High gain holmium-doped fibre amplifiers

Nikita Simakov,[1,2,*], Zhihong Li,[2] Yongmin Jung,[2] Jae M. O. Daniel,[1,2] Pranabesh Barua,[2] Peter C. Shardlow,[2] Sijing Liang,[2] Jayanta K. Sahu,[2] Alexander Hemming,[1] W. Andrew Clarkson,[2] Shaif-Ul Alam,[2] and David J. Richardson[2]

[1] *Laser Technologies Group, Cyber and Electronic Warfare Division, Defence Science and Technology Group, Edinburgh, South Australia 5111, Australia*
[2] *Optoelectronics Research Centre, University of Southampton, Southampton, SO17 1BJ, UK*
[*]*ns2f11@soton.ac.uk*

Abstract: We investigate the operation of holmium-doped fibre amplifiers (HDFAs) in the 2.1 µm spectral region. For the first time we demonstrate a diode-pumped HDFA. This amplifier provides a peak gain of 25 dB at 2040 nm with a 15 dB gain window spanning the wavelength range 2030 – 2100 nm with an external noise figure (NF) of 4-6 dB. We also compare the operation of HDFAs when pumped at 1950 nm and 2008 nm. The 1950 nm pumped HDFA provides 41 dB peak gain at 2060 nm with 15 dB of gain spanning the wavelength range 2050 – 2120 nm and an external NF of 7-10 dB. By pumping at the longer wavelength of 2008 nm the gain bandwidth of the amplifier is shifted to longer wavelengths and using this architecture a HDFA was demonstrated with a peak gain of 39 dB at 2090 nm and 15 dB of gain spanning the wavelength range 2050 – 2150 nm. The external NF over this wavelength range was 8-14 dB.

OCIS codes: (060.2320) Fiber optics amplifiers and oscillators; (060.3510) Lasers, fiber; (230.2285) Fiber devices and optical amplifiers.

References and links

1. J.-P. Cariou, B. Augere and M. Valla, "Laser source requirements for coherent lidars based on fiber technology," Compt. Rend. Phys. **7**, 213-223 (2006). http://dx.doi.org/10.1016/j.crhy.2006.03.012
2. P. A. Budni, L. A. Pomeranz, M. L. Lemons, C. A. Miller, J. R. Mosto and E. P. Chicklis, "Efficient mid-infrared laser using 1.9-µm-pumped Ho:YAG and $ZnGeP_2$ optical parametric oscillators," J. Opt. Soc. Am. B **17**, 723-728 (2000). http://dx.doi.org/http://dx.doi.org/10.1364/JOSAB.17.000723
3. K. Scholle, S. Lamrini, P. Koopmann and P. Fuhrberg, "2 µm laser sources and their possible applications," in *Frontiers in Guided Wave Optics and Optoelectronics*, B. Pal, ed. (InTech, 2010). http://dx.doi.org/10.5772/3033
4. A. Hemming, N. Simakov, A. Davidson, S. Bennetts, M. Hughes, N. Carmody, P. Davies, L. Corena, D. Stepanov, J. Haub, R. Swain and A. Carter, "A monolithic cladding pumped holmium-doped fibre laser," in *CLEO: 2013* (Optical Society of America, San Jose, California, 2013), p. CW1M.1. http://dx.doi.org/10.1364/CLEO_SI.2013.CW1M.1
5. Z. Liu, Y. Chen, Z. Li, B. Kelly, R. Phelan, J. O'Carroll, T. Bradley, J. P. Wooler, N. V. Wheeler, A. M. Heidt, T. Richter, C. Schubert, M. Becker, F. Poletti, M. N. Petrovich, S. U. Alam, D. J. Richardson and R. Slavík, "High-Capacity Directly Modulated Optical Transmitter for 2-µm Spectral Region," J. Lightwave Technol. **33**, 1373-1379 (2015). http://dx.doi.org/10.1109/JLT.2015.2397700
6. H. Zhang, N. Kavanagh, Z. Li, J. Zhao, N. Ye, Y. Chen, N. V. Wheeler, J. P. Wooler, J. R. Hayes, S. R. Sandoghchi, F. Poletti, M. N. Petrovich, S. U. Alam, R. Phelan, J. O'Carroll, B. Kelly, L. Grüner-Nielsen, D. J. Richardson, B. Corbett and F. C. Garcia Gunning, "100 Gbit/s WDM transmission at 2 µm: transmission studies in both low-loss hollow core photonic bandgap fiber and solid core fiber," Opt. Express **23**, 4946-4951 (2015). http://dx.doi.org/10.1364/OE.23.004946
7. H. Zhang, M. Gleeson, N. Ye, N. Pavarelli, X. Ouyang, J. Zhao, N. Kavanagh, C. Robert, H. Yang, P. E. Morrissey, K. Thomas, A. Gocalinska, Y. Chen, T. Bradley, J. P. Wooler, J. R. Hayes, E. Numkam Fokoua, Z. Li, S. U. Alam, F. Poletti, M. N. Petrovich, D. J. Richardson, B. Kelly, J. O'Carroll, R. Phelan, E. Pelucchi, P. O'Brien, F. Peters, B. Corbett and F. Gunning, "Dense WDM transmission at 2 µm enabled by an arrayed waveguide grating," Opt. Lett. **40**, 3308-3311 (2015). http://dx.doi.org/10.1364/OL.40.003308
8. M. N. Petrovich, F. Poletti, J. P. Wooler, A. M. Heidt, N. K. Baddela, Z. Li, D. R. Gray, R. Slavík, F. Parmigiani, N. V. Wheeler, J. R. Hayes, E. Numkam, L. Grűner-Nielsen, B. Pálsdóttir, R. Phelan, B. Kelly, J.

