503

ACTIVE OPTICAL FIBRES

David N. Payne
Deputy Director,
Optoelectronics Research Centre, Southampton University, United Kingdom

Introduction

The incorporation of rare-earth ions into glass fibres to form fibre lasers and amplifiers is not a recent development. In fact the first glass laser ever demonstrated[1] was flash-pumped in the form of an optical fibre, a configuration which was used to overcome the difficulties of obtaining high-quality glass in bulk form. Apart from a report[2] in 1974 of laser operation in an Nd^{3+}-doped silica multimode fibre, the idea of guided-wave glass lasers attracted little attention for the next 24 years. The idea resurfaced[3] in 1985 because both optical-fibre and laser-diode technologies had advanced to a stage where low-loss, rare-earth-doped, single-mode fibres could be made and high-power semiconductor sources were available to pump them. In addition, low-cost fibre components (couplers, polarisers, filters) were available which allowed construction of complex, all-fibre ring and Fabry-Perot resonators[4] to form a unique and powerful new fibre-laser technology. Even so, it was only the announcement in 1987 of a high-gain, erbium-doped fibre amplifier[5] (EDFA) operating in the third telecommunications wavelength-window at 1.54μm that sparked widespread interest in rare-earth-doped fibres in the optical telecommunications community. From that moment, frenzied worldwide activity has brought numerous new fibre amplifier developments and recently resulted in several commercial products appearing, a time-lag of only three years after the first research announcement.

The fibre laser, on the other hand, is only now beginning to receive widespread attention as a possible contender for a well-controlled, stable light source for telecommunications, despite its obvious advantages of high-power pulsed operation, single-frequency capability, ease of access to the resonator and compatibility with communications fibre.

Fibre Lasers

Fibre lasers are essentially photon convertors. They use the "raw" photons emitted by diode lasers to excite rare-earth ions contained within the fibre core which subsequently emit a well-controlled laser beam. Because of the guiding properties of the fibre, the diode-laser pump light is tightly confined over the distance required for absorption and this leads to a high population-inversion density. This large inversion density is readily obtainable in both three and four-level laser systems at modest pump powers and gives a high single-pass gain without the usual thermal problems associated with bulk-glass lasers. The fibre laser output is well-defined, having a beam profile which is close to diffraction-limited Gaussian. The fibre laser resonator is stable, and provides a well-confined and easily-accessed laser cavity. The diode-laser designer, on the other hand, now freed of the need to produce an optical output suitable for telecommunications, can concentrate on efficient optical power generation. This freedom of design has led to pump lasers becoming available with output powers greater than 10W for pumping mini-YAG lasers, and we can expect similar developments for fibre-laser pump diodes.

The fibre laser geometry allows a compact, flexible layout, easy connection to optical components and a stable, optically-confined laser beam. While much of the commercial interest is likely to be in the area of amplifiers and sources based on Er^{3+} and Nd^{3+} for optical communications, 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. An indication of the optimal pumping environment provided by the fibre laser is that laser action of Pr^{3+} and Sm^{3+} in glass has only been achieved in fibre form.

Fibre-laser oscillation covers the range 651nm (Sm) to beyond 2μm (Tm, Ho). Figure 1 shows the laser lines which have been reported to date, together with the loss windows of silica and fluoride-glass fibres. Erbium sits conveniently at wavelengths of 1.54μm and 2.7μm, both close to the lowest loss wavelengths of these two fibre types. Furthermore, Er^{3+}-doped fibre lasers can operate with close to unity quantum efficiency[6] 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 pump diodes. Alternatively, use of a high-power Ti:Sapphire laser as a pump can provide an output power in excess of 1W, showing that fibre lasers should not necessarily be regarded as low-power devices. A typical fibre laser Fabry-Perot resonator is shown in Figure 2. Numerous resonator configurations are possible based on fibre-optic fused couplers, for example, ring resonators, anti-resonant-ring reflectors (fibre mirrors), Fox-Smith resonators, as well as hybrid versions of these. A useful review of fibre laser configurations is given in Reference 7.

