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7-W single-mode thulium-doped fibre laser pumped at 1230 nm

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Abstract. **An efficient thulium-doped fibre laser emitting at ~ 2 μm upon pumping into the long-wavelength $^3H_6 \rightarrow {}^3H_5$ absorption band of Tm^{3+} ions is developed. The maximum output power of the single-mode thulium laser pumped at 1230 nm was 7 W at 1956 nm for a pump conversion efficiency of 35 %.**

Keywords*: fibre laser, Raman laser, thulium.*

1. Introduction

At present thulium-doped fibre lasers are one of the most efficient sources of single-mode radiation in the 2-μm spectral region. As in Yb^{3+}- and Nd^{3+}-doped fibre lasers, to obtain a few watts of cw radiation, double-clad fibres are used in thulium lasers. In this case, the pump radiation is coupled into the first cladding, while the output 2-μm radiation propagates in a single-mode fibre core. As a rule, two pump schemes are used:

(i) Pumping of a Tm^{3+}-doped fibre laser into the first cladding by radiation from multimode laser diodes at $\sim$ 800 nm.

(ii) Pumping of an Yb^{3+}/Tm^{3+}-doped fibre laser into the first cladding by radiation from multimode laser diodes at 975 nm.

Figure 1 shows the energy level diagrams of the Yb^{3+} and Tm^{3+} ions. Lasing occurs on the $^3F_4 \rightarrow {}^3H_6$ transition of thulium ions at ~ 2 μm. Note that we use in Fig. 1 the notation of energy levels of Tm^{3+} presented, for example, in [1], which differs from the more accepted order of sequence of the $^3F_4$ и $^3H_4$ levels. In our opinion, this notation is more correct.

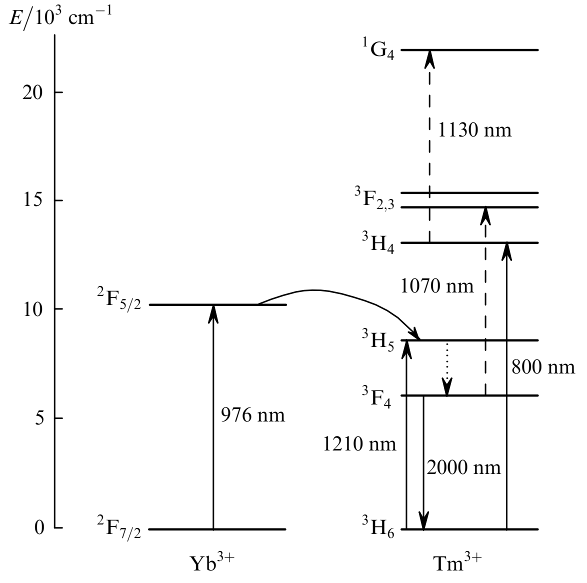

Figure 1. Energy level diagram of Yb^{3+} and Tm^{3+} ions.

Upon pumping according to scheme (i), the Tm^{3+} ions are excited from the $^3H_6$ state to the $^3H_4$ state. Then, according to analysis performed in [2], the ions undergo transitions from the $^3H_4$ state to the upper $^3F_4$ laser level due to a combination of radiative and nonradiative transitions and cross relaxation accompanied by the simultaneous transition of one ion downward from the $^3H_4$ level to the upper $^3F_4$ laser level, and another upward from the $^3H_6$ ground level also to the upper $^3F_4$ laser level. Therefore, this scheme allows one to obtain the quantum efficiency more than unity, and indeed the slope quantum efficiency equal to ~ 1.2 was achieved in [3], which corresponds to the energy slope efficiency equal to ~ 49 %.

When scheme (ii) is used for pumping, radiation at 975 nm is first absorbed by the Yb^{3+} ions at the $^2F_{7/2} \rightarrow {}^2F_{5/2}$ transition and then is transferred to thulium ions, exciting them to the $^3H_5$ state, from which they undergo the nonradiative transition to the upper $^3F_4$ laser level. The maximum slope efficiency achieved in this case was ~ 35 % [3]. This pumping scheme requires the use of a special optical fibre doped with ytterbium and thulium ions. Its advantage is the possibility of using the pump system of ytterbium lasers for pumping thulium lasers.

