NARROW-BAND HIGH-REPETITION-RATE NEAR-IR SOURCES WITH ONLINE CONTROL OF THE RADIATION PARAMETERS

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The results of investigations of the lasing characteristics of high-repetition-rate lasers based on Al_2O_3: Ti^{3+} crystals are presented. A high-repetition-rate (up to 50 kHz) narrow-band laser, tunable in the ranges 680–960 nm and 350–460 nm with regulation of the spectral, temporal, and energy characteristics, is described.

The solution of a number of problems in atmospheric sounding and ranging requires the development of high-repetition-rate tunable solid-state lasers with a pulse repetition frequency of up to 100 kHz. Existing designs of high-repetition-rate tunable lasers based on dyes and crystals with color centers (CCs) are not widely used in practice owing to poor operating characteristics of the active media employed. Among other active media based on activated crystals, the crystals Al_2O_3: Ti^{3+}, owing both to their optical-physical and lasing characteristics as well as significant success achieved in the design and assimilation of potential pumping sources (copper-vapor lasers and industrial neodymium lasers with frequency doubling and acoustooptical Q -switching), are currently of greatest interest.[1,2]

The first results on the realization of the high-repetition-rate regime of lasing of Al_2O_3: Ti^{3+}-based lasers using an LTI-702 industrial laser with an average power of up to 2.6 W and a pulse repetition frequency of up to 25 kHz, have already demonstrated that these active media are highly reliable.[3] The operating lifetime of the active media exceeds 10^{11} pulses. Reports of the achievement of this operating regime using copper-vapor lasers as the pump appeared somewhat later.[4] The use of the indicated laser pump sources has its own peculiarities, associated with the small diameter of the waists of the active region ($\leq$ 100 μm) with which the energy densities of the exciting radiation necessary for efficient lasing were realized, and this imposed a number of requirements on the structure and parameters of the resonators employed.

In this paper we present the results of investigations of the lasing characteristics of high-repetition-rate tunable lasers based on Al_2O_3: Ti^{3+}. These studies were directed toward the development of narrow-band tunable sources with online control of the parameters. The main series of investigations was performed using for the pump source an LTI-702 industrial neodymium laser with an average power of up to 4 W in a single-mode regime, pulse width exceeding 100 ns, and pulse repetition frequency of up to 50 kHz(with an external generator). Al_2O_3: Ti^{3+} crystals grown by Verneuil's and Czochralski's methods with an activator concentration of up to 0.2 wt.% and 6–10 mm long were employed in the experiments.

CHARACTERISTICS OF THE LASING OF CHERENTLY PUMPED Al_2O_3: Ti^{3+}-LASERS

The use of lasers for pumping has certain peculiarities associated with the fact that the geometry of the resonator and the distribution of the inversion in the active volume depend on the intensity of the exciting radiation. These dependences are caused by absorption processes and phase disturbances in the active medium under the action of the pump radiation. A characteristic feature of the dynamics of the phase distortions is their relatively long decay time (~ 20–80 μs for the thermally induced distortions and ~ 4 μs for the populations), which exceeds by at least an order of magnitude the durations of the pumping and lasing processes. The degree to which the phase distortions affect the geometry of the active channel and the resonator is determined by, aside from the pump-energy density, the concentration of the activator and becomes significant for Ti^{3+} concentrations exceeding 0.1 wt.% and pump dwensities exceeding 1 J/cm^2. Experiments on probing the active volume in Al_2O_3: Ti^{3+}-crystals indicate that the thermally-induced distortions predominate over inversion both in the pump process and in the lasing processes.

Because of the indicated processes as well as because of the high diffraction losses for waists of the active channel less than 0.1 mm and with pump energies less than 1.0 mJ iit is best to employ resonator designs analogous to those employed in tunable continuous-wave lasers, in particular, two- and three-mirror resonators with an intraresonator telescope, one component of which is employed for focusing the pumping radiation. The second element of the telescope could be a lens or a spherical mirror, whose purpose is to collimate the radiation generated in the selective arm of the resonator. The focal length of this collimating element is chosen to be equal to the radius of curvature of the wavefront of the beam, which is determined by the transverse size of the active region in the Al_2O_3: Ti^{3+}-crystal; this makes it possible to obtain in the plane of the second element of the telescope a waist with the required size, which corresponds to a beam with a fixed divergence. It should be noted that the small sizes of the waists of the active region in Al_2O_3: Ti^{3+}-crystals (less than 100 μm) make it possible to empoy optical components with small focal lengths (up to 0.3 m). A specific design of one variant of such a resonator is examined below.

