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Er^{3+}-Yb^{3+} and Er^{3+} doped fibre lasers

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Abstract

Single-mode fibre lasers operating at ~1.57 μm are described. Output powers of >2 mW are reported for laser diode pumped operation. Direct comparison is made between fibre lasers employing sensitized erbium (Er^{3+} and Yb^{3+}) and erbium on its own. The performance of Er^{3+}-Yb^{3+} fibre lasers is then analyzed in more detail as a function of fibre length. Both CW and Q-switched operation are studied and the results obtained demonstrate that practical sources at 1.5μm are available from diode pumped Er^{3+}-Yb^{3+} systems.

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Introduction

Optical fibres doped with erbium (Er^{3+}) have been developed for use as both optical amplifiers and lasers [1-7]. These devices are of considerable importance since their operating wavelength coincides with the third window for optical fibre communication, around 1.55 μm. To obtain a practical device however, the Er^{3+} doped fibre must be laser diode pumped and to date only modest output powers have been achieved, of order 100μW [4,6,7], for available diodes operating at around 810nm. (Recently, [8], pumping with laser diode arrays has allowed up to 8 mW to be obtained). Furthermore, since the operating wavelength of a laser diode is temperature dependant and the $^4I_{13/2}$ - $^4I_{15/2}$ absorption of Er^{3+} in silica is spectrally narrow, fluctuations in temperature will lead to a change in performance of the fibre laser. One solution to this problem is to sensitize the fibre by co-doping the Er^{3+} with Yb^{3+} [4,9,10]. The Yb^{3+} then absorbs much of the pump light and cross relaxation between adjacent ions of Er^{3+} and Yb^{3+} allows the absorbed energy to be transferred to the Er^{3+} system (fig 1), thus providing another route for pumping the laser. Comparison of lasers' made with Er^{3+}-Yb^{3+} and just Er^{3+} are made in section 1 whilst a more detailed investigation of the performance of the co-doped system is presented in section 2.

The effect of co-doping the fibre with Yb^{3+} is clearly shown in fig 2 (obtained for a fibre with an Yb^{3+}:Er^{3+} ratio of 30:1). With Yb^{3+} present light can be absorbed both directly into the Er^{3+} band (at ~0.8μm) and to the long wavelength side of it. We may also note that Yb^{3+} contributes essentially no absorption operating wavelengths. This step-like behaviour is in marked contrast to that previously reported, where a gradual transition was seen [5,6]: but is similar to that predicted for a phosphate glass [14] . Since this step occurred for both Er^{3+} and Er^{3+}-Yb^{3+} lasers it seems that the effect is due to Al_2O_3 and/or P_2O_5 used in fabricating these fibres, rather than from the Yb^{3+}. The fibre in refs 5 and 6 had a GeO_2/SiO_2 core glass, rather than $Al_2O_3/P_2O_5/SiO_2$ reported here and it would thus appear that the Al_2O_3 and/or P_2O_5 causes a significant alteration either the $^4I_{15/2}$ ground state, or the $^4I_{13/2}$ metastable level, of Er^{3+}.

The wavelength of operation was independent of pump power up to the maximum available power (~5 times threshold). For one particular fibre length, laser action took place simultaneously at both long (~1.60μm) and short (~1.57μm) wavelengths (see fig 3). Operation could not be shifted from one wavelength to the other by altering the pump power. The lasing linewidth was measured at ~2nm (with an instrument of 0.1nm resolution).

It is important to remember that only the shorter fibre lengths lase in the short wavelength regime (fig 3). Requiring the laser to operate in the short wavelength regime may thus limit the performance. Careful design of the mirror may prevent oscillation at 1.6μm, thus allowing longer lengths to be used.

fibre lengths, the launched power, the attenuation and the absorbed power, could all be determined. The output and absorbed power were subject to ~5% and ~7% systematic errors respectively. All experiments were carried out at room temperature.

For the Q-switching work, the laser cavity was opened by placing a lens and acousto-optic modulator between the output end of the fibre, and the output coupler [1].

SECTION 1 Comparison of the fibre types

Results and discussion

a) Laser wavelength

In a three level laser, such as Er^{3+} in silica, the fibre length used can determine the lasing wavelength [5,6]. For instance, if the fibre length is too long then an un-bleached region remains at the output end of the fibre laser which re-absorbs light preferentially over the short wavelength part of the fluorescent band. The ratio of gain to loss is thus greatest for such a system at long wavelengths and so lasing operation occurs at ~1.6μm. Similarly, reducing the fibre length decreases the effect of re-absorption and the lasing wavelength also decreases.

Several sets of data were acquired for lasing wavelength vs fibre length for both Er^{3+} and Er^{3+}-Yb^{3+} systems, an example of which is shown in fig 3. All the data showed similar behaviour with two distinct regimes of operation, termed the 'long' and 'short' light whilst reflecting ~99.8% of the 1.5-1.6μm light. Several different output mirrors were used, each typically reflecting 20% of the pump light back into the fibre. For both (Er^{3+} and Er^{3+}-Yb^{3+}) fibre lasers, output power was maximized by using mirrors with transmissions in the range 20-30%. The pump laser diodes operated at ~810nm and 826nm with output powers of 30-40mW and, to increase the pump power available some experiments were carried out with two diodes, their beams being combined with a polarizing beam splitter. Launch efficiencies were in the range 30-50% depending on the optical configuration and the diodes used. Fibres were fabricated by the solution doping technique [11] and their properties are summarized in table 1. An $Al_2O_3/P_2O_5/SiO_2$ core was deposited to improve the rare earth ion solubility and prevent devitrification [12]. The co-doped fibre was measured [13] to have a transfer efficiency of 37% for zero population inversion, and an estimated efficiency of 20% for an inversion of 50%.

