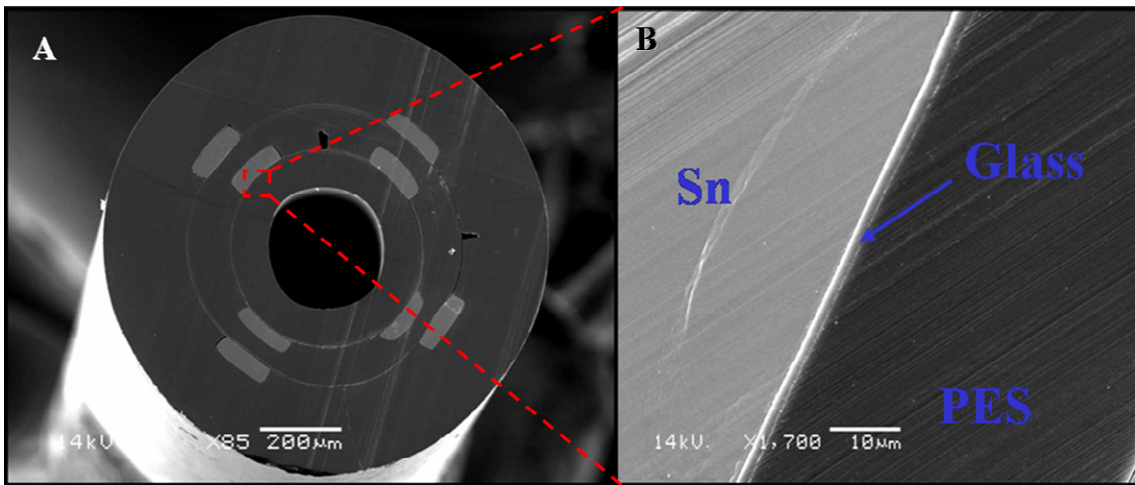


**Figure 1:** (A) Schematic of a preform-to-fiber configuration where the cross section is maintained from the macroscopic to the microscopic fiber scale. (B) (a) Schematics of the cross section structure of a core fiber where the inner core is maintained to zero and (b). (C) Schematics of the cross section structure of a thin film fiber where the thickness  $t$  can be changed and (b) SEM micrograph of a photoconducting thin film fiber device.





**Figure 2:** Ratio of sensitivities of core and thin film fibers for two glasses: AST(6%) in red, and As<sub>2</sub>Se<sub>3</sub> in blue. The wine line is the factor  $(1 - e^{-t/\delta})$  with  $t = 300 \mu\text{m}$ .



**Figure 3:** SEM micrographs of the cross section of a dual thin film fiber (A) and an enlargement of the contact between the elect

