for performing the calculations in accordance with these programs.

[1] Zh.S. Takibaev and E.G. Boos et al., Yad Fiz. 13, 113 (1971) [Sov. J. Nuc. Phys. 13, No. 1 (1971)].
[2] K.A. Ter-Martirosyan, Preprint, High Energy Physics Institute, STF-68-11-K, Serpukhov, 1968.
[3] B. Haber, G. Yekutieli, et al., Phys. Rev. 160, 1410 (1967).
[4] P.C.M. Yock, Nuovo Cim. 41, 635 (1966).

INDUCED RADIATION OF $Y_3Al_3O_{12}$-$(Nd)^{3+}$ EXCITED BY AN ELECTRON BEAM

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The use of pulses of electrons with energy of several dozen keV to excite semiconductors [1] has made it possible to obtain stimulated emission with a quantum energy close to the width of the forbidden band, and with an approximate efficiency 30%. Great interest attaches, from our point of view, to lasing by electron excitation of doped ionic crystals. These materials have a wide selection of radiation frequencies in the visible and the ultraviolet regions of the spectrum, and in addition have much narrower emission lines than semiconductors. Although cathode luminescence of activated ionic substances (such as ruby [2, 3]) has been under study for several decades, we know of no reports that stimulated emission of these materials has been attained.

There is a fundamental difference between the optical excitation used to generate radiation from doped ions in ionic crystals and electron excitation. In the case of optical pumping, the electron shells of the activator ions are directly excited, whereas electronic pumping first produce electron-hole pairs in the allowed bands of the ionic crystal, and only then is their energy transferred to the activator ions. To assess the pumping efficiency of new crystals by electron beams, the energy yield (the ratio of the radiation power produced in the sample to the electron-beam power) and the quantum yield (the ratio of the number of photons emitted by the activator ions to the number of electron-hole pairs produced by the beam) of the emission of single crystals $Y_3Al_5O_{12}$-$(Nd)^{3+}$(0.3 wt.%) were determined with the aid of F4 and F5 photocells by the

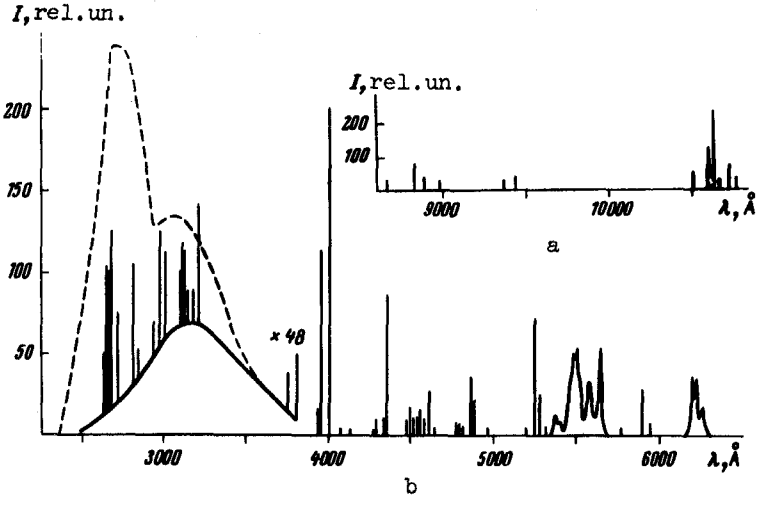

Fig. 1. Emission spectrum at 293 and 80° K (dashed line). The straight lines denote the emission lines with $\Delta < 25$ Å.

procedure described in [4]. The crystals were grown from the melt by the Czochralski method. The excitation was produced by electron pulses of duration t_p = (0.1 - 14) μsec, energy 90 keV, and frequency 10 Hz. The energy of production of electron-hole pairs was assumed to be 20 eV, since the width of the forbidden band in $Y_3Al_5O_{12}$ is 6.5 eV. In the case of electron excitation there appear, in addition to the infrared spectrum resulting from optical excitation and due to transitions from the $^4F_{3/2}$ level (Fig. 1a), also emission lines previously observed [5] upon x-ray excitation and attributed to transitions from the upper S level[1] of the neodymium ions (Fig. 1b).

