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Extruded single-mode high-index-core one-dimensional microstructured optical fiber with high index-contrast for highly nonlinear optical devices

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We report the fabrication of a high-index-core one-dimensional microstructured optical fiber incorporating with high index-contrast layers, using extrusion technique for preform fabrication. Single mode guidance and a high effective nonlinearity of $260 \pm 30\ W^{-1}\ km^{-1}$ were observed in the fiber at 1.55 μm, highlighting the potential of such fibers for use in nonlinear optical devices. © *2005 American Institute of Physics*. [DOI: 10.1063/1.2034094]

Microstructured optical fibers (MOFs), which are also known as photonic crystal fibers (PCFs)[1] or holey fibers (HFs), are attractive for a broad range of applications due to the unique optical performance that can be achieved. Novel optical properties such as photonic bandgaps, single-mode operation combined with very large mode area, dispersion management, and high nonlinearity can be achieved in this new type of optical waveguide.[2] Light can be guided in such waveguides through both photonic bandgap effects or more familiar average index guiding effects. Note that photonic bandgap guidance requires a periodic structure within the cladding whereas no such periodicity is required for average index guiding. Compared to silica glass based MOFs, non-silica glass based MOFs show great promise as a result of the high refractive indices, the high nonlinear refractive indices, low processing temperatures and high transparency in the mid-IR region (2–5 μm)[3] that can be achieved in non-silica glasses.

Previous works on MOFs[1,4] reveal that the main factors responsible for their unique optical performance are (1) wavelength-scale features within the microstructured cladding and (2) high index-contrast between the dielectric materials that constitute the fiber cladding. This is true regardless of the guiding mechanism of the fiber, or whether the microstructured cladding is one-dimensional (1D)[4,5] or two-dimensional (2D)[1] in nature. Figure 1(a) illustrates typical microstructures of 1D and 2D MOFs.

Due to the high purity and excellent homogeneity that is possible in pure silica glass, silica glass based MOFs have the potential to achieve lower attenuation than conventional doped silica fiber.[6] However, the use of a single material is not necessary in order to achieve novel and useful optical properties in MOFs. Indeed, it is possible to envisage fibers composed of two types of glasses with different index rather glass and air. In fact, the existence of air within the holes results in the unavoidable deformation of the microstructure in the cladding region during fiber manufacture which, consequently, makes it challenging to fabricate fibers with predetermined optical performance characteristics. Following this approach, we previously reported the fabrication of the first all-solid 2D MOF, also called a SOHO fiber (SOlid HOley fiber), based on two types of silicate glasses with a high-index-contrast of 0.23 at 1.55 μm.[7] The SOHO fiber has the microstructured cladding of a typical holey fiber but all the holes are filled with low-index glass. This approach enables fibers to be drawn to any practical dimension without any observable deformation of the transverse cladding structure.[7] High nonlinearity and near-zero dispersion have been achieved at 1.55 μm in SOHO fibers.[7]

Moreover, the concept of an all-solid microstructured optical fiber even permits us to fabricate a 1D microstructured cladding in addition to the more usual 2D triangular microstructure [see Fig. 1(a)]. Theoretical predictions indicate that high-index-core 1D MOFs can have useful optical characteristics such as ultra-flat dispersion,[8] which can be difficult to achieve in 2D high-index-core MOFs without significantly compromising the nonlinearity that can be achieved.

In this work we report the fabrication of a high-index-core, 1D, MOF based on high index-contrast optical glasses. The microstructured preform with multiple coaxial rings was fabricated using an extrusion technique. In earlier works on extrusion of glass,[9] it was established that when glass is extruded through a channel with circular cross-section, the flow behavior obeys the Hagen–Poiseuille law, i.e., the isothermal

