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Use of rare-earth elements to achieve wavelength-selective absorption in high-power fibre lasers

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Abstract. **We have studied absorption spectra of optical fibres doped with rare-earth ions (Sm^{3+}, Tm^{3+}, Tb^{3+}, Pr^{3+} and Ho^{3+}) and demonstrated that they are potentially attractive for ensuring wavelength-selective absorption in fibre lasers. Such fibres can be used for pump diode protection against back-reflected light at the operating wavelength of neodymium, erbium, erbium – ytterbium or thulium lasers. A proper choice of a rare-earth element makes it possible to ensure a strong absorption (10 – 20 dB) at the operating laser wavelength in combination with high transmission (loss under a few tenths of a decibel) at pump wavelengths. To demonstrate the potential of the proposed approach, we have fabricated and investigated Tm^{3+}-doped fibre compatible with the output fibre pigtails of standard semiconductor diodes used for pumping (core diameter, 105 μm; numerical aperture, 0.22). We have demonstrated the possibility of effectively suppressing light in the 1550-nm range by more than 20 dB even in the case of a high-power (up to 10 W) undesirable signal. Under such conditions, the total pump loss does not exceed 0.5 dB and can be further reduced by optimising the core composition and fibre design.**

Keywords: *absorption spectrum, rare-earth ion, fibre laser, pump protection.*

1. Introduction

One important issue in developing and implementing new high-power fibre laser designs is the risk of damaging pump laser diodes by the light emitted directly by the gain medium. Particularly dangerous is the output of pulsed lasers because, even at a relatively low average power, short pulses can have high peak power, sufficient for bringing the pump diode out of operation. The pump diodes of cw lasers can be damaged e.g. by the laser light passing through the high (near 100%) reflectivity fibre Bragg grating (FBG) and propagating towards the pump diodes.

In this connection, in implementing a fibre laser or amplifier configuration it is necessary, on the one hand, to control the backwards propagating power in the system and, on the other, to ensure additional pump protection against light at the laser wavelength. In low- and medium-power schemes, this problem is relatively easy to resolve. In particular, there are fibre-optic components based on dichroic filters with single- or multimode input and output fibres, which ensure a high (20 to 50 dB) degree of protection against signal light. There are commercially available spectral filters with a power transmission of up to 30 W, numerical aperture of the fibre under 0.22 and a core diameter of up to 105 μm. It is also worth noting that many manufacturers of semiconductor laser diodes place a dichroic mirror directly in a high-power laser module to ensure protection against light from the most widespread laser models: ytterbium fibre lasers (suppression of light by 30 dB in the wavelength range 1040 – 1200 nm). At the same time, in the case of laser sources having an output power above 30 W, which are used to pump lasers with emission wavelengths beyond the range 1030 – 1200 nm (for example, erbium or thulium fibre lasers), there are no effective pump diode protection solutions.

In some cases, undesirable light penetration into pump diodes can be precluded by optimising the fibre laser configuration. A number of researchers proposed and demonstrated unique pump – signal combiner configurations that eliminated back reflection owing to a proper fibre order in the combiner [1] or the presence of additional fibres intended to remove back-reflected light from the system [2]. A drawback to this approach is that, when pump light propagates through such a combiner, its brightness decreases, which is unacceptable for most high-power laser systems, where the factors determining the maximum output power include the pump brightness.

As a consequence, a search for novel approaches to eliminating light at undesirable wavelengths is a topical issue. In this work, we propose using rare-earth (RE) doped optical fibres for this purpose. An inherent feature of the RE elements is that their absorption spectrum contains relatively narrow bands whose intensity can exceed the background loss in the fibre by several orders of magnitude. Intrinsic lasing of rare-earth ions can be prevented owing to the low pump conversion efficiency, nonradiative relaxation mechanisms and the low RE luminescence quantum yield, as well as by creating conditions favourable for an increase in lasing threshold, e.g. by utilising fibre with a sufficiently large core diameter. In particular, in protecting a fibre-pigtailed multimode pump diode, to match the mode fields of the output fibre pigtail of the semiconductor diode and the protection fibre the core

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diameter of the latter should be of the order of 105 μm. The lasing threshold of the RE element can then exceed tens of watts even for ions having a high quantum yield.