The lasers were characterized by measurements of both pump and output powers with calibrated silicon and germanium detectors, together with measurements of the lasing wavelength by a monochromator (2nm resolution). Since the 1.5μm transition must be bleached to obtain lasing action, a considerable fraction of the pump light is not absorbed by the fibre but instead emerges from the output end of the laser. It is not therefore possible to infer the absorbed power from small signal attenuation data. However, by measuring the transmitted pump power for a series of beyond 1.2μm and we thus expect the laser performance of Er^{3+} and Er^{3+}-Yb^{3+} systems to differ mainly in the way they are pumped. Erbium operates as a three level laser so that a length of unpumped fibre absorbs strongly at the lasing wavelength. This is particularly important for end pumped fibre lasers and means that fibre length is a very important parameter in the design of such a laser. For a given length of fibre, lasing can occur only if the gain available from the bleached section equals, or exceeds, the loss of the remaining length of fibre (and of course, any other losses present). From the foregoing, it is clear that for a given amount of pump power an optimum fibre length will exist. This length will be long enough to absorb a significant fraction of the pump power but short enough to minimize re-absorption in the unbleached section. The optimum fibre length will thus be pump power dependent. The main aim in section two of the present study was to investigate this pump power dependence thus enabling the correct choice of fibre length for a given pump power. Clearly, such length dependences will scale with the dopant level in the fibre.

Experimental

To compare the performance of single and co-doped fibres a series of lasers were assembled and their performance evaluated under different pumping conditions. The lasers were constructed by the standard approach of butting cleaved fibre ends up against dielectric mirrors [6]. The input mirror transmitted ~80% of the pump

b) Dependence of threshold on pump wavelength.

Whilst it was possible to pump the co-doped fibre laser with 826nm diodes (with a somewhat increased threshold) it was not possible to reach threshold for the Er^{3+} laser. The pump wavelength dependence was thus investigated with a CW styryl 9 dye laser as the pump source . Fibre laser thresholds (launched power) were measured for both fibres and the results are shown in fig 4. For both systems the maximum fibre length which permitted operation in the short wavelength regime was used. This length was determined whilst pumping at ~820nm and it was found that the laser then operated in the short wavelength regime over the entire pump wavelength range used.

Several different co-doped fibres were investigated, being different only in the amount of Yb^{3+} they contained. The different dopant ratios used were ~40:1, ~30:1, ~20:1 (reported in detail in this paper) and ~10:1. Of these, 20:1 gave the best performance, the 30:1 being similar but having a higher lasing threshold. The fibre with 10:1 ratio would not lase with diode pump sources whilst the 40:1 fibre lased with poor performance. Under the conditions used in this study the optimum dopant ratio would thus appear to be ~20:1. (As an additional comparison, the pump wavelength dependence on threshold for the 30:1 fibre is shown in fig 4).

As expected, the singly doped fibre laser is very pump wavelength sensitive, the minimum threshold being achieved around 798nm. The peak absorption occurs at 793nm [15] for Er^{3+} doped using Al_2O_3 (cf 808nm for Er^{3+} doped with GeO_2) so that this might be thought to be the best pump wavelength. However, the presence of pump excited state absorption (ESA) [15], centred at 788nm, shifts the minimum laser threshold to longer wavelengths, as observed in fig 6. In contrast, the pump wavelength dependence of the Er^{3+}-Yb^{3+} laser is seen to be much reduced and operation is possible over a broad range of pump wavelengths. A degradation in performance is not noted at ~850nm, the region over which a second ESA band in Er^{3+} exists [15]. This is perhaps due to performance degradation caused by the ESA being offset by increased absorption of the Yb^{3+} at these longer wavelengths, fig 1. Excited state absorption is clearly evident during the experiment since radiative decay from an upper metastable level occurs producing green light. The intensity of this emission is seen to be a minimum at ~822nm but no lowering of threshold was seen at this wavelength. It is, however, possible that the slope efficiency might improve. Further work is therefore required on the effect of ESA on laser performance - and the effect the presence of Yb^{3+} may itself have on the ESA.

c) Comparison of performance.

The performance of the two types of laser are compared in fig 5. Both characteristics were obtained with the maximum fibre length which still operated in the short wavelength regime (both were pumped at 810nm). In this comparison, it is important to note that the singly doped fibre had a lower numerical aperture (NA) than the co-doped fibre. Assuming that laser threshold is inversely proportional to NA^2 then the thresholds are very similar for Er^{3+} and Er^{3+}-Yb^{3+}. (Data for the singly doped fibre normalized to the same NA as the co-doped fibre is also presented in fig 4). The co-doped fibre had an absorbed power threshold of 2.2±0.2 mW and a slope of 11.6± 0.3%. The Er^{3+} only laser had a threshold of 3.9±0.2 mW (normalizing to the same NA as the co-doped fibre gives 1.7 mW) and a slope of 12.2±0.3%. The Er^{3+}-Yb^{3+} laser absorbs more of the pump light than the Er^{3+} laser, 39% vs 29%. This does not necessarily improve the performance since the transfer efficiency whilst lasing is ~20%, indeed, the slope efficiency (absorbed power) of the co-doped laser is lower than that of the Er^{3+} only laser. The increased absorption is due to the effective cross section of the Er^{3+} being increased by the presence of Yb^{3+}. As noted in refs 8 and 10, more pump light can be absorbed in a given length if the output coupler was designed to reflect more of the pump light back into the fibre.

The main conclusion to be drawn from this section is that the co-doped system offers a broader range of available pump wavelengths without significantly impairing the lasers performance.

SECTION 2 DETAILED CHARACTERIZATION OF THE CO-DOPED FIBRE LASER

In addition to effecting the output power and threshold of the laser, the fibre length also influences the lasing wavelength. In silica fibres, with Al_2O_3 and P_2O_5 present in the host glass, this wavelength dependence on fibre length is step like, lasing being obtained at ~1.57μm or ~1.60μm, depending on the prevailing conditions [5,7]. Sources useful for communication purposes need to operate at the shorter of these wavelengths - the present study thus concentrated on operation at ~1.57μm. The mirror used to form the output coupler of the laser was especially chosen so as to have a moderate (40%) reflectivity at 1.57μm whilst having a low reflectivity (18%) at 1.6μm to prevent laser action at this longer wavelength. The input mirror had a reflectivity of >99.8% over the 1.5-1.6μm range whilst transmitting ~80% of the pump light.

