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# Recent developments in rare-earth-doped fibres and fibre lasers

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## ABSTRACT

The development of techniques to produce single-mode rare-earth-doped fibres has led to many passive and active (laser) devices based on these fibres including distributed temperature sensors, high-rejection wavelength selective filters, and fibre lasers and amplifiers. The possibilities offered by fibre lasers and amplifiers are particularly exciting since they present a potential technique for achieving compact, tunable, diode-pumped, narrow-linewidth sources which are compatible with optical fibre technology. Recent developments include diode-pumped fibre lasers operating at 1.08$\mu$m with c.w. output powers of 6mW and Q-switched (pulsed) operation with output in excess of 13W. Single-longitudinal-mode operation with a linewidth of 1.3MHz has been demonstrated, as has single-polarisation operation with an extinction ratio of 37dB. The extension of these techniques to operation at 1.55$\mu$m will find immediate applications in coherent communications system and will be discussed, as will additional active and passive devices including in-line fibre amplifiers and bistable fibre switches.

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# RECENT DEVELOPMENTS IN RARE-EARTH-DOPED FIBRES AND FIBRE LASERS

(INVITED)

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## Introduction

The incorporation of rare-earth dopants into the core or cladding of optical fibres opens up many opportunities for both active and passive fibre devices. However, until recently it was thought that incorporation of these dopants would destroy the hard-won low-loss characteristics of telecommunications fibres and render them inoperable as distributed sensors and amplifiers. Simple, reproducible fibre-fabrication techniques have now been developed[1-3] which do not significantly increase the fibre loss. These processes allow the uniform incorporation of low levels of rare-earth ions in the core or cladding of many types of optical fibres. The dopants used are not limited to the rare-earth elements, and could be applied to any dopant with a solid precursor material, for instance the transition metals.

Using these techniques, single-mode fibres have been fabricated containing various rare-earths (Nd, Er, Dy, Tb, Ce, Eu, Tm, Yb and Pr) with dopant levels of between 0.2ppm and 3000ppm. Remarkably, all exhibit windows in which losses are comparable with conventional fibres, despite the close proximity of very high-loss dopant absorption bands (Fig.1.) Measurements by optical time-domain reflectometry indicate that the dopant is incorporated uniformly along the length of the fibre. The low fibre losses, combined with the consistency of dopant incorporation along the fibre length, make the fibres suitable for absorption filters, distributed sensors, fibre lasers and amplifiers and non-linear devices.

## Rare-earth-doped fibre filters

The very large, sharp absorption bands of rare-earth-doped fibres, combined with the low losses obtainable away from these absorptions, suggest that compact, low-insertion-loss wavelength filters with extremely high rejection can be fabricated. These find application in wavelength multiplexing and also in spectroscopy, where very high rejection of the exciting laser is required. As a demonstration of such a filter, a length of $Ho^{3+}$-doped fibre has been used to separate the anti-Stokes spontaneous Raman scattering from the pump wavelength in a short length of fibre[4]. The fibre used had a differential attenuation of ~ $10^9$ between the pump laser wavelength (HeNe at 633nm) and the anti-Stokes Raman line at 616nm. A 20m length of monomode fibre was used to generate forward-scattered anti-Stokes Raman, with a 7m length of $Ho^{3+}$-doped fibre used to filter the unwanted pump signal. The resulting Raman spectrum obtained is shown in Figure 2 in which the anti-Stokes scattering at 616nm and a weak emission at 684nm (corresponding to the $1183^{-1}$ Raman line in silica) are clearly visible. Some pump throughput is still visible, but greater rejection could be obtained, if required, by simply increasing the fibre length.

## Rare-earth-doped fibre sensors

Whilst $Nd^{3+}$-doped glass point-temperature sensors based on changes in absorption spectrum with temperature have been known for many years, the application of this technique to distributed sensors required the development of low-loss rare-earth-doped fibres described above. In a distributed sensor of this type, the loss of a fibre at a wavelength on the edge of an absorption band is monitored by interrogating the local fibre absorption using optical time-domain reflectometry. The typical temperature-dependence of absorption of a $Nd^{3+}$-doped fibre at a wavelength of 600nm is shown in Figure 3. With this fibre, which contained only 5ppm $Nd^{3+}$, the temperature distribution along the fibre could be determined with 2°C accuracy and a spatial resolution of 15m[5]. Considerable improvements in performance can be obtained by using other rare-earth dopants at higher concentrations. This has been demonstrated by using a $Ho^{3+}$-doped fibre containing 1000ppm $Ho^{3+}$ ions[6]. In this way a sensitivity of better than 1°C with a spatial resolution of 3.5m was obtained over the temperature range -200 to 100°C.

