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Remote OPO Pumping with Photonic Fibres

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Abstract

Photonic crystal fibres are a disruptive technology for power transmission and light manipulation/control. In this paper we seek to assess the advantages offered by index guiding holey fibres and air-core photonic band-gap fibres for high power beam delivery applications with robust single-mode guidance. We explore the practical performance factors associated with each fibre type and consider how these may affect implementation and operation in real aerospace and defence systems. As an example of such a system, we report the use of a photonic crystal fibre as a pump delivery fibre in an optical parametric oscillator (OPO).

Introduction

Specifically this project addresses the problem of integrating high power lasers into air platforms for sensing applications. A suitable delivery fibre would enable a laser to be sited remotely from the sensor head and open up the possibility of several sensor types sharing the same multi-functional laser. This could reduce the complexity and hence the cost of such sensors systems leading to the potential for an affordable, robust system for military platforms.

The remit of the demonstrator system defined within this project was to use PCFs to deliver high-energy pump power to an optical parametric oscillator (OPO). This OPO would then be used to provide a 3-5μm wavelength source for applications such as biological sensing, targeting and threat detection.

Over the course of this project, BAE SYSTEMS have investigated the suitability and performance of PCF, which has been designed and fabricated at the ORC, for a pump delivery fibre to an OPO from a remotely sited laser source. In this paper we

Under the EMRS DTC project: "Photonic Fibres for Active Sensor Systems", BAE SYSTEMS and the University of. present the results of this study and also assess the general suitability of PCF for aerospace applications.

Photonic fibres for delivery of high power radiation

PCFs guide light due to the presence of many small air holes that define the cladding region and are separated into two distinct categories: (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. In both fibre types, the cladding air-holes are typically arranged on a hexagonal lattice and the defining parameters are the hole-to-hole spacing (Λ) and the hole diameter (d).

In optical fibres for high power transmission applications, low nonlinear effects and high damage thresholds are essential. Furthermore, when good beam quality is critical, single-mode guidance is also necessary. Both types of PCF offer attractive qualities for such applications. Using HF technology, large-mode-area, pure silica fibres with robust single-mode guidance can be routinely fabricated. Indeed, the largest mode areas reported to date have been achieved in this way [1]. In addition, the air-guidance offered by PBGFs, which have also been shown to possess good beam quality, presents obvious power handling advantages.

Results from a study into the suitability of HFs and PBGFs for use in high power, high beam quality aerospace applications are presented in the following sections. The key parameters considered include power handling, bend induced loss and the effect of environmental exposure. The two fibre technologies are then assessed and compared for suitability in aerospace applications. Finally, we report the use of a photonic crystal fibre as a pump delivery fibre in an optical parametric oscillator (OPO).

High power results

Samples of HF and PBGF designed and fabricated by the ORC (shown in Figure 1.) are assessed for power handling at 1064 nm. Each fibre is approximately 11m in length, which is representative of the lengths likely to be used in an aerospace platform.

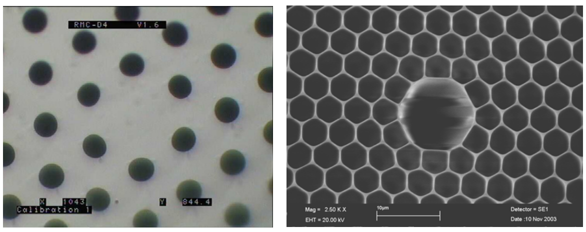

Figure 1. Cross section of HF sample (Left) and PBGF sample (Right)

The effective mode area (A_{eff}) of the HF sample studied here was measured to be ≈ 350 μm^2 at 1 μm. A large mode area is required in order to ensure that the pulse intensity incident in the soild silica core is below the damage threshold for fused silica [2]. Observations show that the HF, which has d/Λ ≈ 0.44 is effectively single-mode at 1 μm and that the mode profile is near-Gaussian in shape.

The PBGF sample studied here has a seven-cell defect core of ≈ 10 μm in diameter and a mode area of ≈ 24 μm^2 at 1μm. 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 localised in the central air core. Indeed, in such fibres, less than 1% of the mode is typically located in the glass of the fibre, suggesting that the damage threshold for such a fibre could be very high.

Although the PBGF considered here is not strictly single mode, the fundamental mode can be selectively excited by optimising the coupling at the fibre launch, and M^2 of between 1.1 and 1.6 have been achieved, depending on launch conditions and cleave quality. The modal profile of this fibre is also observed to be near-Gaussian in shape.

