High gain efficiency amplifier based on an erbium doped aluminosilicate holey fiber

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Abstract: We demonstrate an optical amplifier based on an erbium doped holey fiber (EDHF) with a small core. Owing to the high NA, which is readily achievable using holey fiber technology, and the tight physical confinement of the erbium ions, we show that it is possible to achieve an internal gain efficiency of >8.5dB/mW using an aluminosilicate based glass within the core. The dependence of the gain and noise figure performance with respect to fiber length and wavelength are experimentally characterized.

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OCIS codes: (060.2270) Fiber characterization; (060.2280) Fiber design and fabrication; (060.2410) Fibers, erbium.

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1. Introduction

Since the invention of the erbium doped fiber amplifier (EDFA) [1], there has been a tremendous amount of research into EDFAs for a variety of applications. By optimizing fiber designs, glass compositions and amplifier geometries, high-gain, low-noise, and high-power amplifiers have all now been realized [2]. In the early days of amplifier research considerable effort was expended on the development of high gain efficiency amplifiers however, with the development of more powerful pump lasers and the need for higher-power DWDM compatible amplifiers, this line of amplifier research has become somewhat forgotten. For certain applications though, such as remote-pumping in long-reach unrepeatered transmission links where low pump power levels are available [3], or for applications in the field of optical fiber sensors/monitoring where the amplification of extremely weak signals is important [4],

#4607 - $15.00 US
Received 14 June 2004; revised 14 July 2004; accepted 15 July 2004

EDFAs with high gain efficiency are still required. It is important to remember though when developing such amplifiers that high gain efficiency in itself is not the only critical performance characteristic. For example, low noise and a broad gain bandwidth are often additional essential features and also need to be considered at the fiber design stage.

In order to obtain high gain efficiency it is important to design fibers in which the pump intensity for the available pump power is as high as is possible in order to obtain the maximum inversion of erbium ions. This dictates the use of high NA waveguides in order to minimize the mode field diameter for pump and signal. At the same time, and for the same basic reason, it is also beneficial to physically confine the erbium ions to the central part of the core and to ensure that the pump propagates in the fundamental HE_{11} mode, so that the ions sit at the point of maximum pump field intensity. It is also very important to ensure that the background pump propagation loss is kept very low over the device length to avoid any degradation in gain efficiency performance [6]. Using this approach a record gain efficiency of ~11dB/mW has been reported using a germanium-doped, high-NA EDF with a fluorine-doped cladding, produced by the VAD method [5]. For MCVD based fibers, a gain efficiency of 8.9dB/mW has been reported for a germanium-doped, high-NA fiber [6]. Whilst these are hugely impressive results the need for a high-NA necessitates the use of high levels of germanium doping in order to obtain the high refractive index contrast required. As a consequence this places restrictions on other aspects of the fibers performance. In particular it reduces the emission bandwidth of the Er^{3+} ions [7] and limits the concentrations of Er^{3+} ions that can be reliably achieved relative to other more established glass hosts such as aluminosilicate [8]. This results in narrower gain bandwidths and increased device lengths. The increased device lengths in turn place far tighter requirements on the tolerable background pump loss needed for high gain efficiency. Unfortunately, it is impossible to achieve high-NA waveguides using an aluminosilicate glass host and thus until this work there have been no reports of similarly high gain-efficiency aluminosilicate fiber amplifiers. Ideally, one would like a means to decouple the spectroscopic properties of the core glass material from the passive waveguide properties of the core.

Holey fibers (HFs) contain an array of fine air holes that run along their length and which define the fibers guidance characteristics. HFs can possess a range of unique optical properties and provide a host of opportunities for the development of new types of active fiber and fiber devices. These unique properties include: endlessly single mode operation, anomalous dispersion down to visible wavelengths, and high or low optical nonlinearities – all of which can be achieved by appropriate design of the holey cladding and rely upon the large index contrast between air and silica. To date most work has focused on demonstrating or using these properties in passive holey fibers however many of these new features are extremely attractive for a variety of rare-earth doped fibers and devices. Of particular significance is the fact that holey fiber technology can be used to provide greater control of the overlap between pump-mode, signal-mode and rare-earth dopant than can be achieved using conventional fiber technology – moreover control of the modal properties can be achieved in a way that is largely independent of the rare-earth host glass composition since the modal properties are , for many HF designs, determined primarily by the distribution of air holes within the structure rather than the material properties of the core glass itself.

