Demonstration of fundamental mode only propagation in highly multimode fibre for high power EDFAs

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Abstract

The use of short lengths of large core phosphate glass fibre, doped with high concentrations of Er or Er:Yb represents an attractive route to achieving high power erbium doped fibre amplifiers (EDFAs) and lasers (EDFLs). With the aim of investigating the potential of achieving diffraction limited output from such large core fibres, we present experimental results of fundamental mode propagation through a 20 cm length of passive 300 \(\mu\)m core multimode fibre when the input is a well-aligned Gaussian beam. Through careful control of fibre geometry, input beam parameters and alignment, we measured an output \(M^2\) of 1.1 \(\pm\) 0.05. The fibre had a numerical aperture of 0.389, implying a V number of 236.8. To our knowledge, this is the largest core fibre through which diffraction limited fundamental mode propagation has been demonstrated. Although the results presented here relate to undoped fibre, they do provide the practical basis for a new generation of EDFAs and EDFLs.

Key words: Guided wave optics, Optical fibres, multimode fibre guide, EDFA

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1 Introduction

Conventional EDFAs based on single mode fibre have limited power handling characteristics. For many industrial and military applications these power levels are prohibitively low. By using larger core multimode fibre, power levels can be scaled-up, avoiding non-linear effects (stimulated Brillouin and Raman
scattering) and catastrophic optical damage in the core and at the end facets. Although many research groups have investigated amplifiers based on multimode fibres [1,2], most of the fibres investigated have had core diameters less than 50 µm; and more often less than 30 µm. In practice, bend-loss or tapered fibre sections are used to filter out higher order modes. Koplow [1] showed that the bend-loss technique becomes less effective for larger core fibres. Higher order mode suppression in a 100 µm core fibre is at least a factor of 10 lower than that observed in the more commonly used 25-50 µm core fibres. With regard to the use of tapers, these not only filter out higher order modes but also power. This limits the amplifier gain as shown by Minelly [3].

In earlier work we have demonstrated high fidelity fundamental mode propagation through hollow multimode waveguides with diameters of thousands of microns [4,5]. This was achieved by suitable control of the launch conditions and waveguide linearity. Recently, we have proposed the extension of this concept to the realisation of very large mode area (VLMA) EDFAs with core diameters of 300 µm or more. Similar work has been carried out by W. S. Wong et al [6] who recently demonstrated this propagation in VLMA fibre using photonic crystal fibre. This exploited the natural mode selection which arises through the use of large air holes in the fibre cladding. Having an effective mode field diameter of 42.5 µm, the fundamental mode was excited and propagated over an impressive 4 m fibre length.

In 2004, Qiu et al [7] demonstrated 4 W output power, in single mode, from a 7 cm length of Er:Yb co-doped phosphate glass fibre. The same research group (and others) has shown that phosphate glass fibre is much more soluble to erbium and ytterbium ions and thus provides significantly higher pump absorption per unit length of fibre [8]. The result is that significant gain and output powers can be attained from comparatively short lengths of fibre. It is this approach, in conjunction with the aforementioned single mode propagation in multimode waveguides that is of particular interest. In this letter we describe the potential of VLMA EDFAs and present experimental measurements of the passive fundamental mode propagation characteristics of a 300 µm core multimode fibre using a well-aligned Gaussian as the input beam.

2 Background

The V-number of a fibre is an indicative measure of how many higher order modes can propagate through the fibre [9]. It is given by

\[ V = \frac{2\pi}{\lambda} a \times (\text{NA}) \]  

(1)
where $\lambda$ is the wavelength of the radiation, $a$ is the fibre core radius and NA is the numerical aperture relating to the refractive index step between the core and the cladding. To force a fibre to only support the propagation of the lowest order fundamental mode, the V-number must be kept at, or below 2.405 [9]. If the core diameter is increased whilst maintaining the same index-step, a higher V-number results and the fibre becomes multimode. With respect to maintaining single mode characteristics, an increased core diameter can be offset, up to a point, by a reduced refractive index step as demonstrated by Taverner [10] for a 20 $\mu$m core fibre. However, this is only effective in fibres up to a certain core size and often requires additional fibre bending to achieve single mode output. To fabricate a single mode fibre with a core diameter of 100 $\mu$m using this approach is currently beyond fibre processing constraints.

