Microstructured Fibres for High Power Beam Delivery Applications

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Abstract: *We explore the potential offered by solid and air core microstructured fibres for high power applications and report the use of these fibre types in a pump delivery system for an optical parametric oscillator (OPO).*

Introduction

Fibre delivery of intense laser radiation is important in numerous application areas, from medicine through to industrial processing and aerospace sectors, and offers many practical advantages over free-space solutions. Optical fibres for high power transmission need to offer low values of optical nonlinearity and high damage thresholds. In addition, singlemode operation is often a fundamental requirement for the many applications in which good beam quality is essential.

In recent years, microstructured fibre (MF) technology has revolutionized the field of optical fibres, enabling a wide range of novel optical properties to be realized. These fibres, in which the cladding region is peppered with many small air holes, are separated into two categories, defined by the way in which they guide light: (1) index-guiding *holey fibres* (HFs), in which the core is solid and light is guided by a modified form of total internal reflection, and (2) *photonic band-gap fibres* (PBGFs), in which guidance in a hollow core can be achieved via photonic band-gap effects.

Both of these MF types offer attractive qualities for beam delivery applications. For example, using HF technology, large-mode-area, pure silica fibres with robust single-mode guidance over broad wavelength ranges can be routinely fabricated. In addition, the ability to guide light in the air-core within a PBGF presents obvious power handling advantages. Here we explore the potential offered by solid and air core microstructured fibres for high power applications and report the use of these fibre types in a remote pump delivery system for an optical parametric oscillator (OPO).

The fibres

Two silica MFs, one HF and one PBGF were designed and fabricated at the ORC and are shown in Figure 1. The HF was designed to have a large effective area ($A_{eff} \approx 350\ \mu m^2$ at 1.064 μm) in order to minimise damage and nonlinear effects. Observations show that this HF, which has $d/\Lambda \approx 0.44$, is effectively single-mode at 1.064 μm. The bend loss of this fibre is observed to be negligible for radii > 16 cm at 1.064μm. Note that, as a consequence of the bend loss in a solid core fibre, this A_{eff} is close to the upper practical limit for singlemode operation at 1.064μm [1].

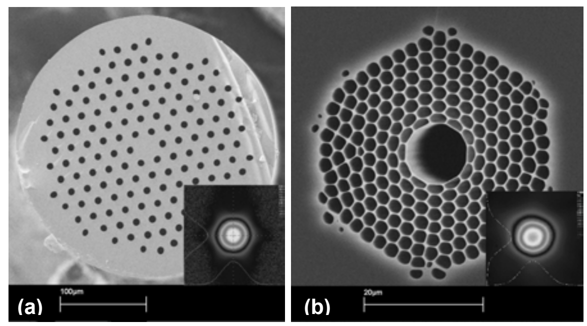

Figure 1. SEM image of (a) HF and (b) PBGF. Inset: fibre near-field at 1.064 μm *(false colour, not to scale).*

The PBGF has a seven-cell defect core of ≈ 10 μm in diameter and a mode area of ≈ 24 μm^2 at 1.064 μm (α =0.27dB/m at 1.064 μm). Although this mode size is considerably smaller than the HF, the PBGF is expected to withstand high intensities due to the fact that the mode is almost entirely localized in the central air core. The PBGF considered here is quasi-singlemode, and we find that the fundamental mode can be selectively excited by optimizing the launch conditions. An M^2 of between 1.1 and 1.6 is typically observed, depending on the launch conditions and cleave quality. The bend loss of this PBGF is observed to be negligible for radii > 1cm. (Measurements were not performed for radii < 1 cm, which is the minimum bend radius considered practical for prolonged installation).

High power results

Using a Nd:YAG operating at λ=1.064 μm, Q-switched mode locked pulses with a maximum average power of 6.7W and repetition frequency of 15kHz (mode-locked rep. rate 76MHz, peak power 30.4kW, pulse duration 300ps) were transmitted through ≈ 11m lengths of each fibre type. This length is representative of that required for many aerospace applications. Coupling efficiencies of > 60 % were observed for the HF, and efficiencies of 70 – 80 % were achieved for the PBGF. The pulses were observed to retain their width and shape after transmission though both fibres.