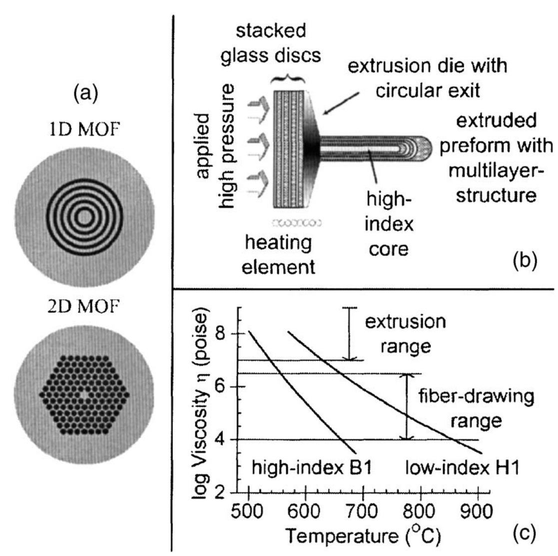

FIG. 1. (a) Schematic illustration of 1D and 2D MOFs. (b) Schematic of disc-stacking extrusion to manufacture the preform with multi-ring structured cladding. (c) Measured viscosity curves of high-index glass (B1) and low-index glass (H1).

laminar volumetric flow rate V is given by $V = \pi\Delta p \cdot r^4/(8\eta \cdot l)$, where Δp is the pressure difference between the entrance and exit of the channel, η the glass viscosity, and r and l its radius and length, respectively. Due to the friction at the die wall, an inhomogeneous distribution of flow velocity V is formed across the die aperture. Given a completely stagnant layer adjacent to the wall, the velocity profile becomes parabolic: $V = \Delta p \cdot (r^2 - x^2)/(4\eta \cdot l)$, where x is the radial coordinate, and $x = r$ at the interference between the flow and the channel. Hence a macroscopically structured preform with multiple coaxial rings can be fabricated by extruding alternatively stacked high- and low-index glass discs through a circular aperture. This is shown schematically in Fig. 1(b). Note that very recently a similar approach using disc-stacking extrusion was used to fabricate 1D microstructured glass-polymer preforms with both solid- and hollow-cores.[10] However, no further fiber fabrication has been reported from those preforms.

As in Ref. 7, a lead-oxide containing borosilicate glass (PbO > 30 mol %) with a refractive index of $n = 1.76$ at 1550 nm (referred as B1 thereafter), and a potassium-fluoride (KF) containing borosilicate glass with index $n = 1.53$ at 1550 nm (referred as H1 thereafter) were selected as the materials for this high-index-core 1D MOF. Figure 1(c) shows the viscosity curves of these two glasses measured on a Perkin Elmer TMA-7 thermomechanical analyzer using the parallel-disc technique.[11] It is seen that there is indeed some thermal mismatch between these two glass compositions when thermally processing them together by extrusion and fiber drawing. However, from the quality of the extruded preform and the final fiber, it is clear that the thermal mismatch is within an acceptable range.

As shown in Fig. 1(b), 1.0-mm-thick high-index glass discs were stacked alternately with 2.0-mm-thick low-index glass discs. The stack of glass discs was heated to the temperatures above the glass softening point (corresponding viscosity: $\sim 10^9$–10^7poise). Using an applied force of up to 1 ton, the viscoelastic glass flow was pressed through the circular exit, and a preform with a multiple ring layer structure was formed. The extruded preform was then reduced in scale on a fiber-drawing tower into cane with 790 ± 10 μm outer-diameter (OD). A piece of 80-mm-long uniform cane was selected and inserted within a high-index B1 glass jacket-tube with 18 mm OD and 800 ± 10 μm inner-diameter (ID). Finally, this rod-in-tube assembly was pulled into a high-index-core 1D MOF. The total fiber yield was near 400 meters, and fibers with a variety of ODs ranging from 825 to 115 μm were produced.

