Soft, stretchable optical fibers via thermal drawing

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Abstract. Optical fibers that can sustain large elastic deformations are promising building blocks in soft robotics, medical and wearable devices, and advanced textiles. Thus far, however, the fabrication methods developed for soft optical fibers have remained unmatured. Here, we present thermal drawing as a materials and processing platform to fabricate 10s of meters-long soft, multi-material optical fibers with intriguing architectures. It offers unprecedented opportunities to realize step-index soft optical fibers, as well as photonic crystal fibers for transmission, reflection, and sensing.

1 Introduction

The preform-to-fiber thermal drawing of thermoplastic elastomers (TPEs) enables the fabrication of soft multi-material optical fibers with intriguing architectures. Thanks to the thermal drawing technique, we are now able to fabricate 10s of meters-long, super-elastic fibers for actuation and sensing [1-6]. Despite these advantages, thermal drawing based on stretchable materials for applications has not yet been studied much until recently.

In this article, we demonstrate TPEs to be thermally drawn into fibers at high viscosity while keeping an elastomer-like behavior at room temperature. We identify materials with good optical transparency and index contrast to realize all-elastomeric step-index fibers with optical losses below 0.5 dB/cm at 520 nm wavelength. We also demonstrate the design, fabrication, and characterization of soft and stretchable one-dimensional (1D) photonic crystal fibers (PCFs) with a bandgap in the visible spectrum. The versatility of designing these soft, functional stretchable fibers, combined with large-scale manufacturing paves the way for novel applications in the fields of sensing, soft robotics, wearable healthcare, and tunable metamaterials.

2 Results and discussion

The challenges associated with designing materials compatible with the thermal drawing process to realize stretchable optical fibers are complex on multiple levels. In principle, we aim to choose suitable TPEs for fabricating soft, conformable optical fibers. TPEs, in general, are physically cross-linked, however, only a few of them exhibit rheological signatures and microstructures that can be deformed at relatively high viscosity [7, 8].

The resistance to high temperatures without any degradation is another fundamental aspect to consider. The added prime requirement is that the temperature-based viscosity gradient must be in a precise range and must not undergo abrupt changes. From the optical standpoint, properties such as reflectance and absorbance are key in selecting these materials.

2.1. Step-index soft optical fibers

We present a facile and scalable method to fabricate highly stretchable step-index fibers as depicted in Fig. 1. The fibers are composed of a cylindrical core made of poly(styrene-b-(ethylene-co-butylene)-b-styrene) (SEBS) and a cladding made of a silicone-based TPE, that is, Geniomer. Both TPEs can be thermally drawn together owing to their comparable viscous response in the same temperature window, that is, 160°-180°C. Opto-mechanical tests confirm that the soft, step-index fibers can undergo a strain of up to 400%, with a 20% decrease in light intensity at a strain of 50%. The index contrast in the visible of the two TPEs is 0.1 and a non-optimized structure shows losses of 0.5 dB/cm at 520 nm wavelength, envisioning potential applications as stretchable waveguides and sensors.

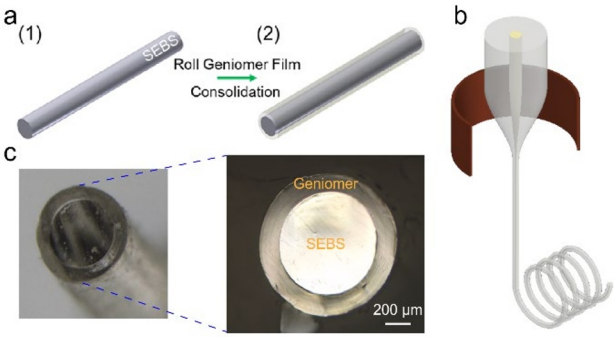

Fig. 1: Soft step-index fiber processing and materials. (a) Schematic of the preform fabrication process. (b) Schematic of the thermal drawing of soft multi-material fibers. (c) Optical microscope images of a step-index fiber with a SEBS core and a Geniomer cladding.

