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High-performace cladding-pumped erbium-doped fibre laser and amplifier

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Abstract. **We report cladding-pumped erbium-doped fibre laser and amplifier configurations. Through fibre design optimisation, we have achieved a record-high laser slope efficiency, 40 % with respect to absorbed pump power (λ = 976 nm), and an output power of 7.5 W. The erbium-doped fibre amplifier efficiency reaches 32 %.**

Keywords: *erbium-doped optical fibre, cladding pumping, slope efficiency.*

1. Introduction

The spectral region around 1.55 μm is employed in many application areas, such as telecommunications, medicine and scientific instrument making, which have a growing need for high-average-power (1 – 100 W) light sources. One advantage of such systems over lasers and amplifiers operating in the 1-μm range is that ~1.55-μm light is eye-safe. At the same time, existing fibre laser sources for this spectral region have serious drawbacks.

The most widespread 1.55-μm light sources are fibre lasers and amplifiers whose core is codoped with Er_2O_3 and Yb_2O_3. The large absorption cross section of the Yb^{3+} ion enables cladding pumping by standard multimode laser diodes at λ_p = 915 or 975 nm, and energy transfer from the Yb^{3+} to Er^{3+} ions ensures 1.55-μm lasing. The slope efficiency (hereafter simply 'efficiency') with respect to launched pump power in Er–Yb codoped fibre lasers and amplifiers reaches 32 % and 40 % in single-mode and multimode operation, respectively, with a laser output power of 100 and 200 W [1, 2]. At the same time, the Er – Yb codoped fibre lasers and amplifiers have a serious drawback: parasitic emission at ~1 μm when the output power reaches ~10 W [3, 4]. This reduces their efficiency and makes the output of such lasers and amplifiers hazardous to eye.

Alternative 1.55-μm light sources are erbium-doped fibre lasers and amplifiers core-pumped by a Raman converter at λ_p = 1.48 μm [5]. However, the highest conversion efficiency from multimode 976-nm pump light to single-mode 1480-nm radiation achieved to date with the use of a high-power (15 to 80 W) Raman converter is within 32 % [6]. In turn, the conversion efficiency from the single-mode 1480-nm pump beam to the 1550-nm output in erbium fibre lasers and amplifiers does not exceed 85 % [7], reducing the conversion efficiency from the multimode 976-nm pump beam to the 1550-nm output down to 27 %. Thus, the use of erbium-doped fibres pumped by a Raman converter adds considerable complexity but fails to exceed the efficiency of the Er–Yb system.

The use of cladding-pumped Er-doped (Yb-free) fibres is limited by the small absorption cross section of erbium and the reduction in pump-to-signal conversion efficiency with increasing erbium concentration. The highest slope efficiency under cladding pumping has been achieved using 1532-nm diodes as pump sources. Because of the small quantum defect and because the absorption at this wavelength is about three times that at 980 nm, the efficiency of such systems reaches 69 %, with an output power of 88 W [8]. The high pump-to-signal conversion efficiency is however counterbalanced by the lower efficiency (by a factor of 1.6 – 2) of such pump diodes in comparison with 976-nm diodes. Moreover, the cost of 1532-nm pump sources is currently an order of magnitude higher than that of the 976-nm diodes.

Note that Er-doped (Yb-free) fibres ensure 976-nm pump to 1550-nm signal conversion efficiencies above 59 % [9], but such efficiency has only been achieved under single-mode core pumping. The highest slope efficiency (30 %) of 976-nm cladding-pumped erbium fibre lasers and amplifiers with output powers above 1 W has been achieved by merely increasing the core diameter, but the output was then multimode [10, 11]. The slope efficiency of cladding-pumped single-mode fibre lasers and amplifiers with output powers above 1 W did not exceed 24 % until recently [12 – 15]. Only very recently have the use of a phosphoaluminosilicate glass host and an increase in the ratio of the core diameter to the first cladding diameter enabled 28 % efficiency to be reached [16].

The purpose of this work was to optimise erbium-doped phosphoaluminosilicate fibre in order to raise the conversion efficiency from multimode 976-nm pump light to a single-mode 1550-nm output. In addition, we aimed at increasing the output power of cladding-pumped lasers and building a cladding-pumped all-fibre (free of bulk elements) amplifier.

