“Point-centered” excitation of coherent hypersound in the millimeter radioband

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High efficiencies have been attained in the excitation, transmission, and reception of hypersound at 37 GHz. Transmission of hypersound through a metallic film at this frequency has been attained for the first time.

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Hypersound research now spans an appreciable frequency band, up to 10 GHz. Further increase of the frequency of coherent hypersound and the mastery of frequencies in the millimeter and submillimeter radiobands is of considerable interest. The submillimeter hypersound wavelength at 1 THz is already close to the limit of the acoustic mode of crystal-lattice vibrations, and at the same time its damping is small at liquid-helium temperature.[1] These circumstances make for attractive possibilities of using millimeter and submillimeter hypersound in spectroscopy, since the larger transparency of solids to hypersound and the specific selection rules for allowed transitions between the energy levels make it possible to study dynamic processes in states that are frequently not accessible to electromagnetic methods. A “resonator” method[2] and slow surface electromagnetic waves[3] were previously used to excite millimeter hypersound in piezoelectric crystalline quartz. In these experiments, however, the attained coefficient η of the double conver-

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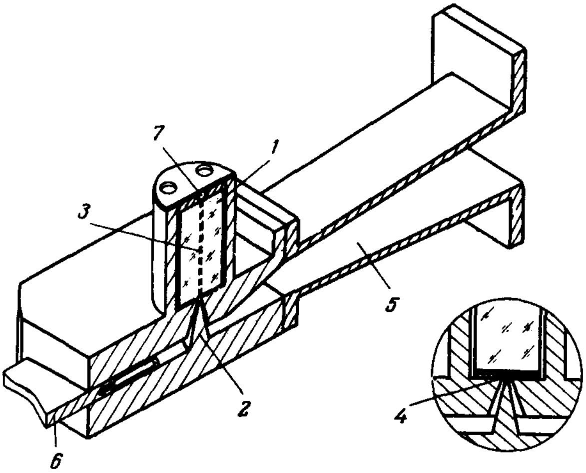

FIG. 1. Installation for the excitation of millimeter hypersound: 1—ruby crystal, 2—needle, 3—hypersound beam, 4—piezoelectric film with metallic sublayer, 5—waveguide junction, 6—waveguide plunger, 7—detail of crystal mounting.

sion of the electromagnetic field into hypersound and back is relatively small, $\eta \approx 10^{-8}$–10^{-10}. For an active use of millimeter hypersound in solid-state investigations it is necessary to be able to receive it with much higher efficiency, and also to transmit it from one solid to another.

To excite hypersound, a piezoelectric crystal bounded by two parallel planes oriented perpendicular to the piezoelectric axis is placed in an external microwave electromagnetic field. This field excites at one of the boundary planes (excitation plane) elastic strains that serves as the source of the volume hypersound, which propagates towards the other boundary plane (receiver plane) and is transformed there into an electromagnetic field. It is easy to show that the expression for the double conversion coefficient is of the form $\eta=\kappa^2 k_e^2 k_s^{-2} Q^2 \chi(\phi)$, where κ is the electromechanical coupling coefficient, k_s and k_e are the characteristic wave numbers of the hypersound and of the electromagnetic field along the normal to the boundary surface, Q is the factor of multiplicity of the interaction of the electromagnetic field with the piezoelectric crystal (if the hypersound is excited with the aid of a cavity resonator, then $k_e=1/h$, where h is the height of the "capacitive" gap, and Q is the figure of merit of the resonator[4]), $\chi(\phi)$ is a factor characterizing the phase coupling of the elastic oscillations in the plane of the receiver during the inverse conversion, and ϕ is the angular deviation from parallelism between the receiver plane and the phase front of the hypersound waves. It is possible to approximate $\chi(\phi)$ by the function $(k_s d_r \phi)^{-2} \sin^2(k_s d_r \phi)$, ($d_r$ is the dimension of the receiving region in the plane of the phase front of the hypersound wave). For effective excitation of hypersound it is necessary to realize the condition $k_e/k_s \simeq 1$; in other words, it is necessary to concentrate the electromagnetic field in a region whose dimension along the normal to the excitation plane is of the order of the millimeter-hypersound wavelength (10^{-6} cm). It is also necessary to ensure phase coupling when converting the millimeter hypersound into an electromagnetic field, i.e., $\chi(\phi) \approx 1$, hence the restriction on the permissible angle $\phi_m \leqslant (k_s d_r)^{-1}$.