HF technology offers several advantages for making EDFs with high gain efficiency relative to conventional fiber fabrication techniques. Firstly, due to the large refractive index difference between silica and air it is possible to achieve very high NAs and hence very small mode areas. Furthermore, it is possible to ensure fundamental mode propagation for both signal and pump beams - even when the wavelength difference is large. Finally, by virtue of the stacking procedure used to fabricate such fibers, the rare-earth dopant can be accurately confined to the central region of the fiber so that it lies at the position of peak intensity for the pump and signal modes. When designing an EDHF for high gain efficiency operation it is important to recognize the various trade-offs that exist, for example between: the effective-NA, spot-size, tendency for multi-mode guidance at the pump-wavelength, pump absorption rate and the background fiber loss. The interconnection loss to other fiberized components

#4607 - $15.00 US Received 14 June 2004; revised 14 July 2004; accepted 15 July 2004
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required within the amplifier is an additional issue that needs consideration for the final device design. The fiber design space is thus seen to be highly complex. However, from our preliminary studies and past experience, we concluded that it should be possible to reduce the mode area below 10μm^2 at 1550nm for an efficient aluminosilicate based EDHF whilst obtaining single mode operation at both signal and pump wavelengths and sufficiently low background and interconnection losses to make a useful high gain efficiency device.

In this paper, we report the fabrication of such a fiber and describe our experimental amplifier characterization results with a particular emphasis on gain efficiency. We have measured internal gain efficiencies as high as 8.5dB/mW, which to our knowledge represents the highest gain efficiency ever obtained from an erbium amplifier without germanium doping. In addition, we demonstrate that our EDHF is fully compatible with conventional fiber-optic components, despite its small core, by integrating it within a fully fiberized gain block.

2. Fabrication and characterization

We fabricated an EDHF with 8 rings of air holes using a conventional capillary stack and draw process other than that we used an Er-doped aluminosilicate rod to define the core within the preform. The core rod was formed by drilling out the core of an (~1000ppm by weight) erbium-doped aluminosilicate based MCVD preform with an NA of 0.14. Conventional Er-doped fibers drawn from this preform were found to show good optical power conversion efficiency (>40%) in simple fiber laser experiments despite the relatively high dopant concentration. Additional polishing and dehydration steps were taken in the perform preparation process to eliminate water from the final fiber and to minimize scattering losses due to surface roughness. The resulting structure is shown in Fig. 1(a). The air hole diameter d and the pitch Λ were 1μm and 2μm, respectively. The absorption spectrum of the fabricated fiber is shown in Fig. 1(b), where a comparison with an ordinary EDF, which was pulled from the same preform, is made. Despite the small doped area within the EDHF a peak absorption of more than 10dB/m can be obtained at the pump wavelength. It is also clearly seen that the absorption at 979nm is relatively strong in the EDHF. We attribute this observation to the better modal overlap that results from the relatively strong modal confinement at short wavelengths that occurs due to the unusual wavelength dependence of the effective cladding index in holey fiber. Note that this is desirable from a device perspective since the tight modal confinement allows us to achieve higher pump intensities for a given pump power.

