4483

Optical Fibre Lasers and Amplifiers

D. N. Payne, R. I. Laming and M. Tachibana

Introduction

The field of rare-earth-doped fibre lasers[1,2,3] and amplifiers has expanded rapidly in recent years and there are now numerous publications in the area. A variety of glass hosts, dopants and pump sources have been used, with the goal of achieving low-threshold, diode-laser-pumped operation of fibre lasers and amplifiers, particularly those operating in either the second or third telecommunication windows.

While much of the commercial interest is likely to be in the area of optical communications amplifiers and sources based on Er^{3+} and Nd^{3+}, it is also important to realise that five other rare earths have successfully been incorporated into silica hosts and operated as fibre lasers, namely samarium, praseodymium, ytterbium, thulium and holmium.

Fibre lasers

Fibre-laser oscillation covers the range 651nm (Sm) to beyond 2μm (Tm, Ho). The small-core size of a single-mode fibre allows high pump intensities for modest ($\simeq$mW) pump powers, but can also dissipate heat effectively. This permits efficient CW, diode-laser-pumped operation of three-level lasers without the usual thermal problems. For example, Er^{3+}-doped fibre lasers can with operate close to unity quantum efficiency[4] when pumped at 980nm and an output power of 5mW is readily obtainable for launched pump powers as low as 15mW, a power well within the range of diodes. On the other hand, use of a high-power Ti:Sapphire laser as a pump can provide an output power in excess of 0.5W.

Figure 1: Self-heterodyne spectrum of Er^{3+} doped fibre ring-laser. Inset is Fabry-Perot spectrum showing single-frequency operation

Although not as advanced as DFB diode-lasers, Er^{3+}-doped fibre lasers show potential as very narrow-linewidth sources for coherent communications at 1.55μm. Whereas in the case of a diode laser it is usually necessary to use an external (often fibre) cavity to narrow the linewidth to less than 1MHz, a typical fibre laser is a metre or more long and gives a natural Fabry-Perot linewidth of considerably less than this. The problem is to select one of the many longitudinal modes, which are typically spaced at 100MHz. A number of mode-selection schemes used in the traditional laser field are available and in a travelling-wave, ring-laser configuration a linewidth of only 60kHz has recently been reported[5]. The self-heterodyne RF spectrum of this fibre laser output is shown in Figure 1. The spectrum exhibits symmetric double peaks based 30kHz from the centre frequency, which are believed to result from interaction with the laser relaxation oscillation frequency which was measured to be 30kHz. Note that the Schawlow-Townes limit for this laser is substantially less than 1Hz, so considerably narrower linewidths should be possible. Current worldwide fibre-laser research covers a broad spectrum. As just one example of recent results[6], the tuning range obtained for a Tm^{3+}-doped fibre laser is shown in Figure 2 for both an Al_2O_3–SiO_2 fibre and a GeO_2–SiO_2 fibre. The tuning range is extremely broad, being almost 300nm (1.66μm to 1.86μm) for the Al_2O_3–SiO_2 host glass. Also noteworthy is the strong effect of the host glass composition (see curve for GeO_2–SiO_2 glass), a characteristic of glass-based lasers which can be usefully employed to adjust the emission wavelength of fibre lasers.

Figure 2: Tuning range of Tm^{3+}-doped fibre for the two host-glasses shown

Although the Tm^{3+} fibre laser is diode-pumpable using an SLD emitting at 785nm, it can also be pumped with a high-power Nd:YAG laser emitting at 1.06μm, when an output power of 1.35 watts can be obtained[7]. This is a significant result, since it indicates that fibre lasers are not necessarily low-power devices, but can rival the performance of conventional miniature lasers. There is no reason why the power should not be scalable to an even higher value. Such power levels, together with the wide choice of laser wavelengths and tuning ranges available from fibre lasers, suggest that they have great potential for use as spectroscopic sources, in medicine and in LIDAR applications.

