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Erbium–ytterbium codoped phosphate core/double silica clad composite optical fibres for compact amplifiers

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***Abstract.* We report a study of composite fibres as gain media of all-fibre amplifiers. A distinctive feature of the fibres is an erbium–ytterbium doped phosphate core in a double silica cladding. The high Yb^{3+} concentration (above 10^{21} cm^{-3}) ensures effective pump absorption from the cladding at fibre lengths under 40 cm and effective erbium ion sensitisation. The silica cladding facilitates fusion splicing to standard fibres. The composite fibres offer a large gain coefficient: about 0.4–0.5 dB cm^{-1} at a signal wavelength of 1550 nm. The maximum gain at a fibre length of just 36 cm and an input signal power of 0.37 mW at λ = 1550 nm is about 13.5 dB. Under such conditions, the amplified spontaneous emission level is lower than the input signal level by 10 dB.**

Keywords: *fibre amplifier, composite fibres,* Er^{3+}/Yb^{3+} *system, phosphate laser glass.*

1. Introduction

Various configurations of erbium-doped fibre amplifiers are used in optical fibre communication systems and for raising the power of fibre lasers with special spectral and temporal output characteristics. They ensure the amplification of optical signals in the range 1.53–1.6 μm. In commercial erbium fibre amplifiers, a typical small-signal gain is near 30 dB [1]. The corresponding gain coefficient is ~0.01–0.03 dB cm^{-1}.

Recent years have seen considerable interest in optical amplifiers with a high gain coefficient that are based on heavily erbium-doped optical fibres and planar waveguides [2–4]. High erbium ion concentration in a guiding core allows the length of the gain medium to be considerably reduced in comparison with amplifiers based on conventional silica fibres at identical gain values.

Multicomponent phosphate glasses are the most suitable materials for an ytterbium–erbium medium, ensuring both high solubility of rare-earth ions and effective sensitisation of erbium ions [5, 6].

Phosphate glass fibres show good performance as a gain medium [2, 7–9]. Note a few studies in which outstanding results were obtained. In particular, Hu et al. [2] demonstrated a core-pumped erbium–ytterbium codoped phosphate fibre amplifier as short as 3 cm with a small (–30 dBm) signal gain of about 12.6 dB at 1535 nm, a wavelength corresponding to the peak gain coefficient of the fibre. The gain at a wavelength of 1550 nm was ~5 dB. However, the output power of core-pumped single-mode optical fibre amplifiers is limited because of the use of low-power single-mode pump diodes.

Record results in Er/Yb-doped phosphate fibres were demonstrated by Shan-Hui et al. [9], who reported a cladding-pumped single-mode fibre amplifier. The maximum gain over a 8-cm-length of fibre was ~41 dB for a small (–30 dBm) signal at a wavelength of 1535 nm. At a signal power of 0 dBm, the gain was about 15 dB throughout the C band.

Unfortunately, the low resistance of phosphate fibres to atmospheric moisture and the fact that they are hard to fusion-splice to conventional silica fibre make it difficult to produce all-fibre laser systems.

Researchers at the A.M. Prokhorov General Physics Institute, Russian Academy of Sciences (RAS), in cooperation with those at the Fiber Optics Research Center, RAS, designed phosphate core/silica clad composite optical fibres. This fibre configuration allows one to take advantage of the benefits of phosphate gain media and the high mechanical and chemical stability of silica fibre [10]. The use of a silica cladding makes it easier to fusion-splice such fibres to conventional silica fibre [11].

The purpose of this work is to assess the feasibility of using composite optical fibres with a heavily Er^{3+}/Yb^{3+} doped phosphate core and silica cladding in producing compact all-fibre amplifiers operating at a wavelength λ_s = 1550 nm.

2. Experimental fibres

For the fabrication of the fibre core, we prepared glass containing 65 mol % P_2O_5, 7 mol % Al_2O_3, 12 mol % Bi_2O_3, 9 mol % Li_2O and 7 mol % rare-earth oxides. The absolute Yb^{3+} concentration was 1.7×10^{21} cm^{-3} and the Er^{3+} concentration was 1.3×10^{20} cm^{-3} [10, 12]. Next, we produced phosphate glass rods and fabricated a fibre preform by the rod-in-

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tube method. The preform was then drawn into fibres which had an inner silica cladding with a square cross section 100×100 and 80×80 μm in dimensions at a core diameter of 13.5 and 10.5 μm, respectively. During the drawing process, the fibre was coated with silicone which had a refractive index lower than that of the silica cladding. This design of the Er^{3+}/Yb^{3+}-doped fibre allowed pump light to be coupled into the inner cladding. After drawing, the interdiffusion of the core and cladding components reduced the P_2O_5 concentration in the core to about 30 mol %, whereas the silica concentration in the core reached ~50 mol %.

