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Phosphate glass core/silica clad fibres with a high concentration of active rare-earth ions

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Abstract. **We report a study of silica-clad composite optical fibres having a phosphate glass core doped with active rare-earth elements. The phosphate glass core allows a high concentration of active rare-earth ions to be obtained, and the silica cladding ensures high mechanical strength and facilitates fusion splicing of such fibres to silica fibres. Owing to the high concentration of active rare-earth ions, this type of fibre is potentially attractive for applications where a small cavity length and high lasing efficiency are needed.**

Keywords: *phosphate glass, active optical fibres, composite fibres, technology of active fibres.*

1. Introduction

Phosphate glass is one of the best hosts for doping with active rare-earth elements. Such glass can be doped with high rare earth ion concentrations. Moreover, phosphate glass ensures high excitation energy transfer efficiency in the case of codoping with ytterbium and erbium ions because, owing to its high phonon energy, the probability of a reverse energy transfer process in it is low [1]. The rare earth ion concentration in phosphate glass is on average an order of magnitude higher than that in aluminosilicate or phosphosilicate glasses that are typically used as a core material in silica-based active fibres. It is possible to fabricate fibres having both a core and cladding of phosphate glass. The high rare earth ion concentration in the core of such fibres allows one to obtain high gain coefficients and output powers per unit fibre length [2, 3] and, hence, to reduce the operating length of the gain element of a fibre laser or amplifier compared to silica-based fibres.

Reducing the length of the gain elements of lasers and amplifiers is appropriate primarily for diminishing undesirable nonlinear optical interaction. Nonlinear optical effects, including self-phase modulation, stimulated Raman scattering and stimulated Brillouin scattering, which emerge at a high light intensity in the fibre core and a long length of fibre lasers and amplifiers, are the most important factor limiting the output power and pulse energy of such devices [4]. Since nonlinear optical interaction increases with fibre length [5], one approach to diminishing undesirable nonlinear optical effects is to reduce the fibre length. For example, one important problem that can be resolved by reducing the active fibre length is the ability to raise the threshold for stimulated Brillouin scattering, which causes partial signal back reflection when a single-frequency laser output is amplified.

In addition, phosphate glass fibres with high gain coefficients per unit length are used in producing single-frequency fibre lasers with high output power (on the order of several hundred milliwatts) [6, 7]. The high concentration of active rare-earth ions in phosphate glass allows a considerable output power to be reached even at a relatively short length of active fibre, which is in turn necessary for achieving single-frequency laser operation. Using an erbium/ytterbium-doped phosphate fibre, Thapa et al. [8] demonstrated a mode-locked laser with a pulse repetition rate as high as 12 GHz. The active fibre length in the laser was less than 1 cm.

A serious drawback to phosphate glass compared to silica is its low resistance to the action of atmospheric moisture, which significantly lowers the reliability of phosphate glass-based fibres, leading to their degradation over time. Moreover, because of the large mismatch in physicochemical properties between phosphate and silica glasses, fibres made from these materials are difficult to join by fusion splicing.

Martin and Knight [9] proposed combining the advantages of phosphate and silica glasses through the fabrication of a silica-clad composite fibre having a neodymium-doped phosphate glass core. In such fibres, on the one hand, the high rare-earth concentration in their phosphate core allows the operating length of the active fibre to be reduced and, on the other hand, their silica cladding makes it possible to ensure mechanical reliability of the fibres and simplify fusion splicing to all-silica fibres.

In this paper, we present results of a study of silica-clad composite fibres having a phosphate glass core doped with active rare-earth ions. We demonstrate the feasibility of fabricating such fibres with acceptable optical characteristics and report the properties of fibres with a phosphate glass core codoped with erbium and ytterbium ions or singly doped with ytterbium ions. Our results show that this type of fibre has considerable potential for making fibre lasers and amplifiers.