## DYNAMIC SURFACE EMITTING FIBER LASER

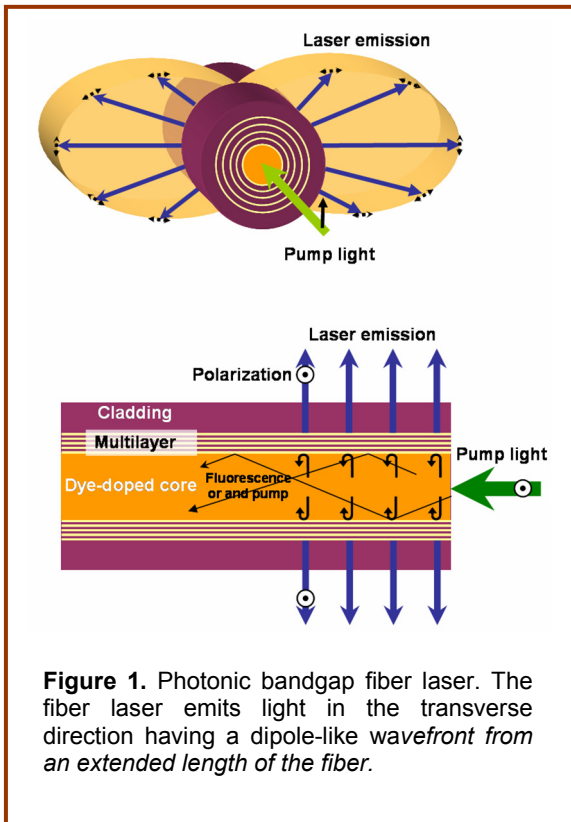
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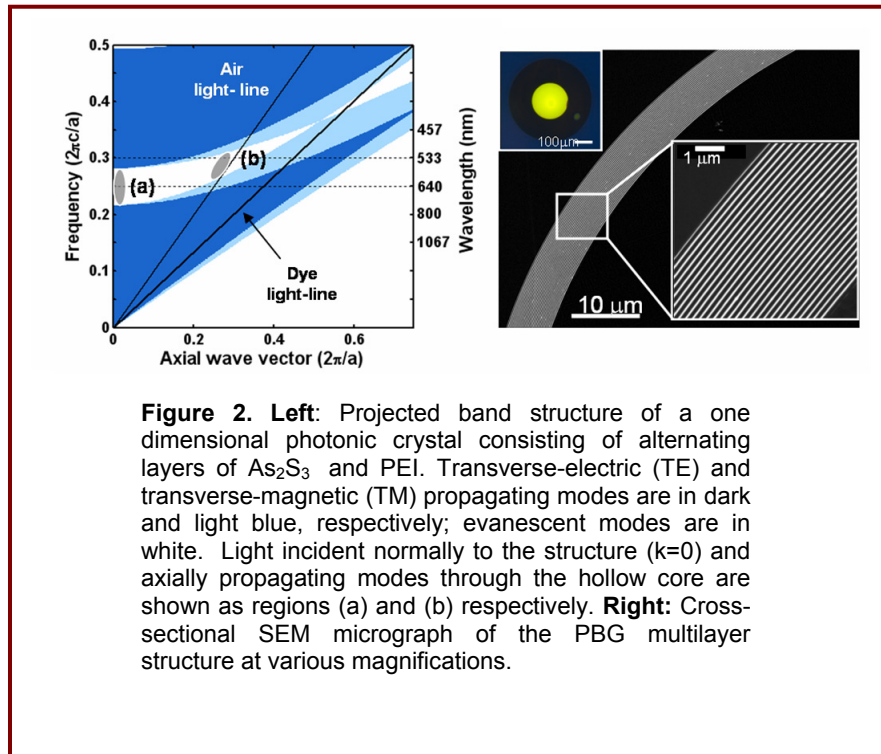
Ofer Shapira, Alexander Stolyarov, Nicholas D Orf, Ken Kuriki, Jean F Viens, Ayman F. Abouraddy, John D. Joannopoulos, and Yoel Fink

