

SPECIAL FIBRES AND FIBRE DEVICES

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Abstract

The various types of optical fibres tailored for specific applications are reviewed. Emphasis is placed on rare-earth-doped fibres for use in fibre lasers and amplifiers. Fibre lasers have potential as well-controlled, quiet sources for telecommunications and sensors, while the erbium-doped fibre amplifier is already well-established as a low-noise, polarisation-insensitive repeater.

1. INTRODUCTION

Optical fibre telecommunications is now considered a mature technology, with silica single-mode fibre extensively installed in the network. However, it has lately been realised that optical-fibres can be employed in many and diverse applications, such as sensors, non-linear optics and active devices where the function of the fibre is considerably more than just a simple and exceptionally low-loss optical conduit. This realisation has been prompted by the development of fibres with characteristics tailored specifically to the application, a well-known example being the polarisation-maintaining fibre.

It is the intention of this review to highlight the proliferation of special fibre types, including those designed to control polarisation (low, high and circular birefringent types), metal/glass composite structures and fibres with controlled photo-refractive and non-linear properties. However, the special fibre which has had by far the greatest impact in recent years is the rare-earth-doped active version, and as a consequence, the majority of this review will concern recent developments in this area.

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 demonstrated¹ 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 report² in 1974 of laser operation in an Nd³⁺-doped silica multimode fibre, the idea of guided-wave glass lasers attracted little attention for the next 24 years. The idea resurfaced³ 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 resonators⁴ 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 amplifier⁵ (EDFA) operating in the third telecommunications wavelength-window at 1.54 μ m 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.

2. 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 $2\mu\text{m}$ (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 $1.54\mu\text{m}$ and $2.7\mu\text{m}$, 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 efficiency⁶ 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 ${}^4\text{I}_{13/2} - {}^4\text{I}_{15/2}$ transition of Er^{3+} at $1.535\mu\text{m}$ is at least 80nm in width³, (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 reported⁸. 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 $1.54\mu\text{m}$.

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-switching⁹. A compact, portable source of high peak-power pulses at $1.54\mu\text{m}$ 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 shown¹⁰ 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 laser¹¹. 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 $1.06\mu\text{m}$. 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.

3. ERBIUM-DOPED FIBRE AMPLIFIERS

The erbium-doped fibre amplifier (EDFA) is now undoubtedly the preferred amplifier for operation in the third telecommunications window at $1.54\mu\text{m}$. 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 ($\sim 3\text{dB}$). 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 reported¹².

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 results¹³, 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 band¹⁴. Somewhat lower pump efficiency¹⁴ 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 1.53 μ m (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 modified¹⁵ to be nearly uniform over the entire 1.53-1.56 μ m 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 crosstalk¹⁶. 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 possible¹⁷.

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 switch¹⁸. 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 200 μ W from a diode laser operating at 1.535 μ m, 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 1.535 μ m. Unfortunately, at present no equivalent rare-earth-doped amplifier exists at 1.3 μ m, the second communications window. Here diode amplifiers reign supreme, since the performance obtained with Nd³⁺, the best candidate rare-earth available, is poor. This is because neodymium suffers from (i) a relatively-short fluorescent time-constant (~450 μ s), (ii) signal ESA at 1.3 μ m and (iii) a disadvantageous branching ratio to the strong 1.06 μ m transition. The combination of these three factors makes it unlikely that neodymium-doped fibre amplifiers at 1.3 μ m will ever show comparable performance to the EDFA.

4. CONCLUSIONS

The availability of several special application-orientated fibre types has ensured the viability of a number of fibre sensors and devices. The best example of this is the rare-earth-doped fibre laser and amplifier. In this area progress has been rapid and applications such as high-power pulse sources for OTDR and distributed sensors, superfluorescent emitters for fibre-optic gyroscopes and

single-frequency sources for coherent communications 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.

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- 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.

