Quantum Electronics **46** (3) 271 – 276 (2016)

DOI: 10.1070/QEL15968

Effect of temperature on the active properties of erbium-doped optical fibres

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Abstract. **We have studied the effect of heating on the performance of erbium-doped fibre based devices and determined temperature-dependent absorption and emission cross sections of the erbium ion in silica glass. The results demonstrate that heating of fibres in cladding-pumped high-power (~100 W) erbium-doped fibre lasers causes no significant decrease in their efficiency. In contrast, superluminescent sources operating in the long-wavelength region (1565 – 1610 nm) are extremely sensitive to temperature changes.**

Keywords: *erbium-doped optical fibre, efficiency, temperature, superluminescent sources.*

1. Introduction

Erbium-doped fibre based devices (lasers, amplifiers and superluminescent sources) find wide application in various areas of science and technology, in particular in telecommunications, medicine, sensors and remote sensing. It is not uncommon that, during the operation of such devices, the temperature of the active fibre may considerably rise. According to the Boltzmann distribution, raising the temperature of the active fibre changes the populations of sublevels of laser levels. This leads to changes in the absorption and emission cross sections of the erbium ion, influencing the inverted population in the fibre and increasing signal reabsorption [1]. It is known that the main factor reducing the pump-to-signal conversion efficiency in erbium-doped fibre lasers and amplifiers is erbium clustering-induced cooperative upconversion [2 – 4]. Additional signal reabsorption increases the negative effect of the clustering on the efficiency of such lasers [4]. Thus, heating may cause a drop in the efficiency and, hence, in the output power of erbium-doped fibre lasers and amplifiers. An increase in population inversion also influences the gain spectrum of active fibres, so heating may change spectra of superluminescent sources.

It is worth noting that, in many applications of erbium-doped fibres, heating produces no significant changes in characteristics of devices based on such fibres. In particular, it is well known that standard C-band (1530 – 1565 nm) erbium-doped fibre amplifiers core-pumped by single-mode laser diodes have extremely low temperature sensitivity: their gain coefficient varies by no more than a few hundredths of a decibel per degree Celsius [5, 6]. Superluminescent sources that are used for gyroscopes are also known to be highly stable: after optimisation of their parameters, the wavelength of such sources varies by a few picometres per degree Celsius [7]. However, the good temperature stability of the above-mentioned light sources is due to the use of relatively short lengths of erbium-doped fibre, corresponding to a small-signal core pump absorption (SSCPA) from 20 to 40 dB, which rules out significant signal reabsorption.

In a number of applications, considerably longer lengths of erbium-doped fibre are needed (with SSCPA in the range 100 – 400 dB), and signal reabsorption in such devices plays a significant role. These are primarily cladding-pumped erbium-doped fibre lasers and amplifiers (cladding pump absorption is an order of magnitude lower than core pump absorption, which requires a proportional increase in fibre length). Long lengths of erbium-doped fibre are also required for superluminescent sources emitting in the long-wavelength L-band (1565 – 1625 nm), where signal is generated through multiple absorptions of a shorter wavelength signal and photon emission at longer wavelengths over a long length of the fibre.

Despite the large number of reports dealing with the properties of erbium-doped fibre and related devices, detailed studies of the temperature sensitivity of devices utilising long lengths of erbium-doped fibre (with SSCPA above 100 dB) are, to our knowledge, missing. The objectives of this work were to study in detail the effect of temperature on the performance of such devices and determine temperature-dependent absorption and emission cross sections of the erbium ion, which is necessary for a theoretical analysis of temperature effects.

