AUTONOMOUS TUNABLE MULTIFREQUENCY NEAR-IR LASER

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Received January 6, 1989

The results of comprehensive studies directed toward the development of a highly efficient, laser-pumped, $Al_2O_3:Ti^{3+}$-crystal laser lasing simultaneously at several frequencies and tunable in the spectral region 680–960 nm, are presented. The selection properties of the active elements themselves and the possibility of using them to achieve multifrequency lasing were investigated. Multifrequency lasing with the intervals between the spectral components ranging from 0.7 to 120 nm was obtained. A series of variants of an autonomous GSGG:Cr^{3+}, Nd^{3+} laser, lasing with up to 70 mJ per pulse and a pulse repetition frequency of up to 25 Hz, has been developed for pumping $Al_2O_3:Ti^{3+}$-based converters.

The solution of a number of problems In atmospheric sounding requires the development of multifrequency laser sources that generate two or more spectral components. Thus the use of multifrequency sources in differential absorption lidar systems makes it possible to measure absorption simultaneously in different sections of the spectrum and thereby to increase significantly the accuracy of identification.[1] Multifrequency sources are also important for Raman backseattering and laser fluorescence lidars.

Conventional sources of wideband radiation based on organic dyes and crystals with color centers do not have adequate photo- and thermal stability. For this reason, from the practical viewpoint, lasers based on crystal activated with transition-group ions are more suitable. The most promising such laser at the present time is a laser operating on $Al_2O_3:Ti^{3+}$ crystals. These crystals lase in an extremely wide spectral range (660–1200 nm), they are small, and they have a long operating lifetime and good operating stability.

In this paper the results of investigations of the physical mechanisms allowing for multifrequency lasing are presented and the basic principles of construction of autonomous multifrequency tunable lasers based on $Al_2O_3:Ti^{3+}$-crystals are examined. Functionally these lasers consist of three basic parts: an autonomous pump laser based on neodymium-activated crystals, a cascade for doubling the fundamental frequency of the pump radiation, and a multifrequency converter.

SPECIFICS OF MULTIFREQUENCY LASING

In spite of the fact that $Al_2O_3:Ti^{3+}$-crystals are characterized by homogeneous broadening the nonstationary operating mode makes possible multifrequency lasing with the help of selective resonators with spectrally separated Q-factor maxima.

The selection properties of the active elements themselves are of special interest for multifrequency lasing in $Al_2O_3:Ti^{3+}$-based lasers. In general the lasing spectra of $Al_2O_3:Ti^{3+}$ in a nondispersive resonator have a quite complicated spectral structure, whose character is determined by the longitudinal and transverse optical inhomogeneity and the intrinsic anisotropy of the active elements as well as by interference processes on the end faces of the active element.

When the polarization characteristics of the active element are not matched with those of the resonator the phase anisotropy ($\Delta n = 8 \cdot 10^{-3}$) and amplification dichroism ($\sigma_e^{\parallel} = 3.7\times10^{-19}$ cm^2; $\sigma_e^{\parallel} = 1.8\times10^{-19}$ cm^2) of $Al_2O_3:Ti^{3+}$ crystals result in the appearance of a spectral structure in which the splitting between neighboring spectral components, determined by the length of the active crystal (l) and the angle between the resonator axis and the optical axis of the active element (Ω), is given by the well-known expression for an interference-polarization filter (IPF)[2]

$$\Delta\lambda = \frac{\lambda^2}{2(n_e - n_0)\, l \sin^2\Omega}. \qquad (1)$$

The determination of the conditions for the appearance of such a spectral structure with the use of the Jones matrix method is, in general, a quite difficult problem. Direct studies have shown that a sufficient condition for the appearance of spectral structure of this type is that the principle plane of the active element must make an angle of at least 5. . . 10 with both the axes of the total or partial polarizer, whose role was played by the active crystals themselves, which were positioned at Brewster's angle relative to the resonator axis, and the principle planes of any additional intracavity anisotropic phase elements.

The position of the spectral components and the spectral splitting between' them is controlled by varying the phase difference between the ordinary and extraordinary components of the radiation in the active crystal (l and Ω) as well as by introducing additional phase elements (tuning of the spectral components). It should be noted that the use of an electrooptical cell with voltage-controlled induced birefringence (the wavelength difference of the o and e components of the radiation ranges from 0 ... λ) as an additional phase element enables, as experimental studies have shown, real-time tuning of the spectral components in a range of $\Delta\lambda$ within the time interval between neighboring pulses with a pulse repetition frequency of up to 10 kHz.