O'Carroll, M. Becker, N. Mac Suibhne, J. Zhao, F. C. G. Gunning, A. D. Ellis, P. Petropoulos, S. U. Alam and D. J. Richardson, "Demonstration of amplified data transmission at 2 μm in a low-loss wide bandwidth hollow core photonic bandgap fiber," Opt. Express **21**, 28559-28569 (2013). http://dx.doi.org/10.1364/OE.21.028559

9. N. Mac Suibhne, Z. Li, B. Baeuerle, J. Zhao, J. Wooler, S. U. Alam, F. Poletti, M. Petrovich, A. Heidt, N. Wheeler, N. Baddela, E. R. Numkam Fokoua, I. Giles, D. Giles, R. Phelan, J. O'Carroll, B. Kelly, B. Corbett, D. Murphy, A. D. Ellis, D. J. Richardson and F. Garcia Gunning, "WDM Transmission at 2 μm over Low-Loss Hollow Core Photonic Bandgap Fiber," in *Optical Fiber Communication Conference/National Fiber Optic Engineers Conference 2013* (Optical Society of America, Anaheim, California, 2013), p. OW1I.6. http://dx.doi.org/10.1364/OFC.2013.OW1I.6
10. N. Mac Suibhne, Z. Li, B. Baeuerle, J. Zhao, J. P. Wooler, S. U. Alam, F. Poletti, M. N. Petrovich, A. Heidt, I. Giles, D. J. Giles, B. Pálsdóttir, L. Grüner-Nielsen, R. Phelan, J. O'Carroll, B. Kelly, D. Murphy, A. Ellis, D. Richardson and F. C. Garcia Gunning, "Wavelength Division Multiplexing at 2 μm," in *European Conference and Exhibition on Optical Communication* (Optical Society of America, Amsterdam, 2012), p. Th.3.A.3. http://dx.doi.org/10.1364/ECEOC.2012.Th.3.A.3
11. F. Poletti, N. V. Wheeler, M. N. Petrovich, N. K. Baddela, E. Numkam Fokoua, J. R. Hayes, D. R. Gray, Z. Li, R. Slavik and D. J. Richardson, "Towards high-capacity fibre-optic communications at the speed of light in vacuum," Nat. Photon. **7**, 279-284 (2013). http://dx.doi.org/10.1038/nphoton.2013.45
12. Z. Li, Y. Jung, J. M. O. Daniel, N. Simakov, P. C. Shardlow, A. M. Heidt, A. Clarkson, S. U. Alam and D. J. Richardson, "Extreme Short Wavelength Operation (1.65 - 1.7 μm) of Silica-Based Thulium-Doped Fiber Amplifier," in *Optical Fiber Communication Conference* (Optical Society of America, Los Angeles, California, 2015), p. Tu2C.1. http://dx.doi.org/10.1364/OFC.2015.Tu2C.1
13. Z. Li, S. Alam, J. Daniel, P. Shardlow, D. Jain, N. Simakov, A. Heidt, Y. Jung, J. Sahu and W. Clarkson, "90 nm gain extension towards 1.7 μm for diode-pumped silica-based thulium-doped fiber amplifiers," in *European Conference on Optical Communication* (2014), p. Tu.3.4.2 http://dx.doi.org/10.1109/ECOC.2014.6964109
14. Z. Li, A. M. Heidt, N. Simakov, Y. Jung, J. M. O. Daniel, S. U. Alam and D. J. Richardson, "Diode-pumped wideband thulium-doped fiber amplifiers for optical communications in the 1800 – 2050 nm window," Opt. Express **21**, 26450-26455 (2013). http://dx.doi.org/10.1364/OE.21.026450
15. A. M. Heidt, Z. Li and D. J. Richardson, "High Power Diode-Seeded Fiber Amplifiers at 2 μm - From Architectures to Applications," IEEE J. Sel. Top. Quantum Electron. **20**, 525-536 (2014). http://dx.doi.org/10.1109/JSTQE.2014.2312933
16. S. D. Agger and J. H. Povlsen, "Emission and absorption cross section of thulium doped silica fibers," Opt. Express **14**, 50-57 (2006). http://dx.doi.org/10.1364/OPEX.14.000050
17. N. Simakov, A. Hemming, W. A. Clarkson, J. Haub and A. Carter, "A cladding-pumped, tunable holmium doped fiber laser," Opt. Express **21**, 28415-28422 (2013). http://dx.doi.org/10.1364/OE.21.028415
18. S. O. Antipov, V. A. Kamynin, O. I. Medvedkov, A. V. Marakulin, L. A. Minashina, S. K. Andrei and A. V. Baranikov, "Holmium fibre laser emitting at 2.21 μm," Quantum Electron. **43**, 603 (2013). http://dx.doi.org/10.1070/QE2013v043n07ABEH015076
19. V. A. Kamynin, S. O. Antipov, A. V. Baranikov and A. S. Kurkov, "Holmium-doped fibre amplifier operating at 2.1 μm," Quantum Electron. **44**, 161 (2014). http://dx.doi.org/10.1070/QE2014v044n02ABEH015361
20. S. A. Filatova, V. A. Kamynin, V. B. Tsvetkov, O. I. Medvedkov and A. S. Kurkov, "Gain spectrum of the Ho-doped fiber amplifier," Laser Phys. Lett. **12**, 095105 (2015). http://dx.doi.org/10.1088/1612-2011/12/9/095105
21. A. Hemming, N. Simakov, J. Haub and A. Carter, "A review of recent progress in holmium-doped silica fibre sources," Opt.Fiber Technol. **20**, 621-630 (2014). http://dx.doi.org/10.1016/j.yofte.2014.08.010
22. N. Simakov, Z. Li, S. U. Alam, P. C. Shardlow, J. M. O. daniel, D. Jain, J. K. Sahu, A. Hemming, A. Clarkson and D. J. Richardson, "Holmium Doped Fiber Amplifier for Optical Communications at 2.05 - 2.13 μm," in *Optical Fiber Communication Conference* (Optical Society of America, Los Angeles, California, 2015), p. Tu2C.6. http://dx.doi.org/10.1364/OFC.2015.Tu2C.6
23. J. W. Kim, A. Boyland, J. K. Sahu and W. A. Clarkson, "Ho-doped silica fibre laser in-band pumped by a Tm-doped fibre laser," in *CLEO-E/EQEC* (2009), p. CJ6_5.
24. S. D. Jackson, "Midinfrared holmium fiber lasers," IEEE J. Quantum Electron. **42**, 187-191 (2006). http://dx.doi.org/10.1109/JQE.2005.861824
25. A. S. Kurkov, V. V. Dvoyrin and A. V. Marakulin, "All-fiber 10 W holmium lasers pumped at λ=1.15 μm," Opt. Lett. **35**, 490-492 (2010). http://dx.doi.org/10.1364/OL.35.000490
26. O. Humbach, H. Fabian, U. Grzesik, U. Haken and W. Heitmann, "Analysis of OH absorption bands in synthetic silica," J. Non-Cryst. Solids **203**, 19-26 (1996). http://dx.doi.org/10.1016/0022-3093(96)00329-8
27. E. J. Friebele, C. G. Askins, J. R. Peele, B. M. Wright, N. J. Condon, S. O'Connor, C. G. Brown and S. R. Bowman, "Ho-doped fiber for high energy laser applications," in *Proc. SPIE* (2014), pp. 896120-1-896120-9. http://dx.doi.org/10.1117/12.2041577
28. B.-H. Choi, H.-H. Park and M.-J. Chu, "New pump wavelength of 1540-nm band for long-wavelength-band erbium-doped fiber amplifier (L-band EDFA)," IEEE J. Quantum Electron. **39**, 1272-1280 (2003). http://dx.doi.org/10.1109/JQE.2003.817582