2. Temperature-dependent absorption and emission cross sections of the erbium ion

As mentioned above, raising the temperature of erbium-doped fibre leads to changes in the absorption and emission cross sections of the erbium ion. Here we present temperature dependences of these cross sections in the range 25 – 120 °C. The absorption and emission cross section spectra of the erbium ion are known to depend on core glass composition [3, 8]. Currently, the most widespread core material is aluminosilicate glass containing 4 – 7 mol % alumina. This glass offers the highest erbium cluster solubility, thus ensuring the highest pump-to-signal conversion efficiency [3]. Aluminosilicate glass-based fibres are widely used in telecommunica-

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Received 11 November 2015; revision received 27 January 2016
Kvantovaya Elektronika **46** (3) 271 – 276 (2016)
Translated by O.M. Tsarev

tions amplifiers and erbium-doped fibre superluminescent sources. At the same time, such fibres have a large core–cladding refractive index difference ($\Delta n > 0.01$). This makes it impossible to obtain large mode area single-mode fibres necessary for high peak power pulse amplifiers [9–11] and high-power, high-performance cw lasers [4, 12].

Recent work has demonstrated that fibres with low Δn values, capable of ensuring high laser efficiency, can be produced using phosphoaluminosilicate glass [3, 13]. The reason for this is that codoping with aluminium and phosphorus oxides leads to the formation of $AlPO_4$ structural groups in the glass network, which are similar in properties to SiO_2 molecules [14]. At an equimolar ratio of aluminium and phosphorus oxides, the refractive index of such glass is even lower than that of pure silica glass. A positive core–cladding index difference can be ensured by a slight excess of alumina or phosphorus oxide. Given that the refractive index of phosphorus oxide is lower, it is technologically convenient to use this oxide, rather than alumina, to obtain a small Δn. In view of this, temperature-dependent absorption and emission cross sections were measured for two types of erbium-doped fibre, which hold the greatest promise for producing 1.55-μm light sources: aluminosilicate (AlSi) and phosphorus-enriched phosphoaluminosilicate (PAlSi) fibres.

Temperature-induced relative changes in emission cross section were measured using the experimental setup schematised in Fig. 1. The output of a single-mode pump laser diode (980 nm, ~100-mW power) was coupled into a segment of erbium-doped fibre using a 980/1550 nm fibre-optic wavelength-division multiplexer (WDM). The other end of the fibre was angle-cleaved to prevent back reflection. The counterpropagating luminescence was outcoupled from the signal port of the multiplexer, equipped with an FC/APC SMF-28 pigtailed connector, and was measured using an optical spectrum analyser (OSA) (Yokogawa AQ6370C). A segment of the active fibre was located on a hot plate equipped with a digital temperature controller (Wisd WiseTherm HP-20D) and was covered with a heat insulation material. Measured spectra were then corrected for the optical loss spectrum of the multiplexer. To ensure thermal equilibrium between the fibre and hot plate, each luminescence spectrum was measured at least 15 min after the temperature of the hot plate was changed.

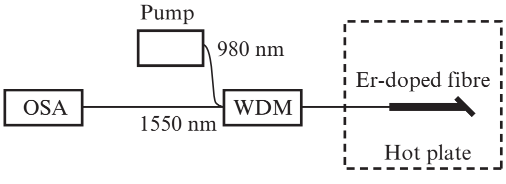

Figure 1. Experimental setup used to measure luminescence spectra.

In our measurements, we used AlSi and PAlSi fibres with maximum absorption coefficients of 23 and 52 dB m^{-1} near 1530 nm, core diameters of 4 and 9 μm and $\Delta n \sim 0.02$ and 0.004, respectively. The claddings of the fibres, 125 μm in diameter, were coated with a high refractive index polymer. To rule out changes in the shape of the luminescence spectrum due to reabsorption/amplification during measurements, the length of the fibre segments was 3 and 1.5 cm, respectively. Figure 2 shows normalised luminescence spectra measured at room temperature (25 °C). It is worth noting that, as would be expected from previous results [3], the emission spectrum of the PAlSi fibre was similar in shape to that of phosphosilicate fibre.