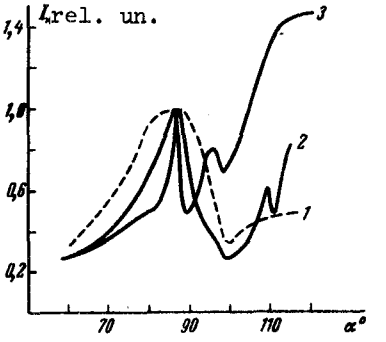

Fig. 2. Dependence of the emission intensity I on the angle α with the plane of the resonator end face at 293° K: 1 - silvered ends, λ_M = 10637 and 4007 Å; end faces with R = 97%; 2 - λ_M = 10637 Å; 3 - λ_M = 4007 Å.

The most intense are the lines with the maximum at λ_M = 4007, 4358, and 5250 Å, with width Δ = 7 - 8 Å. The decrease in the emission intensity of all the lines shown in Fig. 1b was exponential, with a constant τ_S = 3.5 ± 0.3 μsec, thus indicating that these lines are due to electronic transitions from one level. The lifetime of the $^4F_{3/2}$ level was τ_F = 180 ± 10 μsec. In the ultraviolet part of the spectrum we observed a broad emission band with a maximum at 3170 Å, Δ = 700 Å, and τ < 1 μsec (293°K), which is connected with electronic transitions of the crystal lattice of the garnet or its defects. On going from room temperature to 80°K, the intensity of the Nd^{3+} emission was decreased to one quarter, whereas the intensity of the emission of the garnet itself increased; near the edge of the fundamental absorption band there appeared one more emission band with a maximum at 2730 Å and Δ = 400 Å.

At 293°K, the energy yield (η) and the quantum yield (γ) of the radiation were η_1 = 2.5 ± 0.7% and γ_1 = 0.18 ± 0.05 for the spectral region 0.39 - 0.5 μ, η_2 = 4 ± 1% and γ_2 = 0.35 ± 0.1 for 0.5 - 0.63 μ, and η_3 = 4 ± 1% and γ_3 = 0.7 ± 0.2 for 0.86 - 1.1 μ. It follows from these measurements that the quantum yield for the electronic transitions from the level S of the neodymium ions is γ_3 = 0.53 ± 0.17, and is equal within the limits of measurement errors to the value of γ_F for the transitions from the $^4F_{3/2}$ level. The relatively large error in γ can be explained by assuming that the electron-hole pairs produced by the electron beam are bound into excitons of the Frenkel type, which diffuse towards the neodymium ions and excite them by exchange-resonance interaction. It is possible that the emission band with the maximum at 2730 Å is due to exciton annihilation. The intensity of the radiation of the neodymium ions (I) at 293°K increased first linearly with increasing current density j from 10^{-2} A/cm² to 10^{-1} A/cm², and at j ≈ 1 A/cm² it depended little on j, this being due to the excitation of the greater part of the

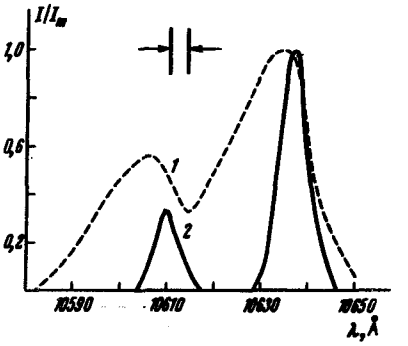

Fig. 3. Emission spectrum at 293°K and j = 0.2 A/cm²: 1 - from the front side of a resonator with unsilvered ends; 2 - from a silvered end of a resonator.