2. Fibre optimisation

The main distinction of cladding-pumped fibres from conventional, core-pumped active fibres is that their effective pump absorption is orders of magnitude smaller, which leads to a proportional increase in active fibre length. This is accompanied by a corresponding increase in the adverse effect of the unbleachable loss, including the loss caused by the clustering-

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induced nonradiative relaxation of some of the excited Er^{3+} ions and the background loss (optical loss beyond absorption bands, which is a weak function of wavelength). The background loss α_b in active fibres is, at best, ~5 dB km^{-1}. The pump loss in the first reflective cladding reaches ~20 dB km^{-1}. The loss due to clustering in the erbium-doped fibre can be roughly estimated as

$$\alpha_{cl} = 2kI\alpha, \quad (1)$$

where $2k$ is the fraction of paired ions; I is the degree of population inversion (30%–40%); and α is the absorption at the signal wavelength at zero inversion.

We examined three types of fibres, with low, medium and high erbium concentrations, and estimated the fibre length needed to ensure a 20-dB absorption of 980-nm pump light in a standard configuration (core and cladding diameters of 10 and 125 μm, respectively) and the signal and pump losses at this fibre length. The k value was taken from Ref. [17]. The estimation results are presented in Table 1. It can be seen that the high signal loss (in conjunction with the high pump loss at low erbium concentrations) prevents the use of standard erbium-doped fibres in cladding-pumped configurations. Increasing the erbium concentration allows one to reduce the working fibre length, but on the other hand it leads to a much more rapid increase in the loss due to erbium ion clustering. Thus, the key to producing efficient erbium fibre lasers and amplifiers lies in reducing the fibre length and increasing the absorption in the fibre under cladding pumping, without changing the erbium concentration.

The cladding pump absorption can be estimated as

$$\alpha_{clad} = \alpha_c \frac{d_c^2}{D_{clad}^2}, \quad (2)$$

where α_c is the absorption in the core; d_c is the core diameter; and D_{clad} is the cladding diameter. This relation suggests two approaches for increasing the absorption under cladding pumping: increasing the core diameter and reducing the cladding diameter. Consider these approaches.

The smallest outer diameter of an optical fibre is determined primarily by the numerical aperture of its second cladding and the characteristics of the pump source. In a previous study [16], the outer diameter of a fibre was reduced to 80 μm (the minimum diameter that allows cleaving and fusion splicing by standard means) and the pump source used was a fibre-pigtailed (core diameter, 105 μm; numerical aperture, 0.22) multimode diode laser, which provided 33 W of output power. As a consequence, the NA of the pump beam in the fibre was within 0.3, which is considerably less than the NA of the polymer coating of most active fibres. On the other hand, pump sources capable of ensuring powers above 20–35 W at the output of 105-μm-diameter fibres with a numerical aperture of 0.22 are currently rather difficult to find, so the output power of the fibre laser was limited to 6.4 W, with a 28% efficiency [16].

The pump power can be raised using pump sources with a larger core size, e.g. 200 μm (which ensures pump powers up to 500 W at a numerical aperture of 0.22), or pump combiners, with the pump light outcoupled through a 125-μm-diameter fibre having a numerical aperture of 0.45. A pump combiner is also necessary in designing a cladding-pumped amplifier.

In this study, to minimise the outer diameter of the active fibre we used Teflon coating, which ensured a numerical aperture of 0.6. When pump sources have a fibre pigtail with a core diameter of 200 μm and NA = 0.22, the pump NA in a 80-μm-diameter erbium-doped fibre will be 0.55 according to the principle of brightness conservation. Using pump combiners, pump light with NA = 0.59 can be coupled into a 95-μm- diameter fibre. It is worth noting that, in addition to large numerical apertures, Teflon coatings ensure other advantages. In particular, the heating of active fibres because of the large quantum defect is a major problem at high pump powers. The thickness of Teflon coatings ranges from 7 to 15 μm, which ensures an order of magnitude better heat removal in comparison with other polymer coatings, whose thickness is typically 50–100 μm. Another advantage of Teflon coatings is the low optical loss throughout the IR spectral region, in particular around 1530 nm, which ensures efficient pumping at this wavelength as well.

To increase the core diameter while maintaining single-mode operation, it is necessary to reduce the refractive index of the core. It should be noted that, according to earlier data [18], single-mode operation at $\lambda = 1550$ nm would be expected at core diameters of up to 40 μm when the index difference is 0.001. The problem is that, in the case of a standard aluminosilicate host, an extremely low alumina concentration (0.3 mol% to 1 mol%) is necessary to obtain this small refractive index of the core (compared to the cladding) even when the core is additionally doped with fluorine [19]. This considerably reduces erbium solubility, thereby increasing the influence of clustering and degrading the efficiency of the fibre [17, 19]. This problem can be obviated by using a phosphoaluminosilicate glass host, which makes it possible to maintain a low refractive index of the core at an acceptable erbium concentration, with no significant drop in efficiency [19].

