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M1 (Invited)

POLYMER MICROSTRUCTURED OPTICAL FIBERS - OVERVIEW OF THE NOVEL GEOMETRIES AND FUNCTIONAL PLASTICS FOR A VARIETY OF APPLICATIONS INCLUDING PHOTONIC TEXTILES AND HIGH BIT RATE DATA COMMUNICATIONS, LOW-LOSS MID-IR AND THZ GUIDING, AS WELL AS PLASMONIC SENSING AND NANOPHOTONICS.

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Abstract: recently, microstructured optical fibers have attracted significant research effort as in addition to offering a highly designable optical performance they also allow integration of the non-optical functionalities such as microfluidics, electrical conductivity, biocompatibility, mechanical actuation, etc. into the same fiber structure. In my talk I will overview the latest advances of our group in the area of fiber design, fabrication and application of several novel fiber types for multidisciplinary and highly practical applications including: photonic bandgap Bragg fibers containing in their structure hundreds of sub-micron layers of two different plastics for application in photonic textiles for flexible displays, colorful illumination and distributed sensing; novel, highly porous subwavelength plastic fibers, as well as hollow core fibers made of ferroelectric materials for guidance of the far-IR and THz light; finally I will present microstructured fibers containing metallic inclusions for building highly compact and ultra-sensitive fiber-on-a-chip biochemical sensors.

1. Introduction

In my talk I will concentrate on multidisciplinary applications of plastic Microstructured Optical Fibers (MOFs). Although being a very active research field for several years, examples of commercial products based on such fibers are scarce. In my talk I will overview several niche applications where, in my opinion, plastic MOFs can be an enabling and cost-effective technology.

2. Photonic bandgap fiber textiles

I will start by presenting fabrication and use of the plastic Photonic Bandgap Bragg fibers in photonic textiles for applications in the interactive cloths, sensing fabrics, signage and art. In their cross section Bragg fibers feature periodic sequence of layers of two distinct plastics such as PMMA and Polystyrene (see Fig.1). For more details about this technology the reader is referred to the following recent publications [1-4].

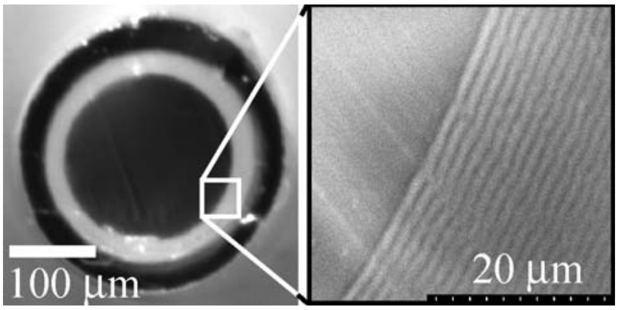

Fig. 1. Example of a plastic photonic bandgap Bragg fiber containing 100s of PMMA/PS layers.

Under ambient illumination the fibers appear colored due to optical interference in their microstructure. Importantly, no dyes or colorants are used in fabrication of such fibers, thus making the fibers resistant to color fading. Additionally, Bragg fibers guide light in the low refractive index core by photonic bandgap effect, while uniformly emitting a portion of guided color without the need of mechanical perturbations such as surface corrugation, thus making such fibers mechanically superior to the standard light emitting fibers (see Fig. 2).

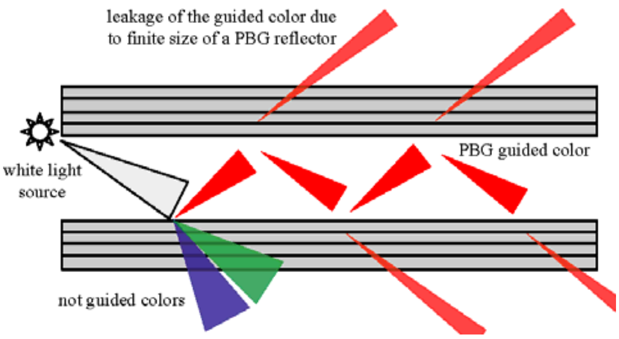

Fig. 2. Light emitting Bragg fiber does not require mechanical perturbations for light extraction.

Intensity of side emission is controlled by varying the number of layers in a Bragg reflector. Under white light illumination, emitted color is very stable over time as it is defined by the fiber geometry rather than by spectral content of the light source. Moreover, Bragg fibers can be designed to reflect one color when side illuminated, and to emit another color while transmitting the light. By controlling the relative intensities of the ambient and guided light the overall fiber color can be varied, thus enabling passive color changing textiles (see Fig. 3).

Fig. 3. Photonic bandgap textiles under ambient illumination and with light launched into it.