Erbium-doped fibre amplifiers

The erbium-doped fibre amplifier (EDFA) has recently attracted very considerable attention in the field of optical

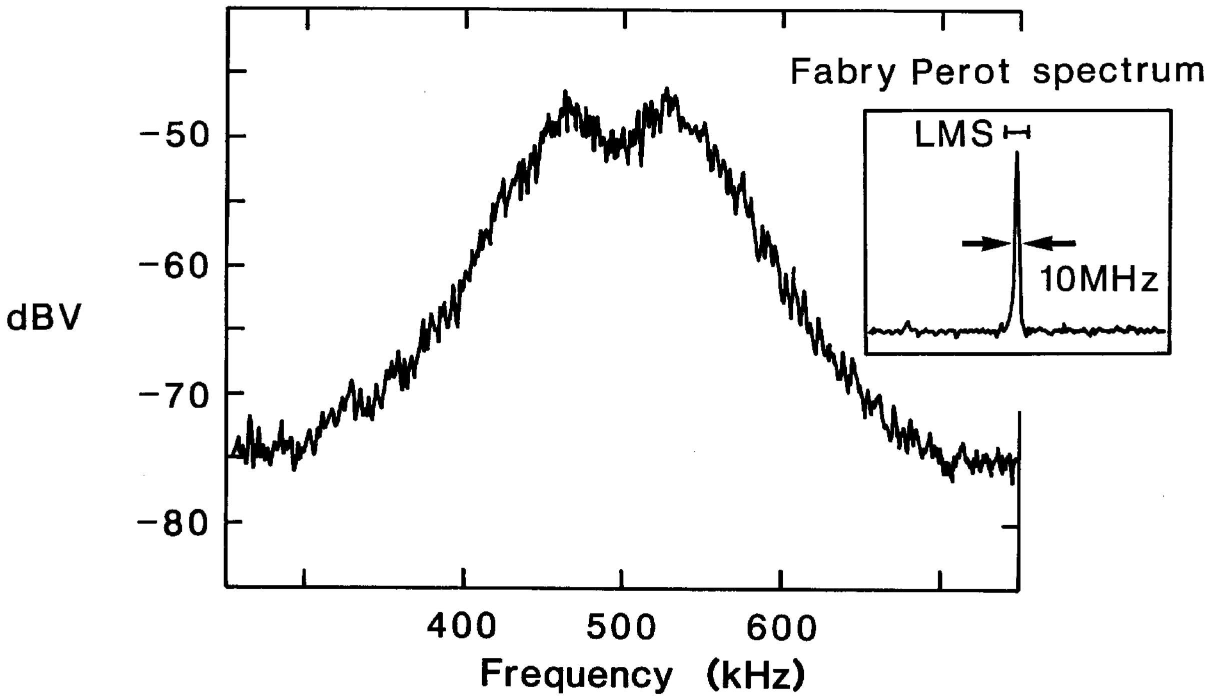


Figure 1: Self-heterodyne spectrum of Er^{3+} doped fibre ring-laser. Inset is Fabry-Perot spectrum showing single-frequency operation

