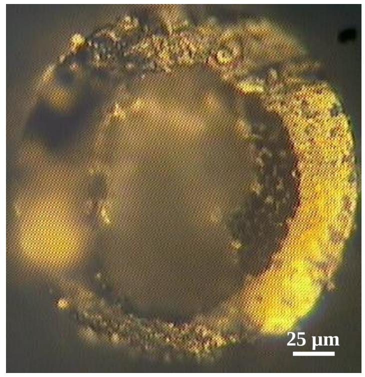

Fig. 5. Optical microscopy image of catastrophic damage at the launch end of the fibre. Most of the periodic structure is destroyed.

However, even with the damaged fibre launch end, it was still possible to guide light through the fibre and a power of 80 mW (5.4 mJ) could still be transmitted. No damage to the output facet was observed during any of the experiments and the output facet had the appearance of a pristine cleaved end (as shown in Fig. 1) which included pulse delivery experiments with the damaged launch facet. To evaluate the LIDT of the HC-PCF, light was deliberately focused onto the cladding structure and the pulse energy required to cause damage was determined. The cladding structure damaged at a fluence of ~30 kJ/cm^2.

Previous work [11] found the LIDT for the cladding structure of a similar silica HC-PCF to be 130 – 140 J/cm^2 for an 8 ns pulse (at 1064 nm). The approximate factor of $t_p^{1/2}$, where t_p is the pulse width, can be used to scale energies [16] from an 8 ns to a 250 µs pulse. Scaling the 8 ns pulse results gives an expected LIDT of 23.5 kJ/cm^2 for a 225 µs pulse which is in close agreement to the value found in these experiments (30 kJ/cm^2). In fact one would expect a slightly different value for the LIDT in these experiments, which were conducted at 2.94 µm compared to 1.064 µm, as materials have be shown to have a different LIDT at different wavelengths [17]. The potential capability of these fibres for pulse delivery can be estimated by considering a Gaussian beam at the input face. Fibre damage will occur if the intensity at the input face incident on the silica glass surrounding the air core exceeds the damage threshold. If the fluence in the silica glass exceeds the 30 kJ/cm^2 measured above, then the fibre will be damaged. The mode field diameter of the fibre is estimated to be the same size as the core i.e. 24 µm. When coupling a Gaussian beam with a 1/e^2 width of 24 µm into the fibre, with a fluence of 111 kJ/cm^2 in the core region, the intensity incident on the silica cladding will be in the order of the damage threshold of 30 kJ/cm^2. At the fluence of 111 kJ/cm^2 in the 24 µm diameter core a pulse of 500 mJ is being delivered. This value could be considered to be the absolute maximum pulse energy deliverable with these fibres using an optimised laser source with sufficiently good beam quality to achieve a Gaussian beam waist of appropriate diameter and divergence.

The output facet of the fibre showed no damage during the experiments, even after the launch end was destroyed. This gives confidence that optimised coupling would lead to improved performance. The grey scale images for the near and far field beam profile and corresponding cross section are shown in Fig. 6 and it can be seen the beam is roughly circular and single-mode like. The pictures were made by capturing the reflection of the laser light from the fibre end on a ceramic surface using a mid-infrared camera (Electrophysics PV320-L2E). A ~15 × magnification telescope was used to take the near field images. Additionally the image was not taken in the exact focal plane however the image plane was still within the Rayleigh length to enhance the resolution. The offset of the pictures is due to background noise.