Despite the simplicity of the proposed technique, the use of RE-doped optical fibres for pump protection has so far been tested in a very limited number of studies [3–6], which is obviously due to insufficient knowledge of the characteristics of RE elements in the silica glass network. For example, Ainslie et al. [7] and Farries et al. [8] presented spectra of RE elements in germanosilicate and phosphosilicate glass networks. However, their results are not informative for the purpose of suppressing undesirable light because they provide only a qualitative idea of the position of absorption bands, without quantifying the ratio of the optical loss at the peak absorption wavelength to that at the minimum loss wavelength. Moreover, a number of reports (see e.g. Refs [9, 10]) present absorption spectra of RE elements measured in an extremely narrow spectral range, which does not include the wavelength range of the most widespread fibre lasers (1000–2000 nm).

In this paper, we report a study of the RE elements that hold the most promise for all-fibre pump diode protection. We analyse absorption spectra of fibres doped with Sm^{3+}, Tm^{3+}, Tb^{3+}, Pr^{3+} and Ho^{3+} ions, which have strong near-IR absorption bands. A number of RE elements are shown to be promising for pump protection in fibre lasers. A thulium-doped fibre with a 105/125 μm core/cladding diameter is demonstrated as experimental confirmation of the viability of the proposed undesirable laser radiation suppression technique. The ability of the fibre to effectively suppress erbium-doped fibre laser light at average powers of up to 10 W, in combination with low optical losses at the pump wavelength (981 nm), has been demonstrated experimentally.

2. Absorption spectra of RE-doped optical fibres

To ensure effective wavelength-selective absorption, the optical loss in the fibre at the signal wavelength should differ from that at the pump wavelength by several orders of magnitude. In particular, for effective signal suppression the level of signal loss should exceed 15–20 dB, whereas the pump loss should be at a level of 0.1–0.2 dB. To identify the most promising dopants, absorption spectra of RE-doped fibres were measured in a wide wavelength range.

Fibre preforms doped with Sm^{3+}, Tm^{3+}, Tb^{3+}, Pr^{3+} and Ho^{3+} ions were prepared by the modified chemical vapour deposition (MCVD) process. The RE elements were incorporated into the silica glass network by the solution doping technique [11]. As substrate tubes, we used Heraeus F300 tubes. In all cases, to reduce RE clustering in the silica glass network and minimise the background propagation loss, the fibre core was additionally doped with aluminium oxide (in the case of the Tm^{3+}, Tb^{3+}, Pr^{3+} and Ho^{3+} dopants) or phosphorus oxide (in the case of the Sm^{3+} dopant). The preforms were drawn into multimode fibres having a core diameter from 18 to 20 μm, numerical aperture from 0.16 to 0.26 and a 125-μm-diameter silica cladding. The fibres were coated with a polymer whose refractive index exceeded that of silica glass. The loss spectra of the fibres were measured using a multiple cut-back technique. Figure 1 shows the measured optical loss spectra of the fibres. For the convenience of comparison of the absorption by the RE elements and the level of background loss at the optical loss minima, the spectra have a logarithmic vertical axis.