29. Y. Li, Y. Zhao, B. Ashton, S. Jackson and S. Fleming, "Highly efficient and wavelength-tunable Holmium-doped silica fibre lasers," in *European Conference on Optical Communication (31st: 2005: Glasgow, Scotland)* (2005), pp. 679–680.

30. V. A. Kamynin, S. I. Kablukov, K. S. Raspopin, S. O. Antipov, A. S. Kurkov, O. I. Medvedkov and A. V. Marakulin, "All-fiber Ho-doped laser tunable in the range of 2.045 – 2.1 µm," Laser Phys. Lett. **9** (2012). http://dx.doi.org/10.7452/lapl.201210141

1. Introduction

Laser amplifiers in the 2.1 µm spectral region are required in many applications – in particular those that require excellent atmospheric transmission[1]. Sources operating at this wavelength are needed for free-space optical communications, atmospheric sensing, LIDAR and as pump sources for optical parametric oscillators for further nonlinear conversion into the mid-infrared [2, 3]. Traditionally sources at 2.1 µm have been based on holmium doped crystalline materials. Holmium-doped fibre lasers (HDFL) provide an attractive and power scalable alternative. Recently a robustly single-mode HDFL was demonstrated to operate at >400 W of average power at 2.12 µm [4].

Another application of 2 µm sources that has recently attracted attention is optical fibre communications [5-10]. This interest is being driven by demonstrations of low-loss hollow-core photonic band-gap fibers (HC-PBGFs) which offer a transmission medium possessing ultra-low nonlinearity, low latency, and with the potential for a broad ultra-low loss window at wavelengths around 2 µm [11]. The transmission loss of HC-PBGF is currently ~2.5 dB/km at 2 µm [5], which is already sufficiently low for certain niche short haul applications. In order to realize an optical communications system, high quality optical amplifiers are indispensable. Thulium-doped fiber amplifiers (TDFAs) have recently been shown to provide high gain, low noise amplification at wavelengths spanning the wavelength range 1660 – 2050 nm [12-15]. Operating a TDFA at wavelengths >2050 nm is however difficult due to the decreasing emission cross-section of thulium [16]. Thus it becomes necessary to seek alternative rare-earth ion dopants to fully access the long wavelength region of the 2 µm transmission window. Holmium-doped fibers (HDFs) typically operate at 2.1 µm and present an attractive gain medium for operation at these longer wavelengths.

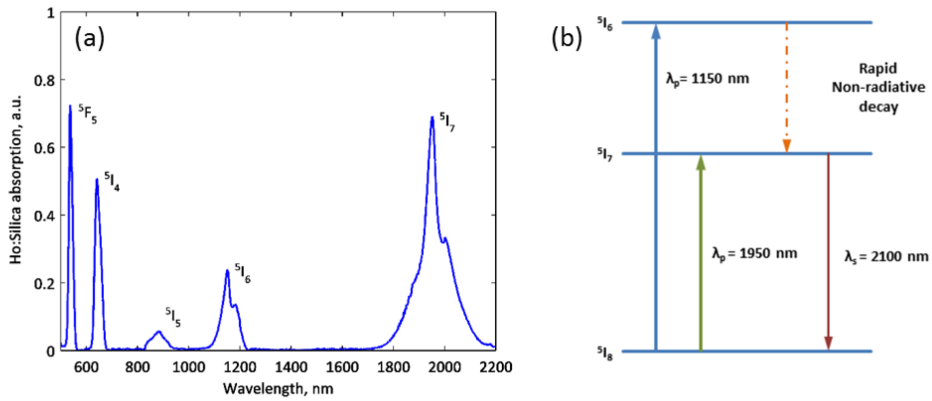
Holmium-doped fibers have been utilized in a tunable laser operating from 2040 – 2171 nm [17], and in a high-Q cavity, a wavelength as long as 2210 nm has been reached [18]. A small-signal holmium-doped fiber amplifier (HDFA) has also recently been demonstrated operating at a specific wavelength of 2100 nm with a reported gain of 28 dB [19]. Filatova *et al.* also recently demonstrated an ytterbium-doped fiber laser (YDFL) pumped HDFA with up to 35 dB of gain [20]. A comprehensive review of holmium-doped silica fiber laser devices is provided in [21]. Recently we have demonstrated a HDFA spanning 2050 – 2130 nm (>15 dB gain) with a noise figure (NF) of 4-9.5 dB [22].

