

CONTROL OF LASER RADIATION PARAMETERS

PACS numbers: 42.55.Wd; 42.60.Fc; 42.60.Rn
DOI: 10.1070/QE2015v045n07ABEH015682

Optimisation of thulium fibre laser parameters with generation of pulses by pump modulation

I.V. Obronov, V.E. Sypin, S.V. Larin

Abstract. **The formation of relaxation pulses of a thulium fibre laser (λ = 1.9 μm) by modulating the power of a pump erbium fibre laser (λ = 1.55 μm) is studied. A theoretical model is developed to find the dependences of pulse duration and peak power on different cavity parameters. The optimal cavity parameters for achieving the minimal pulse duration are determined. The results are confirmed by experimental development of a laser emitting pulses with a duration shorter than 10 ns, a peak power of 1.8 kW and a repetition rate of 50 kHz.**

Keywords: *thulium fibre laser, gain modulation.*

1. Introduction

Fibre lasers based on ytterbium- and erbium-doped waveguides demonstrate impressive results in various operation regimes at wavelengths of 1.06 and 1.55 μm. Thulium and holmium fibre lasers have also been extensively studied and developed. Of interest are various optical schemes of these lasers, including repetitively pulsed ones with pulse durations of the order of several nanoseconds. These lasers are very promising for application in lidars [1], medicine [2], spectroscopy, mid- and far-IR converters [3] and various material treatment processes.

There exist various methods of generation of short pulses with a high repetition rate in the wavelength region near 2 μm. These are *Q*-switching in a solid-state Ho : YAG scheme [4], *Q*-switching in schemes based on thulium-doped waveguides [5] and use of a master laser diode (MOPA scheme). However, these methods either cannot provide high peak powers and short durations of pulses or are very complicated and cumbersome. In addition, traditional schemes with bulk elements in the cavity have high losses and are susceptible to heating, while the output beam quality can be spoiled due to thermal effects. The MOPA scheme requires appropriate semiconductor lasers, which are still rather expensive and whose technology is not as well developed as the technology of distributed-feedback lasers emitting at 1.55 μm.

In contrast to these methods, gain modulation by the pump requires no additional bulk elements in the cavity and allows one to implement a simple all-fibre system. This approach is an effective alternative for obtaining 2-μm pulses. Recently, many researchers have paid attention to this scheme, but the shortest pulse duration obtained by gain modulation is no less than 10 ns [6]. Shorter pulses were achieved only in the case of self-mode-locking in a thulium laser [7–9].

In the present work, we built a theoretical model of an all-fibre pulsed thulium laser, used it to calculate the parameters of needed components and designed a laser with a close-to-optimal configuration. This laser emitted stable pulses with a duration shorter than 10 ns and a peak power of 1.8 kW. As far as we know, this is the first efficient optimisation of a thulium laser scheme based on theoretical calculations performed with varying such parameters as cavity length, output Bragg grating reflection, thulium concentration, pump absorption cross section and pump pulse energy. It is shown that it is possible to obtain pulses shorter than 5 ns.

2. Experimental setup

The experimental setup scheme is shown in Fig. 1. To modulate the laser gain, we pumped the active waveguide by 1558-nm pulses of an erbium fibre laser designed as a MOPA. The pump pulse duration could be changed from 5 to 60 ns, and the pulse repetition rate, from 50 to 200 kHz. The laser cavity consisted of a thulium-doped fibre (TDF) segment (concentration 600 ppm, core and cladding diameters 16 and 125 μm) and two fibre Bragg gratings (FBGs). The highly reflecting (HR) grating reflectance was lower than −25 dB, while the reflectance of the output coupler (OC) was about 8 dB. The

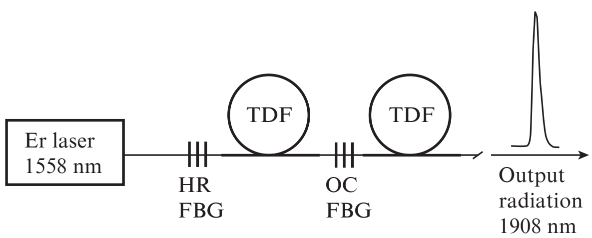

Figure 1. Scheme of the experiment.

