Excitation of coherent electromagnetic waves in the microwave range in ruby by the field of artificial resonant phonons

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The first observation of the excitation of coherent electromagnetic waves in the microwave range in ruby by the field of artificial resonant phonons, produced by means of a stochastic acoustic instability, is reported.

Paramagnetic centers in a dielectric crystal are known to exchange energy with the lattice at low temperatures through direct (one-phonon) processes. As a result, the equilibrium population of low-lying levels is established as a result of a coupling with resonant thermal phonons in a narrow frequency interval. On the other hand, the

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coupling of the resonant phonons with the other, i.e., nonresonant phonons through the anharmonicity of the crystal lattice is extremely weak, as is demonstrated by the weak attenuation of hypersound in the crystals at low temperatures.[1] The resonant phonons thus emerge as a distinct subsystem, which has its own effective temperature T_{ph} and which is in thermal contact with the paramagnetic system formed by the low-lying energy levels.[2]

The following idea then arises naturally: If artificial resonant phonons, i.e. elastic waves with a suitable spectrum which are incoherent in space and time and which have a flat distribution among states, as thermal phonons do, are excited in a crystal, then they can be used to control the effective temperature of a paramagnetic system. In particular, they can be used to create a population inversion among the levels and to thereby set the stage for the excitation and amplification of coherent electromagnetic waves.

In the present study we have, for the first time, used artificial resonant phonons to create a population inversion among the spin levels in ruby and to achieve the excitation of coherent electromagnetic waves in the microwave range with a high frequency stability. The artificial resonant phonons are produced in the crystal by means of a stochastic instability for sound waves in the crystal. For this purpose, a coherent hypersonic wave was excited in the ruby. To convert this wave into artificial phonons, we reflected it from a surface of the sample with a negative curvature; this process causes a stochastic instability.[3] The result was the disappearance of the spatial coherence: Elastic waves coming out of the small region occupied by the hypersonic wave propagated along the entire sample; the amplitude, phase, and polarization of these waves at a given point in the sample became random. The resonant interaction of the waves with paramagnetic centers coupled in a dipole-dipole manner caused a spectral diffusion of magnetic excitations and also of phonon excitations coupled with the latter. The result was a disruption of the temporal coherence of the waves with a time scale $T_2^+ = \Delta\nu^{-1}$, where $\Delta\nu$ is the frequency width of the paramagnetic-resonance line.

To achieve this excitation effect, we used a ruby crystal with a chromium concentration of 0.03%. The sample was a circular rod 2.6 mm in diameter and 17.6 mm long, directed along the optical axis. A "point" transformation along this axis was used to excite a narrow beam of a longitudinal hypersonic wave at a frequency of 23 GHz. For this purpose, a hypersonic transducer based on a zinc oxide film 0.4 μm thick with an aluminum sublayer was fabricated at one end of the rod. The sublayer had a thickness of 0.15 μm and protected the ruby sample from the direct effect of the microwave electromagnetic field. As the hypersonic beam, 0.5 mm in diameter, propagated along the axis of the rod, it was reflected from the second end, which was a concave spherical surface with a radius of curvature of 0.5 mm. As a result of an instability, the wave was scattered.

After numerous rereflections from the rough lateral surface, with a roughness height $d \gg \lambda_s$, where λ_s is the hypersonic wavelength ($\lambda_s = 2.7 \times 10^{-5}$ cm) the entire volume of the crystal sample became filled uniformly with stochastic hypersonic waves.

Treating the hypersonic beam in the geometric-acoustics approximation,[1] which corresponds to the experimental conditions, we can work from Ref. 3 to estimate the time scale for the disruption of coherence (the growth rate of the stochastic instability): $\tau_1 = \tau_0 \ln^{-1}(L/R)$, where R is the radius of curvature of the reflecting surface, and τ_0 and L are the transit time and distance between the reflecting surfaces. In our case we have $\tau_0 = 1.5\times 10^{-6}$ s, $\tau_1 = 4\times 10^{-7}$ s, and $T_2^+ = 1.6\times 10^{-8}$ s.