Fluorescence spectra of the rare-earth ions in glass host materials can be very broad. For example, the $^4I_{13/2}$ - $^4I_{15/2}$ transition of Er^{3+} at 1.535μm is at least 80nm in width[3], (Figure 3). Although this property allows the construction of a broadly-tunable laser source, it means that a wavelength-selective component must be employed to produce a narrow-linewidth source for telecommunications. Because a typical fibre laser has a length which can vary from metres to kilometres, the axial mode-spacing can be from 100kHz to 100MHz. The problem, therefore, is to select one of these numerous, closely-spaced, longitudinal modes. 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[8]. Note that, because of its length, the Schawlow-Townes linewidth limit for the fibre laser is substantially less than 1Hz and it is expected that, with appropriate stabilisation, linewidths approaching this figure will be obtainable. Thus Er^{3+}-doped fibre lasers show considerable potential as very narrow-linewidth sources for coherent communications at a wavelength of at 1.54μm.

Another important attribute of fibre lasers when compared to their diode counterparts is their ability to generate short, high-power pulses using the technique of Q-switching[9]. A compact, portable source of high peak-power pulses at 1.54μm is expected to find many applications in optical time-domain reflectometers, eye-safe laser rangefinders, and fibre sensors. The long fluorescence time-constant of erbium in glass (15ms) makes it highly-efficient at storing energy and therefore ideal as a medium for a Q-switched laser.

An alternative method which may be used to generate even shorter pulses is that of mode-locking. It has recently been shown[10] that bandwidth-limited pulses as short as 4 picoseconds at a repetition rate of 90MHz are obtainable by incorporating a lithium-niobate modulator into the cavity of an erbium-doped fibre laser. By using a monolithic fibre geometry, it was possible to combine the elements of gain, self-phase modulation and negative group velocity dispersion within the one device, leading to a stable, self-contained, mode-locked system.

An interesting new development which complements fibre lasers is the rare-earth-doped planar single-mode waveguide laser[11]. The laser characteristic of this device and its configuration are shown in Figure 4 for an Nd^{3+}-doped laser emitting at a wavelength of 1.06μm. The planar geometry is very attractive for the manufacture of complex laser resonators and functional devices, but has the disadvantage that the pump absorbing region is short and therefore requires a high concentration of rare-earth to be incorporated. This leads to ion-ion interaction and concentration quenching effects which severely degrade laser performance, especially in the case of erbium which is particularly susceptible to concentration effects.

Erbium-Doped Fibre Amplifiers

The erbium-doped fibre amplifier (EDFA) is now undoubtedly the preferred amplifier for operation in the third telecommunications window at 1.54μm. It has high polarisation-insensitive gain (greater than 40dB), low crosstalk between signals at different wavelengths, good saturation output power (greater than 0dBm) and a noise figure close to the fundamental quantum-limit (-3dB). The excellent noise characteristics potentially 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. A simplified schematic diagram of an EDFA is shown in Figure 5.

EDFA gains as high as 45dB have been demonstrated and this would allow in-line communications amplifiers to be spaced some considerable distance apart. Saturation of the amplifier due to amplified spontaneous emission prevents higher gain. In practice, an amplifier used as a repeater is likely to operate at a lower gain of approximately 20dB. Recently a demonstration of coherent communication over 2,000km using 25 EDFAs was reported[12].