A characteristic feature of this multifrequency mode is that the generation of more than two spectral components is possible in a nondispersive resonator only in the spectral range 760 ... .840 nm; this is connected with a relatively weak change in the gain curve in this wavelength range. Figure 1 shows as an example the curve of the wavelength dependence of the lasing threshold, obtained in the case of a selective resonator with total losses of ~ 40%. To enlarge this range it is necessary to use additional dispersion elements, whose type is determined by the required width of the lasing spectrum.

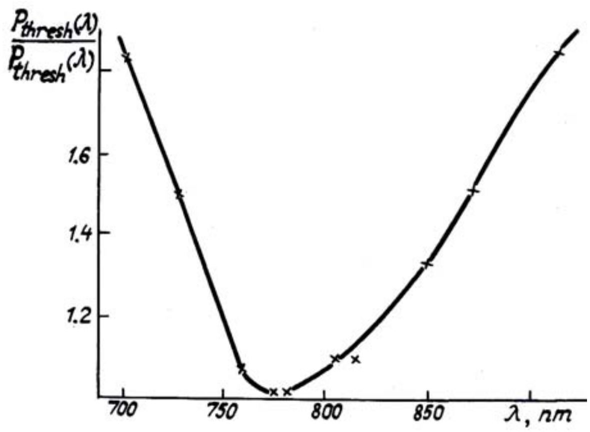

FIG. 1. The lasing threshold versus the wavelength of a Al_2O_3:Ti^{3+} gased laser.

The spectral width of separate lines obtained with multifrequency lasing, just like the period between them, increases as the length of the active crystal is decreased, reaching values greater than 3 nm with $l = 6$ (the period is greater than 12 nm). To reduce the width of the spectral lines it is necessary to use multicomponent IPFs. Thus the use of a three-component Al_2O_3:Ti^{3+} active element with wafer thicknesses in the ratio 1:2:4 made possible multifrequency lasing with a period of 40 nm and individual linewidths ~ 1 nm.

It should be noted that the distance between the neighboring spectral lines is determined by the thickness of the thinnest anisotropic active wafer. When the spectral splitting between neighboring lines is greater than 40 nm (l < 1 mm) it is best to employ combined (consisting of active and passive components) or passive IPFs; this is connected with the relatively low gains realized in Al_2O_3:Ti^{3+} crystals (up to 1 ... 5 cm^{-1}).

It is also of interest to use IPFs in two-frequency sources based on Al_2O_3:Ti^{3+} in a wider range than that indicated above. This is because the losses introduced in the resonator by the IPFs are significantly lower than those of other types of selectors. Thus the use of a four-component Lyot filter with a free dispersion range of ~ 110 nm made possible efficient two-frequency lasing on the lines 740 and 850 nm; each line had a width less than 1 nm and both lines were characterized by the same excess above the lasing threshold, as one can see from Fig. 1, and as a consequence the intensity in each line was approximately the same. When the lines were synchronously tuned the ratio of their intensities changed and the character of the change in the duration and delay of the pulses corresponding to each spectral line was different. The tuning range of the short-wavelength component was 730 ... 770 nm and that of the long-wavelength component 840 ... .880 nm.

The results obtained are also of interest from the viewpoint of solving a number of problems where accurate spectral referencing of the components of two-frequency lasing, is not necessary and the main requirements are imposed on the spectral splitting of the components. Thus to practically any short-wavelength spectral line in the spectral lasing range there corresponds a long-wavelength component with the same gain. The main restrictions on the maximum possible spectral splitting between a pair of lines are connected with the width of the spectral range of lasing (660 ... 980 nm) and the region of free dispersion of the IPF.

To achieve multifrequency lasing with a period of less than 1 nm with frequency-polarization modulation of the radiation spectrum anisotropic wafers (active or passive), whose length is greater than 50 mm, must be used. In addition, to regulate the spectral period the thickness of the active crystals or passive wafers must be varied over a significant range, which is undesirable in most cases. From this viewpoint the results of studies of the effect of transverse phase inhomogeneities in the resonator elements on the formation of the spectral substructure with a characteristic period ranging from hundreds of picometers to several nanometers are of interest. Thus placing in the resonator a thin plane-parallel wafer with the refractive index n and thickness d, partially covering the peripheral part of the cross section of the generated beam, makes it possible to obtain discrete equidistant lasing spectra with the period[2]

$$\Delta\lambda_2 = \lambda^2 \cos\beta/(n-1)d, \qquad (2)$$

where λ is the lasing wavelength and β is the refraction angle.

The position of the elements of this structure and the period of the structure are controlled by varying the phase difference introduced by the wafer by changing the inclination of the wafer or its thickness. Multifrequency lasing with a period of 0.6 ... 5 nm was achieved in experiments using thin plane-parallel wafers of K8 glass and quartz with thicknesses ranging from 100 to 300 μm. In addition, the lasing efficiency was more than 30% higher than that achieved with the Fabry-Perot etalon.