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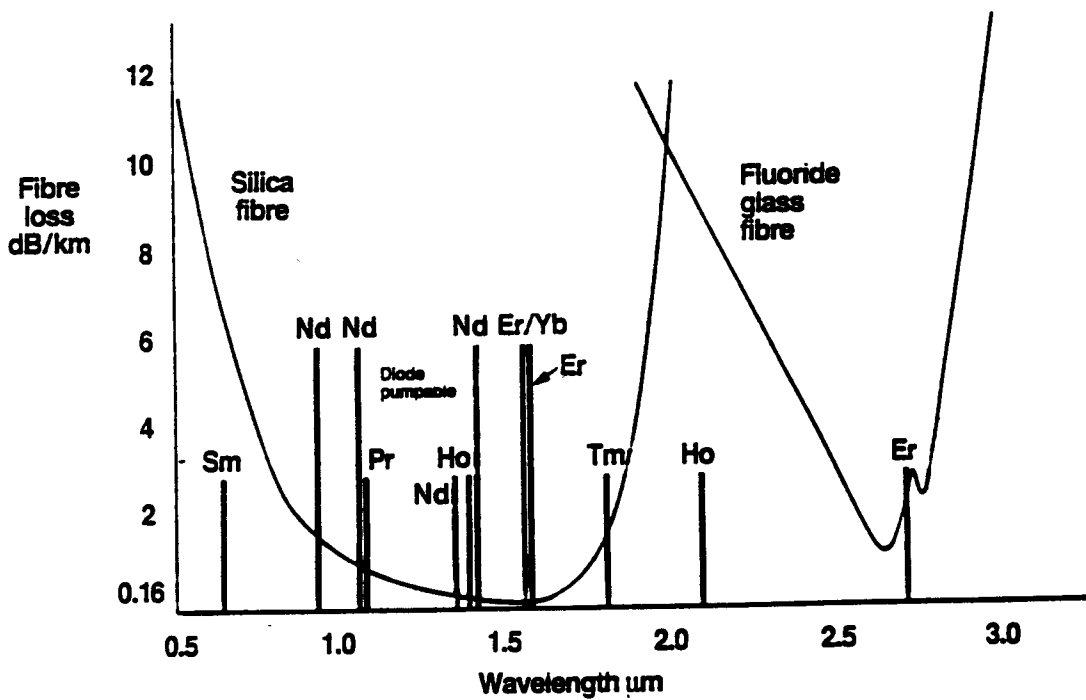


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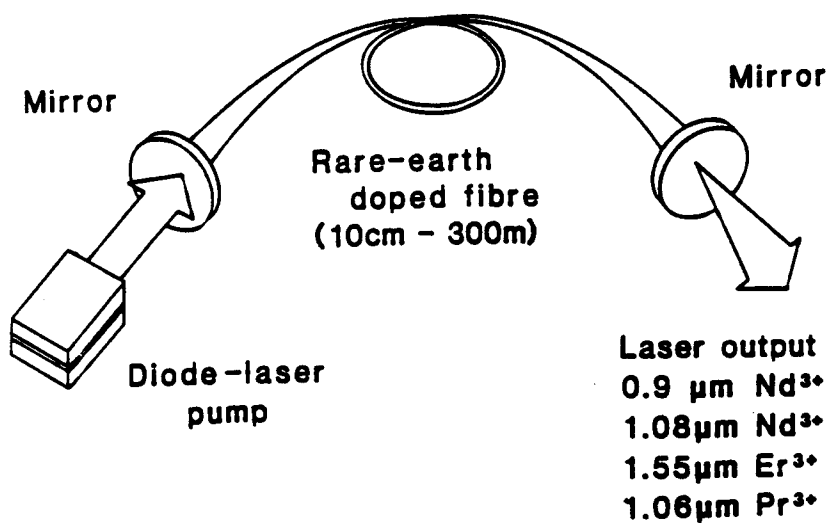


Fig 2 Schematic of a Fabry-Perot fibre laser configuration.

