OAM generation, tunable metamaterials and sensors with highly deformable fibers

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Abstract: A flexible fiber-drawn material, i.e. polyurethane, allows for novel applications from THz to the visible. We exploit its elastic properties to generate orbital angular momentum modes, to make pressure sensors and to realize tunable metamaterials.
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Light propagation in an optical fiber is sensitive to the external perturbations on the fiber itself. In many situations, it is undesirable that such perturbation influences the information carried by the fiber. However, there are cases in which the interaction between external stimuli and the light in the fiber is the purpose of the fiber itself, such as sensors and modulators, and therefore is desirable. The amount of interaction is strongly dependent on the degree of mechanical flexibility of the fiber. In the most common fused silica optical fibers the mechanical deformations are very limited because of a high Young's modulus of about 70 GPa, and elongations are limited to about 1-2%. There are fibers with a Young's modulus almost one order of magnitude lower, i.e. polymer optical fibers, which can be stretched elastically up to 10%. This is an important improvement, but still in a similar range. A complete change of properties would be very interesting: what could be done if optical fibers had the mechanical properties of rubber bands?

We report the fabrication and use of a paradigm changing material in the realization of optical fibers: polyurethane (PU). Its Young's modulus is in the order of 50 MPa and it can withstand deformations as high as 600% [1]. With these properties even centimeter sized tubes and rods are bendable. On top of the mechanical properties, PU has other advantages as it is an approved biomedical material (already used for catheters) and it is often employed in wearables. As a drawback, PU has high optical material loss. However, structuring the material in hollow core structures and limiting propagation to short lengths mitigates this issue.

Of the many applications one could think of for such material, we focus here on generating modes carrying orbital angular momentum (OAM) by twisting the fiber structure, and on exploiting the material compression to obtain tunable metamaterials and sensors.

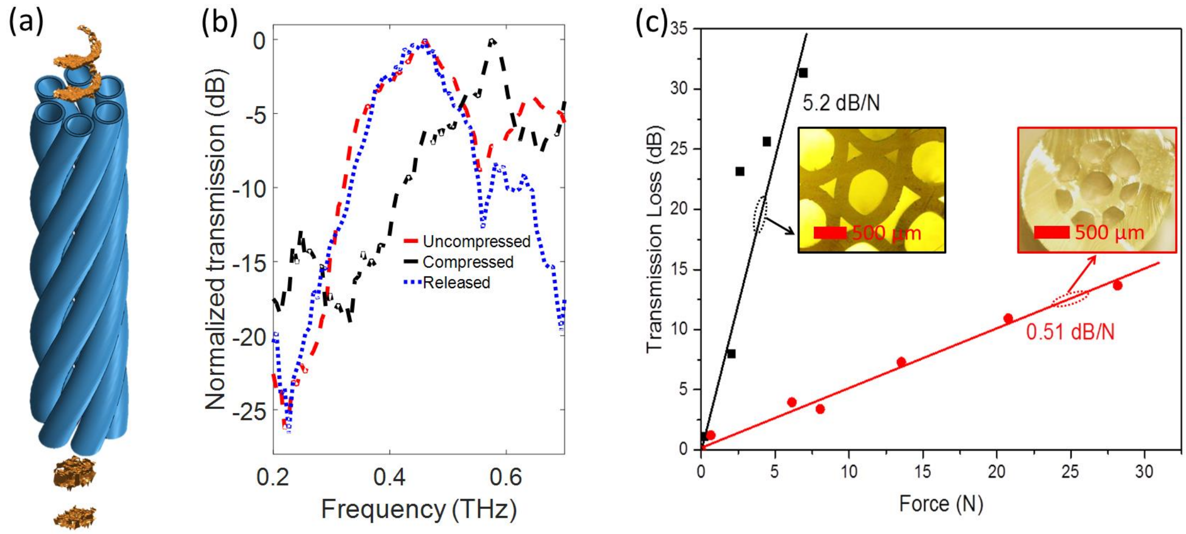

Fig. 1. (a) Schematic of the twisted antiresonant fiber with a flat phase input (bottom) and a vortex phase output (top) beam. In the schematic the orange input and output beam are measurements at 0.7 THz. (b) Tunable metamaterial: transmission through the wire array for different stages of compression. (c) Transmission loss as function of the force applied on the PU fiber for two different fiber designs. Insets: cross sections of the fibers used.

Orbital angular momentum modes with a helical fiber

Interest and applications of OAM are rapidly growing [2]. In this field, it was shown that applying twist to fiber structures can favor OAM modes [3]. The large deformability of PU allows to apply twist to optical fibers mechanically and reversibly and to do it even for large structures, i.e. cm sized THz waveguides [4]. The helicity of the fiber favors a conversion of the fundamental mode into an OAM carrying mode. We demonstrated conversion of a fundamental mode to an $\ell=1$ OAM mode in an antiresonant guiding fiber in the THz. Taking advantage of THz time domain spectroscopy we measured the vortex nature and evolution of the OAM mode [5], Fig. 1(a).

Tunable metamaterials

Metamaterials allow us to obtain electromagnetic properties not available in nature. Such properties are related to the geometry of the fabricated structure, which is generally fixed at time of fabrication. The ability to modify the exotic properties of metamaterials after fabrication is highly desirable both to tune them to desired values and to switch between behaviors [6]. We have explored the use of fiber drawing to fabricate scalable and mass producible metamaterials [7]. However, this also leads to fixed structures unless a reversible modification of the structure can be achieved. To obtain this goal we used a bulk PU matrix and demonstrated the ability to co-draw subwavelength metal wires in it. The material flexibility allowed us to change the wire spacing and therefore to tune the plasma frequency up to 50% [8], Fig. 1(b). We are now extending this regime by making use of hollows within the fibers to access both compression and expansion of the structure.

Sensors: optical and electrical

The simplest application of interaction between a signal and external perturbations is sensing. A wide range of deformation parameters can be monitored this way: twist, compression, elongation and bending. They can be done both statically and dynamically. As a first simple test, we examined the ability to sense compression in an intensity based experiment. The transmission through capillaries was monitored as a function of weight applied on top of them. Tuning of the sensitivity is achieved with fiber structuring, Fig 1(c), and with varying air to material ratio. The sensitivity of the realized PU structures is compared with standard PMMA capillaries. Weights between 4 g and 3 kg are measurable with PU, while PMMA is insensitive to this range of compression [9]. Sensing based on intensity measurements has a lot of sources of noise. Most of them can be eliminated when looking at signals with well-defined periodicity such as, for example, heart rate. We simulated this with a loudspeaker and measured heart rate-like signals [10]. Moreover, we exploited the ability to include metal wires in the fiber to obtain fiber drawn electric pressure sensors. We measured the change in capacitance between wires in the fiber due to compression and used multiple wires to identify compression directions [11].

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