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# Microstructured Fibres: A Positive Impact on Defence Technology?

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## ABSTRACT

In this paper we seek to assess the potential impact of microstructured fibres for security and defence applications. Recent literature has presented results on using microstructured fibre for delivery of high power, high quality radiation and also on the use of microstructured fibre for broadband source generation.

Whilst these two applications may appear contradictory to one another the inherent design flexibility of microstructured fibres allows fibres to be fabricated for the specific application requirements, either minimising (for delivery) or maximising (for broadband source generation) the nonlinear effects.

In platform based laser applications such as IRCM, remote sensing and laser DEW, a suitable delivery fibre providing high power, high quality light delivery would allow a laser to be sited remotely from the sensor/device head. This opens up the possibility of several sensor/device types sharing the same multi-functional laser, thus reducing the complexity and hence the cost of such systems.

For applications requiring broadband source characteristics, microstructured fibres can also offer advantages over conventional sources. By exploiting the nonlinear effects it is possible to realise a multifunctional source for applications such as active hyperspectral imaging, countermeasures, and biochemical sensing.

These recent results suggest enormous potential for these novel fibre types to influence the next generation of photonic systems for security and defence applications. However, it is important to establish where the fibres can offer the greatest advantages and what research still needs to be done to drive the technology towards real platform solutions.

**Keywords:** Photonic Crystal Fibre, Microstructured Fibre, Holey Fibre, Photonic Bandgap Fibre, Defence

## 1. INTRODUCTION

Microstructured Fibres (MF) have been around since the advent of optical fibre technology in the 1970's [1]. However, these fibres took a back seat while 'conventional' step index fibre technology developed and matured into viable commercial products. In the 1990's a resurgence of interest took place when MF technology demonstrated novel optical properties including endlessly single mode guidance [2] and transmission of radiation using the photonic bandgap effect [3] which had been predicted by Yablonovich [4] in the 1980's. Although the technology is relatively new, commercialization of this technology has started to take place which suggests that these fibres have the potential to make a significant impact in applications requiring broadband sources or delivery of high power radiation.

Microstructured fibre technology can be divided into two distinct subgroups, the solid core holey fibre (HF) which guides light by a modified total internal reflection and the photonic bandgap fibre (PBGF) which guides light in air by the photonic bandgap effect (Figure 1). Holey fibres can further be divided into large mode area (LMA) HF and highly nonlinear (HNL) HF, where the LMA fibres have minimal nonlinearity for power delivery while the HNL HF have maximum nonlinearity for broadband generation.

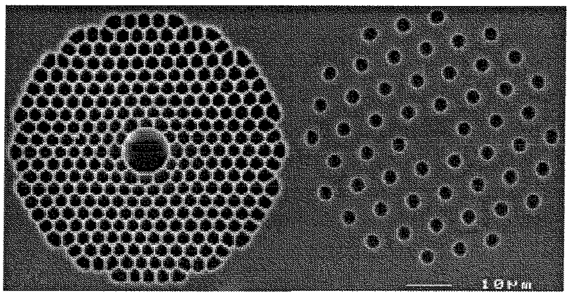


Figure 1: The Photonic Bandgap Fibre (l) and the Holey Fibre (r)

MF are of great interest to a wide variety of research organizations, both academic and industrial as they offer many novel optical properties that are generally not available in standard fibre technology. HF properties of interest to the defence sector could include very large mode area, single mode guidance (for high power delivery), and dispersion shifted and flattened fibres, ideal for nonlinear optics leading to broadband generation.

This paper is divided into three separate sections: high power delivery and application demonstrators, broadband generation and a brief discussion into other types of potentially useful microstructured fibres. The aim is to study where the novel properties of these fibres can make a direct, positive impact on defence technology.

## 2. HIGH POWER DELIVERY

Intense laser radiation is of interest for many applications in the security and defence sector including pumping of frequency conversion sources, laser directed energy weapons (DEW) and electro-optic countermeasures (EOCM). Fibre delivery offers many practical advantages over free space systems in terms of platform design, ease of use and safety. Important for defence type applications is the potential for remotely siting the work piece, be it a frequency conversion source or a laser processing table. This would allow greater flexibility in positioning the active sensor devices and parent laser. If a 'multifunctional laser' approach was to be implemented, a single laser could be used with MF technology 'piping' high power radiation around the platform. This would lead to significant weight and space savings, also allowing greater flexibility in positioning of the optical components, all of which lead to significant cost reductions.

