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Optimisation of the efficiency of tapered erbium-doped optical fibre

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Abstract. **We have developed a cladding pumped tapered erbium-doped fibre with a record-high core diameter for erbium-doped fibres (100 μm) and a near diffraction-limited beam quality ($M^2 \sim 1.3$). Optimisation of the tapered fibre parameters provided a high (18%) efficiency of pump radiation conversion at a wavelength of 976 nm into signal radiation at a wavelength of 1560 nm.**

Keywords: *tapered fibre, erbium-doped fibre, large mode field.*

1. Introduction

Erbium-doped fibre lasers emitting in the spectral region near 1.55 μm are eye safe [1], which explains their wide application in tasks requiring radiation transmission through the atmosphere such as measurement of the wind speed using Doppler lidars [2, 3], differential measurement of gas concentrations from space [4], and space-based [5] and atmospheric communications. Most of the applications described above require a high laser beam quality and high radiation intensity. Fibre lasers are capable of providing diffraction-limited output beam quality, which, combined with a widely developed component base due to the high prevalence of erbium fibre lasers in telecommunications, makes them one of the most promising radiation sources for solving such problems.

However, achieving high intensity with good beam quality is a complex engineering problem. One of the most common ways to solve it is the use of double-clad fibres with a large mode diameter [6, 7]. In such fibres, the core has a diameter of 30–35 μm and operstes in a few-mode regime (supports a small number of higher-order modes). Single-mode operation in such fibres is achieved due to greater amplification of the fundamental mode and the formation of losses for higher-order modes due to fibre bending [8]. It is important to note that an increase in the fibre core diameter leads to an increase in the normalised frequency and a decrease in the bending diameter necessary to maintain single-mode behaviour. This, in turn, results in a decrease in the fibre mode field, which makes applicability of this approach limited [9].

There are a number of methods based on the introduction of additional elements into the fibre cladding for resonant pumping of higher-order modes from the fibre core [10–12]. The disadvantage of these methods is the resonant nature of the interaction between higher-order core modes and modes of the inclusions. This leads to the fact that they are effective for a narrow range of wavelengths. Pumping into the fibre core allows one to selectively excite and amplify only the fundamental mode of a multimode fibre by reducing the overlap of the pump mode with higher-order signal modes [13]. However, such laser and amplifier schemes turn out to be much more cumbersome and less efficient than cladding pumped schemes [14].

In the spectral region near 1 μm, record peak powers were demonstrated in all-fibre amplifiers with diffraction-limited output beam quality using the tapered fibre geometry [15]. The idea of a tapered fibre is to smoothly increase the core and cladding diameters along the fibre length to a value several times larger than the initial one. On a thin single-mode end-face, the fundamental mode is excited, which adiabatically propagates towards a thick multimode end-face without transferring energy to higher-order modes. Erbium-doped tapered fibres also demonstrated record-high or near-record peak powers for pulses of various durations [16–18]; however, due to high clustering, the differential efficiency of converting pump radiation into signal radiation in such fibres did not exceed 3%–4%. The purpose of this work is to optimise the parameters of an erbium-doped tapered fibre to obtain high efficiency.

2. Tapered fibre design optimisation

One of the most important factors determining the efficiency of erbium-doped cladding-pumped fibres is the ratio of the core diameter to the diameter of the first reflective cladding. The greater this ratio, the higher the absorption rate of the pump light from the cladding and the shorter the active fibre can be made, which leads to a decrease in the contribution of concentration effects to overall efficiency. The maximum fibre core size is limited by the requirement of single-mode light propagation at the thin end of tapered fibre. In this work, in order to reduce the sensitivity to bending of the tapered fibre (which was a problem when using the previous version of tapered fibre [16–18]), a fibre design with an aperture of 0.09 was chosen. With such an aperture, as well as using the W-profile (a

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depressed ring outside the core), it is possible to achieve a single-mode operation regime up to the core diameter of about 15–16 μm. At the same time, the use of the method of winding the thin end of optical fibre onto a small-diameter coil [8] makes it possible to somewhat increase the maximum diameter of the fibre core capable of single-mode operation. We have chosen a core diameter of approximately 18 μm.

The second limitation on the maximum ratio of the core and cladding diameters is the requirement to ensure a cladding diameter of at least 80 μm, which is necessary for the compatibility of the developed optical fibres with standard equipment. The use of a fluorine-doped reflective cladding makes it possible to somewhat reduce the diameter of the first reflective cladding that consists of undoped silica glass. To achieve the minimum possible diameter of the first cladding, we have developed a technology for applying a thick layer of fluorine-doped silica glass to a preform fabricated of undoped silica glass (the diameter ratio exceeded 1.4). This allowed us to reduce the diameter of the first cladding to 57 μm with the outer diameter of the fluorine-doped cladding equal to 80 μm. This optimisation resulted in the ratio of the core diameters to the diameter of the first reflective cladding of 0.316.