There exist other possibilities for pumping Tm^{3+} ions. One of them is pumping into the 1.21-μm $^3H_6 \rightarrow {}^3H_5$ absorption band of Tm^{3+} ions. The maximum absorption cross section for this band is approximately half that for the $^3H_6 \rightarrow {}^3H_4$ band. In addition, at present high-power laser diodes emitting in this region are not available. However, the 1.21-μm absorption band is rather broad (approximately 1 – 1.3 μm), so that different single-mode radiation sources

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can be used in this spectral region for pumping directly to the fibre core doped with Tm^{3+} ions. Such a possibility was studied both theoretically [4] and experimentally upon pumping by a single-mode neodymium laser at 1064 nm [5] and a Raman fibre laser at 1210 nm [6].

The principal possibility of generating a few watts of output radiation upon pumping into the $^3H_6 \rightarrow {}^3H_5$ absorption band by a 1064-nm Nd : YAG laser was first demonstrated in [5]. For the 1-W output power at a wavelength of 2 μm, the conversion efficiency was 27 % (the slope efficiency was 37 %). However, it seems that the presence of excited-state absorption at 1.1 μm (Fig. 2) can substantially restrict the efficiency of such pumping schemes. Note that the position and shape of absorption bands are considerably determined by the composition of the fibre core glass. Therefore, the possible influence of the fibre composition should be taken into account by comparing the results of different papers.

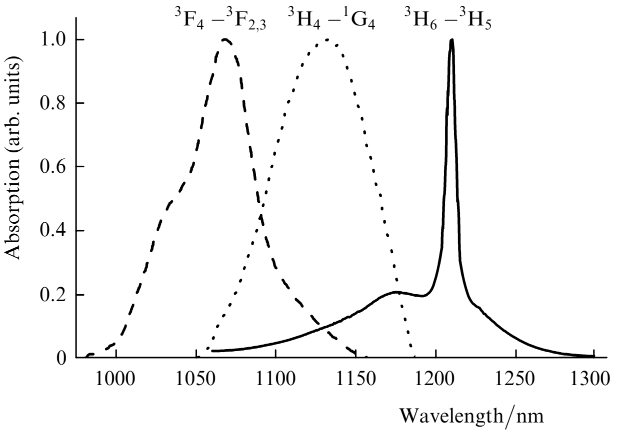

Figure 2. Wavelength dependence of the normalised absorption coefficient of the thulium-doped fibre used in the paper in the 1200-nm region corresponding to the $3H_6 \rightarrow {}^3H_5$ transition (solid curve) and approximate positions of the excited-state absorption bands [4].

More efficient lasing can be expected by pumping at the wavelengths remote from the excited-state absorption bands. Thus, upon single-mode pumping at 1.57 μm into the $^3H_6 \rightarrow {}^3F_4$ absorption band, the maximum slope lasing efficiency was 71 % [7]. Of course, it is also important that upon pumping into this band, the Stokes loss in minimal. However, radiation in the 1.6-μm region is obtained, as a rule, by using an erbium-doped fibre laser, which has a comparatively low efficiency, or with the help of multistage Raman lasers transforming radiation from an ytterbium laser. At the same time, because of a great difference between the corresponding frequencies, no less than three Raman conversion stages are probably required (even when two stages are used with the Stokes shift 1330 cm^{-1} in phosphosilicate fibres), which reduces the total efficiency of pumping.

Another possibility of pumping a thulium laser involves the use of Raman fibre lasers to shift the emission line of an ytterbium-doped fibre laser outside the excited-state absorption bands of thulium ions (but within the $^3H_6 \rightarrow {}^3H_5$ absorption band). Such a pumping scheme was first applied for a thulium laser in [6]. The use of a three-stage Raman germania-doped fibre laser to shift the pump wavelength provided the 400-mW output power at 1790 nm. The active element was a fibre doped with thulium and holmium ions, but lasing was observed at the transitions of Tm^{3+} ions. The lasing efficiency was 18 % and the slope efficiency was 23 %. Such low efficiencies can be explained by the fact that the pump wavelength was not sufficiently remote from the excited-state absorption bands (whose position is known only approximately).

It is interesting to study a thulium-doped fibre laser pumped into the long-wavelength wing of the $^3H_6 \rightarrow {}^3H_5$ absorption band, which is most remote from the excited-state absorption bands of thulium. This paper is devoted to the investigation of such a laser pumped at 1.23 μm.