Optical fibres for high power and energy transmission need to offer high damage thresholds and low values of optical nonlinearity, both of which suggest using large effective mode areas ($A_{eff}$) to keep intensities to a minimum. These parameters suggest that multimode step index fibres would be an ideal solution; however in addition, for many applications single mode operation is often a fundamental requirement. Both single mode step index fibre and LMA-HF technology can have comparable bend loss performances at a given wavelength. However, the advantage of HF technology is that it can provide single mode operation for applications requiring a wide wavelength range [5]. For single mode operation at 1 μm, HF technology would allow an $A_{eff} \sim 500\ \mu m^2$, where a COTS 1-μm guiding single mode step index fibre is restricted to $< \sim 30\ \mu m^2$, so allowing more power to be coupled into the HF before reaching the optical damage threshold, this comes with the caveat that the critical bend radius of the HF is ~12 cm while the single mode fibre is ~13 mm.

PBG fibres have much smaller $A_{eff}$ ($20 - 30\ \mu m^2$) and hence higher intensities in the core; however as most (>99%) of the radiation is guided in air they offer obvious power handling advantages [6]. Also, as air, along with most other gasses, has a low value of nonlinearity and attenuation, these fibres have the potential to deliver very high powers without spectral degradation or absorption of the pump beam.

### 2.1 Peak Power

There are many applications for peak power delivery; in the following section one such application, the pumping of a remotely sited frequency conversion source (optical parametric oscillator), is demonstrated. This application was chosen as it has direct relevance to defence applications as infra-red countermeasure (IRCM) and biochemical sensing wavelengths can easily be accessed using this technique.

Pumping of optical parametric oscillators (OPOs) require high power densities focused into nonlinear crystals [7]. Conventional single mode step index fibres are unable to withstand the intensities required while if multimode fibres are used, the focused spot is no longer diffraction limited and so the frequency conversion will be inefficient. Holey fibres are an attractive solution to this fibre delivery problem as they can have large mode area, diffraction limited guidance. PBG fibres are also a promising solution as the radiation is guided in air, so theoretically very high peak powers could be delivered.

An investigation was made into the pumping of a remotely sited OPO in order to assess the capability of these fibres to deliver radiation of both quality and quantity [8,9]. A Q-switched and mode-locked Nd:YAG laser source with a maximum average power 6.7 W at 1.064 µm, a Q-switch repetition frequency of 15 kHz and envelope of 700 ns was used; mode locked repetition rate was 76 MHz with a pulse duration of 300 ps (Figure 2 a, b) leading to a peak power of 30.4 kW. A free space OPO system was first built before separately inserting ~11 m of both HF and PBGF into the cavity between the pump source and the periodically poled lithium niobate (PPLN) nonlinear crystal (Figure 3). Eleven meters of fibre was chosen as this is representative of lengths required on an air-frame. Some spectral degradation of the pump consistent with Raman shifting was observed when the HF was used to pump the OPO (Figure 2 c); however, as expected, none was observed with the PBGF. Idler power (a wavelength of 3.7 µm) was measured with respect to the input pump power; both the HF and the PBGF gave performances comparable to that of the free space system (Figure 4).

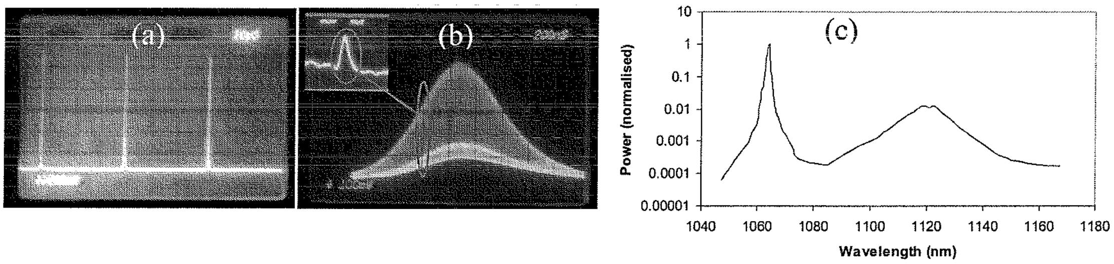


Figure 2: a) Q-switched repetition rate, b) Q-switch envelope with mode-locked pulses, c) spectral broadening of pump after transmission though 11 m of HF