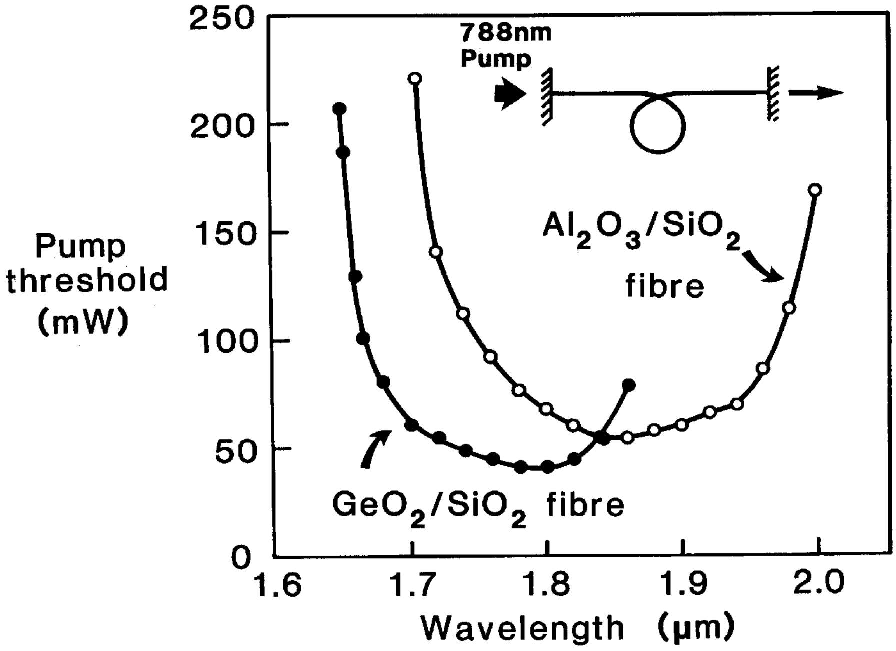


Figure 2: Tuning range of Tm^{3+}-doped fibre for the two host-glasses shown

fibre communications[8,9,10]. The EDFA conveniently operates in the preferred telecommunications spectral window located at a wavelength of 1.55μm. In addition, it has been shown to have high polarisation-insensitive gain (>30dB), low-crosstalk between signals at different wavelengths, good saturation output power (>0dBm) and a noise figure close to the fundamental quantum-limit (~3dB). The excellent noise characteristics potentially[11] allow hundreds of amplifiers to be incorporated along the length of a fibre telecommunication link, which could then span more than 10,000km. Compared to the alternative of a transmission link with electronic repeaters, an all-optical link has the merit that it is transparent to the transmission code format and bit rate. It can thus be uprated by changing only the transmitter and receiver, and not the repeaters.

Potential diode-pump wavelengths for the EDFA are 807nm, 980nm and 1480nm. Unfortunately, the 807nm pump band suffers pump excited-state absorption and the best results have been reported at the latter two wavelengths. Exceptionally high gain (48dB) has been reported using the 980nm pump band[12]. Somewhat lower pump efficiency is obtained using the 1480nm pump band, although diodes are more readily available for this wavelength. The optimal choice of pump wavelength remains an issue to be resolved, but could well depend on the intended amplifier application, i.e. as a pre-, power or line amplifier.

Although Stark-splitting of the ground and metastable levels in erbium-doped glass generates a wide spectral bandwidth in an EDFA, its gain spectrum is typically irregular compared with that of its diode-amplifier rival, having a sharp peak 3.5nm wide around 1.53μm (Figure 3, Curve A). Although the amplifier can be operated at wavelengths away from the peak gain, disadvantages occur due to increased spontaneous-spontaneous beat-noise and possible laser action at the peak gain wavelength.

Figure 3: EDFA gain spectra showing gain-flattening using a shaping filter

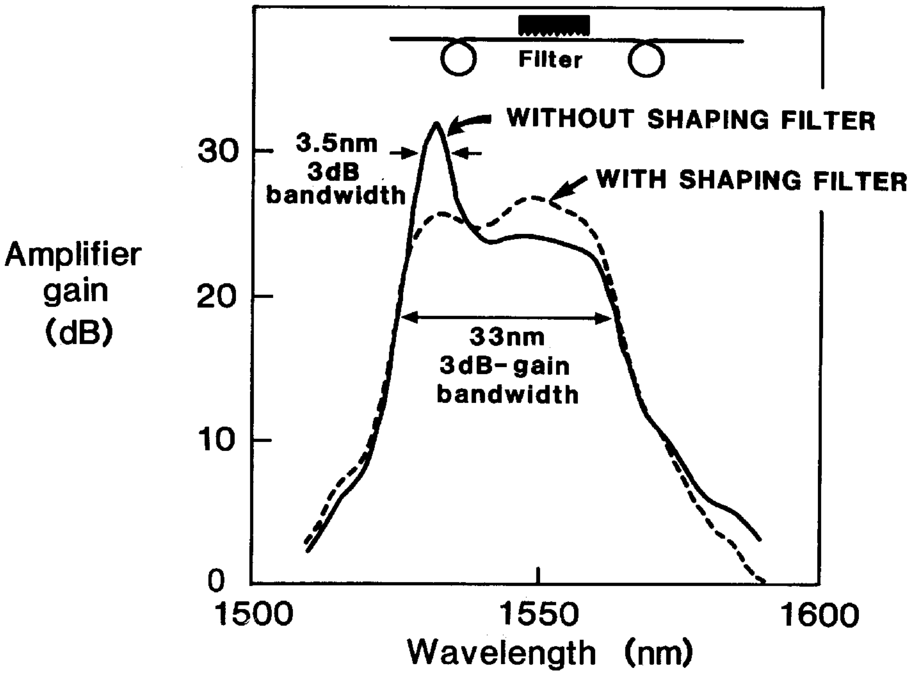
By incorporating an optical filter within the length of an EDFA, the overall gain spectrum and gain characteristics can be modified[13] to be nearly uniform over the entire 1.53–1.56μm range. By using an optical notch filter located the centre of the amplifier and tuned to suppress the gain spectrum at the peak wavelength, a broadband amplifier with a 3dB-bandwidth of 33nm and a gain of 27dB can be obtained. The resulting spectral gain characteristic is shown in Figure 3 (Curve B), which represents the highest gain-bandwidth product demonstrated to date for an EDFA pumped at 980nm. Locating the filter within the amplifier length has considerable advantages, particularly with regard to pump efficiency, since amplified spontaneous emission is suppressed before it has risen to a significant value.