Additionally, by stretching a PBG Bragg fiber, its guided and reflected colors change proportionally to the amount of stretching, thus enabling visually interactive and sensing textiles responsive to the mechanical influence (see Fig. 4). Finally, plastic Bragg fibers offer economical solution demanded by textile applications.

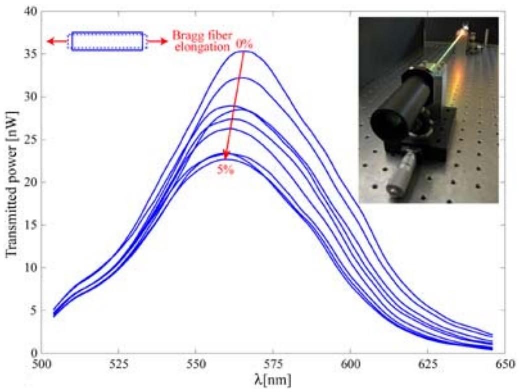

Fig. 4. Transmission peak (color) of a Bragg fiber can be shifted by fiber elongation.

Another interesting application of Bragg fibers is in high bandwidth short range data communications [5]. In multimode bandgap guiding fibers (such as Bragg fibers) higher order modes have high radiation losses. Ones excited, after a short propagation distance such modes are leaked out of the fiber core. Reduction in the number of guided modes leads to decrease of the intermodal dispersion and dramatic enhancement of the fiber bandwidth.

3. Porous fibers for guiding with lossy dielectrics

In the second part of my talk I will describe application of polymer microstructured fibers for the problem of guiding light in the mid-IR and THz regimes.

When using ferroelectric plastics exhibiting high reflectivity in THz as one of the materials in a Bragg reflector one can design very low-loss hollow core fibers for guidance THz radiation, which is otherwise impossible to do with standard solid core fibers due to high absorption loss of plastics in this spectral region [6].

Alternatively I will present novel highly porous, subwavelength plastic fibers for the guidance of far-IR and THz light (see Fig. 5). Made of strongly absorbing plastics, such fibers, nevertheless, allow relatively low transmission loss due to strong light confinement in the air-filled pores of the fiber core. Unlike traditional subwavelength rod-in-the-air fibers, porous fibers also offer significantly reduced interaction of guided light with the environment [7-8] (see Fig. 5).

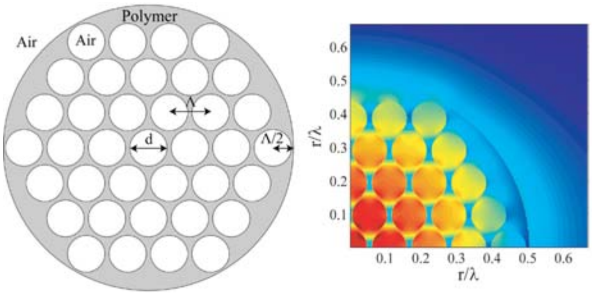

Fig. 5. Highly porous microstructured optical fibers for low loss guiding of THz light. Light is confined predominantly in the air holes.

I will then discuss several strategies for the fabrication of porous subwavelength fibers using low density Polyethylene (PE) plastic for low-loss terahertz light transmission applications (see Fig. 6). Transmission losses of the fabricated fibers were characterized in terahertz using a novel non-destructive directional coupler method. Within this method a second fiber is translated along the length of the test fiber to probe the power attenuation of a guided mode. The method is especially suitable for measuring transmission losses through short fiber segments, a situation in which standard cutback method is especially difficult to perform. We demonstrate experimentally that introduction of porosity into a subwavelength rod fiber, further reduces its transmission loss by as much as a factor of 10. The lowest fiber loss measured in this work is $0.01 cm^{-1}$ and it is exhibited by the 40% porous subwavelength fiber of diameter 380μm.

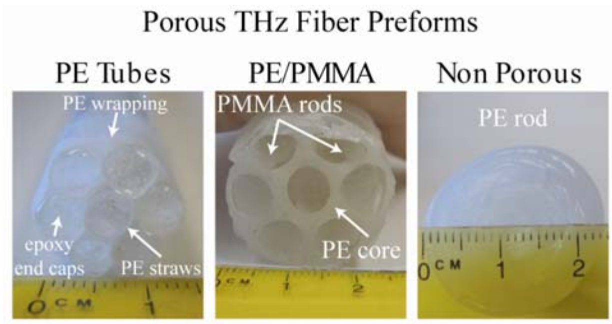

Fig. 6. Porous microstructured optical fiber preforms made by PE tube stacking, PE molding in a PMMA mold, and, finally, molding of a rod fiber preform in a Teflon tube.