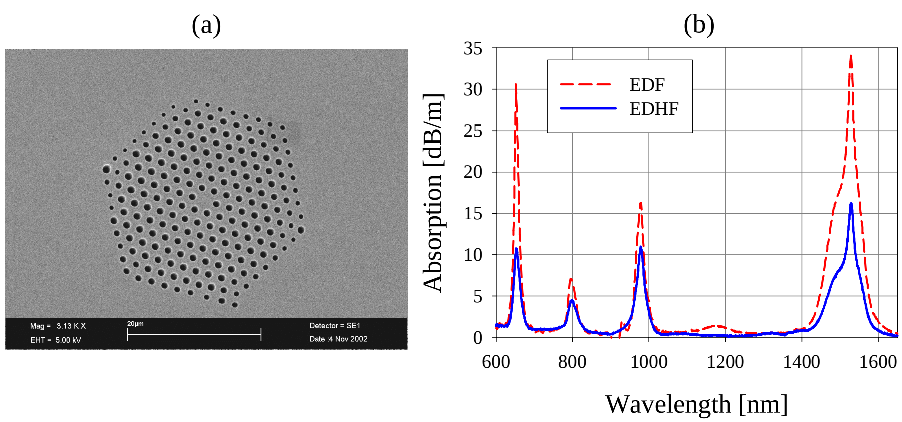

Fig. 1. (a) SEM photograph of the EDHF, (b) absorption spectra of the EDHF and the EDF.

#4607 - $15.00 US
Received 14 June 2004; revised 14 July 2004; accepted 15 July 2004
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3.Amplifier characterization

An amplifier experiment was performed by integrating our EDHF into a fiberized gain block based on conventional fiber-optic components using fusion splicing. The amplifier setup consisted of two isolators and WDMs at both input and output as shown in Fig. 2. The total loss of the input components was 0.8dB and that of the output components was 1dB. We used a single mode laser diode operating at 976nm as a pump source. A high NA intermediate fiber was used between the EDHF and SMFs in order to provide better mode matching between these fibers. Under appropriate splicing conditions, the air holes within the EDHF are collapsed slightly so as to taper the effective mode area in the vicinity of the splice to match that of the high NA fibers. It turned out that the heat applied for this purpose was more than sufficient to fuse two fibers together with reasonable strength. The diffusion of germanium from the high NA fiber into the EDHF, although not entirely desirable in the sense that it lowers the NA of the intermediary fiber at the splice point, appears responsible for reducing the return loss of the splice. In our experiments we managed to achieve a low return loss of -47dB from the spliced ends [9]. Using this approach total splice losses as low as 0.7dB at the signal wavelength going from SMF to the EDHF were achieved (including the splice losses between the SMF and the intermediate fiber). When the splice process was optimized for the signal, the splice loss was typically 0.3~0.5dB higher for the pump wavelength due to the significant wavelength dependence of the effective mode area. (If we optimized for the pump wavelength the typical losses were ~1.0dB and ~1.5dB at the pump and signal wavelengths respectively). The splice losses at the output were typically smaller than those at the input. This is because the mode area within the intermediary fiber is greater than that of the EDF such that radiated power due to the mode mismatch is largely captured by the intermediate fiber.

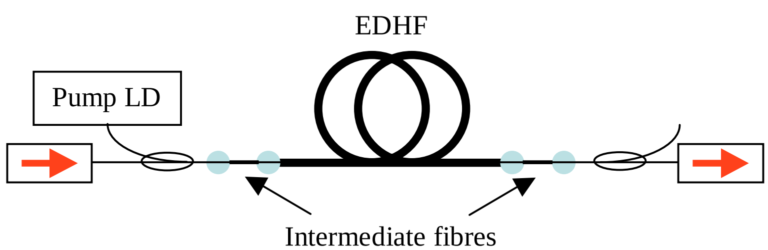

Fig. 2. Schematic of the experimental setup for the amplifier experiment.

The gain efficiency of the amplifier was first investigated using a forward pumping configuration with a -30dBm signal input at first 1533nm and then 1557nm. For a given length of the EDHF, we varied the pump power by changing the drive current of the pump LD. The measurement was taken for different lengths of the EDHF by cutting back the fiber and resplicing. The results are shown in Fig. 3. At 1533nm, the gain was seen to increase by moving to the shorter fiber lengths, however gain saturation is clearly more significant for the fiber length of 2.5m, where the highest external gain efficiency of 7.75dB/mW (internally 8.61dB/mW) was obtained**.** Since the minimum pump power was limited by the stability of the laser diode, it was difficult to reliably determine the derivative of the curves. Thus we make our estimate of the gain efficiency value by evaluating the gain per unit pump power at the minimum pump power of 2.48mW. Note that in general this leads to an underestimate of the gain efficiency value as conventionally defined. The gain saturation is more obvious at 1557nm for shorter fiber lengths however the gain efficiency values are less sensitive to the variation of the fiber length in this instance owing to the reduced signal absorption at this wavelength. We found that the highest gain efficiency of 6.93dB/mW (internally 7.86dB/mW) can be obtained using 3~3.5m at this wavelength.