Potential diode-pumping wavelengths for the EDFA are 807nm, 980nm and 1480nm. Unfortunately, the 807nm pump band suffers pump excited-state absorption (ESA), leading to a relatively-low pump efficiency. Recent results[13], however, show that by appropriate fibre design and the use of a large numerical aperture to maintain high pump intensity, good results can be obtained. Although for the same fibre design the pump efficiency reported is an order of magnitude less than that obtained at the other two wavelengths, this may be offset by the ready-availability of high-power diodes at 807nm. Exceptionally-high pump efficiency (10.2dB/mW) has been reported using the 980nm pump band[14]. Somewhat lower pump efficiency[14] is obtained using the 1480nm pump band (5.1dB/mW), although diodes are more easily obtainable for this wavelength. The optimal choice of pump wavelength remains an issue to be resolved, with current opinion favouring 980nm for pre-amplifiers (owing to its lower amplifier noise figure) and 1480nm for power-amplifier applications.

The gain spectrum of an EDFA is typically irregular compared with that of its diode amplifier rival, having a sharp peak 3.5nm wide around 1.53μm (Figure 6, solid curve). However, by incorporating an optical filter within the length of an EDFA, the overall gain spectrum and gain characteristics can be modified[15] to be nearly uniform over the entire 1.53-1.56μm range. By using an optical notch-filter located at the centre of the amplifier and tuned to suppress the gain spectrum at the peak wavelength, a broad-band amplifier with a 3dB bandwidth of 33nm and a gain of 27dB can be obtained without loss of pump efficiency. The resulting spectral-gain characteristic is shown in Figure 6 (dashed curve), which represents the highest gain-product demonstrated to date for an EDFA pumped at 980nm.

An important characteristic of an optical amplifier is its saturation output power. Unlike a diode amplifier, an EDFA has both a saturation output power which increases with pump power, as well as an ability to operate deep in saturation without signal distortion and interchannel crosstalk[16]. 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[17].

Apart from its obvious use as a telecommunications pre-, line- and power-amplifier, the EDFA has a number of potentially-attractive uses in devices such as lossless power-splitters for local area networks and in the subscriber loop. An example of how the availability of a high-gain, high-peak power-amplifier can revolutionise the development of functional optical devices is the low-threshold Sagnac switch[18]. The switch configuration is shown in Figure 7, where an EDFA is placed within a non-linear Sagnac interferometer (or loop-mirror). Counter-propagating pulses within the loop differ in amplitude by the gain of the amplifier. One of the pulses is amplified on entering the loop and the other on exiting. Since the pulses propagating in opposite directions around the loop differ in amplitude, they accumulate a net phase-difference due to the optical Kerr effect. On recombination of the pulses at the coupler, they are routed to one or other of the outputs, depending upon their acquired intensity-dependent phase difference. Thus pulse routing between the outputs occurs as a function of intensity of the input pulse. Because of the high gain available from an EDFA (46dB), it was possible to construct an amplifying Sagnac loop which could be switched with an input power of only 200μW from a diode laser operating at 1.535μm, a figure more than three orders of magnitude lower than the best previously-reported. Thus the addition of the EDFA makes non-linear fibre switching and pulse-shaping a practical reality.

It is clear that the EDFA has an assured future in telecommunications amplification and switching at 1.535μm. Unfortunately, at present no equivalent rare-earth-doped amplifier exists at 1.3μm, the second communications window. Here diode amplifiers reign supreme, since the performance obtained with Nd^{3+}, the best candidate rare-earth available, is poor. This is because neodymium suffers from (i) a relatively-short fluorescent time-constant (-450μs), (ii) signal ESA at 1.3μm and (iii) a disadvantageous branching ratio to the strong 1.06μm transition. The combination of these three factors makes it unlikely that neodymium-doped fibre amplifiers at 1.3μm will ever show comparable performance to the EDFA.

Conclusions

Rare-earth-doped fibre lasers and amplifiers are inexpensive, easily-constructed devices. As a result, progress has been rapid and applications as high-power pulse sources for OTDR and sensors, superfluorescent sources for fibre-optic gyroscopes and in distributed sensors can be projected. Mode-locked fibre lasers are a very attractive to generate sub-picosecond pulse trains for application in soliton transmission systems. The fibre amplifier has already achieved commercial exploitation and is expected to find numerous applications in long-distance trunk telecommunications, particularly on undersea routes. Moreover, the availability of the fibre-based optical amplifier as a commonplace optical component is expected to revolutionise fibre components and functional optical devices.