Results and discussion

A typical laser characteristic is shown in fig 6. Combining many such characteristics allows us to plot laser threshold as a function of fibre length, fig 7. As expected, the general trend is for the threshold to increase with fibre length. This increase is required in order that the fibre may be bleached through. The launched power required to reach threshold rises again at short lengths since in this region the fibre only absorbs a small fraction of the launched power. As the length increased, the lasing wavelength rose from 1.559μm at 0.4m to 1.572μm at 3.3m.

As discussed earlier, for a given amount of pump power an optimum fibre length exists for which output at the lasing wavelength is maximized. By interpolating data from the laser characteristics it is possible to plot the output power as a function of fibre length for various pump powers; this is shown in fig 8. Again, as expected, the optimum fibre length is seen to increase with available pump power. For the maximum pump power available in these experiments, the optimum fibre length was 1.45m (fig 6), and this particular laser had a threshold of 12.7±0.4 mW (launched), and a slope efficiency of ~15.3% (launched).

With the possible application as a source for fibre sensors in mind, pulsed operation was also investigated. The insertion of an acousto-optic modulator into the cavity allows the laser to be Q-switched. With the modulator on, light is deflected out of the cavity and lasing action is 'held off' and energy is stored in the Er^{3+} system. If the modulator is now turned off a single q-switched pulse is produced: repetitive operation of the modulator produces a stream of pulses.

The width (FWHM) and peak power of such pulses are shown as a function of fibre length in fig 9. The total length of the cavity consisted of the fibre length plus a 0.3m air gap, containing the modulator. All pulses were obtained for a launched power of 17mW. Looking first at peak power we see that an optimum length exists. With increasing fibre length, the peak power initially rises as more of the pump energy is absorbed by the fibre. As the length of the cavity increases so does the pulse width, so that eventually, for a fixed pulse energy, the peak power falls. A similar argument may be used to explain why the pulse width initially falls and then rises as the length, and hence round trip time of the cavity, increases.

The data in fig 9 is plotted along with an 'expected' fit. That the experimental data does not match this is due to insufficient hold off of the modulator. An undeflected fraction of light passes straight through the modulator and is feed back (via a second pass through the modulator) into the fibre. As the power in the cavity builds up, this reflected fraction eventually becomes sufficient to set off CW lasing action, thus degrading the Q-switched performance. During the experiment this effect manifests itself as instabilities in the pulse, in particular, successive pulses are no-longer identical. To cure this a more efficient modulator is required and the output end of the fibre must either be AR coated or polished off at an angle. Choosing a launched power of 17mW meant that only pulses close to the optimum length suffered from a lack of hold off.

The repetition rate of Q-switched operation could be raised to ~70Hz before the peak power started to fall (this rate is governed by the lifetime of the metastable level - 13ms). The repetition rate may be raised to 250Hz before the peak power falls to half of its maximum value.

Conclusions

Direct comparison with an Er^{3+} fibre laser has shown that the acceptable range of pump wavelengths is considerably greater in the case of the co-doped fibre, without significantly degrading the laser performance. Operation of the co-doped Er^{3+}-Yb^{3+} fibre laser has been investigated as a function of fibre length. The idea of an optimum fibre length has been both discussed and demonstrated and will be of particular importance in the design of practical three-level fibre lasers. The results on Q-switching show that significant peak powers may be obtained from a diode pumped system; this is particularly important in view of the potential for eye-safe range finding. It is anticipated that the performance of such lasers will be considerably improved by pumping at 980nm [15] (away from any excited state absorption bands) and results on this will be presented in a future publication.

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Figure captions

Table 1   Parameters of the single and co-doped fibres

1) The relevant energy levels for the co-doped system.

2) Attenuation spectrum of a co-doped fibre, with a dopant ratio of 30:1 (Yb^{3+}:Er^{3+}).

3) Operating wavelength of co-doped fibre laser vs fibre length. An 826 nm laser diode pump and R=70% output coupler were used.

4) Fibre laser threshold, in terms of launched power, for the two fibre lasers as a function of wavelength. A dye laser was used as the pump source and the output coupler was R=80% (also shown is the same data for a fibre with a dopant ratio of 30|1).

5) Comparison of the lasing characteristics of the single (Er^{3+}) and co-doped (Er^{3+}-Yb^{3+}) fibre lasers. Both were pumped with two 810nm laser diodes and the output coupler was R=80% Data is also presented for the single doped laser, normalized to have the same NA as the co-doped fibre.

6) Lasing characteristic for a fibre length of 1.80m. An output coupler with a reflectivity of 40% was used and lasing took place at ~1.57μm.

7) Lasing threshold (for both launched and absorbed pump power) as a function of fibre length.

8) Power output of the fibre laser vs fibre length, for various launched pump powers.

9) Q-switched performance as a function of fibre length. Both pulse width (FWHM) and peak power are shown.