Even though a fibre might have a multimode nature, it is still possible to excite just the fundamental mode. This depends on the input beam profile and the way the beam is injected into the fibre. Since our primary objective is to demonstrate the propagation of the fundamental mode and not any particular input beam, we have chosen a Gaussian beam as the input field. In this case, fundamental mode propagation can be achieved by holding the fibre rigid and straight, and controlling the alignment with respect to the injected Gaussian beam. In this manner, fundamental mode propagation can be maintained over some distance. This assumes that there are no perturbations (periodic or non-periodic) in the fibre and that the input beam-width is carefully selected to ensure that the value of the overlap integral between the single mode input field and the fundamental mode of the fibre is maximised. Figure 1 shows a plot of fundamental mode power coupling coefficient $C(\gamma)$ as a function of $\gamma = w/a$, the ratio of input beam (assumed Gaussian) waist $w$ and fibre core radius $a$, for a 300 $\mu$m core diameter. Also shown are the values of $C(\gamma)$ for various values of $\gamma$ near optimum coupling. It is evident that a Gaussian input having a beam waist corresponding to $\gamma \sim 0.65$ is required for optimum coupling of power into the fundamental mode of the fibre. It can be shown that a more precise value of $\gamma$ for this purpose is given by $\gamma = 0.6463$. In our experiment, the value of $\gamma$ was chosen to be 0.65.

Assuming an input beam from a laser source has a Gaussian form, it can be shown [11] that the magnitude of the field overlap integral with the sum of all the guided modes of the fibre (having forms of Bessel functions) has a value of 0.99. This implies that 98% (absolute square of overlap integral) of input power is coupled to guided modes of the fibre. If the fibre is aligned to the input in both angular and longitudinal senses, then it can be further shown through modal analysis that 99.8% of the light coupled to the guided modes of the fibre is, in fact, coupled to the fundamental mode – the remaining 0.2% to low order modes LP_{02} and LP_{03}. To illustrate mode-coupling as a function of misalignment further, figure 2 shows the power coupling coefficient calculated as a function of both angular and translational misalignment of fibre with
Fig. 1. Power coupling coefficient from free space to the fundamental mode of the fibre, as a function of input field beam waist. These results are numerical predictions based on a 300 µm core fibre with NA of 0.389. The coupling coefficient is defined as the modulus squared of the overlap integral between a Gaussian input field and each of the indicated modes at the misalignments shown. It is evident that

\[
\begin{array}{|c|c|}
\hline
\gamma & C(\gamma) \\
\hline
0.60 & 0.97403 \\
0.61 & 0.97669 \\
0.62 & 0.97866 \\
0.63 & 0.97997 \\
0.64 & 0.98065 \\
0.65 & 0.98073 \\
0.66 & 0.98033 \\
0.67 & 0.97919 \\
0.68 & 0.97763 \\
0.69 & 0.97559 \\
0.70 & 0.97309 \\
\hline
\end{array}
\]

Fig. 2. Power coupling coefficients to each of the four lowest order modes, numerically calculated for a 300 µm core fibre of NA=0.389 (a) translational misalignment (b) angular misalignment.

the tolerances on alignment are very high for such a multimode fibre, with an angular tolerance of greater than 3 µm required to suppress excitation of LP11. Figure 2(a) shows that coupling to all guided modes diminishes with increasing misalignment, with very little coupling to any mode beyond 200 µm. In contrast, figure 2(b) shows significant higher order mode excitation for
angular misalignments up to and exceeding 20 mrad. Although not shown, significant higher-order mode coupling (coupling coefficient \( \sim 0.2 \)) occurs at angles exceeding 100 mrad. It is therefore of vital importance that controls are taken over these sources of misalignment and mode mismatch. We end this section by noting that the above analysis is valid only for a Gaussian input beam. The next section will cover the experimental realization of the fundamental mode VLMA fibre principle.