Using a Nd:YAG system operating at λ = 1064 nm, Q-switched mode locked (QSML) pulses have been successfully transmitted through both fibre types. Coupling efficiencies of above 60 % have been observed for the HF and efficiencies of 70 – 80 % have been observed for the PBGF sample. The mode locked pulses were observed to retain their pulse width and shape after transmission though the fibre, as shown in Figure 2.

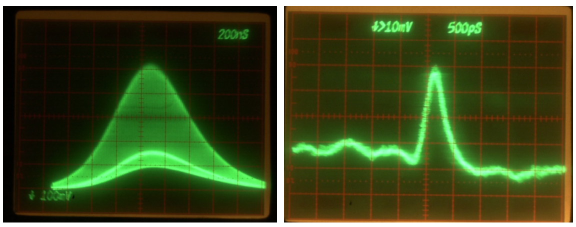

Figure 2. QSML pulses observed at the HF output (left) single QSML pulse, 200ns/div (right) Resolved mode locked pulse, 500ps/div

The input QSML signal had an average power of 6.7W and a pulse repetition frequency (prf) of 15kHz. It is important to note that the different mode areas for the two fibre samples results in different peak energies for each case. For the HF, peak energy of ≈ 2.6 Jcm^{-2} was focussed onto the fibre face. No damage was observed, demonstrating, as expected, that this energy density is below the damage threshold of the solid silica core [2]. The average output power was 4.1W with a calculated peak power per pulse of ≈18.4 kW.

A measurement of the spectral output of the 11 m length of HF is shown in Figure 3. This spectrum demonstrates that, as a result of the large mode size, the power density in the core is not sufficient to generate significant non-linear effects. The output spectrum clearly shows the pump wavelength at 1064 nm, and a very small amount of power is also observed at a wavelength of 1120 nm. This spectral line contains in the order of 1 % of the power in the pump wavelength and is consistent with a spontaneous Raman shift in the fibre.

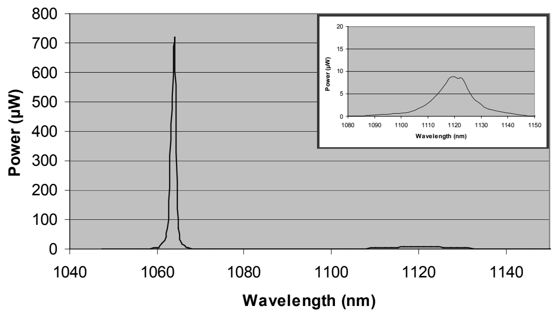

Figure 3. Spectrum of HF output after transmission over 11m showing pump wavelength of 1064 nm and presence of Stokes shift at 1120 nm

As a result of the small mode area of the PBGF, the intensities within the fibre are significantly higher than in the HF considered here. Indeed, calculations reveal that intensities up to 62 Jcm^{-2} are present in this fibre. However, due to the fact that the majority of this energy is confined within the air core, no nonlinear effects are observed for transmission along a 10.5m length. Furthermore, no damage is observed to this fibre for optimal coupling conditions.

However, it is important to note that misalignment at launch can cause significant damage to the endface of the fibre due to delicate nature of the cladding microstructure. Consequently, the tolerances on laser stability/coupling optics are far more demanding than for solid core. Yet it is worth noting that PBGFs have the potential to transmit far higher optical powers than is possible in any solid silica core.

The loss per unit length of the PBGF studied here is $\alpha = 0.27$ dBm^{-1}. The average power received after transmission over 10.5 m was 2W. Note that the attenuation losses reported for the PBGF studied here are similar to those reported in commercially available seven-cell band-gap fibres at 1μm [3].

This investigation has shown that both fibre types provide sufficient power handling for high power applications. However, performance differences have been highlighted between the two fibre technologies, specifically that of laser alignment and mode quality. It is important for the systems designer to be aware of the challenges involved in implementing a 'real' PCF system. The following section further outlines the differences.

Comparison of HF and PBGF for real high power systems

In this section we discuss the characteristics of the PBGF and the HF considered here in terms of practicality for high power delivery systems and assesses how these differences affect fibre handling, installation and alignment.

