Holey fiber amplifiers and lasers

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Abstract We review our recent activities in the development of small-core, active holey fibers and describe a number of experiments that highlight the advantages of this technology within a range of both linear and nonlinear devices.

Introduction

The area of holey optical fibers (HFs) has developed into a topic of acute research interest in recent years. This is primarily due to the many unique optical properties that can be achieved in these waveguides relative to conventional fiber types. The remarkable properties of HFs are made possible by the wavelength-scale structure and the large refractive index contrast between silica and air and include: endlessly single-mode operation [1], anomalous dispersion down to visible wavelengths [2], and high optical nonlinearities per-unit-length [3,4]. These novel properties have so far mostly been demonstrated and used in passive forms of HF, however it is becoming increasingly clear that many new and interesting laser and amplifier devices can be realised by incorporating rare-earth ions into this radically different class of fiber structure [5-9]. For example, the possibility of achieving large single transverse mode core areas, and high-index contrasts for pump confinement in dual-clad fibers has recently led to interesting developments in the area of high-power (>100W) holey fiber lasers and amplifiers [10]. At the other extreme, small-scale structures with core-dimensions of order of the wavelength of light offer great potential for reduced pump-power requirements for continuous-wave lasers and amplifiers, and new possibilities for novel pulse sources employing nonlinear effects. The possibility of practical application of such fibers has been greatly enhanced by the recent development of reliable splicing techniques that allow low-loss, low back-reflection interconnection to standard fibers and components enabling active-HF based devices in an all fiber format. In this paper, we review some of our recent activities on lasers and amplifiers based on small-core ytterbium and erbium doped HFs.

An ytterbium doped holey fiber pulse generator

To demonstrate the possibility of using the unique nonlinear and dispersive properties of small-core HFs to develop soliton based pulse sources at new wavelengths we fabricated an ytterbium doped holey fiber (YDHF) with anomalous dispersion at 1µm. The YDHF had a pitch Λ~2µm and contained a high fraction of air ($d/\Lambda>0.9$; where d is the air hole diameter). Yb ions were incorporated into the fiber by drilling the core from a conventional Yb doped preform and then using the resulting doped rod, which was first etched and polished, to define the solid core within a stacked capillary HF preform. The preform was then pulled down to fiber in a two stage drawing process. An SEM of the resulting fiber is shown inset in Fig.1. Although it was difficult to experimentally characterise the dispersion of our YDHF at wavelengths within the fibers gain bandwidth our numerical simulations predicted a zero-dispersion wavelength around 800nm and a large anomalous dispersion at 1.06µm, (as shown in Fig.1). The fiber has extremely high birefringence due to the elliptical shape of the core and we measured a beat length of 0.3µm at 1.55µm. As a consequence the dispersion profile is different for each polarisation axis. The effective mode area of the fiber is around 2.5µm^2 at 1.06µm thereby allowing the onset of soliton effects at very low pulse energies and amplifier pump powers.

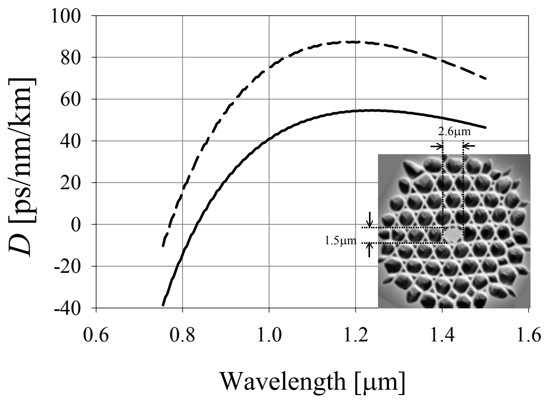
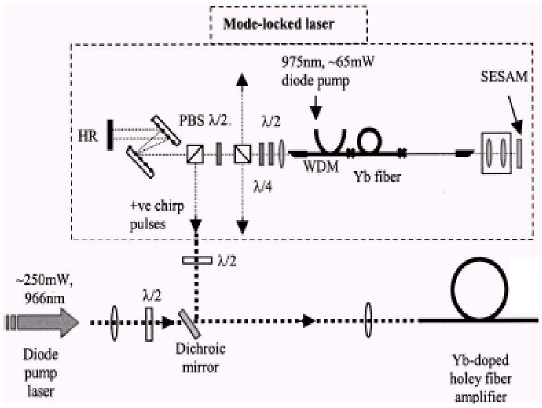