In this paper we investigate the operation of several HDFAs under different pumping configurations. An 1150 nm diode pumped HDFA is demonstrated with a 15 dB gain spanning the wavelength range 2030 – 2100 nm. A 1950 nm pumped HDFA is demonstrated with 15 dB gain spanning the wavelength range 2050 – 2120 nm. A 2008 nm pumped HDFA is demonstrated with 15 dB gain spanning the wavelength range 2050 – 2150 nm. We also examine the impact of fiber length on the gain bandwidth and amplified spontaneous emission (ASE) spectrum. Finally we discuss the limitations of the various components such as wavelength division multiplexers (WDMs), isolators and circulators in this wavelength region.

2. Background

2.1 Holmium-doped fibre laser

The absorption of holmium-doped silica is shown in Fig. 1(a). The most commonly used pump bands are: (i) 1150 nm which can be addressed by long wavelength ytterbium-doped fibre lasers, Raman fibre lasers and diode lasers; and (ii) 1950 nm which can be addressed by thulium-doped fibre lasers (TDFLs) [23-25]. The pumping mechanism and relevant non-radiative transitions as well as the 2100 nm transition are shown in Fig. 1(b).



The effective gain cross-section as a function of inversion is shown in Fig. 2. When resonant pumping is utilized, there is significant bleaching of the absorption that occurs due to a combination of ground state depletion and stimulated emission. These effects limit the achievable fractional inversion achievable in this pump configuration. In contrast, when pumping at 1150 nm the bleaching occurs only due to ground state depletion. Due to the rapid non-radiative decay to the $^5I_7$ level in silica the $^5I_6$ level is unable to maintain a large inversion thereby removing the bleaching effect due to stimulated emission. As a result, in this pump configuration high inversions are achievable. The combination of these effects enable a given HDFA to be designed with a gain profile tailored to the required emission bandwidth. In particular 1150 nm pumping enables the achievement of high inversions (>50%) and can be potentially extend the operation of such HDFAs to shorter wavelengths than are accessible with fibre laser pumped devices.

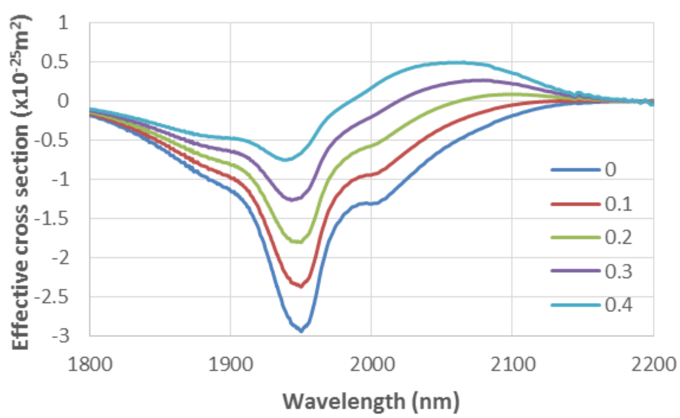


Fig. 2. The effective cross-section gain in Ho:silica as a function of inversion.

3. Experimental set-up

3.1 Holmium-doped fibre

The holmium-doped fibre used in these experiments was fabricated in-house and has a 10 µm diameter core with a 0.12 NA and 125 µm diameter cladding. The holmium ion concentration is 0.25 wt. % and corresponds to a core absorption strength of 35 dB/m at 1950 nm. The hydroxyl ion content of the fibre is measured at 0.1 ppm and corresponds to a 0.03 dB/m absorption at 1.38 µm [26]. To the best of our knowledge, this represents one of the lowest hydroxyl levels ever demonstrated in a holmium doped fibre [27].

3.2 Tunable Laser Source

A tunable Cr:ZnSe laser (IPG) was coupled into single-mode fibre and passed through an all-fibre attenuator. A 99/1 tap coupler and a photodiode were used to monitor the power levels subsequently launched into the holmium amplifiers. The amplifiers were characterized for 2 different input signal power levels corresponding to a saturating signal (0 dBm) and a small-signal (-20 dBm). The spectral quality of the output was excellent with an in-band optical signal to noise ratio (OSNR) of ~65 dB. The reproducibility and stability of the calibrated output was measured to be ±0.2 dB which was attributed in part to the stability of the fibre coupling and the pointing stability of the tunable laser source. The laser was not operated at wavelengths below 2030 nm due to a degradation in performance of the 99/1 tap coupler at the shorter wavelengths and also due to the potential risk of damage occurring to the tunable laser source when tuning to <2030 nm.