The refractive index difference between the phosphate core and silica cladding was 0.035. At the operating wavelength in the 1.55 μm range, the fibres were multimode. Cladding pump absorption at a wavelength of 971 nm in the 13.5 μm core fibre was 0.3 dB cm^{-1}. Small-signal absorption in the core at a wavelength of 1535 nm was 1.5 dB cm^{-1} [12].

3. Experimental configurations and measurement procedure

Figure 1 shows a schematic of the experimental setup for studies of signal amplification at $\lambda_s = 1.55$ μm in the composite fibre. After a pump–signal combiner, the light was launched into a double-clad passive fibre, which ensured pump coupling into the guiding cladding of the active fibre and 1.55-μm signal coupling into the core of the active fibre. As a pump source, we used a multimode diode laser delivering 2.7 W of power at a wavelength of 971 nm. The signal source used was a cw laser with a centre wavelength of about 1550 nm and spectral full width at half maximum no greater than 0.15 nm. Its output power was varied from 0.37 to 4.25 mW. The optical scheme included an optical isolator to prevent reflected signal propagation towards the signal source.

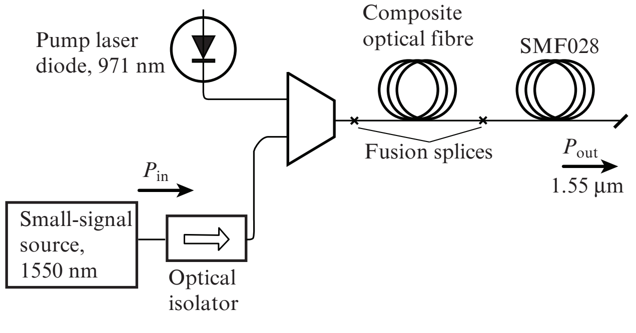

Figure 1. Schematic of the 1.55-μm fibre amplifier.

The output end of the composite fibre was fusion-spliced with an angle cleaved SMF028 single-mode fibre (NA = 0.14). This allowed the signal to be prevented from being reflected from the output end face of the device and led to spatial filtering of the amplifier output, removing the unabsorbed pump light propagating through the inner cladding of the composite fibre. As a result, like in a previous study [10] the pump power at the output of the fibre device was lower than the signal level by more than 30 dB, so it was left out of account in assessing the performance of the fibre amplifier. Moreover, the use of SMF028 fibre at the output of the experimental setup allowed us to obtain single-mode output, even though the active fibre was multimode.

The composite and silica fibres were fusion-spliced using a Sumitomo Electric Type-36 splicer, intended for standard silica fibres. In optimising the fusion splicing conditions, the splice loss was 1.7 to 3.7 dB, approaching the level reached in a previous study [13], where the splice loss was about 3 dB. The splice loss was evaluated by the cut-back technique at 70 mW of transmitted power at a wavelength of 1550 nm.

The output amplifier parameters, emission spectrum and power were measured at the output end of the SMF028 single-mode fibre at different pump currents and input signal levels. Emission spectra were obtained with a 0.1 nm resolution using an optical spectrum analyser.

4. Experimental results and discussion

We studied active-fibre segments 10 to 50 cm in length. Each segment was fusion-spliced to silica fibre. Unfortunately, the fusion splice loss varied from 1.7 to 3.7 dB, even though a standard splicer was used. This prevented us from quantitatively comparing experimental data for different lengths of active fibres and optimising the length of the composite fibres.

The best results were obtained for 23- and 36-cm lengths of the fibres with the inner silica cladding 100×100 and 80×80 μm in cross-sectional dimensions, respectively.

For the amplifier based on the 36-cm-long 80×80 μm composite fibre, we measured the total output power and output emission spectrum. Figure 2 shows the gain as a function of pump power and emission spectra at the output of the single-mode fibre at different 1550-nm input signal power levels.

Since the output spectrum contains, in addition to the spectrum of the amplified signal, the spontaneous emission spectrum in the erbium luminescence region, to determine the gain at $\lambda_s = 1550$ nm from output spectra we estimated the fractions of the powers corresponding to the signal being amplified and amplified spontaneous emission. The gain can be represented in the form

$$G = 10\log\frac{P_{\mathrm{out}} - P_{\mathrm{ASE}}}{P_{\mathrm{in}}} = 10\log P_{\mathrm{out}}\frac{1-\alpha_{\mathrm{ASE}}}{P_{\mathrm{in}}},$$

where P_{in} is the signal source power; P_{out} is the total output power; P_{ASE} is the amplified spontaneous emission power; and α_{ASE} is the fraction of the amplified spontaneous emission power relative to the total power at the output of the experimental setup.

