Nonlinear optical characteristics of Cr^{4+}:YAG crystals

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Received 20.10.2022, revised 25.11.2022

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Исследованы нелинейно-оптические характеристики Cr^{4+}:YAG кристалла методикой Z-сканирования по схеме с открытой апертурой. В качестве пробного источника использовано излучение непрерывного лазера на длине волны 1030 нм мощностью до 400 мВт. При этом наблюдалось нелинейное поглощение лазерного излучения, которое связано с насыщением возбужденного состояния кристалла. Определена интенсивность насыщения и проведена оценка сечений поглощения в основном и возбужденном состояниях Cr^{4+}:YAG кристалла.

Ключевые слова: Cr^{4+}:YAG, Z-сканирование, интенсивность насыщения, сечение поглощения, обратное насыщающее поглощение.

The nonlinear optical characteristics of a Cr^{4+}:YAG crystal were studied using the standard Z-scan technique. Open aperture scheme of Z-scan was utilized to estimate normalized transmittance as a function of the sample position. As a probing laser source, a 1030 nm CW laser with a power of up to 400 mW was used. Nonlinear absorption of laser radiation was observed, which is associated with saturation of the excited state of Cr^{4+}:YAG. The saturation intensity for Cr^{4+}:YAG crystal is determined. Absorption cross sections of the ground and excited states of the Cr^{4+}:YAG were estimated.

Keywords: Cr^{4+}:YAG, Z-scan, saturation intensity, absorption cross-section, reverse saturable absorption.

DOI: https//doi.org/10.52304/.v24i4.384

I. Introduction

The Cr^{4+}:YAG crystal is one of the most popular saturable absorbers used in lasers to generate nanosecond pulse trains. This crystal is mainly used in neodymium and ytterbium lasers operating at a wavelength in the vicinity of 1 μm due to the significant absorption of the Cr^{4+}:YAG crystal in this wavelength range. Although a reasonably large number of lasers with a Cr^{4+}:YAG saturable absorber exist and several studies of the nonlinear optical characteristics of the latter have been carried out, reported results vary widely, raising the consistency issue. For example, the absorption cross section for the ground state varies from 3×10^{-19} to 7.5×10^{-18} cm^2 at a wavelength of 1064 nm [1-11]. In addition, even though Cr^{4+}:YAG is often used for Q-switching in Yb:YAG lasers [12-18], operating in particular at a wavelength of 1030 nm, the nonlinear optical characteristics of Cr^{4+}:YAG at 1030 nm are not studied. In this regard, this work studies the nonlinear optical characteristics of a Cr^{4+}:YAG crystal by Z-scan technique at 1030 nm in continuous wave (CW) regime with Yb:YAG laser with a power of up to 400 mW. For

this, we have created an experimental setup for conducting research using the Z-scan technique.

II. Experimental setup and the analytical procedure

The experimental setup is shown in Fig. 1. The sample is mounted on a moving table, controlled by a stepper motor along the z-axis. The length and step of movement are set by software compiled in the MATLAB/Simulink programming language (Fig. 2). Arduino Uno microcontroller was used to control the experimental setup, where the amplitude of the signal coming from the photodiode is measured and the corresponding control signals for the stepper motor are generated, as shown in Fig. 2.

The measuring system operates in interrupt mode. An internal signal source is used for a continuous laser to initiate an interrupt. In the case of a pulsed laser, the interrupt is initiated by an external signal from an additional photodiode installed at the laser output (the photodiode is not shown in Fig. 1).

When a trigger signal (interrupt signal) appears in the Arduino Uno microcontroller, the signal amplitude is read from the amplitude-to-digital converter and transmitted via the clipboard to the oscilloscope, where a data array is created for transmission to a regular MATLAB program for further processing and output of graphs.