Fibre type	Numerical aperture	Cutoff wavelength (nm)	Dopant ion concentration (Wt %)	
			Er^{3+}	Yb^{3+}
Er^{3+}	0.15	1280	0.08	0
Er^{3+}, Yb^{3+}	0.23	1400	0.06	$1.3^{+0.4}_{-0.2}$

Table 1

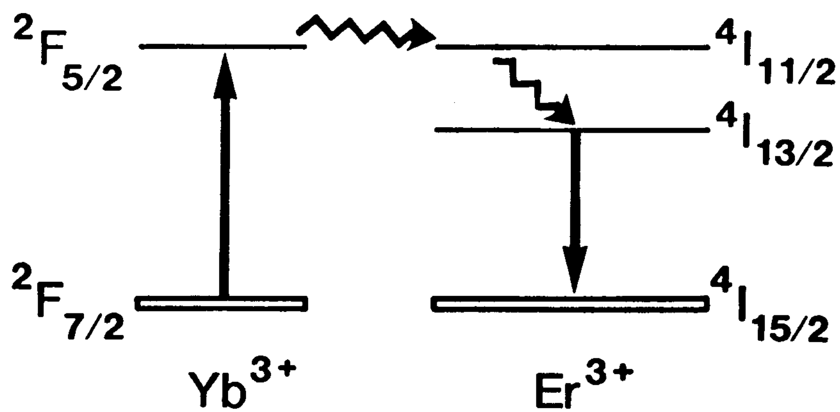
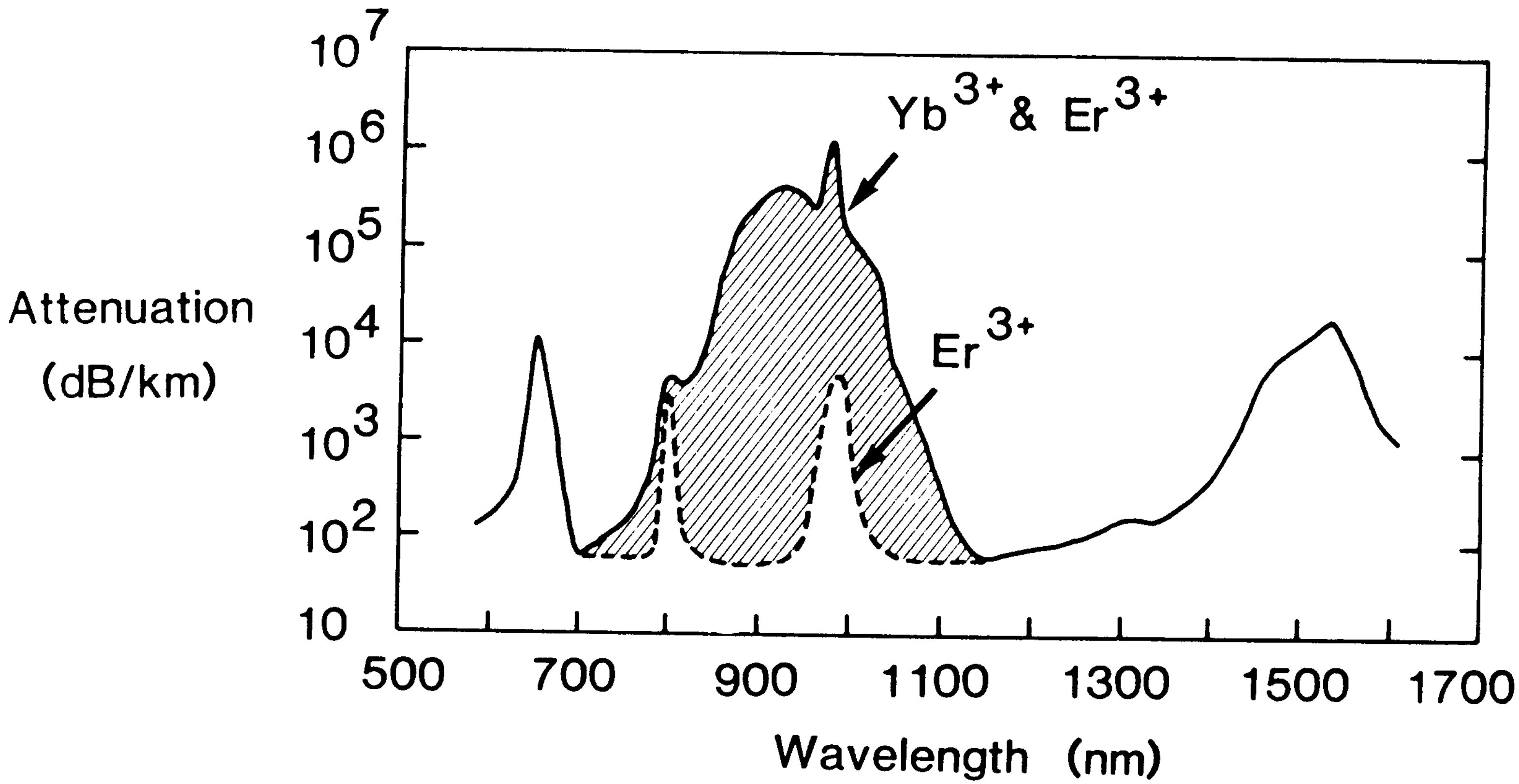


Fig 1



Attenuation
(dB/km)
10
10^2
10^3
10^4
10^5
10^6
10^7
Yb^{3+} & Er^{3+}
Er^{3+}
500
700
900
1100
1300
1500
1700
Wavelength (nm)