Fig.1 The predicted dispersion for the two birefringence axes of the YDHF (SEM shown inset).

We incorporated the fiber into a pulse amplifier with a forward-pumped geometry. A diode-pumped fs fiber laser was used as a seed (Fig.2a). The launched seed pulse energy was only ~10pJ and the minimum pulse duration ~100fs. The centre wavelength of the input pulses was 1060nm. As we increased the amplifier pump power, individual Raman solitons formed due to the interplay of the fiber nonlinearity, dispersion and gain. By varying the amplifier gain we were able to continuously tune the Raman soliton wavelength from 1.06μm up to 1.33μm, as shown in Fig.2b. Measurements of the pulse spectrum and autocorrelation traces showed that the generated solitons maintained a good pulse quality throughout the tuning range. Multi-coloured soliton generation and supercontinuum were observed at higher pump powers.



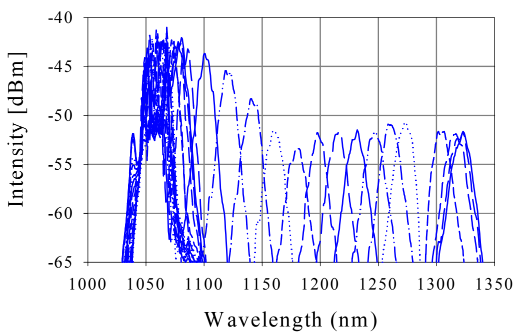


Fig.2 (a) Schematic of system. (b) The spectra of continuously-tunable Raman solitons at the YDHF output for pump-powers in the range 0-200mW.

High gain-efficiency erbium doped HF amplifiers

We later fabricated an erbium doped holey fiber (EDHF) using the same general approach as for the ytterbium variant, but including a dehydration process to reduce the water content within the final fiber [9]. The structural parameters were Λ=2μm and d/Λ=0.5 which ensured single-mode excitation at the relevant wavelengths (i.e. around 980nm and 1550nm). Note that the doped region within the core was very small, (of the order of 1μm in diameter), and centred at the peak of the pump and signal mode profiles. The peak absorption at the pump (976nm) and signal wavelengths (1536nm) was 10dB/m and 15dB/m respectively. The tight physical-confinement of the dopant, and tight optical-confinement of the pump and signal modes, ensures high-pump and signal intensities across the gain region. This in turn provides great scope for high gain-efficiency amplifiers, low-threshold lasers and extended operating wavelength ranges.

To demonstrate the possibility of low laser thresholds we constructed a Fabry-Perot cavity using 3.4m of the fiber [11]. Output coupling was through a cleaved fiber facet (~4% reflectivity) with a high reflector closing the cavity. We observed a pump power threshold of just ~0.5mW, which is around an order of magnitude lower than the values observed for typical commercial EDFs. The slope efficiency was estimated to be 57.3%, close to the theoretical maximum quantum efficiency of 63.8%, confirming the excellent background loss and the beneficial mode overlap properties of the fiber.

We next established splicing techniques to allow us to splice the small-core EDHF to conventional fiber amplifier components (i.e. isolators and pump-couplers). To minimize mode-mismatch we used an intermediary high-NA buffer fiber and had to control the collapse of the EDHF holes and diffusion of Ge in the vicinity of the splice. Total splice losses of <1dB and back reflections below <-47dB were achieved. Splicing allowed us to construct connectorised EDHF gain blocks which greatly facilitated our work. Initially we constructed a reverse-pumped, high-gain EDHF amplifier (EDHFA) as shown in Fig.3.