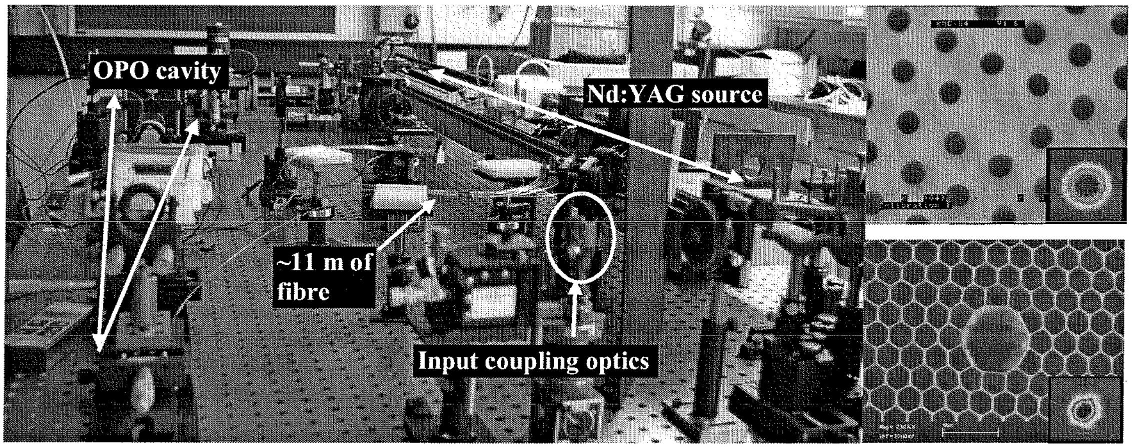


Figure 3: Pumping of a Remotely Sited OPO – experimental system. Inset: HF and PBGF endfaces and output profiles

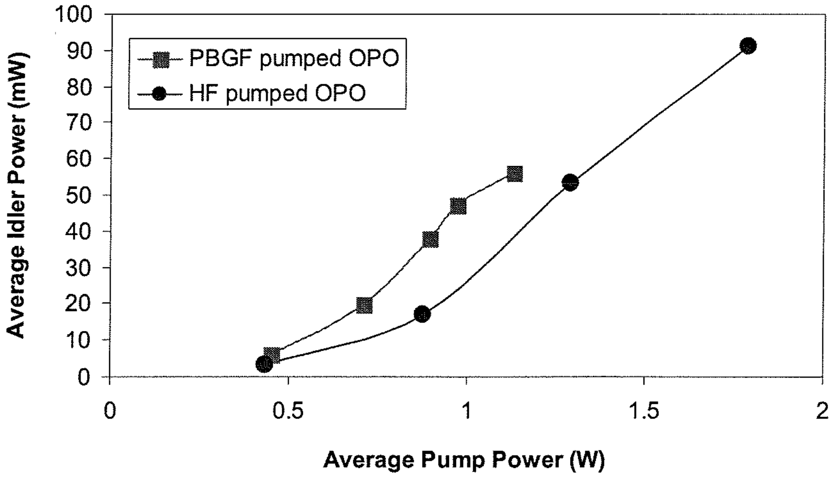


Figure 4: Comparison of PBGF and HF pumped OPO

Note that the input power to the OPO was limited by the available laser power, rather then any limitation on the part of the fibres. This demonstrator shows that MF fibres can be used to deliver pump radiation to an OPO and hence generate wavelengths in the mid-IR as required for active sensor systems.

## 2.2 Energy

The delivery of high energy nanosecond pulses is also of interest. Currently, the majority of this high energy MF research has been pushed from the industrial processing areas. Indeed, there have already been practical demonstrations involving micromachining of metals [10] and direct write components [11].

PBGF technology has been studied for the transmission of nanosecond (65 ns) sources and energies of greater than 0.5 mJ have been delivered over 2 m lengths of fibre. These hold the advantage over step index fibre technology as they provide delivery of near-diffraction-limited beams [10]. Holey fibre technology has also been studied as a comparison to PBGFs for delivery of 1.064 μm radiation. A fibre with $A_{eff}$ = 485 $\mu m^2$ and a length of 2 m was used for these experiments. Pulse energies of 1.5 mJ were successfully delivered through the fibre without spectral, temporal or modal distortion. In Figure 5 we show the input and output facets of the fibre after power delivery and also the near and far fields of the output profile. Although the measured $M^2$ of the output is 2.6, this value corresponds to the measured beam quality of the pump laser used and no spatial higher order modal content was observed in the output beam.

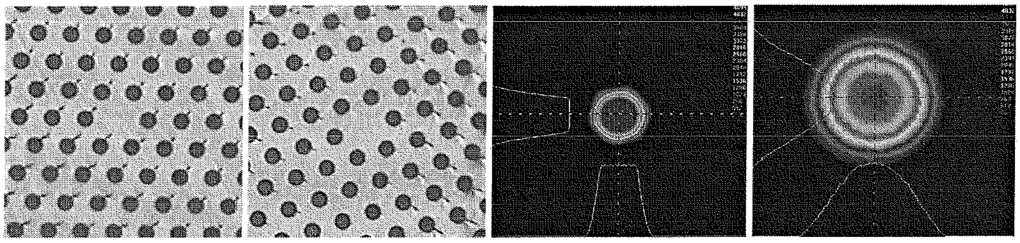


Figure 5: Input and Output faces of HF after high energy transmission, near field and far field mode profiles

These levels of energy are able to machine aluminium sheets of 300 μm thickness as can be seen in Figure 6.

Direct write (DW) is an out of vacuum deposition technique which allows inks and pastes to be transferred directly onto surfaces from CAD / CAM models. The inks and pastes can be resistive or conductive allowing circuits and 'stealthy surfaces' to be written onto both planar and conformal surfaces (Figure 7). Direct write structures were machined using radiation at 532 nm over 1.5 m lengths of HF [11] giving the laser processing system the ability to frequency tune circuits.