4. Integration of plasmonics into MOFs

In the last part of my talk I will present design and fabrication of the ultra-sensitive and compact plasmonic sensors of the analyte refractive index based on metallized microstructured optical fibers. By integrating metallic inclusions into the structure of microstructured fibers one can enable excitation of highly localized plasmonic modes using a regular core mode of a fiber for optical interrogation [10-12]. Practical implementations of such fibers will be discussed, as well as their potential application as highly sensitive integrated sensors of the analyte refractive index. With a proper choice of plastics such plasmonic sensors can be realized anywhere from the visible to THz frequencies.

In the simplest implementation of a MOF-based plasmonic sensor, plasmons on the inner surface of a large metallized channel containing analyte can be excited by a fundamental mode of a single mode microstructured fiber (Fig. 7). Phase matching between plasmon and a core mode can be enforced by introducing air filled microstructure into the fiber core. For example, effective refractive index of a fundamental mode can be lowered to match that of a plasmon by introducing a small central hole into the fiber core. Resolution of the MOF-based sensors is demonstrated to be as low as $3 \cdot 10^{-5}$RIU, with a sensor length as small as 1mm. Ability to integrate large size microfluidic channels into the structure of a sensor directly during fiber fabrication is attractive for the development of highly integrated and ultra-sensitive bio- and chemical sensors.

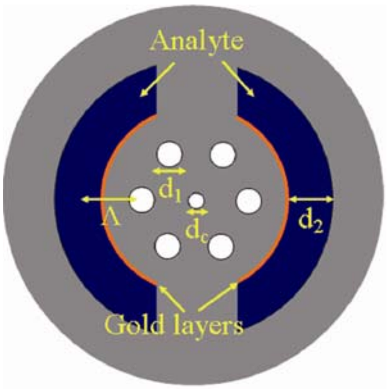

Fig. 7. Plasmonic sensor using metallized microstructured fiber. Central region is a core of a single mode waveguide. On the periphery one finds a metallized air channel filled with analyte.

To demonstrate operational principle of such a sensor in Fig.8 we present dispersion relations of the core guided mode (solid line) and a plasmon wave (dashed line). Phase matching point is located at 640nm where the difference between the modal refractive indexes is the smallest. Energy flux distributions in the vicinity of a phase matching point (insets (a,b) in Fig. 8) allow clear differentiation of the nature of two modes. In the vicinity of a phase matching point the two modes become strongly mixed (inset (c) in Fig. 8), with losses of a core guided mode increasing dramatically due to the energy transfer into the lossy plasmon mode. Core mode losses calculated as Im(n_{eff}) are presented in Fig. 8 in a thin solid line. Detection of increase in the loss of a core guided mode at the point of its phase matching with a plasmon constitutes the core of many sensor designs.

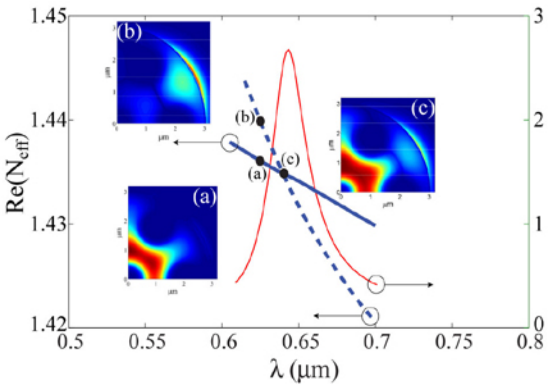

Fig. 8. Dispersion relations of a core guided mode (thick solid line) and a surface plasmon (thick dashed line) in the vicinity of phase matching.

Finally, I will describe a novel principle in designing of the fiber-based plasmonic waveguides, which allows phase matching of a Gaussian-like core mode of a photonic bandgap fiber with that of a plasmon mode at practically any desired wavelength from the visible to THz [13-15].

Particularly, I will present the concept of photonic bandgap fiber-based surface plasmon resonance sensor operating with low refractive index analyte (see Fig. 9). In such a sensor, plasmon wave on the surface of a thin metal film embedded into a fiber microstructure is excited by a leaky Gaussian-like core mode of a fiber. We demonstrate that by judicious design of the photonic crystal reflector, the effective refractive index of the core mode can be made considerably smaller than that of the core material, thus enabling efficient phase matching with a plasmon, high sensitivity, and high coupling efficiency from an external Gaussian source, at any wavelength of choice from the visible to near-IR. To our knowledge, this is not achievable by any other traditional sensor design. Moreover, unlike the case of total internal reflection waveguide-based sensors, there is no limitation on the upper value of the waveguide core refractive index, therefore, any optical materials can be used in fabrication of photonic bandgap fiber-based sensors. Based on numerical simulations, we finally present designs using various types of photonic bandgap fibers, including solid and hollow core Bragg fibers, as well as honeycomb photonic crystal fibers. Amplitude and spectrum based methodologies for the detection of changes in the analyte refractive index are discussed. Furthermore, sensitivity enhancement of a degenerate double plasmon peak excitation is demonstrated for the case of a honeycomb fiber. Sensor resolutions in the range 7·10^{-6} were demonstrated for an aqueous analyte.