I.V. Obronov LLC NTO 'IRE-Polus', pl.Vvedenskogo 1, Bld. 3, 141190 Fryazino, Moscow region, Russia; National Research Nuclear University 'MEPhI', Kashirskoe sh. 31, 115409 Moscow, Russia; e-mail: iobronov@ntoire-polus.ru;
V.E. Sypin LLC NTO 'IRE-Polus', pl. Vvedenskogo 1, Bld. 3, 141190 Fryazino, Moscow region, Russia; Moscow Institute of Physics and Technology (State University), Institutskii per. 9, 141707 Dolgoprudnyi, Moscow region, Russia;
e-mail: vsypin@ntoire-polus.ru;
S.V. Larin LLC NTO 'IRE-Polus', pl. Vvedenskogo 1, Bld. 3, 141190 Fryazino, Moscow region, Russia; e-mail: slarin@ntoire-polus.ru

Received 27 September 2014; revision received 7 November 2014
Kvantovaya Elektronika **45** (7) 617–620 (2015)
Translated by M.N. Basieva

cavity length was ~7 cm, and the active waveguide was ~5 cm long. To filter the unabsorbed pump radiation, 3 m of the same active fibre was fused to the output waveguide of the OC.

An important feature of the used Er laser is its strongly broadened spectrum due to nonlinear effects leading to the formation of a supercontinuum in the anomalous dispersion region (Fig. 2). The laser spectra were measured by a Yokogawa AQ6375 spectrum analyser, while the pulse oscillograms at wavelengths of 1.5 and 1.9 μm were recorded by an InGaAs photodetector and a Tektronix DPO 3054 oscilloscope.

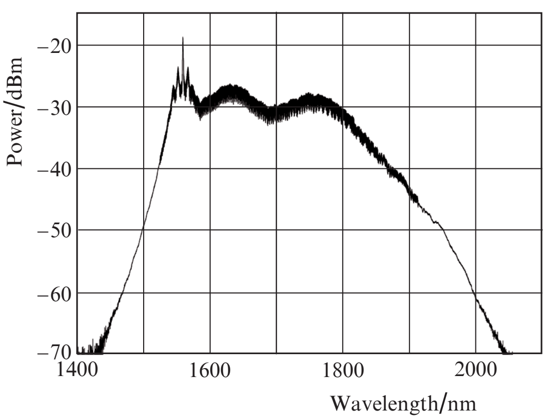

Figure 2. Laser emission spectrum.

3. Numerical simulation and variation of parameters

The dynamics of processes occurring in a thulium laser under 1.55-μm pulsed pumping can be described by a system of rate equations [10, 11]. This system was numerically solved using a two-dimensional (time–distance) grid (Fig. 3). The power evolution of emitted photons with a wavelength of 1908 nm was studied for the right- and left-propagating (P^+ and P^-) photon fluxes. The numerical calculation was performed using the second-order Runge–Kutta method. In the equations below, the symbols of variables are omitted (they are given in Fig. 3):

$$\frac{n_c}{c}\frac{dP^{\pm}}{dt} = [(\sigma_e^s + \sigma_a^s)N_2 - \sigma_a^s N_0]P^{\pm} + \frac{\Delta\Omega}{4\pi}\frac{N_2}{\tau}h_P \nu_s \frac{\sigma_e^s \Delta\lambda}{\int \sigma_e d\lambda}A_c,$$

$$\frac{n_c}{c}\frac{dP_p}{dt} = [(\sigma_e^p + \sigma_a^p)N_2 - \sigma_a^p N_0]P_p,$$

$$\frac{dN_2}{dt} = \frac{P^+ + P^-}{A_c h_P \nu_p}[\sigma_a^p N_0 - (\sigma_a^p + \sigma_e^p)N_2] + \frac{P_p}{A_c h_P \nu_s}[\sigma_a^s N_0 - (\sigma_a^s + \sigma_e^s)N_2] - \frac{N_2}{\tau}.$$

Here, N_2 is the concentration of excited electrons, P_p is the pump pulse power, P^+ and P^- are the powers of right- and left-propagating beams at 1908 nm, N_0 is the concentration of thulium ions, τ is the lifetime, σ_a^p and σ_a^s are the pump and signal absorption cross sections, σ_e^s and σ_e^p are the signal and pump emission cross sections, h_P is the Planck constant, ν_p and ν_s are the pump and laser frequencies, A_c is the area of the waveguide core, c is the velocity of light, n_c is the core refractive index, $\Delta\Omega = 2\pi[1 - \cos(\alpha/2)]$ is the solid angle in which the waveguide confines light, and α is the numerical aperture of the fibre.

