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Factors reducing the efficiency of ytterbium fibre lasers and amplifiers operating near 0.98 μm

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Abstract. **We have studied the factors that reduce the efficiency of cladding-pumped ytterbium fibre lasers and amplifiers operating in the spectral range around a wavelength of 0.98 μm. It has been shown that the core of the active fibre being not single-mode leads to accelerated development of amplified spontaneous luminescence around λ = 1.03 μm, which reduces the highest possible amplifier efficiency. We have examined the effect of spontaneous luminescence propagating in the first reflective cladding. It has been shown theoretically that the pump-to-signal conversion efficiency is highest when the ratio of the core and cladding diameters in a multimode active fibre lies in the range 0.7 – 1. We have fabricated and characterised an optical fibre with a core-to-cladding diameter ratio of 0.76 (core and cladding diameters of 95 and 125 μm, respectively), which allowed a pump conversion efficiency of 66% to be reached, a record level for cladding-pumped ytterbium fibre laser systems emitting near 0.98 μm.**

Keywords: *ytterbium-doped optical fibre, large mode area fibre, ytterbium fibre laser.*

1. Introduction

Improving the performance of ytterbium fibre lasers and amplifiers is currently one of the most actively developing directions in fibre optics. One important advantage of the ytterbium ion over the other rare-earth ions is that it has the simplest energy level diagram, which rules out concentration quenching processes such as up-conversion and excited state absorption. The Stark splitting of the energy levels of the ytterbium ion ensures lasing in the range $\lambda > 1$ μm according to a four-level laser scheme, characterised by a low threshold pump power (low population inversion level necessary for amplification). As a consequence, it is the use of ytterbium fibre lasers which has ensured the highest efficiency and the maximum average and peak output powers so far.

At the same time, the energy level diagram of the ytterbium ion allows as well three-level laser operation in a spectral range near 0.98 μm. Such lasers are rather promising for a wide variety of applications. High-power single-mode lasers emitting near $\lambda = 0.98$ μm can be used for core-pumping single-mode ytterbium and erbium fibre lasers (for amplifying laser pulses to high peak power and producing ultrashort cavities). In addition, frequency doubling and quadrupling of such lasers offer the promise of replacing the argon laser. One approach attractive from the practical point of view is to use multimode fibre diodes emitting near 0.98 μm instead of multimode semiconductor pump diodes. In this case, one advantage of fibre sources over their semiconductor analogues is that they have a narrow emission spectrum, offer higher centre wavelength stability and potentially allow the output power to be scaled up to a subkilowatt level [1].

It is worth noting that the ytterbium fibre lasers emitting near 0.98 μm have been the subject of relatively few studies, and such lasers are essentially not used at present. The reason for this is that a variety of requirements should be met to ensure high lasing efficiency of the ytterbium fibre lasers emitting in the 0.98 μm range. One requirement is that high inverted population (at least 50%) be maintained along the entire active fibre. Another important requirement is that the undesirable luminescence in the range $\lambda > 1$ μm be suppressed. For this purpose, one has to reduce the operating length of the ytterbium-doped fibre, which leads to an increase in the fraction of unabsorbed pump light and a decrease in the overall efficiency of the fibre laser. Numerical calculations indicate that the main way of improving the efficiency of lasers in the range under consideration is by increasing the ratio of the core and cladding diameters, which makes it possible to raise the cladding pump absorption rate, thereby reducing the fraction of unabsorbed pump light [2].