2. Fabrication and characterisation of composite fibres

Composite fibres were produced using phosphate glass prepared at the A.M. Prokhorov General Physics Institute, Russian Academy of Sciences [10]. In addition to phosphorus oxide, the glass contained aluminium, boron, lithium and rare-earth (RE) oxides: $9\,Li_2O - 7Al_2O_3 - 7\,RE_2O_3 - 12\,B_2O_3 -$

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$65P_2O_5$. This glass composition ensured higher mechanical strength in comparison with other phosphate glass compositions, a low thermal expansion coefficient (7.2×10^{-6} K^{-1}) and high resistance to the action of atmospheric moisture. The glass was prepared in a platinum crucible placed in an induction furnace. A key requirement for the process was thorough dehydration of the glass because of the high hygroscopicity of phosphorus oxide. Because of this, the process was run in a hermetically sealed furnace under a dry atmosphere for 10–20 h. The melt was maintained at a temperature of 1350 °C.

Preforms for the composite fibres were fabricated by the rod-in-tube method. To this end, 4-mm-diameter rods were cut from the bulk of phosphate glass using a hollow diamond drill bit and then inserted in a silica glass tube. Next, the preform assembly was consolidated in a drawing furnace and 'stretched' into a rod about 1 mm in diameter. To obtain a necessary ratio of the core and cladding diameters, the rod was jacketed in an additional silica tube. The resultant preform was then drawn into fibre at a temperature of 2000 °C. All steps were carried out under the same temperature program and with the same equipment as are commonly used to fabricate silica fibres.

Two types of samples were prepared and characterised: codoped with erbium and ytterbium and singly doped with ytterbium. The mechanical strength of the fibres was high enough for handling. We were able to fusion-splice them to a standard silica fibre without bubble formation in the core region. The erbium/ytterbium-doped fibre was drawn in a double cladding to enable cladding pumping. Figure 1a shows a cross-sectional micrograph of such fibre. The fibre comprises an erbium/ytterbium-doped phosphate glass core, an inner cladding of silica glass and a second cladding (outer polymer coating, not shown in Fig. 1a), which has a refractive index lower than that of silica glass. To maximise pump absorption, the inner cladding of the fibre had a square cross section. This was ensured by mechanically processing the preform before fibre drawing. The inner cladding was 100×100 μm in dimensions and the core diameter was 13.5 μm. The refractive index difference between the core and inner cladding, evaluated from the measured numerical aperture of the fibre core at a wavelength of 633 nm, was 0.035. At these parameters, the fibre core was multimode.

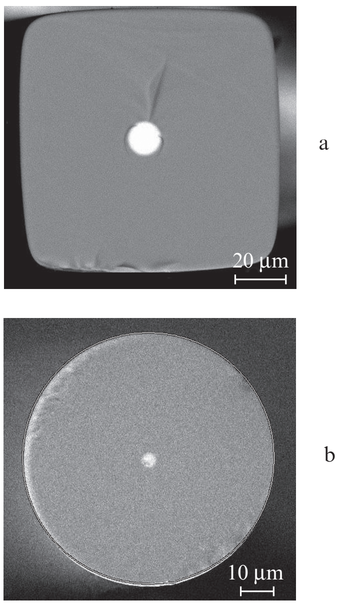

Figure 1. Cross-sectional electron micrographs of (a) the fibre codoped with erbium and ytterbium and (b) the fibre singly doped with ytterbium.

Figure 1b shows a cross-sectional micrograph of the fibre singly doped with ytterbium. The fibre was drawn for core pumping and its core had a circular cross section. The core diameter was 4.8 μm. The refractive index difference between the core and inner cladding, evaluated from the measured numerical aperture, was about 0.035, as above. At these core parameters, the fibre was also multimode.

