Multimaterial and Flexible Devices Made by Fiber Drawing

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ABSTRACT

The ability to co-process different materials at the same time in a thermal process opens up the possibility of scalable fabrication of volumetric multimaterial and multifunctional devices with operation spanning from the UV to the microwave. Combining optical, mechanical and electronic properties of dielectrics (such as glass and polymers) and metals enables a plethora of applications in radiation manipulation.

In this presentation I will discuss the process and the challenges of fiber drawing novel materials and material combinations such as: elastic polymers, biocompatible polymers, arsenic free soft-glasses and combinations of metal-dielectric structures. After discussing the process behind the realization of the novel fibers, I will show some very diverse uses of these exotic materials. I will report on our latest results on flexible fibers in generation of orbital angular momentum, realization of tunable metamaterials and wearable sensors, and I will present some applications of fiber drawn metamaterials for THz radiation.

Keywords: Multimaterial fibers, Soft fibers, Fiber drawn metamaterials, Sub-diffraction imaging, Twisted fibers, Wearable devices.

1. INTRODUCTION

The fabrication to high standards and quality of optical fibers for telecommunications drove the development of the fiber drawing technique. Such fibers are conventionally made of fused silica and have a solid cross-section. However, this fabrication technique has been modified to be able to process a variety of materials and structures.

This paper reports our most recent results in exploiting the fiber drawing fabrication method using novel materials and material combinations to realize specialty fibers for a very broad range of applications. This work can be largely separated in two main categories: fiber drawn metamamterials and extremely soft polymer fibers.

2. FIBER DRAWN METAMATERIALS

The combination of dielectric and metal structures allows to tailor the permittivity and permeability of an effective material and to obtain properties beyond what is possible to achieve with naturally occurring materials. Given the nature of the fabrication process, the typical structures realized are longitudinally invariant, they combine a dielectric matrix (a polymer or a glass) with metallic sub-wavelength inclusions in the form of rods or slotted cylinders [1].

The chosen dielectric matrix is correlated with the wavelength of operation of the metamaterial. This is due to limitations in scaling the metallic inclusion, which are to be sub-wavelength, below a certain size depending on the material used. Therefore, a polymeric matrix (Zeonex and Polymethylmethacrylate, PMMA) with metal inclusions (indium) is used to realize structures operating at THz wavelength, while a glass (soda-lime) matrix with metallic inclusions (tin) allows for operation into the infrared.

The type of metallic inclusion affects which property is modified: rod/wires are used to modify the permittivity, while slotted cylinders/split ring resonators modify both permittivity and permeability.

2.1 Sub-diffraction imaging and focusing

The main application that drove the work on fiber drawn metamaterials was sub-diffraction imaging. Structures allowing for sub-diffraction imaging require the ability to guide high spatial frequencies and to convert them to low spatial frequency to be imaged with conventional instruments. A straight wire array has the correct dispersion profile to allow high spatial frequencies to propagate in it. A geometric modification is then needed to do the conversion to low spatial frequencies. We have investigated two approaches to the conversion, i.e. a taper and a prism, and we have realized structures for operation from the THz to the IR.

A tapered hyperlens was fabricated with an 8x magnification factor. This allowed sub-diffraction imaging 13x below the diffraction limit [1]. Realizing a tapered structure has fabrication challenges. Therefore, a different method of magnifying the spatial frequencies was investigated theoretically and experimentally: a prism structure. This structure allowed a 2x magnification in the near-field [2]. Theoretical investigation has shown the ability to use this design to address high-spatial frequencies [3].

In order to reduce the size of the hyperlens a change of materials was necessary. We realized wire array structures in soda-lime glass and using tin as the metal. Wire sizes as small as 150 nm are possible [4]. A 3x magnification hyperlens made of such materials was cascaded with the polymer 8x hyperlens to achieve focusing of radiation to 1/176x the size of the operating wavelength [5].

The small feature sizes achieved in the soda-lime/tin hyperlens are suitable for operation in the Mid-IR. We showed that operation in the 3-4 µm regime is possible. However, the power handling of the hyperlens due to the high metal loss is quite poor and damaging of the structures occurs easily [6].

2.2 Tunable metamaterials

The electromagnetic response of most metamaterials is given by their structure, which is fixed at the time of fabrication, therefore this poses a limitation to this type of structure, including our fiber drawn metamaterials. To overcome this limitation, we substituted the rigid polymer matrix of the metamaterials with a low Young's modulus polymer, i.e. polyurethane, allowing for deformation of the structure and therefore tunability of the metamaterial response, demonstrating a 50% shift of the plasma frequency of the structure [7].

2.3 Waveguides

The ability to manipulate the permittivity presents itself as an opportunity to realize structures that can guide light. We have realized several different demonstrations of how such control can be achieved. All the waveguides investigated are realized for THz frequencies and they use PMMA and/or Zeonex and indium.

Using an array of slotted cylinders as the cladding of a hollow waveguide, we showed how various field confinement mechanisms are achieved by changing the relative orientation of the propagating electro-magnetic field and slotted cylinders in the waveguide [8].

Wire array cladding, hollow core waveguides have been realized to address some of the issues related to THz waveguides (flexibility of the waveguide and loss). A single mode TM sub-wavelength waveguide was realized in a size that allowed it to bend tightly [9]. A hybrid metamaterial antiresonant waveguide was demonstrated to combine guiding the TE modes, due to the antiresonant structure, and the TM modes, due to the effectively metallic behaviour of the cladding. Such combination has the potential to realize low loss THz waveguides [1].

3. EXTREMELY SOFT POLYMER FIBERS

Extremely deformable materials are very interesting when mechanical deformation is to be used to modify optical fields and when having to comply with the mechanical properties of the surrounding environment. To this purpose we have fabricated microstructured fibers in polyureathane (PU) and polycaprolactone (PCL).

3.1 OAM generation in twisted fibers

An antiresonant PU fiber for THz radiation was realized. The flexibility of the material allowed the structure to be twisted at a rate such that a mode with orbital angular momentum was generated and experimentally visualized [10]. Such deformation is reversible, and the mode of the untwisted structure does not possess orbital angular momentum.

3.2 Wearable devices for health monitoring

The high deformability can also be used for sensing, where the sensitivity is proportional to the deformation [11]. Moreover, PU fibers are very suitable to be used for wearable devices because of their small size and since the material is already used in the clothing industry. We realized a simple intensity-based sensor to monitor respiration and pace during running [12].

3.3 Biocompatible structures for cell growth

We realized for the first time fiber drawn solid and hollow structures made of the biocompatible material PCL. The realized structures have been used to grow cells along the fibers [13].

4. CONCLUSIONS

In conclusion we have explored the process of novel materials/material combination by fiber drawing to investigate new physics and realize a plethora of new devices for applications spanning from waveguides to imaging to cell growth.

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