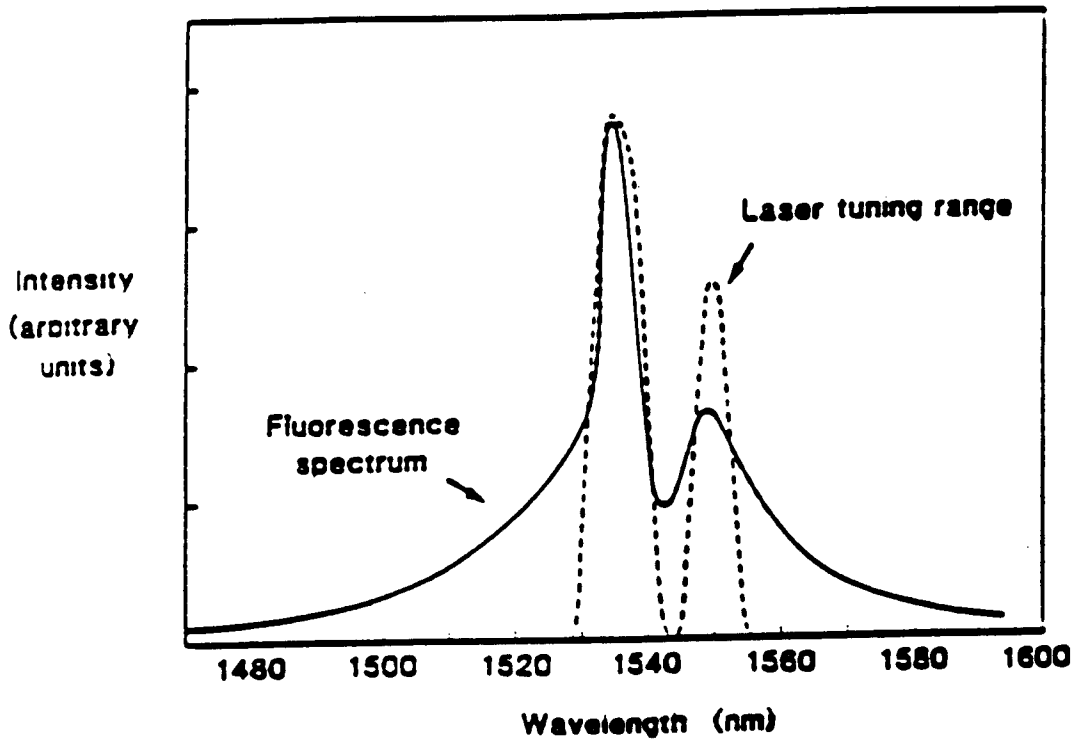


Fig 3 Tuning range and fluorescence spectrum of an Er^{3+} -doped fibre laser.

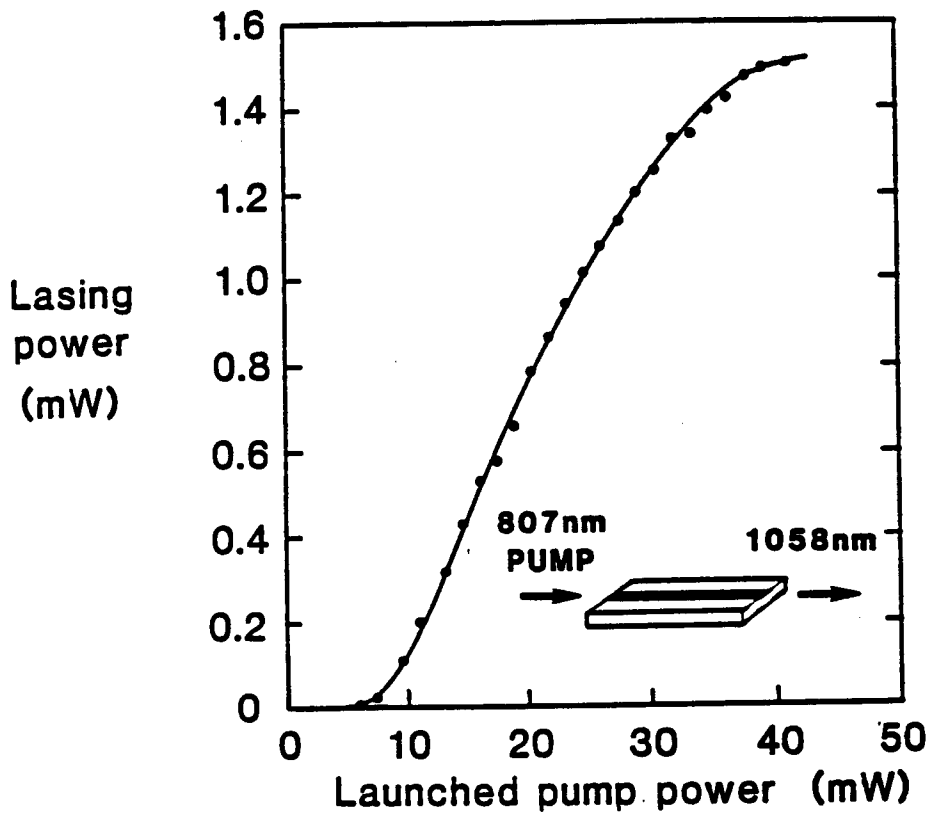


Fig 4 Laser characteristic of a low-threshold Nd^{3+} -doped single-mode planar glass laser.

