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STIMULATED EMISSION FROM Er^{3+} *IONS IN* CaF_2

Yu. K. VORON'KO, G. M. ZVEREV, and A. M. PROKHOROV

Institute of Nuclear Physics, Moscow State University

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Stimulated emission has been obtained from Er^{3+} ions in CaF_2 at 1.7 μ due to transitions between the $^4S'_{3/2}$ and the $^4I'_{9/2}$ levels.

Kiss and Duncan [1] reported observation of stimulated emission from Er^{3+} ions in the $CaWO_4$ lattice at a wavelength of 1.612 μ. Recently Pollack reported [2] stimulated emission from Er^{3+} in the CaF_2 lattice, also at a wavelength of about 1.6 μ.

We have obtained stimulated emission from Er^{3+} ions in a CaF_2 crystal at 3 wavelengths in the region of 1.7 μ and also at about 1.26 μ. Emission was not obtained near 1.6 μ.

We investigated a single crystal of CaF_2 containing 0.1% erbium, grown by lowering the crucible in a fluorine atmosphere. Stimulated emission was obtained in those crystals in which oxygen atoms compensated the excess charge of the Er^{3+} ion (which replaced Ca^{2+} in the lattice). These crystals exhibited intense paramagnetic resonance spectra corresponding to Er^{3+} in centers of trigonal symmetry. The results of a detailed investigation of the optical and paramagnetic resonance spectra of CaF_2 crystals containing erbium, but differing in the methods for achieving compensation, will be published elsewhere.

The absorption spectrum of Er^{3+} in CaF_2 crystals containing oxygen is shown in Fig. 1. The strongest absorption bands, corresponding to the pumping bands of the laser, occur at wavelengths of 0.52 μ and 0.38 μ. They correspond to the excitation of ions from the ground $^4I'_{15/2}$ level to the levels $^2H'_{11/2}$ and $^4G'_{11/2}$ (Fig. 2). Absorption at wavelengths shorter than 0.3 μ is due to the oxygen impurity.

Laser action was obtained at liquid nitrogen temperature in crystals 60 mm long, 8 mm in diameter, having silvered ends. Excitation was provided by a xenon flashlamp. The lamp energy at threshold for rather inefficient illuminating geometry was about 1000 J.

The spectral characteristics of the stimulated emission were studied with a ZMR-3 monochromator. The detector was a PbS photocell.

At threshold emission occurred at 1.715 and 1.726 μ. When the excitation was increased by a factor of 2 above threshold, emission occurred at 1.696 μ [1)]. At this excitation level there was also emission at 1.26 μ.

The emission in the 1.7 μ region was observed on an oscilloscope to have the form of several pulses which were damped by the slow response of the photoconductor. The total duration of the laser emission at maximum pumping energy was

[1)]The wavelength measurements were made with a spectral slit width of 0.003μ. The calibration was carried out with mercury lines.

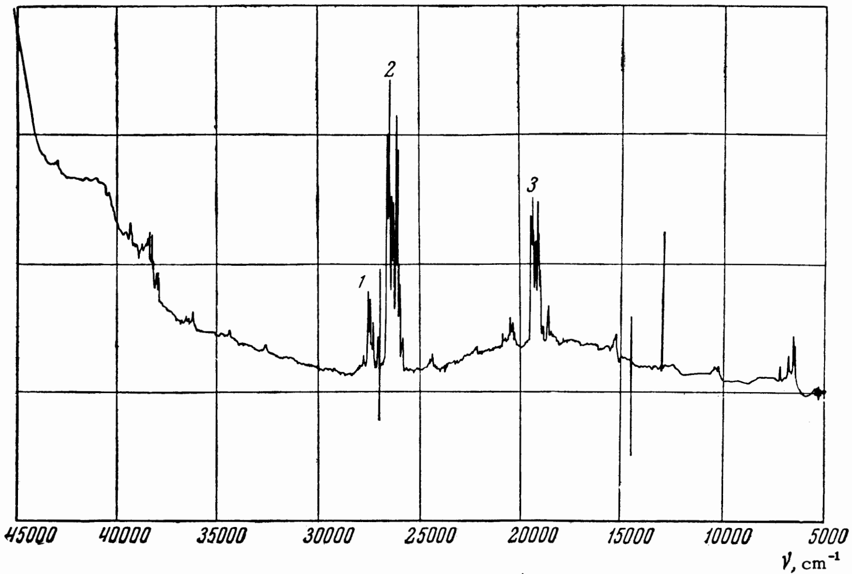


FIG. 1. The absorption spectrum of Er^{3+} in CaF_2 at 77°K.

about 1 μsec. The emission at 1.26 μ occurred in a single pulse of about 0.1 μsec duration near the peak of the flashlamp pulse.