We have solved this problem by using "point-centered" excitation and reception of millimeter hypersound, in the form of a thin needle-like beam on a base of textured piezoelectric films with metallic sublayer. The use of this method is based on the following. With increasing frequency, at fixed d_r, the permissible angle ϕ_m decreases. When the methods indicated above are used for the

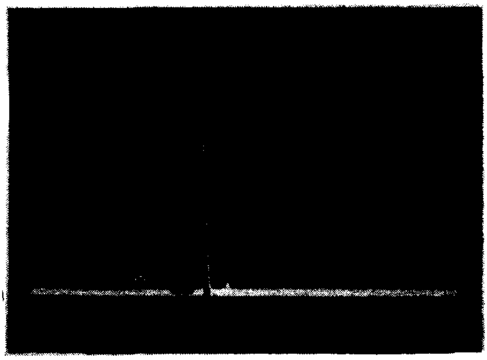

FIG. 2. Hypersonic echo signals in ruby at 37 GHz. The sound impulse is suppressed by selection. $T=4.2$ K.

excitation, this angle becomes so small that its realization is one of the main difficulties in the application of millimeter hypersound. By decreasing the cross section of the hypersound beam, and accordingly d_r, it is possible to increase ϕ_m substantially. The lower bound of d_r is imposed by the diffraction divergence of the beam, the role of which is small so long as $d_r > 2\sqrt{\lambda_s L}$ (λ_s is the wavelength of the hypersound and L is the length of the acoustic path). To excite a thin beam one can use half-wave textured films of piezoelectric materials deposited by vacuum evaporation on the surface of the sample. This surface is coated beforehand by a metallic sublayer of thickness $\rho < \lambda_S$, needed to concentrate the microwave electric field in the piezoelectric film. Since the beam cross section is small, the region of the piezoelectric film to which it is necessary to apply the electric microwave field is likewise small (hence the "point-centered" excitation). It is important that this film region, which serves as an antenna, has an impedance on the order of the wave resistance of the transmission line and can therefore be matched to it in a wide frequency band.

On the basis of the foregoing reasoning, we realized excitation, transmission, and reception of longitudinal hypersound at 37 GHz in a ruby crystal at low temperatures (4.2–77 K). The crystal sample was a round rod of 2.6 mm diameter and 13 mm length. The geometric axis of the rod was oriented along a threefold symmetry axis. The end faces of the rod were optically flat and parallel (roughness less than 0.1 μm, deviation from parallelism less than 1"), and one of the faces was coated by vacuum evaporation with a textured ZnO film with an Al sublayer. The thicknesses of the film and of the sublayer were 0.3 and 0.12 μm, respectively. The film preparation procedure was described previously.[5] The "point-centered" excitation of the hypersound in ruby was effected with the aid of the device shown in Fig. 1. Its principal element is a metallic needle placed in a waveguide, the microwave electric field being concentrated between the end of the needle and the sublayer in the ZnO films. The waveguide is a rectangular slot cut in a metallic disk and having a cross section of variable height. The needle is located in the narrower section of the waveguide, and the end face of the needle, of 0.07 mm diameter has a flat surface placed flush against the flat surface of the disk, the two of them being being finished with optical precision. Since the film texture axis is directed along the normal to the end face, a longitudinal hypersonic wave is excited in the film, passes through the metallic sublayer, and propagates in the ruby rod. After reflection from the opposite end face of the rod, this wave returns to the same film and is transformed into an electric microwave-field signal registered by a receiver. The value of η at 37 GHz, with the losses to transmission and propagation of the hypersound in the sublayer and in the ruby taken into account, was not less than 10^{-5}; the transducer band width was approximately 1 GHz.

It should be noted that in the described experiment we succeeded, for the first time ever, in realizing transmission of hypersound of so high a frequency through a thin aluminum film. This offers definite possibilities for investigation of metals with the aid of millimeter hypersound, especially superconductors, under conditions when the hypersound elastic-oscillation quantum is of the order of the energy gap of the superconductor at zero temperature.

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