	PBGF	**HF**
Core	Hollow	Solid
Guidance Mechanism	Photonic bandgap effect	Modified total internal reflection
Beam quality (M^2)	1.1 – 1.6	~1
Critical Bend Radius (3	≤ 1 cm	~ 16 cm

dB/loop)		
Mode area	24 µm^2	350 µm^2
Intensity into core region	62 Jcm^{-2}	2.6 Jcm^{-2}
Alignment	Critical	Tolerant
Nonlinearity	None	Some effects
End face preparation	Critical	Sensitive

Table 1. Comparison of functional performance and handling characteristics of PBGF and HF.

The table above summarises the observed differences between the two PCFs considered here. In the following subsections we focus in detail on those parameters that we consider being key to further developing this technology. We briefly discussed the mode quality of the two fibres and the requirement for alignment stability in the high power results section above; the other main differences between these two fibres are those of bend induced loss and robustness to environmental exposure.

Bend Induced Loss

By its very nature, optical fibre enables light confinement along a long flexible length that can be coiled compactly. However, there is a lower limit on the size of the bend that can be used in practice, with respect to both mechanical strength and transmission loss. PCFs have been shown to possess similar levels of mechanical strength to conventional solid fibres (in which the minimum long term bend radius is typically considered to be a few cm) [4]. However, in HFs, attenuation due to bending can become apparent at bend radii much larger than a few cm. For example, for the HF considered here, the critical bend radius (defined as the radius at which the loss = 3dB/loop) is ≈ 16 cm. It should be noted that this is a typical value for a single-mode HF with a large mode size, and in general, the bending losses of HFs have been shown to be comparable to that of similarly sized step-index fibres at any given wavelength [5].

The mode area of the PBGF considered here is much smaller than that of conventional telecommunications fibre and, as a result, one would not expect this fibre to suffer loss as a result of the mode size. However, the light confinement mechanism in a PBGF is strongly dependant on the fibre structure and one may expect that this fibre type could be sensitive to bending via stress induced changes in the fibre structure. However, we find that bending actually has a negligible effect on the transmission window for the fibre considered here, as can be seen in Figure 4, which demonstrates that the transmission is unchanged by radii as small as 1cm. Consequently, the minimum bend radius for this fibre is therefore determined purely by the mechanical strength.

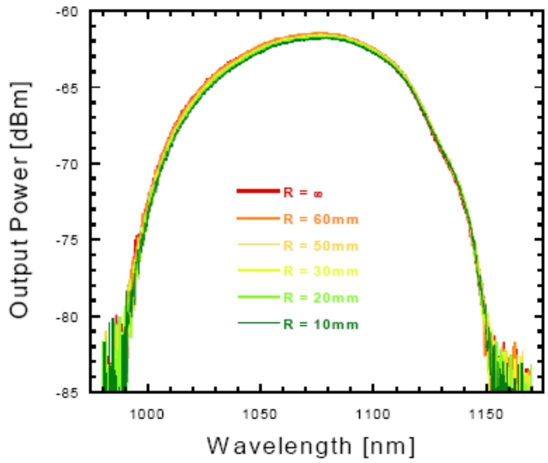

Figure 4. Output power vs. wavelength as the PBG fibre is bent at an increasingly tight radius

The effect of environmental exposure

In any system, damage to the fibre end faces can be detrimental to performance. Structural integrity is more critical in the PBGF than in the HF because the guidance mechanism depends strongly upon the fibre's microstructure. Whilst it has been shown that changes to the structure of the bandgap fibre caused by bending do not affect the guidance of the fibre, the integrity of the bandgap at the point of coupling in the light is very important.

During exposure to the laboratory environment, water and dust particles settle to the fibre end faces. In the HF, the presence of such contamination is evident as a slight distortion in the mode profile. However, equivalent debris on the PBGF is found to prohibit the coupling of any amount of light into the fibre.

Under laboratory conditions it is possible to carefully control the environmental exposure of the PBGF end faces thus reducing the damage incurred. However, in a real platform/application it is essential that these fibres are properly terminated with sealed end faces.

Demonstration of Holey Fibre Pumped OPO

In this section we present results of a holey fibre pumped OPO. This specific example is presented in order to practically demonstrate that photonic fibres have the potential to make an impact as a light delivery technology. Typically OPOs are pumped using bulk optics and free-space beams. The insertion of a photonic fibre to 'pipe' the pump source to the OPO crystal is the first known example of such a pumping scheme.

The OPO used for this demonstrator is a simple laboratory assembled device using a PPLN crystal. This project is not an OPO optimisation exercise; rather, it is important to establish whether the HF pumped OPO can offer comparable performance to that of the equivalent free-space pumped system.