Figures 2(a) and 2(b) show scanning electronic microscope (SEM) photographs of this high-index-core 1D MOF with 825 and 135 μm OD, respectively. The high-index region (with density $\rho = 5.2$ g/cm^3) shows a higher brightness than the low-index region (with density $\rho = 2.9$ g/cm^3), due to the intensity contrast of the backscattered electrons from the regions with different matter densities.[7] The high-index-core is surrounded by nine alternate rings of coaxial low-index and high-index layers. Observe that the resulting core and rings are highly circular and concentric. After normalizing the parameters of the microstructure such as the core diameter and the thickness of each individual ring by the OD of the fiber, it is observed that for all the fibers with an OD ranging from 825 to 135 μm, the microstructure of this high-index-core 1D MOF is dimension-independent, consistent

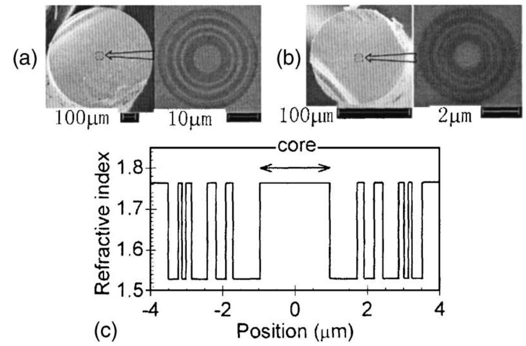

FIG. 2. SEM photographs of high-index-core 1D MOF with (a) the OD of 825 μm and (b) the OD of 135 μm. (c) Refractive index profile along the center of the fiber with 1.9 μm core diameter as deduced from the SEM photograph.

with previous observations in the 2D-structured SOHO fiber.[7] This is believed to be one of the most important advantages of an all-solid MOF relative to an air-filled holey fiber, since it allows the stable and repeatable definition of transverse structure as is essential for achieving optical fibers with predetermined optical characteristics. Note that due to limitations of the SEM photo resolution, we cannot distinguish the boundary between the high-index layer and the low-index layer for fiber with ODs less than 135 μm.

The velocity of the glass flow within the extrusion die is determined by (1) the friction coefficient between the glass flow and the metal die and (2) the internal friction of the glass within the channel in the die.[10] Additionally, when different glasses are employed during extrusion, the effect of the internal friction of the glass flow becomes more complicated due to the thermal mismatch between the two glasses. As a result, although the starting high-index (or low-index) glass discs were uniform in thickness, significant thickness variations are evident in the final ring fiber [see Figs. 2(a) and 2(b)]. By adjusting the thickness of the starting discs to compensate this non-uniformity, it should be possible to achieve preforms with controllably thick ring layers of controllable thicknesses for example periodically spaced ring layers if required.

A fiber with a 1.9 μm core diameter, corresponding to a fiber OD of 175 μm, was selected for optical characterization. Figure 2(c) shows the index profile of this fiber deduced from the SEM photo, assuming the refractive indices of all regions are unchanged after fiber-drawing. It is seen that the thickness of the high-index rings ranges between 100 and 250nm, while the thickness of the low-index rings ranges between 120 and 780 nm.

The guidance properties of this 1.9 μm core fiber were evaluated using a range of laser sources including a CW Argon ion laser operating at 514 nm, a laser diode at 635 nm, a Nd:YLF laser at 1047 nm and a erbium doped fiber laser operating at 1560 nm. A COHU 7512 CCD camera was used with Spiricon LBA-PC v 3.23 software (Spiricon Inc., Logan, Utah) for imaging the near-field beam profile from the output end of the fiber.

Figure 3(a) shows the guidance at 514, 635, 1047, and 1560 nm. It is seen that at the short wavelength of 514 nm, the fiber is at least two moded, and light can even be weakly guided in the thickest high-index layer, while at 635 nm, light is guided within the core alone, and the fiber is still slightly multimode. At the relatively longer wavelengths of