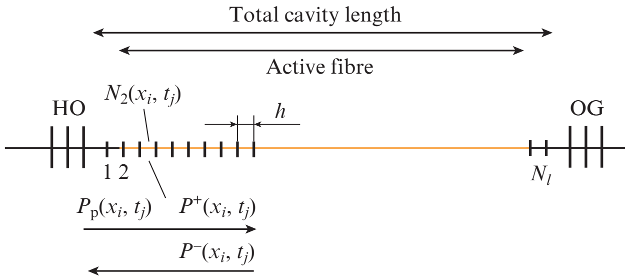

Figure 3. Cavity calculation scheme ($h = h_t c/n_c$, $N_l = L/h$, h is the coordinate step, h_t is the time step).

In the calculations, we used the following constants: $N_0 = 3.3 \times 10^{25}$ m^{-3}, $\tau = 334 \times 10^{-6}$ s [12], $\sigma_a^p = 1.5 \times 10^{-25}$ m^2, $\sigma_e^s = 4 \times 10^{-25}$ m^2 [13], $\sigma_e^p = 5 \times 10^{-27}$ m^2 [13], $\sigma_a^s = 3 \times 10^{-27}$ m^2 [13], ν_p = 192.421 THz, ν_s = 157.124 THz, A_c = 200 μm^2, and α = 0.095.

The pump pulse duration in the calculation and experiment was 20 ns. This pulse duration was used to avoid a considerable temporal overlap between the pump and laser pulses because this disturbs stable lasing. Since numerical calculations for a broadband emission are difficult to perform, we, for simplicity, chose a large pump absorption cross section. This cross section was determined based on the spectral ratios of pump radiation (Fig. 2) and absorption cross sections for different spectral components (Fig. 4). Of course, this averaging results in an error in the absorbed power, but, according to the simulation, this error is small because the cavity length is short and the absorbed energy comprises an insignificant part of the total pump pulse energy.

Using the described numerical model, we determined the dependences of the generated relaxation pulse characteristics

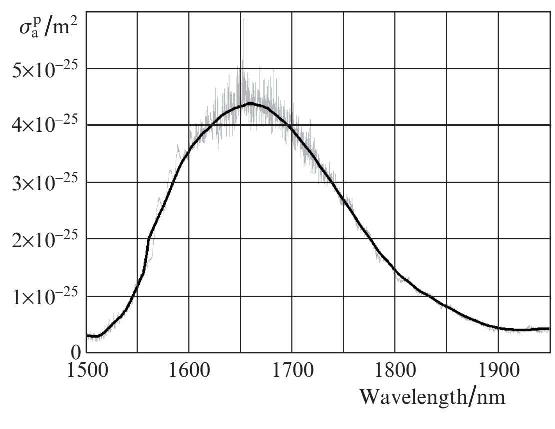

Figure 4. Thulium fibre absorption cross section.

(duration and peak power) on the cavity parameters (OC transmission, cavity length, active fibre absorption cross section, and concentration of thulium ions), as well as on the pump pulse energy. These dependences are presented in Figs 5–9. In the experiment, we used active waveguides with a thulium concentration of 0.5 wt %. The other cavity parameters were chosen based on the calculated dependences in order to obtain the optimal output pulse characteristics. The optimal cavity parameters are determined to be as follows: OC reflection 85%, cavity length L = 7 cm and active fibre length L_f = 5 cm.