3.3 Diode pumped HDFA

A schematic of the diode-pumped HDFA is shown in Fig 3. A circulator (AFR) was used to separate the input signal and the amplified output. Two linearly polarised diode lasers at 1150 nm (Innolume) were combined by a fibre coupled polarisation combiner (AFR). Each diode produced 440 mW of CW output power and the combined power at the output of the all-fibre polarisation combiner was 770 mW. The output of the polarization combiner was coupled into the HDF by a fused WDM at 1150/2100 nm (AFR).

After performing a cut-back measurement, the optimum length of 1.5 m of HDF was used for characterization of this amplifier configuration. A fibre-coupled retroreflector was employed to double-pass the radiation through the HDF. The output of the circulator was spliced to an SMF-28e angled (APC) connectorized patch-cords.

An optical spectrum analyser (Yokogawa AQ6375) and a thermal power meter (Ophir 3A-FS) were used to measure the output spectrum and power from the amplifier. These measurements were used to calculate the gain and noise figure (NF).

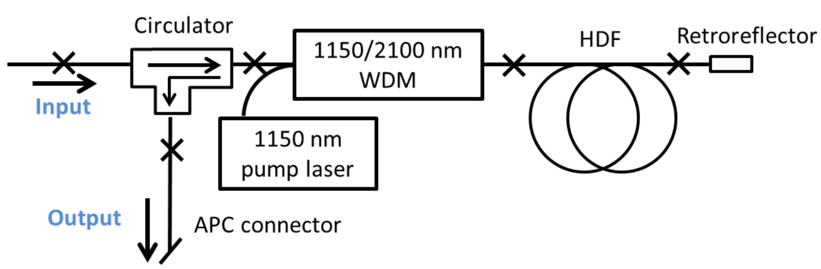


Fig. 3. Schematic of the double-pass diode-pumped HDFA. WDM: Wavelength division multiplexer; HDF: Holmium-doped fiber.

3.4 Fibre laser pumped HDFA

A schematic of the fibre laser pumped HDFA is shown in Fig 4. In these experiments the pump source was a TDFL operating at either 1950 nm or 2008 nm. The (in-house built) TDFLs were grating stabilized and operated at 3 W of output power. Due to the large amplifier gain (40 dB) and relatively weak isolation of the circulator (~20 dB) an additional isolator was required at the input to isolate the seed source. A circulator (AFR) was used to separate the input signal and the amplified output. The 1950 nm or 2008 nm pump radiation was coupled into the core of the HDF by a 1950/2100 nm WDM. In order to obtain a broad operating bandwidth this WDM was based on a fibre-coupled dichroic filter which had a high reflectivity in the range 1600 – 2010 nm and a high transmission for wavelengths in the range 2045 – 2200 nm.

The optimum length (in order to maximize the gain) of HDF for the amplifier was found to be 3.5 m when pumping at 1950 nm. A 10 m length of HDF provided the highest gain results when pumping at 2008 nm. The longer fibre length for 2008 nm pumping was required due to the weaker pump absorption observed. The intensity required to bleach the fibre was also lower at the longer pump wavelength due to the reduced ratio of absorption cross-section to emission cross-section in comparison to that at 1950 nm. The resulting lengths then agree with the effective cross-sections presented in Fig. 2.

A fibre-coupled retroreflector was used to double-pass the radiation through the HDF. The output of the circulator was spliced to an SMF-28e angled (APC) connectorised patch-cord.

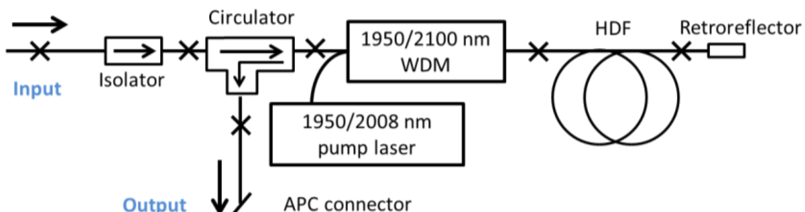


Fig. 4. Schematic of the double-pass fiber-laser pumped HDFA. WDM: Wavelength division multiplexer; HDF: Holmium-doped fiber.