Fig 2

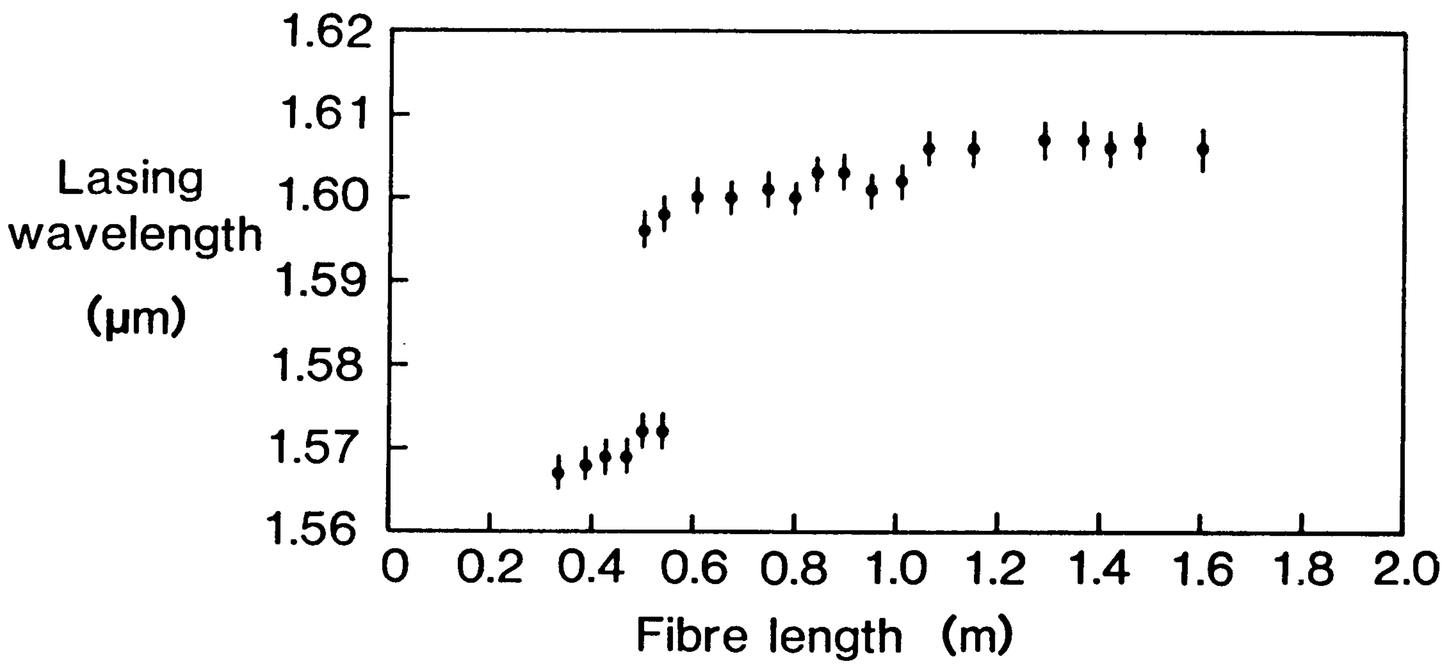
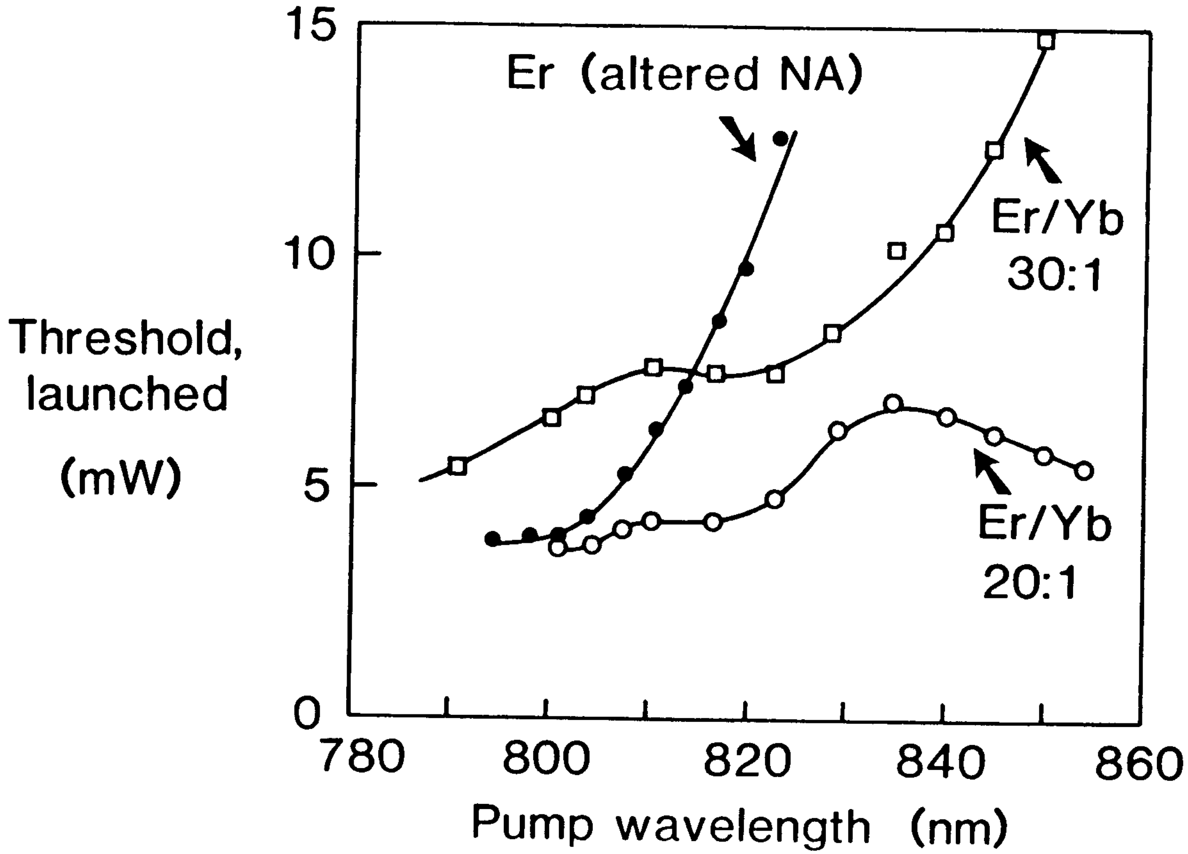
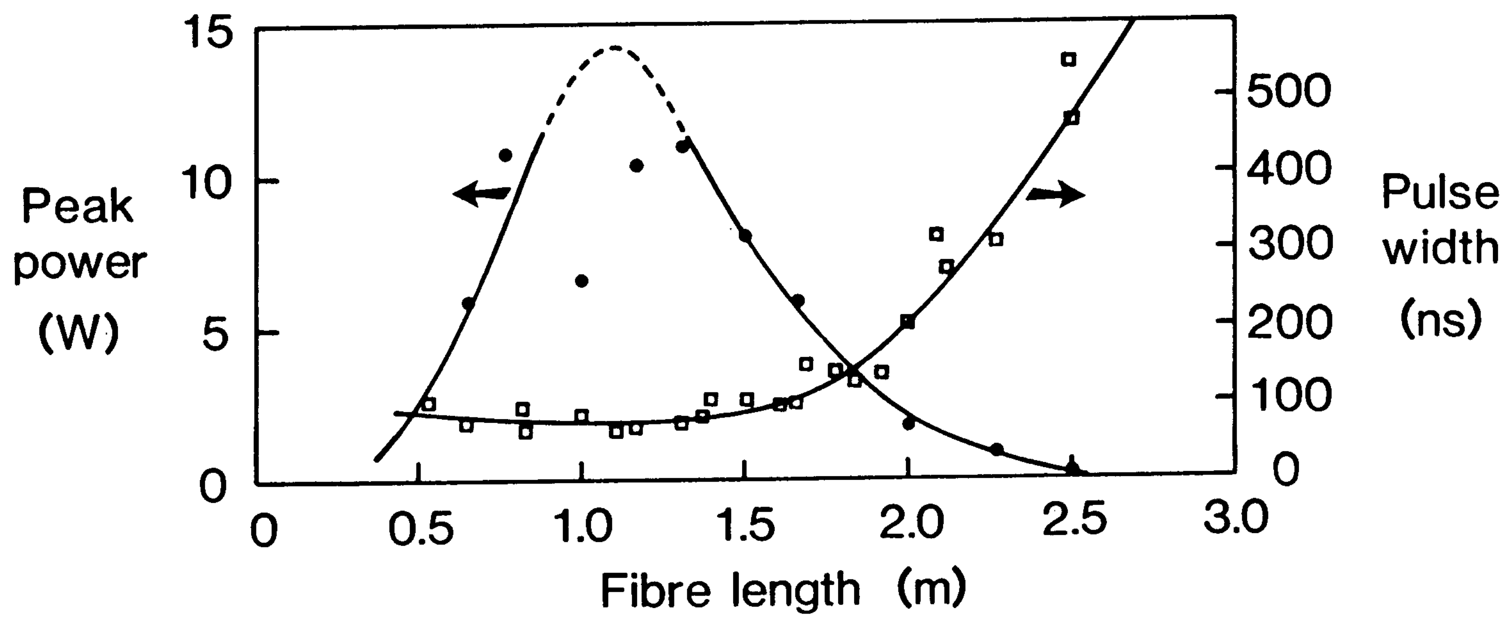