Fibre lasers

A class of active fibre devices compatible with single-mode optical fibre sensor systems is highly desirable to supplement the hybrid semiconductor-diode/optical-fibre technologies currently in use. As a first step towards this goal, lasing action in rare-earth-doped silica single-mode fibre lasers has been demonstrated. These possess a number of advantages over their bulk counterparts. By virtue of their small active areas, very-low thresholds and high gains can be achieved and this has allowed the demonstration of lasing action on a transition never previously observed in glass[7]. Since the typical fibre diameter is 125$\mu$m, thermal effects which plague bulk-glass lasers are minimal. Silica, the host material, has good power-handling characteristics; moreover, it broadens the rare-earth transitions, enabling compact, tunable diode-pumped lasers at various wavelengths to be constructed.

It is now possible to construct a wide range of active fibre devices and sensors which exploit the numerous fibre components available, such as 4-port couplers, ring-resonators, polarisers and filters. The very-low losses of the fibres permit the construction of long amplifiers and lasers (1400m has been demonstrated) as well as non-linear devices and distributed active-sensors.

For $Nd^{3+}$-doped fibres, a lasing threshold as low as 100$\mu$W can be obtained using a semiconductor-laser end-pump[8] whilst in an optimised cavity, an output exceeding 5mW at a wavelength of 1088nm has been observed, with a slope efficiency of 40%. Tuning of the output wavelength can be accomplished by substituting a grating for one of the mirrors[9] and a tuning range of 92nm (from 1065-1150nm) is possible. This is the most extensive tuning range yet obtained in a Nd:glass laser and compares favourably with that of a dye laser.

Erbium-doped fibre lasers operate between 1530nm and 1555nm on the $^4I_{13/2}$ - $^4I_{15/2}$ (ground-state) transition, which coincides with the important minimum-loss window for optical communications. The fluorescence spectrum with a typical tuning curve for an $Er^{3+}$-doped fibre laser superimposed on it is shown in Figure 4. Despite being a 3-level laser system, CW operation is possible and a threshold of only 1.6mW has been reported[10]. At the time of writing this represented the lowest threshold 3-level glass laser yet reported. The recent demonstration of a diode-pumped $Er^{3+}$ fibre laser[11] will lead to many practical applications of this device. Optical bistability has also been observed in an $Er^{3+}$-doped fibre laser operating at 1.54$\mu$m[12]. This is based on the mechanism of saturable absorption and has many potential applications including optical memories, switching and amplification.

Q-switching of fibre lasers using an acousto-optic modulator or rotating chopper is also possible and peak powers of up to 250 watts have been observed in pulses ranging from 30ns to 1$\mu$s. Recently, a number of optical fibre devices have been integrated into fibre lasers. These include fibre polarisers, to give single-polarisation operation of the laser with the exceedingly high extinction ratio of 37dB[13], and fibre gratings to reduce the output linewidth to as little as 1.3 MHz from the free-running linewidth of >5nm[14]. In addition, a number of novel resonant configurations have been demonstrated which obviate the need for dielectric mirrors[15,16]. These demonstrate the possibilities of creating all-fibre systems containing no bulk optical components.

## Fibre amplifiers

Optical amplifiers are of interest as wideband in-line repeaters for telecommunications and as signal regenerators for a variety of sensor applications. An optical fibre amplifier based on an $Er^{3+}$-doped fibre which has a maximum gain at a wavelength of 1.536$\mu$m has been reported[17]. The gain characteristic at 140MHz modulation rate is shown in Figure 5 and from this it can be seen that a single-pass gain of 26dB is obtained, with a maximum output power of 13dB/m. The input equivalent noise power was measured at -45dBm in a 140MHz bandwidth. These preliminary results show that $Er^{3+}$-doped fibre amplifiers have excellent gain and noise characteristics which make them attractive as wideband optical repeaters.