[1]) An arbitrary designation for one of the high levels of $(Nd)^{3+}$, introduced by Dicke [6].

neodymium ions. Since at $j = 1$ A/cm^2 the rate of pair generation is $g \approx 10^{25}$ pairs/cm^{3}sec, it follows that the number of excited neodymium ions in this case is $\Delta N = g\tau_S \approx 3 \times 10^{19}$ cm^{-3}, which is close to the Nd^{3+} concentration in the crystal. An investigation of the emission from resonators 2 mm long at 293°K has shown that if silver coatings with reflectivity 97% are deposited on their end faces, the directivity pattern of the radiation from the resonator end narrows down from 30° to 10° for radiation with $\lambda_M = 10637$ Å, corresponding to the transition $^4F_{3/2} \rightarrow {}^4I_{11/2}$, and to 15° for the emission $\lambda_M = 4007$ Å, which corresponds to the transition $S \rightarrow {}^4F_{7/2}$ (Fig. 2). The emission line of the $^4F_{3/2} \rightarrow {}^4I_{11/2}$ transition was narrowed down from 20 to 7 Å (Fig. 3). The fact that the directivity patterns and the emission lines become narrower when the surfaces of the resonators are silvered indicates stimulated emission. The stimulated character of the radiative transitions is confirmed also by the fact that the intensity of the radiation in a direction close to normal to the plane of the silvered ends of a resonator with R = 97% decreases only to one-half of the intensity of the radiation from the front unsilvered face of the resonator, whereas in the absence of stimulated emission, the intensity of radiation from the ends should be approximately one-thirtieth the intensity of emission from the front face. When j is decreased from 0.2 to 10^{-2} A/cm^2, the directivity pattern remains unchanged, and the radiation intensity decreases linearly with j, from which it follows that the threshold of the stimulated emission lies at electron-current densities $j < 10^{-2}$ A/cm^2. The results of the investigations have shown that electronic excitation makes it possible apparently to construct a laser based on $Y_3Al_5O_{12}:Nd^{3+}$ not only in the infrared band, but also in the visible region, using transitions from the S level. It is of interest to excite with electron beams garnet crystals activated with other ions, such as gadolinium. This may yield stimulated emission in the ultraviolet region, with an approximate efficiency 20%.

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[1] N.G. Basov, O.V. Bogdankevich, and A.G. Devyatkov, Dokl. Akad. Nauk SSSR 155, 783 (1964) [Sov. Phys.-Dokl. 9, 288 (1964)].
[2] E.W. Mutchell and P.D. Townsend, Proc. Phys. Soc. 81, 12 (1963).
[3] Yu.V. Voronov and Yu.P. Timofeev, Zh. Prikl. Spektr. 2, 126 (1965).
[4] V.S. Vavilov, E.L. Nolle, and S.N. Maksimovskii, Fiz. Tverd. Tela 7, 1558 (1965) [Sov. Phys.-Solid State 7, 1253 (1965)].
[5] Yu.K. Voron'ko, B.I. Denker, V.V. Osiko, A.M. Prokhorov, and M.I. Timoshechkin, Dokl. Akad. Nauk SSSR 188, 1258 (1969) [Sov. Phys. Dokl. 14, 998 (1970)].
[6] G.H. Dicke and H.M. Crosswhite, Appl. Optics 2, 675 (1963).

OBSERVATION OF INDUCED ANTIFERROMAGNETISM ABOVE THE NEEL POINT IN FeF_3

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In the investigation of the Mossbauer spectrum on Fe^{57} nuclei in the antiferromagnet FeF_3 in an external magnetic field H up to 20 kOe, we have observed induced antiferromagnetic ordering in the temperature region above the magnetic-transformation point (T_N). According to crystallographic [1] and neutron-diffraction [2] data, FeF_3 forms a bimolecular rhombohedral cell and has an antiferromagnetic structure with isotropy of the "easy plane" type. Such structures, in accordance with the Dzyaloshinskii theory [3], admit of the existence of weak ferromagnetism due to the "tilting" of the antiferromagnetic