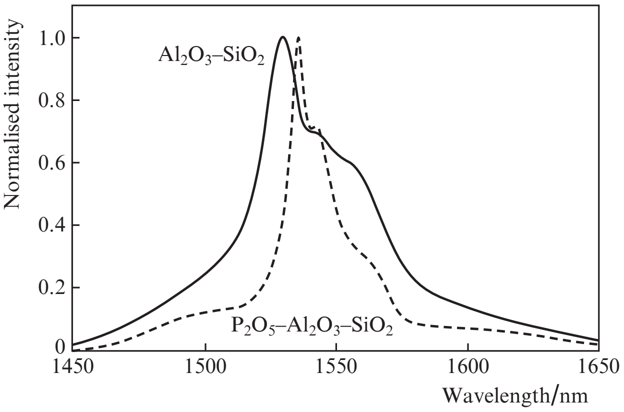

Figure 2. Luminescence spectra of the erbium ion in the AlSi and PAlSi glasses.

Figure 3 shows relative changes in luminescence spectra at temperatures T = 40, 80 and 120 °C, corresponding to changes in emission cross section for the AlSi and PAlSi fibres at T = 25 °C.

Temperature dependences of absorption cross sections were obtained using the cutback technique (by sequentially

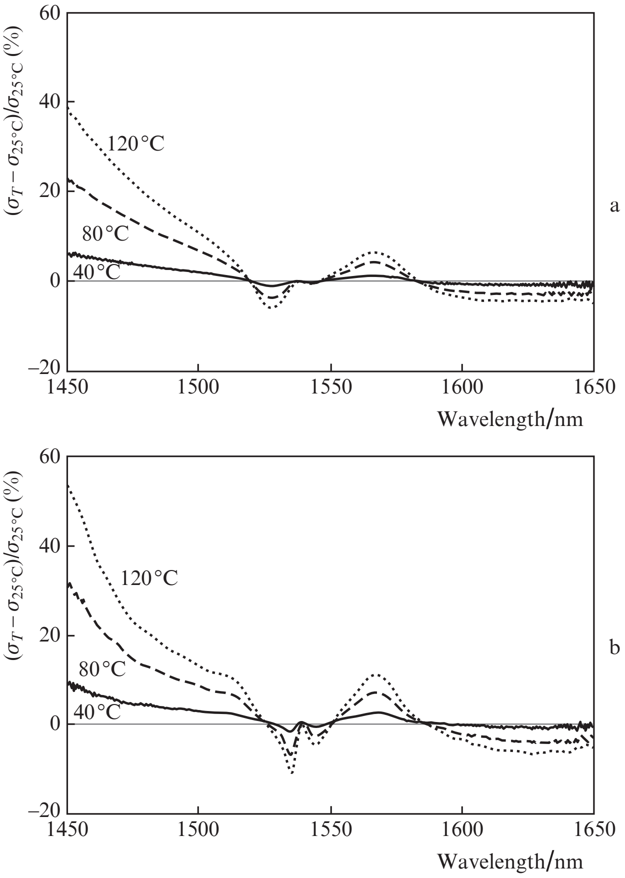

Figure 3. Temperature-induced relative changes in the emission cross sections of the erbium ion in the (a) AlSi and (b) PAlSi fibres.

reducing the fibre length). Figure 4 presents normalised room-temperature absorption spectra. Figure 5 shows temperature-induced relative changes in the shape of the spectra and, hence, in absorption cross sections for the AlSi and PAlSi fibres.

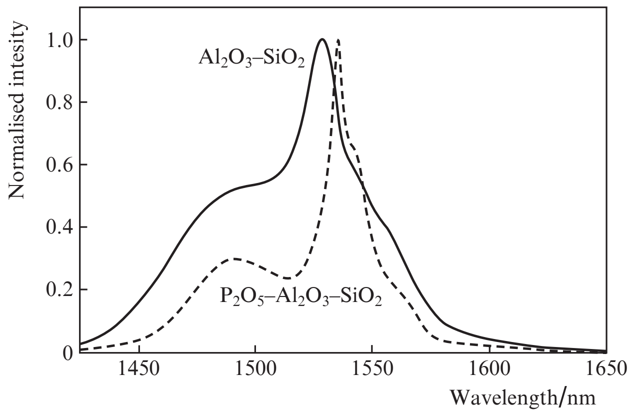

Figure 4. Absorption spectra of the erbium ion in the AlSi and PAlSi glasses.