It should also be noted that it is possible to build multifrequency converters based on Al_2O_3:Ti^{3+} which generate a discrete set of spectral lines with a period of the same order of magnitude as in the preceding case; the formation of the lines is connected with interference of aperture-limited beams on the end faces of the plane-parallel active element. A characteristic feature of this substructure is that the spectral splitting between these elements is more than an order of magnitude greater than the region of free dispersion of the interferometer, which the active crystal is.[3,4] Tuning of the spectral lines is achieved by varying the optical thickness of the crystals. Thus the use of active elements with small tapering of the faces (up to 1...3 mrad) made it possible to achieve synchronous tuning both by displacing them perpendicularly to the axis of the resonator and by varying the operating temperature. A change in the optical thickness by $-\lambda/2$ corresponds to tuning of the elements of the structure by one period. The temperature coefficient of tuning for Al_2O_3:Ti^{3+} crystals 6 mm long was equal to 3 nm/deg. Figure 2 shows as an example spectrograms for these crystals with Brewster (a) and normal (b) orientation of the working faces; the spectrograms were obtained in a quasiconcentric lens resonator.

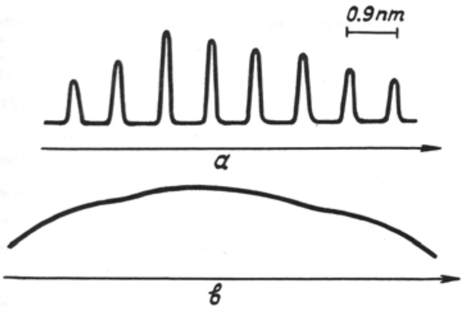

FIG. 2. Lasing spectra with Brewster (a) and normal (b) orientation of faces of the active element.

AUTONOMOUS TUNABLE LASERS BASED ON Al_2O_3:Ti^{3+} CRYSTALS

The high optical-physical and lasing characteristics Al_2O_3::Ti^{3+} crystals make the construction of lasers based on these media relatively simple as compared with other types of tunable lasers, and it also makes their operation under different climatic conditions convenient and reliable. The possibility of operation at temperatures up to 300°C makes it possible to use the "dry" version of these lasers. The operating lifetime of the active elements exceeds 10^{11} ... 10^{12} pulses.

The specifics of the design of highly efficient tunable lasers based on Al_2O_3:Ti^{3+} are connected both with the optimization of the parameters of the converter itself based on these crystals and with the improvement of pump sources based on neodymium lasers and cascades for converting their radiation into the second harmonic.

Optimization of the autonomous versions of new highly efficient pump lasers based on GSGG (YSGG, GSAG):Cr^{3+}, Nd^{3+} makes it possible to solve problem of building wideband tunable near-IR lasers suitable for atmospheric sounding under field conditions. At the present time, to pump Al_2O_3:Ti^{3+}-based converters, we developed a number of variants of an autonomous laser based on GSGG: Cr^{3+}, Nd^{3+} with an improved mass-to-size ratio, which provide a lasing energy of up to 70 mJ per pulse with a pulse repetition frequency of up to 25 kHz. In these designs power can be supplied by a storage battery as well as by other onboard power sources, and a cooling system of the combined type (liquid one-loop system with forced air ventilation) is also employed. The mass of the entire system does not exceed 10 kg. When necessary the pump laser can be equipped with amplification cascades. The use of YSGG and GSAG crystals makes it possible to increase further the lasing pulse repetition frequency.

The total efficiency of the pump laser – Al_2O_3:Ti^{3+} converter system is largely determined by .the efficiency of conversion of pump radiation ($\lambda \sim 1.06$ nm) into the second harmonic (CSH). To obtain a powerful tunable laser we chose a Al_2O_3:Ti^{3+}–based scheme with successive CSH and separate excitation of the master oscillator and amplification cascades (Fig. 3). This gave a lasing efficiency of ~ 10 ... 15% at the fundamental harmonic of the pump radiation (50% at the second harmonic) and thereby substantially increased the efficiency of the laser system as a whole.

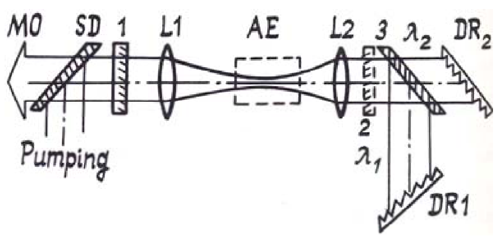

FIG. 3. The optical layout of multifrequency laser based on Al_2O_3:Ti^{3+}: SD – spectrum divider; 1, 2 – resonator mirrors; AE – active elements; L1, L2 – lenses; 3 – beam splitter; DP1, DP2 – autocollimation gratings; AE – active element.