Lasing wavelength (µm)
1.62
1.61
1.60
1.59
1.58
1.57
1.56
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
Fibre length (m)

Fig 3



Threshold,
launched
(mW)
15
10
5
0
780
800
820
840
860
Pump wavelength (nm)
Er (altered NA)
Er/Yb
30:1
Er/Yb
20:1

Fig 4



Peak power (W)
15
10
5
0
0
0.5
1.0
1.5
2.0
2.5
3.0
Fibre length (m)
500
400
300
200
100
0
Pulse width (ns)

Fig 9

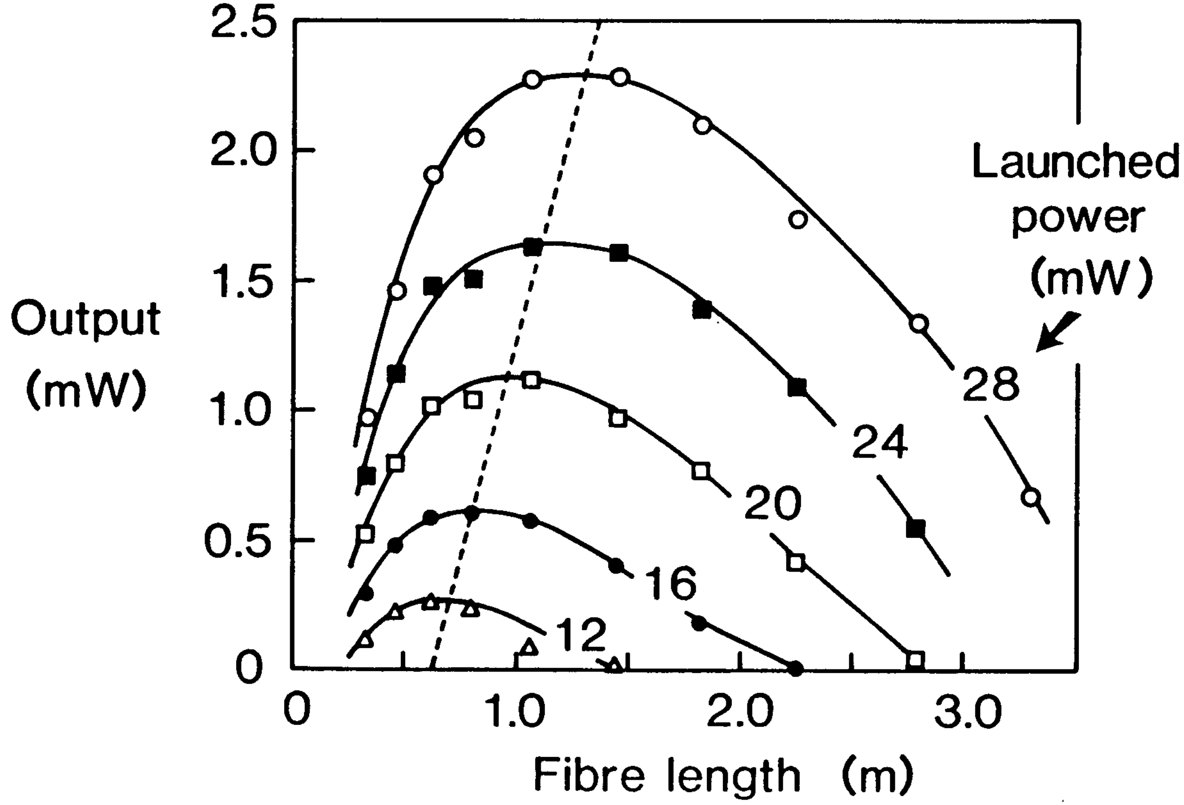

Output
(mW)
2.5
2.0
1.5
1.0
0.5
0
0
1.0
2.0
3.0
Fibre length (m)
Launched
power
(mW)
28
24
20
16
12