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2.2 Soft, stretchable photonic crystal fibers

We demonstrate thermal drawing as a materials and processing platform to fabricate 10s of meters-long soft 1D PCFs with photonic bandgaps in the visible spectrum. To design the soft 1D PCFs, we proceed with the dip-coating technique: SEBS and Geniomer alternate films are deposited directly on the preform while it is extracted from a chloroform solution with 2 wt.%, 2.5 wt.% SEBS and Geniomer dissolved, respectively. The control over the extraction velocity (~ 1 mm/s) and the concentration of the chloroform-polymer solution determines the thickness and homogeneity of the deposited films.

To validate the dip-coating technique's efficacy experimentally, we turn to scanning electron microscopy. The cladding of the preform is carefully removed and frozen in liquid nitrogen, while, Osmium is used for coating. Fig. 2 demonstrates the cross-section of the preform where an optimally designed multilayer stack of ~ 4 µm thickness each is visible. Moreover, the dip-coating process allows us to distinguish clearly the two different elastomers in the stack and to evaluate their regularity and order.

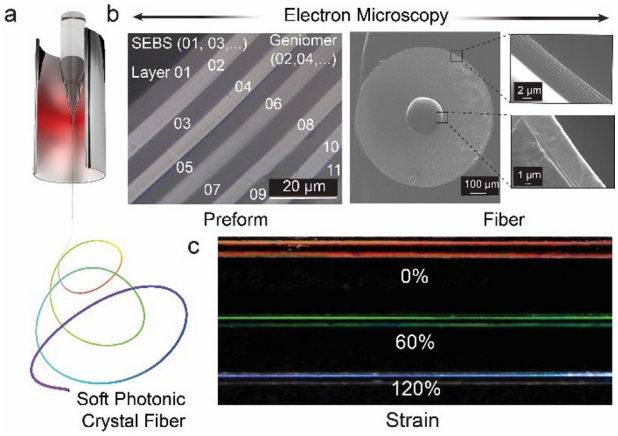

Fig. 2: Soft and stretchable one-dimensional photonic crystal fibers via thermal drawing. (a) Schematic representation of thermal drawing tower and soft photonic crystal fibers from a preform. (b) SEM images of the multilayer stack deposited inside and outside after thermal drawing. (c) Mechano-chromic fiber upon the uniaxial stretch.

Next, to characterize the resonance peak shift under strain, we use a 50% beam splitter with a bifurcated optical fiber through a single tip on one end and a double on the other. White light is injected by one of the two ends of the bifurcation and guided to the single tip pointing perpendicularly on the fiber. In Fig.2, we demonstrate the effect of the resonance shift upon stretching via the reversible change of the color of the elastomeric fiber. The mechano-chromic effect is revealed by stretching the 1D photonic crystal fiber at multiple relative elongations from rest to 120%.

We validate the stability of these mechano-chromic effects after multiple stretching cycles. To monitor the fiber at the same location, the stretching is induced by moving each clamp with the same amplitude on the individual side and observing always the central portion of the fiber. The spectra are normalized on the source, and the light contribution reflected from the splitter is subtracted and then fitted to obtain the exact position in the spectral peak.

The perceived colors are fairly uniform over the specific portions of the fiber which demonstrates that with a simple and scalable process such as thermal drawing, we could fabricate soft and stretchable PCFs with sub-100 nm feature sizes. These results demonstrate that the thermal drawing approach is an alternative of choice as a scalable and potentially low-cost production for all-elastomeric advanced photonic fibers. It paves the way for novel applications in the field of minimally-invasive surgery, mechano-chromic sensing, and smart textiles.

3 Conclusion

In this article, we demonstrated thermal drawing as a materials and processing platform for fabricating highly stretchable optical and photonic bandgap fibers. This novel methodology can bridge the gap between concepts of stretchable photonic systems and large-scale fabrication while opening novel device configurations. Given the soft mechanical properties, the step-index fibers, 1D PCFs can be weaved into textiles. It enables novel opportunities in robotics, medical devices and implants, sensing and monitoring, and smart textiles.

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