Invited Paper

Multimaterial Fiber Sensors

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Abstract: Recent discoveries have enabled the integration of metals, insulators and semiconductors structures into extended length of polymer fibers. This has heralded a novel path and platform towards sensing of different physical quantities such as temperature, chemicals, acoustic waves, and optical signals. The challenges and opportunities associated with this new class of fiber devices will be presented. In particular, we will discuss the materials and fabrication approach of multimaterial fibers. We will then present the latest results on photodetecting fiber sensors patterning to their performance and use in novel sensing designs. We will also introduce the recent development of active fiber devices that integrate a thin ferroelectric polymer layer for acoustic sensing applications. Finally, some aspects of the coming innovation and future prospect of the multimaterial fiber sensing technology will be discussed.

The recent development of fiber devices integrating a prescribed assembly of conducting, semiconducting and insulating materials into specific geometries with intimate interfaces and microscopic feature dimensions has heralded a novel path towards large area, flexible and light weight electronic and optoelectronic systems[1]. Functionalities such as optical transport[2,3] and external reflection[4], lasing[5], but also sensing of optical[6-9] and thermal[10] radiation, as well as accoustic wave[11] and chemicals, may be delivered in a single fiber system, at length scales and uniformity typically associated with optical fibers. While these fibers share the basic device attributes of their traditional

Fourth European Workshop on Optical Fibre Sensors, edited by José Luís Santos, Brian Culshaw, José Miguel López-Higuera, William N. MacPherson, Proc. of SPIE Vol. 7653, 765305
 · doi: 10.1117/12.868255

electronic and optoelectronic counterparts, they are fabricated using conventional preform-based fiber-processing methods, yielding kilometers of functional, thin and flexible devices. This renders these fiber systems a compelling candidate for applications such as remote and distributed sensing, large-area optical-detection arrays, and functional fabrics[1,6-11].

This paper is the proceeding for an invited talk at the European Work Shop on Optical Fiber Sensors (EWOFS) 2010, that provides a review of the recent progress in multimaterial fiber sensors research. We will first describe the materials involved and the fabrication approach for multimaterial fiber devices. The principle of photodetecting fibers will then be presented, and the latest results and applications described. We will then present recent advances in active devices with the demonstration of multimaterial piezoelectric fibers and the different sensing applications this can entail. Finally, recent progressses on in-fiber device complexity will be presented as well as some aspects of the different projects and future direction for this emerging fiber sensing technology.

The fabrication of multimaterial fibers involves the construction of macroscale preforms that are subsequently stretched into long (hundreds of meters), thin, flexible, and light-weight fibers that deliver prescribed functionalities[1]. In order to give an outline of the steps involved in fiber fabrication, we consider an integrated device that consists of both a cylindrical omnidirectional mirror structure and a metal-semiconductor-insulator optoelectronic device as depicted in Figure 1. Fabricating the device fiber begins with synthesizing a chalcogenide glass rod using standard sealed-ampoule techniques. A hollow polymer tube is prepared having an inner diameter that exactly matches the outer diameter of the glass rod, and a thickness exactly equal to that of thin metallic ribbons. The glass rod is then slid into the tube, the electrodes are inserted into pockets cut in the tube (Fig. 1a), and finally a protective polymer cladding is wrapped around the structure (Fig. 1b). In this way, the metal electrodes are completely enclosed between the polymer and the glass rod, preventing any leakage when it melts during drawing. The electrodes may be contacted to thin glass films with this method as well.

Fabrication of hollow multilayer structures in fibers begin by thermally evaporating a high-index chalcogenide glass (typically from the As-Se-Te glass system) on both sides of a free-standing low-index thin polymer film. To create a hollow fiber, the film is wrapped around a silicate glass tube and consolidated through heating in a vacuum oven. The silicate tube is then removed from the preform core by etching with hydrofluoric acid. When the structure is placed on the external surface of the fiber, no quartz tube is needed. Instead, the coated film is rolled directly around a polymer cylinder with a thin protective polymer layer wrapped around it. Both procedures are combined in preparing the preform shown in Fig. 1, where an external multilayer structure surrounds the optoelectronic device. The preform is then consolidated under vacuum at a high temperature (typically 10-3 Torr and 260 Cº). The resulting fiber preform is thermally drawn into extended lengths of fiber using the tower draw procedure common in the fiber-optic industry. During the draw process, the mirror layers are reduced in thickness by a factor of ~20-100 and the nominal positions of the PBGs are determined by real-time laser micrometer monitoring of the fiber outer diameter.