References

1. E. Snitzer : "Optical maser action of Nd^{3+} in a barium crown glass", Phys. Rev. Lett., Vol. 7, p. 444, 1961.
2. J. Stone & C.A. Burrus : "Neodymium-doped fiber lasers: room temperature cw operation with an injection laser pump", Appl. Opt., Vol. 13, p. 1256, 1974.
3. S.B. Poole, D.N. Payne & M.E. Fermann : "Fabrication of low-loss optical fibres containing rare-earth ions", Electron. Lett., Vol. 21, p. 737, 1985.
4. R.J. Mears, L. Reekie, S.B. Poole & D.N. Payne : "Neodymium-doped silica single-mode fibre lasers", Electron. Lett., Vol. 21, p. 738, 1985.
5. R.J. Mears, L. Reekie, I.M. Jauncey & D.N. Payne : "High-gain, rare-earth-doped fibre amplifier at 1.54μm", Proc. OFC 1987, Reno, Paper WI2.
6. W.L. Barnes, P.R. Morkel, L. Reekie & D.N. Payne : "High quantum efficiency Er^{3+} fibre lasers pumped at 980nm", Opt. Lett., Vol. 14, pp. 1002-1004, 1989.
7. P. Urquhart : Review of rare-earth-doped fibre lasers and amplifiers", IEE Proc., Part J, Vol. 135, p. 385, 1988.
8. P.R. Morkel, G.J. Cowle & D.N. Payne : "A travelling-wave erbium fibre ring laser with 60kHz linewidth", Electron. Lett., Vol. 26, pp. 632-634, 1990.
9. R.J. Mears, L. Reekie & I.M. Jauncey : "High-power tunable erbium-doped fibre laser operating at 1.55μm", Proc. CLEO '87, Optical Society of America Technical Digest, Vol. 14, p. 122, 1987.
10. J.D. Kafka, T. Baer & D.W. Hall : "Mode-locked erbium fiber laser", Proc. CLEO '89, Optical Society of America Technical Digest, Vol. 11, p. 372, 1989.

11. E.K. Mwarania, L. Reekie, J. Wang & J.S. Wilkinson : "Low-threshold monomode ion-exchanged waveguide lasers in neodymium-doped BK-7 glass", Electron. Lett., Vol. 26, pp. 1317-1318, 1990.

12. S. Saito, T. Imai, T. Sugie, N. Ohkawa, Y. Ichihashi & T. Ito : "Coherent transmission experiment over 2223km at 2.5Gbit/s using erbium-doped fibre amplifiers", Electron. Lett., Vol. 26, pp. 669-670, 1990.

13. M. Horiguchi, M. Shimizu, M. Yamada, K. Yoshino & H. Hanafusa : "Highly efficient optical fibre amplifier pumped by a 0.8μm band laser diode", Electron. Lett., Vol. 26, pp. 1758-1759, 1990.

14. M. Nakazawa, Y. Kimura, K. Suzuki : "An ultra-efficient erbium-doped fibre amplifier of 10.2dB/mW at 0.98μm pumping and 5.1dB/mW at 1.48μm pumping", Proc. Topical Meeting on Optical Fibre Amplifiers and their Applications, Monterey, California, Postdeadline Session, Vol. 13, 1990.

15. 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, Vol. 13, pp. 44-47, 1990.

16. R.I. Laming, L. Reekie, P.R. Morkel & D.N. Payne : "Multichannel crosstalk and pump noise characterisation of Er^{3+}-doped fibre amplifier pumped at 980nm", Electron. Lett., Vol. 25, pp. 455-456, 1989.