Direct numerical calculations predict the possibility of 0.92-μm pump power conversion to a signal at a wavelength of 0.98 μm with an efficiency of almost 80% with respect to launched pump power. At the same time, in practice this high efficiency has not yet been reached in high-power laser systems (with output powers above several watts). The highest efficiency of pump conversion to a signal at a wavelength of 0.98 μm, about 50%, has been demonstrated in a laser based on a photonic crystal fibre (PCF) with a core-to-cladding diameter ratio of 0.4 [3]. It is worth noting studies by Minelly et al. [4] and Leich et al. [5], who in fact implemented pumping directly through a multimode core, with a nearly single-mode laser operation achieved by producing a conical taper on one side of the fibre. This approach appears to be the most promising: theoretical calculations predict that the pump-to-signal conversion efficiency is highest when the size of the region

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where pump light propagates is equal to that of the core. However, the single-mode laser efficiency reached in the studies in question [4, 5] was just above 30%–35% (50% in the case of multimode operation [5]). A conversion efficiency of 81% was reached only in a core-pumped, low-power configuration, where a single-mode fibre with a core diameter of 6 μm was used as a gain element [6].

It should be emphasised that the rate equations used to describe lasers and amplifiers were derived under the assumption that fibres used in a scheme are single-mode at luminescence wavelengths [7], but in general this is not so. In particular, Boullet et al. [3] and Röser F. et al. [8] studied an identical PCF with core and cladding sizes of 80 and 200 μm, respectively. The beam quality factor M^2 ranged from 1.2 to 2.2 (the fundamental mode was selectively excited using bulk optics), indicating that the structure was not single-mode. An even more spectacular example is tapered fibres, in which single-mode propagation is ensured by selectively exciting the operating mode in a highly multimode fibre [4, 5].

In all the above-mentioned cases, the 1.03-μm luminescence emitted by ytterbium ions can readily be captured by both the fundamental and higher order modes, which requires appropriate modifications in the rate equations (a larger number of propagating modes corresponds to higher captured luminescence power). The question also arises whether the spontaneous luminescence captured by the aperture of the inner fibre cladding can be amplified. Despite the smaller gain coefficient in comparison with the modes propagating through the fibre core, a (several orders of magnitude) higher spontaneous luminescence 'seed' signal level should be expected because the numerical aperture of the first reflective cladding considerably exceeds that of the core.

In this paper, we present theoretical and experimental studies of the effect of spontaneous ytterbium luminescence with a peak emission wavelength $\lambda = 1.03$ μm on the output characteristics of fibre laser systems emitting in a spectral range near 0.98 μm. Our calculations take into account the fraction of luminescence captured by the higher order modes of the core and the modes confined by the first reflective cladding. We have optimised the characteristics of ytterbium-doped optical fibres which make it possible to maximise lasing efficiency. In accordance with the calculation results, we fabricated a fibre amplifier for a wavelength of 0.976 μm which is based on a multimode ytterbium-doped fibre with optimal characteristics. A record high pump-to-signal conversion efficiency has been reached in comparison with the efficiency of other high-power laser systems operating near $\lambda = 0.98$ μm and pumped by multimode semiconductor sources.

2. Theory

First, we carried out a theoretical analysis of a cladding-pumped ytterbium fibre amplifier in the copropagating pump and signal configuration. Simulation was performed by solving standard rate equations for two energy levels, with electron transitions between them accompanied by photon emission or absorption [7]. In calculations, we took into account photon absorption and emission at the pump (= 0.915 μm), signal ($\lambda = 0.976$ μm) and spontaneous luminescence wavelengths (the luminescence spectrum between 0.915 and 1.1 μm was divided into 60 portions, and the variation in the luminescence power was calculated separately for each portion). For simplicity, the overlap integral of the fundamental mode of the fibre core with the doped region (I_s) was assumed to be unity and the overlap integral of the cladding modes with the doped region (I_p) was taken to be equal to the ratio of the core area (A_{core}) to the cladding area (A_{clad}). The doped region corresponded to the core region.