2. Raman fibre laser emitting at 1231 nm

The thulium laser was pumped by a single-stage Raman fibre laser, which in turn was pumped by a single-mode ytterbium-doped fibre laser. The Raman laser was based on a phosphosilicate fibre of length 50 m. Fibre Bragg gratings (FBGs) were produced directly in this fibre, which provided the high conversion efficiency. The laser design is described in more detail in [8] (where it is denoted as 1L1). The Raman laser was pumped by a 1058-nm, 32-W cw single-mode ytterbium-doped fibre laser. The scheme of the experimental setup is shown in Fig. 3.

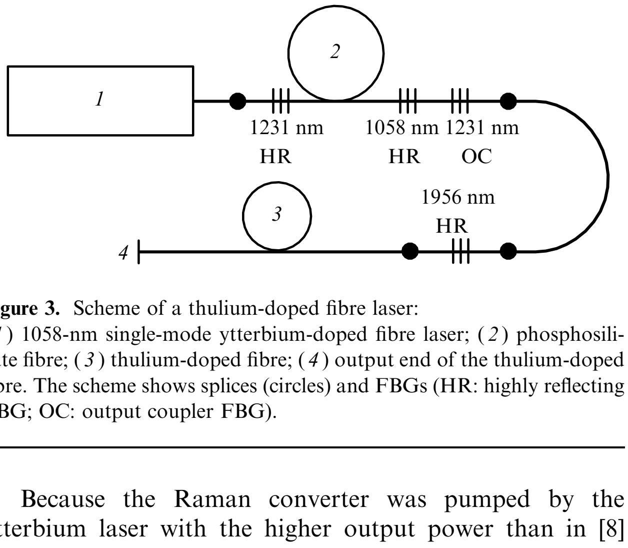

Figure 3. Scheme of a thulium-doped fibre laser:
(*1*) 1058-nm single-mode ytterbium-doped fibre laser; (*2*) phosphosilicate fibre; (*3*) thulium-doped fibre; (*4*) output end of the thulium-doped fibre. The scheme shows splices (circles) and FBGs (HR: highly reflecting FBG; OC: output coupler FBG).

Because the Raman converter was pumped by the ytterbium laser with the higher output power than in [8] (where the maximum pump power was 8 W), we obtained a considerably higher output of the Raman laser (up to 20 W) at 1231 nm. Although the emission spectrum of the laser at such high output powers was substantially broadened compared to the spectrum for the ~ 1-W output power (Fig. 4), this circumstance almost does not reduce the conversion efficiency. The dependence of the output power of the Raman laser on the pump power remains linear up to 20 W, without any indication of saturation (Fig. 5).

3. Thulium-doped fibre laser

The active element of the thulium laser was a silica fibre with a core doped (in weight percents) with 4 % of Al_2O_3, 1.5 % of GeO_2, and 0.8 % of Tm_2O_3. The fibre was fabricated by the MCVD technique, all the impurities being doped from a gas phase. The fibre core diameter was 16 μm, the cut-off wavelength for the second mode was ~3.0 μm. The spectral dependence of the absorption coefficient

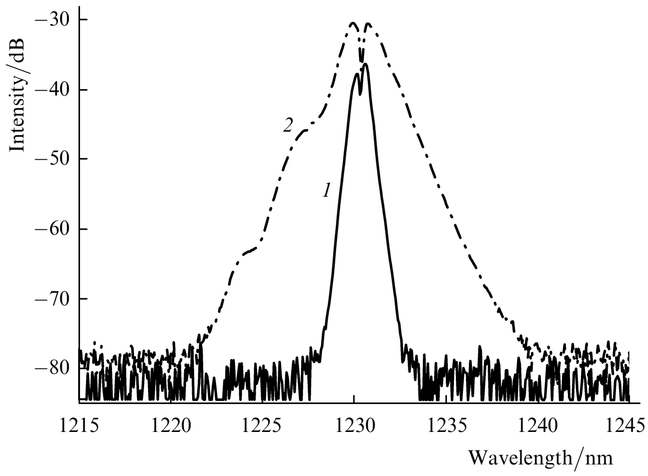

Figure 4. Lasing spectra of the Raman converter for the output power 1.15 (*1*) and 12.3 W (*2*).

