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# Thin-rod active elements for amplification of femtosecond pulses

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***Abstract.*** **To study the possibility of amplifying the radiation of femtosecond fibre lasers in thin-rod active elements, amplifying modules based on thin rods made of broadband Yb : $CaF_2$ and Yb : $Y_2O_3$ materials are developed. It is shown that the gain in Yb : YAG and Yb : $Y_2O_3$ elements is limited because only part of the broadband signal is amplified, while amplification in Yb : $CaF_2$ elements occurs in a wider spectral range but is weak due to a small emission cross section. Amplification from submicrojuole to submillijoule level in the regenerative amplification regime is demonstrated. The new broadband Yb : $CaF_2$ and Yb : $Y_2O_3$ materials can amplify radiation with a considerably broader spectrum than Yb : YAG.**

***Keywords:*** *femtosecond laser pulses, thin-rod active elements, ytterbium-doped laser materials, spectral narrowing.*

## 1. Introduction

Combining of fibre femtosecond lasers with solid-state output amplifiers is a promising way to develop simple, stable, and reliable femtosecond systems with millijoule pulses and an average power of tens of watts. Solid-state amplifiers in these systems must amplify radiation by 2–3 orders of magnitude and be simple, reliable, and free of thermal effects. A promising approach to this problem is the development of solid-state amplifiers based on thin-rod active elements [1]. The small diameter (below 1 mm) of such an active element allows efficient heat transfer, while its length (up to 4 cm) makes it possible to achieve a high gain per pass under diode pumping. Recently, a pulse energy exceeding 2 mJ [2, 3] and an average power exceeding 160 W [4] were demonstrated upon signal amplification in thin Yb : YAG active rods. However, the insufficiently broad emission band of Yb:YAG active elements does not allow one to retain pulse duration in the case of amplification of radiation of femtosecond fibre lasers. Indeed, the typical minimum duration of pulses amplified in Yb : YAG is 500–1000 fs depending on gain [5, 6], whereas the pulse duration of high-power femtosecond lasers requiring additional amplification may be smaller than 200 fs. In this connection, the development of amplifiers with reliability and efficiency comparable with those of thin Yb : YAG rods but with a broader emission band remains an important problem.

In the present work, we study the possibility of extending the emission band of thin-rod active elements by using new (for this geometry) materials. Amplifying modules based on such elements made of broadband Yb:$CaF_2$ and Yb:$Y_2O_3$ materials are developed and fabricated. Amplification of a broadband signal in the developed modules is studied, and the performed comparison showed that they provide efficient amplification in a broader band than modules based on thin Yb : YAG rods.

## 2. Study of the spectral characteristics of Yb : $Y_2O_3$ and Yb : $CaF_2$ laser materials

The alternative method of fabricating amplifying modules with thin active rods described in [7] allows one to use not only materials obtained by vertical pulling [8] but also other crystalline and ceramic materials. This approach considerably extends the possibility of optimising thin-rod active elements for solving one or another problem by using ytterbium-doped laser media. Sesquioxide ceramics Yb : $Y_2O_3$, Yb : $Lu_2O_3$, Yb : $Sc_2O_3$, etc., belong to the most promising materials for thin active rods, which is explained by their high thermal conductivity and a broader gain band compared to Yb : YAG. Fluoride-family crystals ($CaF_2$, $SrF_2$, $BaF_2$, and so on) have the broadest gain band among ytterbium-doped materials. These crystals have good thermooptical characteristics, while their main drawback is a small gain cross section.

The spectral distributions of absorption and gain cross sections, as well as the lifetimes of the upper laser level in the studied Yb : YAG (3 at.%), Yb : $CaF_2$ (0.5 at.%), and Yb : $Y_2O_3$ (0.5 at.%) materials were measured by the method described in [9, 10]. Figure 1 shows that the gain spectrum of Yb : $Y_2O_3$ is by a factor of 1.5 broader than that of Yb : YAG, but the gain cross section is several times smaller. The gain cross section spectrum of Yb : $CaF_2$ is much broader than that of Yb : YAG or Yb : $Y_2O_3$, but the gain cross section is several times smaller. The measured lifetimes are 0.95 ms in Yb : YAG, 1 ms in Yb : $Y_2O_3$, and 2 ms in Yb : $CaF_2$, and the difference between these values insignificantly affects the gain. Thus, we can expect that the developed laser heads will make it possible to considerably increase the gain bandwidth at a lower gain per pass.