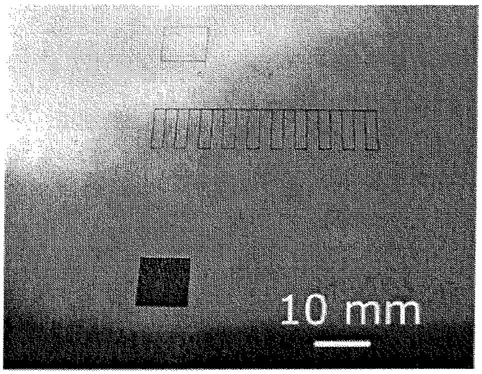


Figure 6: Machining of Aluminium

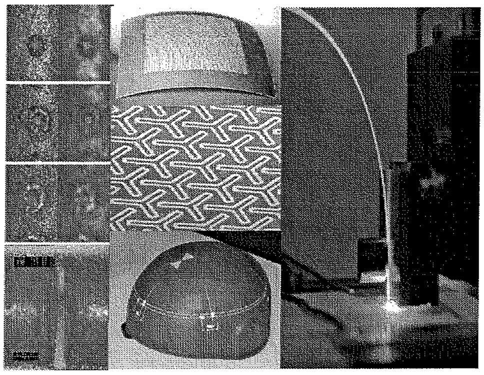


Figure 7: DW Components and Fibre Delivered Machining

The brief demonstrators discussed above show that both PBGF and HF technology can deliver energies required to carry out remote laser processing tasks. The decision as to exactly which fibre is best for an application lies in the design and requirements of the optical system. A brief comparison detailing differences between the PBGF and the HF follows in Table 1.

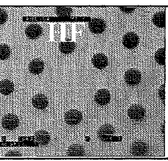
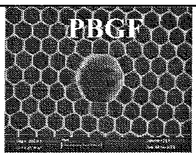
| **Installation issues** |  |  |
|---|---|---|
| Critical bend radius | Can be large and the limiting factor | Very small, mechanical limitation |
| Nonlinear effects | Sometimes observed, especially over longer lengths of fibre | None |
| Sensitivity to alignment | Some loss of power will be observed but no damage | Very, misalignment will often lead to catastrophic damage of guidance mechanism |
| Sensitivity to source quality ($M^2$) | Little – slight reduction in coupling efficiency | Very, 'excess' radiation can be dissipated into the cladding and solid glass structure causing thermal effect and leading to misalignment |
| **Pulsed Power delivery** | | |
| Picosecond source (~300 ps), mode-locked, Q-switched Delivered pulse energy (through 11 m) | 5.1 µJ (300 ps), 18.4 kW (start of spectral broadening) | 2.6 µJ (300 ps), 9 kW, limited by source and losses in fibre |
| Nanosecond source, Q-switched Delivered pulse energy (through ~2 m) | 1.5 mJ (100 ns), 15 kW | 0.5 mJ (65 ns), 14 kW |

Table 1: Comparison of Holey Fibre and Photonic Bandgap Fibre for Installation in Systems

## 3. BROADBAND SOURCE GENERATION

Broadband (continuum) source generation has been of interest to the science community since the advent of laser technology. However, generation often requires long interaction lengths (> cm) with high power densities in the material. Standard fibre technology goes a long way to solving the interaction length issue as radiation can be well confined for many kilometres. Holey fibre technology is also of great interest to this application as the optical properties of the fibres can easily be tailored by altering the cladding design. There are two components fundamental to the production of continuum, the fibre and the source. Of importance in the fibre is the dispersion profile relative to the source and the effective nonlinearity of the fibre (a relationship between the nonlinear refractive index and the effective area). The pump source should ideally be matched to the fibre dispersion with high peak pulses and the appropriate pulse length for the desired spectral features.

The effective nonlinearity of the fibre is given by

$$\gamma = \frac{2\pi n_2}{\lambda A_{eff}}$$

where $n_2$ is the nonlinear refractive index, $A_{eff}$ is the effective area and $\lambda$ is the wavelength [12]. This relationship implies that a small effective area can significantly increase the nonlinearity of the fibre. Currently commercially available silica HF can have effective areas down to ~1 $\mu m^2$, resulting in a nonlinearity of up to ~215 $(Wkm)^{-1}$ - ~200 times greater than standard single mode step index fibre.

Another method of increasing the nonlinearity is by changing the host material – i.e. changing the $n_2$ values. Changing the material can have added advantages as the transmission window can be expanded past that of silica (~2 μm) into the short wave IR (SWIR) and mid-IR wavelengths - of great interest for IRCM and eye-safe, covert, active hyperspectral imaging sources.