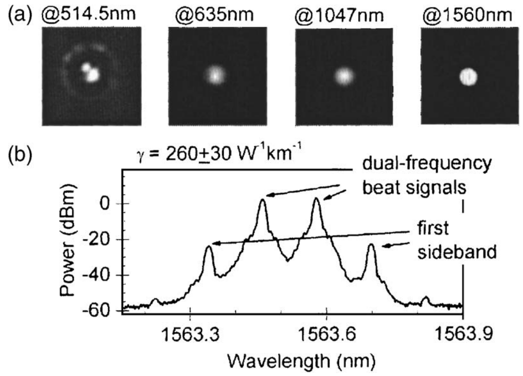

FIG. 3. (a) Guided modes as measured at 514.5, 635, 1047, and 1560 nm. Note that each black square box has the side length of 8.0 μm. (b) One of the measured spectra for the nonlinear mixing in this solid-core 1D fiber (input power: 420 mW, fiber length: 67 cm). Note the generation of sidebands due to self-phase modulation in the fiber, which correspond to a nonlinear phase shift of 0.125 rads (the nonlinearity of the measuring system has been taken into account in the calculation of the nonlinear phase shift).

1047 and 1560 nm, only the Gaussian fundamental mode can be observed in the high-index core.

Using the cutback technique, the fiber loss was measured as 3.6±0.5 dB/m at 1560 nm. Our modeling indicates that the confinement loss of this 1D MOF at 1560 nm should be ~1 dB/m. From the results of our detailed numerical simulation we estimate that ~1 dB/m of this loss at 1560 nm can be accounted for by confinement loss with the balance likely to be due predominantly to a combination[7] of: (1) impurities in the starting chemicals for glass melting; (2) impurities introduced during the fabrication procedure; (3) defects generated by the thermal processing; and (4) OH absorption at 1.4–1.5 μm. Note that this disc-stacking extrusion technique can be extended to introduce more layers into the cladding in order to reduce the confinement loss to negligible levels. There is also great scope for reducing the material and fabrication process losses by using high-purity chemicals and improving cleanliness during the processing. Ultimately we would anticipate <0.5 dB/m losses should be achievable for this fiber type.

The effective nonlinearity of the 1D MOF with a 1.9 μm core diameter was measured in a 67 cm-long fiber, using the self-phase-modulation (SPM) based technique first introduced by Boskovic *et al.*[12] Using a CW high power dual-frequency beat signal at 1560 nm as the pump signal, the optical spectrum at the end of the fiber exhibits peaks at multiples of this beat frequency because of the SPM-induced phase modulation [see Fig. 3(b)]. Assuming that the fiber dispersion is negligible in the short length of the measured fiber, the nonlinear phase shift experienced by the beat signal propagating along the fiber can be expressed as $\varphi_{\mathrm{SPM}} = (2\pi/\lambda)\cdot(n_2/A_{\mathrm{eff}})\cdot L_{\mathrm{eff}}\cdot P$, where λ is the wavelength of the signal, P the average power of the signal, L_{eff} the effective length of the fiber ($L_{\mathrm{eff}} = [1-\exp(-\alpha\cdot L)]/\alpha$, α: the fiber loss, and L: the total fiber length), n_2 the nonlinear refractive index of the core material, and A_{eff} the effective mode area. The ratio of the peak heights depends only on the nonlinear phase shift φ_{SPM}. By varying the signal power, the effective nonlinearity of the fiber, $\gamma(=(2\pi/\lambda)\cdot(n_2/A_{eff}))$ can be deduced from the ratio of the intensities of the first sideband to the spectral intensity at the fundamental frequencies by the linear least-square-fitting.[13] The effective nonlinearity γ of this 1D MOF with 1.9 μm core diameter is measured as $260\pm30\ \mathrm{W}^{-1}\,\mathrm{km}^{-1}$, which is 260 times higher than standard single mode silica fiber, indicating that it is a promising candidate for highly nonlinear optical fiber devices.

In summary, we have demonstrated the fabrication of high-index-core 1D MOF with high index-contrast layers. Robust single-mode guidance has been observed at both 1047 and 1560 nm. A propagation loss of 3.6 dB/m and an effective nonlinearity as high as $260\ \mathrm{W}^{-1}\,\mathrm{km}^{-1}$ was measured at the wavelength of 1560 nm in this fiber, highlighting its potential application of this new fiber in highly nonlinear optical devices. In addition, we have demonstrated a preform fabrication technique that has the flexibility to produce all-glass 1D microstructured fibers either with periodically structured layers or with controllable variations in layer thicknesses.

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