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INFLUENCE OF LASER EXCITATION ON THE SPATIAL CHARACTERISTICS OF THE RADIATION

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The paper examines the impact of the excitation mode of solid-state laser on the spatial distribution of the radiation intensity. It is shown that the process of the active medium non-equilibrium state creating can stimulate collective interaction of active sites, which effects on the properties of the output radiation. The data indicates a decrease of the divergence and more uniform intensity distribution of laser radiation field, which is generated under the complex periodic excitation of the active medium. Effects obtained allow empowering of remote sensing systems. The treatment quality can be significantly increased using such effects for material processing.

INTRODUCTION

A coherent laser radiation is increasingly used in various fields of science and technology. The laser sensing systems use solid-state lasers, which always get in the single-pulse mode, very high values of power. However, the properties of coherent radiation significantly depend on the method of excitation and relaxation of the active centers of lasers. Properties of the generated radiation are significantly affected by the interaction of the excited active centers. This is especially noticeable in systems with an ordered arrangement of the particles, which corresponds to the crystalline active media, examples of which are ruby and yttrium-aluminum garnet. These materials are most commonly used for the construction of radiation sources of remote sensing systems and laser radar systems. Therefore, any improvement of parameters of these lasers is an actual problem.

Relaxation characteristics of individual atoms and particle systems are significantly different. It is shown in [1]. If at the initial moment, the system of particles was in inverted state, coordinated oscillations of the particles may contribute to the formation of a cooperative process. This phenomenon is due to the mutual influence of excited particles. Correlated emission of excited particles was called superradiance [2]. It has a higher intensity than conventional laser radiation and its divergence is close to the diffraction limit.

Studies have confirmed the ability to set correlated states by intense periodic exposure. Such effects can be created by the light pulse pumping of the certain shape. In general, the generated radiation is the sum of stimulated emission of radiation and the collective radiation. Collective radiation due the radiation of particles, which are in correlated states. Effect of collective radiation can be detected by a decrease in the angle of divergence of radiation [3] in comparison with the traditional generation of excitation.

STATEMENT OF THE PROBLEM

This paper analyzes the method of excitation of the solid-state pulsed laser, which allows exciting collective interactions in the active medium and providing spatial redistribution of laser output radiation intensity. In result it ensures a more uniform profile.

ANALYSIS OF RELAXATION PROCESSES OF INVERTED SYSTEMS

The relaxation process of the active medium can occur through several channels. They are ordinary luminescence, amplified luminescence, and superradiance. Luminescence and amplified luminescence have no threshold and characterize the relaxation of the active centers of the laser medium from the beginning of the excitation process. Temporal characteristics of luminescence correspond to the standard values. Contribution to amplified luminescence increases with the number of excited particles. Upon reaching the inverted state of the active medium gain becomes large enough and this kind of relaxation becomes dominant. The higher inversion level of active medium causes the faster decay of the excited state [4].

Analysis of the results showed that there are significant changes in relaxation characteristics at a large excess over a threshold. In this case, the relaxation time of the excited state is reduced by more than an order of magnitude compared to conventional values.

Fig. 1 shows the dependence of the energy generation from the delay factor of Q-switch of the resonator. Speed of falling energy generation allows us to estimate the relaxation characteristics of the excited active medium.
The experimental data correlate well to the theoretical estimates, which are given in [5, 6]. The data obtained are different from the tabular information because the table data were obtained by studying of the luminescence intensity at low excitation levels of the laser medium. In this case, the effect of the luminescence amplification was substantially absented. Changes of relaxation processes acquire particular significance in single-pulse mode generation. In this generation mode gain reaches high of the upper energy states occurs by radiative or nonradiative transitions with characteristic times that are inherent for single atoms. Lifetime of the excited state characterizes the duration of luminescence. This approach does not account for the interaction of the active particles and the radiation field.