It should be noted that, from the viewpoint of the rate equations for the variation of the signal along the length of the fibre, it is unimportant (to within the overlap integral) whether the fibre operates in its multimode or single-mode range: only the propagating light and pump power densities are important. A different situation occurs in amplified spontaneous luminescence power calculations. In the case of a multimode core, we take into account that, as the number of core modes increases, the captured luminescence power increases in proportion to the number of modes, which is given by [7]

$$N_{core} = V_{core}^2/2, \tag{1}$$

where $V_{core} = \pi D_{core} \mathrm{NA}_{core}/\lambda_{lum}$ is a normalised frequency; D_{core} is the core diameter; NA_{core} is the numerical aperture of the core; and λ_{lum} is the emission wavelength. In addition, our calculations take into account that spontaneous luminescence propagates in both the forward and backward directions (relative to the signal propagation direction).

A somewhat different situation occurs in calculation for spontaneous luminescence confined in the first reflective cladding. In this case, the emitting region is the core, but the first reflective cladding captures all the luminescence in its aperture, NA_{clad}. The number of modes propagating through the cladding can be estimated as

$$N_{clad} = \frac{1}{2}\left(\frac{\pi D_{clad} \mathrm{NA}_{clad}}{\lambda_{lum}}\right)^2. \tag{2}$$

The fraction of captured spontaneous luminescence is proportional to the product of the number of modes propagating through the cladding and the overlap integral of the cladding modes with the doped region: $N_{clad} I_p$. To assess the effect of the cladding modes on the output characteristics of the amplifier, the system of rate equations was supplemented by appropriate equations. The level of 'background' losses was taken to be 50 dB km^{-1}.

Finally, the rate equations have the following form:

$$\begin{aligned}
\frac{dP_p}{dz} &= (N_2\sigma_p^{(e)} - N_1\sigma_p^{(a)}) I_p P_p - \alpha_p^0 P_p, \\
\frac{dP_s}{dz} &= (N_2\sigma_s^{(e)} - N_1\sigma_s^{(a)}) I_s P_s - \alpha_s^0 P_s, \\
\frac{dP_A^+(\nu_j)}{dz} &= (N_2\sigma_{\nu_j}^{(e)} - N_1\sigma_{\nu_j}^{(a)}) I_s P_A^+(\nu_j) - \alpha_{\nu_j}^0 P_A^+(\nu_j) \\
&\quad + N_2\sigma_{\nu_j}^{(e)} I_s \nu_j \Delta\nu_j N_{core}, \\
\frac{dP_A^-(\nu_j)}{dz} &= -(N_2\sigma_{\nu_j}^{(e)} - N_1\sigma_{\nu_j}^{(a)}) I_s P_A^-(\nu_j) + \alpha_{\nu_j}^0 P_A^-(\nu_j) \\
&\quad - N_2\sigma_{\nu_j}^{(e)} I_s \nu_j \Delta\nu_j N_{core},
\end{aligned} \tag{3}$$

$$\frac{\mathrm{d}P^{+}_{A\,\mathrm{clad}}(\nu_j)}{\mathrm{d}z} = (N_2\sigma^{(\mathrm{e})}_{\nu_j} - N_1\sigma^{(\mathrm{a})}_{\nu_j})I_{\mathrm{p}}P^{+}_{A\,\mathrm{clad}}(\nu_j)$$

$$-\alpha^{0}_{\nu_j}P^{+}_{A\,\mathrm{clad}}(\nu_j) + N_2\sigma^{(\mathrm{e})}_{\nu_j}I_{\mathrm{p}}\nu_j\Delta\nu_j N_{\mathrm{clad}},$$

$$\frac{\mathrm{d}P^{-}_{A\,\mathrm{clad}}(\nu_j)}{\mathrm{d}z} = -\,(N_2\sigma^{(\mathrm{e})}_{\nu_j} - N_1\sigma^{(\mathrm{a})}_{\nu_j})I_{\mathrm{p}}P^{-}_{A\,\mathrm{clad}}(\nu_j)$$

$$+\alpha^{0}_{\nu_j}P^{-}_{A\,\mathrm{clad}}(\nu_j) - N_2\sigma^{(\mathrm{e})}_{\nu_j}I_{\mathrm{p}}\nu_j\Delta\nu_j N_{\mathrm{clad}},$$

