Phaser generation of transverse phonons by impurity centers of divalent nickel in corundum

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We report the first observation of phaser generation of transverse phonons in the system $Ni^{2+}:Al_2O_3$.

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Phaser generation of coherent phonons under stimulated emission by paramagnetic centers was investigated in detail by us on Cr^{3+} ions in corundum (Al_2O_3). It was established that for this generation to set in it is necessary, first, that the gain at the natural frequency of the acoustic resonator exceed the losses of these frequencies and, second, that the rate of diffusion of the spin excitations in the crystal be small enough. In this case, multimode generation at the natural frequencies of the acoustic resonator is excited in a narrow spectral interval, and occurs under conditions when the excitations that feed the generating modes are spatially separated.

The question whether similar conditions can be realized for phaser generation in another system of paramagnetic centers has until recently remained unanswered. From the point of view of the realization of phaser generation, interest attaches to the system of paramagnetic centers Ni^{2+} in corundum, which has an electron energy spectrum that contains well allowed transitions in both acoustic and electromagnetic fields. Moreover, the Ni^{2+} ion has a much larger spin-orbit coupling that Cr^{3+}, so that its interaction with the acoustic field is expected to be more effective than in the case of Cr^{3+}. However, an earlier attempt to realize phaser generation in the $Ni^{2+}:Al_2O_3$ system, by Peterson and Jacobsen,[2] was unsuccessful.

We report here experiments aimed at realizing phaser generation in such a system. The experiments were performed on a corundum crystal with an Ni^{2+} concentration 2.4×10^{18} cm^{-3}. The ground state of the Ni^{2+} ion in this crystal is a triply spin-degenerate orbital singlet. The spin triplet is partially split by a crystal field of trigonal symmetry into the ground spin doublet $|\pm1\rangle$ and a singlet $|0\rangle$ located at a distance $\delta=1.33$ cm^{-1} from the ground doublet. The spin-phonon interaction of the spin multiplet was determined by the APR method. To this end, the coefficients of resonant absorption of hypersound were measured along the twofold symmetry axis x in transitions between the levels of the $|\pm1\rangle$ doublet split by a magnetic field H directed along the threefold symmetry axis z. The resonant absorption of the longitudinal, slow, and fast transverse hypersound at 3 GHz and at 1.8 K is 0.066, 0.16, and 0.23 dB/cm, respectively. The width of the APR line for all three types of waves is 11 Oe. These data were used to determine the spin-phonon coupling tensor components responsible for the absorption (and in case of inversion, for the enhancement) of the hypersound: $|G_{11}-G_{12}|=30$ cm^{-1}, $|G_{14}|=5.5$ cm^{-1}, and $|G_{15}|=9.7$ cm^{-1}. These values greatly exceed the corresponding components G_{ij} for ruby.[3]

The APR measurements have disclosed a circumstance of importance for the realization of phaser generation, namely that the most effectively interacting with the paramagnetic Ni^{2+} centers is not the longitudinal hypersound wave with which the experiments were performed in Ref. 2, but the fast transverse wave whose resonant absorption greatly exceeds (by five times) the absorption of the longitudinal wave.

Phaser amplification and generation were investigated by us under condition of population inversion of the levels of the spin doublet $|\pm1\rangle$ with the aid of electromagnetic pumping of the $|-1\rangle\rightarrow|0\rangle$ transition at a frequency $\nu_p=41.3$ GHz. The frequency of the signal transition $|-1\rangle\rightarrow|+1\rangle$ amounts to $\nu_s=3.0$ GHz at $H=0.49$ kOe. In the system Ni^{2+}:Al_2O_3 at $H\|z$ the signal transition for which $\Delta m=2$ is fully allowed for sound, and the pump transition for which $\Delta m=1$ is fully allowed for the electromagnetic field. The large value of the ratio ν_p/ν_s favors the attainment of effective population inversion of the signal doublet $|\pm1\rangle$.

The phaser experimental setup in which the amplification and generation of phonons was investigated is close to that described earlier in Ref. 1. The principal phaser element is an acoustic resonator cut from an Ni^{2+}:Al_2O_3 single crystal in the form of a cylinder with geometric axis along the x axis and with plane-parallel end faces, on one of which a thin-film hypersonic converter was deposited for the excitation of hypersound in the crystal and for the registration of the phaser radiation. To concentrate the pump field in the acoustic resonator, the latter was placed along the axis of a tunable electromagnetic cylindrical resonator tuned to the pump transition frequency. The pump-resonator Q at helium temperatures was 10^4.