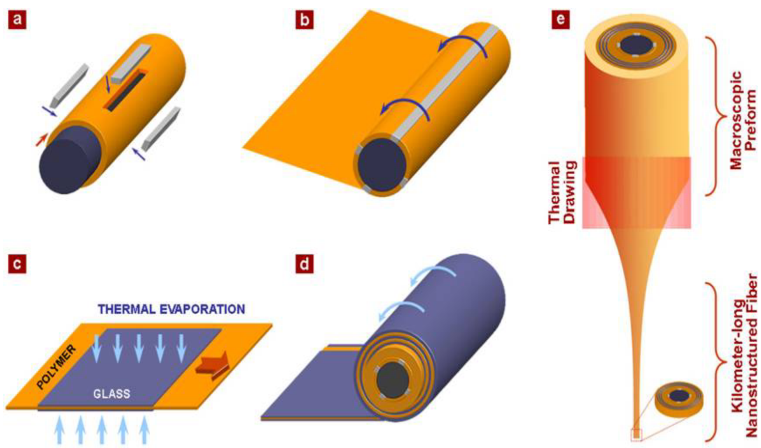

Fig. 1: (a) A chalcogenide semiconducting glass rod is assembled with an insulating polymer shell and four metal electrodes; and (b) a polymer sheet is rolled around the structure to form a protective cladding. (c) The high-index chalcogenide glass is evaporated on both sides of a low-index thin polymer film before (d) being rolled around the cylinder prepared in (a-b). A polymer layer is wrapped around the coated film for protection. (e) The preform is consolidated in a vacuum oven and is thermally drawn to mesoscopic-scale fibers. The cross-section of the resulting fibers retains the same structure and relative sizes of the components at the preform level.

The result is kilometer-long functional mesoscopic-scale device fibers, integrating metal, insulator and semiconductor structures. Consequently, it is conceivable that all the basic components of modern electronic and optoelectronic devices (such as junctions, transistors and so on) could potentially be incorporated into fibers produced with this simple and yet low-cost technique on a length scale beyond the reach of traditional electronics[12]. Let us consider for example the detection of optical signals. Distributed sensing based on optical fibers can measure quantities such as temperature, chemicals or stress[13]. But these techniques are not amenable to the detection of light. To the contrary, multimaterial fibers integrates a semiconducting material, the electronic bandgap of which can be tuned to be able to absorb photon in a given frequency range. Indeed, when light impinges externally on the (amorphous) semiconductor in the fiber core, free charge carriers are generated. The metal electrodes (which interface with the core along the fiber length) are connected to an external circuit. The fiber undergoes a change in electrical conductivity when externally illuminated that can be measured and signals the presence of an incoming optical wave front from any direction and anywhere along the extended fiber axis. These photodetecting fibers hence allow device-like performance at length scales and mechanical flexibility hitherto associated with optical fiber sensors. New photodetecting screens have been developed made out of these fibers that open up new applications in interactive screens, medical imaging and lensless imaging systems. These fibers being light weight, flexible, low profile and easy to address with conventional electronic components, are ideal candidates for smart fabrics systems. Friend-foe recognition and optical communication systems are being developed using this emerging technology.