where P_{p} is the pump power; P_{s} is the signal power; $P^{+(-)}_{A}(\nu_j)$ is the power of the luminescence co- and counterpropagating with the signal, respectively, in the core; $P^{+(-)}_{A}(\nu_j)_{\mathrm{clad}}$ is the power of the luminescence co- and counterpropagating with the signal, respectively, in the cladding; $N_1 = A/(A + B)$ is the population of the lower laser level; $N_2 = N_0 - N_1$ is the population of the upper laser level; N_0 is the rare-earth concentration in the glass network; $\sigma^{(\mathrm{e}),(\mathrm{a})}_{\mathrm{s}(\mathrm{p},\nu_j)}$ is the emission (absorption) cross section of the signal (pump and luminescence); $\alpha^{0}_{\mathrm{s}(\mathrm{p},\nu_j)}$ is the background loss at the signal (pump and luminescence) wavelengths;

$$A = A_{\mathrm{e}} + W_{\mathrm{se}} + W^{\mathrm{e}}_{\mathrm{ASE}} + W^{\mathrm{e}}_{\mathrm{ASE\,back}}$$

$$+ W^{\mathrm{e}}_{\mathrm{ASE\,clad}} + W^{\mathrm{e}}_{\mathrm{ASE\,clad\,back}} + R_{\mathrm{pe}};$$

$$B = W_{\mathrm{sa}} + W^{\mathrm{a}}_{\mathrm{ASE}} + W^{\mathrm{a}}_{\mathrm{ASE\,back}} + W^{\mathrm{a}}_{\mathrm{ASE\,clad}}$$

$$+ W^{\mathrm{a}}_{\mathrm{ASE\,clad\,back}} + R_{\mathrm{pa}};$$

$A_{\mathrm{e}} = 1/\tau$ is the spontaneous transition probability;

$$W_{\mathrm{se(sa)}} = P_{\mathrm{s}}\frac{\sigma^{\mathrm{e(a)}}_{\mathrm{s}}I_{\mathrm{s}}}{h\nu_{\mathrm{s}}A_{\mathrm{core}}};\quad R_{\mathrm{pe(pa)}} = P_{\mathrm{p}}\frac{\sigma^{\mathrm{e(a)}}_{\mathrm{s}}I_{\mathrm{p}}}{h\nu_{\mathrm{p}}A_{\mathrm{core}}};$$

$$W^{\mathrm{e(a)}}_{\mathrm{ASE(ASE\,back)}} = \int P^{+(-)}_{A}(\nu)\frac{\sigma^{\mathrm{e(a)}}_{\nu}I_{\mathrm{s}}}{h\nu A_{\mathrm{core}}}\mathrm{d}\nu;$$

and

$$W^{\mathrm{e(a)}}_{\mathrm{ASE\,clad(ASE\,clad\,back)}} = \int P^{+(-)}_{A\,\mathrm{clad}}(\nu)\frac{\sigma^{\mathrm{e(a)}}_{\nu}I_{\mathrm{p}}}{h\nu A_{\mathrm{core}}}\mathrm{d}\nu.$$

Figure 1 shows the calculated signal amplification efficiency at a wavelength of 0.976 μm as a function of the core-to-cladding diameter ratio for fibres with single-mode and multimode cores. The following parameters were used in the calculations: ytterbium concentration in the core, 0.88×10^{25} m^{-3}; core–cladding index difference $\Delta n = 0.0025$; numerical aperture of the reflective cladding NA = 0.46. As a host for the active fibre core, we chose phosphosilicate glass, insensitive to the photodarkening effect [9]. The relevant luminescence and absorption cross sections were borrowed from Mel'kumov et al. [10]. The input signal level was adjusted in each case so that the amplifier operated in the saturation regime (changing the input signal level by a factor of 2 led to a change in output signal power by no more than a few percent). Efficiency was estimated at a pump power approximately one order of magnitude above the threshold gain (in particular, with allowance for spontaneous luminescence capture by the modes of the first reflective cladding). It is seen from Fig. 1 that increasing the core-to-cladding diameter ratio leads to an increase in the efficiency of the ytterbium fibre lasers emitting at a wavelength of 0.976 μm, which can be accounted for by an increase in cladding pump absorption. At the same time, the fact that the fibre core is not single-mode considerably reduces the pump-to-signal conversion efficiency. Increasing the number of modes propagating in the core leads to an increase in the 1.03-μm luminescence capture in the core and, accordingly, to a more rapid increase in its power. Thus, to suppress undesirable lasing at a wavelength of 1.03 μm, an appropriate decrease in the operating length of the active fibre is necessary, which would reduce the fraction of absorbed pump light and the efficiency of the entire laser system.