With increasing pump power, the resonant absorption of the hypersound gives way to amplification. We registered amplification of both the longitudinal and the slow and fast transverse waves. At $T=1.8$ K and at a pump power 10 mW, the gain for these waves amounts to 0.32, 0.78, and 1.6 dB/cm, respectively. The inversion coefficient is $I=4.8$. Figure 1 shows oscillograms of the echo-pulse series for fast transverse sound in the passive regime and in the regime of the pre-threshold amplification. For fast transverse hypersound we also attained an excess of gain over the

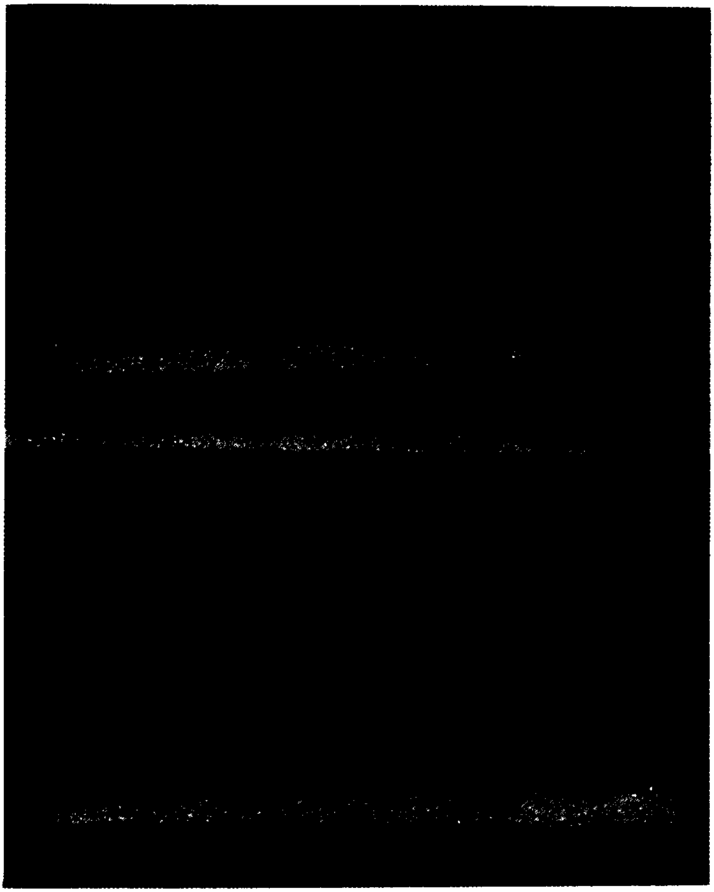

FIG. 1. Sequences of echo pulses of fast transverse hypersound of frequency 3 GHz along the x axis in the Ni^{2+}:Al_2O_3 system. Sweep duration 215 μsec. $T=1.8$ K: a—pre-threshold phaser-amplification regime, b—passive regime (without amplification).

phonon losses, and this made it possible to realize phaser generation of transverse phonons. In continuous pumping strictly at the center of the Ni^{2+} line, phaser generation was observed with integrated phonon-flux intensity not less than 10^{-6} W/cm^2. The generation occurs not in the entire above-threshold region of the gain line, but only in a small vicinity of its peak, in a magnetic field interval ≈ 1 Oe, whereas the width of the above-threshold region is 6–7 Oe. This character of the phaser-radiation spectrum corresponds to the conditions of spatially non-uniform excitation of the generating system, which were considered in Ref. 1.

A phenomenon of considerable interest from the point of view of phaser generation was observed by us in the case of continuous frequency-manipulated pumping when, at a fixed value of the magnetic field, the frequency of the pump source passed within a time on the order of 1 msec through the resonances of the electromagnetic pump resonator in an interval ± 50 MHz relative to the peak of the pump line. The

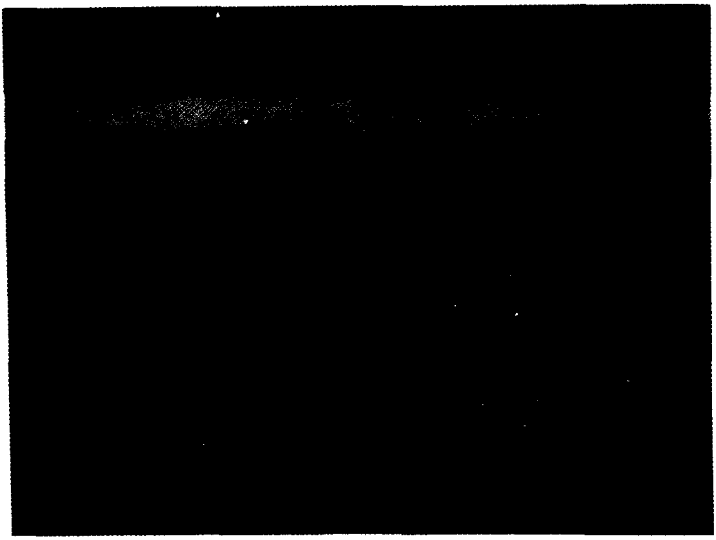

FIG. 2. Pulsed phaser generation of fast transverse phonons in the case of frequency-manipulated intermittent pumping. The repetition period of the pump pulses is 20 msec, $T = 1.8$ K.

phaser generation in this case acquired a regular pulsed character (Fig. 2) and, most importantly, the intensity of the phaser radiation increased by more than one order of magnitude compared with the continuous pump regime. In the regime of frequency-manipulated pumping, we observed also a 20–30% increase in the gain of both the transverse and the longitudinal waves.

The cause of such a large increase of the intensity of the generation is not yet clear, but it can be assumed that nonstationary thermodynamic phenomena come into play here, analogous to those investigated by us earlier in a ruby phaser,[1] when the large heat capacity of the nuclear spin pool exerts a substantial influence on the increase of the spin temperature of the pump system when the saturation conditions vary rapidly in this system.

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