17. R.I. Laming, D.N. Payne, F. Meli, G. Grasso & E.J. Tarbox : "Highly-saturated erbium-doped-fibre power amplifiers", Proc. Topical Meeting on Optical Fibre Amplifiers and their Applications, Monterey, California, Vol. 13, pp. 16-19, 1990.

18. D.J. Richardson, R.I. Laming & D.N. Payne : "Very-low theshold Sagnac switch incorporating an erbium-doped fibre amplifier", Electron. Lett., Vol. 26, pp. 1779-1781, 1990.

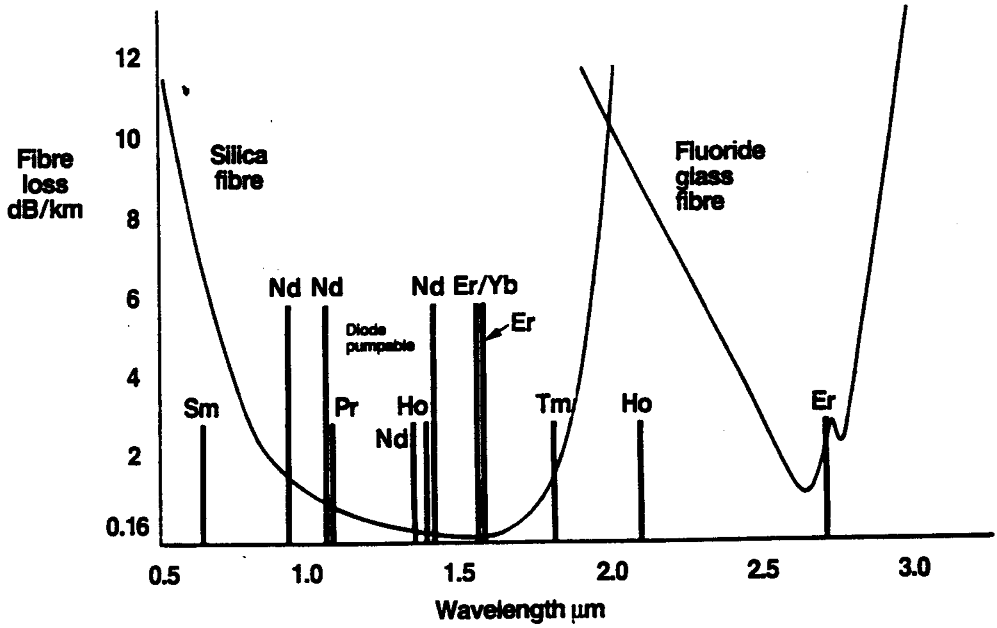

Fig 1 Fibre-laser emission wavelengths compared with the transmission windows of silica and fluoride fibres.

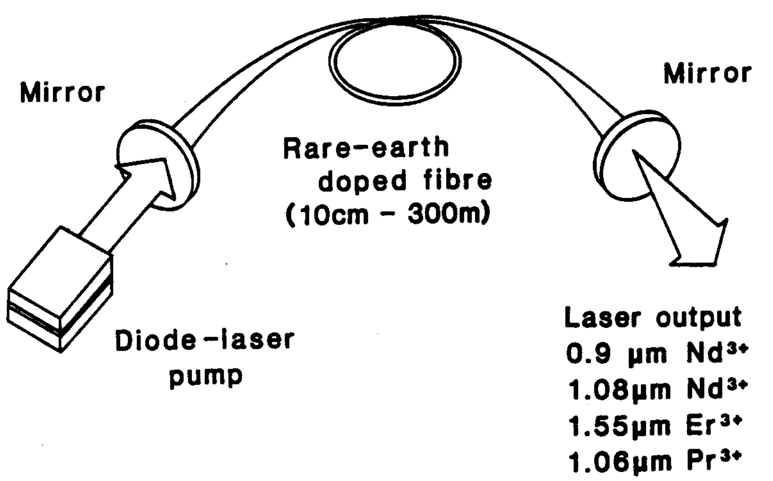

Fig 2 Schematic of a Fabry-Perot fibre laser configuration.