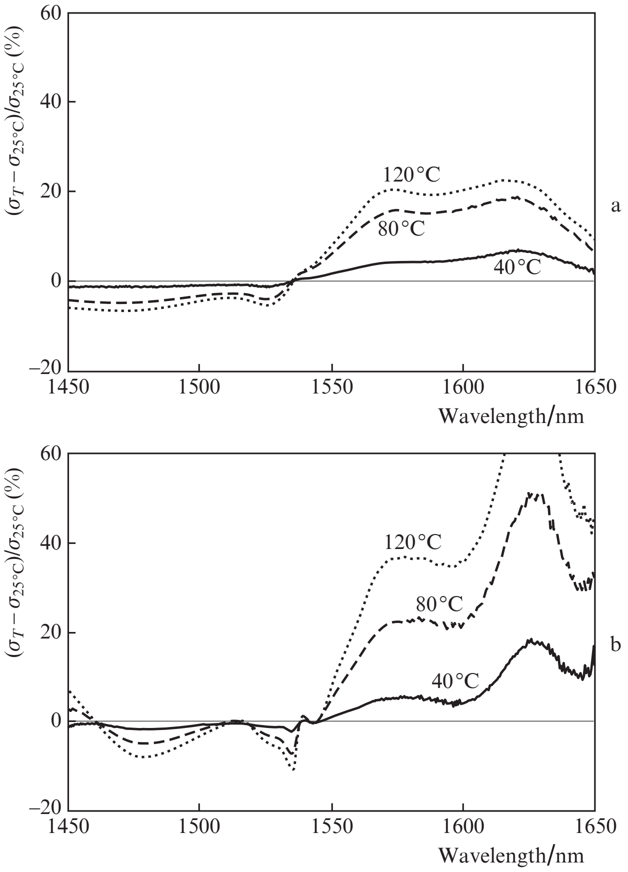

Figure 5. Temperature-induced relative changes in the absorption cross sections of the erbium ion in the (a) AlSi and (b) PAlSi fibres.

Comparing the data in Figs 3 and 5, we note that heating the fibres increases the absorption and emission cross sections around 1570 nm and that the relative increase in the absorption cross sections is about three times that in the emission cross sections. Moreover, the relative change in the absorption cross sections does not decrease with increasing wavelength above 1585 nm, in contrast to that in the emission cross sections. As pointed out above, an increase in absorption cross section may lead to an increase in the negative effect of cooperative upconversion. Thus, heating would be expected to impair the output characteristics of lasers, amplifiers and superluminescent sources operating in the long-wavelength region.

3. Effect of heating on the characteristics of erbium fibre superluminescent sources

Erbium fibre superluminescent sources find wide application in environmental monitoring, fire safety and other systems, where a refractive index fibre Bragg grating is used as a sensing element. One way of improving the performance of such systems is by extending the spectral range of their light sources, which will increase the measurand range or the number of measurement channels. This can be achieved by simultaneously using erbium fibre sources operating not only in the standard C-band (1530–1565 nm) but also in the long-wavelength L-band (1565–1625 nm). Long-wavelength sources are difficult to make because of the small emission cross section of the erbium ion in this range, and erbium-doped fibres considerably longer than the pump absorption length are used to produce such sources. As a result, short-wavelength luminescence is first generated in such fibre. During subsequent propagation through the fibre, the signal wavelength shifts to the long-wavelength region as a consequence of the absorption and re-emission of the signal. As shown in Section 2, the absorption and emission cross sections of the erbium ion in the long-wavelength region vary considerably with temperature, and the large number of signal absorption and re-emission events in L-band superluminescent sources further increases the effect of temperature on their output characteristics (through accumulation of this effect). It should also be noted that temperature instability of characteristics, including that of the weighted-average wavelength of superluminescent sources, may significantly limit their application in fibre-optic gyroscopes.