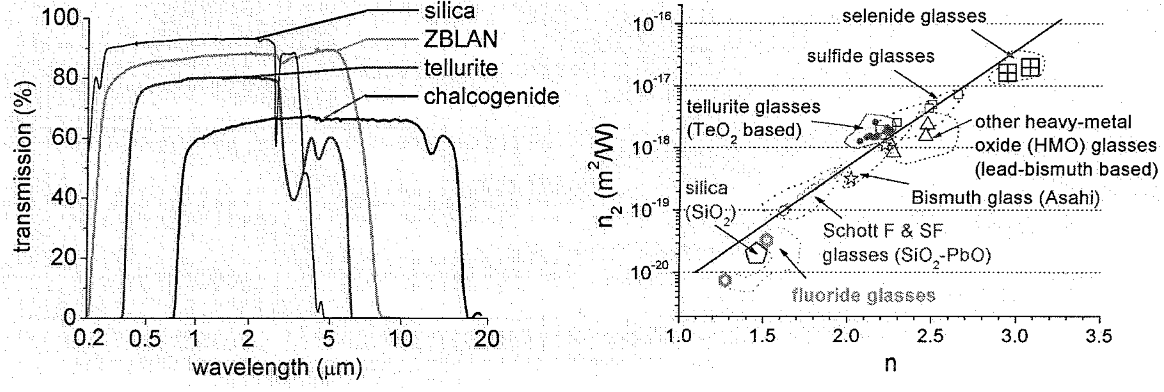


Figure 8: Transmission Curves from Various Glasses, $n_2$ values for novel glasses [13]

Figure 8 shows both the transmission curves and the nonlinear refractive index for various materials, which demonstrate that several of the soft glasses do have the potential to cover the mid-IR wavebands if correctly pumped.

Fibre dispersion ($D_T$) is an addition of material ($D_M$) and waveguide dispersion ($D_{WG}$) and is also of great importance for continuum production as it directly affects which nonlinear interactions will be involved and how efficiently they will interact and broaden. Material dispersion is inherent and cannot be changed; however, HF technology allows the waveguide dispersion profile to be tailored by changing the design of the cladding structure. The total dispersion profile can then be flattened [14], the zero dispersion point (ZDP) can be changed to match pump sources [15] or two ZDPs can be introduced to the profile [16]. The fibres can also be designed to be highly birefringent [17] which can significantly enhance nonlinear processes.

By pumping fibres in different regions of their dispersion profile, different nonlinear effects can be initiated allowing a plethora of continua to be realised. For a large degree of spectral broadening, ideally the pump source should be close to the ZDP of the fibre [18] and the dispersion profile should be flat.

### 3.1 Visible / IR Continuum Generation

Since the arrival of HF technology, there has been much interest in the generation of continuum in the fibres [18,19]. Much work has been carried out into understanding the processes involved in many different pumping regimes (femtosecond, picosecond and nanosecond). Femtosecond pulse pumping using a Ti:Sapphire laser has been widely used, as the system produces high peak powers in the near-IR region, easily capable of generating visible wavelengths through nonlinear interactions in HF (Figure 9). These types of fibres would be ideal for producing illumination sources for head up displays and helmet mounted displays. At the ATC we have used a Ti:Sapphire-HF system as described above to demonstrate the principles of active hyperspectral illumination, where man-made foliage was distinguished from its organic counterpart using hyperspectral analysis [20].

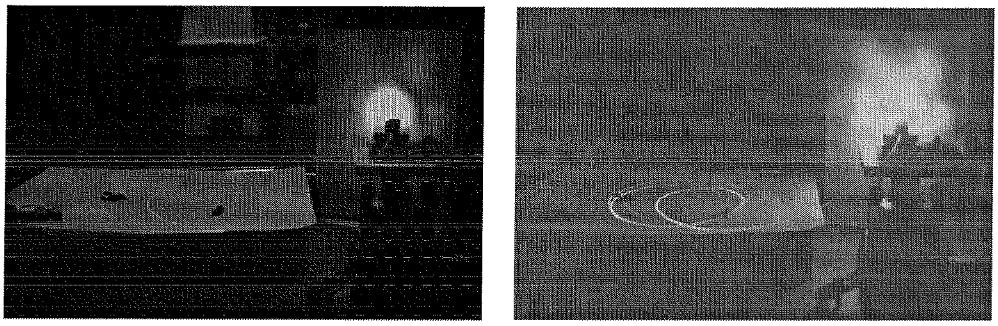


Figure 9: Visible continuum (predominantly red (l) and yellow (r)) using a Ti:Sapphire femtosecond source

However, for some applications the delivered broadband power from such a system is insufficient. This, combined with the fibres having very small cores and thus being susceptible to damage, limits the amount of output power available to use. Nd:YAG / Nd:YVO$_4$ lasers are also often used and with higher available average powers may be better suited to defence type applications. The commercially available fibres have a slightly larger core than those designed for 800 nm pumping and so more power can be coupled directly into them.