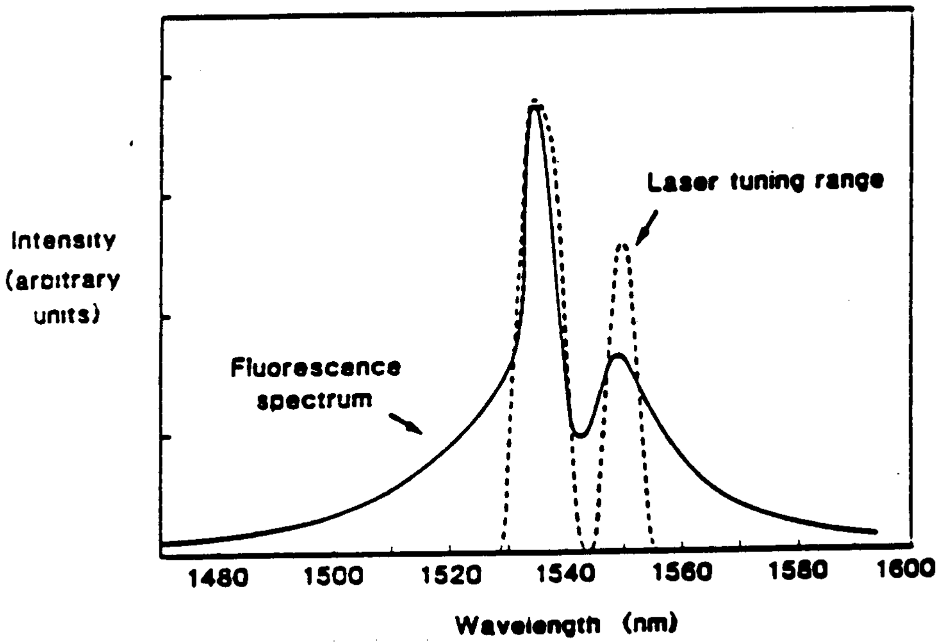

Fig 3 Tuning range and fluorescence spectrum of an Er^{3+}-doped fibre laser.

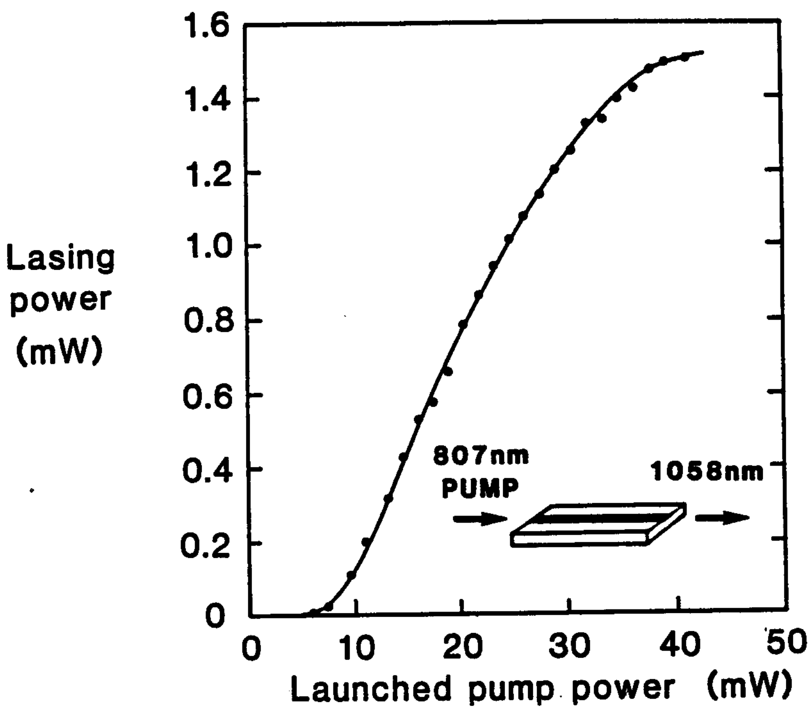

Fig 4 Laser characteristic of a low-threshold Nd^{3+}-doped single-mode planar glass laser.