Based on the performed measurements, we determined the optimal pump wavelength, calculated the active element length needed for efficient absorption of pump radiation, and developed amplifying modules. An element 10 mm long and 0.8 mm in diameter for pumping at $\lambda$ = 940 nm was made of an Yb : YAG (3 at.%) crystal. The absorption linewidth in the region of 975 nm in Yb : $Y_2O_3$ is larger than in Yb : YAG,

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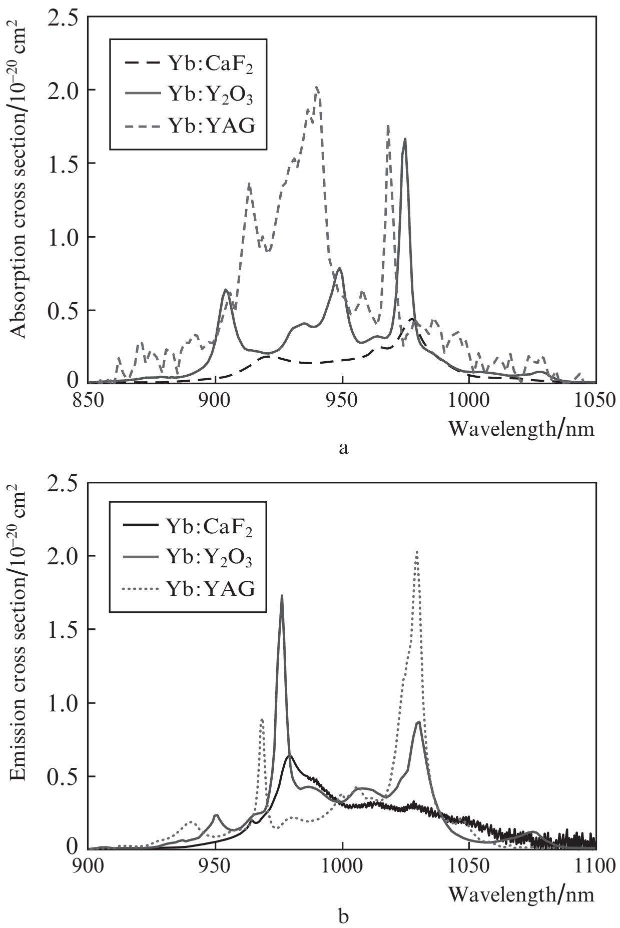


**Figure 1.** Spectral dependences of the absorption and emission cross sections in the studied materials.

which allows one to pump this crystal by 975-nm laser diodes. The Yb:$Y_2O_3$ (1 at.%) laser element had a length of 15 mm and a diameter of 1 mm. Yb:$CaF_2$ elements also can be pumped by radiation with $\lambda$ = 975 nm. The optimal length of the Yb:$CaF_2$ (0.5 at.%) element was 12 mm at a diameter of 1.2 mm. The amplifying modules based on the fabricated thin-rod active elements were made by the method described in [7].

## 3. Direct amplification of a broadband signal in fabricated laser modules

The amplifying modules were studied in the broadband small-signal amplification regime. The optical scheme of gain measurement is shown in Fig. 2. A femtosecond fibre laser

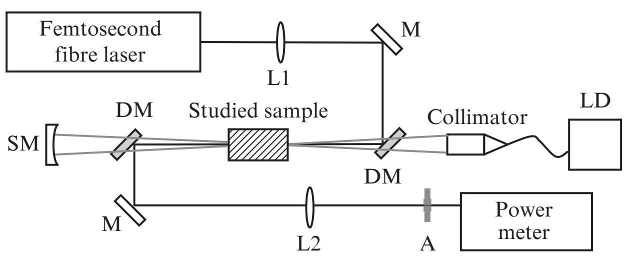


**Figure 2.** Optical scheme for measuring the gain of broadband radiation in the studied samples.

with a linewidth of 8 nm and a centre wavelength of 1030 nm was used as a radiation source. Part of this radiation with an average power of 200 mW was sent to the studied sample and superimposed with the beam of a pump laser diode (LD) using dichroic mirrors. A lens L1 with a focal length of 75 mm focused the laser beam into a spot 0.2 mm in diameter inside the studied element, which was pumped by a high-brightness fibre-coupled laser diode module. The fibre diameter was 105 μm at a numerical aperture of 0.22. The pump radiation from the fibre was collimated by an aspheric lens L2 and focused into the thin active rod with a magnification of $3^{\times}$ (the lenses were placed in a collimator); the pump spot diameter in the element was 0.3 mm. The unabsorbed part of radiation was reflected back into the element by a highly-reflecting spherical mirror S3 with a radius of curvature of 50 cm. The Yb:YAG active element was pumped by a diode module with a wavelength of 940 nm and a maximum power of 100 W, while the Yb:$Y_2O_3$ and Yb:$CaF_2$ elements were pumped by a diode module with a wavelength of 975 nm. The pump and amplified beams were superimposed using dichroic mirrors DM. The amplified signal was sent to a power meter, while the remaining part of the pump radiation was filtered by a spatial filter (lens L2 and aperture A).