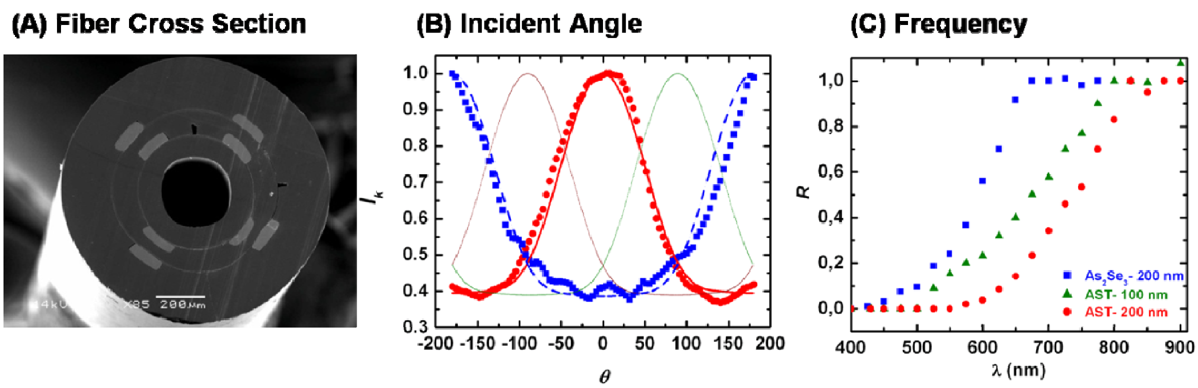

Fig. 2: (A): Scanning Electron Microscope (SEM) micrograph of a dual-ring fiber (scale bar 200 microns). (B): Angle measurement of an incoming light beam as demonstrated and explained in Ref []. The currents (I_k) measured in the different integrated optical sensors vary with the angle of illumination (θ), which enables the reconstruction of θ with a 4 degree resolution. (C): Frequency measurement of an incoming monochromatic beam as demonstrated and explained in Ref []. By looking at the ratio of the photo-generated current in the inner and outer layer, one can reconstruct the incoming beam's wavelength. The frequency range within this is possible can be tuned by varying the composition or thickness of the semiconducting layers.

Many improvements at the fiber level have been performed since the first solid-core photodetecting fibers. Substituting the bulk semiconducting glass core with a thin-film glass layer leads to an increase in photosensitivity (by almost two orders of magnitude) by eliminating the dark current produced by the volume of the core to which light does not penetrate[7], and further suggests wider possibilities for fibers. The integration of several optical detectors within a single fiber have also enabled novel capcities and functionalities[8]. In Figure 2 we show the SEM cross section of a fiber integrating eight independant photo-detecting devices. We showed how this configuration enables to find the direction and wavelength of an incoming monochromatic beam[8]. This work has also led to the fabrication of a polychromatic lensless imaging system with a single fiber grid. These photodetecting fibers offer a novel platform for sensing of various stimuli that rely on the fluorescence of scintillating or chemoluninescent materials that can be introduced in the fiber hollow core. The optical signal generated upon exposure to a stimuli can be detected by the in-fiber integrated optical sensor that span the enitre fiber length, as exemplified in Figure 2A.

So far however, the challenges associated with extracting any information about the intensity distribution of the stimuli along the fiber axis haven't been addressed. In addition to new capability, this could significantly impact multimaterial fiber performance. For example, defects in self-monitored optical fibers could not only be detected but also localized[14]. Also, fiber grid in lensless imaging systems[8,9] would require simpler or no back projection algorithm procedure to extract a 2D intensity pattern, significantly improving their practicality. Envisionned applications in medical imaging and smart fabric would also benefit from this capbability. We will show in this presentation that recent advances in materials and structures have enabled us to adress these challenges. In

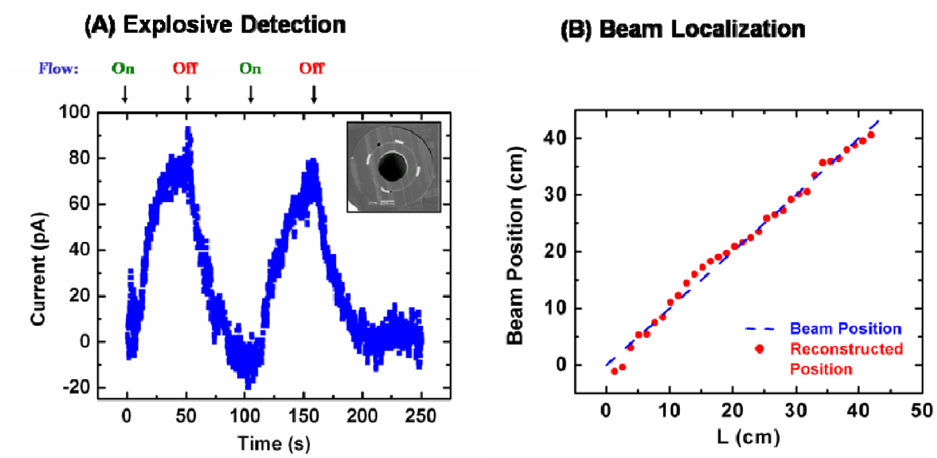

Fig. 3: (A): Photo-current varying over time as peroxyde molecules are introduced inside the hollow core of a photodetecting fiber integrating a semiconducting film around it. The inner core was coated with a chemoluminescent polymer made by ICX Nomadics, Inc. When the flow of molecules inside the fiber core is on, some attached to the polymer surface. This generates light that get absorbed in the semiconducting resulting in an increase in photo-current. When the flow is turned off, the current returns to base-line. The inser shows a SEM micrograph of the fiber cross section used. (B): Position reconstructed (dots) of a beam of light incoming at different locations along the axis of a fiber with a novel design.