In order to select the optimal concentration of erbium ions in the core, we performed numerical calculations of the efficiency of pump-to-signal conversion. In the calculations, we used the characteristic dependence of the tapered fibre diameter on its length, obtained in preliminary experiments (the minimum diameter, 70 μm; the maximum diameter, 420 μm; and the tapered fibre length, 3.6 m). It should be noted that it is necessary to take into account the vignetting effect when pumping erbium-doped tapered fibre through the thick end. This effect is that the pump beam aperture increases as the pump propagates through tapered fibre. As a consequence, this aperture may exceed the maximum allowable aperture supported by the first reflective cladding of fibre, after which the pump radiation, having propagation angles exceeding the angle of total internal reflection, comes out through the lateral end-face of fibre. In this case, we proceeded from the assumption that pumping was introduced along the fibre axis, and the angular distribution of the radiation intensity of a diode with a numerical aperture of 0.15 corresponded to that we measured earlier in work [19].

In this work, aluminosilicate glass with a high fluorine concentration was used as a glass matrix for doping with erbium ions [7]. For such a matrix, the dependence of the clustering of erbium ions on their concentration has not been studied, but it is logical to assume that this dependence lies between the dependences obtained earlier for glasses with a low and high aluminium oxide concentration [14]. Both dependences were used in calculations, the results of which are shown in Fig. 1.

It is important to note that the efficiency of pump-to-signal conversion in the fibre described in works [16–18] was only 3%–4%, while the concentration of erbium ions corresponded to approximately 60×10^{24} m^{-3}. Despite the fact that this fibre had a phosphorous aluminosilicate core matrix, the results of work [7] suggested that its efficiency would be comparable to that of aluminosilicate fibres strongly doped with fluorine. Considering our previous studies, it was reasonable to expect that the efficiency of this fibre would also be between the efficiency of fibres weakly and strongly doped with aluminium oxide. However, it can be seen that the efficiency of such fibre turned out to be several times lower than the calculated one. We believe that in this case, some additional factor plays a role in the reduction of the fibre efficiency. For example, it can be a much higher numerical aperture of the pump radiation caused by coupling the pump through the fibre end-face polished at an angle (in this case, it is quite difficult to accurately control the alignment). In any case, the implementation of the same (or higher) concentration of erbium ions in the core seems inadvisable, given the low efficiency observed in such fibre. Based on the results of performed calculations and measurements, it makes sense to look for the optimum concentration of erbium ions in the region of $(20-30) \times 10^{24}$ m^{-3}. Indeed, at lower concentrations of erbium ions, the absorption from the cladding itself becomes quite small, and the efficiency relative to the injected pump inevitably decreases. In addition, an increase in the proportion of the unabsorbed pump in this case may lead to a damage of the tapered junction at the point where the pump radiation comes out [20].

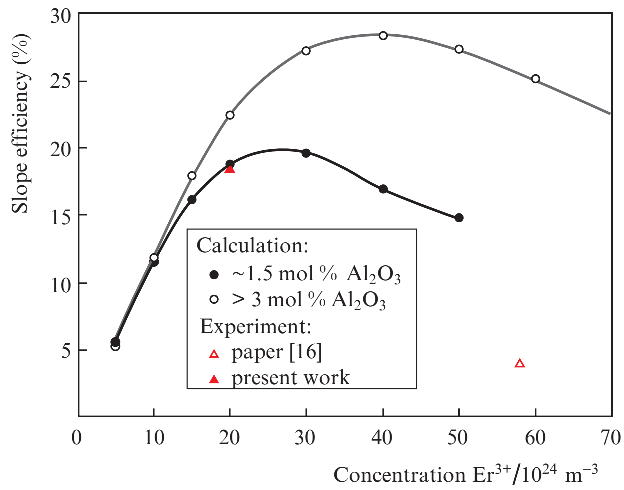

Figure 1. (Colour online) Calculated slope efficiency of tapered fibre as a function of the Er^{3+} ion concentration for an aluminosilicate matrix with low and high concentrations of erbium ions and the results of measuring the efficiency of tapered fibres.

