AMPLIFICATION OF 9.3-kMc/sec ULTRASONIC PULSES BY MASER ACTION IN RUBY

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The observation of the attenuation of 9.3-kMc/sec ultrasonic pulses by the spin-phonon interaction[1] in ruby implies that amplification should be observable in the same system if the spin population is inverted. We have now observed the amplification of 9.3-kMc/sec pulses of ultrasonic energy in passing through a ruby rod in which the spin system was inverted. This is the first observation of amplification of energy other than electromagnetic in such a system.

The conditions for the observation of maximum gain from the inverted spin system are identical with the conditions for the observation of the maximum attenuation except for the inversion, rather than the normal thermal equilibrium, of the spin system. The published results for attenuation in ruby[1] show that one of the highest ultrasonic interactions occurs, for longitudinal waves, at an angle of 60° between the magnetic field and the ruby c axis ($\theta = 60°$) for the 2-3 transition at high field (3700 gauss for 9.3 kMc/sec). Fortunately, the conditions for use of push-pull pumping[2] (saturation of both the 1-3 and the 2-4 transitions) at a single frequency occur at $\theta = 55°30'$. The actual orientation used for the experiment is a compromise between the above requirements. Since the ultrasonic transition probability is a slow function of angle near $\theta = 60°$, it was found that the best inversion was obtained at an angle of 56° using pump power of 23.3 kMc/sec.

The experimental observations were made using the same methods previously described[1] except that the ruby was contained in a K-band pump cavity. The crystal configuration consists of a $1\frac{1}{2}$-cm X-cut quartz crystal bonded, with indium, to a $1\frac{1}{4}$-cm length of Linde pink ruby (Cr^{+++} in Al_2O_3). Both crystals are in the form of cylindrical rods 3 mm in diameter and the c axis of the ruby is parallel to the rod axis to within $\frac{1}{2}$ degree. The experiments were carried out at 1.5°K.

The traces of Fig. 1 illustrate the effects of the spin system on the first few echoes observed. The echo to the right of the center graticule has made a single return trip through the ruby while the echo to the left of center has made two passes through the ruby. The larger amplitudes of these two echoes in the top picture as compared to the bottom trace is due to the amplification through interaction with the spin system. Similarly, the smaller amplitudes of the center trace as compared to the bottom are the result of attenuation due to transfer of energy to the spin system in thermal equilibrium at 1.5°K. The gain observed is 0.12 per centimeter of travel in the ruby.[3] This is somewhat higher than the attenuation of 0.09 per centimeter and is an indication of the efficiency of inversion.

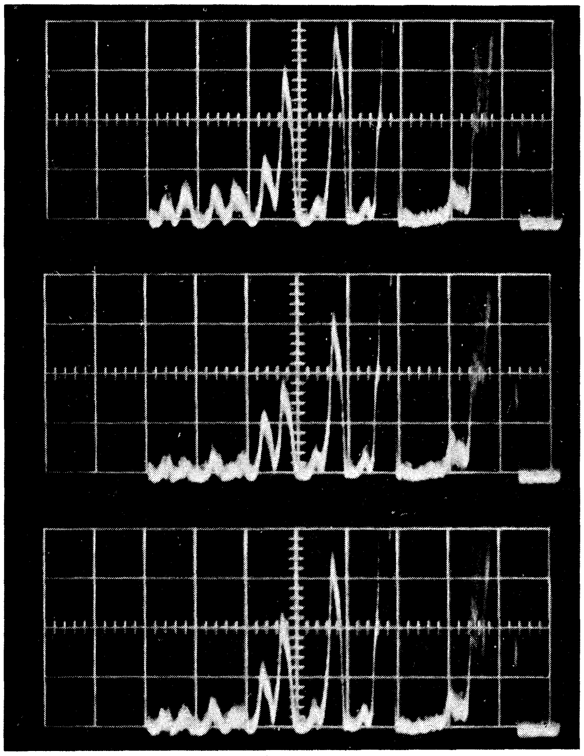

FIG. 1. Echo patterns observed for 9.3-kMc/sec ultrasonic pulse of 0.5-microsecond duration. Large echoes to the right and the left of the center graticule have passed through the ruby once and twice, respectively. Time increases from right to left. Top picture: magnetic field on resonance line and pump on. Center picture: magnetic field on resonance line, no pump. Bottom picture: magnetic field off resonance line.

The slower traces of Fig. 2 illustrate much more graphically the magnitude of the effect. The upper picture shows clearly a number of

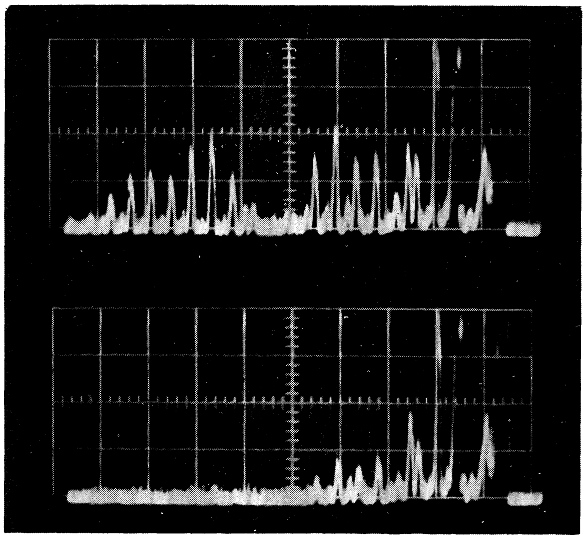

FIG. 2. Echo patterns observed for 9.31-kMc/sec ultrasonic pulse of 0.5-microsecond duration. The change in frequency accounts for the amplitudes of the first few echoes being different from those of Fig. 1. Sweep speed of oscilloscope is about 5 microseconds per centimeter. A round trip through the ruby requires 2.1 microseconds. Time increases from right to left. Top picture: magnetic field on resonance line and pump on. Bottom picture: magnetic field off resonance line.

