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# RARE-EARTH-DOPED FIBRE LASERS AND AMPLIFIERS

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## ABSTRACT

Rare-earth-doped fibre lasers and amplifiers have been demonstrated at several wavelengths in the visible and near infrared regions. We describe recent advances in the field with particular attention to applications in telecommunications.

## INTRODUCTION

The field of rare-earth-doped fibre lasers [1,2,3] has expanded rapidly in recent years and there are now several groups working actively in the area. A variety of glass hosts, dopants and pump sources have been used, each with their own particular advantages and disadvantages. The goal is to achieve low-threshold, diode-laser-pumped operation of fibre lasers and amplifiers, particularly those operating in the second and third telecommunication windows. However, there is also considerable interest in the traditional laser area where the fibre laser is seen as a route to compact, tunable sources operating at wavelengths from the visible to the infra-red.

The small core size of the single-mode fibre allows high pump intensities for modest ($\sim$mW) pump powers. Moreover, the intensity can be maintained over long lengths and this leads to ultra-low lasing thresholds [4] and even permits CW diode-laser-pumped operation of three-level lasers [5]. In conjunction with the long fluorescent lifetime of rare-earths in glass, the high pump intensity allows high-gain ($>$30dB) operation of fibre amplifiers with excellent saturation properties[6]. In addition, compatibility with existing fibre components is excellent, allowing all-optical fibre circuitry to be assembled with both active and passive components. This is particularly beneficial for the fibre amplifier, where splicing of the active fibre into the telecommunication link virtually eliminates troublesome Fresnel-reflection feedback which normally limits the gain in optical amplifiers.

A particular attribute of fibre lasers is that the optical-damage threshold of silica is significantly higher than that of the materials used in semiconductor laser fabrication and it is therefore possible to obtain higher peak-power pulses from fibre lasers using the techniques of Q-switching and mode-locking. Recently [7], pulses at a wavelength of 1.060$\mu$m with a peak power in excess of 100W and a duration of 15ns have been obtained from a Q-switched 15cm length of $Nd^{3+}$-doped fibre for a pump power of only 12mW. Similar performance can be obtained from an $Er^{3+}$-doped fibre, suggesting exciting prospects as a practical source for OTDR's, non-linear optics and photonic switching.

The unique nature of the fibre laser allows lasing to be obtained with dopants and transitions that have not previously operated in glass, such as $Pr^{3+}$ [8] and $Sm^{3+}$ [9], or with three-level systems such as the 1.55$\mu$m transition in $Er^{3+}$[5]. A list of the fibre lasers demonstrated to date is given in Table 1. Here $SiO_2$ refers to the silica/germania host used in the fabrication of normal telecommunication fibres and also includes such materials as phosphorous and alumina which are often used as co-dopants to enhance the properties of the laser.

## FIBRE LASERS FOR TELECOMMUNICATIONS

Apart from the possibility [12] of 1.3$\mu$m operation in $Nd^{3+}$-doped fluoro-zirconate glass which has so far only been gas-laser pumped in multimode form, interest centres on a diode-pumped $Er^{3+}$-doped fibre source [5] for the third window at 1.55$\mu$m. Narrow linewidth (1MHz) operation of fibre lasers has been achieved [19] and therefore a highly-stable DFB fibre laser emitting tens of milliwatts can be projected as a source for coherent communications. Unfortunately, the pump band at 807nm is weak and narrow (Fig. 1) and the laser prefers to oscillate at a wavelength of 1.6$\mu$m where $Er^{3+}$ behaves as a quasi four-level system.

Recently the incorporation of alumina has allowed co-doping of the $Er^{3+}$-doped fibre laser with large quantities of $Yb^{3+}$, leading to resonant energy-transfer between the two species and subsequent alleviation of the pump-laser requirements [10]. Figure 2 clearly shows the additional absorption due to $Yb^{3+}$ superimposed on the $Er^{3+}$ absorption spectrum. We have subsequently obtained diode-laser-pumped operation of this laser (Fig. 3) without the need for stringent pump-laser wavelength selection. As can be seen, the $Yb^{3+}/Er^{3+}$ laser gives 1mW at the required telecommunications wavelength of 1.56$\mu$m and therefore appears to be an attractive source.

