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Silica hollow core microstructured fibres for mid-infrared surgical applications

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Abstract

In this paper two silica hollow core microstructured fibres (Negative Curvature Fibre and Photonic Crystal Fibre) are presented with attenuations of 1.1dB/m and 0.06dB/m at 2.94 μ m wavelength, respectively. This is an important regime for medical applications, specifically surgery due to the existence of a strong absorption peak for water around 3 μ m. The guidance of high energy pulses in the order of 195mJ and 14.4 mJ respectively has been demonstrated. These energies are sufficient to ablate soft and hard biological tissue. As verification porcine bone was ablated in air and submerged in a water to simulate practical application of a surgical device. These fibres open the way to a new and fully flexible delivery system for high energy Er:YAG laser radiation.

Introduction

An Er:YAG laser ($\lambda=2.94\mu\text{m}$) is particularly suitable for laser surgery because the water contained in human tissue strongly absorbs this radiation ($\alpha\sim 12000\text{ cm}^{-1}$ [1]). If this laser beam is precisely delivered only to the areas that need cutting or ablating via surgical operation then damage to surrounding tissue can be minimised. It is because of this that surgical lasers are being increasingly used in medical fields like dentistry and optometry. Additional generic advantages of laser based procedures are that no pressure is applied reducing the pain for the patient e.g. dental drilling [2] and the cut geometry is not limited by the drill/scalpel geometry but is dictated by the focused spot size which generally can be significantly smaller than traditional surgical tools.

Currently the most common method of delivery of surgical lasers, for use in the operating theatre, is achieved using articulated arms. There are a number of shortfalls with these systems in that there are often misalignment issues, the arms are unreliable and they are difficult to install which requires a dedicated, skilled technician. Additionally, the articulated arm, although useful for delivering laser light to the patient, is perhaps less user friendly than a surgeon using a blade and there is significant restriction to movement. Therefore the benefits of using laser light for surgery are offset by the restriction to the surgeon's skill that the articulated arms can impose. Consequently, because of this need for truly flexible IR fibre delivery there have been extensive studies carried out with the aim of developing a practical system. A robust delivery fibre, as proposed here, would alleviate these problems and radically increase the usefulness of surgical lasers. Also, the flexibility and small physical size of a fibre system opens new fields for lasers in medicine like endoscopy and minimal invasive surgery.

Many groups have carried out research into fibres delivering laser radiation around 2.94 μ m, which are mainly based on Chalcogenides [3, 4], GeO₂ [4] or Sapphire [5]. As shown appreciable powers could be delivered with those fibres, however to overcome the Laser Induced Damage Threshold (LIDT) these generally tend to be large core fibres. This leads to a multimode behaviour of the fibre and therefore to a high bend sensitivity, due to bend-induced mode coupling [6]. Also, some of these fibres contain toxic materials and compared to silica, are mechanically and chemically less robust; hence they are not ideal for medical applications.

One approach to overcome the limitations of the above mentioned fibres is to use a hollow-core fibre design. These fibres guide the laser radiation mainly by Bragg reflection, or by internal reflection at a dielectric coated metallic interface in the case of the leaky tube waveguide [6-8]. Due to the nature of the hollow-core the light is mainly guided through air/gas, and therefore the LIDT can be significantly higher than in solid core fibres [9-13]. Also Fresnel reflection at the end of the fibre can be reduced, however if the fibres are used in a medical device at least one end has to be capped which therefore reintroduces Fresnel reflections. If the capsulation is done with sapphire these reflection losses would be around 6.5% per surface.

In this paper two new fibre designs are described based on the principles of hollow core microstructured fibres. Due to the shape of the central hollow core geometry, as shown in Figure 1a [14], the first fibre is referred to as a Negative Curvature Fibre (NCF). The second type is the Photonic Crystal Fibre (PCF), as shown in Figure 1b [13].

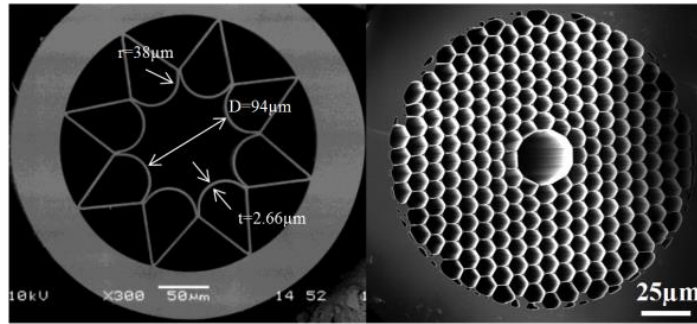


Figure 1: SEM pictures of the fibres used for this paper. a) Negative Curvature Fibre (NCF) b) Photonic Crystal Fibre (PCF)

Material and methods

The laser used in our experiments was an Impex High Tech ERB 15 laser. The operating wavelength is $2.937 \mu\text{m}$ and the pulse-length is $225 \mu\text{s}$ FWHM with an M^2 of ~ 2.5 at a repetition rate of $\sim 15 \text{ Hz}$. The spatial profile of the laser has a donut shape.