particular, we will demonstrate that a one meter-long photodetecting fiber can localize a single incident optical beam with a sub-centimeter resolution. This system also enables the full reconstruction of an arbitrary rectangular optical wave front profile, as well as the localization of up to three points of illumination under given constraints, incident along the fiber axis.

The fiber devices presented so far are static devices, incapable of controllably changing properties at arbitrary frequencies. Enabling electrically-modulated fibers could pave the way for unprecedented technological capabilities, impacting the repertoire of functionalities and applications for multimaterial fiber sensors. This could include sensitive flow measurements in capillary blood vessels, *in vivo* endovascular acoustic imaging through acoustically-*opaque* organs, and minimally-perturbative sensor meshes for large-area studies of pressure/velocity fields in fluid flows[15]. Previous approaches have focused on non-linear optical mechanisms realized in silica glass fibres[16-19], inherently limited by simple geometries, short fibre lengths and high driving fields. Here we will present a new approach where we lift these limitations through the composition of an internal phase that is simultaneously crystalline and non-centrosymmetric. Tens of metres of fibers containing a thin ferroelectric polymer layer spatially confined and electrically contacted by internal viscous electrodes are thermally drawn entirely from a macroscopic preform. The viscous state of the draw enables fibre cross sections of variable symmetry and resulting acoustic wave fronts, as exemplified in Figure 4A where the cross-section of a flat fiber is shown. Also shown in Figure 4 is the principle of fiber vibration detection enabled by the integration of a piezoelectric material.