Given the above, we fabricated two active fibres for an all-fibre laser and amplifier with core/cladding diameters of 25/80 and 22/95 μm, respectively. The fibres had the same core composition: 9 mol% Al_2O_3, 9 mol% P_2O_5, 1.5 mol% GeO_2 and ~0.1 mol% Er_2O_3. To increase absorption from the cladding, the fibres had a square cross section. Figure 1 shows their refractive-index profiles and a photograph of the fibre end face. Figure 2 presents the optical loss spectra of a small signal propagating through their core and cladding. The fibres with a reflective Teflon coating had a numerical aperture of 0.6.

Table 1.

Er concentration/10^{24} m^{-3}	980-nm absorption in the core/dB m^{-1}	k (%)	Necessary fibre length, L/m	α_{cl}/dB km^{-1}	Single-pass loss/dB	
					Signal (λ = 1580 nm) $\alpha_{cl} + \alpha_b$	Pump
3	2.7	0.5	1157	2.4	2.8 + 5.8 ~ 8.6	23
8	7.2	2.5	440	40	17.6 + 2.2 ~ 19.8	8.8
100	69.8	8.5	45	680	30.6 + 0.2 ~ 30.8	0.9

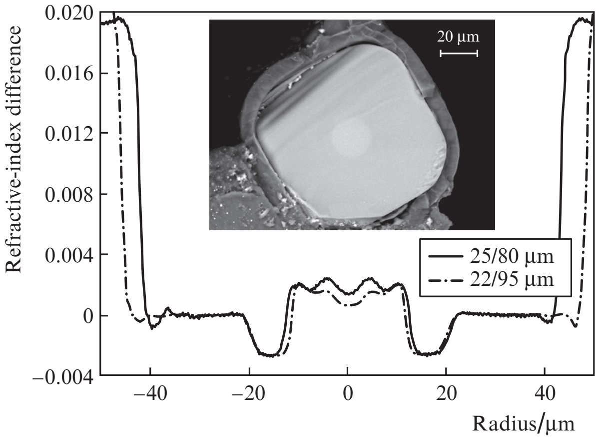

Figure 1. Refractive-index profiles of the fibres with the core/cladding diameters indicated in the box. Inset: photograph of the fibre end face.

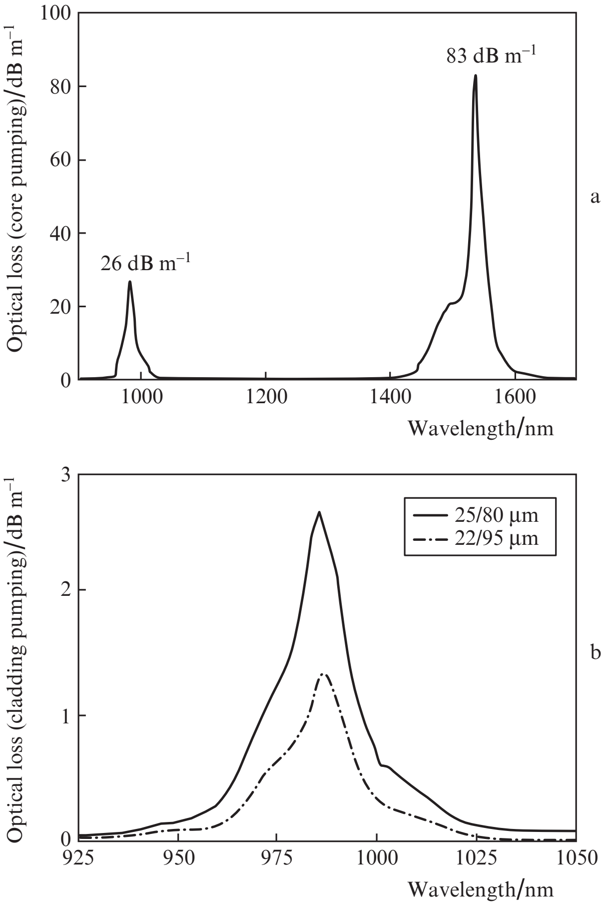

Figure 2. Optical loss spectra of a small signal propagating through the (a) core and (b) cladding of two fibres.

