Photonic Fibres for Active Sensor Systems

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Abstract

Under the EMRS DTC project: "Photonic Crystal Fibres for Active Sensor Systems", BAE SYSTEMS is investigating the use of photonic fibres to support high power transmission at a wavelength of 1 μm in order to provide high-energy pump power to an optical parametric oscillator (OPO). The OPO is to be used to provide a 3-5 μm wavelength source for active sensor applications such as laser radar, laser vibrometry, earth observation and other LIDAR systems. Here we present results of experimental work undertaken during Year 1 of the project.

Keywords: Photonic Crystal Fibre, Holey Fibre, Optical Parametric Oscillator

Introduction

Situation awareness and self-protection is of vital importance in today's defence and aerospace environment. On-board systems in aircraft, for instance, are already used to detect and counter the potential security threats. Sensor capability across the electro-magnetic spectrum (RF through to infrared and visible) can enable the aircraft to gather and analyse information (from threat, intelligence, surveillance and/or reconnaissance sources) and thus provide a complete overview of the operational scenario.

Photonic fibres are a disruptive technology for power transmission and light manipulation/control. Under the EMRS DTC project: "Photonic Fibres for Active Sensor Systems", BAE SYSTEMS ATC is investigating the use of photonic fibres to support high power transmission at a wavelength of 1 μm (from lasers such as Nd:YAG) in order to provide high-energy pump power to an optical parametric oscillator (OPO). The OPO is to be used to provide a 3-5 μm wavelength source for applications such as irradiation and biological sensing, targeting and threat detection.

Photonic Fibres

Delivery of high power radiation is not possible using conventional fibre, as the fibres would need to be highly multimode to handle the high intensities without damage. This would necessitate the use of very large aperture optics to collimate the laser beam and is therefore impractical in most sensor systems. The recent invention of Photonic Fibres (PF) could overcome this problem as they can operate single mode with relatively large core diameters.

PF is a unique type of optical fibre incorporating an array of air holes that run along its length, reminiscent of a crystal lattice, which give this type of fibre its name. There are two main types of PF: air-guiding which guides light via a photonic band-gap effect and index-guiding which guides via a modified total internal reflection mechanism.

In air-guided PF, the core is hollow, and light is guided by the photonic bandgap (PBG) effect, a mechanism that does not require a higher refractive index in the core in order to confine and guide light. The PBG guidance effect relies on coherent backscattering of light into the core. The capillaries of air strongly scatter the light preventing its escape into the cladding. For particular wavelengths and angles of incidence the multiple scattering process results in constructive interference of all rays back into the core. Characteristics of this guidance mechanism mean that only certain bands of wavelengths are transmitted. Typically these fibres are referred to as Photonic Bandgap Fibres (PBGF).

Index-guided PF is commonly referred to as Holey Fibre (HF) to differentiate it from the air-guiding PF. In HF the core area is solid and the light is confined to a central core by a modified form of total internal reflection (TIR), rather than the refractive index step of a conventional fibre. HF consists of a pure silica fibre with an array of airholes running the full length of the fibre, Fig.1. The core is formed by the absence of an airhole. The lower effective refractive index of the surrounding holes forms the cladding resulting in an index guidance mechanism analogous to total internal reflection.

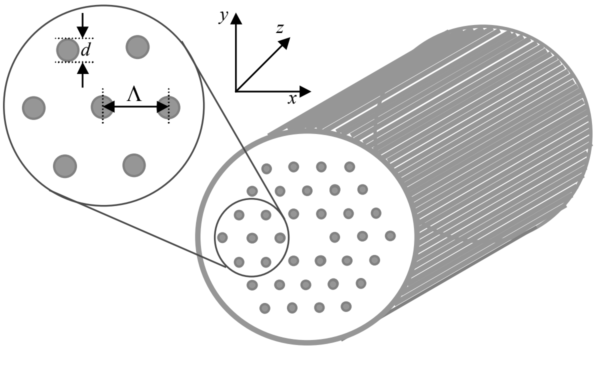

Fig.1: Schematic of a Holey Fibre showing hole diameter, d, and hole-to-hole spacing (pitch), Λ

Both types of PCF offer the potential for delivery of high power laser radiation with diffraction-limited performance. However, initially the EMRS PCF project has investigated the more established technology of index-guiding HF.

