4D optical fibers thermally drawn from shape-memory polymers

Clément Strutynski*, Marianne Evrard, Frédéric Désévédavy, Grégory Gadret, Claire-Hélène Brachais, Bertrand Kibler and Frédéric Smektala.

Laboratoire Interdisciplinaire Carnot de Bourgogne (ICB), UMR CNRS 6303, Université de Bourgogne, 21078 Dijon, France

Abstract. Adaptative objects based on shape-memory materials are expected to significantly impact numerous technological sectors including optics and photonics. In this work, we demonstrate the manufacturing of shape-memory optical fibers from the thermal stretching of additively manufactured preforms. First, we show how standard commercially-available thermoplastics can be used to produce long continuously-structured microfilaments with shape-memory abilities. Shape recovery as well as programmability performances of such elongated objects are assessed. Next, we open the way for light-guiding multicomponent fiber architectures that are able to switch from temporary configurations back to user-defined programmed shapes. We strongly expect that such actutable fibers with light-guiding abilities will trigger exciting progress of unprecedented smart devices in the areas of photonics, electronics, or robotics.

1 Introduction

In recent years, both the variety and complexity of fiber profiles manufactured by the thermal drawing process have greatly diversified while the intricacy level of the tasks they are assigned has considerably widened [1,2]. Fibers are no longer passive objects, on the contrary, they can now combine a multitude of optical, electrical, and mechanical, functionalities providing them the ability to sense and react to their surroundings [3]. Fiber-based devices can even dynamically adapt to their environment and are able to perform three-dimensional motion by means of various strategies [4–6]. However, although a single fiber can nowadays gather a multitude of different materials (glasses, metals, polymers, semiconductors, etc.), exploiting shape-memory (SM) materials for thermal stretching has never been reported to date. In this work, we take advantage of the highly scalable preform-to-fiber drawing process to produce tens of meters of continuous polymer-based optical fibers with shape-memory abilities. The fabrication methodology is presented and the performance of light-guiding fibers possessing the ability to perform shape recovery cycles from different curvatures are discussed.

2 Results and discussion

2.1 Preform fabrication and fiber drawing

The preforms are additively manufactured from standard commercially-available thermoplastics. In particular, the elongated objects integrate semi-crystalline polylactic acid (PLA) domains which are responsible for the shape-memory effect. PLA is a semi-crystalline polymer, and is therefore not suitable for fiber drawing, because the process requires a material that gradually softens upon heating. Indeed, semi-crystalline polymers, unlike amorphous thermoplastics, generally remain solid until they rapidly transform into a low-viscosity liquid when reaching temperatures above their melting point \( T_m \). To overcome this limitation, semi-crystalline materials have to be associated, in most cases, with amorphous claddings (glasses or polymers) to be successfully integrated into elongated structures. Polyethylene terephthalate glycol (PETG) is used here as the amorphous cladding to control the flow of molten PLA during the thermal elongation process.

![PETG-core Step-index Shape-Memory optical fiber](image)

**Fig. 1.** (a) 2D diagram and pictures of the cross-sectional profile of a shape-memory optical fiber. (b) Shape-memory fiber transitioning from a temporary configuration to its programmed shape spelling “memory” in cursive. (c) Pictures of a light-guiding SM-fiber recovering its original straight shape when heated. (d) Pictures of a shape-memory optical fiber delivering light around an obstacle.

Description of a fiber fabricated using the proposed methodology is given in Fig. 1a. It is built from a main
PETG frame possessing (i) two lateral slots in which PLA parts are inserted and (ii) a central hole filled with an ABS tube (acting as the optical cladding) and a PETG cane (acting as the optical core of fiber).

2.2 Performance of the shape-memory optical fibers

As first experiments, we evaluate the shape-memory performances of the fabricated fiber, i.e. its ability to retain and recover a particular shape. PLA is responsible here for the shape-memory effect and the fiber can be programmed into a chosen shape using the following procedure: (i) the fiber is molded on a template object that determines the final shape, (ii) the assembly is heated above the melting temperature of PLA (here 1 min at 190 °C) to reprogram the semi-crystalline material and (iii) the fiber is rapidly cooled down to room temperature and subsequently released from the template object. After that, if the fiber sample is deformed, it will be able to recover its programmed shape when heated up. Fig. 1b shows pictures (from top to bottom) of a deformed fiber which recovers its programmed shape (spelling “memory” in cursive) when heated on a hot plate at ≈90 °C.

Going further, we now assess the ability of our fiber to transmit light while performing shape-changing operations. Fig. 1c shows pictures of a light-guiding fiber completing a recovery cycle, i.e. transitioning from a temporary bent shape to a programmed rectilinear shape. The transmission of the shape-memory waveguide in the visible range at 635 nm is then monitored throughout a series of straightening/bending cycles. In practice, straight as drawn samples are selected and bent at room temperature to form a 90° angle. After that, they are heated up using a heating block to recover a rectilinear shape. At the same time, a measurement of the output power is performed when the fibers are in a straight or curved configuration. This operation is repeated up to 20 times and corresponding experimental results are recapped in Fig. 2. The sample performs well and is able to maintain, in the rectilinear configuration, 90% of transmission after 18 cycles. After that, the transmitted power decreases drastically due to fatigue-related damage induced to the light-guiding core. In the bent configuration, the fiber preserves a good transmission of 50-70% also up to the 18th test iteration.

As a final experiment, an SM-PETG fiber is tested to transport a 635-nm laser beam toward a target object placed behind an obstacle (herein a black screen). The shape-memory fiber is heated to recover its programmed shape and is able to deliver the optical signal at a ≈170° angle from its original direction. The experimental operation is depicted in Fig. 1d. To minimize the bending losses, a curve with a 2.5-mm-bending radius is programmed to the sample. We confirm that shape-memory fibers can be successfully employed here to circumvent obstacles and illuminate hard-to-reach targets, which opens the way to new light delivery strategies in challenging and exiguous environments.

Other fiber geometries (fibers with an H-shaped PLA inclusion or featuring a larger polystyrene core, shape-memory fibered sleeves that can be combined with commercial fibers, etc.) or programmed shapes (coils, U-shapes, hooks, etc.) were produced and will be the subject of further discussions.

Fig. 2. Transmitted power at 635 nm as function of cycle number for a 450-µm outer diameter shape-memory fiber. Yellow circles refer to measurements performed when the fiber has a straight shape (see left inset) and black squares when it is bent (see right inset).

This research was funded by French program “Investments for the Future” operated by the National Research Agency (ISITE-BFC, 4DMeta project, contract ANR-15-IDEX-03; and EIPHI Graduate School, SMILE project, contract ANR-17-EURE-0002). The authors also acknowledge support from the French ANR (through the TRAFIC project, contract ANR-18-CE08-0016-03), from CNRS Institute of Physics (Emergence 2017, 3D-printed optical fibers), and from European Regional Development Fund. This work benefited from the facilities of the SMARTLIGHT platform funded by the French ANR (EQUIPEX+ contract "ANR-21-E5RE-0040") and the Région Bourgogne Franche-Comté.

References