Both fibre types are fabricated from fused silica in a conventional stack and draw technique. The material is Suprasil F300 which has a bulk attenuation of $\sim 50 \text{ dB/m}$ at $2.94 \mu\text{m}$ [15], however as light is mainly confined to the hollow core the influence of this high absorption is significantly reduced allowing low loss fibres to be made in this wavelength region [9].

The broad band guidance of the NCF has been previously described, with low attenuation ranges from $2 \mu\text{m}$ to $2.5 \mu\text{m}$ and from $2.8 \mu\text{m}$ to $3.8 \mu\text{m}$ [14] (Figure 2). The lowest attenuation achieved was 0.034 dB/m at $3.05 \mu\text{m}$ and 0.06 dB/m at $2.94 \mu\text{m}$. A cutback measurement was carried out from 83m to 3m . The core size is $94 \mu\text{m}$, the core wall thickness $2.66 \mu\text{m}$ and the radius of curvature for the core wall is $38 \mu\text{m}$ (Figure 1a). The NA of the fibre was measured to be 0.03 .

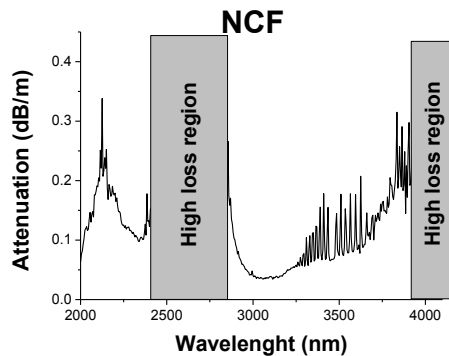


Figure 2: Attenuation of the Photonic crystal Fibre

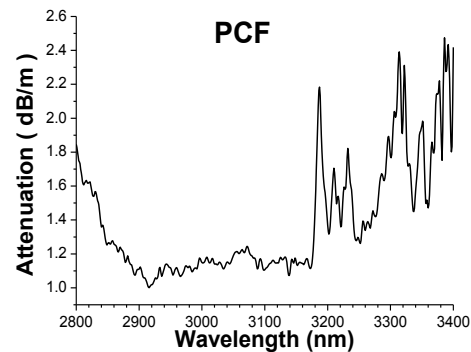


Figure 3: Attenuation of the Negative Curvature Fibre

The attenuation measurement for the PCF is shown in Figure 3. The average loss in the wavelength range $2.9 \mu\text{m}$ to $3.15 \mu\text{m}$ is $\sim 1.2 \text{ dB/m}$ and the loss at the wavelength of $2.94 \mu\text{m}$ is 1.1 dB/m . Attenuation was measured using a Bentham TM300 monochromator with a spectral resolution of $\sim 20 \text{ nm}$ using a cut-back technique. A tungsten halogen bulb was used as a broadband light source. The core size is $24 \mu\text{m}$ with a pitch of $7 \mu\text{m}$ and a NA of 0.12 . The pitch is the distance between two neighbored air holes.

It should be noted that no particular care or special procedures were taken during fabrication of the fibres to control or minimise OH levels.

Theory

The guidance of the NCF is achieved by the Anti-resonant reflecting Optical Waveguide (ARROW) principle [16]. As described by Litchinitser et. al. [16] wavelengths which are in resonance with the core wall cannot be confined in the core but leak away through the wall, resulting in a high attenuation. However, frequencies that are anti-resonant with the wall cannot propagate within it and will be more confined inside the core. The two interfaces of wall and air can be described as a Fabry-Perot-like resonator. Anti-resonant wavelengths experience a low leakage through the wall and hence a lower attenuation as a result of destructive interference in the Fabry-Perot resonator. As the wavelength which is confined inside the core is depending on the wall thickness it can be selected by adjusting this parameter.

The guidance of the PCF on the other hand is described by Russell et. al. [17]. The periodical structure surrounding the fibre core leads to a photonic bandgap effect, so that no states are available and the light is

guided along the fibre. The wavelength which is confined inside the core is dependent on the pitch of the surrounding structure, where the pitch is the distance of two of the air holes. By changing the pitch of the fibre structure a selection of the guided wavelength is possible.