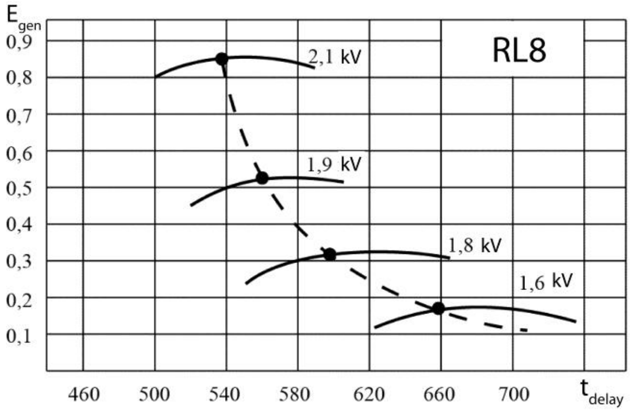


Fig. 1. The dependence of the output energy of a single pulse from the ruby crystal (RL8) shutter delay time

Since all the relaxation processes in the laser active medium occur in the presence of an intense field, these interactions must be considered. Moreover, it is possible to affect by fields on the relaxation processes between excited particles, and involve them in the correlated state. Thus, we can influence the parameters of the generated radiation.

The radiation occurs when the thermodynamic equilibrium in the system of active centers violates. It starts at the slightest excitement. Amplified luminescence occurs when the gain of the active medium becomes greater than 1. It corresponds to the excess of the threshold conditions and amplified luminescence becomes the dominant process if the Q-factor of the laser cavity is small. The luminescence undergoes amplification in 10^3 and even more times at high amplification [3].

Laser generation occurs when losses in the resonator are compensated (threshold condition):

$$\exp(2lk_{\Pi} - \sigma) R_1 R_2 \geq 1, \tag{1}$$

or

$$\delta = \left(N_2 - \frac{g_B}{g_H} N_1 \right)_{\Pi} = \frac{c\Delta\nu_{\Pi}\left(\sigma + \ln\frac{1}{R_1R_2}\right)}{gnh\nu_r B_r 2l}, \tag{2}$$

where δ is threshold population inversion; R_1 and R_2 are reflection coefficients of the resonator mirrors; l is length of the rod; σ represents losses in the resonator at a double pass, and it is associated with a value of the resonator Q as:

$$Q = \frac{\nu_r}{\Delta\nu_p} = \frac{4\pi nl\nu_r}{c\left(\sigma + \ln\frac{1}{R_1R_2}\right)}. \tag{3}$$

At the same time the correlation of radiating dipoles happens in the collective excitation of the active centers. The system tends to a state in which the individual particles of radiation correlate each other when a threshold conditions are made. Moreover, the correlation is caused by spontaneous emission. The system tends to self-organization if the critical number of particles is in correlate state. It was shown in [7]. For the active centers system in correlated state the radiation has the nature of collective radiation. It should be noted that the length of the system volume that is occupied by the particles in correlated state of dipoles, is limited to the interaction, the magnitude of which is comparable with the wavelength of the radiation. Thus, there is a thread-like structure of the radiation of correlated particles. These findings are consistent with the conclusions [9]. Formations of these filaments are chaotically. Mode with the agreed radiation of these filaments can be considered as the most favorable mode of radiation. Such active medium state could lead to the formation of macrodipoles [8] and to acquisition of new properties of radiation: lesser divergence of radiation and greater intensity.

Implementation of such a regime is the subject of this study.

RESULTS

Research results indicate the possibility of coherent states formation by external impact. This effect is realized through the optical pumping channel. Radiation pump pulse is intensity modulated with a period of about 30 ms. It corresponds to the velocity of elastic vibrations propagation in the crystal lattice. The observed effect can be explained by magnetic-dipole interaction of the active centers. Precession phases of dipole moments are synchronized via a transverse field [8]. After the delay time t_0 system spontaneously goes into superradiative coherent state with phased dipoles.

$$t_0 \approx \frac{T_1 \ln(N\lambda^2 / S)}{N\lambda^2 / 2S}, \tag{4}$$

T_1 is the longitudinal relaxation time (lifetime of the excited state); λ is the wave length of radiation; N is the number of particles in the excited state; S is the cross-sectional area of the sample

A number of papers [10, 11] pointed out that the waveform of the collective radiation system becomes deformed. It oscillates with frequency that is associated to active centers relaxation characteristics.

$$\Omega = \left[\frac{2R_0}{T_0^2} - \frac{1}{4}\left(\frac{1}{\tau} - \frac{1}{T_2}\right)^2 \right]^{\frac{1}{2}}, \tag{5}$$

where $R_0 = -N\left(1 - \frac{2}{\mu L}\right)$; $\mu = \frac{\lambda^2}{4\pi}\frac{N}{V}\frac{T_2}{T_1}$;

T_2 is the phase relaxation time; $\tau = \frac{L}{c}$;

It can be expected an increase in the radiation intensity due to the increasing of collectivized particles number during perturbation of the active medium by signal with a period that multiplies the value of $\frac{1}{\Omega}$. The part of collective radiation increases in this case. If we consider that the collective radiation divergence is smaller than the usual stimulated emission

$$\Omega = \frac{\pi D^2}{16 l^2} \text{ [3]}, \qquad (6)$$

the overall picture of the generated radiation distribution must change. Laser output directivity pattern becomes narrower.