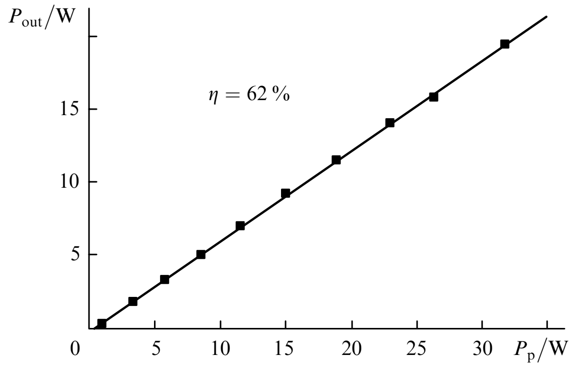

Figure 5. Dependence of the output power of the 1231-nm single-stage Raman laser on the 1058-nm pump power. The Raman laser efficiency is $\eta = 62\,\%$.

normalised to unity for radiation propagating in the fibre core in the 1200-nm region is shown in Fig. 2. The maximum value of the absorption coefficient is 185 dB m^{-1}. A large width of the $^3\text{H}_6 \rightarrow {}^3\text{H}_5$ absorption band provides efficient absorption of the pump in the spectral range from 1050 to 1270 nm. However, as follows from Fig. 2, the excited-state absorption spectra are strongly overlapped with this absorption band, which can substantially restrict the lasing efficiency. We preformed pumping at 1231 nm in the long-wavelength wing of the $^3\text{H}_6 \rightarrow {}^3\text{H}_5$ absorption band, sufficiently away from the excited-state absorption bands.

The luminescence spectrum of this fibre excited at 1.23 μm is presented in Fig. 6. Luminescence was detected in the direction perpendicular to the fibre axis to avoid reabsorption. The luminescence spectrum has a maximum at 1765 nm. Note that the maximum of luminescence of a thulium-doped fibre studied in [5] was observed at 1860 nm, and according to the measurement of the luminescence cross section in [4], at 1800 nm. It seems that this can be explained first of all by different chemical compositions of fibre cores. However, the shape of luminescence spectra (*1*), (*2*), and (*3*) in Fig. 6 is also substantially different. Luminescence spectrum (*3*) is substantially narrower, which can be explained by a smaller inhomogeneous broadening due to a higher degree of ordering of the fibre doped with thulium ions in [5].

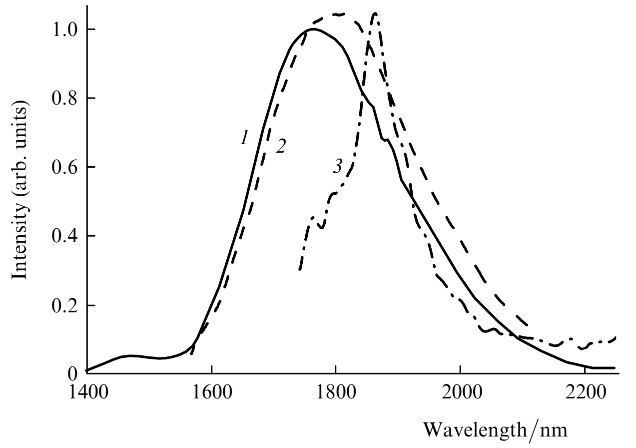

Figure 6. Luminescence spectra at the $^3\text{F}_4 \rightarrow {}^3\text{H}_6$ transition: (*1*) spectrum of our fibre; (*2*) spectrum calculated from the luminescence cross section [4]; (*3*) spectrum from [5].

The lifetime of the upper $^3\text{F}_4$ laser level measured by us was 670 μs. The measurements were performed using a PbS photodetector with a time resolution of 25 μs. Luminescence corresponding to the transition was selected against the background of pump radiation and luminescence at other transitions with the help of a germanium filter. Luminescence excited at 1.23 μm decayed exponentially. The lifetime of the $^3\text{F}_4$ level that we measured (670 μs) substantially differs from lifetimes determined in [5] (200 μs) and [9] (500 μs). It seems that the lifetimes, as luminescence spectra, strongly depend on the glass composition and can differ more than three times in different fibres.

The small-signal absorption coefficient at the pump wavelength (1231 nm) in a thulium-doped fibre was 27 dB m^{-1}. The laser resonator was formed by the FBG on the side of pump radiation coupling and the fibre end cleave on the opposite side. The lasing wavelength in this scheme was determined by the resonance wavelength of the FBG and was equal to 1956 nm in our experiments. The length of the active fibre was selected experimentally to achieve the maximum efficiency and proved to be ~ 1 m. In this case, the pump power coupled to the fibre was almost completely absorbed by thulium ions.

