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SOHO (SOLID 'HOLEY') FIBER

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Abstract *We report the first successful fabrication of an all-solid microstructured fiber based on large index contrast glasses. High effective nonlinearity* 230 $W^{-1}km^{-1}$ at 1550nm *has been predicted and measured.*

Introduction

The invention of all-silica photonic crystal fibers, or so-called holey fibers or microstructured fibers [1] has attracted wide interest over the past few years. With the assistance of the air-filled holes which surround the solid or hollow core, the unique guidance properties such as narrow photonic bandgaps, very-large-core with endless single-mode guidance, nonlinearity enhancement, supercontinuum generation, polarization maintenance and dispersion management [1, 2] arise and promise various novel applications. However, for air-filled holey fibers, due to the effects of the pressure inside the holes and the surface tension of the glass, the fiber profile typically changes during drawing, and so it can be practically difficult to fabricate long uniform holey fibers with predictable and controllable holey microstructured cladding configurations. Note it was pointed out that the optical characteristics of holey fibers critically depend on the cladding configuration and even minor changes in the microstructure can cause significant deviations in sensitive properties such as dispersion [3]. In this paper, we demonstrate what is to our knowledge the first all-solid 'holey' fiber based on large index contrast glasses. A low index glass was used to fill the holes, which successfully avoids the problems generated during the fabrication of air-filled holey fibers. The characteristics of this all-solid microstructured fiber are measured and predicted.

Experimental

A high lead-oxide (PbO) containing borosilicate glass (PbO>30mol.%) with refractive index n=1.76 at 1.55μm, was selected as the background material (***B1*** thereafter) for this SOHO fiber, while another high alkali-oxide (Na_2O, K_2O etc) containing silicate glass with index n=1.53 at 1.55μm was selected as the material to fill in the holes (***H1*** thereafter). These two glasses show good compatibility in term of mechanical, rheological, thermo-dynamic, and chemical properties. An ultrasonic drilling machine was employed to fabricate uniform rods and tubes from the bulk B1 and H1 glasses. The conventional capillary-stacking technique [1] was then applied to make the structured preform by stacking thirty-five B1-H1 dual-layer rods with uniform 730 ±10μm diameter around a B1 rod within a B1 glass jacket tube (Fig.1(a)). After caning (Fig.1(b)) and fiber drawing, fiber with 440±20μm (Fig.1(c)) and 220±20μm diameters (Fig.1(d)) has been fabricated. Cross sectional profiles, transmission losses, and effective nonlinearity have been characterized.

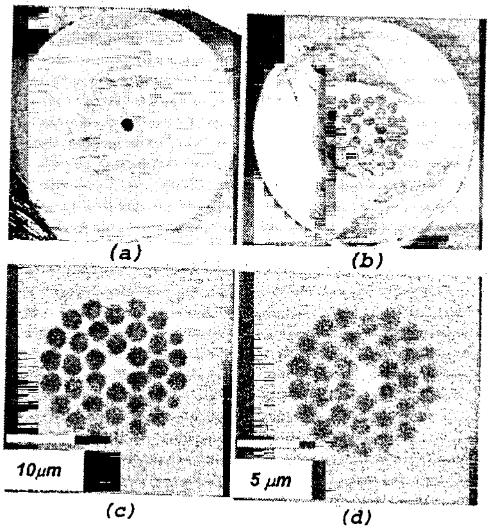

Figure 1 (a) stacked preform (OD=14mm)(Note that the core rod is marked by black pen in order to distinguish it from other solid rods in the stack);
(b) microstructured cane from (a) with 0.97mm OD;
(c) central region of 440μm diameter SOHO fiber;
(d) central region of 220μm diameter SOHO fiber
(c,d are reflection images under optical microscope.)

(a) (200μm bar) (b) (100μm bar)

Fig.2 SEM photographs of cross section of SOHO fibers with 440μm (a) and 220μm diameter (b)

Results and discussion

Fig. 1(a-d) show the microstructure of the stacked preform, the subsequent cane and the resulting fibers, respectively. All the low-index regions maintain their original circular shape without any significant deformation after caning and fiber drawing. The ratio of ***d/Λ*** (***d***: diameter of the low index circular region, ***Λ***: the pitch (center to center spacing) of the low index circular region, i.e., solid 'hole') is also maintained as 0.81 from the stacked preform to the final fibers.

In the SEM photographs of the fiber cross section (see Fig.2(a)&(b)), no holes can be observed. It is clear that due to the effect of surface tension, all the interstitial air holes between the solid 'capillaries' in the stacked preform have completely collapsed after caning and fiber drawing.

