Optica Applicata, Vol. XXXI, No. 3, 2001

The 1.3 μm Q-switched Nd:YAG laser

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The paper presents experimental results of investigation of flash lamp pumped Nd:YAG laser operated at wavelength $\lambda = 1.32$ μm. Thresholds and resonator losses have been determined. In the active Q-switched mode, output pulses up to 29 mJ energy and pulse width of 37 ns have been obtained. Moreover, an intracavity Raman laser producing 1.53 μm radiation when pumped by Nd:YAG laser operated at 1.32 μm is presented. Output Raman pulses up to 10 mJ energy have been obtained. Raman beam cleanup and 36% energy conversion efficiency have been observed.

1. Introduction

The Nd:YAG lasers technology is well known and fully developed [1]. Due to their properties, they are used in various industrial branches, medicine, science and in military applications. Unfortunately, radiation of the dominant transition at a wavelength of 1.064 μm can cause eyesight damage, which limits possible applications of these lasers. Especially it is dangerous when radiation is propagated in the open space, *e.g.*, using laser rangefinders during field training of the allied forces. Thus, recently, eye-safe lasers are extensively investigated and developed. Among others, the Nd:YAG lasers with Raman shift in spectral range over 1.5 μm were examined [2], [3].

This paper is aimed at investigation of eye-safe laser systems for transmitters of laser rangefinders with direct receiving. Special attention is paid to the possibility of giant pulse generation at 1.32 μm in Nd:YAG and subsequently, the Raman shifting of this radiation to spectral range over 1.5 μm.

It results from spectroscopic investigations of Nd^{3+}:YAG crystal that there are a few dozen transitions between the manifolds $^4F_{3/2} \rightarrow {}^4I_{9/2}, {}^4I_{11/2}, {}^4I_{13/2}$, [4] and laser emission should occur at most of them. It was verified experimentally due to the quenching of the strongest transition at the line 1.064 μm by placing in the resonator such dispersion elements as prisms [5], [6] or etalons [7], or using adequate selective mirrors [7]. The transition at the line 1.318 μm seems to be relatively attractive. Stimulated emission cross-section is several times smaller than the cross-section of basic transition but its value is 8.7×10^{-20} cm^2, so that significant energy per pulse can be obtained during Q-switched operation [4]. For giant pulses generated at this line, so-called frequency shifter can be applied [2], [3] that uses the phenomenon of stimulated Raman scattering. For this purpose, especially $Ba(NO_3)_2$ crystal is suitable, which ensures a value of Raman shift of 1047 cm^{-1}, which for line 1.32 μm gives radiation at a wavelength of 1.53 μm, fully eye-safe and well propagating in the atmosphere. Frequency conversion can be made either inside the resonator [8] or outside it [9], but in the former case with significantly higher efficiency.

2. Free running mode

The investigations on generation in Nd:YAG crystal at the 1.318 μm line were carried out with the system having dispersion resonator. Optical scheme of the resonator is shown in Fig. 1. Nd:YAG crystal in the form of a rod 4 mm in diameter and 85 mm long was excited with xenon flash lamp of arc length 75 mm and bore 4 mm in a diffusive water-cooled head of "closed-coupled" type. Rod faces were covered with AR layers for the wavelength of 1.064 μm.

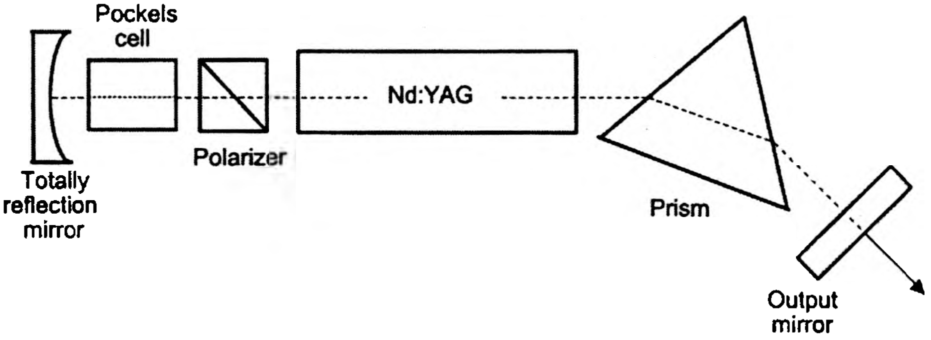

Fig. 1. Optical scheme of dispersion resonator.

