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# RARE-EARTH-DOPED GLASS FIBRE LASERS AND AMPLIFIERS

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## Abstract

When grouped with rare-earths, glass optical fibres provide the ideal amplifier and laser medium. Amplifiers exhibiting gains in excess of 50dB can be made with a noise figure close to the quantum limit. In addition, fibre lasers have been demonstrated using various rare-earths which give emission wavelengths spanning the region 400nm to 3.4$\mu$m. This exciting new technology is reviewed with particular reference to the advantages which can be obtained by adopting new glass hosts, such as germanates, phosphates, halides and chalcogenides.

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The erbium-doped fibre amplifier (EDFA) has developed rapidly since its announcement in 1987. The EDFA is now established as a key component for future high-speed, silica-based optical fibre communication networks operating at a wavelength of 1.55$\mu$m. Its major attributes are high gain, high efficiency, low noise and potential multichannel operation with low interchannel crosstalk. Expected applications are as fibre power-amplifiers in transmission systems and distribution networks, as signal repeaters in point-to-point optical links, as fibre pre-amplifiers in amplifier/receiver combinations and as distributed fibre amplifiers for soliton propagation.

As a result of its almost ideal amplifier performance and its wide applicability in telecommunications systems, the development of the amplifier as a component has already reached the point where today the EDFA can be considered as almost mature. Inevitably, therefore, further scope for major improvements is limited. However, there are a number of areas where enhanced performance may be expected in the future and which remain the subject of intensive worldwide investigation.

## Pump Efficiency and Noise

Factors which have emerged as important in achieving maximum gain for minimum pump power (max. dB/mW) are fibre numerical aperture, erbium concentration and confinement, and background loss. Unfortunately, these factors are interrelated; it is found that increasing the numerical aperture increases the fibre background loss, especially for high erbium concentrations. The best reported result of 11dB/mW [1] was for a fibre made by the VAD process. Results which exceed this value have yet to be reported, although fibres made in our laboratory using the MCVD fabrication process have achieved 8.9dB/mW. However, is should be recognised that a trade-off exists between gain efficiency and noise figure [2] owing to backward-travelling ASE which saturates the input to the amplifier. Thus with the conventional (co-directionally pumped) configuration it is virtually impossible to obtain a combination of high gain (>30dB) and quantum-limited NF. Incorporating an isolator in the middle of the EDFA overcomes these problems and we have demonstrated an amplifier with 54dB gain and 3.1dB NF for only 45mW of pump power.

## High Output Power

The search for EDFA's with output power is excess of +20dBm depends largely upon the availability of a sufficiently-powerful and practical pump source. Approaches vary from the use of multiple-diode lasers [3], to the adoption of Nd:YAG mini-lasers [4] and $Nd^{3+}$-doped fibre lasers [5]. The latter two emit at a wavelength around 1.06$\mu$m and can give output powers in excess of 1 Watt, thus showing considerable potential as pumps for EDFA's with output power approaching +30dBm. To exploit this pump wavelength requires an erbium/ytterbium co-doped fibre [6]. Recently, we have shown that it is also possible to directly pump an $Er^{3+}/Yb^{3+}$ amplifier or laser using a 1W 962nm multi-stripe diode using a cladding-pump configuration [7]. This is an extremely attractive route to high power operation of these devices and should be scalable to diode-pumped amplifiers giving is excess of 1W output.

### Planar EDFA's

Although the planar waveguide approach to erbium-doped amplifiers is attractive particularly for lossless splitting of a signal into a large number of output ports, the search for a planar amplifier is plagued by erbium concentration effects which result in a large loss of radiative quantum efficiency once the erbium concentration exceeds a few hundred ppm. This effect limits the length of the amplifier to around a metre. The search continues to find a glass host which is able to accept a high level of erbium doping from which amplifiers of a few mm in length can be fabricated.

### Soliton Generation

Several fibre laser soliton laser configurations have been reported, although most suffer from low repetition rates or pulse position uncertainty. Recently, a means whereby high-purity 70 Gbit/s cw soliton trains can be generated has been reported [8], using only two DFB laser diodes and an EDFA. The technique is based on the non-linear propagation and compression of a dial-frequency beat signal, amplified by an EDFA and propagated through a length of fibre having a dispersion-decreasing characteristic. The method is applicable to soliton train generation in the range 30-200 Gbit/s and yields mark space ratios from 1:5 to 1:11.

### 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 these have recently been used to obtain fibre laser output powers in excess of 4W.

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$\mu$m (Tm, Ho). Erbium sits conveniently at wavelengths of 1.54$\mu$m and 2.7$\mu$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 efficiency 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. 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.

## Conclusions

Some areas remain for improvement before the ultimate EDFA is achieved. As the EDFA matures, attention is now switching to areas where obvious gains can be made, for example low-loss components (isolators, WDM couplers), system control and engineering issues. Fibre lasers have seen far less adoption in practical systems, but can be seen as a general-purpose, widely-tunable, compact laser source which will rival miniature crystal lasers in the future.

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