To demonstrate the temperature sensitivity of long-wavelength superluminescent sources, we used the configuration schematised in Fig. 6. The pump power (980 nm) was 150 mW, and a fibre loop mirror based on a 50/50 fibre coupler was fusion-spliced to the signal port of the multiplexer. The erbium-doped aluminosilicate fibre segment used in our experiment had a core diameter of 4 μm, absorption of 40 dB m^{-1} at 980 nm and a length of 10 m (400-dB SSCPA). The output emission spectrum of the erbium-doped fibre segment at $T = 25\,°C$ is shown in Fig. 7a by a solid line. The average output power of the source was 1 mW. Heating the erbium-doped fibre to 60 °C reduced the output power by more than a factor of 2 (to 450 μW).

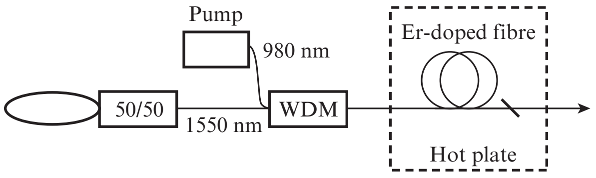

Figure 6. Schematic of the superluminescent source.

To assess the effect of temperature on the output spectrum of the superluminescent source using numerical simulation, we calculated the gain spectrum of the fibre under the described experimental conditions. Solving rate equations with allowance for upconversion [15], we modelled simultaneous small-signal propagation at different wavelengths in the copropagating pump and signal configuration. In our calculations, we used room-temperature emission and absorption cross sections from Barnes et al. [8]. At $T = 60\,°\mathrm{C}$, these cross sections were corrected with allowance for the experimental data in Section 2. The calculation results are presented in Fig. 7b. It is seen that the calculated gain spectrum of the fibre correlates well with the measured output spectrum of the superluminescent source and allows the observed variation in the spectrum and reduction in power with increasing temperature to be accounted for. The reason for the observed distinctions between the calculation results and experimental data is that the seed signal used in the superluminescent source was the erbium ion luminescence signal, which propagated in both the forward and reverse directions (owing to the presence of the fibre loop mirror). Since the luminescence spectrum is not flat, this leads to distinctions between the output and gain spectra.

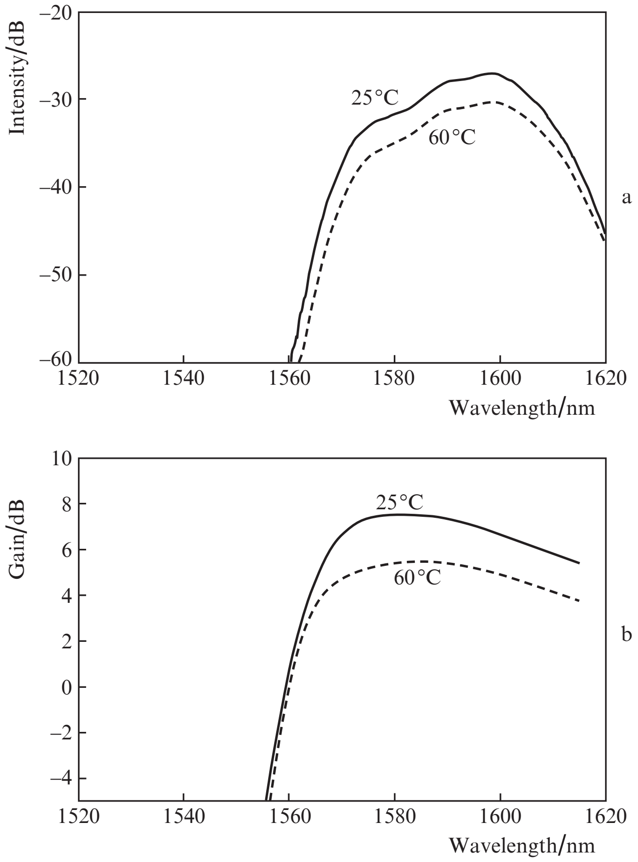

Figure 7. (a) Measured output spectra of the superluminescent source and (b) calculated gain spectra of a 10-m length of erbium-doped fibre at temperatures of 25 and 60 °C.

