Selectively fluid-filled microstructured optical fibers and applications

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Abstract
A versatile technique based on micromachining is demonstrated to fill selectively one or several different types of fluids into desired air holes in a microstructured optical fiber (MOF). Unique optical properties and applications of the selective-filled MOF are investigated.

1. Introduction
Microstructured optical fibers (MOFs) allow various advanced materials to be filled into their air holes [1, 2]. Unique optical properties could be achieved by selectively filling a fluid into desired air holes of MOFs [3-5]. Many methods have been developed to selectively fill a fluid into MOFs. Directly manual gluing technique, however, is an experimentally difficult approach because it is required to inject directly a UV curable polymer into air holes to seal them[3]. Another selective-filling technique based on the filling speed dependence cannot realize to fill selectively air holes with similar or same sizes [4]. In this paper, we report a versatile technique based on micromachining that can fill selectively one or several different types of fluids into desired air holes in a MOF. Unique bending properties and applications of the selective-filled MOFs are also investigated.

2. Selective-filling technique
Fig. 1 illustrates the approaches of our proposed selective-filling techniques. Firstly, as shown in Fig. 1(a), a fan-shaped groove is carved at a distance of about 5 mm from the fiber end by the use of a micromachining system consists of a femtosecond laser and a microscope. Consequently, desired air holes of the MOF are exposed to atmosphere at the grooved section, where the angle, α, the depth, d, and the width, w, of the fan-shaped groove can be controlled to expose the desired number of air holes. Secondly, as shown in Fig. 1(b), the grooved end of the MOF is fused into a spherical end to collapse completely the air holes at the fiber end by the use of an arc discharge technique. Thirdly, as shown in Fig. 1(c), the spherical end of the MOF with the groove is immersed into a fluid. It is critical point to immerse completely the fan-shaped groove into the fluid. So the fluid is filled into the exposed air holes of the MOF through the fan-shaped groove with the well-known capillarity action. Finally, the spherical end of the filled MOF is cleaved to move the fan-shaped groove, as shown in Fig. 1(d). Thus a selectively-filled MOF is achieved.

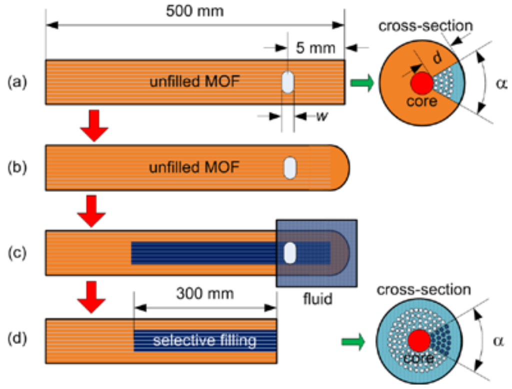

Fig. 1 Schematic flowchart for filling selectively a fluid into desired air holes of a MOF; (a) to carve a fan-shaped groove with an angle of α; (b) to collapse completely the air holes at the grooved end; (c) to immerse the grooved end of the MOF into a fluid; and (d) the selectively-filled MOF.

In our experiments, a pure-silica solid-core MOF (LMA-10 from Crystal Fibre) with a fiber diameter of 125 μm and a core diameter of 4.1μm was employed to demonstrate our proposed selective-filling technique. For the first filled MOF sample, as shown in Fig. 2(a), a fan-shaped groove with an angle of about 60°, a depth of about 55 μm and a width of about 30 μm was carved.

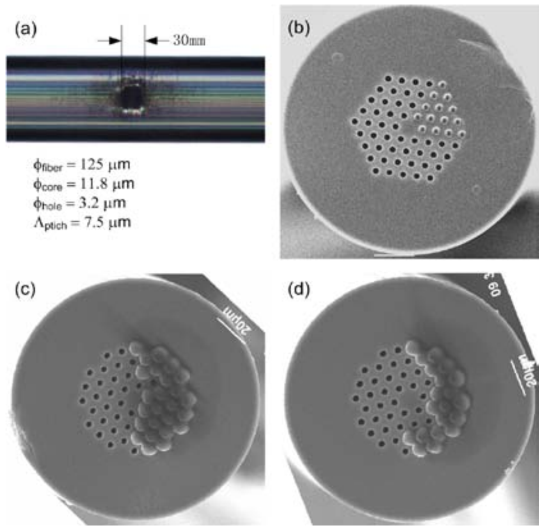

Fig. 2 (a) Side image of the MOF with a fan-shaped groove; Cross-section scanning electron micrographs of the MOFs in which (b) one sixth of air holes, (b) half of air holes, and (d) the air holes within the outside two rings were selectively filled by the fluid employed.

on the surface of the MOF. Consequently, as shown in Fig. 2(b), about one sixth of air holes were exposed to atmosphere at the grooved section and then were filled by a refractive index matching liquid (Cargille Labs, n = 1.485). For the second filled MOF sample, a fan-shaped groove with an angle of 180° and a depth of about 55 µm was fabricated on another type of MOF with similar fiber parameters. Consequently, as shown in Fig. 1(c), about half of air holes were exposed to atmosphere and then were filled by the same fluid. For the third filled MOF sample, we fabricated another 180° fan-shaped groove with a depth of only about 40 µm on the same type of MOF to demonstrate the versatility of our proposed selective-filling technique. Consequently, as shown in Fig. 1(d), only air holes within the outside two rings were exposed to atmosphere and then were selectively filled.