The HF has several unique and potentially useful properties. The fibre is constructed from undoped silica, which provides very low losses and sustains high powers and temperatures. This raises the possibility of propagating high power densities without exciting any unwanted non-linear effects. Integration of high power lasers into air platforms for remote sensing applications, LIRCM and other applications such as Laser DEW would therefore be facilitated, as the fibre delivery would enable the 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.

During the first year of the DTC project the ATC have investigated the use of index-guiding HF to transmit high peak powers to an OPO from a remotely sited laser source.

Functional Performance and Handling

HFs can have a diverse range of parameters such as a large air filling fraction, very large mode field area and a very low numerical aperture (NA). Therefore the preparation and light coupling methods required are likely to be significantly different from those used with standard fibres.

An investigation into the preparation and handling of several HF samples fibres was made in order to see how different fibre structures affect the optimal cleaving tension. The fibres were obtained from commercial supplier Crystal Fibre in Denmark and from the University of Southampton's ORC.

Standard fibre cleaving conditions (a required tension of 200 – 250 g for a fibre diameter of 125 µm) are inadequate for holey fibres, and in fact can cause significant damage. The optimal cleaving tension required for HF is strongly dependant on the fraction of air that the fibre contains. A HF with a large air fraction will demand a lower optimal cleaving tension to minimise damage around the holes than a corresponding fibre with the same diameter but a lower air fraction. Once the optimal tension has been found it was shown that this could be applied repeatedly with predictable results.
The fibre samples obtained from Crystal Fibre all have a fibre diameter of 125 µm, the accepted diameter for telecomm fibre. Importantly, this is compatible with standard cleaving and splicing equipment and connector ferrules. However, the samples obtained from the ORC had a larger outer diameter of ~ 250 µm. It has been experimentally observed that these larger fibre diameters, with the addition of extra 'rings' into the holey fibre structure, clearly increases the modal confinement and reduces losses due to bending, especially at lower wavelengths. In turn, this allows enhanced transmission performance for wavelengths in the visible region. Crystal Fibre has since redesigned their large mode area (LMA) fibre with a larger outer diameter and hence more rings of holes to confine the light.

The structure of the photonic fibre can also affect the guidance properties of the fibre in terms of the number of modes that can be supported. The aim of the EMRS project is to produce a singlemode output in the 3-5 µm wavelength region. In order to achieve this the pump source for the OPO should be singlemode. Therefore it is important to ensure that the photonic fibre used in this application guides only a singlemode at the pump wavelength of 1064nm.

Using a singlemode pump also serves to enhance the performance and conversion efficiency (pump to signal and idler) of the OPO with a singlemode beam capable of tighter focussing and higher intensity than a larger multimode beam. Therefore the photonic fibre used for this application should be robustly singlemode at a wavelength of 1 µm.

In conventional fibres, operation can become multimode for sufficiently low wavelengths or as the refractive index difference (NA) is increased.

$$V = \frac{2\pi a}{\lambda} NA \qquad (1)$$

Where V is the number of guided modes, λ is the wavelength, *a* is the radius of the fibre core and NA is the numerical aperture of the fibre.

In holey fibres multimode operation typically occurs as the size of the airholes increases relative to the pitch (or hole-to-hole spacing) of the fibre. Rigorous singlemode operation is said to be possible only for values of hole diameter $d \le 0.45\Lambda$ [1, 2] after which the fibre can potentially support transmission of higher order modes. However, the higher order modes suffer significantly more loss and hence after a length of several metres are not observed in the nearfield / farfield profile. Operation at short wavelengths (approaching the dimensions of the fibre) can also be subject to high losses due to the short wavelength bend loss edge and the weakly guided higher order modes are lost. Operation in this case can be said to be near singlemode.

In order to demonstrate how a fibre can support lossy higher order modes an experiment is conducted with a short (~75 cm) length of HF with a hole diameter of $d = 0.5\Lambda$. This short length is used in order to emphasise the presence of the higher order modes, which are usually ‘stripped out’ after a length of several meters.