In the past year a new fibre laser host to appear is the multicomponent fluoride glass, or ZBLAN. Owing to its superior long-wavelength transmission, it has advantages over silica in the region beyond 1.6$\mu$m using dopants such as $Tm^{3+}$, $Ho^{3+}$ and $Er^{3+}$. The low multi-phonon decay-rates observed in a fluoride glass host allows lasing on transitions not available in silica, such as the 2.7$\mu$m line in $Er^{3+}$ [11]. This property will also be beneficial for upconversion schemes into the visible region.

Fluoride glasses also provide a means of perturbing the energy levels in such a way that the detrimental effects of excited-state absorption (ESA) to certain levels may be minimised, as has been demonstrated with laser action at 1.34$\mu$m in $Nd^{3+}$ [12]. A disadvantage is that the low phonon-decay rates leads to bottlenecking in the upper energy levels, thus reducing the gain available to low-lying lasing transitions, as evidenced by the poor performance of the 1.56$\mu$m transition in $Er^{3+}$-doped fluoride glasses [13]. Moreover, no report has yet been made of single-mode operation of a fluoride-glass fibre laser due to difficulty in fabricating monomode fluoride fibres. Despite these drawbacks, fluoride-glass fibre lasers are expected to play a significant role in the future.

## FIBRE AMPLIFIERS

Exceptionally high gain ($>$30dB) and low noise have been demonstrated [6,20,21] in erbium-doped fibre amplifiers which are also able to inject 10mW or more into a fibre. However, to date best performance has been obtained (Fig. 4) using impractical $Ar^{+}$-ion and dye-laser pump sources at wavelengths of 514nm and 660nm. Similar performance has yet to be demonstrated with more realistic solid-state pump sources.

Reference to the absorption spectrum of an erbium-doped fibre (Fig. 1) shows that potential practical pump-bands exist at wavelengths of 532nm, 670nm, 807nm and 980nm. Of these, sources at 532nm (frequency-doubled mini-YAG lasers) and 807nm (multi-stripe laser diodes) are available today, while for 670nm and 980nm relatively low-power laser diodes have been reported. Also shown on the Figure are regions of pump excited-state absorption (ESA), a phenomenon which particularly plagues three-level, longitudinally-pumped optical amplifiers. The effect occurs when a further transition is present above the (highly-populated) upper laser level with an energy difference corresponding to that of the pump photons. In this case an additional absorption occurs at the pump wavelength which drains pump power and limits the available gain. It can be seen that whereas 532nm, 670nm and 980nm are relatively clear of ESA, the most practical pump band (807nm) is quite strongly affected and limited gain is therefore available[22].

Current research on erbium fibre amplifiers is aimed at (i) developing solid-state sources to exploit the available ESA-free pump bands and (ii) investigating alternative host glasses in the hope of shifting the ESA bands away from the desirable 807nm pump band. Unless ESA at 807nm can be overcome, the 532nm frequency-doubled mini-YAG is the best pump prospect to exploit the full performance of the amplifier.

We note that a preliminary report [23] has shown the feasibility of pumping in-band at 1490nm, for which high-power laser diodes are available, but further work is required before high gain can be demonstrated.

## CONCLUSIONS

Considerable progress on fibre lasers and amplifiers has been made for application both in telecommunications and the traditional laser area. For telecommunications it is anticipated that applications will be as (i) a high-power pulse source for OTDR and non-linear effects, (ii) a narrow-linewidth source at a wavelength of 1.55$\mu$m and (iii) a high-gain in-line and power amplifier in the third window. Further in the future, sources based on ZBLAN glass for operation at the longer wavelengths required for fluoride-glass fibre transmission are anticipated.

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| DOPANT | HOST | WAVELENGTH | PUMP | REF. |
|---|---|---|---|---|
| $Sm^{3+}$ | $SiO_2$ | 651nm | 488nm | 9 |
| $Nd^{3+}$ | $SiO_2$ | 938nm | DIODE | 14 |
| $Nd^{3+}$ | ZBLAN | 1.05μm | 514nm | 12 |
| $Yb^{3+}$ | $SiO_2$ | -1.06μm | 850nm | 15 |
| $Nd^{3+}$ | $SiO_2$ | -1.06μm | DIODE | 3 |
| $Pr^{3+}$ | $SiO_2$ | 1.07μm | 590nm | 8 |
| $Nd^{3+}$ | ZBLAN | 1.34μm | 514nm | 12 |
| $Ho^{3+}$ | ZBLAN | 1.38μm | 488nm | 16 |
| $Nd^{3+}$ | $SiO_2$ | 1.4μm | DIODE | 18 |
| $Er^{3+}$ | $SiO_2$ | 1.55μm | DIODE | 5 |
| Er/Yb | $SiO_2$ | 1.55μm | 820nm | 10 |
| $Er^{3+}$ | ZBLAN | 1.56μm | 488nm | 13 |
| $Tm^{3+}$ | $SiO_2$ | 1.8μm | 820nm | 17 |
| $Ho^{3+}$ | ZBLAN | 2.08μm | 488nm | 16 |
| $Er^{3+}$ | ZBLAN | 2.7μm | 476nm | 11 |