The gain measurement results are presented in Fig. 3. Taking into account that the average radiation power incident on the amplifier was low, we can assume that the measurements were performed in the small-signal approximation. One can see that the gain in the Yb:YAG element is higher than in the Yb:$Y_2O_3$ and Yb:$CaF_2$ samples, but is considerably lower than the gain achieved in the case of amplification of narrowband radiation [3]. The low gain in Yb:YAG and Yb:$Y_2O_3$ is explained by the fact that only a part of the broadband input signal is amplified. In contrast, the Yb:$CaF_2$ element amplifies all spectral components of the input signal, but the gain is low due to a small emission cross section. Using a conical active element in the amplifying module [11], as well as two- or four-pass schemes, one can increase a broadband signal gain in the studied media by several times.

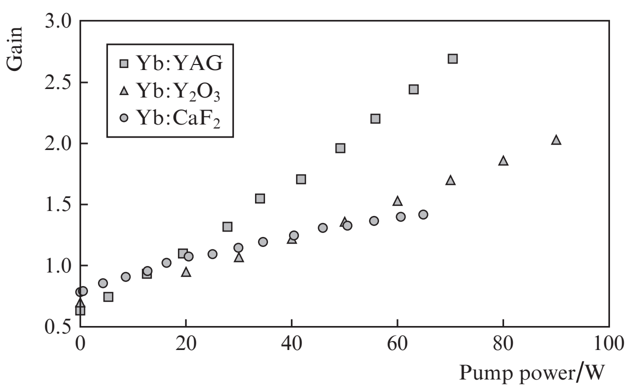


**Figure 3.** Dependences of gain on the pump power in the studied laser modules.

## 4. Regenerative amplification in fabricated amplifying modules

As was mentioned above, the developed thin-rod laser modules can amplify broadband femtosecond radiation by several times. In the case of amplification in Yb:YAG and Yb:$Y_2O_3$ elements, one observes spectral narrowing of the signal, which decreases the peak power of femtosecond laser pulses. This decrease for $Yb:CaF_2$ elements is insignificant, but the gain in these crystals is low. To determine the maximum possible width of the amplification band, the studied laser modules were tested in the regenerative amplification regime (Fig. 4). The beam of a femtosecond laser with a pulse energy up to 1 μJ is sent to a conventional regenerative amplifier scheme through a Faraday isolator FI. The pump and amplifying beams are superimposed by dichroic mirrors DM. Plain mirrors M and spherical mirrors SM2 with radii of curvature of 80 cm form a stable cavity. A Pockels cell in combination with a polariser P and a $\lambda/4$ plate serve to couple laser radiation in and out of the regenerative amplifier cavity with a controlled number of passes. A thin-rod element in the cavity amplifies the signal. In the case of Yb:YAG and $Yb:CaF_2$ elements, the pulse repetition rate was 11 kHz at 14 passes through the cavity, and the femtosecond pulse was stretched to 50 ps. The gain of the laser module based on $Yb:Y_2O_3$ was measured at a pulse repetition rate of 50 kHz, and the duration of the stretched pulse was 200 ps.

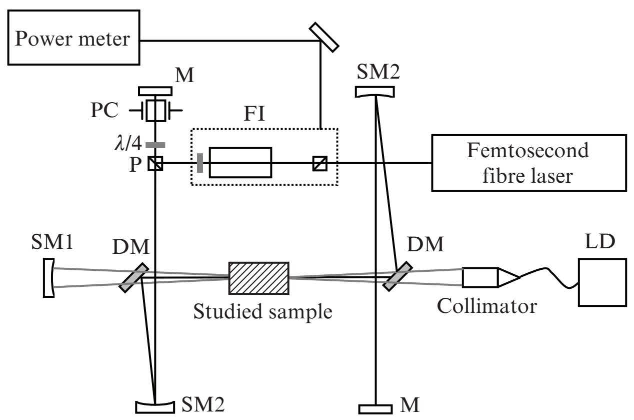


**Figure 4.** Optical scheme of regenerative amplification of a broadband signal in the studied samples.

The results of gain measurements in the regenerative amplification regime are shown in Figs 5 and 6. One can see that significant amplification (from submicrojuoles to submillijoules) was achieved in all three active media. Further

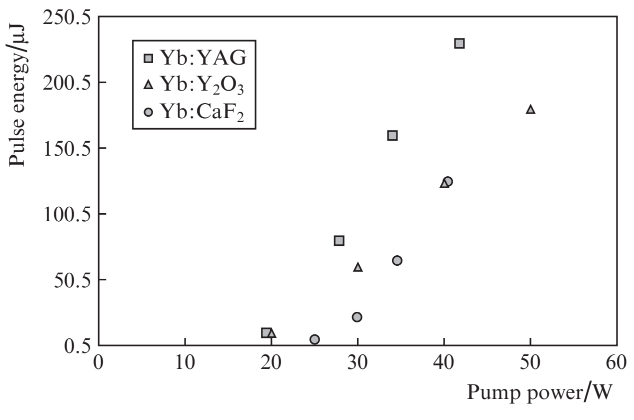


**Figure 5.** Dependences of the output pulse energy $E$ of the regenerative amplifier on the pump power $P$ for the studied laser modules.