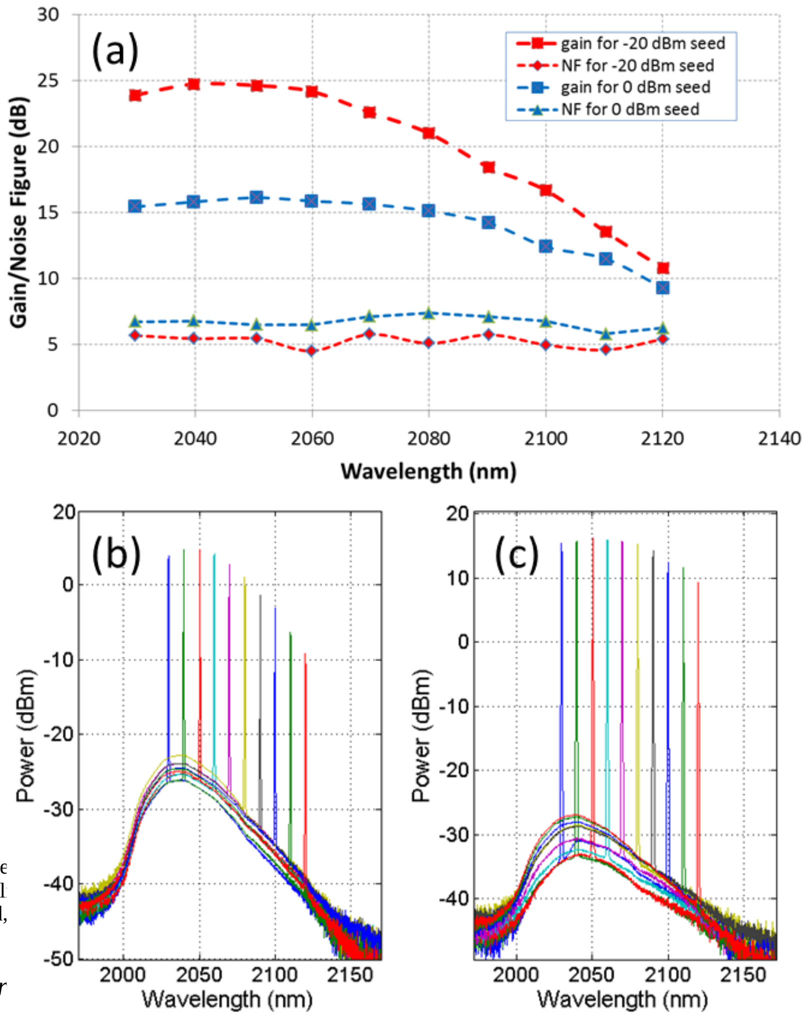
4. Results

4.1 Diode pumped HDFA

The performance of the diode-pumped HDFA is summarized in Figs. 6(a)–6(c). The diode pumped HDFA achieved more than 15 dB small-signal gain over the range 2030–2100 nm and a peak gain of 25 dB at 2040 nm as shown in Fig. 5 (a). The saturated gain was measured to be 12–16 dB over this wavelength range. The NF ranged between 5–7 dB over this bandwidth for both the small-signal (-20 dBm) and saturating (0 dBm) input power levels as shown in Fig. 5(a). Spectra of the amplified small-signal and saturated outputs are shown in Fig. 5(b) and Fig. 5(c) respectively. The amplified small-signal has ~30 dB in-band OSNR across the entire amplification band, whereas the amplified saturated signal has ~50 dB in-band OSNR.

Fig. 5. Pe
(b) ampl
saturated,

4.2 1950 nm fibr



As shown in Fig. 6(a) the 1950 nm pumped HDFA incorporating the 3.5 m long HDF demonstrated a >20 dB small-signal gain for wavelengths in the range 2050–2120 nm with a peak gain of 41 dB at 2060 nm. The saturated gain curve was relatively flat, varying between 20–25 dB across the entire tested waveband. The external NF ranged from 7–10 dB over the 70 nm bandwidth for both the small-signal and saturating input power levels as shown in Fig. 6(a). Spectra showing the amplified small-signal and saturated outputs are provided in Figs. 6(b) and 6(c) respectively. The amplified small-signal has ~25 dB in-band OSNR across the entire amplification band, and the amplified saturated signal has ~45 dB in-band OSNR.