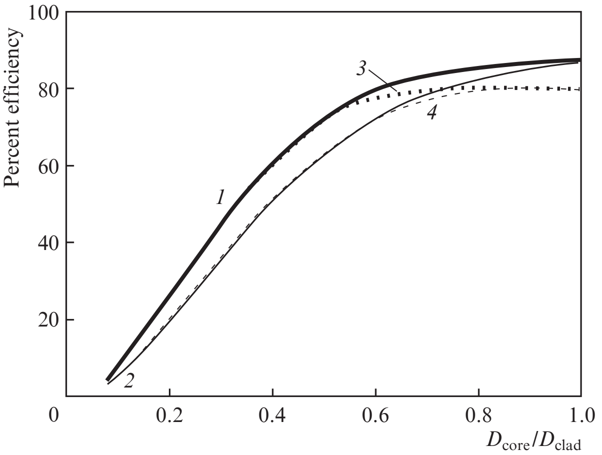

Figure 1. Calculated signal amplification efficiency as a function of the core-to-cladding diameter ratio in ytterbium-doped fibre under the following assumptions: (*1*) single-mode core; (*2*) core supporting multimode propagation at the luminescence wavelengths; (*3*) single-mode and (*4*) multimode cores at the luminescence wavelengths with allowance for spontaneous luminescence capture by the modes of the first reflective cladding.

An analogous situation occurs if the captured luminescence propagating through the first reflective cladding is taken into account. However, according to the present calculations, the effect of luminescence propagating in the cladding becomes significant only when the ratio of the core and cladding diameters is near unity. Note that, at such a ratio of the diameters, the effect of core multimodedness is, in contrast, substantially weaker (Fig. 1). The reason for this is that, because of the high cladding pump absorption rate, most of the pump light is absorbed over an active fibre length shorter than the length required for the development of spontaneous luminescence around $\lambda = 1.03$ μm. That the core is multimode plays no significant role in this case (at least at the relatively small core numerical aperture used in our calculations).

As follows from Fig. 1, the optimal ratio of the core and cladding diameters, maximising the lasing efficiency, is 0.7–1. In such a case, cladding pump absorption is sufficient for most of the pump light to be absorbed, whereas the core modes are weakly amplified and cannot have a significant effect on the laser source efficiency.

3. Experimental

Experiments aimed at amplifying laser light at a wavelength of 976 nm in multimode optical fibres were carried out in