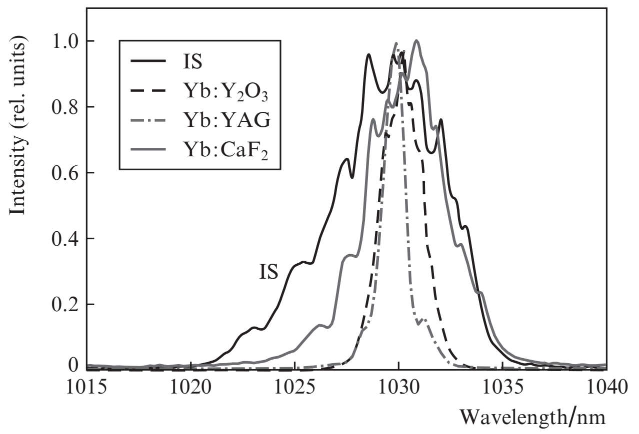


**Figure 6.** Spectral distribution of the amplified radiation and the initial signal (IS).

increase in the pulse energy was restricted by the possibility of optical breakdown of the thin active rods. The slightly lower slope of the $E(P)$ dependence for the $Yb:Y_2O_3$ sample in Fig. 5 is explained by a higher pulse repetition rate. A more pronounced difference between the results is observed for the spectral distributions of amplified signals (Fig. 6). In the case of amplification in the laser module with Yb:YAG, the initial signal spectrum (8 nm) narrows to 1.4 nm, which corresponds to a transform-limited pulse duration of ~800 fs. According to Fig. 1, the emission cross section spectrum in $Yb:Y_2O_3$ is approximately 1.5-fold broader than in Yb:YAG. This relation is also retained upon regenerative amplification. The spectral width of the signal amplified in the laser module with $Yb:Y_2O_3$ is 2.2 nm, which corresponds to a transform-limited pulse duration of ~500 fs. Note that amplification in the laser module with $Yb:CaF_2$ also occurs with a slight narrowing of the signal spectrum, which is probably related to the wavelength-dependent transmission function of the Pockels cell, $\lambda/4$ plate, and polariser. Nevertheless, the emission bandwidth in the thin $Yb:CaF_2$ rod was 4.5 nm, which corresponds to a transform-limited pulse duration of ~240 fs.

## 5. Conclusions

Amplifying modules based on thin-rod active elements made of new (for this geometry) broadband $Yb:CaF_2$ and $Yb:Y_2O_3$ materials are developed and fabricated. The spectral characteristics of these laser materials are studied; the obtained results are used to determine the optimal pump wavelengths and calculate the length of active elements. The gain of broadband radiation in thin-rod amplifying modules with both Yb:YAG, which is traditional for this geometry, and $Yb:CaF_2$ and $Yb:Y_2O_3$ elements is studied. It is found that the gain per pass in this case is considerably lower than the gain of a narrow-band signal in Yb:YAG. This is explained both by a considerable narrowing of the amplified signal spectrum (for Yb:YAG and $Yb:Y_2O_3$) and by a small emission cross section (for $Yb:Y_2O_3$ and $Yb:CaF_2$). Nevertheless, all the three laser materials can directly amplify broadband femtosecond radiation by several times (for example, in two- and four-pass amplification schemes). Strong amplification of a femtosecond signal in the regenerative amplification regime is demonstrated and narrowing of the amplified signal spectrum is studied. It is shown that the laser modules with thin-rod active elements made of the new laser materials ($Yb:Y_2O_3$

and Yb:$CaF_2$) make it possible to amplify laser pulses with a smaller transform-limited duration than modules with similar Yb:YAG elements.

One of the main drawbacks of the studied broadband media in the new thin-rod geometry is a small gain. However, this drawback can be overcome using different methods. In particular, the use of pumping with longer wavelengths for Yb:$Y_2O_3$ and Yb:$CaF_2$ elements considerably decreases the quantum defect upon amplification, which allows one to considerably increase the peak pump power compared to Yb:YAG elements. In addition, gain can be considerably increased by using a conical geometry of thin-rod active elements. These approaches will be studied in subsequent works in this field.

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