Using bulk samples of the core and cladding materials (glasses), we measured their refractive index at a wavelength of 589 nm and obtained 1.458 for the silica glass (Heraeus F300) and 1.5365 for the phosphate glass. The refractive index difference thus obtained (0.079) markedly exceeds that in the fibres (about 0.035). The smaller index difference in the fibre compared to the starting glasses is the result of interdiffusion between the two glasses during the fibre drawing process. Chemical analysis data for the cores of the composite fibres (Fig. 2) demonstrate that the interdiffusion between the two glasses reduces the phosphorus oxide concentration from 65 mol% in the starting glass to 30–35 mol% in the fibre. Nevertheless, this phosphorus oxide concentration is still far higher than the concentration that can be reached by chemical vapour deposition.

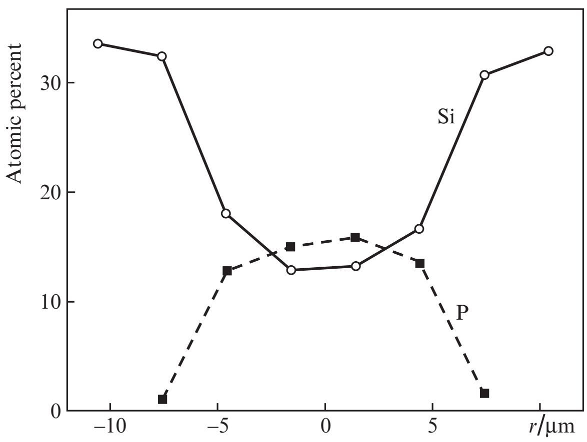

Figure 2. Phosphorus and silicon concentration profiles across the core of the composite fibre (energy dispersive X-ray spectroscopy data).

Optical losses measured for a signal propagating through the cores of the two fibres are shown in Fig. 3. The minimum optical loss of 2 dB m^{-1} was observed in the range 1.2–1.3 μm, where neither erbium nor ytterbium has absorption. This level of optical losses results, first, from the contamination with transition and rare-earth metals during the preparation of the phosphate glass in a platinum crucible and, second, from the absorption by the OH groups present in the phosphate glass because of the high hygroscopicity of phosphorus oxide. In the phosphate laser glass used in the fabrication of the fibre, the maximum absorption by OH groups was 475 dB m^{-1} at a wavelength of 3.33 μm. The relationship between the absorption coefficients of analogous glasses (with no erbium additions) allows the absorption by OH groups in the starting

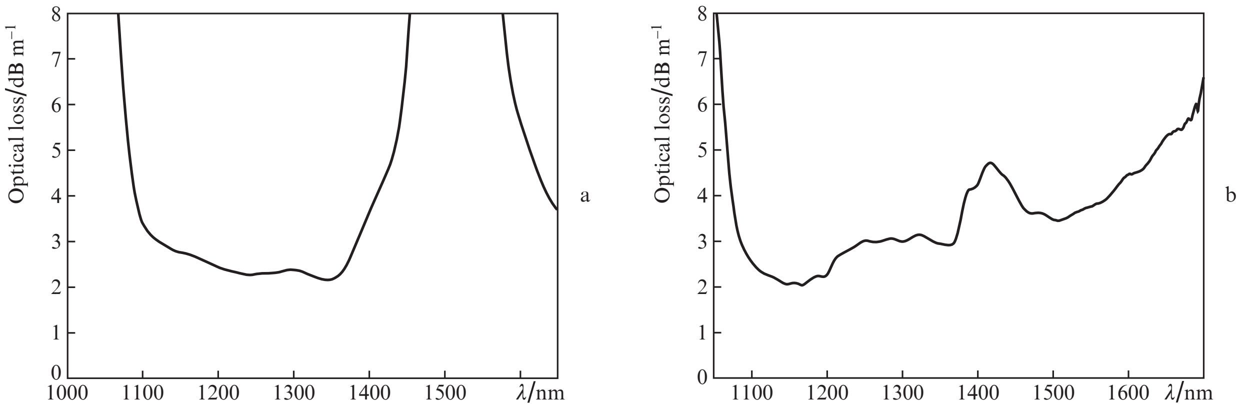

Figure 3. Optical loss spectra measured for a signal propagating through the core of (a) the fibre codoped with erbium and ytterbium and (b) the fibre singly doped with ytterbium.