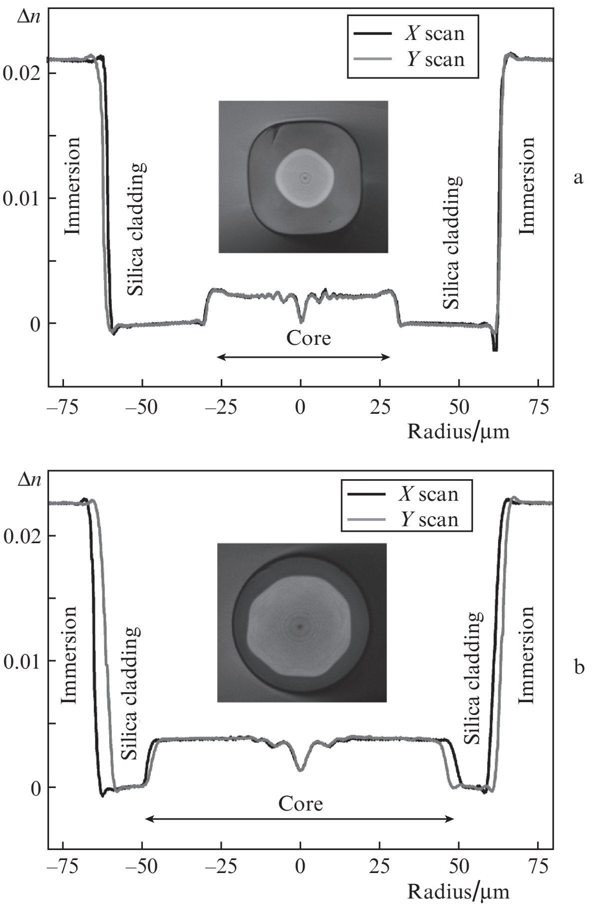

Figure 2. Measured refractive index profiles of fibres with ratios of their core and cladding diameters of (a) 0.43 and (b) 0.76. Insets: optical microscope images of the end faces of the fibres.

order to verify the main conclusions drawn in Section 2. To this end, we produced two multimode fibres with ratios of their average core and cladding diameters of 0.43 and 0.76.

Multimode ytterbium-doped fibre preforms were produced by the modified chemical vapour deposition (MCVD) process. Ytterbium ions were incorporated into the glass network via vapour phase doping [11]. To ensure the best cladding mode mixing, the cylindrical symmetry of the preforms was distorted. The fibres were drawn in a reflective polymer which ensured light propagation through the first cladding with a numerical aperture of 0.46. The former fibre had a square cross section with a side length of about 125 μm, which ensured compatibility of the fibre with standard pump–signal combiners. The average core and cladding diameters were 60 and 140 μm, respectively. In the latter fibre, the ratio of the average core and cladding diameters was 95/125. Originally, we intended to produce an octagonal outer cladding, but because of the large volume of the low melting point glass the outer cladding became rounded in the course of drawing. The core–cladding index difference Δn was 0.0025 in the former fibre and 0.0038 in the latter. Figure 2 shows measured refractive index profiles of the fibres and optical microscope images of their end faces. Structures with a sufficiently low refractive index of their core were chosen in order to reduce the number of modes propagating in the fibre core, thereby maximising the lasing efficiency in the 0.98 μm range.

The experimental setup for amplifier efficiency measurements comprised a master oscillator and power amplifier based on one of the multimode fibres under investigation (Fig. 3). As the master oscillator, we used an all-fibre laser whose design was similar to that proposed previously [12], with a maximum output power of up to 5.5 W. The 1.03 μm light was further suppressed at the output of the fibre laser by a wavelength-selective fibre filter, which ensured attenuation of about 50 dB at a wavelength of 1.03 μm and had low losses at the signal wavelength (0.976 μm).

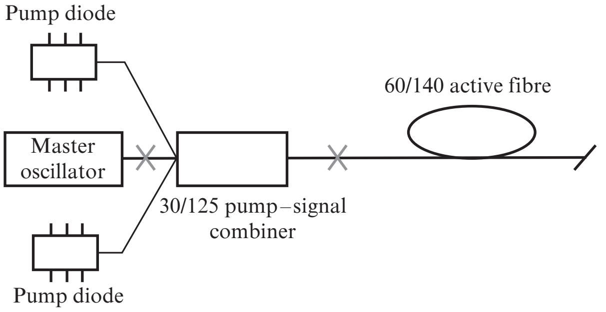

Figure 3. Schematic of the amplifier in the experimental setup.