The laser resonator has formed a totally reflecting concave mirror of a curvature radius 200 cm and a plane transmission output mirror. The length of the resonator was about 60 cm. As a dispersion element, an equilateral prism made of SF14 glass (length of prism base 60 mm and breaking angle 60°) was placed in the resonator, between the output mirror and the Nd:YAG rod. The output mirror was properly aligned in order to obtain laser generation at the wavelength of 1.318 μm.

The Pockels cell and Glan polarizer were placed in the resonator, in order to obtain active Q-switching. Both elements were covered with AR layers for radiation at a wavelength of 1.064 μm. The dispersion prism was at the same time a polarising element but, because of its location in a resonator and depolarisation effects in a rod, an additional polarizer should be inserted.

For experimental investigations, three various output mirrors were used, the percentage transmission of which are given the Table.

The measured output energies of free generation vs. the pump energy (*i.e.*, the electrical energy delivered to a flash lamp) for the output mirrors applied are shown in Figs. 2–4. The pump energy was changed within the range of 2–22 J while pumping pulse duration was 150 μs (measured at the level of 10%), and pulse repetition rate was 1 Hz.

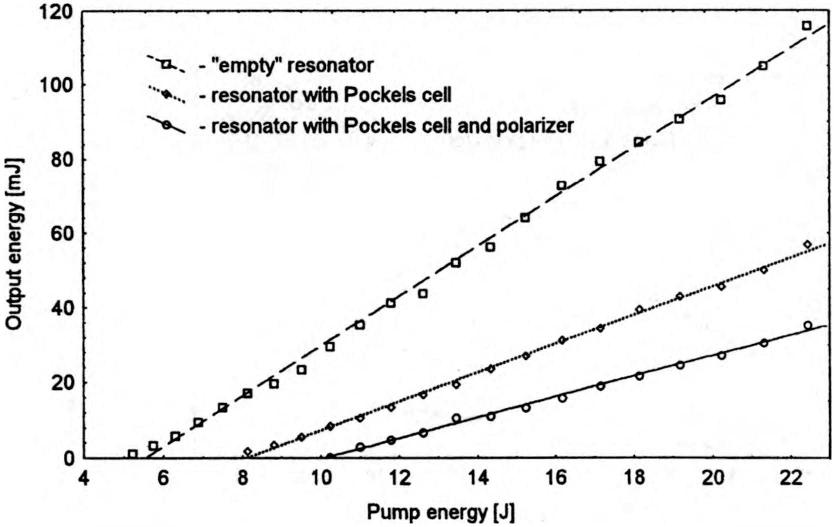

Fig. 2. Output energy of free running laser vs. pump energy; the output mirror transmission $T = 47\%$.

Experimental data shown in Fig. 2–4 were used for determination of the slope efficiency η and values of the threshold pump energies E_{th}, by means of the least square method and the relationship

$$E_{out} = \eta(E_p - E_{th}).$$

Next, the values obtained in this way and listed in the Table were used for determination of both the resonator losses L and the slope gain coefficient k [10].