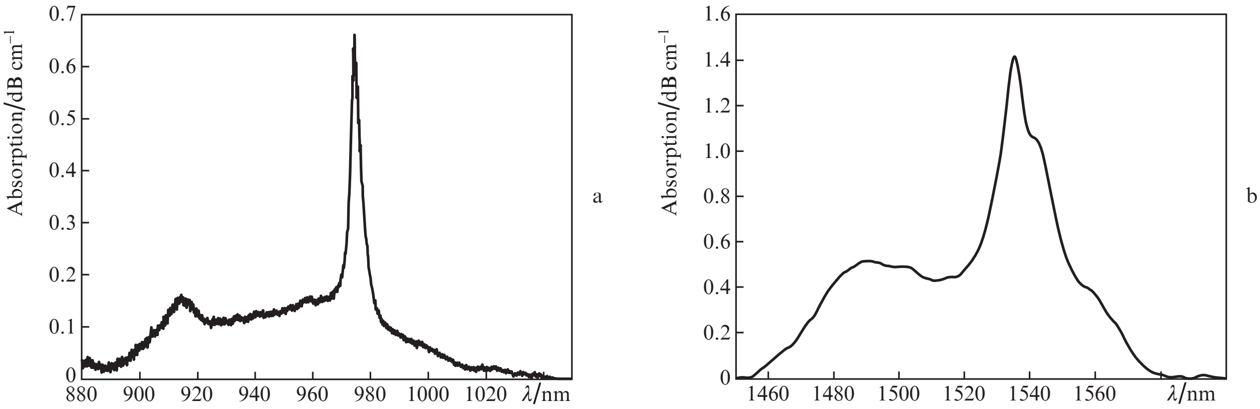

Figure 4. Absorption spectra of the erbium/ytterbium-doped composite fibre: (a) spectrum measured around a wavelength of 1 μm for light propagation through the inner cladding; (b) spectrum measured around a wavelength of 1.5 μm for light propagation through the core and arising from absorption by the erbium ions.

glass at a lasing wavelength of 1.54 μm to be estimated at 0.5 dB m^{-1}.

The ytterbium/erbium-doped composite fibre was fabricated using phosphate glass with an ytterbium concentration of 1.7×10^{21} cm^{-3} and erbium concentration of 1.3×10^{20} cm^{-3}. The value of the absorption by the rare-earth ions in the fibre and the increase in the fibre core diameter relative to the calculated one indicate that, in the course of fibre drawing, interdiffusion between the silica and phosphate glasses in the fibre core reduced the rare-earth concentration by about a factor of 2 relative to the starting phosphate glass.

Figure 4 shows absorption spectra of the active rare-earth ions in the erbium/ytterbium-doped composite fibre. Small-signal absorption measured around a wavelength of 1 μm (predominantly due to absorption by the ytterbium ions) for light propagating through the inner cladding was 0.6 dB cm^{-1} at a wavelength of 976 nm and 0.15 dB cm^{-1} at a wavelength of 914 nm (Fig. 4a). The measured absorption by the erbium ions for light propagation through the core at a wavelength of 1535 nm was 1.5 dB cm^{-1} (Fig. 4b). The luminescence spectrum of the erbium ions in the composite fibre differs in shape from that of the erbium ions in the starting glass (Fig. 5). Clearly, the shape of the luminescence spectrum changes because some of the erbium ions are surrounded by silica glass that diffused to the core during the drawing process. The excited state lifetime of the erbium ions was determined to be 7.6 ms.