Submitted considerations were taken into account when the experiment was carried out. Ruby and garnet lasers were used as a test object. The diameter of active elements was 8 mm and their length was 100 mm. Pumping was did by flash lamps with a complex current pulse, which is shown in Fig. 2.

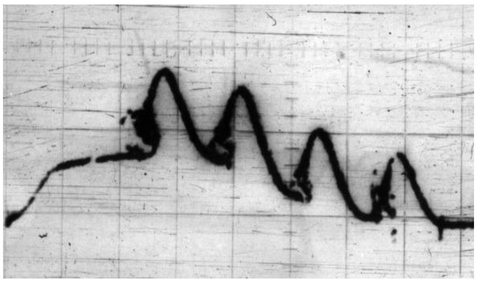


Fig. 2. Oscillogram of the pumping current pulse. Graduation is 20 microseconds

As seen from the oscillogram, prior extensive drive pulse results the active medium inverted state, which is corresponded to the threshold. Thereafter, the medium was exposed by low-intensity pumping at certain intervals. Change in the cavity Q-factor was provided by electrooptic shutter. It was switched on after the last spike after a time equal to the spike-repetition interval.

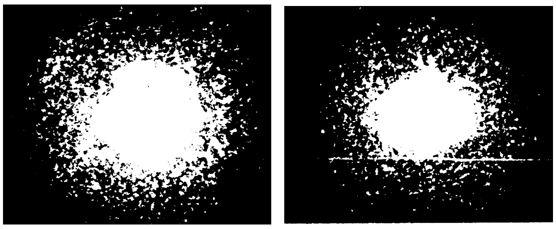
Output radiation changes its intensity and divergence at spike-repetition interval of about 30 ms. Figure 3 shows prints of the radiation intensity at the “smooth” pumping and “complex” pumping.

Prints were obtained on photosensitive film by the focal spot using long-focus lenses. Quantitative assessment of the intensity level showed that the divergence of the half-width decreases 1.4 times. It indicates an increase in the proportion of collective radiation upon complex pump pulse excitation of the active medium.

Estimation of the intensity distribution over the cross section of the active element showed a more uniform distribution (Fig. 4).

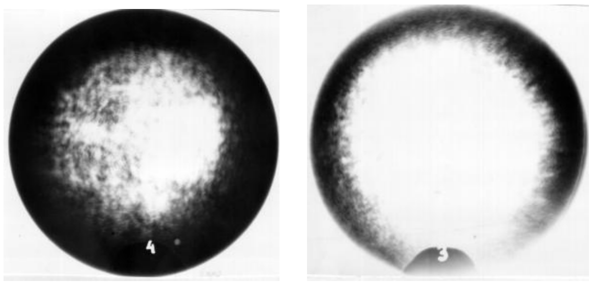
It should be noted that the collective emission is due to the in-phase (i.e. correlated) state of radiating dipoles. The possibility of such radiation in extended systems confirms that the relaxation characteristics of the active sites vary considerably, especially at the quite strong interference of the particles. In this case, the phase correlation is supported by an external periodic force, which is a multiple of the collective radiation oscillation period.

Presented property of radiation at “resonance” pumping was successfully used for the surface treatment of materials. Balancing of radiation intensity can improve the treated surface quality during the processing as it’s shown in Fig. 5. Uneven intensity distribution leads to the formation of cavities and substantially alters the mechanical properties of the sites where the maximum emission intensity was reached. It should be noted that the distribution is not repeated from pulse to pulse. Examples of cavities are shown in Fig. 6.



a *b*

Fig. 3. Distribution of the laser radiation field in the focal plane of the long-focus lens.
Scale is 100: 1 a – “smooth” pumping:
b – “resonance” pumping



a *b*

Fig. 4. The cross section intensity distribution of the active element at the “smooth” pumping (a) and “complex” pumping (b) for $E_{pump} \cong 720$ J

Even filling of the laser beam can be obtained by using of the resonant excitation pumping mode (see Fig. 3,b).