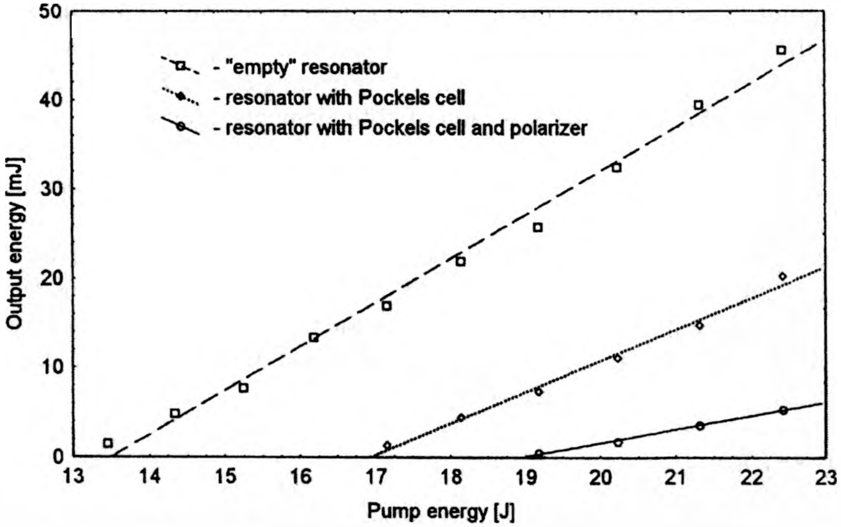

Fig. 3. Output energy of free running laser vs. pump energy; the output mirror transmission $T = 93\%$.

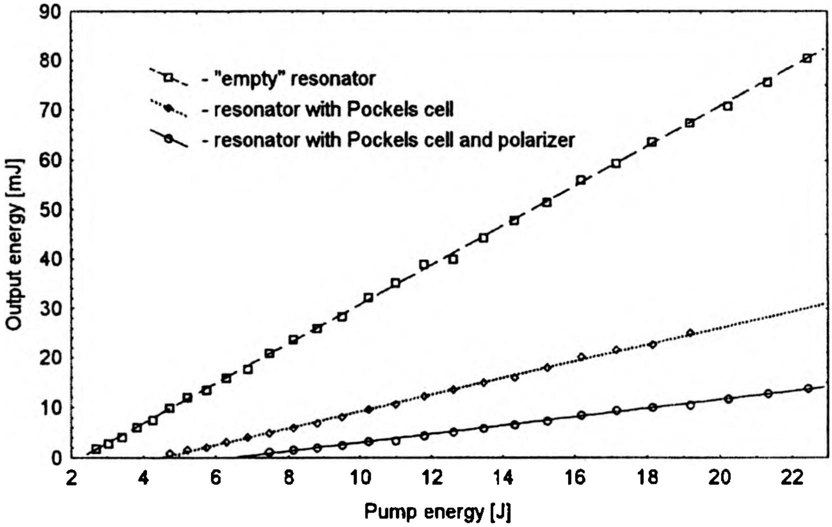

Fig. 4. Output energy of free running laser vs. pump energy; the output mirror transmission $T = 9\%$.

A commonly known Findlay–Clay method [11] was used and the equation applied was of the form

$$-\ln R_{\text{out}} = 2kE_{\text{th}} - L$$

where R_{out} is the reflectivity coefficient of the output mirror.

This procedure allowed us to obtain the resonator losses and the slope gain coefficient of the laser under investigation, which are presented in the Table.

It should be pointed out that the pulse energies for free generation and with the Pockels cell and the polarizer being removed, were significantly higher and reached the value of 115 mJ. Dissipation losses determined by means of the Findlay–Clay method were then 0.035 cm^{-1}, but after insertion of both elements, they increased up to 0.089 cm^{-1}. Thus, elements of a Q-switch gave additional significant resonator losses and caused the energies obtained to decrease by 70%, and generation threshold to increase from 5.5 J to about 10 J.

The measurements of transmission of a Pockels cell were made by means of a spectrophotometer and the results are shown in Fig. 5. For the line 1.318 μm, the transmission value was about 83% (0.025 cm^{-1}). Also the transmission of a cell in a resonator was determined by the measurements of threshold energies of free generation. Its transmission is expressed as [10]

$$T_{\text{KP}} = \exp(-k\Delta E),$$

where k is the slope gain coefficient, and ΔE is the difference of the threshold energies of a pump in a resonator with and without a Pockels cell. The transmission of a Pockels

T a b l e Determined parameters of the investigated laser.

