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Fabrication of multiple parallel suspended-core optical fibers by sheet-stacking

Jindan Shi, Xian Feng *, Zhenggang Lian, Nicholas White, Wei H. Loh, Francesco Poletti, Peter Horak

Optoelectronics Research Centre, University of Southampton, Southampton SO17 1BJ, UK

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We demonstrate the fabrication of a novel type of optical fibers with multiple parallel air-suspended cores by the sheet-stacking method. Using this technique we have constructed optical fibers with up to 10 parallel micron-size suspended cores. No extra scattering loss from the fabrication process was observed in a fabricated dual air-suspended core fiber. The sheet-stacking method opens the way towards using a wide range of optical glasses for manufacturing multiple parallel suspended-core specialty optical fibers with novel optical functionalities such as dispersion tunability. Fusion splicing has also been successfully used to connect such a multiple core fiber with a conventional silica fiber.

1. Introduction

Multi-core optical fiber technology is an attractive and promising approach to enhance the functionalities and capacities of the traditional single core optical fiber. One example is the recent progress of using multicore single-mode fibers for largely enhancing the transmission capacity of the long-haul fiber optical telecommunication network [1,2].

Multicore optical fiber technology is also a powerful way for achieving novel optical components such as broadband directional couplers [3], narrow-band fiber filters [4], variable fiber attenuators [5], two-dimensional bending sensors [6], fiber lasers and amplifiers [7,8], and dispersion compensators [9]. For these applications, due to the rigid core/cladding physical structure, the fiber geometry is static, i.e., relative core-to-core movement is not possible. However, if the core-to-core separation can be modified in a well-controlled manner, this additional degree of freedom will further enhance the functionality and capability of multicore optical fiber technology in the areas of optical sensing, optical switching and optical processing. This motivates our target to develop novel multicore optical fibers with movable cores.

In a conventional all-solid optical fiber, core and cladding are composed of different glasses. With the invention of holey fibers (HFs) [10] it became possible to fabricate single-material optical fibers with air-filled microstructured cladding. Most HFs demonstrated to date have quite short and thick glass bridges between the air holes in the cladding. Thus the cores of these HFs are static, just as in conventional solid optical fibers. An exception is a HF exhibiting a micron-size core attached to a long glass membrane with submicron thickness. For this type of air-suspended-core (ASC) HF the light is guided along the glass core, which is surrounded by the air cladding, and thus optically the core is effectively suspended in air. Because of the long and thin supporting membrane, the core can be physically displaced from its stationary position by an appropriate external force. By adding a second air-suspended core parallel to the first one with a small distance on the wavelength scale, any relative movement between the two cores can be observed optically due to the light coupling between the two neighboring cores.

Such a type of multiple parallel ASC fibers with two cores has already been demonstrated [11,12]. When an external force, such as air pressure [12], electrostatic actuation [13] or even optical force [14–16], is applied to one of the cores, the light coupling between the neighboring cores can be modified in a well-controlled manner. In order to allow the mechanical actuation of the cores by weak external forces and also to ensure low confinement loss of the cores, the supporting glass membranes are required to be longer than 10 µm and thinner than 200 nm. However, these requirements present a significant challenge for the fiber fabrication.

So far, two methods have been employed to fabricate such a type of novel optical fibers: (i) capillary stacking and (ii) glass extrusion.

In the former case, silica glass was adopted as the fiber host. Three major capillaries and four assisting capillaries were stacked inside a jacket tube (as shown in Fig. 1(a) and high air pressure was applied into these three major capillaries so that two thin and long membranes were finally formed in the fiber [16,17]. But

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* Corresponding author.
E-mail address: xif@orc.soton.ac.uk (X. Feng).

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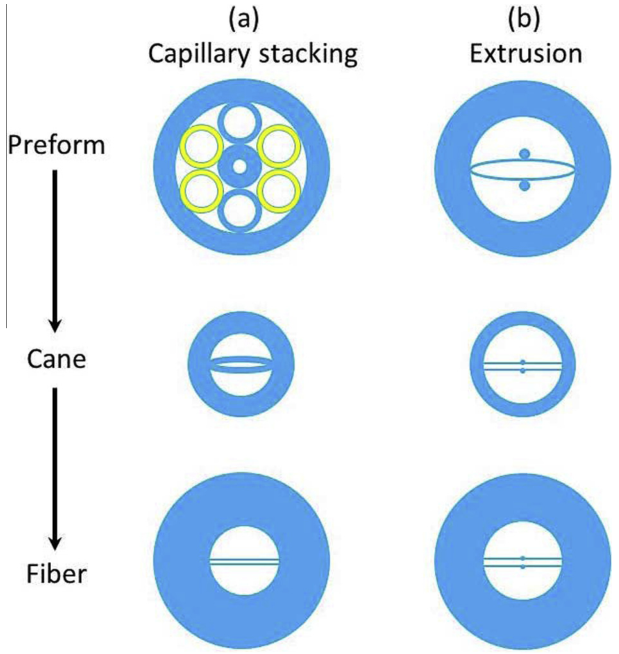

Fig. 1. Schematic diagrams of (a) the capillary-stacking method to fabricate dual-membrane fiber and (b) the extrusion method to make dual-ASC HF. Note that in the case of (a), during the caning procedure from the preform to the cane, high gas pressure was applied to the central three major capillaries (in blue). The four side assisting capillaries (in yellow) were collapsed after caning. For both cases, at the last step of fiber drawing, the cane was inserted into a jacket tube and this ensemble was drawn into the dual-ASC (or dual-nanoweb) fiber. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

it should be noted that there was no core formed in the fiber and the transmission loss at 1550 nm was therefore measured to be 35 dB/m, which is extremely high for silica based index-guided holey fibers. As described in Ref. [17], attempts to attach cores to the capillaries in the stacking were made but a large offset was observed between the two formed cores and the core size was still as large as several microns in diameter. This is because the high pressure can expand the capillary and make the membrane as thin as a few hundred nanometers and as long as tens of micrometers [18], but due to mass preservation the core size will approximately follow the reduction of the outer fiber diameter from that of the preform.