Table 1: Fibre lasers to date

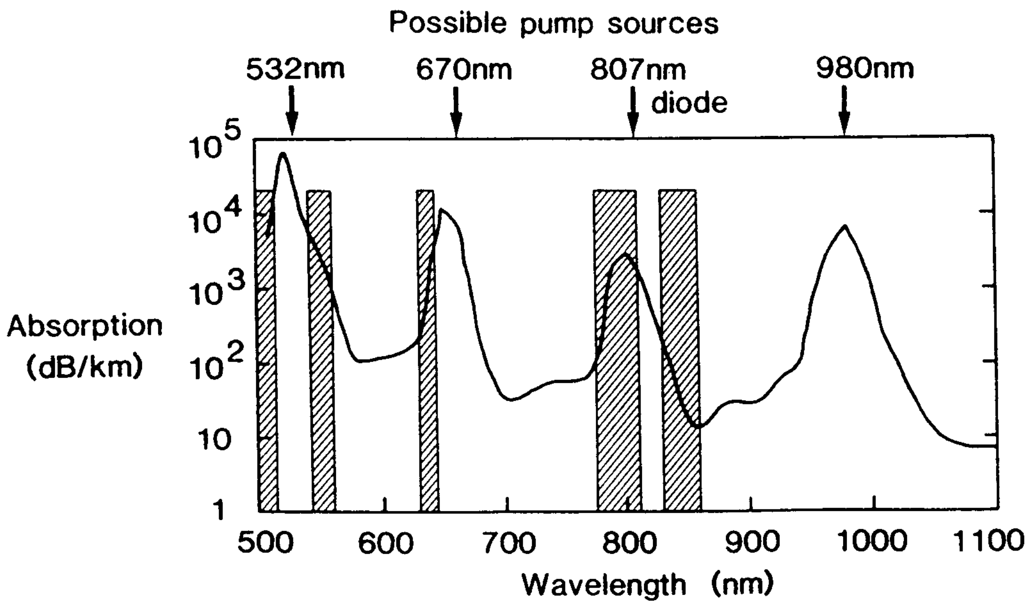

Fig. 1 Absorption spectrum of $Er^{3+}$ in a fibre co-doped with $Al_2O_3$. Shaded areas are regions of excited-state absorption. Possible pump-source wavelengths are also marked.