Figure 2 shows the multimode behaviour of the HF at a wavelength of 1064 nm. This is a low loss wavelength and therefore the light is well confined in the core. The length is insufficient to ‘strip out’ the higher order modes and therefore a multimode output is observed in the farfield profile. At a shorter wavelength of 540 nm the fibre suffers much higher losses and is very sensitive to bends. Although the fibre is of short length there is a small curve in the fibre and this curvature plus the high loss is sufficient to ‘strip out’ the higher order modes and a near Gaussian output is observed in the farfield. Operation in this case can be said to be ‘quasi-singlemode’.

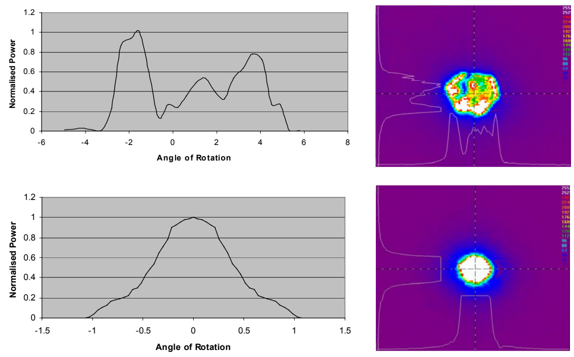

Fig. 2: Farfield profiles of 75 cm length of HF with d = 0.5 Λ (Top) λ = 1064 nm, showing the presence of higher order modes, (Bottom) λ = 540 nm, effectively singlemode

Another performance measure of the HF is that of bend loss. The large mode area HF is of interest to the EMRS DTC project because of its ability to be used for high power applications, requiring high quality beams and efficient power delivery, potentially within a small space as an alternative to free space beams. However there may be a limit to the amount of bending that can be tolerated within the fibre. It is important to establish the transmission loss caused by bending and to draw conclusion as to the minimum bend radius and a practical loss limit.

The critical bend radius, R_c, is defined as the radius at which the transmitted power has been attenuated by 3dB. The samples under test have values of R_c of between 4.8 mm (core diameter 10 μm, mode area 48 μm^2) to 68 mm (core diameter 20 μm, mode area ~200 μm^2).

From these measurements it is observed that an increase in the mode area causes increased bend loss. Fibres with small mode areas have reduced bend loss because they have increased values of NA and therefore tighter mode confinement. If NA can be increased whilst retaining a sufficient mode field area then the bend loss may be improved but there is a limit to this. An increase in NA for a fixed wavelength is a direct consequence of increasing the ratio of d/Λ and if this ratio is above 0.45 then the fibre is no longer robustly singlemode. Therefore the NA can only be increased to the boundary between singlemode and multimode operation.

Characterisation of System Demonstrator

The laser used in the experiments is an Nd:YAG system operating in the fundamental mode (λ = 1064 nm). The laser can be operated both mode locked (150 ps pulses) and Q-switched mode locked (QSML) with pulse repetition frequencies (prf) from 500Hz to 25KHz. This enables the peak power per pulse to be controlled from a few kW to over 1MW.

Typically OPO’s are pumped using bulk optics and free-space beams and in previous OPO experiments at the ATC this laser was directly coupled into the OPO by a lens system. The non-linear material used as the OPO crystal was Periodically Poled Lithium Niobate; commonly referred to as a PPLN crystal.

Insertion of a photonic fibre to 'pipe' the pump source to the OPO crystal will be the first known example of such a pumping scheme. Based upon the peak energies and power distributions used for previous successful free space pumping it is possible to make assumptions about the performance requirements of the photonic fibre.

The issue of fibre damage is an important consideration. It is vital to the success of the project that the power requirements of the OPO are not greater than power levels that will damage the fibre. The damage threshold for a fused silica cleaved fibre with picosecond pulses is in the region of 8-15 Jcm^{-2} [3]. It is therefore important to have as large a mode area as possible in order to limit the power intensity into the fibre and hence the potential damage caused during operation. Based on the minimum expected damage threshold for 'solid' silica fibres and estimated energy intensities required to pump the OPO, it is concluded that fibres with a mode area of no less than 110 μm^2 should be used.