In producing C-band superluminescent sources, use is typically made of a relatively short length of fibre, in which the number of signal reabsorptions is considerably smaller than in a long segment of fibre. Moreover, the temperature variation of the emission and absorption cross sections of the erbium ion in the range 1535–1565 nm is markedly smaller than that in the long-wavelength region. Therefore, the output spectra of such sources should be expected to vary considerably less with temperature. Figure 8a shows calculated gain spectra of a 1-m length of the same erbium-doped fibre (10-dB SSCPA). It is seen that, in this case, heating the fibre produces no significant changes in its gain spectrum. Measurements of spectra of a superluminescent source based on a 1-m length of the fibre also detected no significant changes (Fig. 8b).

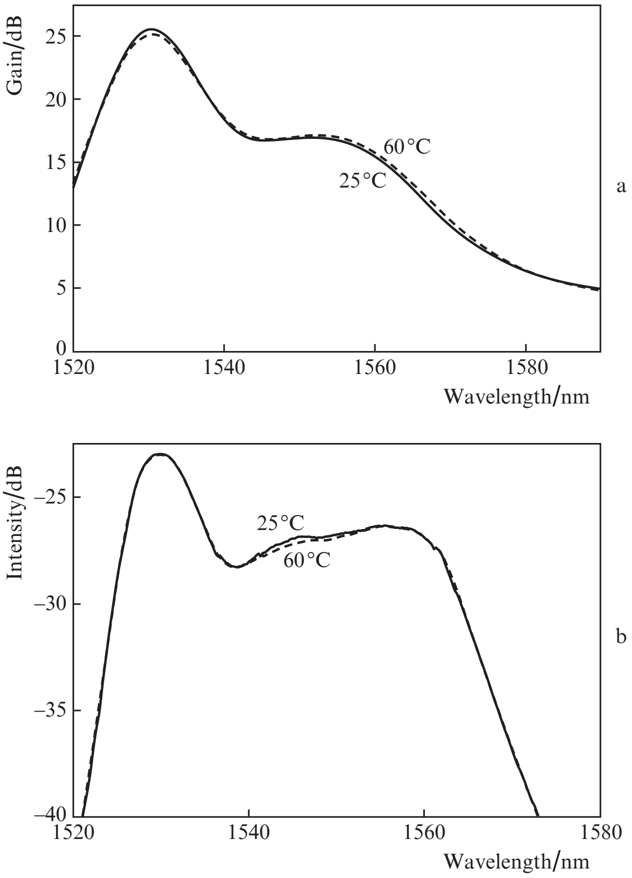

Figure 8. (a) Calculated gain spectra of a 1-m length of erbium-doped fibre and (b) measured output spectra of a superluminescent source based on this fibre at temperatures of 25 and 60 °C.

Thus, the effect of temperature on the output characteristics of L-band erbium-doped fibre superluminescent sources is much stronger than that on the characteristics of standard C-band sources. This is because signal generation in the long-wavelength region requires a considerably longer length of fibre and because the temperature sensitivity of absorption and emission cross sections is here higher than that in the C-band.

4. Effect of heating on characteristics of high average power erbium-doped fibre lasers

As mentioned in the Introduction section, cladding-pumped high-power erbium-doped fibre lasers and amplifiers may also have high temperature sensitivity.

Kuhn et al. [16] calculated heating of the core of an erbium-doped fibre laser cladding-pumped at a wavelength of

980 nm. Their results suggest that, in the case of passive fibre cooling ($T = 20\,^{\circ}$C), the temperature of the core should be expected to reach ~60 °C at a laser output power of ~100 W. To assess the reduction in the pump conversion efficiency of erbium fibre lasers, we carried out an experiment schematised in Fig. 9.