The emission in the 1.7 μ region could be ascribed to two different transitions: from the $^4S'_{3/2}$ level to the $^4I'_{9/2}$ level or from the $^4I'_{13/2}$ level to the $^4I'_{15/2}$ level (Fig. 2). The luminescence corresponding to the transition between the two lowest levels is easily observed and its peak occurs at 1.55 μ. The stimulated emission from Er^{3+} observed in [1,2] is ascribed to transitions between these latter levels.

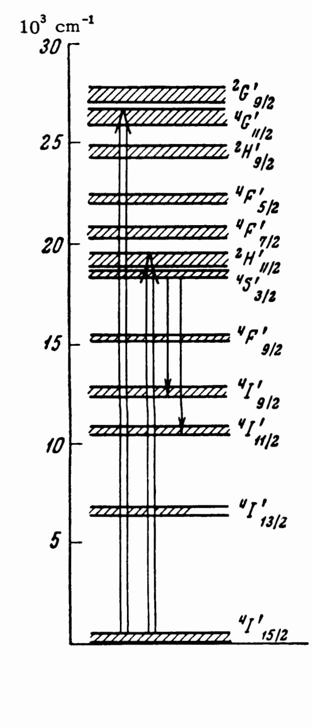
We carried out experiments using filtered pump light with the aim of choosing between these two possible laser machanisms. A yellow filter which removed radiation at wavelengths shorter than 0.5 μ raised the laser threshold by a factor of 2. An orange color filter which attenuated the pump light in the 0.52 μ band prevented oscillation from occurring. A liquid filter consisting of water, which attenuates radiation with wavelengths greater than 1.4 μ, lowered the laser threshold by 30%. A solution of copper sulphate in water, which absorbs light with wavelength greater than 0.6 μ, had practically no effect on the threshold.

As a control experiment we measured the intensity of the luminescence in the 1.55 μ region excited by the flashlamp mounted in the illumination system of the laser. The luminescence pulse was easily observed on the oscilloscope because of the long lifetime of the $^4I'_{13/2}$ level (about 15 μsec) which makes it easy to separate the luminescence from the scattered lamp light. The intensity measurements were made 5 μsec after the flash of the pumping lamp. It was found that the water filter, which attenuated the long wavelength pumping radiation, weakened the luminescence by 20%, whereas the copper sulphate filter weakened it by a factor of 2. These results are approximately in agreement with the results on the effectiveness of various excitation bands for the 1.55 μ luminescence obtained in [2].

Thus the laser action at 1.7 μ is due to the transition of the Er^{3+} ion from the $^4S'_{3/2}$ level to the $^4I'_{9/2}$ level. The $^4S'_{3/2}$ level is metastable and luminescence occurring from it to the ground level $^4I'_{15/2}$ is observed easily at room temperature as well as at liquid nitrogen temperature. The lifetime of this level at liquid nitrogen temperature is about 300 μsec.

The Stark splitting of the $^4S'_{3/2}$ level and the $^4I'_{9/2}$ level by the crystal field was observed in

FIG. 2. The energy level-scheme for the Er^{3+} ion in CaF_2. The widths of the levels correspond to the total Stark splittings. The upward arrows indicate most effective pumping bands; the arrows pointing down indicate the laser transitions.