The fibre singly doped with ytterbium ions was fabricated using phosphate glass with an ytterbium concentration of 5.0×10^{20} cm^{-3}. Small-signal absorption measured for light

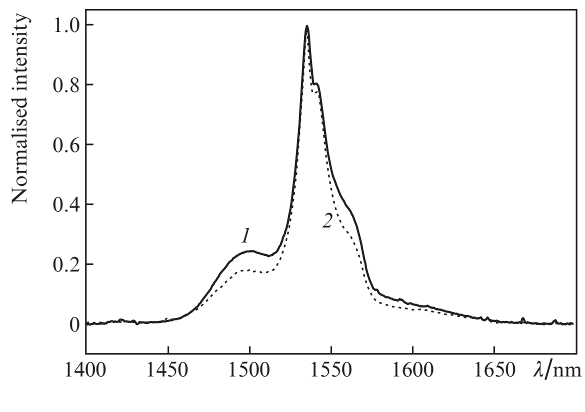

Figure 5. Luminescence spectra of the erbium ions in the (*1*) starting glass and (*2*) composite fibre.

propagating through the core was 2.5 dB mm^{-1} at a wavelength of 976 nm.

3. Lasing

3.1. Erbium/ytterbium-doped composite fibre

The lasing characteristics of the erbium/ytterbium-doped fibre were studied using the setup schematised in Fig. 6. The cavity was formed by the fibre end facets, both with 4% reflectivity. As a pump source, we used a multimode semiconductor diode laser bar. The full width at half maximum of the pump spectrum was 4 nm. With increasing pump power, the centre wavelength in the pump spectrum shifted to longer wavelengths in the range 964–969 nm. Note that the spectral range of the pump light was 962–971 nm, where the small-signal pump absorption was essentially constant (Fig. 4a) at 0.13 dB cm^{-1}, which was a factor of 4 lower than the maximum absorption by the ytterbium ions in the fibre under consideration. The pump light was launched into the inner cladding of the fibre using a lens. The laser beam was outcoupled from the cavity using dielectric mirrors at its input and output. The laser output power was measured at the two fibre ends (giving identical values) and the results were added up. The laser emission spectrum showed two bands, centred at wavelengths of 1535 and 1545 nm, both ~3 nm in width. In lasing tests, neither lasing no luminescence was detected around a wavelength of 1 μm.

Figures 7 and 8 show the laser output power as a function of launched and absorbed pump power at different fibre lengths. The maximum laser slope efficiency η with respect to launched pump power was about 28%, which was obtained at fibre lengths in the range 40–60 cm. At shorter fibre lengths, η was lower because of the insufficient pump absorption; at longer lengths, it was lower because of the rise in optical loss. The highest slope efficiency with respect to absorbed pump power (39%) was obtained at a fibre length of 24 cm. Increasing the fibre length reduced η because of the increase in optical loss. The slope efficiency with respect to absorbed pump power was the same as in a 7-cm-long fibre consisting entirely of phosphate glass [3] and approached the slope efficiency of a 1.4-m-long silica-based fibre [11].

3.2. Ytterbium-doped composite fibre

The considerable refractive index difference between silica and phosphate glasses leads to a large core–cladding index difference in the composite fibre. As a consequence, the fibre turns out to be multimode even at relatively small core diameters, which is a serious drawback to this type of fibre because high beam quality is necessary for most laser applications.

In the case of the composite fibre singly doped with ytterbium ions, we examined the feasibility of ensuring high beam quality by launching 1-μm light from an external source into the fibre core. Analysis of the light leaving the fibre through its end showed that excitation of higher modes was possible, i.e. the fibre was multimode at a wavelength near $\lambda = 1$ μm.