The fibre chosen for initial experimental investigations was a sample with an effective mode area (A_{eff}) of ~200 μm^2, Fig.3. This mode area is well in excess of the minimum required to avoid damage and therefore should be suitable for the application. The fibre has a d/Λ of ~0.3 and hence is robustly singlemode.

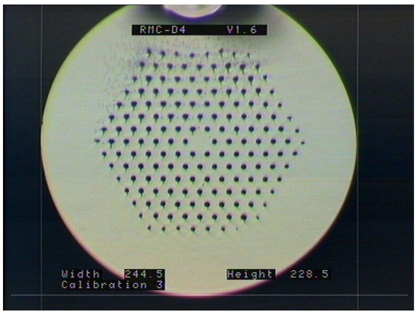

Fig.3: Cross section of HF sample

A measurement of the fibre farfield profile using a knife-edge scanning technique, Fig.4, confirms the near Gaussian shape of the mode and determines the numerical aperture of the fibre.

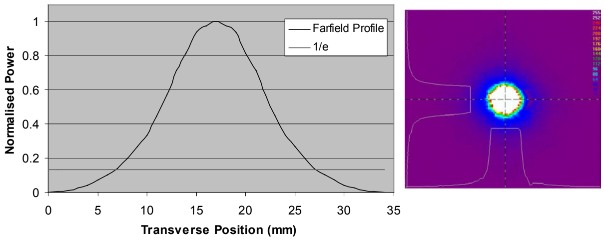

Fig.4: Farfield profile of HF sample showing near Gaussian distribution. The image on the right shows the farfield profile as measured on a CCD camera (saturated)

The characteristics of the photonic (holey) fibre are not the only aspects to be considered in designing a successful mid-IR generation scheme. It is of vital importance to minimise the losses in the coupling stage. The coupling efficiency should be kept as high as possible, not only to ensure that most of the radiation flows through the fibre core but also to avoid too much radiation penetrating the "airy cladding" where the damage threshold is expected to be much lower than in the core.

The required optics are dependent upon laser beam diameter and beam divergence as well as the mode area and numerical aperture of the fibre. The measured laser and fibre output power distributions were used in a Zemax design to determine the optimum solution. There are only two practical solutions to projecting a beam waist onto the core of the photonic fibre: a single lens solution taking the Fourier transform of the beam and a two lens 'imaging' solution. Whilst this second design may allow more flexibility in the coupling, a simple single lens solution was judged to be suitable for initial investigations of coupling and transmission performance.

High power measurements including insertion loss and pulse characteristics have been made in order to move towards the project's first year demonstrator: generation of high quality mid-IR radiation from a PCF pumped OPO.

CW mode locked (CWML) and Q-switched mode locked (QSML) pulses have been successfully transmitted through the fibre with coupling efficiencies of 66 %.

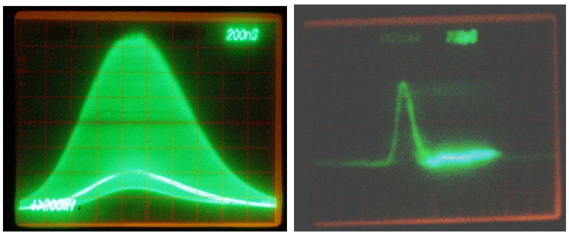

Fig.5: QSML pulses observed at the fibre output, 20mV/div (left) single QSML pulse, 200ns/div (right) Resolved mode locked pulse, 200ps/div

The input QSML signal had an average power of 7W and a pulse repetition frequency, prf, of 15 kHz. This resulted in peak energies of ~ 3 Jcm^{-2} focussed onto the fibre face. No damage was observed, demonstrating that this energy density is below the damage threshold of the fibre. The average output power after transmission through the fibre was 3.6W with the peak power per pulse calculated as ~22 kW.

Future Directions and Summary

Results obtained in the first year of this project have demonstrated that photonic fibres have the potential to make an impact in the aerospace and defence sector as a light delivery technology for active sensor systems. It is clear that further work must be undertaken to establish the potential limitations of this technology and to align with application requirements. The most critical issue is that of power handling and damage.

During the second year BAE SYSTEMS will partner the University of Southampton's ORC, world leaders in the design and fabrication of photonic fibres, and the programme will investigate novel photonic fibre structures including photonic bandgap fibres.

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