Fig 8

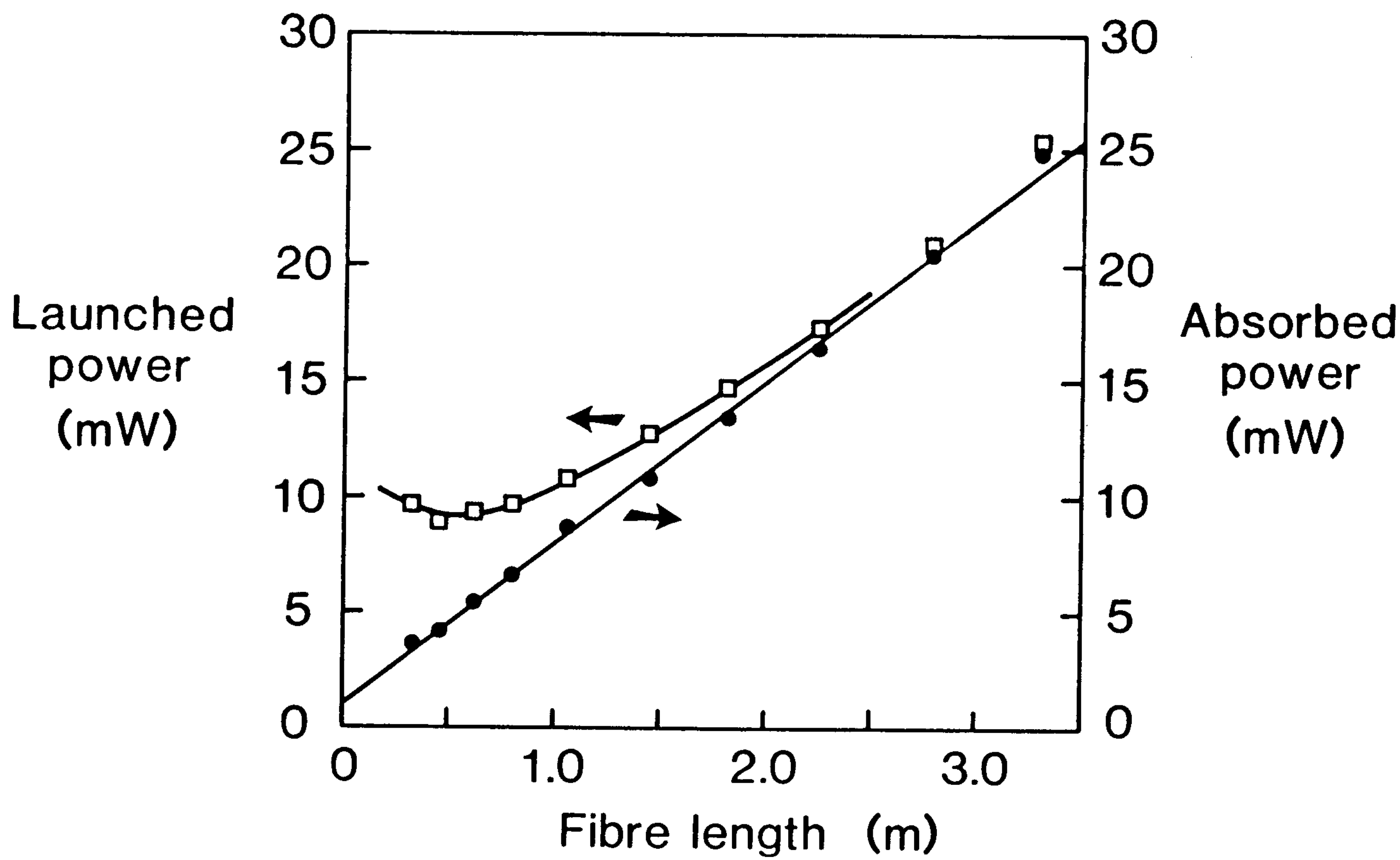

Launched power (mW)
Absorbed power (mW)
Fibre length (m)
0
5
10
15
20
25
30
1.0
2.0
3.0

