Hypersound amplification by an intense hypersonic field in ruby

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This letter reports the first observation of an amplification of hypersound in the course of a stimulated emission of phonons in ruby in which a population inversion among spin levels has been created by an intense hypersonic wave.

As a hypersonic wave propagates through a crystal containing paramagnetic centers and modulates the internal electric field in the crystal, it acts on the system of electron energy levels belonging to these paramagnetic centers if the conditions for an acoustic paramagnetic resonance are satisfied. There is accordingly the possibility of using an intense hypersonic wave to create in such a system states which are highly nonequilibrium states in the thermodynamic sense. One such state might have a population inversion between a selected pair of levels. In this case a convective instability would arise and would be manifested by an amplification of a weak hypersonic signal. This instability would be driven by a stimulated emission of phonons by the paramagnetic centers.

Since the interaction of hypersound with a system of paramagnetic centers is of a quadrupole nature, in contrast with that in the case of an electromagnetic field, where the transitions allowed between levels consist not only of those involving a change in magnetic quantum number $\Delta M = \pm 1$ but also of those with $\Delta M = \pm 1, \pm 2$ [sic], the possibilities of using induced emission with a hypersonic pump are considerably richer than those presented by the use of an electromagnetic pump. Electromagnetic pumps are widely used in amplifying electromagnetic and hypersonic[1] microwave signals.

Although the idea of creating an inverted state of paramagnetic centers by means of an intense hypersonic field dates back some time,[2] it has yet to be experimentally confirmed. Whether electromagnetic (or hypersonic) signals can indeed be amplified by paramagnetic centers activated by a hypersonic field has thus remained an open question.

In this letter we report the first experiment on the amplification of a weak hypersonic signal in a paramagnetic system, in which a population inversion among electron spin levels has been produced by the application of an intense hypersonic field. As the active medium we selected a crystal of pink ruby with a chromium concentration of 0.03%. We used a symmetric arrangement of spin levels, with a magnetic field oriented at an angle $\varphi = \cos^{-1}(1/\sqrt{3})$ with respect to the optic axis of the crystal. A hypersonic field was produced in the ruby when a cw longitudinal hypersonic wave with a frequency of 23 GHz propagated through it, along the optic axis. In a magnetic 3.9-kOe field, this hypersonic field sets up a simultaneous resonant saturation of the transitions between equidistant spin levels $E_1 - E_3$ and $E_2 - E_4$ (the levels are numbered in order of increasing energy), and it creates a state of a population inversion on the $E_2 - E_3$ transition. This inversion is required for amplifying a weak pulsed signal of a longitudinal hypersonic wave with a 9-GHz frequency, which corresponds to this transition.

The ruby crystal used as the sample in which the hypersound was amplified was a rod of circular cross section with a diameter of 2.6 mm and a length of 17.6 mm. The optically flat ends of the rod were parallel. The geometric axis of the rod was directed along the threefold symmetry axis of the crystal. This propagation direction for the hypersound and this orientation of the rod in the magnetic field resulted in an efficient interaction of the longitudinal hypersonic wave with paramagnetic centers at the frequency ν_p of the $E_1 - E_3$ and $E_2 - E_4$ transitions and also at the frequency ν_s of the $E_2 - E_3$ transition, with the population inversion. A wide-band hypersonic transducer was vacuum-deposited on one end of the rod; this transducer simultaneously excited an intense longitudinal hypersonic wave along this axis and a weak pulsed hypersonic signal at these frequencies. The transducer consisted of a piezoelectric zinc oxide film, 0.4 μm thick, with an aluminum sublayer, deposited on the end of the rod. The microwave electric field was concentrated in this aluminum sublayer. The concentration of the field at the frequencies ν_p and ν_s was carried in the same part of the film by means of a thin metal needle, with an optically flat end, pressed tightly against the surface of the film. This needle was used to maintain the electromagnetic field, along with the two-frequency waveguide resonator system shown schematically in Fig. 1. The particular diameter chosen for the end of the needle, $D \approx 5 \times 10^2 \lambda$, where λ is the hypersonic wavelength at the frequency ν_s, made it possible to produce a hypersonic wave with a relatively high intensity in the crystal, with only a slight diffractive divergence of the wave at these frequencies. As a result, the intense hypersonic wave and the weak (signal) hypersonic wave were excited in and propagated through the same region of the crystal. This region had the shape of a straight filament with a cross-sectional diameter equal to the diameter of the end of the needle. In this region, the transitions between the levels of paramagnetic centers were saturated by the hypersonic field, and the weak hypersonic pulse was amplified by stimulated emission. The aluminum sublayer in the hypersonic transducer served not only to concentrate the