The field of artificial resonant phonons at a frequency of 23 GHz created a population inversion among spin levels with a transition frequency of 9.1 GHz in the ruby. The conditions in the crystal corresponded to a symmetric arrangement of the spin levels, with the magnetic field directed at an angle $\varphi = \arccos(1/\sqrt{3})$ with respect to the axis of the sample. The magnetic field strength was 3.9 kOe. To achieve excitation, we placed the ruby rod in a cylindrical volume resonator, in which H_{011} waves were excited (Fig. 1). At a temperature of 1.7 K the loaded Q of the resonator was $Q_H = 2.5\times 10^4$, and the magnetic Q was $Q_m = 2.8\times 10^3$. Since the relation $Q_H \gg Q_m$ holds, the excitation threshold corresponds to a situation in which the population of the upper level is just barely greater than that of the lower level for the transition frequency of 9.1 GHz, with an inversion coefficient $I_t = 0.1$. In order to exceed this threshold, according to calculations based on the kinetic equations for the populations in a system of four spin levels, it is necessary to raise the effective spin temperature of the transition between levels with a frequency of 23 GHz and to introduce 3×10^{11} artificial resonant phonons in the crystal for this purpose.

When an electromagnetic power of about 1 mW was applied to the hypersonic transducer, an excitation of coherent electromagnetic waves occurred at 9.1 GHz. Since the power coefficient of the conversion of the electromagnetic field into hypersound is 10^{-4}, and since the lifetime of the resonant phonons—estimated from measurements of the attenuation of hypersound in insulating crystals at low temperatures[1]—is $\tau_{ph} \approx 10^{-5}$ s, the Debye model brings the number of artificial resonant phonons which are required in the crystal in order to reach the excitation threshold into a satisfactory agreement with the estimate above.

As the number of artificial resonant phonons introduced into the crystal is increased, the excitation power increases monotonically and then reaches a saturation region. When the extent to which the number exceeds the threshold is $\approx 10^2$, we

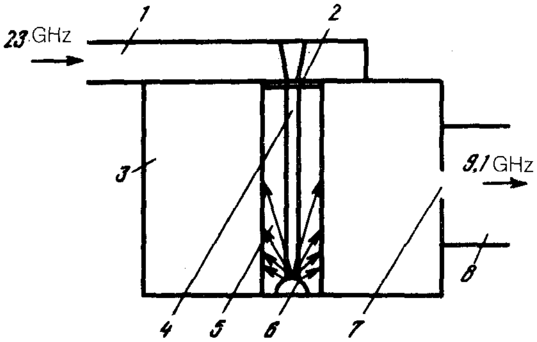

FIG. 1. Arrangement for achieving the excitation of electromagnetic waves in the field of artificial resonant phonons. 1—waveguide for exciting hypersound at the frequency 23 GHz; 2—hypersonic transducer; 3—volume resonator; 4—hypersound beam; 5—ruby rod; 6—concave spherical surface; 7—coupling aperture; 8—waveguide for the radiation of coherent electromagnetic waves at 9.1 GHz.

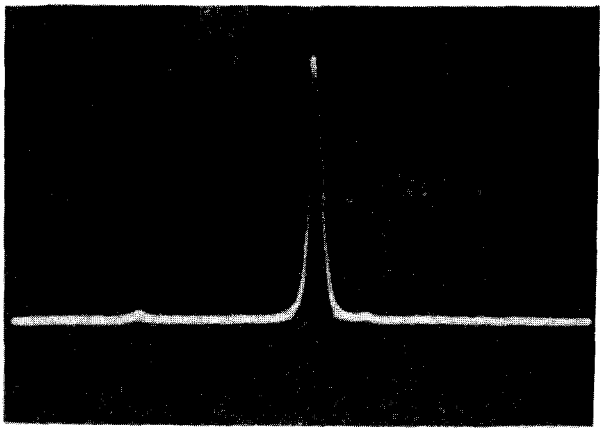

FIG. 2. Spectrum of the excitation of electromagnetic waves at 9.1 GHz. The frequency scale is shown by the markers, which are separated by 100 kHz.

observe a stable, steady-state excitation with an output power of 5×10^{-7} W in this region. The output spectrum is shown in Fig. 2. In a regime of steady-state excitation we measured the frequency stability of the electromagnetic waves which were radiated. Over a time on the order of 1 s the relative change in the frequency did not exceed 10^{-9}.

The realization of an excitation effect shows directly that during the excitation of a coherent hypersonic wave in a crystal under conditions corresponding to a stochastic instability some artificial resonant phonons appear. These phonons are similar to thermal phonons with a high effective temperature. As they interact with paramagnetic centers, they can selectively raise the spin temperature corresponding to a particular pair of energy levels. Since the attenuation of these phonons in a crystal is extremely slight at low temperatures, it is completely realistic to produce artificial resonant phonons with $T_{ph} = 10^4$ K in a crystal. Such phonons can be used as an instrument for studying the kinetic properties of solids.

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