The use of such quasiconcentric resonators with an intraresonator telescope makes it possible, in addition to reducing the diffraction losses and increasing the stability with respect to dynamic phase distortions, to reduce substantially the radiant load on the resonator mirrors and the selecting elements, to narrow significantly the spectral width of the lasing line in the selective resonator (by almost an order of magnitude compared with the plane-parallel resonator), to increase the stability with respect to misalignment of the mirrors (up to 12 mrad), to reduce the divergence of the radiation to less than 0.3 mrad, to increase significantly the width of the lasing spectrum in the nonselective resonator (up to 60–70 nm) to vary over wide limits (up to 3–4 m and more) the resonator length without appreciably reducing the lasing efficiency as well as to realize a series of lasing regimes – *Q*-switching and mode-locking.

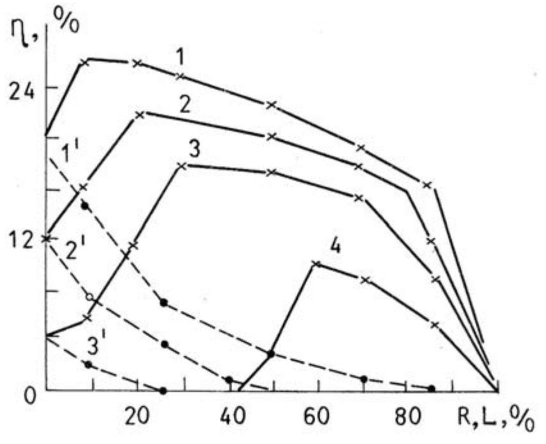

FIG. 1. The lasing efficiency versus the effective (curves 1–4) and parasitic (curves 1′–3′) losses for different pump energy densities (J/cm2): 2.0 (1, 1′), 1.8 (2, 2′), 1.6 (3, 3′), and 1.2 (4).

Figure 1 shows for different pump-energy densities the characteristic dependences of the conversion efficiency η on the reflection coefficient *R* of the output mirror of a resonator with a lens telescope (curves 1–4) and on the intracavity losses *L* for the case when the end of the active element (curves 1′–3′) plays the role of the output mirror. One can see by comparing these dependences that for energy densities exceeding 2 J/cm^2 the optimal resonator scheme is the one in which the ends of the active element are employed as the output mirror. The use of this scheme also makes it possible to avoid the technological difficulties of fabricating wide-band mirrors. In the case of the selective resonator it is necessary to take into account the fact that an increase in the conversion efficiency at the maximum of the tuning curve at the expense of an increase in the effective losses with fixed pump energy density results in narrowing of the tuning range. Figure 2 shows for comparison the wavelength dependences of the conversion efficiency obtained in the selective resonator.

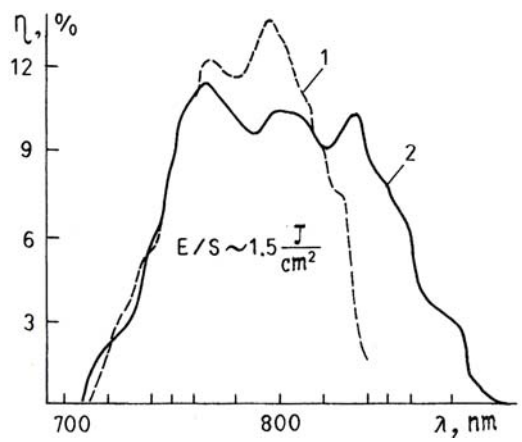

FIG. 2. The wavelength dependence of the lasing efficiency achieved using the end of the active crystal as the output mirror (1) and with the use of an output mirror with R = 70% (2).