The next logical step in producing high power continuum would be to move away from the fibres designed for nonlinear processes and towards those designed for high power transmission, ideally reaching a point where nonlinearity and mode area are both at an optimum. The difficulty in using these LMA HF is that their ZDP is very close to the bulk material (~1.3 μm for silica) [21] and their nonlinearity ($\gamma$) is low (in the order of 2 $(\mathrm{Wkm})^{-1}$) meaning that the fibres have to be very long and pumped fairly hard in order to obtain sufficient, sustained intensity in the core region. Despite these difficulties, continuum in LMA holey fibres has been demonstrated by other research groups [22].

We have studied some LMA fibres for high power continuum generation and obtained ~1 W of average output power. The source used was the same as for the OPO pumping with a reduction of Q-switched repetition rate to 4 kHz leading to a maximum available average power of ~3.3 W and a peak power of 89 kW. This was coupled into different lengths of LMA-18 fibre (fabricated at the University of Southampton) to produce the spectra shown in Figure 10. In the short (0.89 m) length of fibre, we observe large spectral features from four wave mixing which then propagate through longer lengths of the fibre, broadening and flattening the spectra until after 36.5 m a 10 dB spectral bandwidth of ~700 nm is formed.

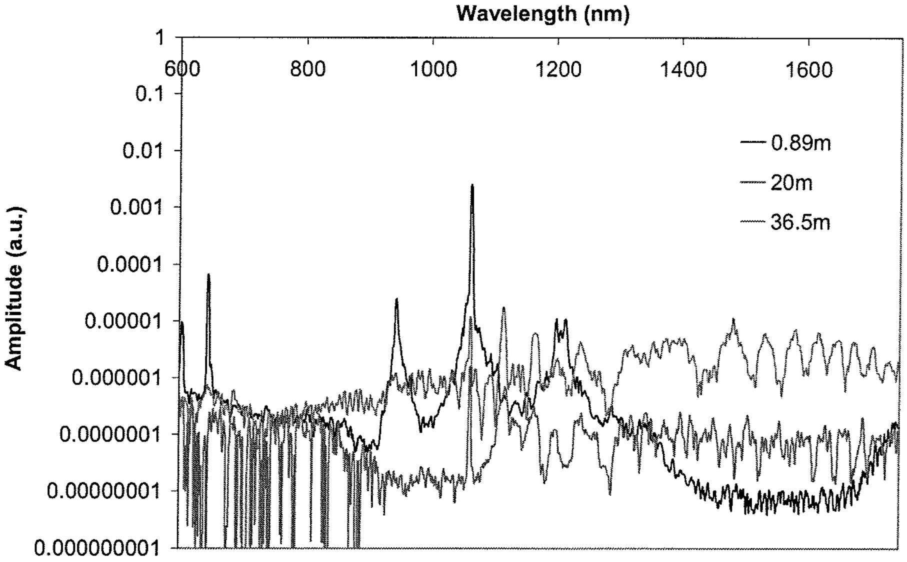


Figure 10: Spectra from LMA-18 fibre with increasing fibre length

It is important to note here that higher average powers have been demonstrated in other papers [23,24]. However, using LMA fibres should theoretically allow a much larger amount of delivered power.

### 3.2 Towards Mid-IR Continuum Generation

The previous section looked at continuum generation with the assumption that the HFs were silica based. However as mentioned briefly, by changing the fibre material to e.g. lead silicates or chalcogenide, the transmission window can be extended into the mid-IR (Figure 8). Also, as the fibres are inherently more nonlinear, the device (fibre) lengths can be scaled down to millimetres rather than 10's metres.

Silica HF are generally fabricated using a 'stack and draw' method – many capillary tubes are stacked in a macroscopic preform of the fibre which is then drawn to the correct outer dimensions [25]. Soft glasses have a lower melting temperature [26] and so other methods of preform fabrication can be used. A common method is extrusion [27], where a glass disc is squeezed through a mould to form the preform, which is then drawn to the correct fibre dimensions. This technique can allow greater flexibility in the design of the fibre cladding structure.

Using a single mode tellurite wagon wheel fibre [29], where only three large holes surround the very small core, continuum has been produced spanning ~0.9 – 2.5 μm (Figure 11). The fibre was pumped using the output from an OPO source at a wavelength of 1.5 μm (corresponding with some military sources) and output power from the fibre was ~30 mW [28]. It exhibited a slight birefringence as the two optical axes were observed by polarisation rotation: the fast axis aligning with one of the struts and the slow axis at 90° to this. By aligning the input radiation with the fast axis, slightly more efficient broadening was observed. The spectrum is fairly flat over the SWIR wavelengths due to soliton self frequency shifting, demonstrating suitability as an active imaging source.