To compare with the selective-filled MOFs, we also made a fully-filled MOF sample in which all air holes were filled with the same type of fluid. As shown in Fig. 3, four bandgaps occur within the measured wavelength range of each fluid-filled MOF sample, resulting from the higher index (n = 1.485) of the filled fluid than that (n = ~ 1.450) of the pure-silica background in the MOF [2]. Hence, the bandgap-guiding light occur in the fluid-filled section of the fibers, whereas, the unfilled holes in the one-sixth- and half-filled MOFs remains an air/silica index-guiding structure.

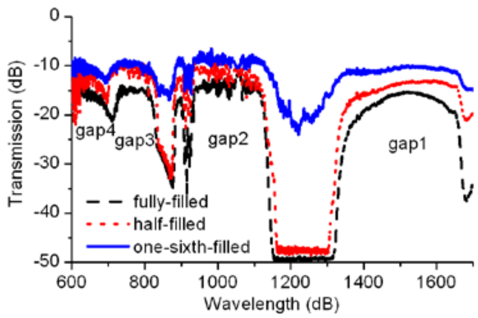

Fig. 3 Transmission spectra of the one-sixth-, half-, and fully-filled MOFs, in which four bandgaps were observed within the measured wavelength range of each fluid-filled MOF sample.

3. Orientation-dependent bending properties and applications of half-filled MOFs

We investigated the bending properties of the half-filled MOF[5]. As shown in Fig. 4, orientation-dependent bending properties were observed when the half-filled MOF was bent toward different fiber orientations, where the ‘0°’ orientation corresponds to the direction being perpendicular to the bottom of the groove [5]. As shown in Figs. 4(b), the transmission spectrum hardly changed while the half-filled MOF was bent toward the filled-hole side, i.e. the ‘0°’ orientation. Whereas, while the half-filled MOF was bent toward the unfilled-hole side, i.e. the ‘180°’ orientation (Fig. 4(e), and another two fiber orientations of ‘90°’ (Fig. 4(c) and ‘270°’ (Fig. 4(f), the ‘blue’ edge of each bandgap shifted toward the longer wavelength and the ‘red’ edge shifted toward the shorter wavelength. Compared with the fully-filled MOF, the half-filled MOF has a lower bend-sensitivity and even is insensitive to the increased curvature while the fiber is bent toward the side of the fluid-filled holes. This is of advantage to the communication applications of the fluid-filled MOFs.

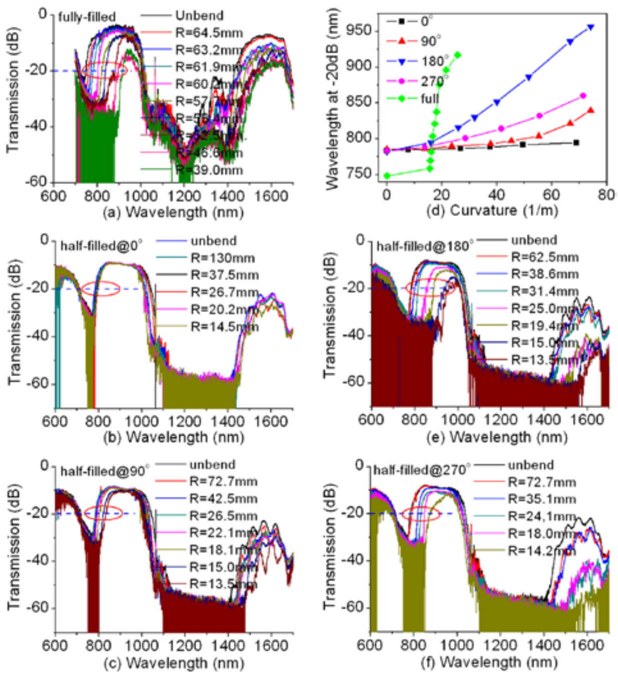

Fig. 4 Transmission spectrum evolutions of (a) the fully-filled MOF and the half-filled MOF bent toward the (b) 0°, (c) 90°, (e)180° and (f) 270° orientations with the decrease of the bend radius; (d) Wavelengths, corresponding to the transmission of -20dB, at the ‘blue’ edge of the second bandgap (see ‘red’ circles in (a), (b), (c), (e), and (f)) with the increase of the bend curvature [5].

4. Conclusions

A versatile selective-filling technique was demonstrated to improve or change the optical properties of a MOF. Providing two or more grooves are fabricated on different orientation/locations along the surface of a MOF, different types of fluids may be filled, in proper order, into desired air holes through each fabricated groove, thus achieving a hybrid fibre. The selectively-filled MOFs exhibit unique optical properties and could find novel applications in the fields of sensing and communications. This work was supported by a Marie Curie International Incoming Fellowship within the 7^{th} European Community Framework Programme, the Hong Kong Special Administrative Region Government through a GRF grant PolyU5190/08E, and a Foundation for the Author of National Excellent Doctoral Dissertation of PR China (No. 200940).

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