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Broadband optical amplifier of IR pulses based on a F_2^+:LiF crystal

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***Abstract*. The possibility of the 300-fold optical amplification of broadband 900-nm nanosecond IR radiation pulses with the help of LiF crystals with stabilised F_2^+-colour centres in a single-pass amplifier is demonstrated.**

Keywords: *LiF crystals, colour centres, broadband amplification.*

Broadband amplifiers of weak light pulses in the IR range are extensively used in modern optical technologies such as optical communication [1], femtosecond optical tomography [2], and low-coherent interferometry [3]. The achievement of the required amplification of broadband femtosecond pulses from $Ti^{3+}:Al_2O_3$ and $Cr^{3+}:LiSAF$ lasers at the wings of the gain profile of active media of the same composition is problematic due to a low gain in these media. This drawback can be overcome by using crystals with colour centres as active media [4–6].

In this paper, we present the experimental studies which allow us to estimate the potential of F_2^+:LiF crystals for application in broadband amplifiers of weak light pulses in the spectral range from 0.84 to 1.06 μm. Note that the spectroscopic parameters of thermally stable laser F_2^+ colour centres in a LiF crystal [7] are quite favourable for their use in broadband amplifiers. The results of our preliminary study are presented in Ref. [8].

We studied a single-pass optical amplifier based on a F_2^+:LiF crystal, which was collinearly pumped by 10-ns, 5-mJ second-harmonic pulses from a Nd:YAG laser at 532 nm. The F_2^+:LiF crystals of lengths 0.8, 2.0, and 3.8 cm were mounted at the Brewster angle to the optical axis of the amplifier. The absorption coefficient at the pump wavelength was 2 cm^{-1} and was caused by absorption at the long-wavelength wing of the spectrum by active F_2^+-centres and absorption by residual F_2- and N-centres in the crystal.

A pump laser beam was focused by a positive lens ($f = 60$ cm) to the rear surface of the active crystal. Such geometry of the longitudinal pump provided a more uniform distribution of the inversion density of F_2^+-centers in the active medium with strong absorption.

We used a GaAs laser diode as a source of radiation being amplified, which emitted 85-ns pulses of linearly polarised light at the central frequency $\lambda_{max} = 900$ nm with the spectral width $\Delta\nu = 55$ cm^{-1}. The emission spectrum of this laser diode lies near the maximum of the luminescence spectrum of F_2^+-centres, the intensity of the luminescence band (of width $\Delta\nu \sim 2000$ cm^{-1}) being virtually constant within the emission range of the laser diode (Fig. 1). For this reason, we could expect the optimal (maximally possible) amplification without the distortion (or minimal distortion) of the shape of the emission spectrum of the laser diode.

The beam of radiation being amplified and the pump beam were made coincident over the entire length of the active crystal. The electronic delay line provided the timing of laser pulses and continuous tuning of the time delay between the pump pulse and a longer emission pulse from the laser diode. The amplified pulse and the pump pulse were separated behind a F_2^+:LiF crystal with the help of a dichroic mirror. IR laser pulses at the amplifier output were detected with an avalanche photodiode and a Tektronix TDS-360 digital oscilloscope with a pass band of 200 MHz. The emission spectra of the laser diode were measured before and after amplification with an MDR-3 monochromator with a spectral resolution of 2 cm^{-1}.

The ratio of the peak intensity I_p of the probe signal propagated through the amplifier during pumping to the intensity I_0 of the probe signal propagated through the amplifier in the absence of pumping (before or after pumping) determines the single-pass optical amplification of the

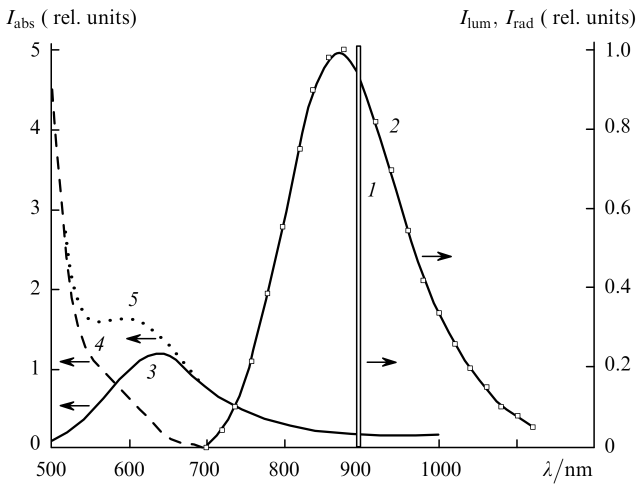

Figure 1. Emission spectrum I_{rad} of a laser diode (*1*), luminescence spectrum I_{lum} of F_2^+-centres in a LiF crystal (*2*), absorption spectra I_{abs} of F_2^+colour centres (*3*) and F_2 colour centres (*4*), and the sum of two latter spectra (*5*).

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system $G = I_p/I_0$. The maximum value G_{max}, obtained under the assumption that all the laser centres are excited and the amplification is not saturated, depends on the crystal length l as [8]

$$G_{max} = \exp(\sigma_e N_0 l) = \exp(\alpha_{th} l), \quad (1)$$

where σ_e is the emission cross section at the amplification wavelength; N_0 is the concentration of laser centres; α_{th} is the limiting theoretical value of gain.