The activator concentration and, correspondingly, the optical density of the Al_2O_3: Ti^3 -crystal also affect the conversion efficiency; this is connected, in particular, with the existence of absorption in the region of lasing.[3] Thus the characteristic feature of the dependences of the lasing energy on the pump energy for crystals with Ti^{3+} concentration exceeding 0.15 wt.% and unsaturated absorption of greater than 80% is the existence of a number of sections in them with anomalously low lasing efficiency. Investigations of the parameters of the pump radiation with a gaussian intensity profile, passing through the active element, indicate that the inversion in the active volume is nonuniformly distributed over the cross section and its configuration changes as the pump-energy density is varied. In the above-threshold regime, especially in resonators with a low *Q*-factor, the peripheral sections of the cross section of the pump beam make virtually no contribution to lasing, and this gives rise to lower values of the differential efficiency than in the general regime. Increasing the pump energy density results in more complete utilization of the energy in the peripheral part of the beam of exciting radiation and, as a consequence, in an increase of the differential lasing efficiency. The optimal situation, from the viewpoint of reducing the nonuniformity of the inversion and, correspondingly, increasing the lasing efficiency, is to use active elements with unsaturated absorption coefficient of 60–80%, as well as to take special measures to increase the uniformity of the pump-energy density in the excited volume, in particular, by using bilateral pumping or a corresponding distribution of the activator in the Al_2O_3: Ti^{3+}-crystals.

The characteristics of the kinetics of the build-up of lasing impose a number of significant restrictions on the maximum values of the pump energy density and, correspondingly, the conversion efficiency. Thus in the above-threshold regime the generation of a single pulse with a delay reaching values of ~ 1 μs relative to the pump pulse is observed. Increasing the pump energy density results in a decrease of the width and delay and an increase in the amplitude of the generated pulses. When the delay relative to the maximum of the pump pulse is reduced to values less than the width of its trailing edge and the temporal and energy parameters of the generated spike are stabilized, which corresponds to lowering the differential efficiency of lasing, a second spike is generated, and when the pump level is further reduced further spikes are generated. The section where the lasing energy depends on the pump energy density, corresponding to the given process, acquires a "step" character, where generation of a new spike corresponds to each subsequent "step". For crystals with an activator concentration of less than 0.1 wt.% the character of the development of spike lasing as a whole can be described in terms of relaxational oscillations and is hardly manifested in the energy dependences. In the case of crystals with higher concentrations the absorption processes and dynamic phase distortions result in a significant change of the geometry of the active channel in the pumping and lasing process and, as a consequence, in the development of the regime of "self-modulation", characterized by a weaker dependence of the temporal and energy parameters of separate lasing spikes on the pump energy. The energy dependences corresponding to this case have a distinct "step" form (Fig. 3).

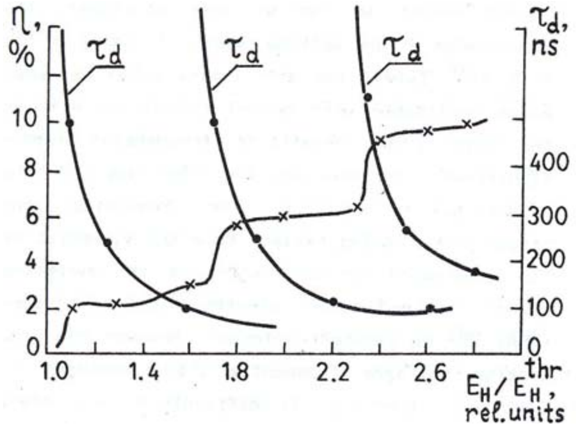

FIG. 3. The lasing efficiency and the delay of the lasing spikes as a function of the excess above threshold.

The energy limit of the development of the spike regime is a function of the width of the pump pulses. Based on the radiation strength of the active crystals, the optimal range of widths of the pump pulses for realizing single-pulse lasing, corresponding to a more than three-fold excess above threshold, is 20–100 ns for resonators with the typical parameters (total losses ~ 40% baseline ~ 300 mm). This range can be extended by using crystals with higher radiation strength as well as by lowering the intraresonator losses and increasing the length of the resonator.

TABLE I.

Parameter	Type of selector				
	Block of three prisms	Four-component Lyot filter	Grating: glancing incidence	Grating: autocollimation (AC)	AC-grating and Fabry-Perot interferometer
Efficiency, %	25-30	30	5-10	20-25	15-20
Linewidth, nm	0.2	1.0	0.05	0.15	0.015

As a result of optimizing the parameters of the resonator, the active element, and the conditions of pumping, taking into account the characteristics of the lasing, studied above, in a nonselective resonator constructed based on a quasiconcentric arrangement with an intraresonator telescope, a differential efficiency of ~ 50% and a total efficiency of ~ 40% were realized. The typical efficiencies of lasing in a selective resonator and the llnewidth at the maximum of the tunable curve are presented in Table I for a number of selectors. With the use of these selectors the spectral tuning range is 660–980 nm.