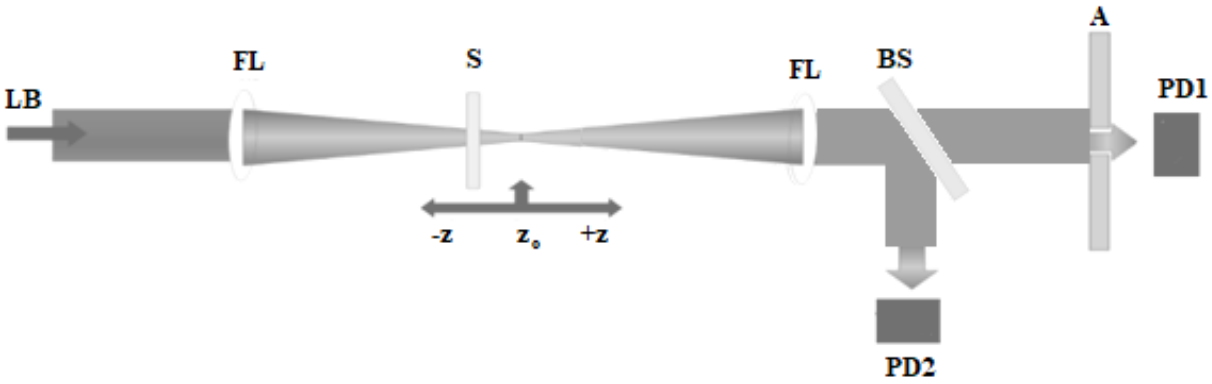


Figure 1. Scheme of the Z-scan experimental setup. LB – laser beam; FL – focusing lens; S – sample, BS – beam splitter; A – aperture; photodiodes PD1 and PD2 are designed for measurement in closed and open aperture modes, respectively.

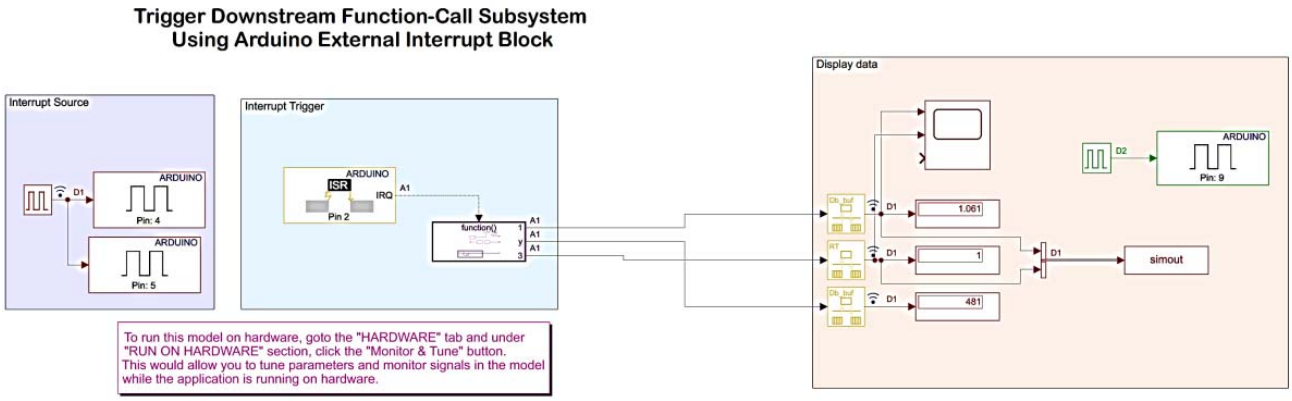


Figure 2. MATLAB/Simulink model to control the experiment.

The following procedures were used to determine the saturation intensity and estimate the absorption cross sections. The initial absorption coefficient α_0 was determined from the measurement of the initial transmission T_{in} at relatively low intensities

$$T_{in} = 1 - \exp(-\alpha_0 L) \tag{1}$$

by the expression

$$\alpha_0 = -\frac{\ln(1 - T_{in})}{L}. \tag{2}$$

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The Rayleigh range (assuming a Gaussian beam) is given by

$$z_0 = 0.5k\omega_0^2, \quad (3)$$

where $k = 2\pi/\lambda$ – wave number, ω_0 – laser beam radius at focus.

$$I(z) = \frac{I_0}{1+\left(z/z_0\right)^2}, \quad (4)$$

where $I_0 = P/\pi\omega_0^2$ – laser beam intensity at focus.
The ground state absorption coefficient was written as

$$\alpha = \frac{\alpha_0}{1+I(z)/I_{sat}}, \quad (5)$$

where $I_{sat} = h\nu/\sigma\tau$ – saturation intensity.
Writing the equation for the intensity in the form [19-21]

$$\frac{dI}{dl} = -\alpha I - \beta I^2, \quad (6)$$

we used the analytical solution [20, 21] for the normalized transmission in the following form

$$T(z) = \frac{\exp\left[-(\alpha-\alpha_0)L\right]}{1+\frac{\beta}{\alpha}I(z)\left(1-\exp(\alpha L)\right)}, \quad (7)$$

where the symbol β denotes the parameter that determines the absorption coefficient in the excited state (reverse saturable absorption); l in (6) varies within the values [0, L], where L is the thickness of the Cr^{4+}:YAG crystal.

III. Results and discussion

The experiments were carried out on the above-mentioned Z-scan setup with an open aperture using a CW laser at a wavelength of 1030 nm with a power up to 400 mW. Figure 3 shows the experimentally obtained normalized transmission at a laser power of 400 mW at values of z in the interval [–2, 2] for a Cr^{4+}:YAG sample, which also shows the theoretical dependence obtained using expression (7) for comparing and determining the parameters of the nonlinear optical characteristics of the considered sample.

The following figure (Fig. 4) shows the results for a power of 350 mW, with the values of z in the range of [–1, 1], measured in small steps to more accurately determine the marked parameters.