3. Experimental results

3.1. Cladding-pumped fibre laser

Figure 3a shows the fibre laser configuration used in our experiments, similar to those used in previous studies [16, 20]. The beam from a multimode 980-nm pump source (*1*) (core diameter, 105-μm; numerical aperture, 0.22) was coupled into a fibre taper (*2*), whose diameter decreased from 105 to 80 μm over a length of the order of 30 cm. The pump beam emerging from the taper (80 μm diameter, NA = 0.29) was coupled into a fibre cavity formed by a highly reflective Bragg grating (*3*) and the end facet (*5*) of an 80-μm-diameter erbium-doped fibre (*4*). The peak-reflection wavelength of the Bragg grating was optimised so as to obtain the highest laser efficiency. The Bragg grating was inscribed in a single-mode germanosilicate fibre with core and cladding diameters of 16 and 80 μm.

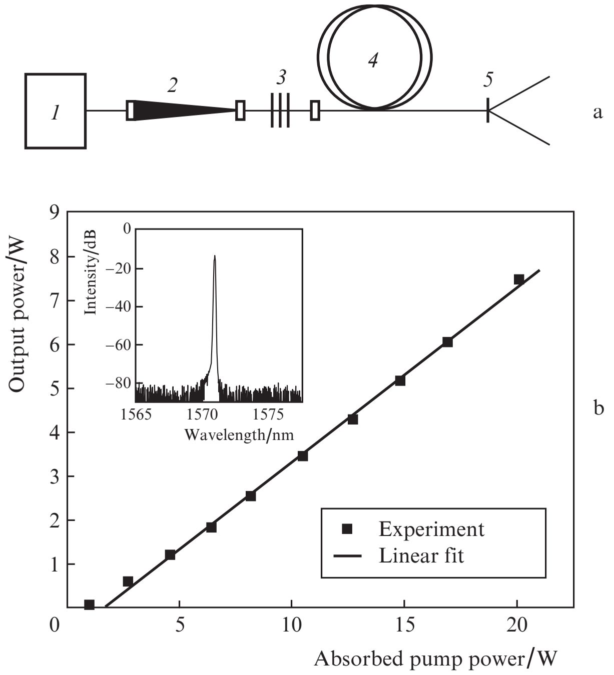

Figure 3. (a) Laser configuration. (b) Output power as a function of absorbed pump power (slope efficiency, 40%); inset: laser emission spectrum.

Owing to the high absorption of the pump light coupled into the cladding, the optimal erbium-doped fibre length, which ensured the highest laser efficiency, was just 5 m. The output signal power at 1570 nm as a function of absorbed pump power and the laser emission spectrum are shown in Fig. 3b. At an absorbed pump power of 21 W and launched power of 26 W, the maximum single-mode output power of the fibre laser was above 7.5 W. The slope efficiencies with respect to absorbed and launched pump powers were 40% and 35%, respectively. Single-modedness of the fibre laser output was verified by examining the laser mode-field pattern in the far field.

The efficiency achieved in this study is record-breaking for cladding-pumped erbium-doped fibre lasers and compares well with the best results obtained with Er–Yb codoped fibres. It is worth noting that the output power in the proposed laser configuration can be raised further by using higher power pump diodes with output fibre pigtails having a 200-μm- diameter core. It will then be necessary to use a fibre taper with an outer diameter varied from 200 to 80 μm.

3.2. Cladding-pumped fibre amplifier

The amplifier configuration is shown in Fig. 4a. To make an all-fibre amplifier configuration, we used a pump combiner

(*3*). The pump (*1*) and signal (*2*) beams were coupled into the combiner (*3*). Its output was coupled into a 95-μm-diameter erbium-doped fibre (*5*) using a 125/95-μm fibre taper (*4*). It should be noted that the fibre taper used had a core diameter of 6 μm at its input and 4 μm at its output. To match the fibre taper output to the erbium-doped fibre, which had a considerably larger core diameter, we used an intermediate fibre mode field adapter. The total signal loss between the driving source (*2*) and the input of the erbium-doped fibre (*5*) was within 3 dB. The output end face (*6*) of the erbium-doped fibre was cleaved at a small angle to eliminate Fresnel reflection and suppress lasing. The signal source used (*2*) was a fibre laser whose wavelength could be tuned from 1550 to 1600 nm by changing the Bragg gratings and whose output power was several hundred milliwatts, which ensured operation of the amplifier in the power saturation regime.

