Abstract: We report the fabrication of a square core jacketed air-clad fiber with a top-hat near-field intensity profile. Using this fiber we have successfully produced square shaped ablation marks in ITO without complex beam shaping optics.

1. Introduction.

Fiber delivery of intense laser radiation has many uses in a wide range of application sectors, from medicine through to industrial processing and offers many practical benefits relative to free space solutions. In applications involving highly multi-mode sources, fibers with large cores are needed in order to minimize damage and nonlinear effects, whilst high numerical apertures (NA) are often essential for brightness preservation. Conventionally, high NA fibers are created by cladding a pure silica core with a low index polymer, a technique which is limited by the finite range of suitable polymers. Recently, microstructured fiber technology has been shown to offer a practical route towards such fiber designs [1]. Using this approach, single-material jacketed air-clad (JAC) fibers can be created using a ring of large air holes that isolate the core from an outer jacket of silica. An example of an all-silica JAC fiber with a core diameter > 600 µm is shown in Fig. 1 (a) and (b). JAC fibers possess several advantages over their conventional counterparts. For example, the intrinsically large index contrast between air and silica enables extremely high values of NA to be realized [2], whilst the flexibility of the cladding design allows the NA to be accurately tailored to arbitrary values [2,3].

Fig. 1. Scanning electron microscope (SEM) image of a JAC fiber fabricated at the ORC with a core > 600 µm in diameter. (a) shows the whole fiber and (b) shows a close up of the cladding region. (c) SEM image of a square core silica fiber (core ~ 400 x 400 µm, polymer coating not shown). Note that this fiber was fabricated by SPI Lasers UK Ltd.

In many high power processing applications a square beam shape is highly desirable. In order to achieve this, conventional techniques often utilize complex beam shaping processes (that introduce significant losses) to convert the output from delivery fibers/laser systems with circular beams. One obvious way to bypass this additional beam shaping stage is to use a delivery fiber that itself has the desired beam profile. Polymer clad fibers have recently been produced with square core shapes (as shown in Fig. 1 (c)) and this technology offers the possibility of almost arbitrary core shapes [4]. However, in addition to the NA restrictions of polymer clad fibers, this technique is also limited by structural changes that take place during fiber drawing where the outer shape of the preform (and hence the core) experiences a degree of rounding (as illustrated in Fig. 1 (c)).

In this paper we show that JAC fibers can be made with non-circular core geometry and that sharply defined vertices in the core shape can be preserved through the fiber drawing process. Specifically, we report the fabrication of a JAC fiber with a large square core and show that the near field in this fiber has a top-hat intensity profile without recourse to any externally applied modal mixing even when the launch is under-filled.

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2. Fiber geometry and fabrication

A JAC fiber with a 380 x 380 µm square core surrounded by 48 air-holes each approximately 40 µm long was fabricated and is shown in Fig. 2 (a) and (b). The thickness of the webs between each cladding air-hole is 2 µm, as shown in Fig. 2 (b). The square core of this fiber was fabricated by stacking together many circular silica rods of two different sizes, as illustrated in Fig. 2 (c). Note however, that it is not necessary to fabricate this fiber in this way and we have also created a similar fiber using a milled silica rod as the core element. However, the advantage of constructing the core region from stacked elements is that it offers enormous design flexibility in terms of the core shape.

![Fig. 2. (a) Optical micrograph of the JAC fiber, (b) SEM image showing detail of cladding air holes, (c) Stacking geometry of JAC core](image)