## Conclusions

The availability of low-loss rare-earth-doped fibres has led to many active and passive fibre devices. These device will find applications in sensor and communications systems in the near future.

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## References

1. S.B.Poole, D.N.Payne, M.E.Fermann, "Fabrication of low-loss optical fibres containing rare-earth ions", Electron. Lett., 21, pp.737-8, 1985.
2. J.E.Townsend, S.B.Poole, D.N.Payne,"Solution-doping technique for the fabrication of rare-earth-doped optical fibres",ibid.,23,pp.329-31,1987.
3. C.A.Millar, B.J.Ainslie, I.D.Miller, S.P.Craig, "Concentration and co-doping dependence of the $^4F_{3/2}$ to $^4I_{11/2}$ lasing behaviour of $Nd^{3+}$ silica fibres", Proc. IOOC/OFC., Reno, Nevada, 1987, Paper WI4.
4. M.C.Farries, J.E.Townsend, S.B.Poole, "Very high rejection optical fibre filters", Electron. Lett., 22, pp.1126-1128, 1986.
5. M.C.Farries, et al, "Distributed temperature sensor using $Nd^{3+}$-doped fibre", ibid., 22, pp.418-419, 1986.
6. M.C.Farries, M.E.Fermann, S.B.Poole, J.E.Townsend, "Distributed temperature sensor using Holmium-doped optical fibre", Proc. OFC., Reno, Paper WI5, 1987.
7. L.Reekie, R.J.Mears, S.B.Poole, D.N.Payne, "A $Pr^{3+}$-doped single-mode fibre laser", IOP/IEE Symposium on "Advances in Solid State Lasers", London, 1986.
8. R.J.Mears, L.Reekie, S.B.Poole, D.N.Payne, "Neodymium-doped silica single-mode fibre lasers", Electron. Lett., 21, pp. 738-740, 1985.
9. L.Reekie, R.J.Mears, S.B.Poole, D.N.Payne, "Tunable single-mode fibre lasers", J. Lightwave Tech., LT-4, pp. 956-960, 1986.
10. I.M.Jauncey, L.Reekie, S.B.Poole, D.N.Payne, "Extended wavelength operation of an $Er^{3+}$-doped fibre laser pumped at 808nm", Submitted to OFC'88, New Orleans, 1988
11. L.Reekie, I.M.Jauncey, S.B.Poole, D.N.Payne, "Diode laser pumped operation of an $Er^{3+}$-doped single-mode fibre laser", Electron. Lett, 23, 1986

12. L.Reekie, R.J.Mears, S.B.Poole, D.N.Payne, "Optical bistability at 1.54$\mu$m in an $Er^{3+}$-doped fibre laser", Proc. CLEO., San Francisco,1986.
13. J.T.Lin, L.Reekie, L.Li, "Single polarisation operation of a $Nd^{3+}$-doped single-mode fibre laser", Proc. CLEO., Baltimore, Md, 1987.
14. I.M.Jauncey, et al, "Narrow-linewidth fibre laser with integral fibre grating", Electron. Lett., 22, pp.987-988, 1986.
15. D.N.Payne, "Special fibres and their applications", Invited Paper at IOOC/OFC., Reno, Paper WI1, 1987.
16. I.D.Miller, D.B.Mortimore, B.J.Ainslie, W.P.Urqhart, S.Craig, C.A.Millar, D.B.Payne, "A new type of all-fibre laser", ibid., Paper WI3, 1987.
17. Mears, R.J., L.Reekie I.M.Jauncey, D.N.Payne, "High-gain rare-earth-doped fibre amplifier at 1.54$\mu$m", ibid., Paper WI2, 1987.