The single-mode master oscillator and pump beams were coupled into the multimode fibre under study using a pump–signal combiner [(2 + 1)×1 configuration]. The active fibre under study was fusion-spliced directly to the output end of the combiner. The unabsorbed pump light was outcoupled by placing a small section of the output end of the multimode fibre in a high refractive index immersion liquid. To avoid back reflection, the output end of the ytterbium-doped fibre was angle-cleaved at about 8°, so that the numerical aperture of the reflected light exceeded that of the fibre core. The output signal power was measured by an OPHIR Photonics FL250A-BB-35 power meter. The light emerging from the fibre output was detected by a Yokogawa AQ6370 spectrum analyser.

In the first stage, we studied the 60/140 fibre, with a core-to-cladding diameter ratio of 0.43 (according to the present calculation results, in this case the core being not single-mode has the most dramatic effect on the laser efficiency). Figure 4 shows the pump-to-signal conversion efficiency as a function

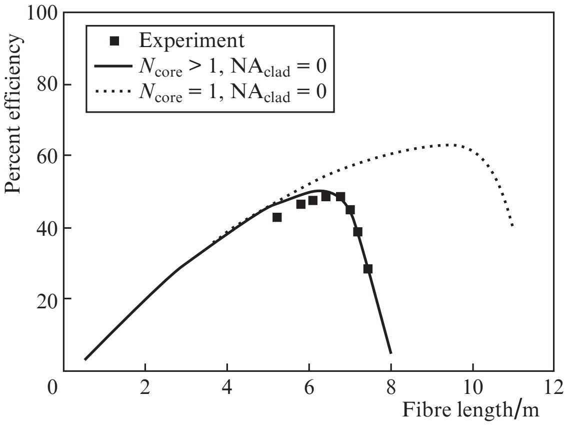

Figure 4. Calculated and measured amplifier efficiencies at $\lambda = 976$ nm as functions of ytterbium-doped fibre length (average core and cladding diameters of 60 and 125 μm, respectively; $\Delta n = 0.0025$; NA = 0.46).

of fibre length at pump and signal wavelengths of 0.915 and 0.976 μm. The data were obtained theoretically, with allowance for the multimode state of the fibre core (solid line), and experimentally (filled squares). In the calculations, the power of the signal from the master oscillator was taken to be 0.8 W, which corresponds to the power used in the scheme. The dotted line in Fig. 4 represents the calculation results for the case where the fibre core has the same diameter but is single-mode. It is seen that the calculation results for the multimode core agree well with the experimental data. Comparison of the efficiency curves obtained for the single-mode and multimode core fibres leads us to conclude that the observed reduction in the efficiency of the laser sources is primarily due to the decrease in the optimal length of the active fibre and is caused by the faster growth of spontaneous luminescence in structures that support the propagation of several modes in their core at luminescence wavelengths. It is worth noting that the slight decrease in the maximum calculated pump-to-signal conversion efficiency with respect to the highest possible one (Fig. 1) is due to the fact that the ‘seed’ signal power (0.8 W) was insufficient for complete saturation of the amplifier.

Figure 5 shows the calculated and measured gain curves for the fibre with core and cladding diameters of 95 and 125 μm ($D_{\text{core}}/D_{\text{clad}} = 0.76$), at which the highest pump-to-signal conversion efficiency should be expected according to our calculations. The refractive index of the core relative to that of the silica cladding in the fibre was 0.0038. The input signal power was increased to the highest possible level (5.5 W) to ensure that the amplifier operated in saturation mode. It is worth noting that our calculations adequately predict the optimal fibre length, but the experimentally measured amplifier efficiency is somewhat lower than the calculated one. One possible cause of the discrepancy is that, as a result of inappropriate processing in the course of the fibre fabrication, the outer cladding was circular in shape, which considerably reduced the cladding mode mixing efficiency and, as a consequence, the cladding pump absorption efficiency.

In spite of this drawback, the use of the 95/125 fibre as the gain element of the amplifier allowed us to obtain a pump-to-signal conversion slope efficiency of 66%, which is a record level for multimode pump high-power lasers and amplifiers operating around $\lambda = 0.98$ μm. Figure 6 shows the output power spectrum and the variation of the output power with pump power at the optimal fibre length. The fraction of 1.03-μm luminescence evaluated from the output emission spectrum does not exceed 0.5% of the total output power.