In the second fabrication method, glass extrusion [11,12], a non-silica glass (commercial lead silicate glass, Schott F2) was chosen as the fiber host material. The dual-core fiber preform was made by extrusion under a temperature around 600 °C. The extrusion method is a well-developed method for making non-silica glass (or so-called soft glass) HF [19] above the glass softening temperature, which is typically below 800 °C. It is very powerful in directly making microstructured preforms with glass features even as small as 7 μm [20]. But due to the lack of suitable die materials capable of working at temperatures above 1000 °C and at high pressures of 0.1–10 kN/cm^2, the glass extrusion technology has not shown any success in making preforms using glasses with high softening temperature such as silica.

Therefore, it is necessary to develop a new approach for the fabrication of multiple parallel ASC fibers using a wide range of materials covering both silica and non-silica glasses.

Here we demonstrate an interesting alternative to produce the geometry of multiple parallel ASC optical fibers: We employ a sheet stacking method where a unit element comprising a glass core sitting on a thin glass sheet is periodically repeated. In the simplest case, a single-ASC fiber can be drawn from a preform consisting of a core rod, a thin sheet and a surrounding thick walled jacket tube [10], as illustrated in Fig. 2(a). Fibers with multiple parallel suspended cores can be built on this platform, as shown in Fig. 2(b and c). The obvious advantages of this approach over the extrusion method are that (i) no metal extrusion die needs to be fabricated, (ii) the materials for the core and the membrane can be different from each other and (iii) different materials can be used for different cores in the same fiber, as long as all materials employed are thermally compatible during the fabrication [21].

In this work, two thermally-compatible commercial borosilicate glasses have been used for the fiber cores and membranes. A dual-ASC fiber and a 10-ASC fiber with micron-size cores and long and thin membranes have been fabricated, indicating that the sheet stacking method is a scalable approach to fabricate multiple cores. The loss of the dual-ASC fiber has been measured to be the same as the bulk loss of the original core glass, showing that the extra loss introduced by this approach is negligible. Numerical simulations show that the dual-ASC fiber can be used as a broadband dispersion tuning device by adjusting the core-to-core distance. In addition, fusion splicing has been successfully used for connecting the dual-ASC fiber with a commercial silica fiber.

2. Fabrication of multiple parallel ASC holey fibers

2.1. Preform preparation and fiber drawing of dual-ASC fiber

The sheet stacking method was inspired by the procedure of Kaiser used in the early 1970s to make the first single-material silica HF, i.e., a single-ASC HF [10,22]. In that work, the ensemble of the preform included a silica core rod with a diameter up to 1.5 mm, a polished silica supporting sheet with a thickness of 100 μm and a width of 6.5 mm, and a silica jacket tube with an inner diameter (ID) of 6.5 mm and an outer diameter (OD) of 10 mm. The core rod was either centered in the jacket tube by a capillary tube or attached to the top end of the supporting sheet with high temperature cement. Because the reduction ratio from the preform to the fiber was approximately 100 to 1, the preform was directly drawn into fiber with diameters of 100–200 μm [22].

As described above, the multiple parallel ASC HF requires center-to-center distance between the neighboring cores in the fiber of wavelength scale in order to have strong light coupling between the cores. The reduction ratio from the preform to the fiber should therefore be approximately 1000 to 1, if the starting core rod of the preform is 1 mm in diameter. This is impractical, and an intermediate caning process is thus necessary before the final fiber drawing. This step was not included in Kaiser's works for making a single-ASC HF [22]. As we will show in the following, the caning process is crucial for fabricating multiple parallel ASC HF rather than a single-ASC HF, because an offset of the neighboring cores will occur if the fabrication conditions are inappropriate.

We chose commercial Schott N-BK7 glass and D263T glass as the materials for the cores and sheets, respectively. These glasses are both borosilicate glasses but with slightly different thermal properties [23]. The concept of the construction of the preform with N cores ($N = 2$ and 10) is schematically illustrated in Fig. 2(b and c). The outer walls of the preform were constructed using four pieces of matted N-BK7 plates, each with 2 mm thickness. N slots of 1.0 mm depth and 200 μm width were machined on each vertical wall using a commercial dicing saw (Isomet 5000 Linear Precision Saw). The gap between the neighboring slots was precisely controlled between 1.3 and 1.5 mm by the digital micrometer gauge on the dicing saw. Commercial borosilicate glass sheets (Schott D263T) with a thickness of 100 μm and a width of 22 mm were employed in the stacked preform. Each sheet was horizontally slipped into the pair of symmetric slots on the vertical