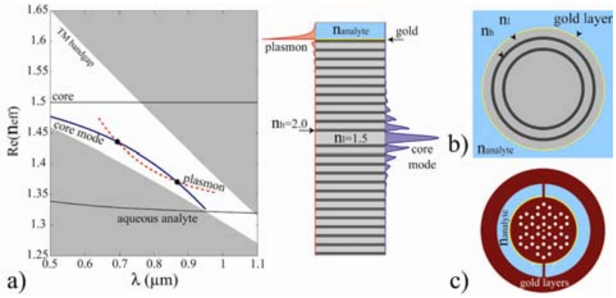

Fig. 9. Schematics of various photonic crystal waveguide-based SPR sensor implementations. a) Single mode planar photonic crystal waveguide-based SPR sensor. The dispersion relation of the core guided mode is in solid blue, that of the plasmon is in thick dashed red. Inset - coupler schematic; $|S_z|$ of a plasmon (left) and a core mode (right). b) Solid core Bragg fiber-based SPR sensor. c) Microstructured core, honeycomb photonic crystal fiber-based SPR sensor.

5. Conclusions

In my talk I discuss near-term commercial potential for the plastic microstructured fibers by giving several examples of their niche applications. Practical devises demonstrated in this talk include photonic bandgap fiber textiles for sensing, illumination, and short range data communication; porous subwavelength fibers for mid-IR and THz guidance; and ultra sensitive and highly integrated plasmonic bio- and chemical sensors.

Acknowledgement

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References

[1] News and Views, “Colour-tunable textiles,” Nature Photonics, **2**, 650 (2008).

[2] B. Gauvreau, N. Guo, K. Schicker, K. Stoeffler, A. Ajji, R. Wingfield, C. Dubois, M. Skorobogatiy, “Color-changing and color-tunable photonic bandgap fiber textiles,” Opt. Express, **16**, 15677-15693 (2008).

[3] B. Gauvreau, K. Schicker, N. Guo, C. Dubois, R. Wingfield, M. Skorobogatiy, “Color-on-demand photonic textiles, ” The Textile Journal, **125**, 70-81 (2008).

[4] http://xslabs.net/karma-chameleon/

[5] M. Skorobogatiy and N. Guo, “Bandwidth enhancement by d5fferential mode attenuation in multimode photonic crystal Bragg fibers,” Opt. Lett., **32**, 900 (2007).

[6] M. Skorobogatiy and A. Dupuis, “Ferroelectric all-polymer hollow Bragg fibers for terahertz guidance,” Appl. Phys. Lett., **90**, 113514 (2007).

[7] A. Hassani, A. Dupuis, and M. Skorobogatiy, “Low Loss Porous Terahertz Fibers Containing Multiple Subwavelength Holes,” Appl. Phys. Lett, **92**, 071101 (2008).

[8] A. Hassani, A. Dupuis, and M. Skorobogatiy, “Porous polymer fibers for low-loss Terahertz guiding,” Opt. Express, **16**, 6340-6351 (2008).

[9] A. Dupuis, J.-F. Allard, D. Morris, K. Stoeffler, C. Dubois, and M. Skorobogatiy, “Fabrication and THz loss measurements of porous subwavelength fibers using a directional coupler method,” Opt. Express, **17**, 8012–8028 (2009).

[10] A. Hassani, M. Skorobogatiy “Design of the microstructured optical fiber-based surface plasmon resonance sensors with enhanced microfluidics,” Opt. Express, **14**, 11616-11621 (2006).

[11] A. Hassani, M. Skorobogatiy, “Design criteria for the Microstructured Optical Fiber-based Surface Plasmon Resonance sensors,” JOSA B, **24**, 1423-1429 (2007).

[12] A. Hassani, A. Dupuis, and M. Skorobogatiy, “Surface Plasmon Resonance-like fiber-based sensor at terahertz frequencies,” JOSA B, **25**, 1771-1775 (2008).

[13] Research Highlights - “Plasmonics: Sensors tune in,” Nature Photonics, October 2006.

[14]M. Skorobogatiy and A.V. Kabashin, “Photon Crystal waveguide-based surface plasmon resonance bio-sensor,” Appl. Phys. Lett., **89**, 143518 (2006).

[15] B. Gauvreau, A. Hassani, M. Fassi Fehri, A. Kabashin, and M. A. Skorobogatiy, “Photonic bandgap fiber-based Surface Plasmon Resonance sensors,” Opt. Express, **15**, 11413-11426 (2007).