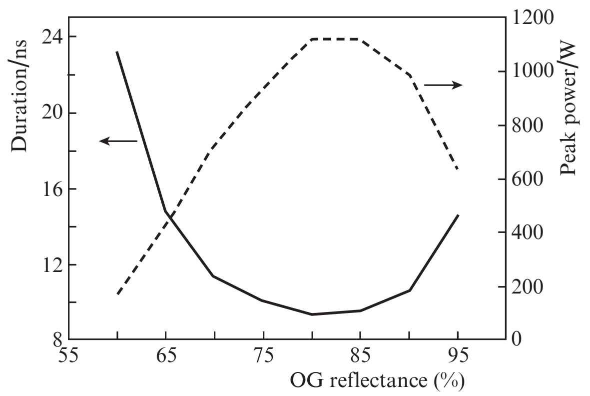

Figure 5. Dependence of the laser pulse duration and peak power on the OC reflectance at L = 7 cm; L_f = 5 cm and E_p = 60 μJ.

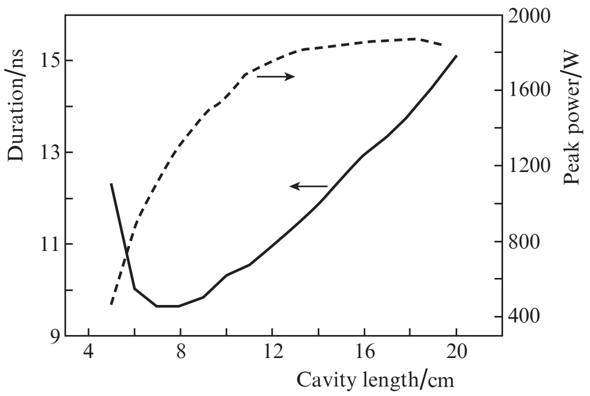

Figure 6. Dependences of the pulse duration and peak power on the cavity length. In all the cases, the active fibre length is 2 cm shorter than the cavity length; E_p = 60 μJ.

Note that the dependences of the pulse duration and peak power on the thulium ion concentration (Fig. 7) were calculated at unchanged cavity configuration and pump pulse energy. However, with increasing dopant concentration, the optimal OC transmittance decreases.

Some dependences of laser parameters close to ours were presented in [12], but they were obtained with insufficient accuracy, in particular, the range of cavity lengths shorter than 0.2 m was not considered. In addition, the best result achieved by the authors of [12] – pulse duration 120 ns – is noticeably higher than in other works. The dependences of laser characteristics on the pump pulse energy and on the cavity length, which qualitatively agree with our results, were experimentally obtained in [8, 9, 14].

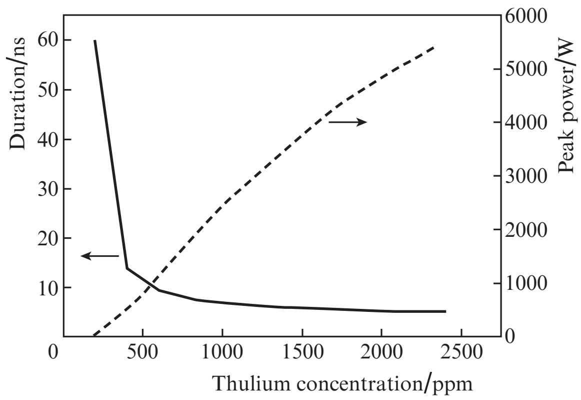

Figure 7. Dependences of the pulse duration and peak power on the thulium ion concentration at L = 7 cm, L_f = 5 cm and E_p = 60 μJ.

The slight deviation between the theoretical and experimental curves (Fig. 8) can be explained by temperature and nonlinear optical effects in the waveguides.

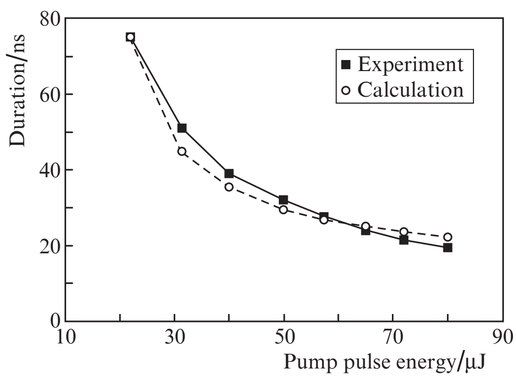

Figure 8. Dependences of the pulse duration on the pump pulse energy at L = 7 cm and L_f = 5 cm.