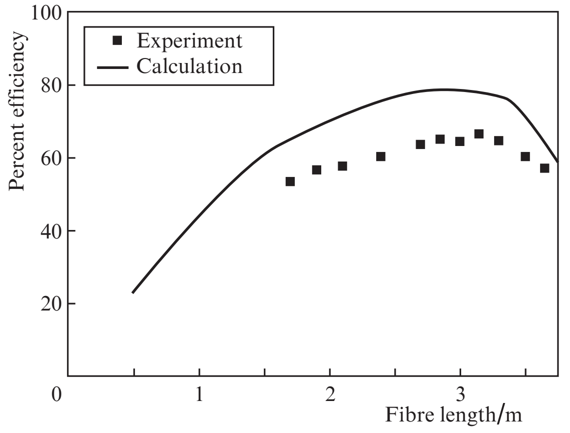

Figure 5. Calculated and measured amplifier efficiencies at 976 nm as functions of ytterbium-doped fibre length (average core and cladding diameters of 95 and 125 μm, respectively; $\Delta n = 0.0038$; NA = 0.46).

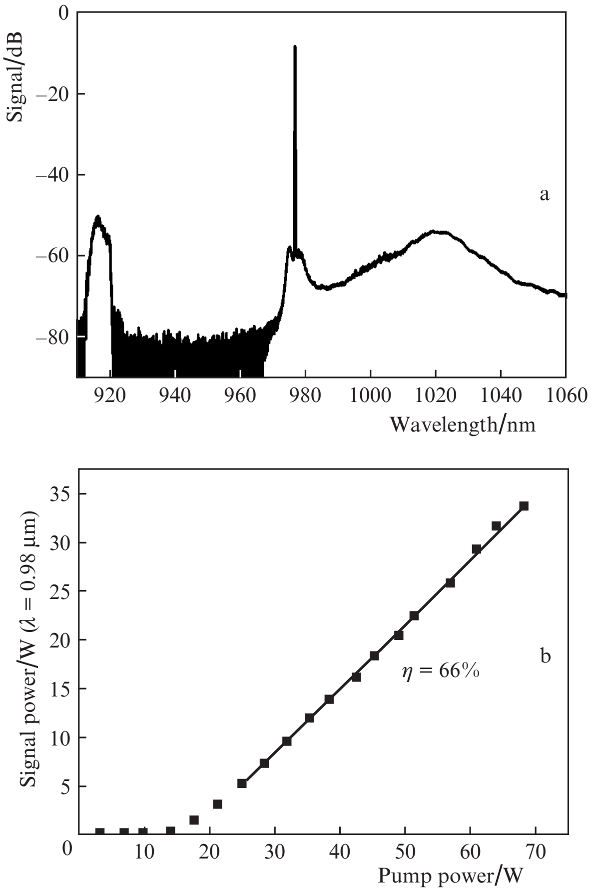

Figure 6. (a) Signal power spectrum and (b) variation of the signal power with pump power at the output of the fibre with a core-to-cladding diameter ratio of 0.76.

4. Conclusions

It has been shown theoretically in this study that the possibility of high-order mode propagation in the core of an ytterbium-doped fibre in the case of light amplification around $\lambda = 0.98$ μm may lead to a considerable reduction in pump-to-signal conversion efficiency. The calculation results have been confirmed by experimental data for a multimode fibre with a core-to-cladding diameter ratio of 0.43. It has been shown that fibres with a core-to-cladding diameter ratio from 0.7 to 1 should be used to maximise the pump-to-signal conversion efficiency. We have demonstrated a multimode fibre with an average core diameter of 95 μm and cladding diameter of 125 μm. It has been used to make a multimode amplifier operating at a wavelength of 0.976 μm and offering a slope efficiency of 66%, a record level for multimode pump schemes.

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