The threshold pump power in the scheme described above was 860 mW. The slope efficiency (with respect to the pump power coupled to the thulium-doped fibre) was 37 % (Fig. 7). The corresponding quantum efficiency was 59 %. The maximum output power achieved 7.0 W at a wavelength of 1956 nm for a pump power of 20 W (the 35 % efficiency). The laser linewidth determined by the width of the FBG reflection line was ~ 1 nm. Lasing occurred in the single-mode regime despite a comparatively large cut-off wavelength for the second mode in the fibre.

It is important from the practical point of view to see whether it is possible to use the radiation of the ytterbium laser itself for pumping the thulium laser. This would exclude the Raman converter from a setup, thereby providing a higher pump power and a higher efficiency of the system as a whole.

However, as was already mentioned and discussed in the literature [4, 5], due to the peculiarities of the energy level diagram of the Tm^{3+} ions, they strongly absorb radiation from the excited state. The $^3\text{F}_4 \rightarrow {}^3\text{F}_{2,3}$ and $^3\text{H}_4 \rightarrow {}^1\text{G}_4$

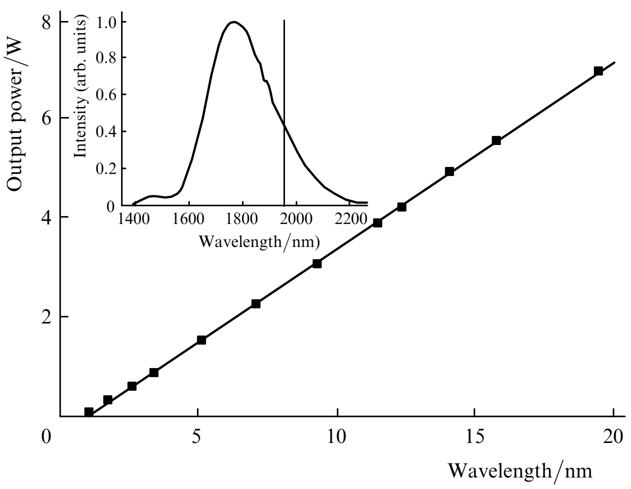

Figure 7. Dependence of the output power of the thulium-doped fibre laser on the pump power. The inset shows the relative positions of the luminescence band of thulium ions and the laser line.

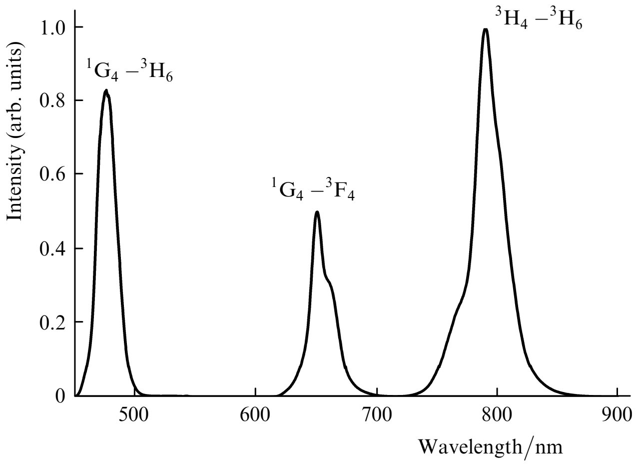

Figure 8. Luminescence spectra of the Tm^{3+}-doped fibre in the visible and IR regions excited at a wavelength of 1085 nm.

absorption bands of these ions are broad and have maxima at ~ 1070 and 1130 nm, respectively (Fig. 2). Therefore, the absorption of pump radiation in the 1100-nm region leads to the three-stage excitation, resulting in a considerable population of the $^1G_4$ level. This is observed by blue emission corresponding to the $^1G_4 \rightarrow {}^3H_6$ transitions (Fig. 8).

We used a single-mode ytterbium-doped fibre laser emitting at 1085 nm to find out whether it is possible to employ ytterbium-doped fibre lasers for pumping and to study the influence of described processes on lasing. Although the wavelength of this laser falls on the tail of the absorption band of Tm^{3+} ions, the pump radiation is comparatively well absorbed. The small-signal absorption coefficient in our fibre was 6 dB m^{-1}.

