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Experimental demonstration of single-mode operation of large-core segmented cladding fiber

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Abstract: Segmented cladding fibers were fabricated with PMMA polymer. Single-mode operation at 1.55 μm was observed with a 36.5-cm long fiber that consisted of 4 cladding segments and had a core diameter of 20 μm.

OCIS codes: (060.2430) Fibers, single mode; (060.2280) Fiber design and fabrication; (060.2400) Fiber properties; (060.2310) Fiber optics

1. Introduction

A segmented cladding fiber (SCF) is an unconventional fiber design, in which a uniform core of high refractive index is surrounded by a cladding with alternate regions of high and low refractive indices in the angular direction [1-3]. The SCF structure was first proposed [1] to demonstrate an alternative design to the now well-known holey fiber structures [4],[5] for the provision of single-mode operation over an extended range of wavelengths. It was then shown that an SCF could be designed into an ultra-large-core single-mode fiber for optical communications [2], which could suppress effectively nonlinear optical effects because of its large core size and, at the same time, provide a much higher transmission capacity because of its potentially weak birefringence, compared with a holey fiber. Recently, it was realized that the SCF structure is a leaky structure in the sense that all the modes in the fiber suffer from finite leakage losses [3]. For the fiber to operate as an effective single-mode fiber, the leakage loss of the fundamental mode must be sufficiently lower than that of the higher-order mode [3]. As a matter of fact, holey fibers are also leaky structures [6,7] and the differential leakage loss in a specific holey structure is calculated recently [7]. While all the previous studies on the SCF are theoretical, in this paper, we report the first experimental demonstration of single-mode operation of a large-core SCF.

2. Leakage loss in segmented cladding fiber

Figure 1 shows the leakage loss curves for two SCF designs, one consisting of 4 low-index segments with 75% duty cycle and the other consisting of 8 low-index segments with 50% duty cycle, where the duty cycle is defined as the angular span of a low-index segment relative to the angular period of the segmentation. The refractive index of the core and the high-index segments is n_1 = 1.501 and that of the low-index segments is n_2 =1.489, which corresponds to a relative index difference of Δ = 0.8%. The core diameters for the 4-segment and 8-segment designs are 20 μm and 35 μm, respectively, and the cladding diameters are 200 μm and 235 μm, respectively. These parameters are chosen to match those of the fabricated PMMA fiber samples. The index beyond the cladding is assumed to be equal to the core index. The results in Fig. 1 are obtained by the radial effective-index method [8], which reduces the segmented cladding structure to an equivalent circular graded-index profile [1-3] so that the mode indices and the leakage losses can be calculated by the transfer matrix method [9].

It is seen from Fig. 1 that, for both designs, the leakage loss of the fundamental mode (the LP_{01} mode) is larger than that of the higher-order mode (the LP_{11} mode) by three orders of magnitude over the entire range of wavelengths shown in Fig. 1 (from 600 nm to 1700 nm). These results suggest that, if the fiber is long enough, only the fundamental mode will survive and all the high-order modes will be stripped off because of their much higher leakage losses. The fiber is effectively single-moded over an extended range of wavelengths. However, because the leakage losses of the modes decrease with the wavelength, as shown in Fig. 1, a longer fiber is needed for the observation of single-mode operation at a shorter wavelength. For example, to achieve an extinction ratio larger than 20 dB between the LP_{01} mode and the LP_{11} mode at the wavelength 1.55 μm, the 4-segment fiber needs to be at least 2.6-cm long. For the same criterion at the wavelength 0.633 μm, the fiber needs to be at least 46-cm long. Furthermore, Fig. 1 shows that the 4-segment design produces higher leakage losses than the 8-segment design. Therefore, we need a longer length of the 8-segment fiber to observe single-mode operation. The leakage losses in an SCF can be controlled by changing the arrangement and the size of the segments in the cladding [3].