#4607 - $15.00 US
Received 14 June 2004; revised 14 July 2004; accepted 15 July 2004
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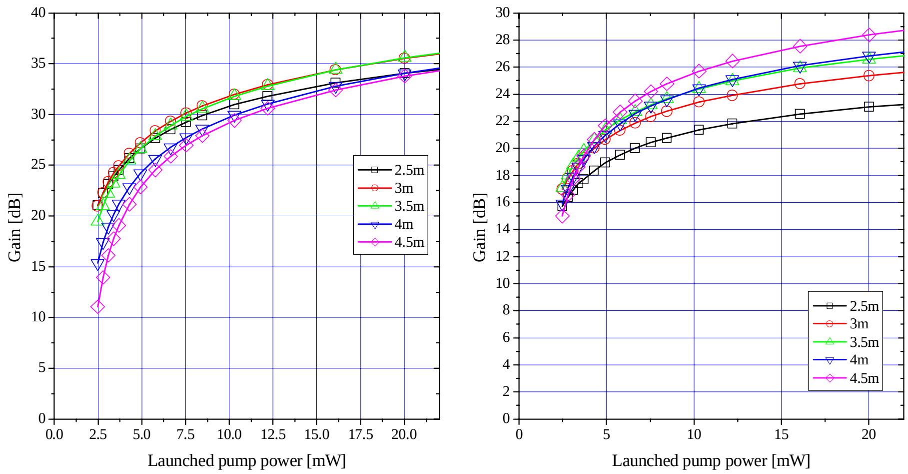

Fig. 3. Gain efficiency curves at 1533nm (left) and at 1557nm (right) for different fiber lengths

Our gain efficiency results are summarized in Table.1. A maximum external gain efficiency of 7.75dB/mW was obtained at 1533nm using a length of 2.5m. Although this is an underestimated value due to the stability of the laser diode this is, to the best of our knowledge, the highest value ever reported for a germanium free EDF. Gain efficiencies of more than 7dB/mW were obtained for fiber lengths between 2.5m and 3.5m at 1553nm. As previously stated and expected, the gain efficiency at 1557nm was relatively insensitive to fiber length and varied from 6.04dB to 6.93dB for fiber lengths between 2.5m and 4.5m.

Table. 1 Gain efficiencies for different fiber lengths and signal wavelengths.

	@1533nm		@1557nm	
Length [m]	net	internal	net	internal
2.5	7.75*	8.61	6.37*	7.5
3	7.52*	8.49	6.93*	7.86
3.5	7.09*	7.95	6.93*	7.86
4	5.51	6.33	6.55*	7.5
4.5	4.59	5.25	6.04	6.98

* : the values are calculated from the gain value at the minimum reliably achievable pump power.

It is important to evaluate the amplifier performance in terms of saturation and noise figure. Figure 4(a) shows the saturation characteristics of the amplifier at 1533nm and 1557nm when pumped with 8.46mW (9.35dBm). A saturated output power of ~5.8dBm is obtained and is almost independent of the fiber length. Thus the fiber is seen to be very efficient with >40% of the pump power converted into signal power.

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Received 14 June 2004; revised 14 July 2004; accepted 15 July 2004
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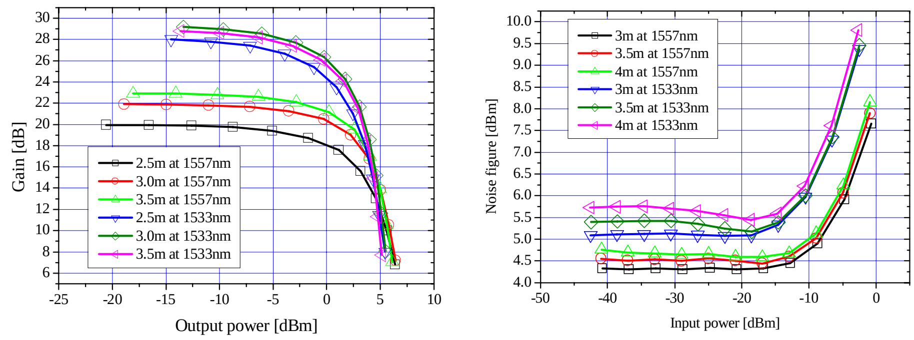

(a) (b)

Fig. 4. Gain saturation curve (a) and noise figure as a function of input power (b) for different fiber lengths.