Experimental

The laser light was coupled into both of the fibres using a CaF₂ lens of focal length $f=100\text{mm}$. The beam diameter onto this lens was adjusted to fit the focus spot size to the different core sizes of the fibres, $24\mu\text{m}$ and $94\mu\text{m}$ for the PCF and NCF, respectively. For the NCF a focus spot size diameter of $67\mu\text{m}$ and a NA of 0.03 was used.

In the case of the PCF the spot size was set to be $46\mu\text{m}$ with an NA of 0.1, this is larger than the core of the fibre, however due to the relatively poor laser beam quality a compromise had to be made between the optimal spot size and NA. Tests with other NA values (0.2 and 0.05) resulted in reduced coupling efficiencies. However, it was apparent that there was still a significant mismatch between the laser and fibre fundamental mode which led to a very low coupling efficiency of around 5%. We would expect this coupling efficiency to be significantly improved by using a laser with improved beam quality to allow optimised matching into the fundamental mode of the fibre.

Optimal fibre alignment conditions were achieved by using a 3-axis micro block with the additional alignment of pitch and yaw, to maximise the output power. The initial alignment was performed with the laser running just above threshold and additional attenuation with microscope slides ($T=47\%$ per slide) [18]. This was done to protect the fibres from unwanted damage around the core. After the alignment was optimized the slides were removed and the laser power increased until the maximum output power could be determined. The front facet of the fibres was monitored with a camera to detect any damage due to laser radiation.

Results

The maximum output energy delivered through the NCF was $195\pm 1\text{mJ}$ for a 33cm length of fibre and $54\pm 4\text{mJ}$ for a 988cm length. These pulse energies translate to energy densities of $2300\text{J}/\text{cm}^2$ for the short length and $764\text{J}/\text{cm}^2$ for the long length immediately at the end of the fibre with a core diameter of $94\mu\text{m}$. It should also be noted that the limiting factor for the power delivery capability of the fibre was the laser source so in this case the maximum threshold of the fibre could not be determined. Both the input and output facets of the fibre were undamaged during the transmission experiments. It is likely that given a laser with higher output energy and/or better beam quality higher pulse energies could be delivered.

The maximum output energy delivered through the PCF was measured to be 14 mJ for a 44cm long fibre. This translates to an energy density of $3465\text{J}/\text{cm}^2$ at the output end of the fibre with a core diameter of $24\mu\text{m}$. At higher powers the fibre launch end sustained catastrophic damage and the cladding area surrounding the core was completely destroyed. The output facet was undamaged during any of the experiments and it had the appearance of a pristine cleaved end (as shown in Figure 1b). This gives confidence that optimised coupling would lead to improved performance.

Both fibres guide in a single mode and are relatively bend insensitive. The NCF shows no appreciable loss of power at bend radii of around 15 cm whereas the PCF can be bent to diameters of less than 5 mm with no effect.

To demonstrate that tissue ablation is possible with this system a porcine bone was used. The fibre was sealed with a sapphire tip as was reported in [19], to protect the fibre core from debris and other contaminations. Successful cutting/drilling of the bone was performed using the fibre in contact and non-contact mode in air and under water. Figure 4 shows ablation using single shot pulses in contact mode.

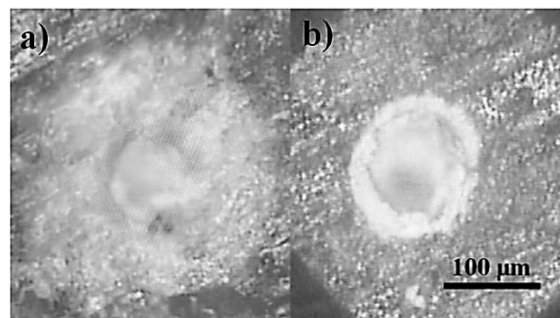


Figure 4: Demonstration of porcine bone ablation. a) Single shot in air. b) Single shot under water.

Discussion and conclusion

The delivered power energies for both types exceed the energies needed for biological tissue ablation by far. As reported by Pierce et. al. [20], human dental enamel has the highest ablation threshold with 35 J/cm^2 . For a 10m long NCF fibre the energy density delivered is a factor of >21 higher than that required. To verify this statement ablation of porcine bone was demonstrated in different environments. Both fibres demonstrate that they would be suitable components in a surgical laser delivery system and hence a promising alternative to the existing delivery systems already used in medicine and other high power applications at $2.94 \mu\text{m}$. Ultimately it is believed that these fibres may pave the way for novel minimally invasive surgical procedures.

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