Resonator setup	Output mirror transmission T [%]	Slope efficiency η [mJ/J]	Threshold E_{th} [J]	Resonator losses L	Slope gain coefficient k [1/J]
"Empty" resonator	47.1	6.67	5.55	0.526 (0.035 cm^{-1})	0.116
	92.9	4.91	13.50		
	9.2	3.99	2.29		
Resonator with Pockels cell	47.1	3.84	8.08	0.926 (0.062 cm^{-1})	0.104
	92.9.	3.51	16.92		
	9.2	1.68	4.47		
Resonator with Pockels cell and polarizer	47.1	2.75	10.12	1.349 (0.089 cm^{-1})	0.104
	92.9	1.50	18.95		
	9.2	0.85	6.49		

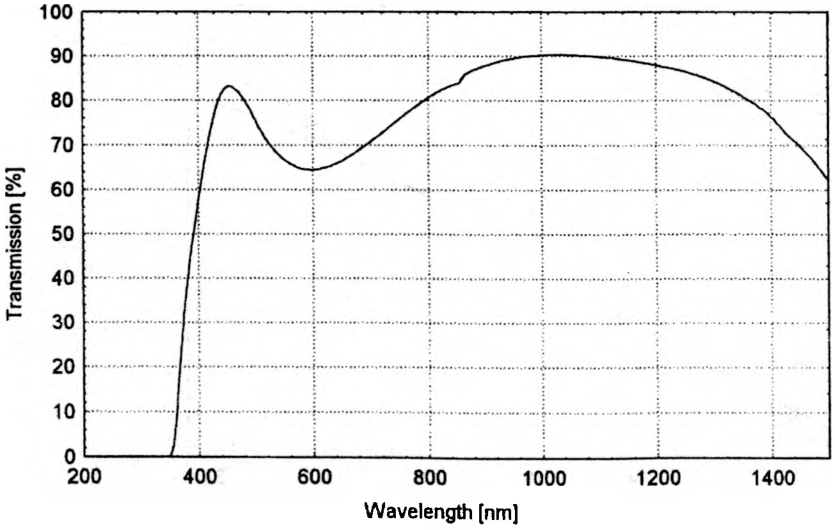

Fig. 5. Spectral characteristics of the KDDP Pockels cell transmission.

cell was about 80% (0.030 cm^{-1}). It can also be calculated from the following relationship:

$$T_{\text{KP}} = \exp\left(-\frac{\Delta L}{2}\right)$$

where ΔL is the difference of the resonator losses, with and without a Pockels cell. From the data listed in the Table, the transmission of a Pockels cell obtained in this way was about 82% (0.027 cm^{-1}).

A significant discrepancy between the first and the second values can result from an error in determination of a slope gain coefficient which was defined on the basis of measurements for three transmissions of the output mirror, with no possibility of introducing a suitable correction factor [10]. However, all of the values above prove that the same Pockels cell with KDDP crystal does not cause significant resonator losses and it can be successfully used as a Q-switch at the line 1.318 μm in the Nd:YAG laser.

3. Active Q-switched mode

Energy of the generated giant pulses vs. the pump energy, for various transmissions of the output mirrors, is given in Fig. 6 and Fig. 7. For the mirror transmission of 47%, the values of energy obtained were up to 29 mJ and pulse duration of about 37 ns FWHM, which gives a peak power of over 0.7 MW. Using two other output mirrors of 93% and 9% transmissions, the pulses of significantly lower energies of 6.5 mJ and 7.75 mJ, respectively, were obtained.