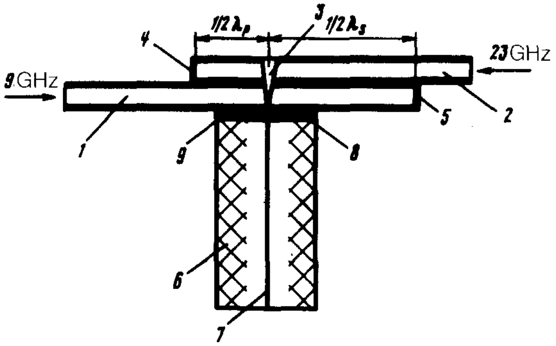

FIG. 1. Two-frequency waveguide-resonator system for amplifying hypersound in ruby in the field of an intense hypersonic wave. 1, 2—Signal and pump waveguides; 3—needle; 4, 5—short-circuiting plungers; 6—ruby; 7—region in which the hypersonic signal and the pump wave propagate; 8—zinc oxide film; 9—aluminum film; λ_s, λ_p—lengths of the electromagnetic waves in the signal and pump waveguides.

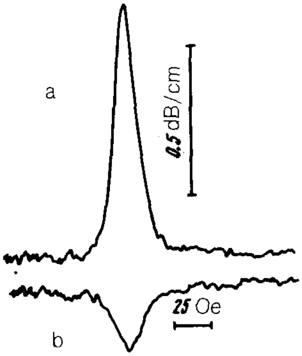

FIG. 2. a—Resonant amplification of a hypersonic signal in the field of an intense hypersonic pump wave; b—acoustic-paramagnetic-resonance line.

electric field but also to protect the crystal sample from the direct effect of the microwave electromagnetic field.

Experiments were carried out at a temperature of 1.7 K, at which a hypersonic field, even one of low intensity, causes a substantial change in the state of the spin system in ruby, and an amplification of hypersound comparable to the nonresonant absorption of hypersound in the crystal can be achieved. The experimental results are shown in Fig. 2.

In the absence of the intense hypersonic wave we observe the ordinary acoustic paramagnetic-resonance involving Cr^{3+} ions (Fig. 2b). As it propagates through the crystal, the acoustic-paramagnetic-resonance line becomes inverted (Fig. 2a), and the hypersonic signal is amplified. This amplification increases monotonically with increasing intensity of the wave and eventually hits a plateau; it reaches a value of 0.8 dB/cm at an intensity $S_p = 5$ mW/cm^2. This figure corresponds to an effective inversion coefficient $I_s = 4.2$. The nonresonant absorption of the longitudinal hypersound at the frequency of 9 GHz in the ruby sample was 1.2 dB/cm.

The inversion coefficient achieved here is substantially higher than the maximum value $I_m = 3.3$ which has been achieved in maser and also laser experiments.[1] This substantial increase can be explained in the following way: In those previous experiments the amplification which was observed was an amplification of an electromagnetic signal and also of a hypersonic signal with electromagnetic pumping. In that situation, all the paramagnetic centers in the sample were subject to the inversion; the propagation of the amplified signal occurred through a uniformly inverted active crystal and was accompanied by a diffractive divergence of the hypersonic wave. In the present experiments, in contrast, the only paramagnetic centers that are inverted are those which are in the region occupied by the intense hypersonic wave. The hypersonic signal thus propagates through a sort of waveguide channel, formed by the intense hypersonic wave as a result of saturation of the resonant dispersion of the phase velocity of the hypersound.[3] In this case, the diffractive loss is reduced substantially; estimates show that the effective gain for the hypersound is increased by the same amount.

The hypersonic gain achieved here is approaching the threshold value set by the loss in the crystal. Accordingly, the use of low-loss crystals will make it possible to achieve a self-generation of coherent phonons in the intense hypersonic field.

[1] E. M. Ganapol'skiĭ and D. N. Makovetskiĭ, Zh. Eksp. Teor. Fiz. **72**, 203 (1977) [Sov. Phys. JETP **45**, 106 (1977)].
[2] E. M. Ganapol'skiĭ, in: Proceedings of the Tenth All-Union Conference on Acoustoelectronics and Quantum Acoustics [in Russian], Tashkent, 1978, p. 4.
[3] E. M. Ganapol'skiĭ, Zh. Eksp. Teor. Fiz. **65**, 2421 (1973) [Sov. Phys. JETP **38**, 1209 (1973)].

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