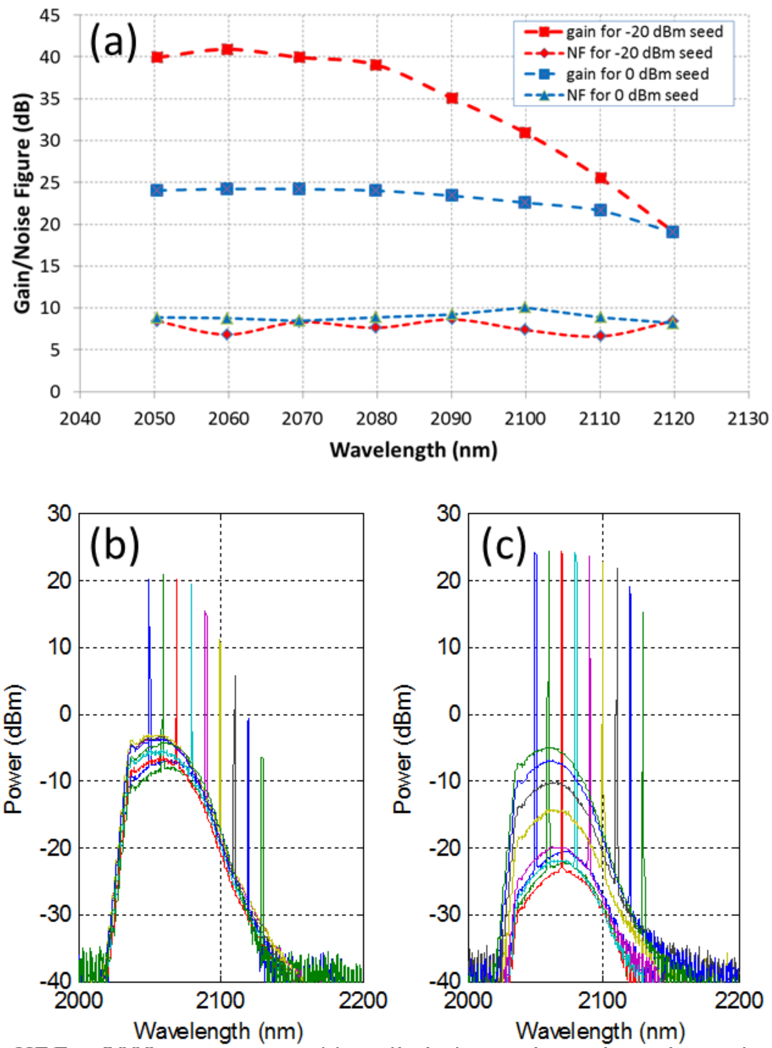


Fig. 6. I
waveler
the satu

4.3 2008 nm fil

By pumping the HDF at 2008 nm, we were able to limit the maximum inversion and ensure a low threshold for pump saturation. This had the beneficial effect of redistributing the pump radiation over a substantially longer length of fiber. In this configuration we were able to excite a 10 m long HDF and as a consequence of the longer length and lower inversion, the gain-peak shifted to longer wavelengths. This is evident in the shift of the peak of the ASE between Fig. 6 and Fig. 7. As shown in Fig. 7(a) the 2008 nm pumped HDFA provided a 15 dB gain bandwidth spanning the wavelength range 2050–2150 nm with a peak gain of 39 dB at 2090 nm. The NF ranged from 8–14 dB over the 100 nm bandwidth for both the small-signal and saturating input power levels (Fig. 7(a)). There is a ~5 dB penalty in the NF by using this approach at the shorter wavelength (2050–2080 nm) in comparison to the 1950 nm pumped HDFA – this is attributed to the increased reabsorption losses due to the longer length of HDF in the amplifier. However at wavelengths >2100 nm we see a very similar NF performance. The gain peak and edge are also shifted by 30 nm to longer wavelengths with almost no penalty in terms of the maximum gain. Pumping at an even longer wavelength was not possible without redesigning the WDM component, however, in principle this strategy could be employed to shift the gain to even longer wavelengths. Spectra of the amplified small-signal and saturated outputs are shown in Figs. 7(b) and 7(c), respectively. The amplified small-signal has 22–27 dB in-band OSNR across the entire amplification band, whereas the amplified saturated signal has 40–45 dB in-band OSNR.

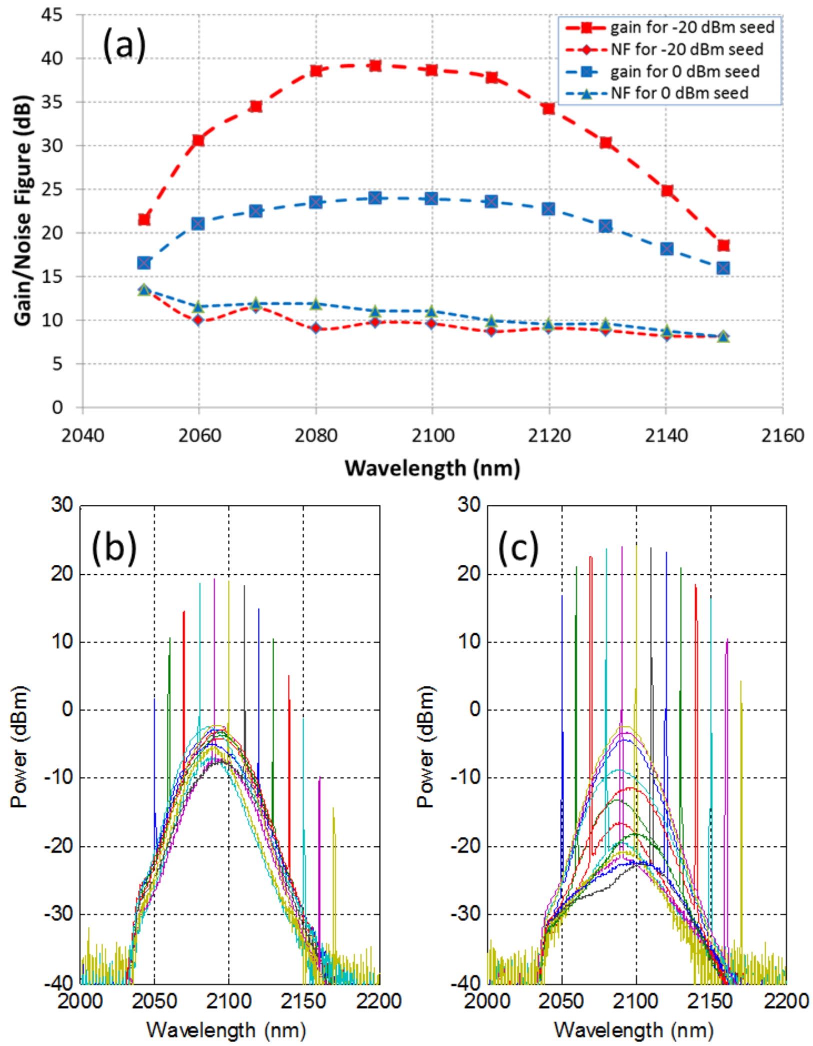


Fig. 7.
waveler
the satu

5. Discussion

5.1 Summary of amplifier performance

The performance of all of the amplifiers that have been presented is summarised in Table 1. The diode pump HDFA achieved a maximum gain of 25 dB at 2040 nm. The peak gain observed was limited by the available pump power. The lifetime of the $^5I_7$ level in Ho:silica is dominated by multi-phonon decay and so the amount of power required to reach transparency is substantial. In order to further improve the performance of the diode pumped configuration, a larger pump power can be provided by introducing a dual-pumped arrangement. The other method of increasing the pump intensity would be to use a fibre with reduced core diameter and to increase the core NA to maintain single-mode propagation. This would greatly reduce the number of holmium ions that need to be excited in order to achieve a similar gain, thereby reducing threshold and allowing higher gains to be achieved for a given pump power. The higher pump intensity would also enable operation at a larger inversion and potentially to improve the NF performance. This strategy can be applied to both the TDFL pumped and the directly diode pumped HDFAs.

Table. 1. Summary of the HDFAs reported in this paper.

Pump source	HDF length	Peak gain	Gain peak	15 dB gain window	Bandwidth	NF range
1150 nm LD	1.5 m	25 dB	2040 nm	2030–2100 nm	70 nm	5–7 dB
1950 nm TDFL	3.5 m	41 dB	2060 nm	2050–2120 nm	70 nm	7–10 dB
2008 nm TDFL	10 m	39 dB	2090 nm	2050–2150 nm	100 nm	8–14 dB

The use of long wavelength resonant pumping has been demonstrated in erbium-doped fibre amplifiers (EDFAs) to achieve similar improvements in long wavelength amplification as well as a reduction in short wavelength ASE [28]. By changing the pump wavelength from the peak of the absorption at 1950 nm to the longer wavelength of 2008 nm we were able to shift the gain by 30 nm to longer wavelengths as shown in Fig. 8. There is however a penalty in the NF associated with this operating regime, as the amplifier is now operating at a lower inversion.