It has not been generally appreciated that the erbium-doped fibre amplifier has both a saturation output power unlike a diode amplifier, which increases with pump power, as well as an ability to operate deep in saturation without signal distortion and interchannel crosstalk[14]. The latter is a consequence of having slow gain dynamics which are quite different from those of the diode-amplifier. As a consequence of these two attributes, when EDFAs are employed as power (post) amplifiers where the input signal is large and the amplifier heavily saturated, near quantum-limited differential pump to signal conversion efficiencies are possible[15].

The saturated amplifier large signal characteristics are shown in Figure 4 which plots amplifier output signal as a function of pump power for various fibre lengths. It can be seen that for larger pump powers it is necessary to use a longer fibre length and a (non-critical) optimum length exists. The curves demonstrate that highly-saturated EDFAs are efficient power amplifiers with a maximum absolute pump-to-signal power conversion efficiency as high as 47%. The slope efficiency is near quantum-limited at 53%. It is also noteworthy that power amplifiers operating in the highly-saturated mode have virtually flat spectral-gain characteristics, owing to their largely homogeneously-broadened behaviour.

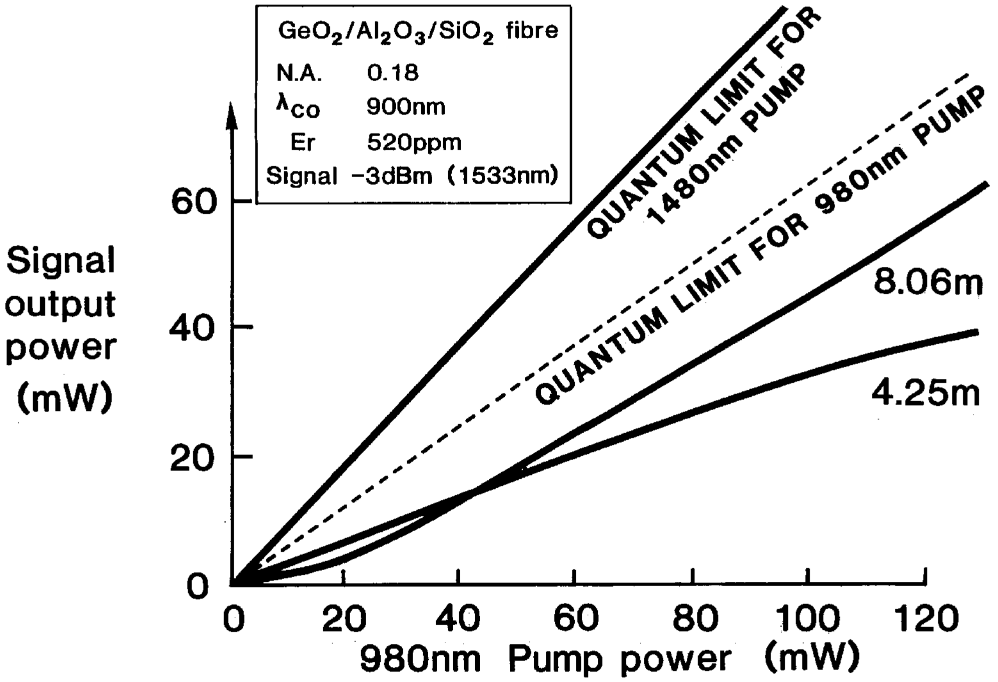
Figure 4: Dependence of EDFA saturated output power on 980nm pump for different fibre lengths

From the above two examples, it is clear that considerable scope exists to tailor the performance of the EDFA to a given application. The designer has the freedom to choose to operate in small-signal or saturated regime and can adjust the amplifier characteristics accordingly. The fibre format allows these adjustments to be made with relative ease, an attribute which makes the EDFA even more attractive.