3. Fiber characteristics

The fiber output was examined under three different launch conditions; using white light (incandescent bulb) illumination, a single-mode HeNe laser (633 nm) and a single-mode Nd:YAG (1.06 µm) laser. The far-field was observed to be circular at all wavelengths. At 633 nm and 1.06 µm light was coupled into the fiber using a x20 microscope objective with an NA of 0.54. The NA of the fiber was evaluated by measuring the divergence of the far-field light from the fiber end. The beam width is defined as the width at which 95% of the total power is transmitted through a circular aperture. Using this technique, the NA of fiber was measured to be 0.12 at and 0.11 at 633 nm and 1.06 µm respectively, as shown in Fig. 3. Estimated values of the NA, made using the simple model in [2], indicate values of approximately 0.15 and 0.22 at 633 nm and 1.06 µm respectively. Whilst the measured NA is in reasonable agreement with predicted values at 633 nm, the results at 1.06 µm suggest that the fiber is significantly under-filled. However, this is unsurprising given that the input beam is single-mode. Note that the expected relationship between NA and wavelength is confirmed by observations of a red fringe around the perimeter of the white light far-field output.

![Fig. 3. Beam width (for 95% power transmitted through circular aperture) vs. propagation distance from fiber end (note: zero of z is offset by some arbitrary value)](image)
Despite the fact that the single-mode launch conditions do not fully excite all the modes of this fiber (as expected), we find that a good quality top-hat beam shape can be obtained in reasonably short lengths (~ 2 m) of fiber, as shown in Fig. 4 (a) and (b), which show near-field intensity profiles (imaged onto a CCD camera) at 633 nm and 1.06 µm. For these launch conditions the transmission losses at 1.06 µm were measured to be < 10 dB/km over 40 m of fiber. One point to note is that the core shape is reflected in the near-field profile, with the fine notches at the core edge creating a “postage stamp” effect in the beam shape. However, it can be seen that these crenulations are far less noticeable at the longer wavelength of 1.06 µm than at 633 nm.

![Fig. 4. Near field intensities of the square core fiber at (a) 633 nm and (b) 1.06 µm](image)

Fig. 4. Near field intensities of the square core fiber at (a) 633 nm and (b) 1.06 µm (c) ITO ablation with square JAC fiber at 1.06 µm

The JAC fibers considered here are specifically designed for the delivery of intense laser radiation from highly multimode sources. Indeed, we have successfully transmitted 35 ns pulses (rep rate 3 kHz) with an average power of ~ 80 W at 1.06 µm from a highly multi-mode Nd:YAG laser through the circular JAC shown in Fig. 1 (a) without incurring damage. The combined coupling and fiber losses in this case were estimated to be ~ 1 dB. However, with the design of the square JAC fiber pictured in Fig. 2 (a) our aim was two-fold; requiring both the capability to transmit sufficiently high powers and also the ability to deliver that power with a square beam profile. As an example demonstration, the square JAC fiber shown in Fig. 2 (a) was used to ablate indium tin oxide (ITO) on a glass substrate, using 50 ns pulses (rep rate 3.5 kHz) with 92 W average power at 1.06 µm from a highly multi-mode Q-switched Nd:YAG laser. The results from this preliminary experiment are shown in Fig. 4 (c), which show a series of ablation marks made as the sample was translated beneath the imaged fiber output. The output from the fiber end was imaged using a single lens. Although this process was not optimized (the particular lens available resulted in significant loss of power at the work-piece end) it can be seen that this fiber can be successfully used to produce square shaped ablation marks in ITO without the need for complex beam shaping optics. As such, this fiber type offers significant advantages in terms of power conservation and ease of use for high power applications requiring non-circular beam shapes. Furthermore, although this process has been demonstrated using a large solid state laser, one can easily envisage the creation of a compact system by using a fiber laser source.

4. Conclusions

A jacketed air-clad fiber with a square core has been fabricated using microstructured fiber technology that offers enormous design flexibility both in terms of the fiber NA and also in terms of the core shape and size. We have shown that a well defined square output beam can be obtained in short lengths of this highly multi-mode fiber even with a single-mode launch at both 633 nm and 1.06 µm. Preliminary results indicate that this type of fiber offers significant potential for high power applications that require non-circular intensity profiles, and that it is possible to produce square shaped ablation marks in ITO without the need for complex beam shaping optics.

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5. References