The master oscillator of the laser converter is built based on a scheme with an intracavity catadioptric telescope (Fig. 4). The active element consists of two components, and for a certain orientation of their optical axes relative to one another it combines the function of a frequency-polarization selector, which separates the spectral components of multifrequency lasing, and tuning of the components with a spectral period in the range 0.7 ... 70 nm via variation of the phase difference between the *o* and *e* components of the generated radiation. To narrow the spectral width of each of the generated lines the construction of the resonator provides the possibility of using additional anisotropic elements, whose parameters are determined by the required spectral characteristics of the generated radiation. Combining the functions of a selector in the active element makes it possible to reduce the intracavity losses and thereby increase the conversion efficiency up to 40 ... 50% (with respect to the absorbed pump energy). In addition, in this scheme it is also possible to use a number of the other mechanisms, studied in the preceding section of this paper, for spectral self-selection of the generated radiation.

The traditional mode of two-frequency lasing with independent tuning of the spectral lines it achieved by matching the optical axes of the components of the active element and by replacing the "nontransmitting" mirror *1* with a two-arm dispersion element with spectrally separated *Q*-factor maxima. The ratio of the intensities of the generated spectral lines is changed in this case by varying the *Q*-factor of one of the coupled cavities. The width of the spectral line and the pump radiation conversion efficiency are determined by the parameters of the selectors employed, which were chosen based on the required parameters of the generated radiation. The typical values of the lasing efficiency and the linewidth at the maximum of the tuning curve, realized in this resonator with single-frequency lasing for a series of selectors, are given in Table I. The spectral range of independent tuning of each line using these selectors was equal to 660 ... 980 nm.

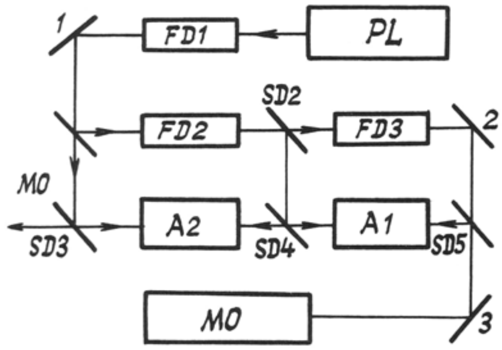

FIG. 4. Block diagram of a multifrequency laser: PL — pump laser; FD1–FD3 — frequency doublers; 1, 2, 3 — mirrors; SD1–SD5 — spectrum dividers; A1, A2 — Al_2O_3:Ti^{3+} —based amplifiers; MO — Al_2O_3:Ti^{3+} — based master oscillator.

TABLE I.

selector	Unit consisting of three prisms	Lyot filter with four components	autocollimation grating (ACG)	ACG and Fabry-Perot interferometer	ACG and a prism telescope
Efficiency, %	25...30	30	20...25	15...20	10...15
Linewidth, nm	0.2	1.0	0.15	0.02	0.003

A characteristic feature of the kinetics of this two-frequency mode was the generation of two spikes with different durations and delays, corresponding to each of the spectral lines of the generated radiation with different excesses above threshold. In the tuning process the pulse duration of each of the lines was varied in the range 20 ... 150 nsec with a corresponding change in the delay relative to the maximum of the pump pulse (τ = 50 nsec) ranging from 30 to 400 nsec.

CONCLUSIONS

Thus our studies have demonstrated that Al_2O_3:Ti^{3+} crystals are suitable for use as active media in multifrequency tunable near-IR lasers. The wide spectral range of amplification of Al_2O_3:Ti^{3+} crystals makes possible different multifrequency lasing regimes both in the existing two-arm resonators with independent tuning of each line and with the use of IPFs. The phase anisotropy and amplification dichroism of Al_2O_3:Ti^{3+} crystals makes it possible to use them to build active or combined (consisting of passive and active components) selectors in which the functions of dispersion and active resonator elements are combined.

Experiments on the formation of a discrete spectral structure with a period in the subnm-nm range, determined by interference processes associated with the transverse optical inhomogeneity and aperture limitation of the generated beam, were performed.

The development of small, highly efficient, autonomous neodymium lasers made it possible to solve the problem of building wideband tunable, including multifrequency, near-IR lasers suitable for atmospheric sounding under field conditions. To increase the efficiency of the "pump laser – $Al_2O_3:Ti^{3+}$ converter" system a $Al_2O_3:Ti^{3+}$-based scheme with successive CSH and separated excitation of the master oscillator and amplification cascades was proposed; it enabled increasing the lasing efficiency with respect to the fundamental harmonic of the pump laser radiation up to 10 ... 15%.

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