Due to the difference in mode area between the HF and the PBGF, the maximum peak energy density present in the PBGF ($\approx$ 37 Jcm^{-2}, peak intensity $1.2x10^{11}$ Wcm^{-2}) is an order of magnitude higher than that present in the HF ($\approx$ 2.6 Jcm^{-2}, $0.9x10^{10}$ Wcm^{-2}). However, since the majority of this energy is confined within the air core, no damage or nonlinear effects were observed for the PBGF under these conditions. (Note that these findings are consistent with other reports – see [2] and refs. therein). Similarly, no damage was observed in the HF, indicating that the pulse intensity present in the solid silica core is below the damage threshold for fused silica [3]. However, the spectral output (shown in Figure 2) demonstrates that the power density in the silica core is sufficient to generate a small amount of nonlinear effects; the small peak at a 1.12 μm contains $\approx$ 1 % of the power at the pump wavelength of 1.064 μm and is consistent with Raman scattering.

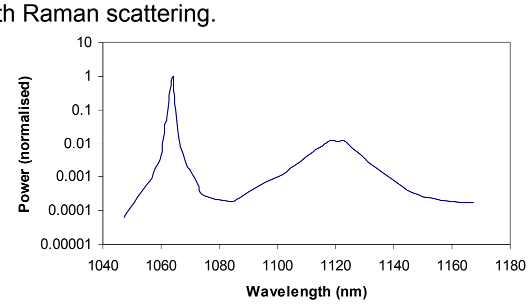

Figure 2. Spectral output from 11m of HF.

These results show that both types of microstructured fibre can be useful for moderately high power applications with diffraction limited beam quality. However, we see clearly that it is the PBGF that demonstrates real potential for intense beam delivery applications. Most importantly, we observe an absence of nonlinear effects at peak energies that are an order of magnitude above the nonlinear threshold in the solid core HF considered here. Indeed, the intensities inside the PBGF are noted to be beyond the damage threshold for ps pulses in silica [3]. Moreover, we also see benefits from the bend tolerance of the PBGF. This has particular advantages for practical system design, enabling a compact and flexible remote delivery system.

Demonstration of MF Pumped OPO

Here we present results from an OPO system in which the two MFs detailed above are used as pump delivery fibres. This system is chosen simply to illustrate the potential that MFs can offer in real delivery systems. OPOs are tuneable coherent wavelength sources based on nonlinear optical frequency conversion, and require good beam quality for efficient operation. OPOs are typically pumped using bulk optics and free-space beams, and have also been pumped using fibre lasers. However, this is, to our knowledge, the first demonstration of a MF pumping scheme for an OPO.

The OPO used for this demonstrator is a simple laboratory assembled device using a PPLN crystal. Note that this is not an OPO optimization exercise; we wish only to establish the relative performance of the MFs as pump delivery fibres. The OPO is a synchronously pumped device; i.e., the cavity length is set to match the repetition rate of the mode locked pump pulses. The pump laser is as described in the power transmission results section above. The same OPO cavity is used for both a free-space reference measurement and for the pump delivery demonstration with the HF and the PBGF.

The performance of the HF and PBGF are shown in Figure 3, and are both comparable with the results obtained for the free-space pumped system. Note that the input power was limited by the available laser power in the PBGF example, and not by any limitation on the part of the fibre.

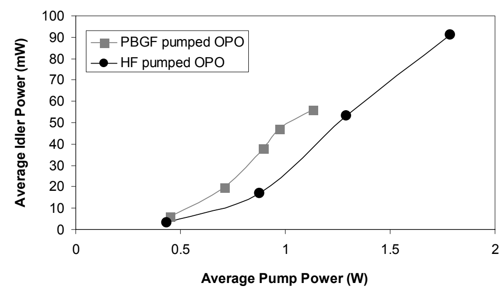

Figure 3. Generated idler power vs. input pump power for PCF pumped OPO systems.

Summary

Here we present results from an investigation into the power handling performance and bend tolerance of an index-guiding holey fibre and an air-core photonic band-gap fibre and their use in a pump-light delivery system for an optical parametric oscillator (OPO). These results show that the air-core photonic band-gap fibre demonstrates real advantages over solid core designs for applications involving intense beam delivery with diffraction limited performance where compactness and flexibility is essential.

Acknowledgements

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References

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