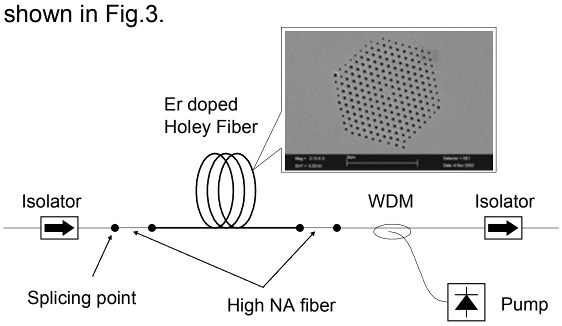


Fig.3: Schematic of the EDHFA gain-block (reverse pump configuration). Inset shows the SEM picture of the EDHF core.

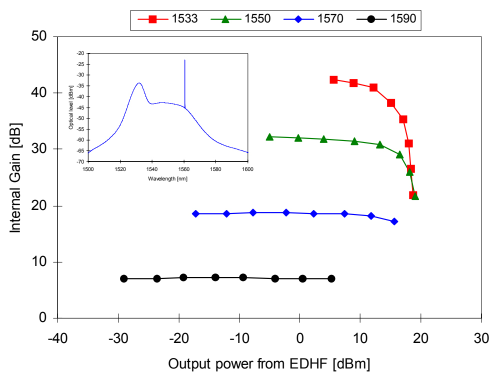


Fig.4 Gain saturation characteristics of the EDHFA at various wavelengths. Inset shows the ASE spectrum with small signal gain conditions at 1560 nm.

Fig.4 shows the gain saturation characteristics of an EDHFA based on 4.5m of EDHF at various operating wavelengths. A maximum small signal internal gain of 44dB at 1533nm was achieved. No evidence of unwanted end facet lasing due to potential stray reflections from the EDHF to conventional fiber splices was observed as evidenced by Fig.4 (inset) which shows the ASE spectrum under small signal gain conditions at 1560 nm.

The internal gain efficiency of this amplifier was measured to be ~8dB/mW. More recently, using a forward pumped geometry, we have achieved a gain efficiency of >8.6dB/mW from a ~3m length of this EDHF (see Figs.8&10), which is comparable to the best gain-efficiency ever reported for a fiber produced from an MCVD preform. Note that aluminosilicate is the preferred glass host option for broadband Er amplifiers. However, it is difficult to achieve such a high gain-efficiency in conventional fibers due to the limited NAs that are possible with aluminium doping. Our results highlight the benefits to be obtained by using HF technology to define the guidance properties of active fibers in a way that is independent of the core glass composition.

Next, to demonstrate the potential for low laser thresholds combined with broad-gain bandwidth operation we constructed a tunable EDHF ring laser (EDHFRL) based on the gain-block shown in Fig. 3. The EDHFA input was connected to a 95% port of a 13dB coupler, and the output was connected through a fiber Bragg grating (FBG) based tunable narrowband filter to a common port of the coupler thereby closing the cavity (see Fig.5). The output coupling for the EDHFRL was thus 5%. Two tunable filters with a 3 dB bandwidth of 0.6nm were required to investigate the laser tuning range. Filter 1, had a tuning range from 1525nm to 1620nm and a minimum loss of 3dB. Filter 2, had a tuning range from 1470nm to 1575nm and a lower minimum loss of 1.5dB. The loss of both filters rose steadily to >5dB at the extremes of their tuning ranges.

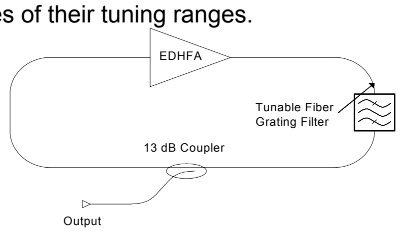


Fig.5 Schematic diagram of the EDHFRL.

