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Supercontinuum generation in thulium-doped fibres

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Abstract. **Supercontinuum generation in thulium-doped fibres under pumping at 1.59 μm is investigated. Amplification of supercontinuum in the range of 1.8--2.0 μm is found for a fibre doped to a level of 2×10^{19} cm^{-3}. For a fibre with an activator concentration of 2×10^{20} cm^{-3} amplification is also observed in the (2.1–2.45)-μm band, which suggests the occurrence of the $^3H_4 \rightarrow {}^3H_5$ optical transition in the fibre. The occupation of the $^3H_4$ level can be explained by cooperative effects.**

Keywords: *supercontinuum generation, optical fibre, thulium ions.*

1. Introduction

Supercontinuum generation in optical fibres is of great interest for researchers. The main efforts in this field were aimed at obtaining broadband generation in the visible and near-IR spectral ranges. At the same time, it is of interest to obtain broadband radiation at wavelengths above 2 μm. Such radiation sources can be used in spectroscopy, medicine, analysis of atmosphere, etc. Generally, special fibres are applied to generate a supercontinuum in this spectral region. For example, a sapphire fibre and a microstructured fibre based on complex-composition oxide glass were used in [1] and [2], respectively. The use of a fluoride fibre with pumping by a femtosecond 1.45-μm source ensured generation at wavelengths up to 3.8 μm [3]. A ZBLAN fibre provided supercontinuum generation up to 4.8 μm [4]. At the same time, much less attention was paid to supercontinuum generation in silica glass fibres, which can be used as a basis to design an all-fibre compact supercontinuum generator for practical applications. For example, supercontinuum generation at wavelengths up to 2.4 μm in standard silica fibres with pumping by a pulsed fibre laser was demonstrated in [5, 6]. Generation at wavelengths up to 2.7 μm was obtained in a fibre with a core doped with germanium oxide to a concentration of about 64 mol % [7].

Another interesting direction in the studies in this spectral region is the use of active fibres and amplifiers for supercontinuum generation. For example, generation in the range of 1–1.75 μm in an ytterbium-doped fibre amplifier was obtained in [8]. A holmium-doped fibre amplifier was used in [9] for generation in the range of 2–2.5 μm. In this paper, we report the results of studying the long-wavelength supercontinuum generation in a thulium-doped fibre. The same source was used to excite active ions and implement subsequent generation.

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2. Experimental

A schematic of the experiment is shown in Fig. 1. A *Q*-switched fibre laser was used as a master oscillator [10]. The active medium of the laser was an erbium-doped double-cladding fibre with a core diameter of 20 μm. The fibre laser was pumped by a semiconductor laser at a wavelength of 0.98 μm. *Q* switching was performed by introducing a saturable absorber into the laser cavity; the absorber was based on a fibre heavily doped with Tm ions. The basic parameters of pulsed laser radiation were as follows: wavelength, 1.59 μm; maximum average power, 0.85 W; maximum repetition rate, 4 kHz; pulse width, 35 ns; peak power, 6 kW; and pulse energy, 0.21 mJ. The samples of active fibres under study were welded to an output fibre Bragg grating (FBG).

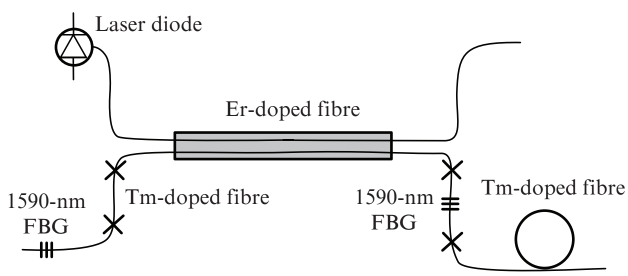

Figure 1. Schematic of the experimental setup.

Two samples of fibres with a core based on thulium-doped aluminosilicate glass were used to generate a supercontinuum. The activator concentration was $\sim2\times10^{19}$ cm^{-3} (sample 1) and $\sim2\times10^{20}$ cm^{-3} (sample 2). The spectral composition of the output radiation was analysed by a monochromator with an InGaAs photodetector, characterised by a working spectral range of 1.2–2.6 μm and a frequency response up to 15 MHz.

3. Results

Figure 2 shows the supercontinuum spectrum at the output of a 3-m-long fibre (sample 1). The spectral broadening at the base of the excitation pulse is caused by four-wave mixing. The transformation of the lasing spectrum into long-wavelength radiation is due to the joint action of stimulated Raman scattering (SRS) in the range of large anomalous dispersion and amplification at the $^3F_4 \rightarrow {}^3H_6$ transition (Fig. 3). The excitation to the $^3F_4$ level is due to the pumping by a pulsed erbium-doped fibre laser. As a result, the supercontinuum spectrum exhibits a pronounced peak near 1.95 μm. The total average power at the active-fibre output was 100 mW.