The highest gain, about 13.2 dB, was obtained at a signal power of 0.37 mW and pump power of 1.75 W. Raising the pump power to 2.7 W led to an increase in gain to 13.5 dB, i.e. the amplifier passed into the saturation regime.

At low signal powers, we observe a considerable increase in the contribution of the spontaneous emission power, which can degrade the signal-to-noise ratio. It is seen from Fig. 2b that the amplified spontaneous emission level is lower than the signal level by about 10 dB at a signal power of 0.37 mW and by about 30 dB at a 4.25-mW input signal and the maximum pump power (about 2.5 W).

The highest gain of the all-fibre amplifier based on the 80×80 μm composite fibre was about 13.5 dB at an input signal power of 0.37 mW and about 9 dB at a signal power of 2 mW. For comparison, note that Hu et al. [2] obtained a maximum gain of 5 dB in a core-pumped phosphate fibre at the same wavelength (1550 nm) and a signal power of 1 μW. Thus, the use of cladding pumping ensured a substantial increase in gain.

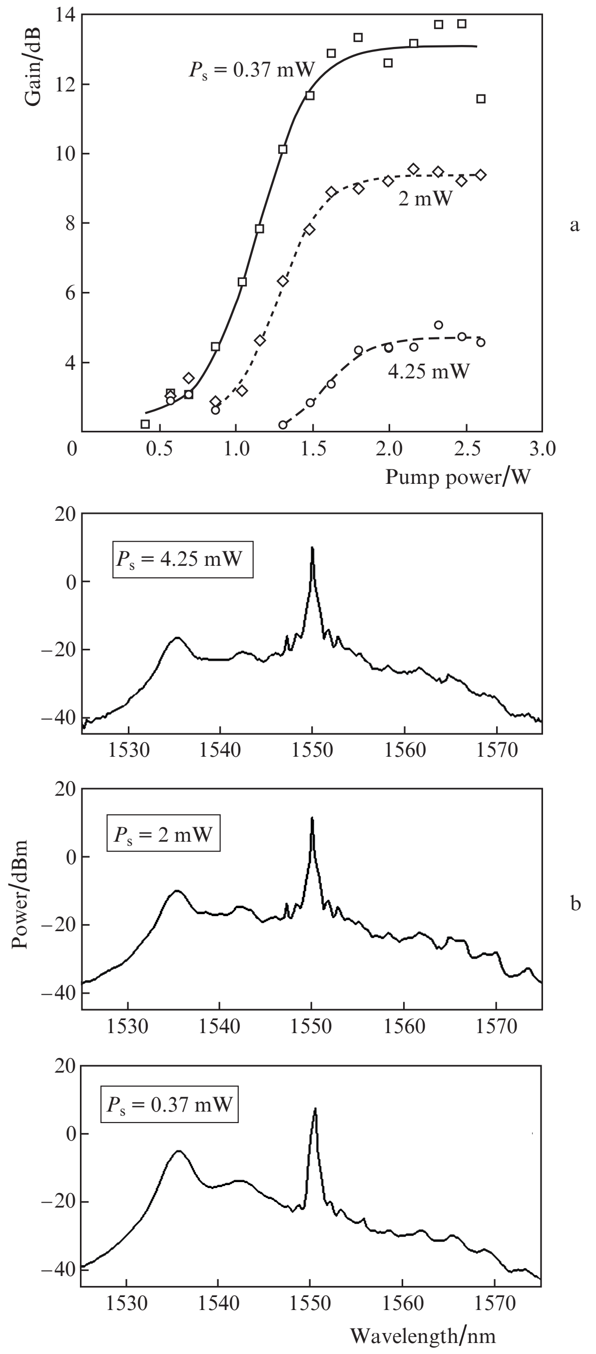

Figure 2. (a) Gain as a function of launched pump power (36-cm-long 80 × 80 μm composite fibre) and (b) emission spectra at the output of the experimental setup at a pump laser diode output power of 2.5 W and different input signal powers P_s.