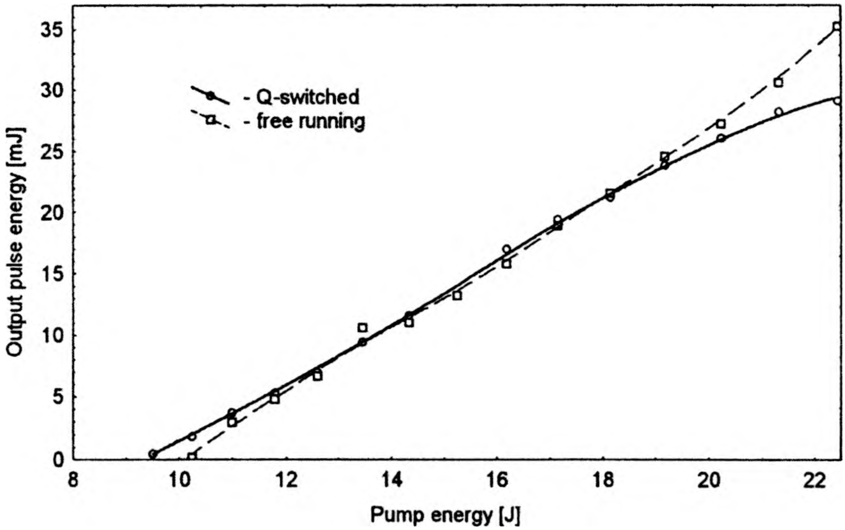

Fig. 6. Pulse energy vs. pump energy of the Q-switched laser; the output mirror transmission $T = 47\%$.

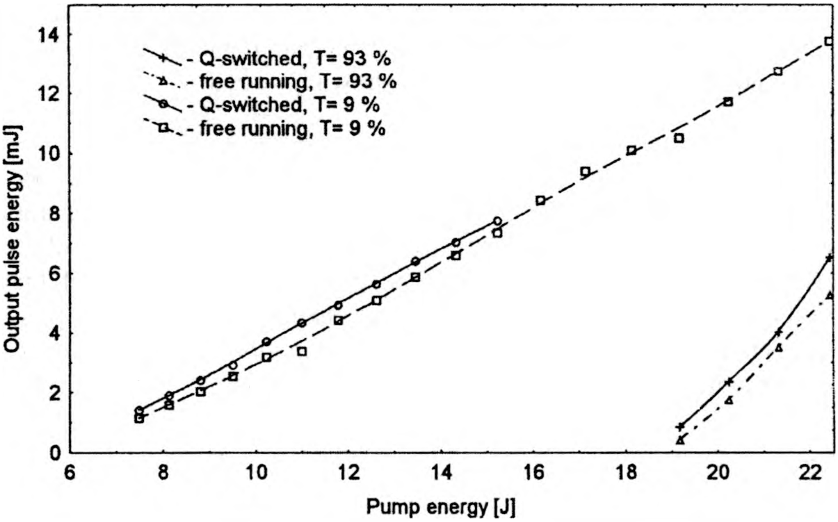

Fig. 7. Pulse energy vs. pump energy of the Q-switched laser; the output mirror transmission T = 93% and T = 9%.