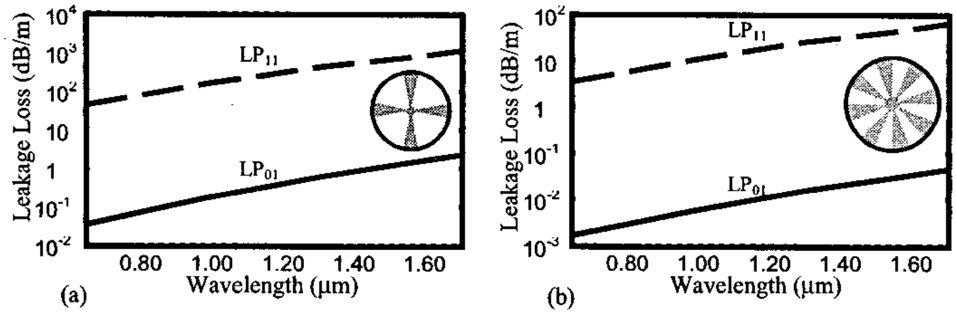


Fig. 1. Calculated leakage loss curves for (a) a 4-segment fiber with 70% duty cycle and (b) an 8-segment fiber with 50% duty cycle.

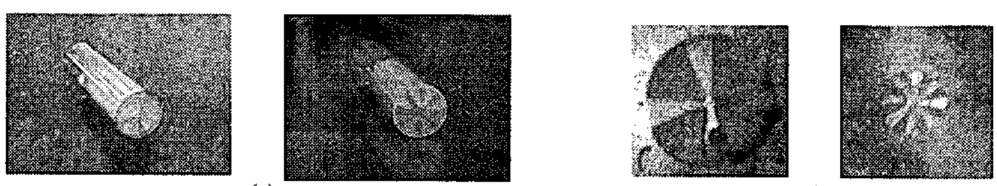
3. Fiber fabrication and characterization

Polymer SCF were fabricated by following the approach described in [10]. The basic materials used were the combination of MMA (MethylMethAcrylate) and EMA (EthylMethAcrylate). Both MMA and EMA have low refractive indices in the range of 1.41 to 1.42. Depending on the thermal polymerization conditions, the polymerized materials (PMMA and PEMA) have indices in the range of 1.84 to 1.49 after polymerization. The refractive index can be adjusted to match that of silica by adding other methacrylates. Two methods of fabricating SCF performs were developed.

The first method is called the cladding-segment-in-tube technique. The prefabricated polymer low-index segments were first placed in a glass tube to form the desired alternate segment pattern. The high-index monomer was then poured into the tube. The filled glass tube was placed in a temperature-controlled oven at ~90 °C for several days. A thermal polymerization process was initiated to obtain a polymerised preform that consisted of a periodic array of high- and low-index segments. The disadvantage of this method is that the high-index monomer, which is an active solvent, may dissolve the low-index segments during polymerization, if the low-index segments are too small. A 4-segment fiber preform with 75% duty cycle was fabricated with this method.

The second method is called the cladding-core-segment-in-tube technique. Prefabricated polymer high-index and low-index segments were arranged in a periodic fashion and made to fit tightly in a glass tube. This method produced more distinct segment interfaces compared with the first method. However, it was important to remove any air bubbles that might be trapped at the segment interfaces before the initiation of thermal polymerization. The thermal polymerization of the segment interface regions was undertaken in a temperature-controlled oven. The polymerization process was optimized according to the amount of initiator and chain transfer agent. An 8-segment fiber preform with 50% duty cycle was fabricated with this method.

Fibers were drawn from the preforms. In the drawing process, the tip of the preform was slowly fed into the furnace under computer control at a temperature between 280 °C and 290 °C. At this temperature, the preform began to melt. The diameter of the fiber was controlled by the feeding speed of the preform and the drawing speed of the fiber. The 4-segment and 8-segment preforms and the corresponding fiber cross sections are shown in Fig. 2.