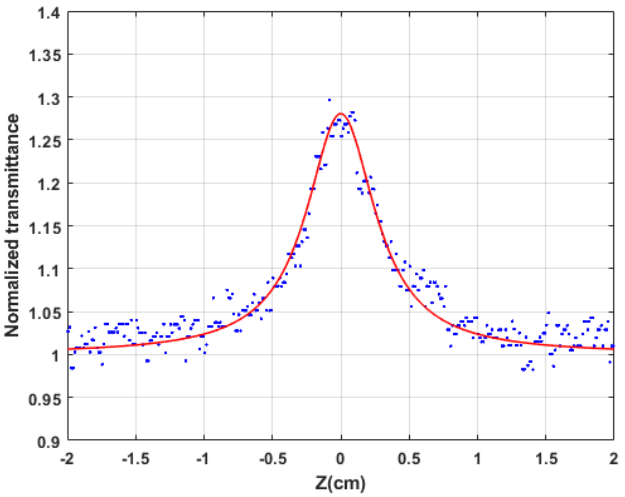


Figure 3. Normalized Cr^{4+}:YAG transmission at laser power of 400 mW. Dots – experiment, solid curve – calculation.

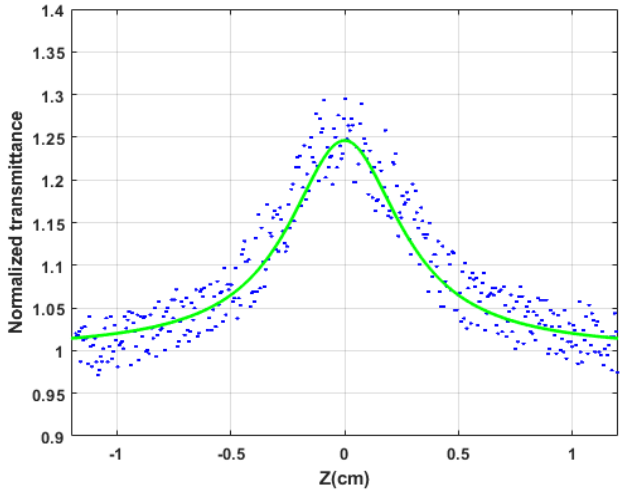


Figure 4. The central part of the normalized Cr^{4+}:YAG transmission measured at a laser power of 350 mW. Dots - experiment, solid curve – calculation.

Thus, from comparisons and based on the best agreement between theoretical and experimental results, the value for the saturation intensity I_{sat} ~ 34 кВт/см^2 is determined. For the absorption cross-section of ground state $\sigma_{GSU} \sim 1.8\times10^{-18}$ см^2, and the excited state absorption cross section $\sigma_{ESU} < 1.6\times10^{-19}$ см^2 were estimated.

IV. Conclusion

The nonlinear optical characteristics of the Cr^{4+}:YAG crystal were studied using the Z-scan technique with an open aperture regime at 1030 nm CW

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laser with a power of up to 400 mW. From the best agreement between the theoretical and experimental results, the values for the saturation intensity I_{sat} ~34 kW/cm^2, for the absorption cross-section of ground state σ_{GSU} ~1.8×10^{-18} cm^2, and the excited state absorption cross section σ_{ESU} <1.6×10^{-19} cm^2 were determined and estimated. The automated and software-assisted Z-scan setup can be used to conduct studies of the nonlinear optical characteristics of optical materials with both CW and pulsed lasers.

The results obtained will be further used in theoretical calculations and optimization of lasers with Q-switching based on Cr^{4+}:YAG at high repetition rates, where thermal effects are noticeable and limit the use of saturable absorbers

Acknowledgments. The studies have been carried out within the framework of the joint Uzbek-Belarusian project MRB-2021-543.

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Cr^{4+}:YAG кристалларининг ночизиқли оптик характеристикалари

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Очиқ диафрагма схемаси билан Z-сканерлаш техникасидан фойдаланган ҳолда Cr^{4+}:YAG кристаллининг ночизиқли оптик характеристикалари ўрганилди. Манба сифатида 400 мВт гача қувватга эга 1030 нм тўлқин узунлигидаги узлуксиз лазернинг нурланиши ишлатилди. Бунда лазер нурланишининг ночизиқли ютилиши кузатилди, бу кристаллнинг қўзғатилган ҳолатининг тўйинганлиги билан боғланган. Тўйинганлик интенсивлиги аниқланди ва Cr^{4+}:YAG кристаллининг асосий ва қўзғатилган ҳолатларидаги ютилиш кесимлари баҳоланди.

Калит сўзлар: Cr^{4+}:YAG, Z-сканерлаш, тўйинганлик интенсивлиги, ютилиш кесими, тескари тўйинганлик ютилиши.

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