NARROW-BAND TUNABLE Al_2O_3: Ti^{3+}-LASER CONVERTER

As mentioned above, the requirements on the width of the tuning range and the lasing efficiency with a fixed pumping level are contradictory, since an increase of the lasing efficiency owing to an increase of the effective losses is accompanied by a narrowing of the tuning range. The resonator arrangement, shown in Fig. 4, with the external coupling coefficient regulatable in the tuning process made it possible to make these, at first glance, contradictory requirements compatible and to stabilize the linewidth and the width of the lasing pulse in the process of tuning the wavelength. The pump radiation was directed through the "nontransmitting" flat mirror of the resonator $M1$ and focused by the length $L1$ on the front working face of the active element AE, oriented at Brewster's angle to the axis of the resonator. The special mirror $M2$, which collimated the generated beam with a diameter of 3.5 nm, was employed as the second component of the intraresonator telescope. Further reduction of the divergence at the expense of increasing the transverse dimensions of the beam was achieved using a one-component prism telescope PT, after which the radiation was directed onto an autocollimation diffraction grating DG with 1200 lines/mm. Radiation was extracted from the resonator from the working surface of the wedge with an angle of 20° at the vertex. The effective losses were regulated in the tuning process in the range 20–80% by varying the angle of incidence of the radiation on the working surface of wedge in the range 70–85%. The generated radiation was directed by the mirror $M3$ onto the lens $L2$ and focused by this lens on a frequency converter FC based on an $LiIO_3$ crustal. The lens component $L3$ collimated the radiation at the fundamental frequency and the second harmonic frequency passing through the FC. The mechanism of tuning of the lasing wavelength enabled synchronous adjustment for phase matching of the nonlinear crystal.

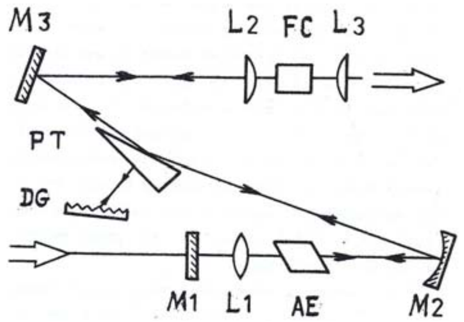

FIG. 4. The optical arrangement of an Al_2O_3: Ti^{3+}-based laser converter.

An operating model of a narrow-band tunable Al_2O_3: Ti^{3+}-laser with frequency doubling was built based on the arrangement examined above using for the pump source an industrial LTI-701 laser. To eliminate the spiking lasing regime the baseline of the resonator of the laser converter was increased to 1.2 m, which made it possible to realize high-repetition-rate lasing of single pulses with a lasing efficiency of up to 10–12% with respect to the absorbed pump energy (1.5 W). Further increase of the lasing efficiency at the expense of increasing the pump power was accompanied by generation of a second and subsequent spikes with a single pulse of exciting radiation.

The parameters of the radiation of the model Al_2O_3: Ti^{3+} - laser converter are presented below.

Average lasing power with a pulse repetition frequency of 8 kHz at the maximum of the tuning curve, mW:	
at the fundamental frequency	180
at the second harmonic	20
Pulse repetition frequency, kHz	5–50
Tuning range, nm:	
fundamental frequency	680–960
second harmonic	350–450
Lasing pulse width at half-width, ns	12–40
Spectral width of the lasing line at the maximum of the tuning curve, pm less than	5

ONLINE CONTROL OF THE PARAMETERS OF THE TUNABLE RADIATION FROM A HIGH-REPETITION-RATE Al_2O_3: TI^{3+}- LASER

The relatively large widths of the radiation pulses from the neodymium pump lasers (exceeding 10 ns) result in, as we have mentioned, the development of the spiking regime of lasing of the Al_2O_3: Ti^{3+} - laser. The wide tuning range and high gains realizable with pulsed pumping as well as the high pulse repetition frequencies impose significant restrictions on the use of the traditional Q-switches for realizing the single-pulse lasing regime. From the viewpoint of the enumerated characteristics of the operating regime examined above, electrooptical modulators (EOM) are of greatest interest. However the high working voltages (exceeding 1 kV) employed in industrial EOM make it difficult to use these modulators with pulse repetition frequencies exceeding 100 Hz.