3 Experimental configuration and results

As a first step in assessing the concept, we set out to investigate if it was possible to achieve high fidelity fundamental mode excitation and propagation through a passive multimode fibre. In order to achieve and maintain high fidelity fundamental mode propagation in a multimode fibre, the launch conditions and the linearity of the fibre must be appropriately controlled. The fibre needs to be kept as straight as possible, as bending will cause the fundamental mode field to be coupled to higher order modes. Fibre-guides with a "V" shaped cross-section were milled into the surface of a machinable ceramic (Macor) substrate using computer-aided machining techniques [4]. The fibre-guides ranged in length from 5 cm to 20 cm. Lids of the same material held the fibres in position. The fibre-guides accommodate fibres with cladding diameters ranging from 125 \( \mu \text{m} \) up to 1500 \( \mu \text{m} \). A fibre (mounted in such a fibre-guide) was held in position on a commercially available Newport translation stage (565-XYZ-TILT) with five degrees of freedom: three translational (with a resolution of \( \sim 0.1 \mu \text{m} \)), and two angular (with a resolution of \( \sim 2 \mu \text{rad} \)). The fibre used in this experiment was supplied by Thorlabs (FT-300-EMT) and had a 300 \( \mu \text{m} \) core diameter and 325 \( \mu \text{m} \) cladding diameter. The value of NA was 0.389. The tolerance on the outer diameter of the polymer coating was 30 \( \mu \text{m} \), which was a factor of three worse than that of the silica inner cladding. For this reason, the polymer coating was removed in order to minimise micro bending from this source.

Prior to mounting in the fibre-guide, the fibre end faces were cleaved and polished to a surface flatness of \( \sim \lambda/30 \) at 1550 nm. This prevented phase distortion of the fundamental mode input field.

The large V number of the fibre leads to a strong confinement of the field within the core. In this context, the input beam was chosen to have a diameter which ensured optimum coupling to the fibre. Through numerical analysis of overlap integrals between input field and the fundamental mode of the fibre, it was predicted that an input beam with a \( 1/e^2 \) mode field diameter of 0.646 of the fibre core diameter, would provide optimum power coupling to the fundamental mode of the fibre.
A fibre-coupled 1550 nm diode laser (Alcatel A1905 LMI 30mW) was focussed via a 10X microscope objective to achieve a beam waist of 195 µm (0.65 X 300 µm). At the output end of the fibre, a second microscope objective was used to produce a magnified image of the emerging field onto a “Gentec BeamR” beam profiler. A Hamamatsu vidicon camera was also used for additional analysis of the fibre output. A schematic of the experimental configuration is illustrated in figure 3. The output from the fibre laser obviously couples to some free-space Hermite-Gaussian mode which we assume to very closely approximate to a quasi-Gaussian field profile at the multimode fibre input.

![Schematic of experimental setup](image)

**Fig. 3.** Experimental setup of fibre, coupling optics and beam profiler.

Alignment of the fibre was by no means trivial and to obtain the desired output required extensive fine-tuning of translational and angular positions. Figure 4 shows the beam profiler plots of the field output of a well-aligned 20 cm length of 300 µm core fibre. As illustrated, the output beam profile had a near Gaussian-form. A measured $M^2$ value of $1.1 \pm 0.05$ confirmed that efficient fundamental mode propagation had been achieved in practice. The

![Beam profiler plots](image)

**Fig. 4.** Measured beam waist profiles in orthogonal orientations X and Y.
profiles shown represent orthogonal axes of measurement. The slight asymmetry between them is most likely due to some higher order mode content, which is of such low amplitude that it does not have significantly adverse effect on the measured $M^2$ parameter. Similar values of $M^2$ were measured for fibre lengths of 5, 10, and 15 cm. These experiments were repeated for a 105 $\mu$m core diameter multimode fibre (again, commercially available from Thorlabs – AFS105/125Y) which gave comparable results, i.e. $M^2$ of $\sim 1.1$ for lengths up to 20 cm.