The output power versus pump power was first measured at a wavelength of 1550nm (using Filter 2 within the cavity). The result is shown in Fig.6. We obtained a laser threshold of 0.48mW of pump (measured at the EDHF input). The optical spectrum under maximum pump power conditions is shown in the inset (a) of Fig.6 where it is seen that an extremely clean, narrowband spectrum, is achieved. Fig.7 shows the results of our experiments on wavelength tunability of our EDHFRL. We obtained a tuning range of more than 104nm which is comparable to the best ever achieved with conventional EDFs and which was limited by the increased losses of the filters at the edges of their tuning ranges.

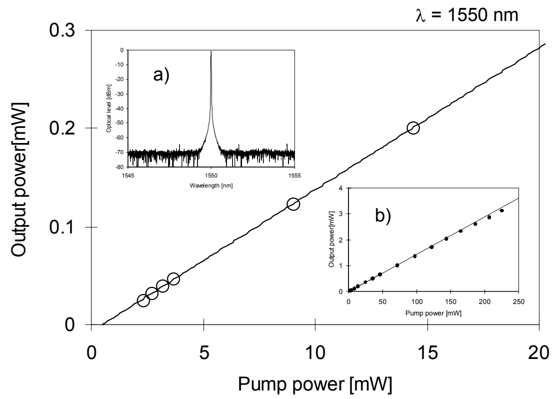


Fig.6 Output characteristics of the EDHFRL at 1550 nm near the threshold. Inset a) shows the optical spectrum (pump power ~200mW) and b) the output characteristics over the full range of pump power.

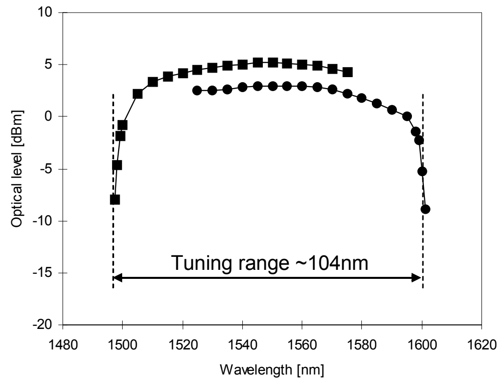


Fig.7 Output power as a function of emission wavelength of the EDHFRL at a maximum pump power. (squares: using Filter1, circles: using Filter 2).

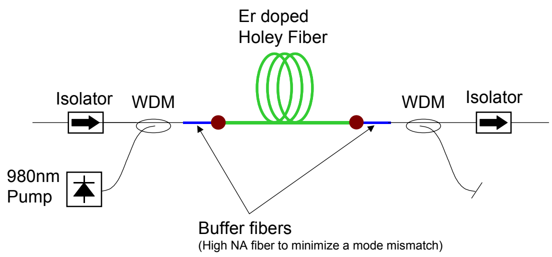


Fig.8 Schematic diagram of the low noise EDHFA.

By moving to a forward pumping geometry (see Fig.8) and by optimising the splicing process to minimise interconnection losses we were able to perform a range experiments geared towards optimising the EDHF gain block for preamplifier applications [10]. The excess losses due to the input/output components (WDMs + isolators) were 0.8dB and 1.0dB respectively, such that the total input/output signal losses were each less than 2dB. The EDHF was pumped using a single co-propagating pump source operating at 976nm. We then varied the length of the EDHF in order to optimize the noise performance of the gain block.