3. Tapered erbium-doped fibre fabrication

The tapered fibre preform was developed using the MCVD method modified to include all dopants from the gas phase. The core had an $Al_2O_3-F-SiO_2$ matrix containing aluminium and fluorine, similar to that implemented in work [7]. The fibre was doped by Er^{3+} ions with a concentration of 20×10^{24} m^{-3}. The core had an aperture of about 0.09. To improve the overlap of the cladding pump modes with the core modes, the preform was polished to a shape close to square, and then covered with a layer of fluorine-doped silica glass. The average values of the core diameter, the diameter of the first reflective cladding, and the outer diameter were 17.8, 56.9, and 80 μm, respectively. A tapered fibre about 3.5 m long with an outer diameter of 67 to 420 μm was drawn from the preforms. A typical dependence of the outer diameter on the position along the fibre is shown in Fig. 2. A photograph of the fibre end-face from the thick end side and the estimated refractive index profile (obtained as a result of measuring the profile in fibre with a diameter of 125 μm and scaled for the case of the thick end) are shown in Fig. 3.

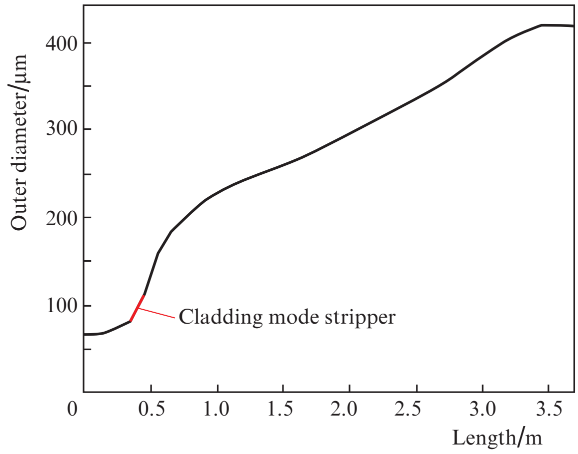

Figure 2. (Colour online) Distribution of the outer diameter of a tapered fibre along its length. The fibre section with a cladding mode stripper is marked in red.

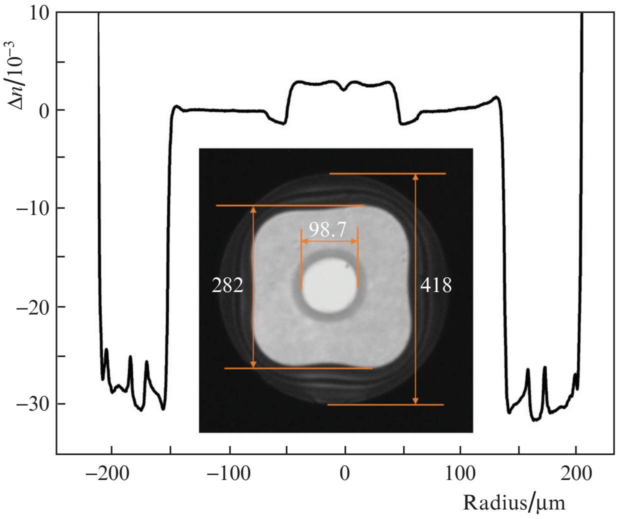

Figure 3. (Colour online) Refractive index profile and a photograph of the face of the thick end of the fabricated tapered fibre.

According to calculations, with an outer diameter of 67 μm, the cutoff wavelength of the first higher-order mode is 1540 nm, and the mode field diameter is about 14.5 μm. On the thick end side, the mode field diameter calculated from the refractive index profile is 56 μm.

4. Results and discussion

The fabricated tapered fibre was examined in a counter-pumped amplifier scheme shown in Fig. 4. Radiation from a source with a centre wavelength of 1560 nm was introduced into the thin end of the tapered fibre under study. The pump radiation from a (wavelength stabilised at 976 nm) multimode pump diode was introduced through the thick end of the tapered fibre towards the signal. The amplified signal at the output from the thick end of the tapered fibre was separated from the pump radiation using a dichroic mirror (DM) and then analysed.

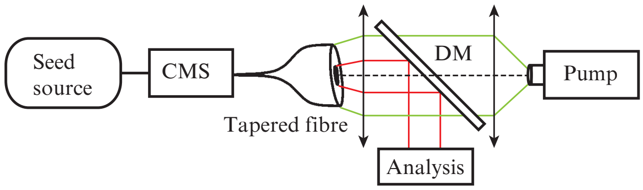

Figure 4. (Colour online) Fibre amplifier scheme based on a tapered fibre.