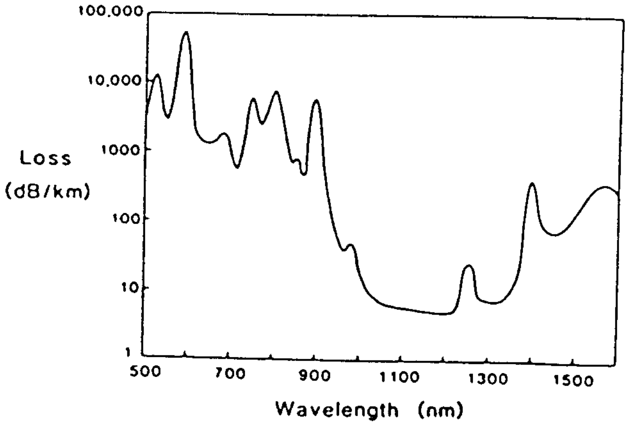

*Figure 1* Absorption spectrum of fibre doped with 300ppm $Nd^{3+}$ ions

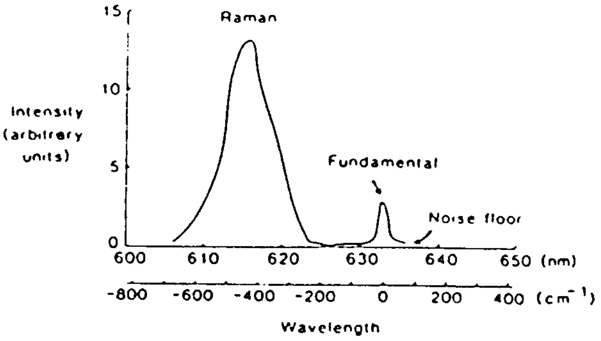

*Figure 2* Transmission of fibre filter showing pump rejection and Raman transmission.

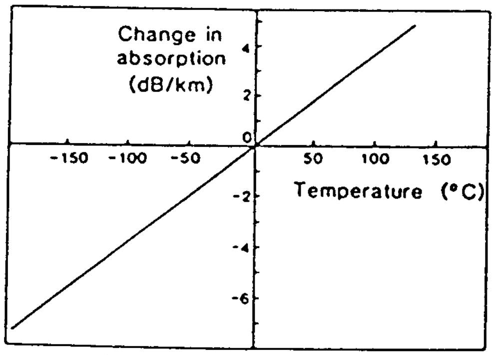

*Figure 3* Temperature dependence of absorption of $Nd^{3+}$-doped fibre at 600nm.

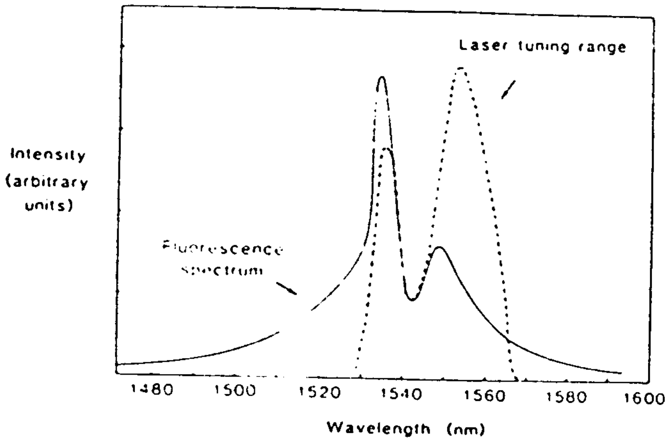

*Figure 4* Laser tuning curve and fluorescence spectrum for $Er^{3+}$-doped fibre laser.

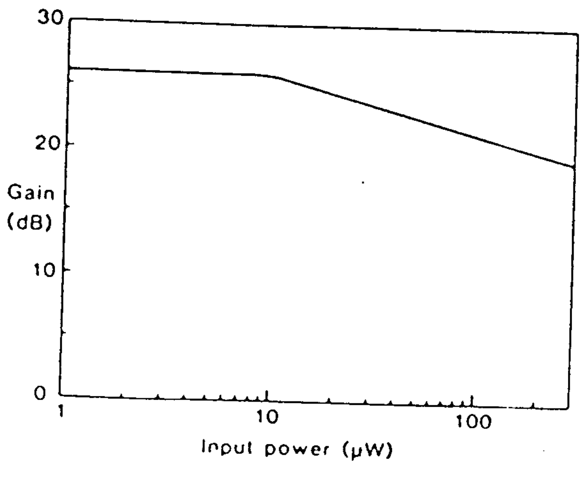

*Figure 5* Gain characteristic of $Er^{3+}$-doped fibre amplifier operating at 1550nm with a modulation rate of 140MHz.