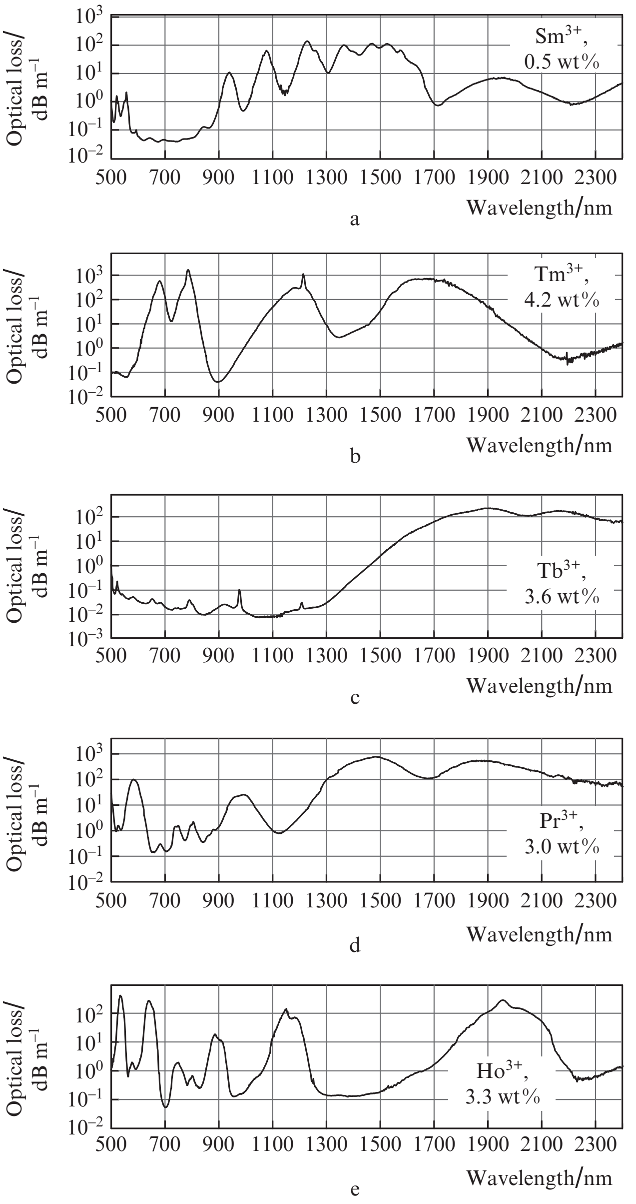

Figure 1. Optical loss spectra of the rare-earth-doped fibres: (a) 0.5 wt% Sm^{3+}, (b) 4.2 wt% Tm^{3+}, (c) 3.6 wt% Tb^{3+}, (d) 3.0 wt% Pr^{3+}, (e) 3.3 wt% Ho^{3+}.

Since laser and amplifier configurations based on optical fibres doped with Yb^{3+}, Er^{3+}, Nd^{3+} or Tm^{3+} ions are currently the most widespread among the existing fibre laser designs, we carried out a comparative analysis of absorption spectra in order to find RE elements suitable for pump diode protection against back-reflected light at characteristic wavelengths of such systems. Consider the potential of each of the RE ions in question for use as a pump diode protection element.

Samarium ions (Sm^{3+}). The Sm^{3+} ion is known to have strong absorption bands peaking at a wavelength of 1070 nm and in the range 1400–1550 nm. As seen in Fig. 1, the loss at a wavelength of 976 nm (a typical pump wavelength of ytterbium- and erbium-doped fibres) is comparatively high due to the overlap of the absorption bands centred at wavelengths of 940 and 1070 nm. For this reason, the ratio of the optical loss (in decibels) at the signal wavelength to that at the pump wavelength is about two orders of magnitude at wavelengths of 1070 and 980 nm or at wavelengths of 1550 and 980 nm.

Thus, samarium ions can be used as an absorbing additive in the protection fibre core at a pump wavelength of 980 nm and signal wavelength of 1070 or 1550 nm, with a justified decrease in pump power due to absorption in the protection fibre. The only exception is the laser configuration proposed by Grukh et al. [3], who placed a multimode fibre with a relatively small core diameter (about 20 μm) directly after a high-reflectivity grating. A signal then propagates (and, accordingly, is absorbed) directly in the samarium-doped core, whereas the pump loss is relatively low, in particular because of the small overlap integral of cladding and core modes.

It also appears promising to utilise samarium ions in lasers based on neodymium-doped fibre and pumped at a wavelength of ~800 nm. The emission wavelength of neodymium lasers lies in the 1064 nm range, and undesirable light at this wavelength can be effectively suppressed owing to the strong absorption band of the Sm^{3+} ion. The ratio of the optical loss at 1064 nm to that at 808 nm reaches three orders of magnitude, so that even (1064 nm) signal suppression by 20 dB will not introduce any appreciable loss (above 0.1 dB) at the pump wavelength (808 nm). Moreover, samarium ions can be effectively used as wavelength-selective additives in protection fibres in neodymium lasers emitting at unconventional wavelengths: 1400 and 915 nm [12–14]. In such a case, the ratio of the loss at 1400 nm to that at 808 nm will reach three orders of magnitude and the ratio of the losses at 915 and 808 nm will be two orders of magnitude. Thus, doping with samarium ions appears to hold the most promise for pump protection in neodymium lasers.