Fig 7

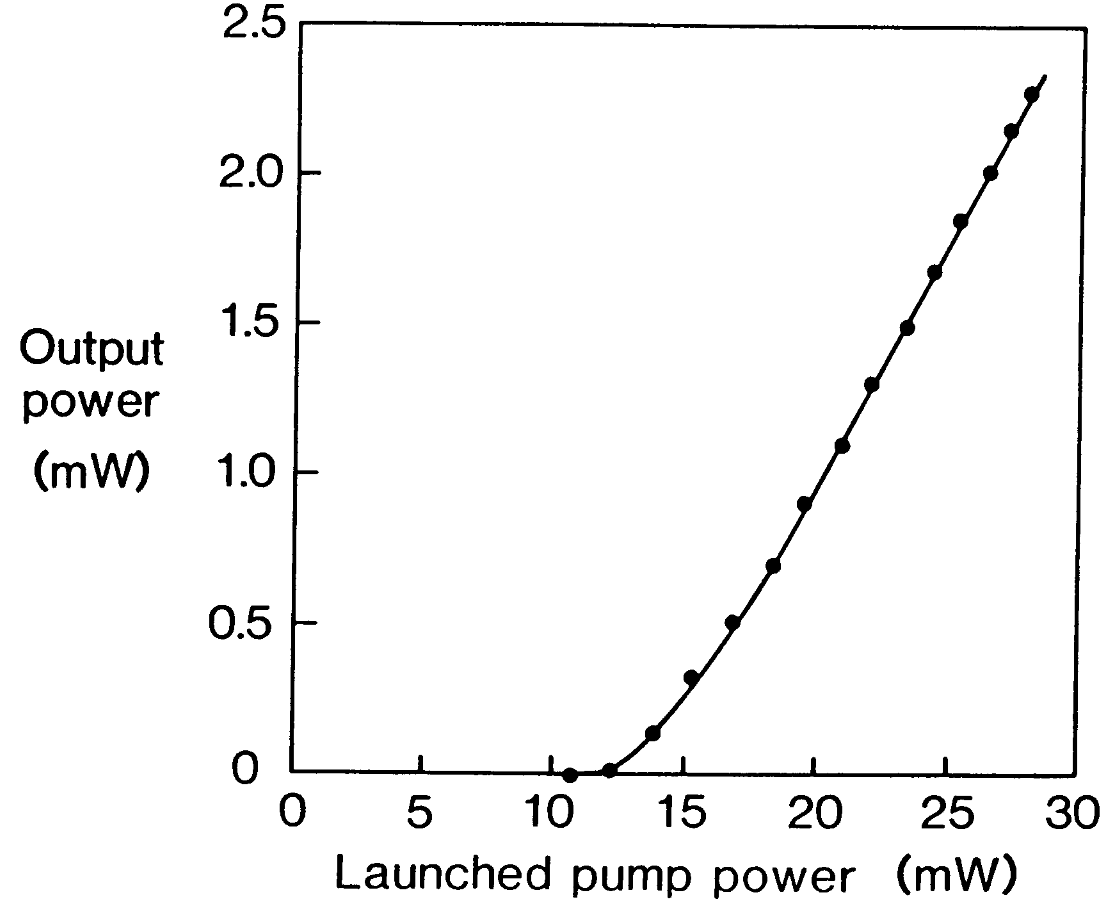
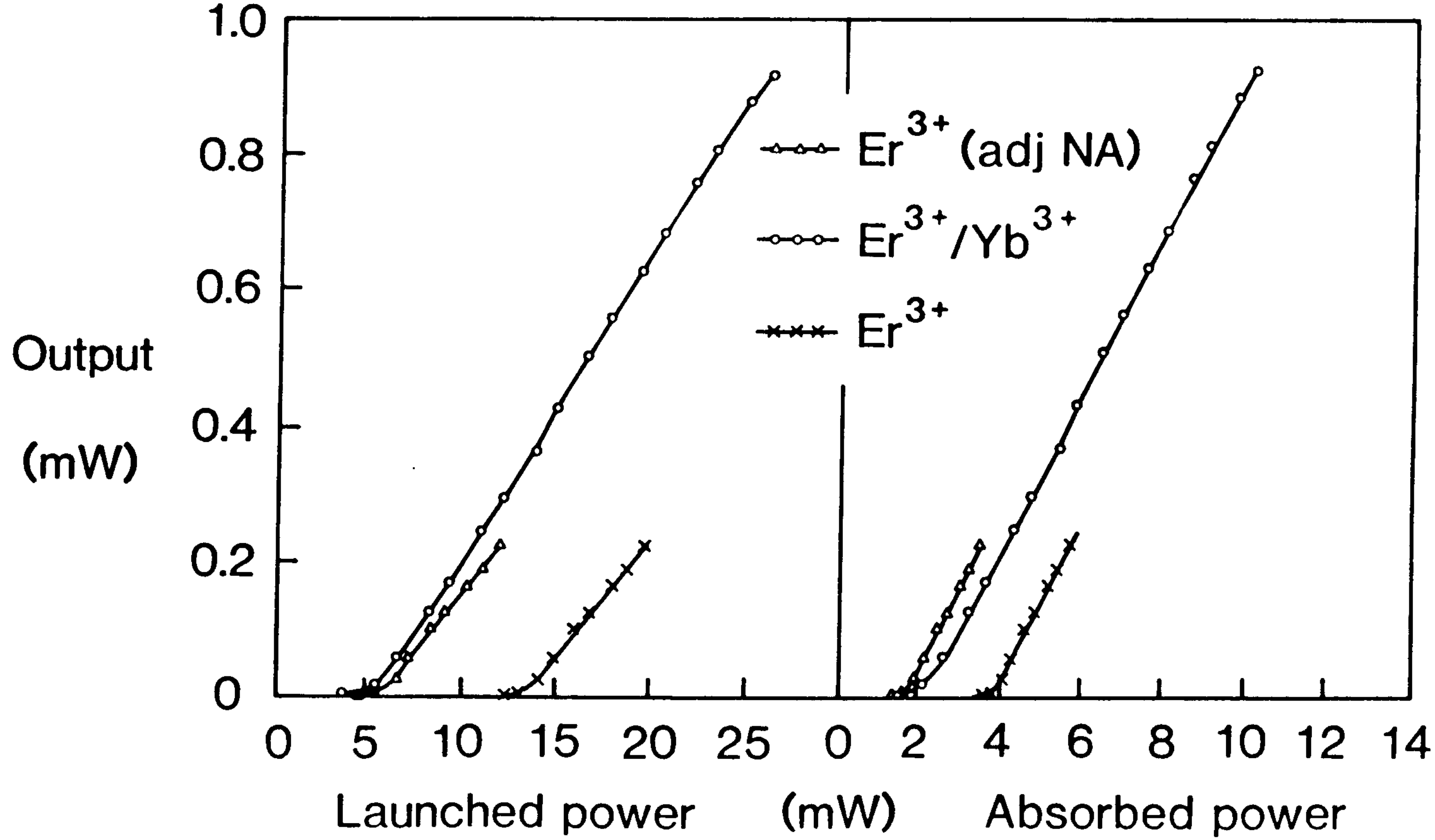

2.5
2.0
1.5
1.0
0.5
0
Output
power
(mW)
0
5
10
15
20
25
30
Launched pump power (mW)

Fig 6



Output
(mW)
1.0
0.8
0.6
0.4
0.2
0
Er3+ (adj NA)
Er3+/Yb3+
Er3+
0
5
10
15
20
25
0
2
4
6
8
10
12
14
Launched power
(mW)
Absorbed power

Fig 5