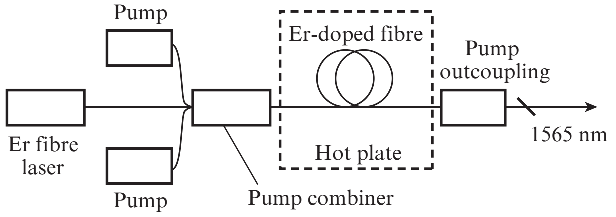

Figure 9. Schematic of the experimental setup.

We used double-clad erbium-doped phosphoaluminosilicate fibre with core and first cladding diameters of 33 and 130 μm, respectively, and 2 dB m^{-1} absorption in the cladding at 980 nm (pump absorption in the core, ~30 dB m^{-1}). The higher order mode cutoff wavelength was ~1700 nm. Thus, a slight bend ensured single-mode operation of the fibre. The fibre length was 3.8 m (115-dB SSCPA). The pump sources used were two fibre-pigtailed multimode laser diodes providing up to 50 W of total power at a wavelength of 980 nm. Their outputs, together with the input signal, were coupled into the active fibre using a commercially available combiner. As a signal source, we used an erbium-doped fibre laser with an output power of 30 mW at a wavelength of 1565 nm. To the output end of the active fibre was fusion-spliced a device for outcoupling unabsorbed pump light. The fusion splice loss and the internal loss of the device totalled ~0.6 dB. The erbium-doped fibre was heated as described in Section 2.

In our experiment, we examined how heating of the active fibre influenced the output power of the amplifier. Thermal equilibrium was reached 1 h after the amplifier had been turned on, with the hot plate de-energised. Since the fibre and the ceramic surface of the hot plate were heat-insulated, their temperature increased to 40 °C by virtue of the heat deposition in the active fibre. The output power of the amplifier at this instant in time was 4.95 W. The heater temperature in the hot plate was then set to 80 °C. As a result, the output power of the amplifier decreased to 4.75 W (Fig. 10). Thus, heating to 80 °C reduces the efficiency of cladding-pumped (980 nm) high-power erbium-doped fibre amplifiers by less than 5%, which occurs, according to Kuhn et al. [16], in the case of fibre lasers with output powers above 100 W.

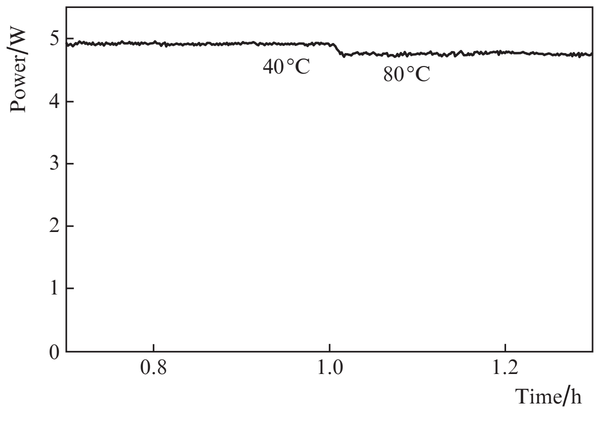

Figure 10. Time dependence of the output power of the amplifier.

To confirm the results obtained, we numerically simulated signal (1565 nm) propagation through an active fibre in the described experiment at temperatures of 40 and 80 °C. The simulation results are presented in Fig. 11a. The calculated output powers obtained at these temperatures, 5.75 and 5.5 W at a fibre length of 3.8 m, are in excellent agreement with experimental data, given that the pump outcoupling loss is 0.6 dB. Therefore, even an appreciable change in the temperature of the core of a double-clad erbium-doped fibre at high average power only slightly reduces the laser efficiency. It is also seen from Fig. 11a that the fibre length used, 3.8 m, is shorter than the length at which the signal power reaches its maximum level. One major application of large-mode-area amplifying fibres is the generation of high peak power, short pulses [10, 11]. In our case, the choice of the length of the fibre was dictated by the requirements that its gain spectrum lie in the C-band [11] and that nonlinear effects be reduced. Even though increasing the length of fibre leads to an increase in its temperature sensitivity, the temperature variation of the signal power remains insignificant (~10% at a fibre length of 7 m, which ensures the maximum output signal).