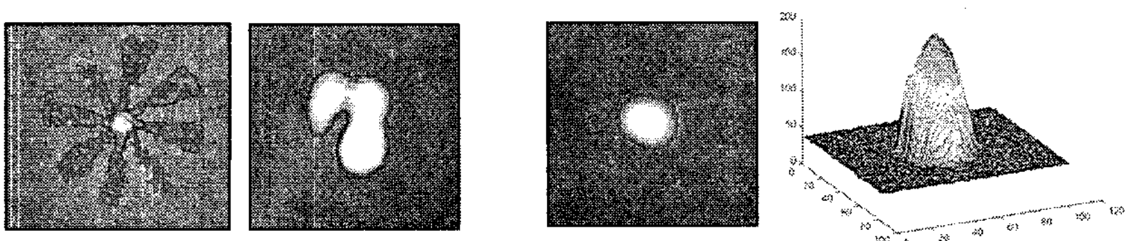


(a) (b)

Fig. 2. (a) 4-segment and 8-segment preforms. (b) Cross sectional views of a 4-segment fiber sample and an 8-segment fiber sample drawn from the preforms.

We were able to draw only short fibers (up to a few tens centimeters) of sufficient uniformity. Here we report our measurements with two fiber samples: a 36.5-cm long 4-segment fiber with a core diameter of 20 μm and an overall diameter of 200 μm, and a 41-cm long 8-segment fiber with a core diameter of 35 μm and an overall diameter of 235 μm. Laser light was launched into the fiber sample and the output from the fiber was monitored by a

CCD camera. Two wavelengths, 0.633 μm from a HeNe laser and 1.548 μm from a semiconductor laser, were used. The attenuation of the fiber was ~1 dB/m at 0.633 μm and at least an order of magnitude higher at 1.548 μm. Index matching liquid (with index 1.534 at 0.633 μm) was applied in the middle of the fiber over a length of several centimeters. At 0.633 μm, the outputs from both fibers showed speckle patterns that illuminated the high-index segments in the cladding, as shown in Fig. 3(a). At 1.548 μm, however, the output from the 8-segment fiber showed a combination of only two or three modes in the core only, as also shown in Fig. 3(a), while that from the 4-segment fiber showed a clean single-mode pattern in the core, as shown in Fig. 3(b). For comparison, a conventional step-index fiber with a core diameter of 35 μm and a relative index difference of 0.8% supports ~20 different spatial modes at 1.55 μm and ~130 spatial modes at 0.633 μm. Even if the core diameter is reduced to 20 μm, the step-index fiber still supports 9 different spatial modes at 1.55 μm. Our experimental results show clearly that the SCF is capable of stripping off high-order modes, in fact, to such an extent that only the fundamental mode remains guided, as predicted. It should be noted that the calculated losses in Fig. 1 are based on the assumption that the entire fiber is coated with an index-matching medium. Our fiber samples were bare fibers placed in hard sleeves and index-matching liquid was applied along only a short length of the fiber. The actual leakage losses of the fibers should be significantly lower than the calculated values. Otherwise, single-mode operation at 0.633 μm would have been observed with the current samples. It can be seen from Fig. 3(a) that the high-index segments were illuminated by weak high-order modes, which would have been stripped off completely by a high-index jacket, if available. A closer look at the speckle pattern in the core of the fiber in Fig. 3(a) indicates that there are in fact not many modes present in the core even at 633 μm. Our experiments agree qualitatively with our theoretical predications.



(a) (b)

Fig. 3. (a) Outputs from the 35-μm-core 8-segment fiber at 0.633 μm (left), showing a large number of cladding modes, and at 1.548 μm (right), showing only a few modes. (b) Output from the 20-μm-core 4-segment fiber at 1.548 μm together with a scan of the intensity distribution, showing clean single-mode operation. The single-mode spot is ~15 μm in diameter.

4. Conclusion

We presented the first experimental demonstration of the operation principle of an SCF as a leaky fiber structure. We observed single-mode operation at 1.55 μm with a 36.5-cm long PMMA SCF that consisted of 4 low-index segments of 75% duty cycle, and had a core diameter of 20 μm and a relative index difference of 0.8%. This research was supported by a grant from the RGC of Hong Kong SAR, China, under Project CityU 1034/02E.

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