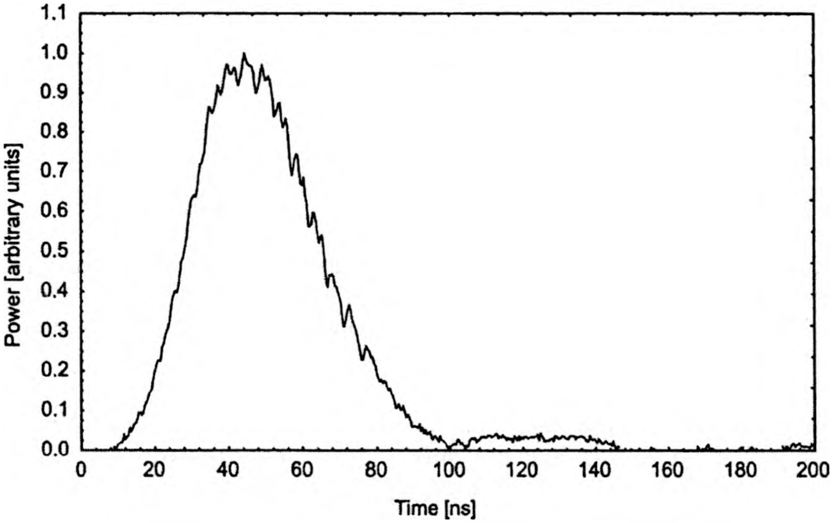

Fig. 8. Oscillogram of a laser giant pulse; pump energy E_p = 19.2 J, pulsewidth τ_i = 37 ns, transmission of the output mirror T = 47%.

The optimising calculation performed for energetic matching showed that mirror transmission of 47% is within the range of the most optimal transmissions of the pumping energies used.

For the output mirror of 9% transmission, the measurements were made for the pump energy lower than 15 J because for such extremely low transmission and hence high power density in a resonator, its elements can be damaged. The power density threshold value of mirror damage was found to be for the pump energy of 15 J. The oscillogram of a temporal profile of a giant pulse is shown in Fig. 8.

4. Raman shifting

Optical system, the scheme of which is shown in Fig. 9, consists of two resonators coupled by equilateral dispersion prism. "Basic branch", formed by the totally reflecting mirrors Z1 and Z2, includes a Nd:YAG rod, polarizer, and Pockels cell that operate as active Q-switch. The pumping energy was changed within the range of 2–22 J. It enabled us to obtain the 27 mJ pulse energy of radiation at a wavelength of 1.32 μm, while minimum pulse duration was about 41 ns FWHM.

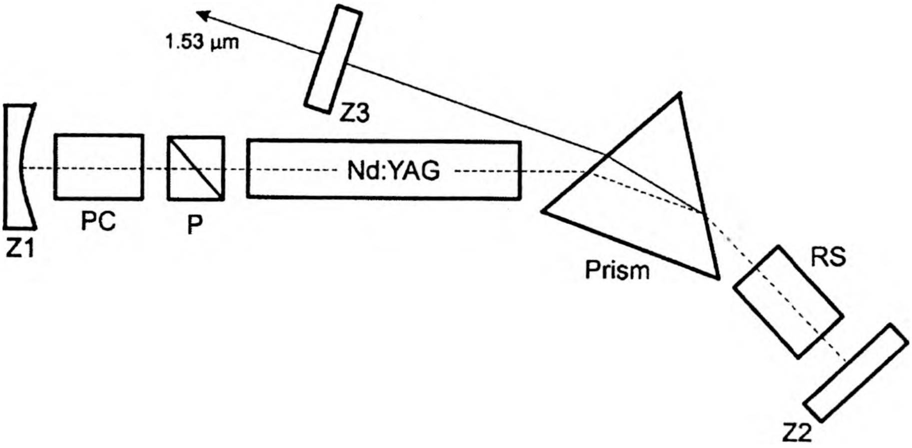

Fig. 9. Optical scheme of Nd:YAG resonator with Raman frequency shifter, PC – the Pockels cell, P – the Glan polarizer, RS – the Raman shifter, Z1 – the mirror of ROC = 2 m, T = 0% at 1.32 μm; Z2 – is the mirror of ROC = 2 m, T = 0% at (1.32 μm and 1.53 μm); Z3 – the plane output mirror, T = 43% at 1.53 μm.

"Raman branch" of a resonator included the totally reflecting mirror Z2 for wavelengths 1.53 μm and 1.32 μm and the mirror Z3 of 43% transmission for a wavelength 1.53 μm. A Raman shifter in the form of a rectangular prism of dimensions 7×7×60 mm was made of a $Ba(NO_3)_2$ crystal and was situated inside a resonator between the mirror Z2 and the dispersion prism. The crystal faces, not covered with antireflection layers, were oriented perpendicularly to the resonator axis.