echoes not visible without the aid of the amplification. From the spacing of these echoes it can be surmised that they are due to pulses which have traveled back and forth in the ruby for as many as eighteen round trips; and that their only traversal of the quartz has been the 3 cm travel to get to the ruby initially and, after the reflections in the ruby, to get back to the transducer end again. Echoes from the bond are almost nonexistent after 10 microseconds. The beating due to phase interference caused by the nonparallel ends and bond as well as crystal inhomogeneities and misalignment is very evident in the top trace of Fig. 2.

The physical perfection required to determine the true propagation characteristics of the quartz-indium-ruby combination is lacking, and hence conclusion of whether or not the gain obtainable from the spin system is sufficient to overcome the system losses is impossible. It is fairly obvious what conditions must be satisfied in order to realize over-all gain, i.e., a phonon maser. Just as in the case of the optical maser[4] the gain from the inverted population must be sufficient to overcome the losses due to attenuation in the materials and reflections at the ends of the cavity, in this case the optically polished ends of the crystals. If one assumes that an attenuation of 0.01 per centimeter (such as is observed in quartz[5]) is attainable in a good ruby crystal, the gain of 0.12 per centimeter is certainly sufficient. For appreciably higher losses either higher spin populations or spin systems with larger magnetoelastic coupling constants, or perhaps both, will be required.

This experimental demonstration of phonon amplification was undertaken after discussions, on the possibility of a phonon maser, with Dr. E. H. Jacobsen and Dr. N. S. Shiren. It is a pleasure to acknowledge their contributions.

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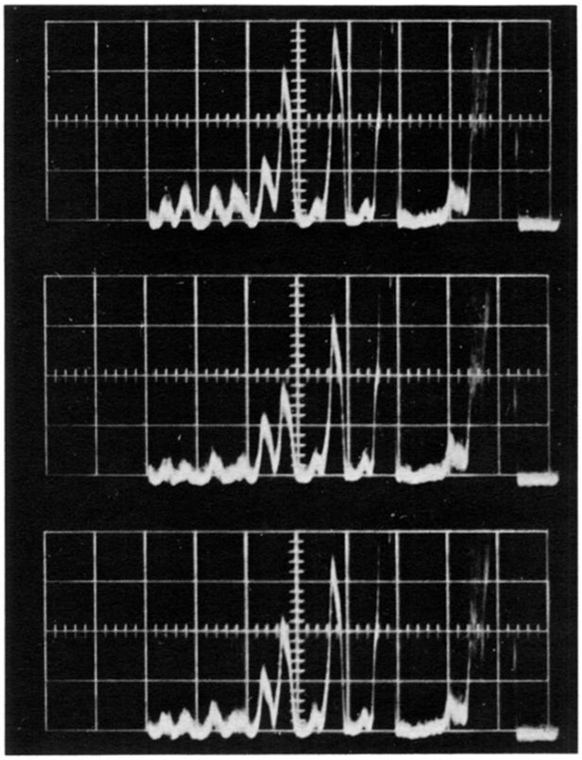
[1] E. B. Tucker, Phys. Rev. Letters 6, 183 (1961).

[2] C. Kikuchi, J. Lambe, G. Makhov, and R. W. Terhune, J. Appl. Phys. 30, 1061 (1959).

[3] The pictures illustrate amplitudes proportional to voltage whereas the attenuations and gains are referred to power.

[4] A. L. Schawlow and C. H. Townes, Phys. Rev. 112, 1940 (1958).

[5] E. H. Jacobsen (private communication); 0.01 per cm includes end losses for a 3-cm X-cut quartz bar.



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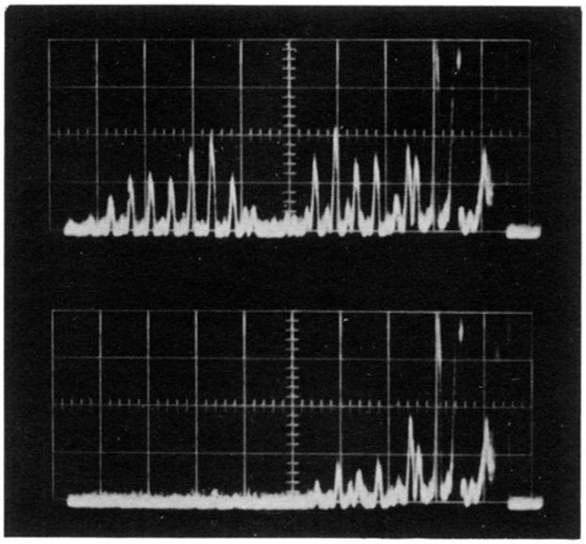

FIG. 2. Echo patterns observed for 9.31-kMc/sec ultrasonic pulse of 0.5-microsecond duration. The change in frequency accounts for the amplitudes of the first few echoes being different from those of Fig. 1. Sweep speed of oscilloscope is about 5 microseconds per centimeter. A round trip through the ruby requires 2.1 microseconds. Time increases from right to left. Top picture: magnetic field on resonance line and pump on. Bottom picture: magnetic field off resonance line.