These results are very encouraging, offering a proof-of-principle that highly multimode fibre, capable of supporting in excess of 28,000 ($\sim V^2/2$) modes can be configured in conjunction with a suitable input field, such that only its fundamental mode is excited and propagated throughout its length. We did not observe any deterioration in beam quality with length for fibres ranging from 5 cm to 20 cm, indicating longer lengths of fibre would also support the fundamental mode only. One might well ask whether the comparatively short fibre lengths considered here are transmitting the light in the form of a guided mode, or whether the fibre is so large as to be simply acting as a piece of bulk silica transmitting the light. However, it is worth noting that the Rayleigh range of a 195 $\mu$m diameter input beam entering the fibre is only 1.9 cm. In view of this, we can be confident that the light is indeed transmitted in a guided mode.

![Fig. 5.](image)

(a) Theoretical plot of fundamental mode of 300 $\mu$m core fibre with $\text{NA}=0.389$, (b) fundamental mode output from 300 $\mu$m core fibre, held straight, well aligned and polished, (c) Near field fibre output profile from the same fibre, but kept unpolished and misaligned demonstrating multimode nature. The white ring on each plot represents the core/cladding interface.

Figure 5 (a) shows an analytically generated image of the field corresponding to the fundamental mode of a fibre of the same specification as used here. Figure 5 (b) shows a vidicon camera image of the near field of the fibre output. This is the same output as illustrated in figure 4. The white circle encompassing the field distributions in all plots represents the core/cladding interface. A 20 cm length of the same 300 $\mu$m core fibre was located in a fibre guide of
inferior quality, such that the fibre was not held straight. Additionally, the end faces were cleaved but not polished. All other parameters were kept the same. The resulting output field is shown in figure 5 (c), which illustrates the highly multimode nature of the fibre, with significant higher order mode content. This also confirms the necessity of the controls we have taken over fibre linearity and minimisation of mode coupling.

4 Conclusions

We have experimentally demonstrated that a 300 µm core multimode fibre can support high fidelity fundamental mode (LP\textsubscript{01}) propagation over lengths of 20 cm or more. Since there was no variance in the output mode quality with length from 5 cm to 20 cm, there is every reason to believe that fibre lengths can be extended to 40 cm and still produce near diffraction-limited output beams. Although the technical discussions outlined here relate to amplifier applications, laser configurations should also be feasible with sufficient controls over preferential mode lasing [12].

With regard to non-linear scattering, a 300 µm core, 30 cm long EDFA would be capable of handling 30 kW optical power before reaching threshold for stimulated Brillouin scattering (SBS). From a thermal damage perspective, it is accepted that a conservative damage threshold for rare earth doped fibre is \(~1\) W/µm\textsuperscript{2} [13]. For a 300 µm core EDFA, this equates to a damage threshold of almost 70 kW. Although these figures are unlikely to be practically realised in EDFAs of this nature, they do illustrate the utility of larger core fibres in overcoming the limiting factors in conventional fibre power amplifiers. Heat generation from the quantum defect in EDFAs and fracture limits would be the first limit reached in fibres such as those presented here, with a limit of around 800 W expected for a fibre of this length based on parameters presented in previous work [14,15].

Provided rare-earth doped fibres behave similarly to the fibre described in this letter in terms of mode propagation, this would appear to offer a way of developing, in a master oscillator power amplifier (MOPA) configuration, a high power, compact and robust, single-mode amplifier, without the need for fibre coiling.

5 Acknowledgements

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List of Figure Captions

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