Fig.9 shows the internal gain and noise figures as a function of output powers using a pump power of 72mW. Small signal gains of more than 35dB and 25dB were obtained at 1533nm and 1557nm, respectively and saturated output powers of ~15dBm were achieved at both wavelengths. Using 2.5m of our EDHF internal noise figures close to quantum limit were measured at 1557nm in the small signal gain regime. The noise figures at 1533nm were slightly higher. Note that the dip in the noise figure curve for the 4.5m length of EDHF at powers just prior to the onset of significant gain saturation is due to the relatively reduced backward ASE level resulting from the use of the forward pumping scheme. Such behavior is characteristic of conventional high gain fiber amplifiers. The good noise performance that we achieved shows that EDHF technology is thus also suitable for pre-amplifier applications. Fig. 10 highlights the high gain efficiency of the fiber as previously discussed.

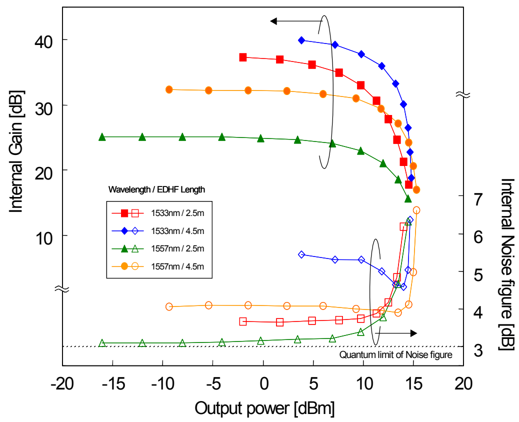


Fig.9 Gain saturation and noise figure as a function of output power for various fiber lengths.

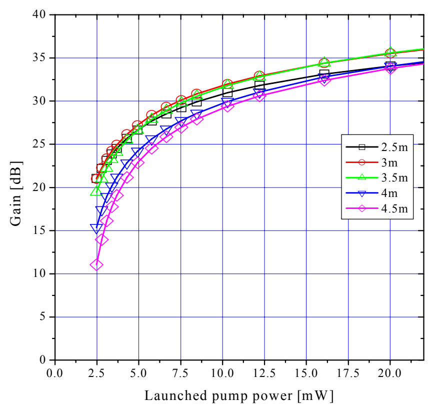


Fig.10 The gain efficiency curves for different fiber lengths. Maximum gain-efficiency = 8.6dB/mW.

We have also recently constructed a booster amplifier based on this EDHF [12]. This module incorporates forward pumping using a LD operating at 976nm (providing a launched power of 80mW), and reverse pumping using LDs operating at 1430nm, 1460nm, and 1490nm (providing a total pump power of 250mW). Fig.11 shows the internal gain saturation and noise figure of the device as a function of output power at various wavelengths when operating in the fully pumped condition. Saturated output powers of ~20dBm, and associated noise figures of less than 5.5dB were obtained for input powers of the order –2 dBm. This combination of high saturated output power levels and with a reasonable noise figure shows that EDHF technology can also be considered suitable for booster amplifier applications.

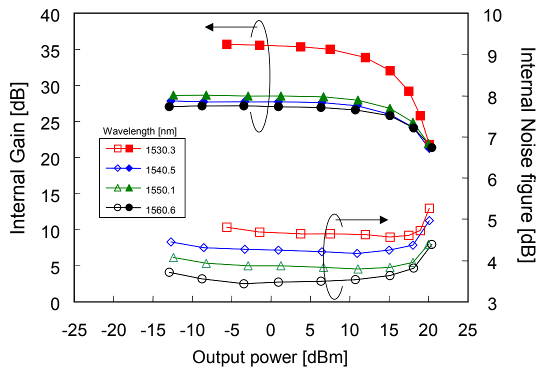


Fig.11 Internal gain saturation and noise figure as a function of output power for various wavelengths.

Conclusions

In conclusion, we have reviewed some of our recent activities in the area of small-core active holey fibers and their applications. We have shown that the unique optical properties of HFs can be exploited within active fibers both to achieve new functionality, and to obtain superior performance compared to conventional active fibers. We believe that HF technology will enable a broad range of novel active fiber applications and that it has great potential for use with many other glass-host/active-dopant systems.

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