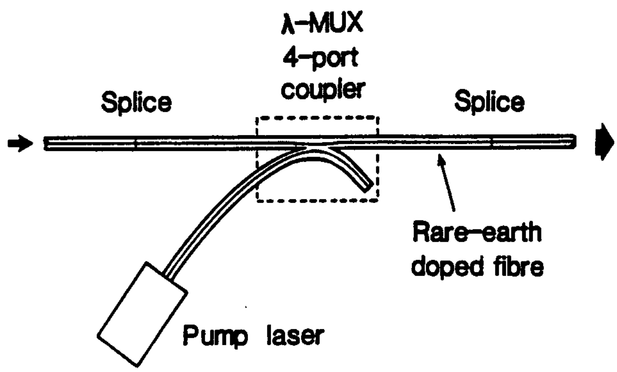

Fig 5 Schematic of an in-line erbium-doped fibre amplifier.

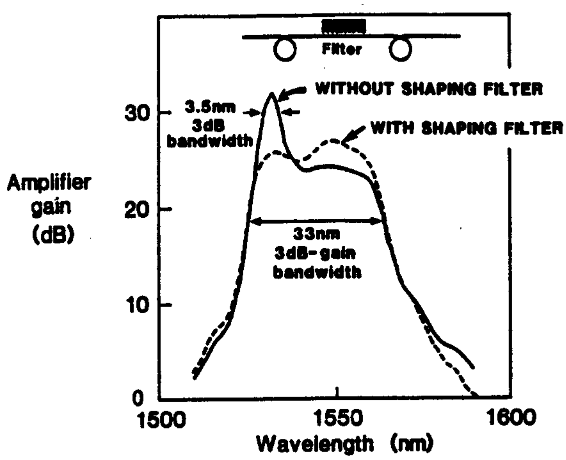

Fig 6 Spectral-gain characteristics of an erbium-doped fibre amplifier with (dashed curve) and without (solid curve) gain shaping using an integral filter.

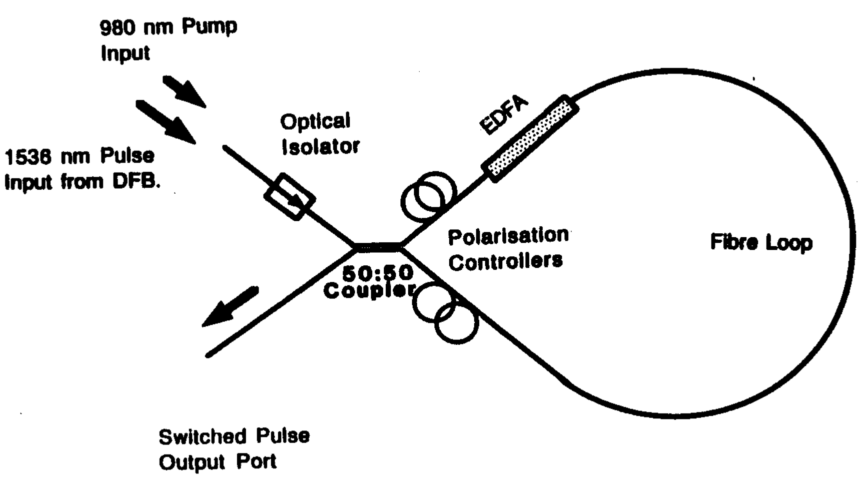

Fig 7 Low-threshold amplified non-linear Sagnac switch incorporating a fibre amplifier.