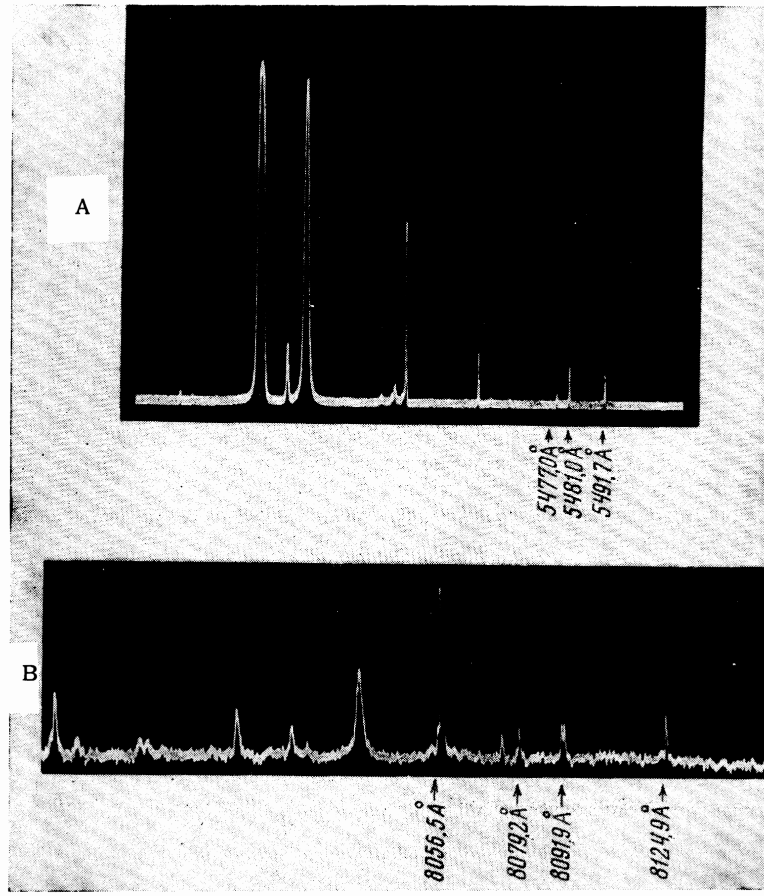


FIG. 3. The absorption spectrum of Er^{3+} in CaF_2 at 4.2°K, showing the Stark splitting of the $^4S'_{3/2}$ level (A) and the $^4I'_{11/2}$ level in the long wavelength region (B).

absorption spectra taken at liquid helium temperature with a DFS-8 spectrograph having a dispersion of 6 Å/mm.

The laser emission at 1.726 μ corresponds to a transition of the ions from the lowest Stark component of the $^4S'_{3/2}$ level (5491.7 Å) to the 8056.5 Å Stark component of the $^4I'_{9/2}$ level (Fig. 3). Laser emission at 1.715 μ may be attributed either to transitions from the 5491.7 component to the 8079.2 Å component or to the transition 5481 → 8056.5 Å. The emission at 1.796 μ may correspond to transitions either between the components 5491.7 and 8124.9 Å, or between the components 5477.0 and 8091 Å.

Comparison of these level separations and the laser emission frequencies is given in the Table. The discrepancies are considerably less than the error in determining the frequencies of the laser emission.

Laser action at 1.26 μ involves transitions between the $^4S'_{3/2}$ and $^4I'_{11/2}$ levels.

The lowering of the laser threshold through the use of a water filter is due to improved focussing of the exciter light into the crystal and to decreased absorption from the metastable level.

Stimulated emission between the levels $^4I'_{13/2}$ and $^4I'_{15/2}$ may probably be obtained by further lowering the temperature of the crystal, so that the excited Stark components of the ground state will be essentially empty.

The authors are grateful to V. V. Osiko for a valuable discussion.

[1] Z. L. Kiss and R. C. Duncan, Proc. IRE 50, 1531 (1962).

[2] S. A. Pollack, Proc. IEEE 51, 1793 (1963).

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Laser wavelength, μ	Laser frequency*, cm^{-1}	Wavelengths of the components of the $^4S'_{3/2}$ level, Å	Wavelengths of the components of the $^4I'_{9/2}$ level, Å	Energy separation between the components, cm^{-1}
1.726	5793	5491.7	8056.5	5797.0
1.715	5831	5481.0	8056.5	5832.5
		5491.7	8079.2	5831.8
1.696	5896	5477.0	8091.9	5900.0
		5491.7	8124.9	5901.2

*Without the vacuum correction.