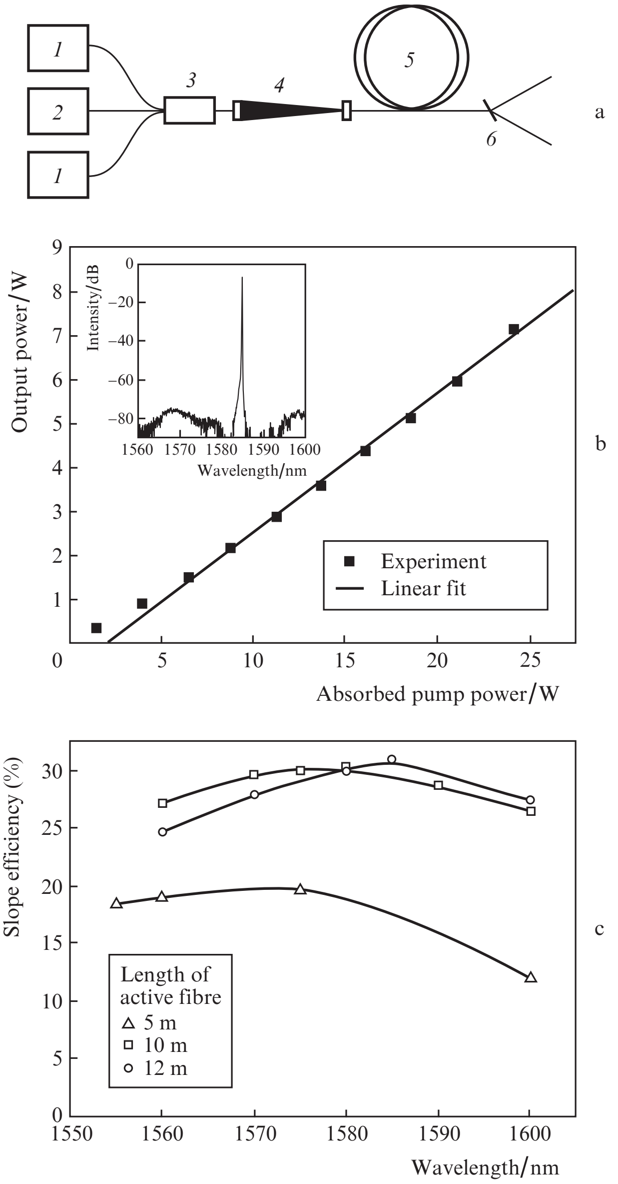

Figure 4. (a) Amplifier configuration. (b) Output power as a function of absorbed pump power (slope efficiency, 32%); inset: amplifier output spectrum. (c) Spectral dependence of the slope efficiency with respect to launched pump power.

Measuring the amplifier efficiency as a function of fibre length and signal wavelength, we obtained the highest output power (7.2 W) at $\lambda = 1585$ nm and a fibre length of 12 m. The slope efficiencies with respect to absorbed and launched pump powers were 32% and 31%, respectively. Figure 4b shows the output power as a function of absorbed pump power and the amplifier output spectrum. Of the 33 W of pump power, the loss in the combiner (*3*) was 4 W, that in the fibre taper was 3 W, and the unabsorbed pump power at the output end of the active fibre was 2.5 W. The amplifier operated efficiently in the range 1560–1600 nm, with the highest output power obtained at active-fibre lengths of 10 and 12 m. Figure 4c shows the spectral dependence of the slope efficiency with respect to launched pump power for the fibre amplifier at fibre lengths of 12, 10 and 5 m. The peak-gain wavelength is seen to decrease with decreasing fibre length. At the same time, because of the increase in the fraction of unabsorbed pump light, the gain efficiency of the amplifier drops considerably.

Like in the case of the fibre laser, the output of the fibre amplifier was single-mode. It is also worth noting that the output power of the amplifier can be raised further by adding one (2 + 1 to 1 pump combiner) or five (6 + 1 to 1) pump diodes.

4. Conclusions

The present results demonstrate that record-high pump-to-signal conversion efficiencies can be reached in a cladding-pumped erbium-doped fibre laser and amplifier. The laser efficiency obtained (40%) compares well with that of the best Er–Yb codoped fibre lasers. The high laser and amplifier efficiencies are due to the use of a phosphoaluminosilicate glass host developed by us, in conjunction with a large-aperture Teflon coating and small outer diameter of the active fibre.

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