● Note spectral redistribution of gain

Figure 3: EDFA gain spectra showing gain-flattening using a shaping filter



Measured pump conversion efficiency = 47%

Figure 4: Dependence of EDFA saturated output power on 980nm pump for different fibre lengths

Conclusions

Despite their relative immaturity, rare-earth-doped fibre lasers and amplifiers have progressed rapidly as a result of their obvious attractions as inexpensive, easily-constructed devices. The issues which remain are frequently concerned with practical considerations, such as developing a well-controlled, robust, temperature-insensitive device for use outside the laboratory. There is every indication that because of the relative simplicity of fibre devices, these problems can be overcome. In this event, fibre amplifiers and lasers will take their place in the market alongside their diode counterparts.

References

1. C. J. Koester & E. Snitzer: "Amplification in a fibre laser", Appl. Opt., 3, 1964, pp. 1182–1186.
2. J. Stone & C. A. Burrus: "Neodymium-doped silica lasers in end-pumped fibre geometry", Appl. Phys. Lett., 23, 1973, pp. 388–389.
3. R. J. Mears, L. Reekie, S. B. Poole & D. N. Payne: "Neodymium-doped silica single-mode fibre lasers", Electron. Lett., 21, 1985, pp. 738–740.
4. W. L. Barnes, P. R. Morkel, L. Reekie & D. N. Payne: "High-quantum efficiency Er^{3+} fibre lasers pumped at 980nm", Opt. Lett., 14, 1989, pp. 1002–1004.
5. P. R. Morkel, G. J. Cowle & D. N. Payne: "A travelling-wave erbium fibre ring laser with 60kHz linewidth", Electron. Lett., 26, 1990, pp. 632–634.
6. W. L. Barnes & J. E. Townsend: "Highly tunable and efficient diode pumped operation of Tm^{3+}-doped fibre lasers", Electron. Lett., 26, 1990, pp. 746–747.
7. D. C. Hanna, I. R. Perry, J. R. Lincoln & J. E. Townsend: "A 1-watt thulium-doped CW fibre laser operating at $2\mu m$", To be published in 1990.
8. R. J. Mears, L. Reekie, I. M. Jauncey & D. N. Payne: "Low-noise erbium-doped fibre amplifier operating at $1.54\mu m$", Electron. Lett., 23, 1987, pp. 1026–1028.
9. E. Desuvire, J. R. Simpson & P. C. Becker: "High-gain erbium-doped travelling-wave fibre amplifier", Opt. Lett., 12, 1987, pp. 888–890.
10. R. I. Laming, M. C. Farries, P. R. Morkel, L. Reekie, D. N. Payne, P. L. Scrivener, F. Fontana & A. Righetti: "Efficient pump wavelenths of the erbium-doped fibre optical amplifier", Electron. Lett., 25, 1989, pp. 12–14.
11. N. Edagawa, Y. Yoshida, H. Taga, S. Yamamoto, K. Mochizuki & H. Wakabayashi: "Non regenerative optical transmission experiment using Er^{3+}-doped fibre amplifiers", Proc. ECOC '89, Gothenburg, Paper PDA-8, 1989.
12. W. J. Miniscalco, B. A. Thompson, E. Eichen & T. Wei: "Very high-gain Er^{3+}-fibre amplifier pumped at 980nm", Proc. OFC '90, San Francisco, Paper FA2, 1990.
13. M. Tachibana, R. I. Laming, P. R. Morkel & D. N. Payne: "Gain-shaped erbium-doped fibre amplifier (EDFA) with broad spectral bandwidth", Proc. Topical Meeting on Optical Fibre Amplifiers and Their Applications, Monterey, California, 6–8 August 1990.
14. R. I. Laming, L. Reekie, P. R. Morkel & D. N. Payne: "Multichannel crosstalk and pump noise in characterisation of Er^{3+}-doped fibre amplifier pumped at 980nm", Electron. Lett., 25, 1989, pp. 455–456.
15. R. I. Laming, D. N. Payne, F. Mekli, G. Grasso & E. J. Tarbox: "Highly-saturated erbium-doped fibre power amplifiers", Proc. Topical Meeting on Optical Fibre Amplifiers and Their Applications, Monterey, California, 6–8 August 1990.