Thulium ions (Tm^{3+}). The use of Tm^{3+} as a dopant is an optimal solution for protecting pump sources of erbium and erbium–ytterbium fibre lasers with a pump wavelength from 910 to 981 nm and an emission wavelength around 1550 nm [4, 6]. The ratio of the losses at wavelengths in the range 1530–1600 nm and at 976 nm (cladding-pumped erbium fibre laser) reaches almost three orders of magnitude (300 to 1000) and that at wavelengths in the range 1530–1600 nm and at 915 nm (erbium–ytterbium fibre laser) reaches almost four orders of magnitude (3000 to 10 000).

Terbium ions (Tb^{3+}). Terbium ions have a strong absorption band in the 2 μm range. Its edge overlaps with the operating range of erbium-doped fibre. The ratio of the optical losses in the ranges 915–981 and 1550–1600 nm is only slightly above two orders of magnitude, but it can be increased to almost three orders of magnitude via proper purification of starting chemicals (the absorption peak in the range 915–976 nm is due to ytterbium impurities in the starting terbium compound). At the same time, the absorption band around 1550 nm is almost one order of magnitude weaker than the absorption achievable by thulium doping, so doping with terbium ions appears less promising for protecting erbium fibre-based laser systems.

Most likely, terbium-doped fibre can be used for protecting pump sources of thulium lasers pumped in the absorption band centred at 798 nm. In this case, the ratio of the loss at 1900 nm to that at 798 nm is almost four orders of magnitude (about 5000) and can be further improved (to about 20 000) by purifying starting chemicals (the peak at a wavelength of 798 nm in the loss spectrum of the fibre is due to a small amount of thulium impurities in the starting terbium compound).

Praseodymium (Pr^{3+}) *and holmium* (Ho^{3+}) *ions.* According to the literature, praseodymium and holmium ions have absorption bands near 1000 nm. However, a detailed analysis of their absorption spectra indicates that the absorption band of holmium-doped fibre is located rather far from the operating signal wavelength (980–1100 nm) and that, in contrast, the absorption band of praseodymium ions overlaps with the potential pump wavelength (915–980 nm) (Fig. 1). Most likely, holmium-doped fibre could be useful for 976-nm pump protection against light from ytterbium fibre lasers, which operate in a long-wavelength region (above 1150 nm), but in such a case intrinsic semiconductor diode protection reflecting light up to 1200 nm should be sufficiently effective. Praseodymium ions can be used as a dopant for 798-nm pump protection against thulium fibre laser light in the range 1900–2100 nm, where the loss ratio reaches almost three orders of magnitude (300).

3. Thulium-doped fibre for pump protection

To experimentally verify the viability of the proposed approach to pump protection, we produced a thulium-doped optical fibre with core and cladding parameters matched to those of the multimode output fibre pigtail of the semiconductor diode used for pumping. The core and cladding diameters of the Tm-doped fibre were 105 and 125 μm, respectively, and its numerical aperture was 0.22. As the host material of its core, we used germanosilicate glass, which was dictated by specific technological features of the fabrication of the step index fibre