First, the output beam image was observed using an infrared camera. It should be noted that the output radiation quality remained relatively low (it contained higher-order modes) until a cladding mode stripper (CMS in Fig. 4) was added at a distance of about 40 cm from the input end (the position is shown by the red line in Fig. 2). In this region, the fluorine-doped coating was removed and replaced with a polymer coating having a refractive index higher than that of silica glass. We believe that due to the large ratio of the diameters of the core and the first reflective cladding, the cladding modes excited during the splicing of the signal fibre and the thin end of the tapered fibre had a high overlap with the fibre core and excited higher-order modes in the core when its diameter became sufficiently high to support their propagation. The developed cladding mode stripper removed undesirable cladding light and provided a significant improvement in the output radiation quality in the tapered fibre (see the inset in Fig. 5a).

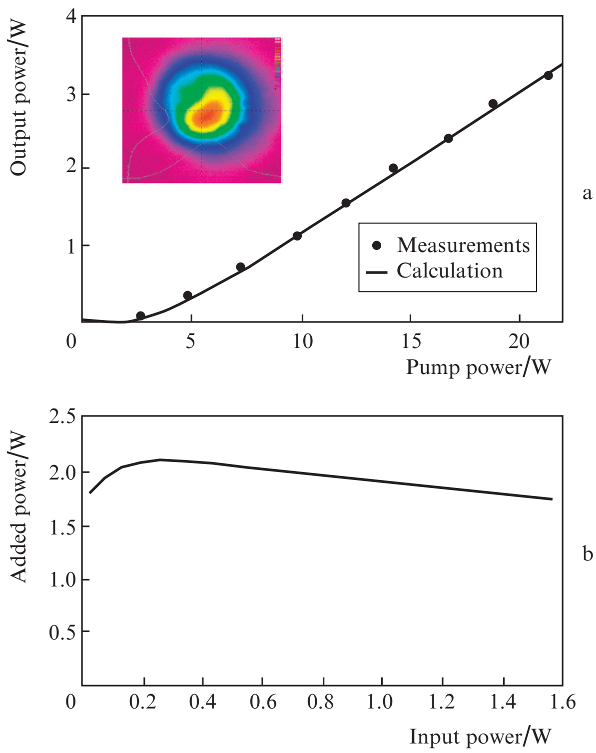

Figure 5. (Colour online) (a) Dependence of the output signal power on the input pump power at an input signal power of 0.36 W (the inset shows the mode image at the tapered fibre output obtained with an infrared camera) and (b) the dependence of the added signal power (the difference between the output and input powers) on the input signal power.

The efficiency of pump-to-signal conversion for the tapered fibre under study was approximately 18% (Fig. 5a), which is about five times higher than the efficiency obtained in the erbium-doped tapered fibre [16–18]. The maximum efficiency was attained with an input signal of about 250 mW (Fig. 5b). The efficiency and the dependence of the output power on the input power are in good agreement with the calculations performed for the case of a matrix of aluminosilicate glass matrix with a low aluminium oxide concentration.

It should be noted that the mode field diameter from the thick end side, estimated from the image on the camera (see inset in Fig. 5a), was about 40 μm. We assume that in this case, the effect of reducing the mode field is observed, which occurs when the fibre is bent. This effect is significantly enhanced by the presence of a central dip in the refractive index profile: when bending, the central dip 'squeezes out' radiation from the centre to the fibre edge. This assumption is confirmed by the distortion of the mode, which seems to be shifted to one of the core edges. It should also be emphasised that this distortion is not a consequence of the presence of higher-order modes. Thus, the measurement of the output beam quality has shown that the M^2 value lies in the range of 1.31–1.34 (see Fig. 6a), which, given the difference in the shape from the Gaussian one, is an evidence of a single-mode operation.

A more accurate way to determine the mode composition of the fibre is the so-called S^2 method [21], which allows one to reconstruct the spatial distributions of the phase and intensity of the modes propagating in the fibre, as well as to determine their power fraction (Figs 6b–6d). The results of these measurements indicated the presence of a high-quality single-mode regime of radiation propagation in tapered fibre, and also allowed us to establish that the admixture of higher-order modes did not exceed 2%. It can be seen that the peak characteristic of the first higher-order mode (the fact that this is the LP_{11} mode follows from the amplitude and phase distributions in Fig. 6d) does not exceed 18 dB measured from the power level of the fundamental mode.