The low-voltage electrooptical shutter proposed in Ref. 5 is more promising for single-pulse lasing. Thanks to the low controlling voltages (less than 1 kV) it can operate with a repetition frequency of the controlling pulses of up to tens of kilohertz. The use of such shutter made it possible to realize online control of the temporal parameters of the generated radiation in the entire spectral range 680–960 nm with an energy lasing efficiency comparable to that of the free-lasing regime and pulse repetition frequencies of up to 50 kHz. The shutter was placed in the arrangement presented in Fig. 4 between the collimating element $M2$ and the prism telescope PT.

The width of the lasing pulse and the delay of the lasing pulse relative to the moment at which the Q-factor of the resonator is switched, as in the case of free lasing, depended on the amount by which the pumping exceeded the threshold and the baseline of the resonator. In a 0.5 m long resonator they varied from 5 to 50 and 10 to 100 ns, respectively. Regulation of the moment to switching on of the *Q*-factor of the resonator relative to the maximum of the pump pulse also made it possible to vary the delay between the pump and lasing pulses over wide limits (approximately up to several microseconds, comparable to the lifetime of the excited state of Ti^{3+} ~ 4 μs). When the lasing wavelength was tuned the static voltage was also tuned in the range from 400 to 600 V.

In addition to the investigations performed above, a series of experiments on the use acoustooptical devices for controlling the parameters of the generated radiation was also performed. As conjectured, the relative long *Q*-factor buildup times of the acoustooptical shutter (~ 100 ns), exceeding the characteristic buildup times for lasing, made it impossible to realize an efficient single-pulse operating regime of the high-repetition-rate Al_2O_3: Ti^{3+} - laser. However the use of an acoustooptical deflector (AOD), operating on the −1 order of diffraction, for controlling the spectral characteristics made it possible to increase substantially the rate of scanning (or tuning) of the wavelength of the laser radiation compared with pulsed (up to 100 Hz) sources, thanks to the combination of the high rate of tuning of the period of the acoustic grating, limited only by the time of filling of the AOD with the acoustic wave, with the high repetition rate of the radiation pulses. Thus replacement of the diffraction grating in the arrangement examined above (Fig. 4) with an AOD and a flat "nontransmitting" mirror placed behind it enabled wavelength tuning in the range 730–870 nm over the time period between pulses with a pulse repetition frequency of up to 25 kHz (the tuning time of the AOD ~ 30 μs). A characteristic feature of the lasing kinetics was that the shape of the pulses of tunable radiation was modulated, and in addition the degree of modulation increased as the spectral line narrowed and reached more than 90% for spectral widths less than 40 pm. The modulation period corresponded to the frequency of the acoustic wave excited in the AOD. When the frequency of this wave was matched with the. axial period of the resonator ultranarrow pulses with a spike width of less than 300 ps in the train (the limiting resolution of the recording apparatus) were generated.

CONCLUSIONS

Our investigations of the high-repetition-rate lasing of a tunable Al_2O_3: Ti - laser demonstrated that this laser is highly reliable and simple to operate. The high values of the gain realizable with pulsed pumping make it possible to use resonators with high admissible total losses (up to 90%), which makes it possible to use practically all currently existing spectral selectors and their combinations. The best results were obtained in resonators with a quasiconcentric configuration, built based on a two- or three-mirror scheme with an intraresonator focusing element.

Based on the results of the investigations of the characteristics of the tunable lasing, a working model of the high-repetition-rate narrow-band tunable laser with an external coupling coefficient that can be regulated during the tuning process was developed. The construction of the model provided for the possibility of installing an electrooptical shutter and acoustooptical devices, enabling online control of the temporal and spectral parameters of lasing in the time between the pulses with a pulse repetition frequency of ~ 10^4–10^5 Hz in active *Q*-switching and mode-locking regimes. The wide tuning range, the combination of a high pulse repetition frequency with the possibility of fast tuning of the wavelength and delay between the pump and lasing pulses of the Al_2O_3: Ti^{3+} -laser converter described above make it possible to increase substantially the speed of operation of systems in which such converters are employed.

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