One of the potential problems with implementing a hollow core fibre in surgical applications is possible contamination due to ingress of blood and other fluids during *in-vivo* use. In order to protect and seal the 'open' end of the fibre from liquid ingress we previously developed a sapphire "end cap" [18]. With such an end-capped fibre, a typical distance of up to 500 µm could be anticipated between fibre end facet and the tissue due to the thickness of the window in the endtip. The NA of the fibre was measured as 0.12, which gives a spot size of 140 µm diameter (core diameter is 24 µm) at a distance of 500 µm from the fibre end. If pulses of energy 12 mJ (180 mW) are delivered through the fibre and assuming a total loss due to the endtip of around 15% the pulse energy incident on the tissue would be 10.2 mJ. Hence the energy density in a 140 µm spot would be 66.2 J/cm^2. A value of 12 mJ (180 mW) for the fibre output was chosen as tests were done at this level to check the stability. The output power was measured for 5 minutes (4425 pulses) at 180 mW with no observable damage to the launch facet. During this time the output power changed by ± 30 mW, which was attributed to the instability of the laser and slight movements of the fibre at the input end. The fluctuations in output power had no effect on the pulse delivery capability of the fibre. However for a clinical system a more stable laser is required to ensure a constant output power. The experiments were carried out over a number of weeks, and during this period no degradation of the fibre was detected. The demonstrated power density of 66.2 J/cm^2 exceeds the thresholds needed for cutting and drilling of biological tissue, as shown in Table 1.

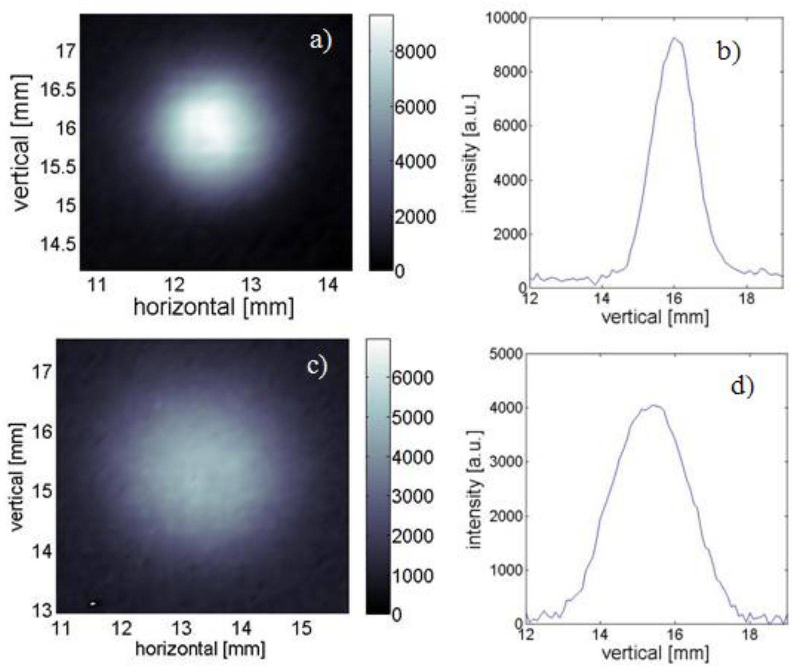

Fig. 6. Near- and far-field beam profiles. a): near-field profile at the fibre end with b) associated line scan (images are magnified); c) far-field profile at a distance of 4 cm from the fibre output end with d) associated line scan.

3 Conclusion

In this paper we demonstrate the ability to deliver, for the first time, high energy microsecond pulsed Er:YAG laser light at a wavelength of 2.94 µm through a silica HCPCF. We have shown that despite the non-optimised launch conditions we are able to deliver pulse energies up to 14 mJ at a pulse length of 225 µs (FWHM). Taking into account practical considerations for realising a surgical delivery system, such as end capping, an estimated power density of

66.2 J/cm^2 is achievable which exceeds previously reported data for the ablation of biological tissue. Additionally, silica HC-PCF's are more mechanically and chemically robust, less bend sensitive and more biocompatible compared to current fibres fabricated from alternative materials for delivery at this wavelength. Our results therefore demonstrate that silica HC-PCF have great potential to be developed into surgical laser delivery systems and offers a promising new alternative to the established articulated arms or large core fibres providing improved flexibility and enabling and enhancing minimally invasive surgical procedures.

Acknowledgments

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