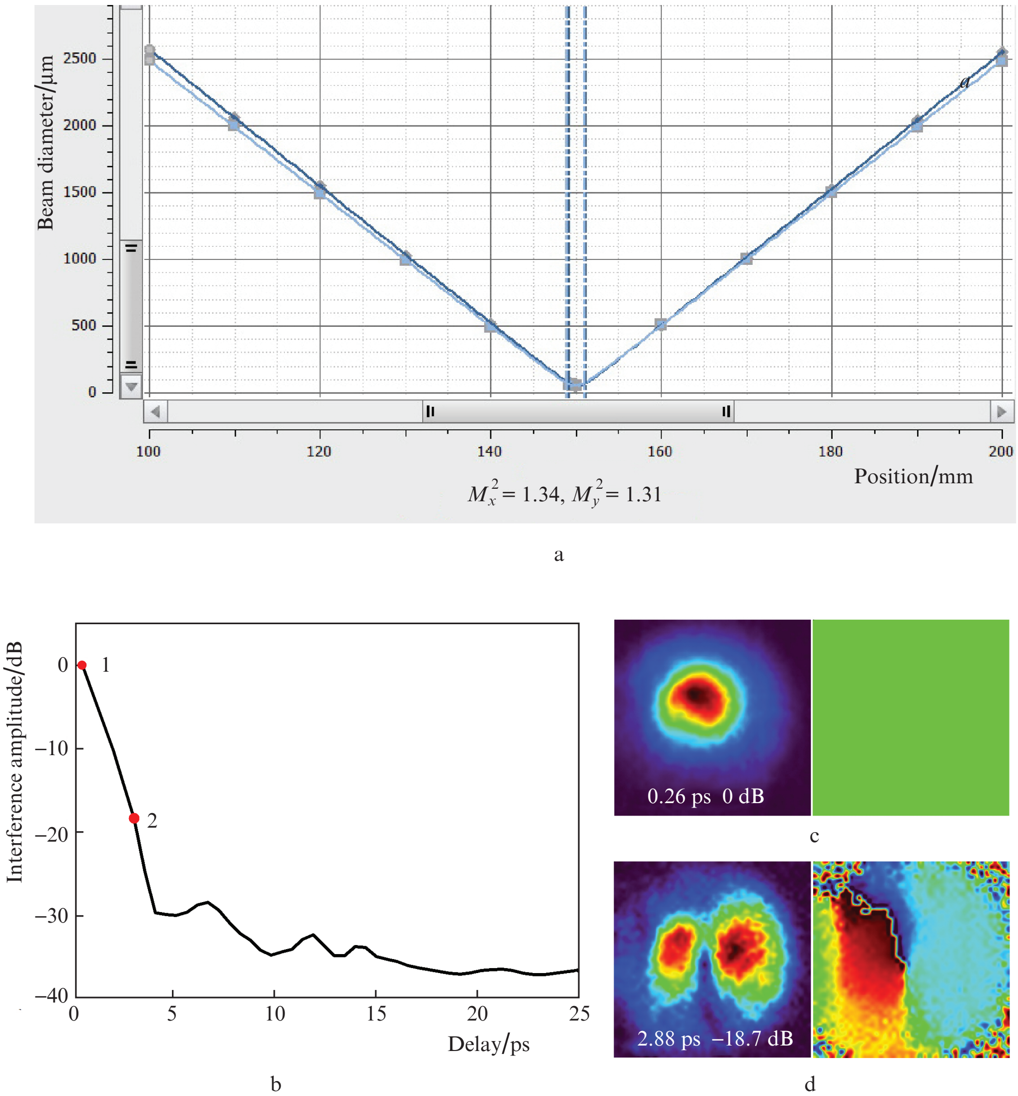

Figure 6. (Colour online) (a) Results of measuring the beam quality parameter M^2 at the maximum output radiation power and (b) S^2 measurements [21] in tapered fibre, as well as (c, d) distributions of amplitude (left, scale from 0 to 1) and phase (right, scale from –π to π) for points (c) 1 and (d) 2 on the S^2-graph.

5. Conclusions

The performed studies have shown for the first time the possibility of attaining high efficiency of pump-to-signal conversion (about 18%) in erbium-doped ytterbium-free tapered fibres. This efficiency was achieved as a result of optimising the fibre geometry itself (primarily, the ratio of core and cladding diameters), as well as by choosing the optimal concentration of erbium ions in the fibre core. In addition, within the frame of this work, for the first time it was possible to implement an erbium-doped tapered fibre with a record-large core diameter (about 100 μm) and high beam quality limited only by diffraction. It is worth noting that the final mode field diameter turned out to be somewhat smaller than the calculated one. We attribute this to the presence of a central dip on the fibre axis, which significantly distorts the output mode shape when bending tapered fibre.

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