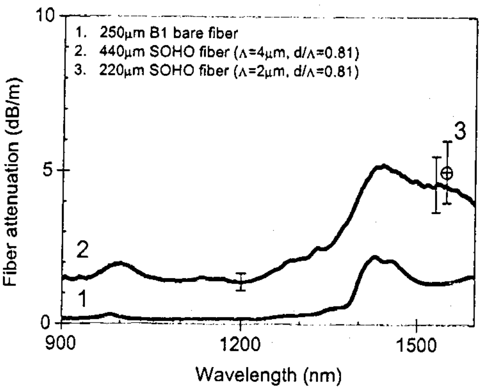

Fig.3 Transmission loss of unclad B1 fiber, and SOHO fibers with 440 μm and 220μm outer diameters

Fig.3 shows the comparison of the transmission loss of an unclad fiber drawn from a drilled B1 glass rod, and the SOHO fibers. The cutback technique was used for loss measurement. A broadband white light source was employed for the unclad B1 fiber and the 440μm SOHO fiber, while an erbium-fiber ASE source was used as the source for the 220μm SOHO fiber. According to our calculations, the confinement loss at 1.55μm in these SOHO fibers with d/Λ>0.8 should be lower than 10^{-3} dB/m even when only 3 rings of structure are used. Therefore the losses at 1.55μm of these SOHO fibers, ~5dB/m are mainly due to non-structural effects such as the hydrogen-bonding in the glass, the scattering on the interface between different solid 'capillaries', and thermally-induced phase-separation. It is anticipated that it should be possible to reduce the total fiber loss in this SOHO fiber to levels below 1dB/m at 1.55μm by melting the glasses in a dry atmosphere [4], chemical processing for the drilled preforms, and shortening the thermal history during fiber fabrication. Note that the losses of these first SOHO fibers are no higher than the current losses in extruded holey fibers [5,6].

As Fig.4 shows, the index contrast between materials B1 and H1 allows the possibility of even higher effective fiber nonlinearities. The calculations presented in Fig.4 show the effective mode area (and corresponding fiber nonlinearity γ) of a rod of material B1 surrounded by a uniform non-structured cladding of material H1. This simplified geometry represents the fundamental limit in mode area that can be achieved in a microstructured fiber made from these two materials. The smallest effective mode area (and hence the highest γ) occurs when the core rod is ≈1μm in diameter. Corresponding results for a silica rod suspended in air are also shown. Observe that even though the index contrast between silica/air leads to a similar mode area as the combination B1/H1, the significantly larger material nonlinearity (n_2) of material B1 results in a dramatic improvement in the nonlinearity. Hence while the maximum nonlinearity that can be achieved in a silica/air holey fiber is ≈60$W^{-1}km^{-1}$ at 1.55μm, more than 500$W^{-1}km^{-1}$ should ultimately be possible in a B1/H1 SOHO fiber. Boskovic method [7] was applied to measure the effective nonlinearity in a 2.92m long 220μm SOHO fiber (Λ=2μm and d/Λ=0.81). Using a high power dual frequency beat signal at 1.55μm, the effective fiber nonlinearity has been deduced from the phase shift due to the propagation in the fiber to be 230 $W^{-1}km^{-1}$, which is ~200 times higher than standard single mode silica fiber and matches Fig.4's modelling very well.

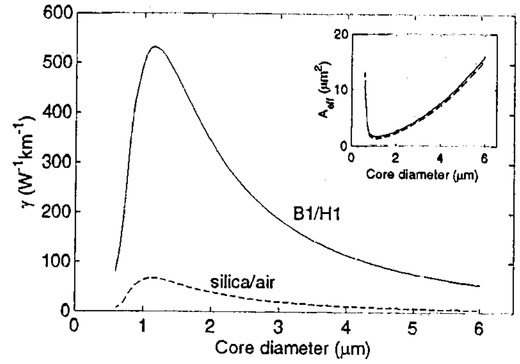

Fig.4 Calculated maximum effective nonlinearity (γ) that can be achieved in silica/air fibers and in B1/H1 SOHO fibers at 1.55μm. The inset shows the corresponding effective mode area in these fibers.

Conclusions

In summary, the fabrication of all-solid microstructured fiber has been firstly demonstrated based on large index contrast glasses. The microstructure has been maintained and no air holes have been detected in the microstructured cladding. Fiber losses at 1.55μm were measured to be 5dB/m. High effective nonlinearity, 230$W^{-1}km^{-1}$ at 1.55μm was measured in good agreement with our modelling. It is anticipated that all-solid microstructured fibers should provide many of the advantages of air-filled holey fibers while eliminating some of the practical challenges associated with the presence of air in the microstructured cladding region.

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