The measured noise figures are plotted as a function of input power in Fig. 4(b). A pump power of 8.46mW is again used. Note that owing to the physical confinement of the erbium ions, the noise figure is almost independent of pump power. An external noise figure of less than 5dB was obtained at 1557nm for input powers below -20dBm. At 1533nm, the external noise figure varied from between 5dB and 6dB due to the increased ASE levels. Hence, the use of shorter lengths of EDHF not only improves the gain efficiency but also improves the noise figure, albeit with some compromise in the maximum achievable gain value. No significant increases in noise figure were observed for signal input powers below -40dBm. This implies interesting opportunities for the amplification of very weak optical signals. Note that the noise figure was found to be slightly dependent upon the polarization states of both the pump and signal beams. This was confirmed by bending the pigtail of the pump LD so as to vary the polarization state of the incident pump beam. Although we do not quantify these observations in detail here this observation indicates that our EDHF exhibits PDG (and thus a polarization dependent noise figure) due to its short beat length (which was measured to be of the order of 1mm). By incorporating polarization sensitive isolators into the system an efficient low noise PM amplifier could also be implemented.

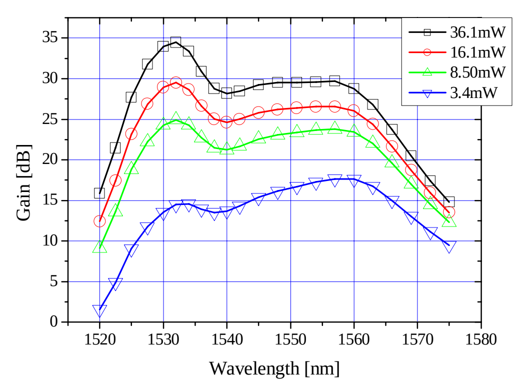

Fig. 5. Gain profiles for different pump powers for a 4.5m length of EDHFA.

Finally, the gain profiles for different pump powers are shown in Fig. 5. Since we used aluminosilicate based glass for the core it was possible to obtain a reasonably flat gain profile from 1540 to 1560nm without any active gain control. Despite the use of a relatively long

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fiber length of 4.5m, for which the gain efficiency is not optimized but a high gain is obtained, it can be clearly seen that the fiber is well inverted even for very modest pump powers.

4. Summary

In summary, we have investigated the performance of an amplifier based upon an erbium doped holey fiber with a small core. It was found that the strong wavelength dependence of the modal properties within HF favors efficient amplifier operation. As a result, we have been able to obtain high gain efficiency from an aluminosilicate based fiber preform. An internal gain efficiency of 8.61dB/mW was obtained at a wavelength of 1533nm using just 2.5m of our EDHF. Note that this gain efficiency value is in fact an underestimate due to our current measurement limitations. By integrating the EDHF within a gain block by fusion splicing we also demonstrated that the fiber is totally compatible with conventional fiber optic components. This makes it possible to obtain good external noise figures of less than 5dB over most wavelengths within the C-band by optimizing the fiber length. Note that much higher NA single mode fibers can be realized with HF technology using structures with higher d/Λ and smaller Λ, although it is to be appreciated that the background and interconnection losses are likely to be increased for such designs. We therefore believe that with optimization of the fiber design and fabrication it should be possible to obtain further increases in amplifier gain efficiency.

Acknowledgments

T. M. Monro is supported by the Royal Society through the Royal Society University Research Fellowship Scheme.

#4607 - $15.00 US Received 14 June 2004; revised 14 July 2004; accepted 15 July 2004
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