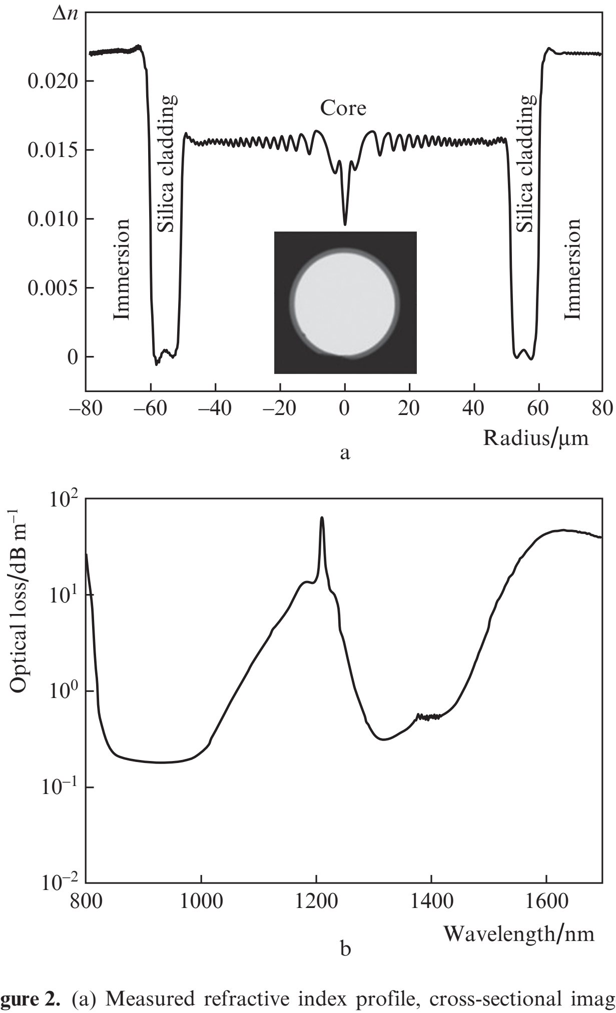

Figure 2. (a) Measured refractive index profile, cross-sectional image (inset) and (b) measured optical loss spectrum of the Tm^{3+}-doped fibre.

with this large core diameter relative to the cladding diameter. Moreover, the higher clustering level in the germanosilicate glass host helped to raise the intrinsic lasing threshold of the thulium ions. At the same time, changing the core material led to an increase in the level of background loss in the fibre due to the lower thulium solubility in the germanosilicate glass network. As a result, the absorption in the fibre at wavelengths of 1532, 1550 and 1590 nm was 13, 21 and 40 dB m^{-1}, respectively, and the absorption at the pump wavelength (976–981 nm) was 0.19–0.20 dB m^{-1}. The measured refractive index profile, cross-sectional image and measured absorption spectrum of the fibre are presented in Fig. 2.

The 105/125 μm thulium-doped fibre was studied from the viewpoint of the feasibility of using it for protecting a pump source of an erbium fibre laser at a pump wavelength of 981 nm and emission wavelength of 1532 nm. The measured small-signal characteristics of the fibre ensure effective undesirable light suppression: absorption at a wavelength of 1532 nm exceeds 26 dB at a protection fibre length of 2 m, whereas the loss in the fibre at the pump wavelength is under 0.4 dB (under 10%). A natural question in this context is to what average power is the fibre capable of effectively suppressing signal light and whether it undergoes bleaching at a high power of undesirable light? To answer this question, we fabricated a laser configuration in which pump light was launched into the core of the thulium-doped fibre, which acted a wavelength-selective component.

To assess light suppression at the signal wavelength, a multimode erbium fibre laser with an emission wavelength of 1532 nm and output power of 10 W was used as a source [4]. The transmission of the fibre at a wavelength of 981 nm (the pump wavelength of the erbium fibre laser) was determined using a wavelength-stabilised multimode semiconductor diode having an output power of 25 W and an output fibre pigtail with a 105/125 μm core/cladding diameter.

Figure 3 plots the loss in the thulium-doped fibre against 1532-nm signal power. It is seen that, raising the power of undesirable light at a wavelength of 1532 nm to an average power of 10 W slightly reduces the absorption at this wavelength at thulium-doped fibre lengths from 0.5 to 1.5 m, which is probably due to the bleaching of the thulium ions. In particular, at a short length of the fibre (0.5 m), the loss decreases by a factor of 1.5 with increasing 1532-nm signal power, but at longer lengths of the thulium-doped fibre its bleaching does not exceed 20%, which ensures pump diode protection acceptable for most practical applications.