No lasing was observed at 1.95 μm upon pumping at this wavelength at pump powers up to 3.5 W. However, blue luminescence was considerably brighter than upon pumping at 1.23 μm. In addition, no bleaching of the medium, which is typical for high pump powers, was observed. All these observations demonstrate that Tm^{3+} ions at the upper $^3F_4$ laser level absorb pump radiation and undergo the $^3F_4 \rightarrow {}^3F_{2,3}$ transition. In this case, the population of the $^3F_4$ level cannot achieve the value sufficient for producing the gain required for lasing.

We observed absorption of pump radiation at 1085 nm by Tm^{3+} ions at the upper $^3F_4$ laser level in the following experiment. CW pump radiation of power ~230 mW was transformed with the help of a mechanical modulator with a switching time of ~ 5 μs to a train of rectangular pulses of duration ~ 5 ms. The intervals between pulses were equal to their duration. The modulated radiation was coupled into a thulium-doped fibre of length ~ 30 cm, and the time dependence of the pump power at the fibre output was observed (Fig. 9). One can see from the oscillogram that the pump power increases up to its maximum upon switching and then decreases down a stationary value during the population of the $^3F_4$ level due to the appearance of additional absorption from the excited state. This additional absorption considerably exceeds a decrease in absorption caused by a partial depletion of the ground level. Therefore, this experiment directly demonstrates the presence of significant excited-state absorption upon pumping at 1085 nm.

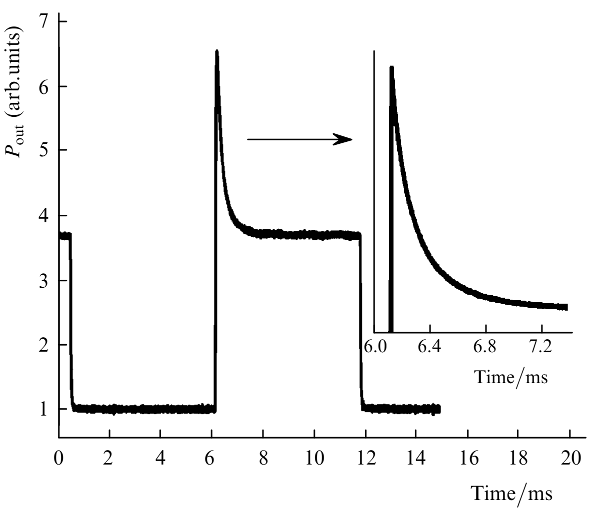

Figure 9. Time dependence of the pump power at the output of the thulium-doped fibre of length ~ 30 cm pumped by 1085-nm rectangular pulses. The inset shows the transmitted pump power decay with a better time resolution.

As mentioned above, in [5] lasing in a thulium-doped fibre was obtained by pumping at a wavelength of 1064 nm, which is close to the wavelength used in our experiments. Unlike our results, lasing observed in [5] had a low threshold (600 mW) and a comparatively high efficiency. This difference can be explained as follows. First, the population inversion was reduced in [5] by using a resonator with the output mirror with a low transmission coefficient. Second, because the luminescence spectrum of Tm^{3+} ions in a fibre [5] was much narrower than that in our fibre and luminescence spectra observed in other papers [4, 6], it seems that the reabsorption of pump radiation in these fibres were substantially different.

Therefore, our experiments demonstrate considerable problems appearing upon pumping thulium-doped aluminosilicate fibre lasers in the 1070-nm region.

4. Conclusions

We have demonstrated high-power lasing in the 2-μm spectral region by pumping a Tm^{3+}-doped aluminosilicate fibre laser into the long-wavelength wing of the $^3H_6 \rightarrow {}^3H_5$ absorption band. Upon pumping into the short-wavelength wing of this absorption band, the excited-state absorption prevents efficient lasing.

By pumping at the wavelength remote from the excited-state absorption band, we obtained lasing in the 2-μm region. The output power a single-mode thulium-doped fibre laser emitting at 1956 nm was 7 W. The laser was pumped by a 20-W, 1231-nm Raman fibre laser. The quantum efficiency with respect to the pump power was 59 %. This pumping scheme allows one to obtain lasing in the 2-μm region by using diode lasers employed for pumping ytterbium-doped fibre lasers, without special fibres co-doped with Yb and Tm ions. Pumping of a thulium-doped aluminosilicate fibre laser at 1085 μm is inefficient because of strong excited-state absorption.

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