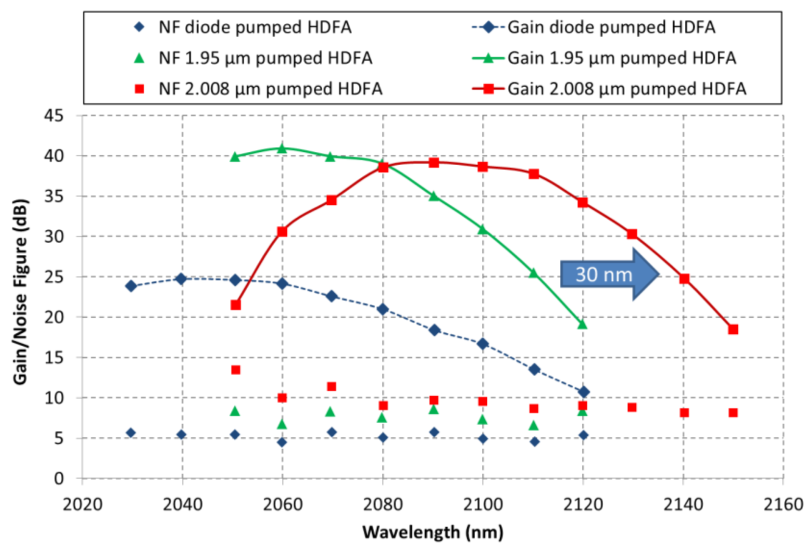


Fig.8. S

5.2 Noise figure performance of the amplifiers

The relatively large NF values are mainly a consequence of the large insertion loss of the passive fibre-coupled components. When pumping at 2008 nm, the NF is further degraded by the lower average inversion.

The circulator has an insertion loss of 1.5 dB for both the input and output radiation at 2100 nm, while the isolator has an insertion loss of 1.3 dB at 2100 nm. The 1950/2100 nm WDM has an insertion loss of 1.4 dB and the 1150/2100 nm WDM has an insertion loss of 0.2 dB at 2100 nm.

The excess loss at 2100 nm for the TDFL-pumped amplifier is 4.4 dB for the input and 2.5 dB at the output. The excess component loss at 2100 nm for the diode-pumped HDFA is 1.7 dB at the input and 1.7 dB at the output.

As a result the NF for the TDFL-pumped amplifier is 1-3 dB larger than that for the diode-pumped amplifier predominantly due to the larger excess loss at 2100 nm. The internal performance of the holmium amplifier is significantly better than the measured external performance and the 15 dB gain band could potentially be extended to >2160 nm with a significant reduction in NF with the use of lower loss components.

5.3 Short wavelength (<2030 nm) operation of HDFAs

The diode pumped HDFA offers gain at wavelengths shorter than 2030 nm and we anticipate the short wavelength limit for 15 dB gain can extend down to 2010 nm. This is supported by other investigations of 1150 nm pumped holmium-doped fibres [29, 30], by the estimate of the gain cross-sections [17] and by the presence of short wavelength ASE in Fig. 5 (b) and Fig. 5 (c). For the TDFL-pumped HDFA case, this gain region is typically inaccessible due to the transmission/reflection characteristics of the 1950/2100 nm WDM pump coupler.

We were unable to investigate the performance of the HDFA at wavelengths < 2030 nm due to the limited tuning range of our seed source (as discussed in Section 3.2). This is however also a wavelength region that is easily accessible by more conventional TDFAs and so was deemed not to be as significant as demonstration of the longer wavelength (>2050 nm) operation.

6. Conclusion

We have investigated the operation of several holmium-doped fibre amplifiers under different pumping conditions. Due to the inherently small gain and low dopant concentration of the fibre, all of the amplifiers relied on a double pass architecture. The 1950 nm TDFL pumped HDFA provided a maximum gain of 41 dB with a 15 dB gain bandwidth extending from 2050 – 2120 nm. A longer wavelength 2008 nm TDFL was used to pump a longer length of holmium fibre and resulted in a shift of the gain peak of ~30 nm and 15 dB gain bandwidth spanning 2050 – 2150 nm. However, fibre laser pumped amplifiers are expensive and will suffer from reduced compactness and reliability. With this in mind we have also demonstrated the first diode-pumped HDFA using commercially available components and achieved an amplifier with a peak gain of 25 dB and a 15 dB gain bandwidth spanning from 2030 – 2100 nm.

The performance of the diode pumped HDFA complements that of the previously demonstrated diode-pumped TDFAs [14] (limited to wavelengths < 2050 nm), by increasing the accessible bandwidth by 50 nm out to 2100 nm. If further bandwidth is desired, then it is possible to use a TDFL pump source to achieve a 15 dB gain out as far as 2150 nm. Lower loss fibre coupled components would significantly improve the noise figure performance of these amplifiers.

These results demonstrate the utility of holmium-doped fibre amplifiers in providing access to the spectral region beyond 2050 nm which is not easily accessed by thulium-doped sources.

Acknowledgment

The authors would like to thank R. Slavik for valuable discussions. This work was supported by the EU 7th Framework Program under grant agreement 258033 (MODE-GAP), 287732 (ISLA) and by the UK EPSRC through grant EP/I01196X/1 (HYPER HIGHWAY).