To study the lasing characteristics of the fibre and assess the laser beam quality we used the experimental configura-

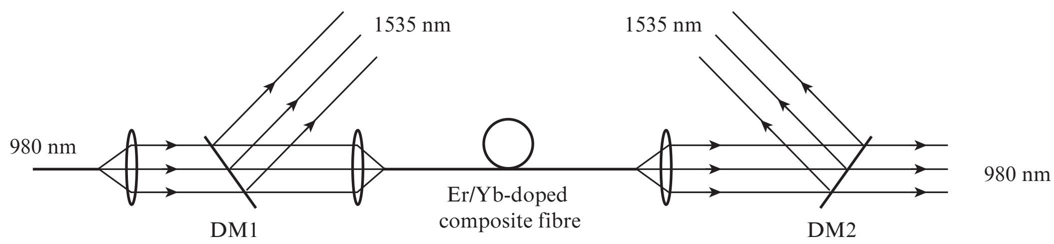

Figure 6. Schematic of the experimental setup used to study lasing characteristics of the erbium/ytterbium-doped composite fibre. DM1 and DM2 are dielectric mirrors having high reflectivities at the lasing wavelength and transparent at the pump wavelength.

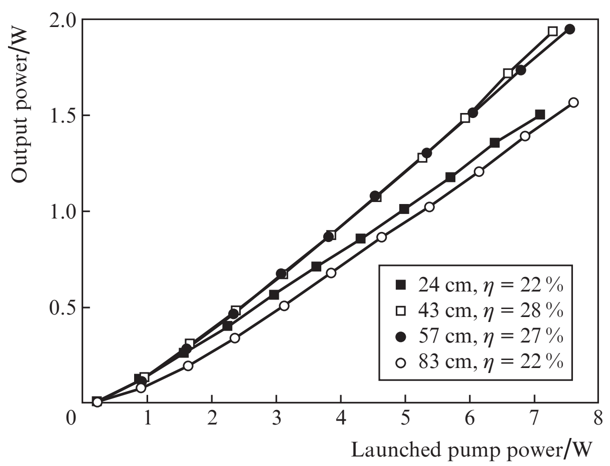

Figure 7. Laser output power as a function of launched pump power at different fibre lengths.

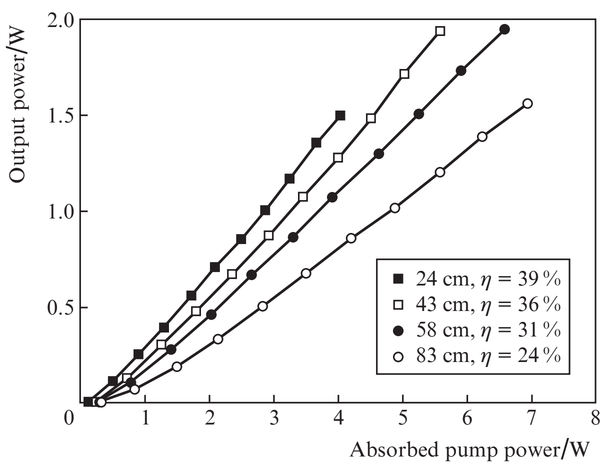

Figure 8. Laser output power as a function of absorbed pump power at different fibre lengths.

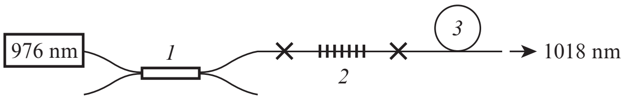

Figure 9. Laser configuration using the ytterbium-doped composite fibre: (*1*) 976/1020 nm fibre multiplexer; (*2*) fibre Bragg grating with high reflectivity (above 99%) at a wavelength of 1018 nm; (*3*) ytterbium-doped composite fibre.

tion schematised in Fig. 9. The laser cavity was formed by a fibre Bragg grating with a reflectivity above 99% at λ = 1018 nm and the fibre end facet, whose reflectivity was 4%. The Bragg grating was inscribed into a single-mode fibre with a germanium oxide-doped core. The pump source used was a single-mode laser diode emitting at a wavelength of 976 nm. The width of the laser emission spectrum was determined by that of the reflection spectrum of the Bragg grating and was 0.5 nm.