Introduced laser mode allows getting of modified areas without mechanical disturbances. These surface areas are characterized by good service properties (Fig. 7).

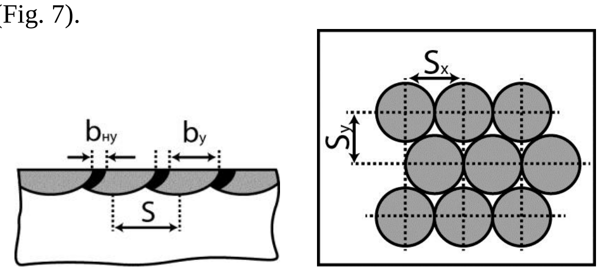
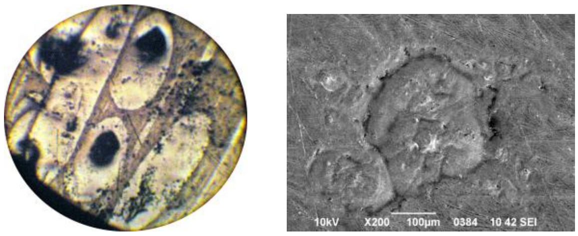


Fig. 5. Diagram of the surface treatment of parts in the pulse regime



а *б*

Fig. 6. Formation of cavities at high non-uniformity intensity distribution over the cross section of the laser beam (a). A scanning electron microscope picture of the cavity (b)

Fig. 7. Treated areas with uniform intensity distribution of the laser radiation

Treated areas are a lighter shade and they cannot be etched. Study of the treated areas microhardness showed an increase in the hardness of 2.5 times compared to the untreated surface. Corrosiveness of treated surface decreased 1.5 times.

CONCLUSIONS

1. Increased percentage of collective radiation during excitation of the active medium by "complex" pump pulse is confirmed by the contraction of the generated radiation pattern.
2. Periodical intense effect on the inverted system may lead to the correlated state of emitting dipole active centers. It makes changes to the usual interpretation of the phase relaxation parameters.
3. Research results indicate a significant decrease of the relaxation time of the excited state at high threshold exceeding. It is caused by the amplification of spontaneous emission at high medium gain.
4. The results were obtained in the optical range of the electromagnetic radiation. They suggest the possibility of the collective radiation obtaining at a more short-wave range, because the control action is several orders below the generation rate.
5. Using this active medium excitation mode in laser systems for material processing improves the surface quality and service performance of parts.
6. Application of presented effect in remote sensing systems will increase both the range and accuracy of angular coordinates determining of distant objects.

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ВЛИЯНИЕ РЕЖИМА ВОЗБУЖДЕНИЯ ЛАЗЕРА НА ПРОСТРАНСТВЕННЫЕ ХАРАКТЕРИСТИКИ ИЗЛУЧЕНИЯ

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Исследуется влияние режима возбуждения твердотельного лазера на пространственное распределение интенсивности излучения. Показано, что способ создания неравновесного состояния активной среды может стимулировать коллективное взаимодействие активных центров, которое влияет на свойства выходного излучения. Приводятся данные, указывающие на уменьшение расходимости генерируемого излучения и более равномерное распределение интенсивности в поле излучения лазера при сложнопериодическом возбуждении активной среды. Полученные эффекты дают возможность увеличить дальность систем дистанционного зондирования. При использовании подобного возбуждения улучшается качество обработки материалов.

ВПЛИВ РЕЖИМУ ЗБУДЖЕННЯ ЛАЗЕРА НА ПРОСТОРОВІ ХАРАКТЕРИСТИКИ ВИПРОМІНЮВАННЯ

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Досліджується вплив режиму збудження твердотільного лазера на просторовий розподіл інтенсивності випромінювання. Показано, що спосіб створення нерівноважного стану активного середовища може стимулювати колективна взаємодія активних центрів, що впливає на властивості вихідного випромінювання. Наводяться дані, що вказують на зменшення розходження генерованого випромінювання і більш рівномірного розподілу інтенсивності в полі випромінювання лазера при складноперіодичному збудженні активного середовища. Отримані ефекти дають можливість збільшити дальність систем дистанційного зондування. При використанні подібного збудження поліпшується якість обробки матеріалів.