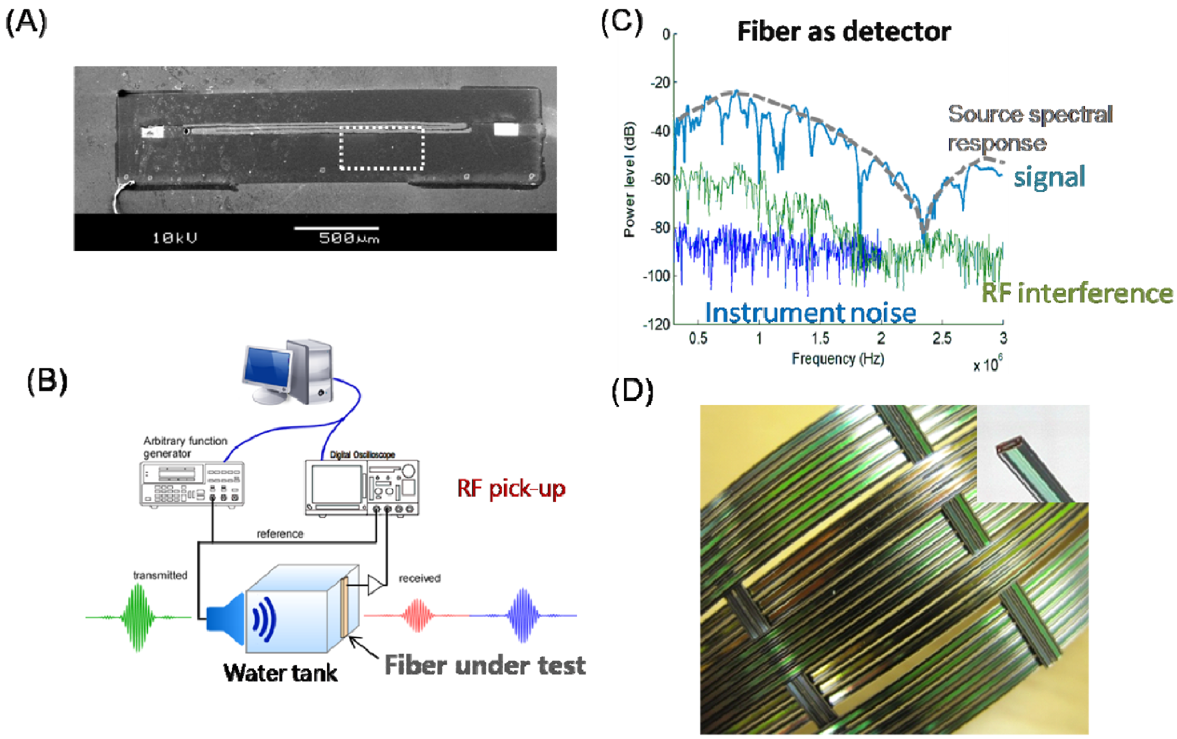

Figure 3 (A): Scanning Electron micrograph of a rectangular shape fiber cross section that integrates a PVDF layer sandwiched between CPE, a carbon black fille Polyethylene polymer**.** Two metallic electrodes are inserted at the edges for electrical contact to exterior circuitry**.** (B): Experimental setup for acoustic characterization of piezoelectric fibres. Acoustic wave travels across a water tank from a water-immersion acoustic transducer to a fibre sample, and vice versa. (C): Acoustic signal detected (blue curve) by a piezoelectric rectangular fibre around 1 MHz. The dotted line is the power spectrum of the (1 MHz-centred) transducer used. Also represented are the RF interference and Instrument noise spectrum. (D) Two-dimensional device fabric constructed by knitting the piezoelectric/FP fibres as threads. Inset is a photograph of an individual fibre.

Finally we will present recent development and direction for multimaterial fibers. One example is the incorporation of electronic junctions having build-in potential, for the realization of transistors, photovoltaics, LEDs, and many other electronic and optoelectronic devices. Until recently, the length and complexity of fiber devices showing rectification behavior have been limited by the processing methods. Their cylindrical geometry is ideal for single device architectures but not amenable to building multiple devices into a single fiber, a requirement for more complex tasks such as signal processing. The multimaterial preform-to-fiber approach addresses the challenges of device density, complexity, and length simultaneously, but the performance of these fiber devices has also been limited by the relatively small set of materials compatible with the drawing process and use of low mobility amorphous inorganic semiconductors. From a processing standpoint, non-crystallinity is necessary to ensure that the preform viscosity during thermal drawing is large enough to extend the time-scale of breakup driven by surface tension effects in the fluids to times much longer than that of the actual drawing. The structured preform cross-section is maintained into the microscopic fiber only when this requirement is met. Unfortunately, the same disorder that is integral to the fabrication process is detrimental to the semiconductors' electronic properties. As a result, multimaterial fiber devices built to date are limited to ohmic metal-semiconductor contacts and suffer from problems common to photoconductor devices including high noise currents, continuous power consumption, and reduced sensitivity. The recent incorporation of phase-changing semiconductors[20], those that may be easily converted between the amorphous and crystalline states, into composite fibers offers a path towards reduction of these defects and the ability to introduce spatially extended internal fields within the device. Indeed, by proper selection of the semiconductor and metallic contacts the synthesis of a crystalline compound semiconductor in fiber can be achieved. This opens the way toward arbitrarily long rectifying junction or field effect devices embedded in polymer fibers[21], that could significantly impact fiber sensor performance.

Acknowledgments: This work is the result of the combined efforts of the authors and all previous and current members of the Photonic Band Gap Fibers and Devices Group led by Prof. Yoel Fink, in the department of Materials Science and Engineering at MIT: Prof. A. F. Abouraddy, Prof. M. Bayindir, Dr. G. Benoit, N. Chocat, Dr. S. Danto, Dr. S. Egusa, Dr. S. D. Hart, Dr. K. Kuriki, G. Lestoquoy, Dr. N. Orf, Dr. P. Rakich, Z. M. Ruff , Dr. O. Shapria, D. Shemully, A. M. Stolyarov, Dr. B. Temelkuran, J. F. Viens, Dr. Z. Wang. With also the help and support of Prof. John D. Joannopoulos from the Institute for Soldier Nanotechnology and the Dpt of Physics at MIT, and Dr. A. Rose from INC Nomadics.

This work was supported by ARO, DARPA, ISN, and the MRSEC program of NSF.

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