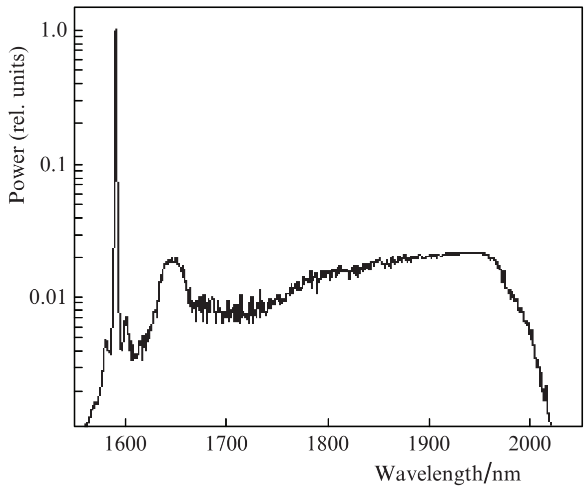

Figure 2. Spectrum of the supercontinuum in the fibre with a thulium concentration of 2×10^{19} cm^{-3}.

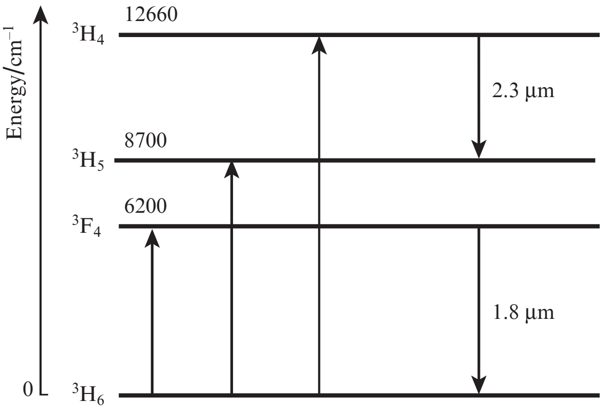

Figure 3. Energy level diagram for thulium ions.

Sample 2 (fibre length 0.5 m) with an elevated concentration of thulium ions exhibited a radically different supercontinuum spectrum (see Fig. 4). One can clearly see two ranges of supercontinuum amplification: (1) from 1.7 to 2 μm, which is due to the $^3F_4 \rightarrow {}^3H_6$ transition, and (2) from 2.1 to 2.45 μm. The occurrence of the second amplification range cannot be explained by nonlinear effects, in particular SRS, because the difference in the spectral peak wavelengths does not correspond to the SRS shift. To explain this effect, one should consider again the energy level diagram of the Tm^{3+} ion (Fig. 3). According to this scheme, there is a $^3H_4 \rightarrow {}^3H_5$ optical transition with a radiation wavelength near 2.3 μm. Note that this transition was used previously to obtain lasing in solid-state Tm : YLF lasers in the aforementioned [11, 12]. The $^3H_4$ level can be occupied due to the energy transfer in a pair of ions at their excitation to the $^3F_4$ level. This cooperative process is characteristic of fibres with a high concentration of active ions; it was thoroughly investigated for erbium-doped fibres [13, 14]. In sample 1, where the concentration of active ions is relatively low, only few of them are combined into pairs; therefore, efficient occupation of the $^3H_4$ level does not occur. Specifically this fact explains the difference in the supercontinuum spectra obtained for the two samples.

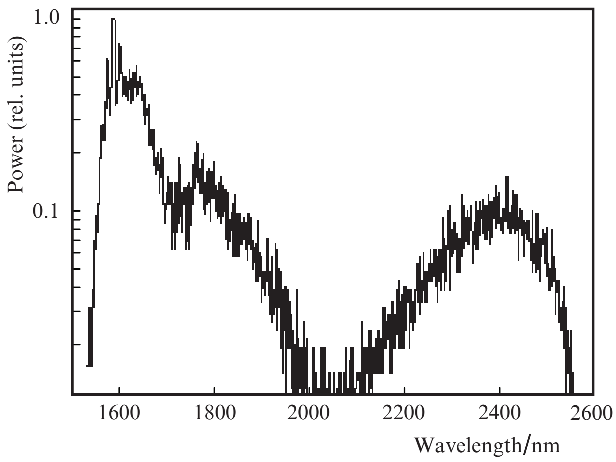

Figure 4. Spectrum of the supercontinuum in the fibre with a thulium concentration of 2×10^{20} cm^{-3}.

4. Conclusions

The supercontinuum generation in thulium-doped fibres was investigated for the first time. The spectra obtained differ significantly from the supercontinuum spectra for conventional or highly nonlinear fibres, because the 1.59-μm excitation radiation not only induces generation of supercontinuum but also pumps the thulium-doped fibre amplifier. The fibre with a high thulium concentration exhibits, along with expected amplification in the range of 1.8 – 2.0 μm, amplification in the range of 2.1 – 2.45 μm, which indicates that the $^3H_4 \rightarrow {}^3H_5$ optical transition may occur in fibre. The occupation of the $^3H_4$ level can be explained by the cooperative processes of thulium ion excitation.

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