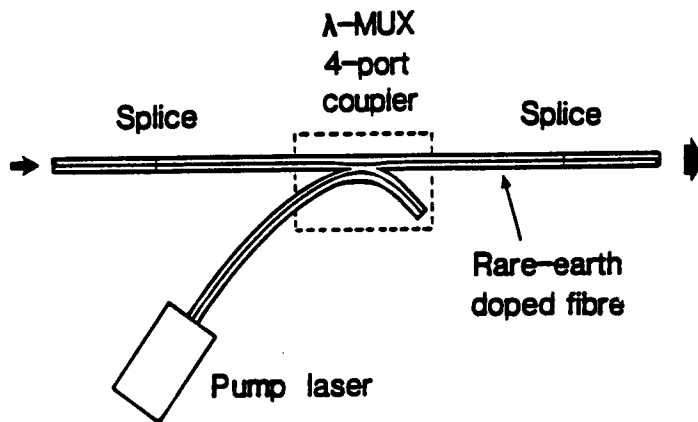


Fig 5 Schematic of an in-line erbium-doped fibre amplifier.

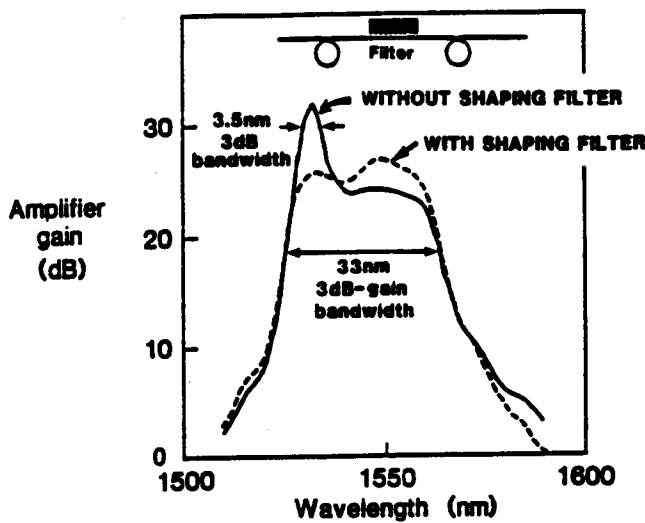


Fig 6 Spectral-gain characteristics of an erbium-doped fibre amplifier with (dashed curve) and without (solid curve) gain shaping using an integral filter.

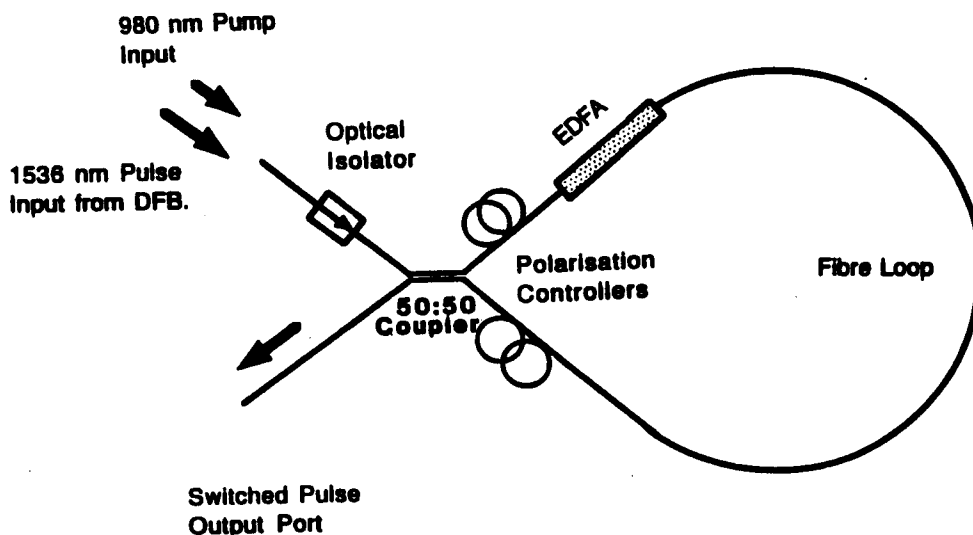


Fig 7 Low-threshold amplified non-linear Sagnac switch incorporating a fibre amplifier.