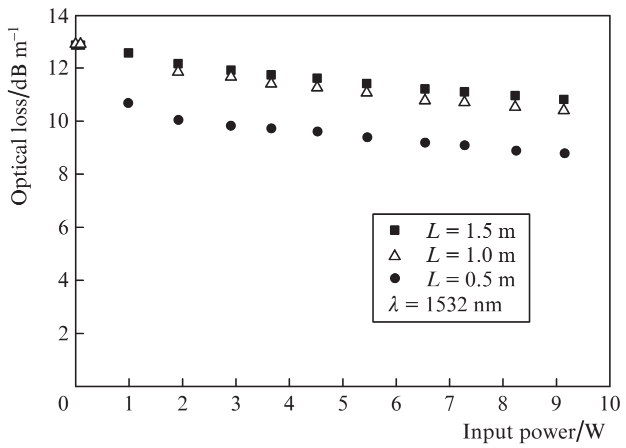

Figure 3. Optical loss as a function of 1532-nm output power for different lengths of the thulium-doped fibre.

To evaluate the level of loss in the thulium-doped fibre at the potential pump wavelength, a 25-W signal at a wavelength of 981 nm was launched into the fibre. The measured loss as a function of Tm^{3+}-doped fibre length is shown in Fig. 4. The slope of the line, which represents the total level of loss at a wavelength of 981 nm, was determined to be 0.24 dB m^{-1}, which correlated with the measured small-signal loss. According to the plot in Fig. 4, the splice loss between the output fibre pigtail of the diode and the thulium-doped fibre does not exceed 0.15 dB. Thus, we are led to conclude that, at a length of about 1.5 m, the thulium-doped fibre demonstrated here is capable of ensuring effective absorption (over 15–40 dB) of undesirable light between 1532 and 1600 nm with a relatively low loss (under 0.5 dB) at pump wavelengths in the range 976–981 nm.

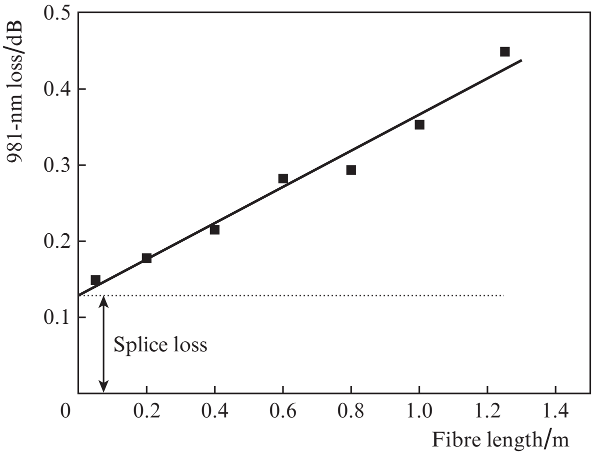

Figure 4. Measured propagation loss in the Tm^{3+}-doped fibre as a function of fibre length at the maximum optical power at 981 nm. The filled squares represent the experimental data and the solid line represents the best fit straight line.

4. Conclusions

We have studied transmission spectra of RE elements (Tm^{3+}, Ho^{3+}, Sm^{3+}, Tb^{3+} and Pr^{3+}). The relationship between absorption peaks of the RE elements and the minimum level of background loss in fibres has been studied experimentally for the first time. We have examined the feasibility of using a number of RE-doped fibres for resolving problems requiring that wavelength-selective optical loss be introduced into the system in the near-IR spectral region. In particular, we assessed the potential of the RE-doped fibres for use in pump diode protection against light at a fibre laser wavelength. The results indicate that Sm^{3+}-doped fibres are potentially attractive for use in neodymium lasers with an emission wavelength of 1064, 915 or 1400 nm at a pump wavelength of 808 nm. Tm^{3+}-doped fibres are capable of ensuring pump diode protection in the case of erbium and erbium–ytterbium fibres emitting in the range 1530–1600 nm when pumped in the range 915–981 nm. Tb^{3+}-doped fibres can find application in thulium fibre lasers for suppressing light in the 1900-nm range and ensuring low optical loss at pump wavelengths (798 or 1200 nm).

We have demonstrated experimentally that the use of Tm^{3+}-doped fibre with a 105/125 μm core/cladding diameter allows one to effectively eliminate (by 15–40 dB) undesirable light in the range 1530–1600 nm of at least 10-W power at low loss (under 0.5 dB) at the pump wavelength (915–981 nm).

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