It is known however that, in conventional silica fibres, the small-signal gain reaches 30 dB and the difference between the amplified spontaneous emission and signal levels is above 30 dB. The lower gain and smaller difference between the signal and amplified spontaneous emission levels in this study may be due to the following factors: (1) losses at the fusion splices between the composite and silica fibres (1.7 to 3.7 dB) and (2) considerable contribution of the amplified spontaneous emission and part of the signal propagating in higher order modes. At the same time, the gain coefficient in our scheme reaches 0.4 dB cm^{-1}, whereas that in silica fibres is 0.01−0.03 dB cm^{-1}.

In the case of the amplifier based on the composite fibre with the inner silica cladding 100 × 100 μm in cross-sectional dimensions, the best results were obtained at a fibre length of 23 cm. Figure 3 shows the gain as a function of pump power at different input signal powers. The highest gain, ~9.1 dB, was obtained at a signal power of 0.5 mW. The corresponding gain coefficient was about 0.4 dB cm^{-1}.

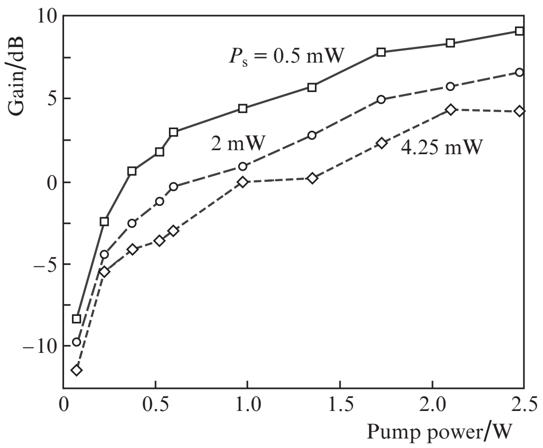

Figure 3. Gain as a function of launched pump power (23-cm-long 100 × 100 μm composite fibre) at different input signal powers P_s.

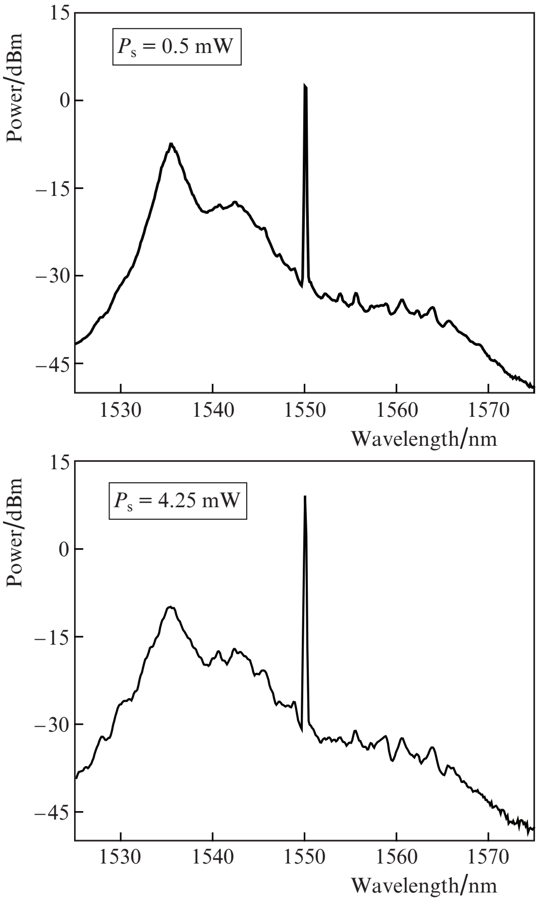

Figure 4. Emission spectra at the output of the experimental setup (23-cm-long 100 × 100 mm composite fibre) at different input signal powers and a pump power of 2.5 W.

As in the case of the 80 × 80 μm fibre, at low signal powers we observed a substantial increase in the contribution of the spontaneous emission power to the total output power. Figure 4 shows output emission spectra at different input signal powers. The amplified spontaneous emission level is lower than the input signal level by about 10 dB at a signal power of 0.5 mW and by 20 dB at an input signal power of 4.25 mW.

5. Conclusions

We have demonstrated all-fibre compact amplifiers based on composite fibres with a heavily Er^{3+}/Yb^{3+} doped phosphate core and silica cladding. The use of a phosphate glass core with a high erbium ion concentration has made it possible to considerably reduce the length of the gain medium compared to that characteristic of similar schemes based on active silica fibres.

The fibres studied here allowed us to obtain a gain of practical interest: ~13.5 dB. The proposed fibres offer a large gain coefficient (about 0.4 dB cm^{-1}), which exceeds that in conventional silica fibres by an order of magnitude.

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