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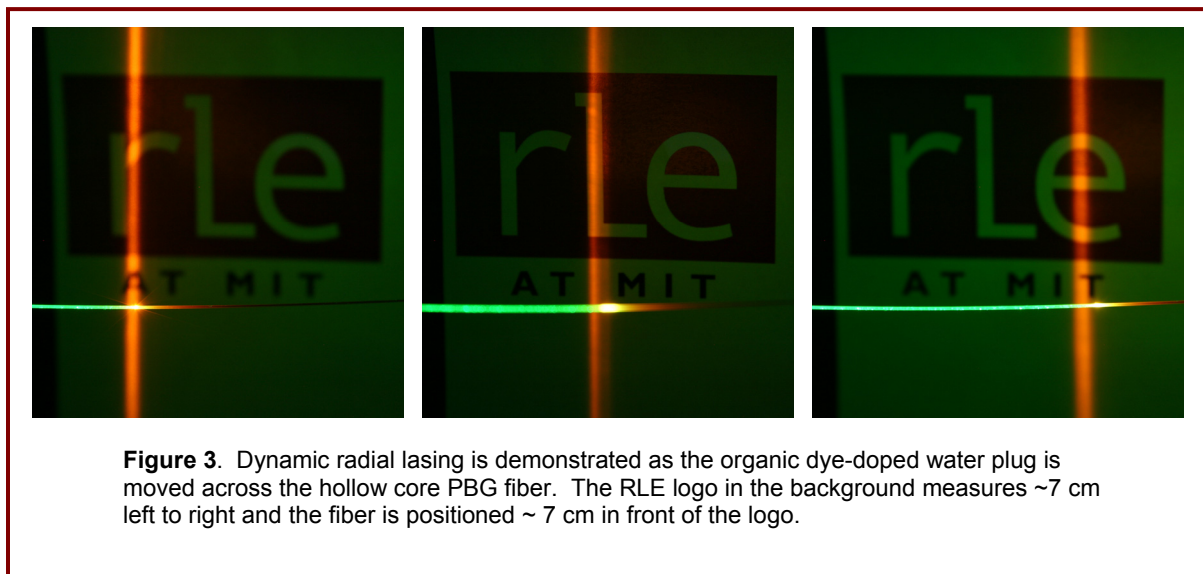
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The great variety of optical cavities and their coupling to gain media has made lasers pervasive in science and technology. In particular, fiber lasers have recently been the focus of much interest. However, all fiber lasers to date emit radiation only along the fiber axis with a spot size dictated by the core radius and a nearly planar wavefront. Here we demonstrate for the first time radially directed optical laser emission from the extended surface area of a polymer fiber. A unique azimuthally anisotropic optical wave front and corresponding surface emission properties result from the interplay between a cylindrical resonator, anisotropic gain, and a linearly polarized axial pump beam. This is enabled by a novel cylindrical fiber-cavity structure consisting of a hollow-core cylindrical multilayer photonic bandgap fiber, and an organic dye gain medium that is introduced into the core. The natural curvature of the photonic band edges towards higher frequencies with increase in the axial wave number provides the longitudinal confinement of the higher-frequency optical pump while at the same time acts as a transverse resonant cavity for the lower frequency laser emission (Figure 2, left). We show that the direction and polarization of the wave front are directly controlled by the polarization of the pump. The structure comprises a gain medium in the core surrounded by a photonic bandgap (PBG) structure made of 58 layers of a wide mobility gap amorphous semiconductor,  $As_2S_3$ , alternating with a high glass-transition temperature polymer, poly(etherimide) (PEI). A scanning electron microscope micrograph of the multilayer structure (Figure 2, right) demonstrates the uniformity of the layer thicknesses throughout the fiber. The individual layer thicknesses of  $As_2S_3$  and PEI are 59 nm and 89 nm, respectively, and the structure is terminated by a 29.5-nm thick layer of  $As_2S_3$  to eliminate surface modes.





In addition to demonstrating radial lasing from a dye-doped polymer fixed in the core, the extended hollow core of the fiber surrounded on all sides by the highly reflective PBG structure sets the stage for another unprecedented phenomena, that of a mobile laser cavity. By introducing a mobile dye-doped liquid plug into the hollow core, we can in effect control the position of the laser cavity. The main challenge here is to find a liquid that does not wet the surface, so that a given volume can be transported along the fiber core as an intact plug, without leaving its trace behind. Water, with its strong surface tension and high contact angle of  $92^\circ$  with  $As_2S_3$  has proven to be the ideal candidate as the dye host. Figure 3 captures three instances of a movable Rhodamine-590 doped water plug, lasing radially from inside a hollow core photonic bandgap fiber. Also visible is the higher frequency green pump light source, incident from the left.



The unique surface emission and dynamic control of the laser cavity achieved with our fiber laser combined with its mechanical robustness, small size and flexibility promises interesting medical applications ranging from photodynamic therapy to in vivo molecular imaging, as well as textile fabric displays.

**References**

[1] Shapira, O., Kuriki, K., Orf, N. D., Abouraddy, A. F., Benoit, G., Viens, J. F., Brewster, M. M., Rodriguez, A., Ibanescu, M., Joannopoulos, J. D., Fink, Y., "Surface-Emitting Fiber Lasers," *Opt. Express* **14**, 3929-3935 (2006).