The estimate of the limiting gain from the spectroscopic parameters of a F_2^+:LiF crystal [8] gives $\alpha_{th} = 2.2$ cm^{-1}. The experimental values of $G(l)$ achieved in F_2^+:LiF crystals for the pump energy 5 mJ are presented in Fig. 2. The solid straight line corresponds to the dependence $G_{max}(l) = \exp(\alpha_{th} l) = \exp(2.2\ \mathrm{cm}^{-1} l)$ for a F_2^+:LiF crystal.

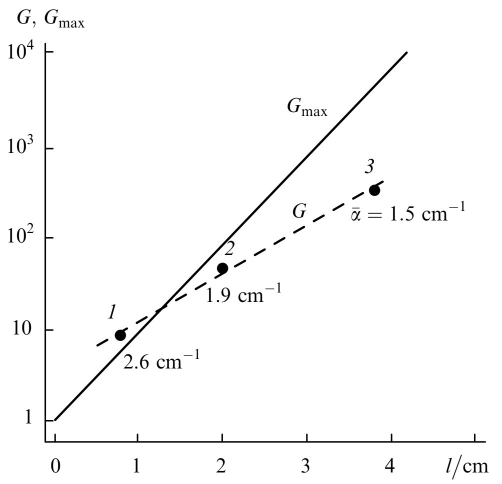

Figure 2. Maximum (solid straight line) and really achievable (dots) single-pass optical amplification of IR laser radiation ($\lambda_{max} = 900$ nm, $\Delta\nu = 55$ cm^{-1}) measured at the output of a F_2^+:LiF amplifier with an active crystal of length 0.8 (*1*), 2.0 (*2*), and 3.8 cm (*3*).

We managed to achieve the 300-fold single-pass optical gain in an amplifier with an active crystal of length 3.8 cm pumped by 5-mJ pulses. This means that the average gain $\bar{\alpha}$ defined in our paper [8] as $\bar{\alpha} = [\ln G(l)]/l$, was equal to (ln300)/3.8 = 1.5 cm^{-1}. The lower experimental value $\bar{\alpha} = 1.5$ cm^{-1} compared to the theoretical value $\alpha_{th} = 2.2$ cm^{-1} can be explained by the gain saturation, the insufficient overlap of the spectral ranges of pump radiation and radiation being amplified or by depletion of the pump energy along the crystal axis, which prevents excitation of all the active centres along the optical axis of the amplifier.

An increase in the pump energy above 5 mJ results in the appearance of intense superluminescence, which restricts the attainable inversion. The amplifier with a crystal of length 0.8 cm (at the same pump energy equal to 5 mJ) exhibits the 8-fold amplification, i.e., the average gain $\bar{\alpha} = 2.6$ cm^{-1} somewhat exceeds the theoretical value $\alpha_{th} = 2.2$ cm^{-1} for the initial concentration of stable F_2^+-centres.

This effect can be explained most reasonably by the photoinduced formation of additional F_2^+-centres in the amplification channel upon pumping, as was observed earlier in Ref. [9]. This is confirmed by a more intense green colour of the crystal, which is typical for F_2^+-centres, in the operating channel of the amplifier after pumping at 0.53 μm. Fig. 2 shows that the gain $G = 48$ achieved in a crystal of length 2.0 cm is close to its theoretical value (i.e., the gain $\bar{\alpha} = 1.9$ cm$^{-1} \approx \alpha_{th}$) for the initial concentration of active stable F_2^+-centres.

Because the closeness of $\bar{\alpha}$ to α_{th} can serve as the efficiency of using the operating length of the amplifier crystal, we can conclude that for the energy and the pump geometry used, F_2^+:LiF crystals of length less than 2 cm should be applied. Moreover, an increase in the pump energy, as note above, can give rise to superluminescence, which disrupts inversion. This suggests the use of a cascade F_2^+:LiF amplifier, which consists of several independently pumped active crystals of length ~ 2 cm. For example, the use of two such crystals will provide the increase in the input-pulse energy by more than three orders of magnitude.

Note that the pump source for a F_2^+:LiF amplifier used by us is one of the most popular but not the most optimal. It follows from [10] that lasers emitting at 590, 660, and even 690 nm can have advantages as pump sources for stable F_2^+-centres. The use of the second harmonic from a diode-pumped Nd:YAG laser ($\lambda = 1.064$ or 1.32 μm) or laser diodes emitting in the red spectral region for pumping the F_2^+:LiF amplifier allows one to built a compact amplifier with the high pulse repetition rate.

The important feature of amplifiers studied is their linearity at least in the nanojoule range of energies of amplified pulses (0.3 – 40 nJ). Another characteristic feature is the conservation of the spectrum of an emission pulse after its amplification. Thus, the emission spectra before and after amplification measured with a time resolution of 5 ns proved to be virtually identical.

The amplification spectrum of F_2^+-centres in a LiF crystal with the record-breaking broad half-width $\Delta\nu = 2200$ cm^{-1} is promising for the efficient amplification of picosecond and femtosecond optical pulses in the spectral range from 0.84 to 1.06 μm, which has not been studied earlier.

Thus, we have demonstrated the possibility of building a highly efficient linear broadband optical amplifier of nanosecond (and in sight, picosecond and femtosecond) IR radiation pulses based on LiF crystals with stabilised F_2^+ colour centres. The amplifier provides an increase in the pulse energy in a simple way, by changing it from the nanojoule range to micro- and millijoule ranges. By pumping F_2^+:LiF crystals of length 3.8 cm by 5-mJ second-harmonic pulses from a Nd:YAG laser, we achieved the 300-fold single-pass amplification of a 900-nm, 40-nJ pulse with the spectral half-width of 55 cm^{-1}.

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