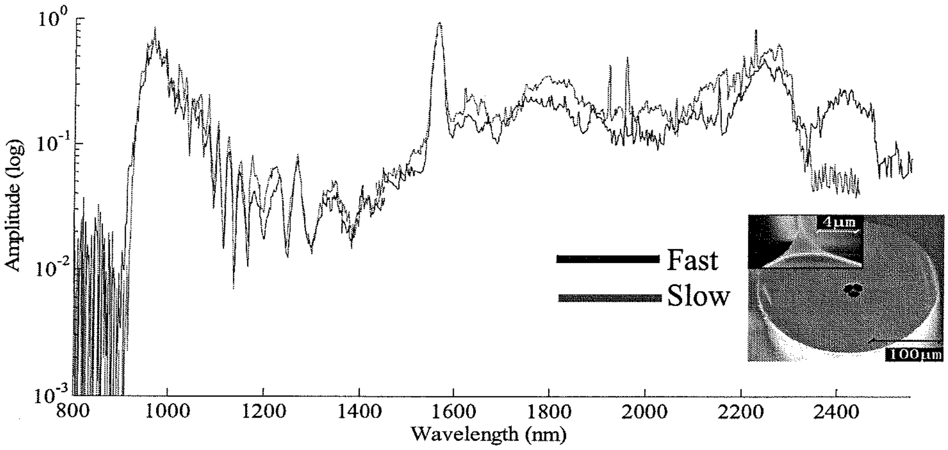


Figure 11: Continuum Produced in a Single Mode Tellurite MF (inset: end face of fibre with close up of core)

There have been a number of papers on the production of soft glass fibres in many different materials, [27,29,30] where each glass type had its advantages for fabrication and continuum production. Indeed, all-fibre based continuum sources have also been demonstrated [31,32,33].

## 4. OTHER TYPES OF MICROSTRUCTURED FIBRES

We have briefly discussed two very different types of microstructured fibre that could directly play a role in aerospace and defence applications. However, the versatility of the cladding structure lends the fibre to other areas in which it could positively impact the wider community. In this section other variations of microstructured fibre are discussed.

In section 2, silica PBG fibres were used to deliver high peak power 1 μm radiation to remotely sited work pieces. A very interesting development for these fibres is the transmission of longer wavelengths – i.e. wavelengths well beyond the transmission window of silica. As the radiation is guided in air, the host material plays a lower role in the transmission window than would be expected for solid core fibres. The advantage of using silica as the base material for these fibres is that the material is mature and well understood, in addition to silica being fairly inert in terms of chemical stability and thermal properties.

It was recently demonstrated [34] that silica PBGF could transmit radiation out to 3 μm, and indeed it is expected that the technology could extend out to ~3.5 μm. PBGF often have a fairly narrow bandwidth of transmission (~100 nm) due to surface modes causing the fundamental mode to couple out of the fibre at specific wavelengths. However, much modelling and fabrication work has been carried out to develop wideband fibres (~315 nm bandwidth) which were demonstrated in [35]. The combination of IR and wideband transmission with the ability to transmit very high peak powers lends these fibres to defence type applications throughout the SWIR region and further.

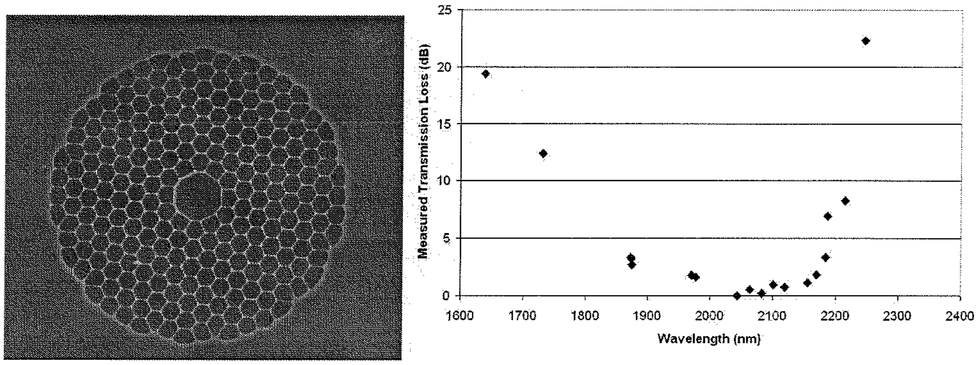


Figure 12: PBGF end face, transmission curve of SWIR Wideband PBGF

Jacketed air-clad (JAC) fibres are also a new form of microstructured fibre. These fibres typically have very large cores (20 - 30 μm diameter) with very high numerical apertures (N.A.) and operate multimode. They are ideal for very high power transmission where beam quality is not an issue and the only requirement is raw power. Of great interest is that these fibres can have shaped cores [36] which could for example be used for efficient coupling of square diode outputs into fibres.