The single-mode fibre with the Bragg grating inscribed into it was fusion-spliced to the composite fibre using standard equipment for fusion splicing of silica fibres. The fusion splice loss corresponded to the difference in mode field diameter between the fundamental modes of the fibres and was ~1.3 dB. The mechanical strength of the splices between the silica and composite fibres was identical to that of splices between two silica fibres and was determined by the mechanical damage to the silica cladding caused by polymer coating removal.

Lasing characteristics were studied using fibres less than 90 mm in length. The minimum fibre length at which lasing was obtained was 32 mm. The laser slope efficiency with respect to launched pump power was 73% to 74% at fibre lengths above 48 mm (Fig. 10) and decreased with decreasing fibre length because of the insufficient pump absorption. At fibre lengths above 40 mm, more than 97% of the pump power was absorbed.

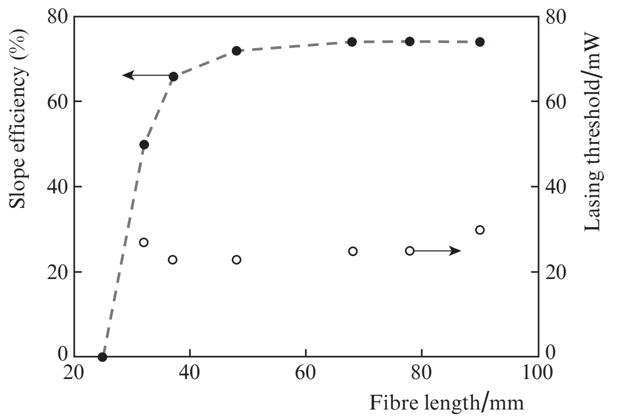

Figure 10. Laser slope efficiency and lasing threshold as functions of ytterbium-doped composite fibre length.

Beam quality was also assessed using the setup schematised in Fig. 9. The pump power was 200 mW and the beam quality factor M^2 measured in different experiments ranged from 1.05 to 1.22. Thus, even though the fibre was multimode, high beam quality was obtained in this configuration. This was possible because the laser cavity contained a single-mode fibre with a Bragg grating inscribed into it, which acted as a mode filter, reflecting only the fundamental mode and suppressing higher order transverse modes. Fundamental mode lasing may also be favoured by the fact that pump light propagates in the fundamental mode of the core. The inverted population distribution over the cross section of the fibre core then corresponds to the fundamental mode intensity distribution, which contributes to the predominant amplification of the fundamental mode of the fibre in comparison with e.g. the first higher mode.

4. Conclusions

We have fabricated and investigated silica-clad composite fibres having a phosphate glass core codoped with erbium and ytterbium or singly doped with ytterbium. The silica cladding ensures mechanical strength and reliability, making it possible to produce durable fusion splices between composite fibres. The phosphate glass core ensures a high concentration of active rare-earth ions, which allows one to use short active fibres.

Lasing efficiency levels acceptable for practical application have been achieved in the erbium/ytterbium-doped composite fibre. Under cladding pumping, we have obtained a laser slope efficiency of 28% with respect to launched pump power and 39% with respect to absorbed pump power. Owing to the presence of a phosphate glass core with a high rare-earth concentration, the optimal length corresponding to the maximum laser slope efficiency with respect to launched pump power was ~50 cm, which is several times smaller than the optimal length of a doped silica core fibre of similar design.

In the ytterbium-doped core fibre, the slope efficiency with respect to launched pump power under core pumping was 73% to 74% at fibre lengths from 48 to 90 mm. Even though the fibre was multimode at the lasing wavelength, we obtained high beam quality owing to the use of a Bragg grating inscribed into a single-mode fibre, which acted as a mode filter in the cavity.

Thus, owing to their high efficiency and high beam quality, composite fibres are potentially attractive for applications where a small length of active fibre is needed.

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