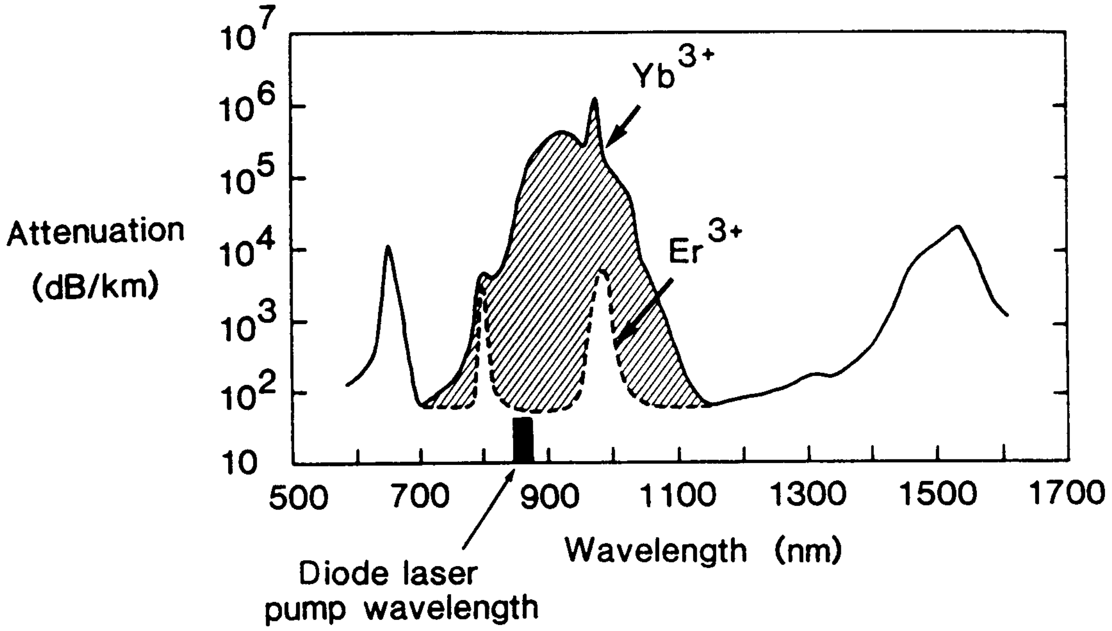

Fig. 2 Absorption spectrum of $Er^{3+}/Yb^{3+}$ co-doped fibre showing increased absorption at diode-laser-pumped wavelength due to $Yb^{3+}$.

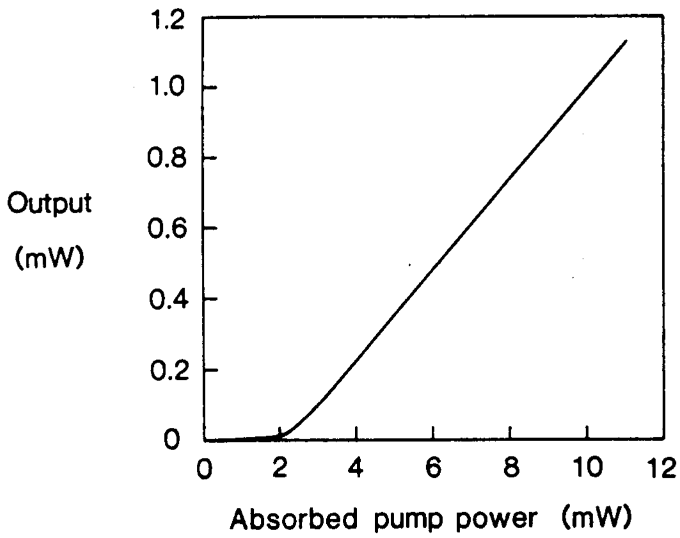

Fig. 3 Laser characteristics of 810nm diode-laser-pumped $Er^{3+}/Yb^{3+}$ co-doped fibre laser emitting at 1.056$\mu$m. Fibre length 37.5cm, NA 0.23.

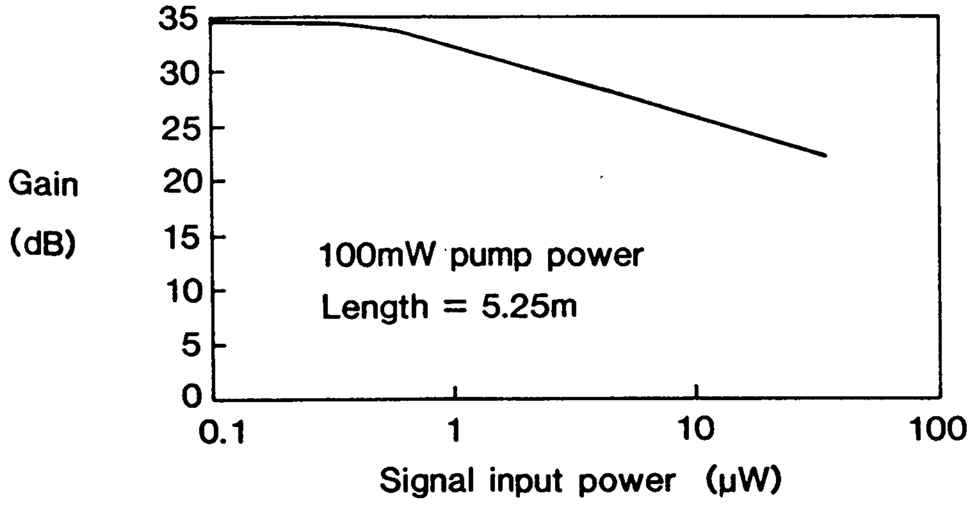

Fig. 4 Gain in an $Er^{3+}$-doped fibre amplifier pumped at 670nm. Fibre NA 0.2, cut-off wavelength 1.1$\mu$m.