It is worth noting that, when an amplifier operates in the range 1570–1600 nm, a considerable decrease in its efficiency might be expected because of the marked increase in the absorption cross section with temperature, at an essentially

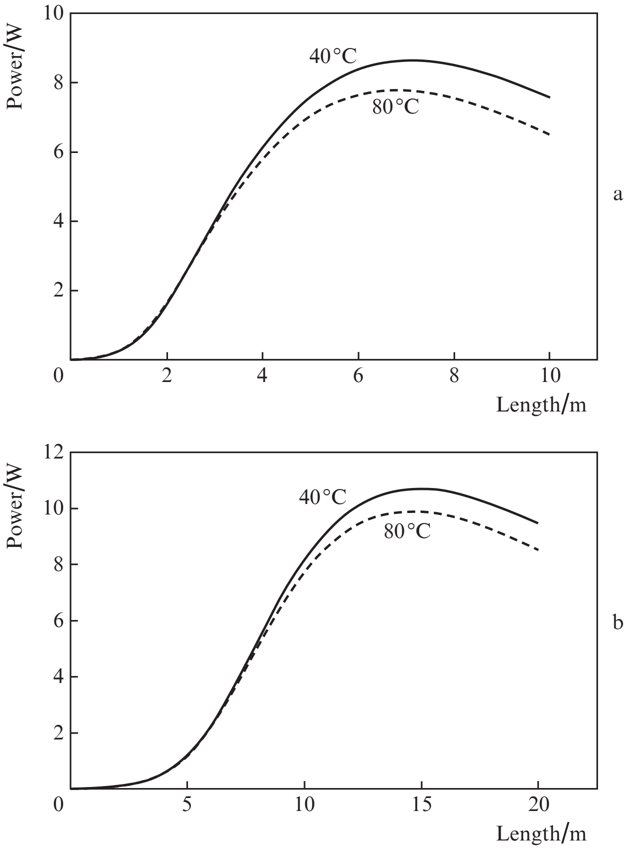

Figure 11. Calculated distributions of the signal output power at wavelengths of (a) 1565 and (b) 1580 nm along the length of erbium-doped fibre at temperatures of 40 and 80 °C.

unchanged emission cross section (Figs 4, 5b). However, calculations for a signal at 1580 nm (Fig. 10b) indicate that the output power of the amplifier drops by no more than 10%. This can be accounted for by the fact that the absorption cross section in this spectral range is small, so even an increase in it by tens percent with increasing temperature does not cause any marked drop in amplifier efficiency.

5. Conclusions

We have assessed the effect of temperature on output characteristics of erbium-doped fibre based devices. We have performed what we believe to be the first temperature-dependent absorption and emission cross section measurements for the erbium ion in aluminosilicate and phosphorus-enriched phosphoaluminosilicate glass hosts, which are of most interest for practical applications. The data obtained in this study allow one to evaluate the effect of temperature on the performance of erbium-doped fibre based devices. It has been shown that the output power of L-band superluminescent sources depends significantly on temperature. We have assessed the effect of heating on the pump-to-signal conversion efficiency in cladding-pumped erbium-doped fibre lasers. The present results suggest that changes in the absorption and emission cross sections of the erbium ion should be expected to cause a decrease in the efficiency of high-power (> 100 W) erbium-doped fibre lasers by no more than 10% in both the C- and L-bands.

Acknowledgements. This research was supported by the Russian Science Foundation (Grant No.14-19-01572).

We are grateful to E.M. Dianov and S.L. Semjonov for their continuous interest in and support of this work.

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