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 (~ 76MHz). The 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 the holey fibre pump delivery demonstration.

The PPLN crystal was obtained from Crystal Technology Inc, California. The signal and idler frequencies generated by the OPO can be tuned by translating the multi-grating crystal across the path of the pump source thereby accessing different phase matching conditions. Using the longest period grating, equating to an idler wavelength of ~ 3.6 μm, the free space reference OPO had a threshold of ~ 700mW. A common value for the optimal pumping regime for OPOs is quoted as ~ 3-4 times the threshold level; a maximum average power level of ~ 4W is available for the pump, so we are well-placed to pump in this regime.

As shown in the section above the HF successfully supports the transmission of QSML pulses as required for OPO pumping. The free-space pumped OPO generated ~ 200mW of average idler power at 3.6 μm with 4 W average pump power. An observation of the same level of idler power using the HF to deliver the 1 μm pump radiation would confirm comparable performance to the freespace pumped system and demonstrate the feasibility of using a photonic fibre for this application.

As with the freespace pumped OPO, the longest period grating is used, equating to an idler wavelength of ~ 3.6 μm. The polarisation of the pump beam is controlled externally using a combination of a $\lambda/2$ and a $\lambda/4$ wave plate in order to access the most efficient parametric generation conditions.

The minimum average threshold power observed was 130 mW, comparing well to the free space OPO and also the theoretical value of 90 mW, which was calculated by combining an analysis of focussed Gaussian beams in an OPO with an analysis of synchronously pumped OPOs [6,7]. The apparent large improvement in threshold power is likely to be explained by non-optimisation of the free space OPO and minor differences in the set-up between the two experiments. A measurement of generated idler power as the pump power is increased is shown below. The measurements of idler power vs. pump power, along with the same measurements as obtained with the free space OPO, are shown on the graph to enable comparison.

It is observed that performance is comparable for the freespace pumped system and the holey fibre pumped system. Therefore, it has been shown that the holey fibre can be successfully used to deliver pump radiation to an OPO and hence generate wavelengths in the mid-IR as required for an active sensor system.

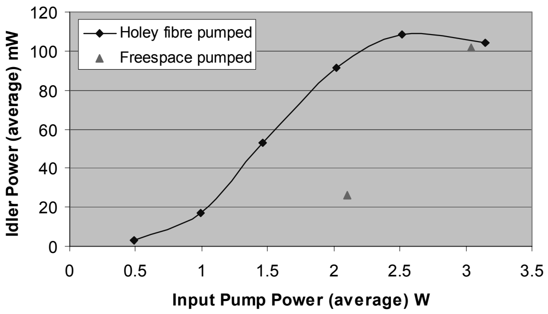

Figure 5. Generated idler power vs. input pump power for holey fibre pumped OPO systems. Idler powers as measured with the freespace OPO are shown for comparison

Note about polarisation

Systems relying on non-linear optical interactions for wavelength conversion (e.g. OPOs) require control of the pump polarisation in order to work efficiently. Although the pump laser in this investigation is linearly polarised, during transmission through the non-polarisation maintaining HF, the polarisation state is modified. As a result of this change in polarisation, efficient parametric generation is not achieved unless the polarisation is externally controlled after transmission. Consequently, in a real platform, a polarisation maintaining photonic fibre would be required.

Summary

This paper details the results of a preliminary investigation into the power handling performance of photonic crystal fibres (PCF). In this study, the performance of two PCFs, one index-guiding holey fibre (HF) and one air-core photonic band-gap fibre (PBGF), which were designed and fabricated at the ORC, have been assessed in terms of power handling at 1064 nm. It has been shown that both the HF and the PBGF studied here exhibit real potential for use as a power delivery technology.

These fibres have also been considered in terms of practicality for real systems by assessing the bending losses and the effect of environmental exposure. A comparison of the two fibres studied here has been presented to highlight challenges that need to be addressed when developing the technology for aerospace, defence and/or civil power delivery applications. Most importantly we find a need for sealing the ends of the PBGFs to prevent degradation and damaged caused by moisture and dust in the environment.

It has been demonstrated that mid IR generation can be obtained from a HF pumped OPO with comparable performance to the equivalent free space system. Therefore, it has been shown that the HF can be successfully used to deliver pump radiation to an OPO and hence generate wavelengths in the mid-IR as required for an active sensor system. To our knowledge the insertion of a photonic fibre to ‘pipe’ the pump source to the OPO crystal is the first example of such a pumping scheme.

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