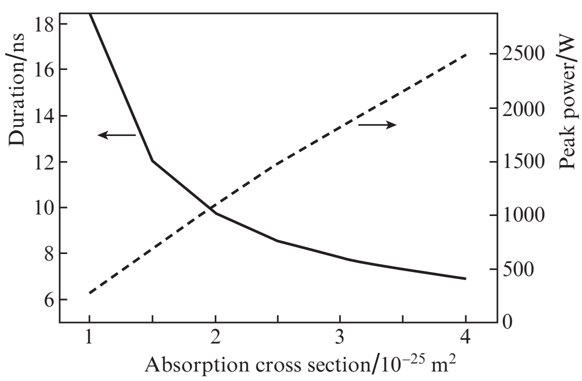

Figure 9. Dependences of the pulse duration and peak power on the absorption cross section at L = 7 cm, L_f = 5 cm and E_p = 60 μJ.

4. Experimental results

Based on the theoretical model, we calculated and fabricated a laser cavity with a close-to-optimal configuration. The duration of experimental pulses was about 10 ns, which rather well agrees with the calculated results (Fig. 10).

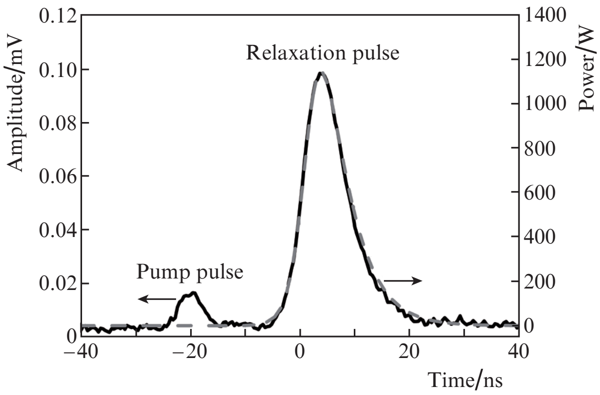

Figure 10. Simulated (dashed line) and experimental (solid line) oscillograms of laser pulses.

The relaxation pulse spectrum is strongly broadened to longer wavelengths (Fig. 11) due to nonlinear effects, such as modulation instability and self-Raman shift of the frequency of formed solitons, which leads to supercontinuum generation [15–17]. The fraction of radiation in the range 1908 ± 5 ns was 80%. The width of the main line (1908 nm) at the level of 3 dB was 0.2 nm. At a pulse repetition rate of 50 kHz and a pulse duration of ~10 ns, the pulse peak power and energy are estimated to be 1.8 kW and 18 μJ, respectively.

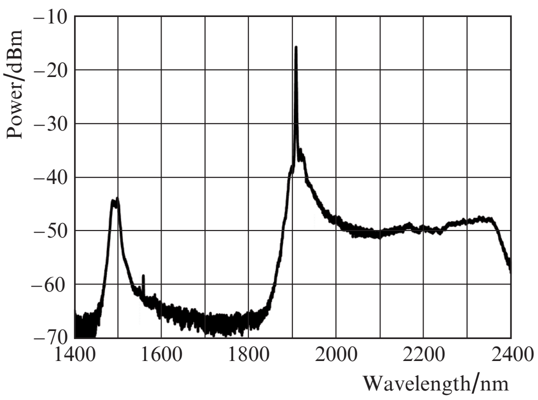

Figure 11. Relaxation pulse spectrum.

5. Conclusions

The formation of relaxation pulses by gain modulation in a thulium laser is numerically simulated. A good agreement between the calculated and experimental results allows us to claim that the dependences plotted by simulation are correct. Therefore, the analysis of the model can suggest new ways to obtain shorter laser pulses. To these ways one can assign, first of all, an increase in the thulium ion concentration in the fibre. The dopant concentration in commercially available lasers is 2 wt %, which approximately corresponds to 2400 ppm. The calculations show that, at the same pump energy, cavity length and OC reflection, the pulse duration can be decreased to 5 nc (see Fig. 9), and, with selection of an optimal grating, to less than 4 ns. In addition, an increase in the pump power will also decrease the pulse duration. In the considered cavity, an increase in the pump pulse energy to 200 μJ will allow one to decrease the pulse duration to 5 ns.

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