For maximal energy of the basic radiation pulse of 27 mJ, the system generated 9.8 mJ per pulse of the Raman shifted radiation. Assuming the conversion efficiency as a ratio of these energies, its value was 36%. No saturation effects were observed, so higher efficiencies can be expected for higher energies of the basic radiation. Limiting efficiency of the frequency conversion 1.32 μm → 1.53 μm in $Ba(NO_3)_2$ crystal is on the level of 85% [9].

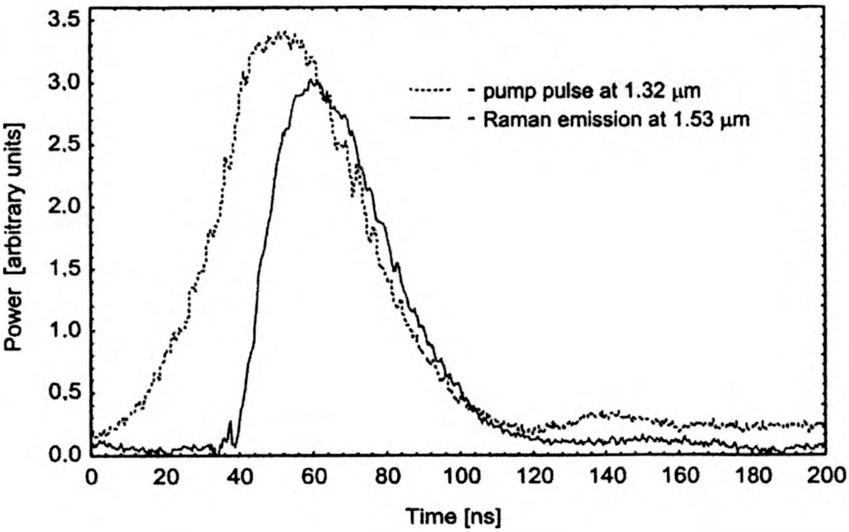

Fig. 10. Oscillogram of laser giant pulse at the line 1.318 μm and Raman emission at the wavelength 1.53 μm.

An example oscillogram of the temporal profile of a basic radiation pulse and Raman emission is shown in Fig. 10. Radiation at 1.32 μm was registered by means of a germanium photodiode, situated just behind the mirror Z1, and radiation at 1.53 μm was registered through the attenuation filters at the system output. Slowly increasing course on the oscillogram is a pulse of basic radiation and the delayed and rapidly increasing course is a signal of the first Stockes' line of 1.53 μm. Clearly seen and well determined is also the threshold of stimulated emission occurrence.

5. Conclusions

It follows from experimental investigations that free generation in the Nd:YAG laser at a wavelength λ = 1.318 μm can be easily obtained and quenching of the strongest transition at a wavelength λ = 1.064 μm is not a difficult problem. The system under investigation does not include the elements covered with suitable antireflection layers, or with the fronts at Brewster's angle that minimise the resonator losses. It is also related to the prism playing the role of a dispersion element.

A stable giant pulse generation at the line λ = 1.318 μm in actively Q-switched Nd:YAG laser is attractive and easy to obtain. Despite a relatively small stimulated emission cross-section, sufficient energy was obtained at this line, *i.e.*, about 29 mJ during a giant pulse of about 37 ns. It has also turned out that application of the Pockels cells, based on KDDP crystals, is reasonable despite the commonly known opinion on their low transmission within the range of 1.3–1.4 μm and usefulness of the application of $LiNbO_3$ crystals [6], [12]. Application of a solid state (crystals) Raman shifter is safe, convenient, less complicated and does not require high-pressure pots, filled with methane, hydrogen, or deuterium [2], [3]. The obtained power exceeding 300 kW per laser pulse at 1.53 μm enables us, for example, in an eye-safe laser range-finder, to fulfil the previously described and required technical-tactical assumptions.

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Received December 4, 2000
in reviced form January 30, 2001