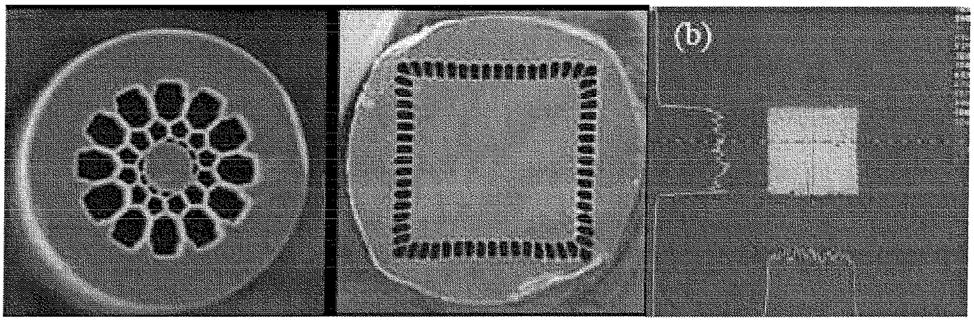


Figure 13: a) Circular JAC Fibre, b) Square core JAC Fibre with near field mode profile at 1.06 μm

# 5. FURTHER DEVELOPMENTAL WORK

In order for these fibres to fulfil their huge potential, a rigorous program of termination and cabling will need to be implemented to comply with aerospace and other harsh environments. Some preliminary investigation has been carried out as to the strength of HF compared with standard single mode fibres of the same outer dimensions and optical properties. By using a two-point bend test [37], it was found that the HF had a similar mechanical strength to the step index fibre (Figure 14). The uneven data point distribution for the holey fibre is thought to be due to the hexagonal shape of the cladding structure – in some areas there is more solid glass casing than in others.

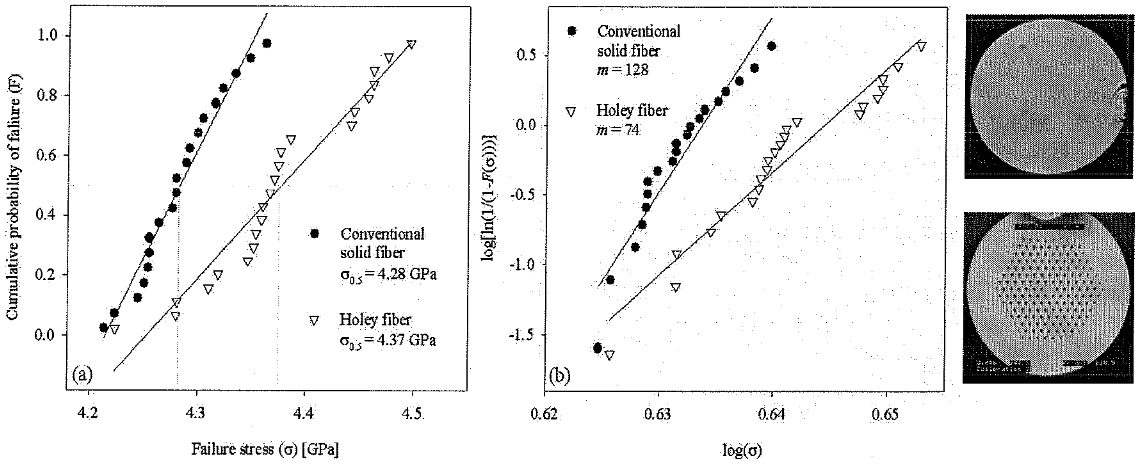


Figure 14: Strength of Microstructured Fibre compared with Single Mode Step Index Fibre

The termination of both types of microstructured fibre will be a critical issue when integrating them into applications as holes can easily become clogged with dust, dirt and condensation. This affects the mode profile of the fibre, reduces coupling efficiency, and can act as damage sites when used for high power applications. Currently, much work is being focused into developing end-capping techniques for the HF; promising methods are fusing the holes and polishing the solid cap back [38], splicing step index fibres onto the ends [39] or filling the very end of the holes with an epoxy which is then polished back [40].

As well as termination issues, parallel research must be conducted into the buffering and cabling of microstructured fibres. This has already occurred with some types of fibres; however if they are to be installed into airframes, a rigorous programme of environmental testing will need to be implemented.

## 6. CONCLUSIONS

In this paper we have demonstrated several different applications into which microstructured fibre technology can make a direct, positive impact. We have shown that both types of MF can withstand power and energy levels required to carry out laser processing and for pumping of frequency conversion sources. Along with the capability of transmitting high power levels, added advantages over step index fibre technology are that the MF can deliver this radiation very close to diffraction limited, and well beyond the material transmission range (PBGF). Broadband source production has also been demonstrated both in the visible and in the IR waveband regions. By using silica and novel glass fibres, continuum could be envisaged as being produced well into the mid-IR regions (if correctly pumped), so covering many wavebands of interest for defence applications.

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