Excitation of nuclear spin echo in magnetically ordered materials using subharmonics and multiple frequencies

V. I. Dudkin, V. Yu. Petrun'kin, and V. I. Tarkhanov
M. I. Kalinin Polytechnic Institute, Leningrad

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Observation of nuclear spin echo signals is reported in lithium ferrites and in thin cobalt films excited at $T = 300$ K and in the absence of an external, constant magnetic field at frequencies that are different from the resonance frequency.

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Intensive signals of the nuclear spin echo from ^{57}Fe nuclei were observed in polycrystalline lithium ferrite samples as a result of excitation of the spin system using the second through the ninth subharmonics. The exciting pulses were produced by one of the frequencies of the series: 35, 23.3, 17.5, 14, 11.6, 10, 8.75, and 7.8 MHz. The echo signals were always observed only at the frequency of the nuclear magnetic resonance (NMR) of ^{57}Fe equal to 70 MHz, irrespective of the excitation frequency. The experiments were performed by using the two-pulses and three-pulse technique. The relaxation times, which were measured from the decrease of the amplitude of the echo signals with increasing intervals between the exciting pulses, are close to the corresponding times for the nuclear spin system for resonance excitation, which are: $T_1 = 8$ msec and $T_2 = 1.2$ msec.

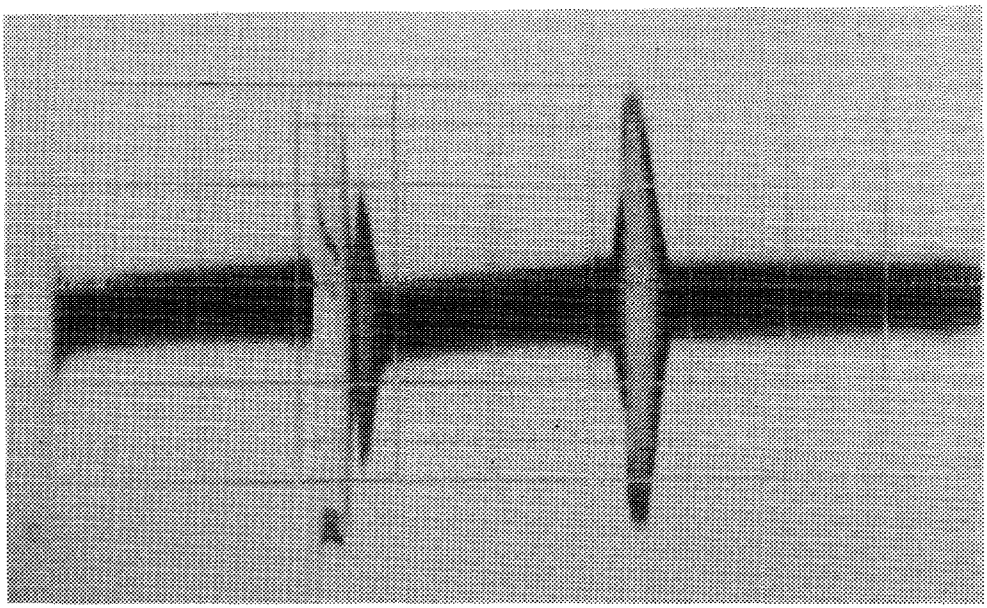

FIG. 1. Echo signal in lithium ferrite excited by two pulses of the second subharmonic (35 MHz). The pulse duration is $\tau_1 = 10$ μsec and $\tau_2 = 16$ μsec. The sweep duration is 50 μsec/cm.

In the experiments we used lithium ferrite samples enriched with ^{57}Fe isotope, which had the shape of a ring with outside diameter of 10 to 20 mm and with a mass of 0.5 to 3 g. The experiments were carried out at room temperature in the absence of the external magnetic field. The power of the exciting pulses was about 0.1 W.

The largest amplitude of the echo signals was observed as a result of excitation using the third subharmonic (23.3 MHz). The amplitude of these echo signals is comparable to that of the echo signals excited at the 70-MHz resonance frequency, if the power of the exciting pulses is the same. The amplitude of the echo signals decreases with increasing number of the subharmonic. The constraint imposed from below by the ninth subharmonic apparently has only an instrumental nature. Figure 1 shows an echo signal excited by two pulses at the second subharmonic (35 MHz).

The echo signals produced by a combined excitation were observed in the same samples. One of the exciting pulses was transmitted at the frequency of any subharmonic and the other (others) at the NMR frequency or at a frequency of the other subharmonic. The shape of the echo signals produced by subharmonic excitations or by combined excitation is analogous to that of the signals of the ordinary nuclear spin echo. The echo signal obtained as a result of a combined excitation at the fifth subharmonic (14 MHz) and the third subharmonic (23.3 MHz) is shown in Fig. 2.

The maximum delay of the echo signal relative to the first pulse due to a combined excitation according to the three-pulse method, when the first and the third pulse were transmitted at the NMR frequency (70 MHz) and the second pulse was transmitted at the frequency of the third subharmonic, is 0.1 sec. The signal-to-noise ratio in this case is equal to three.

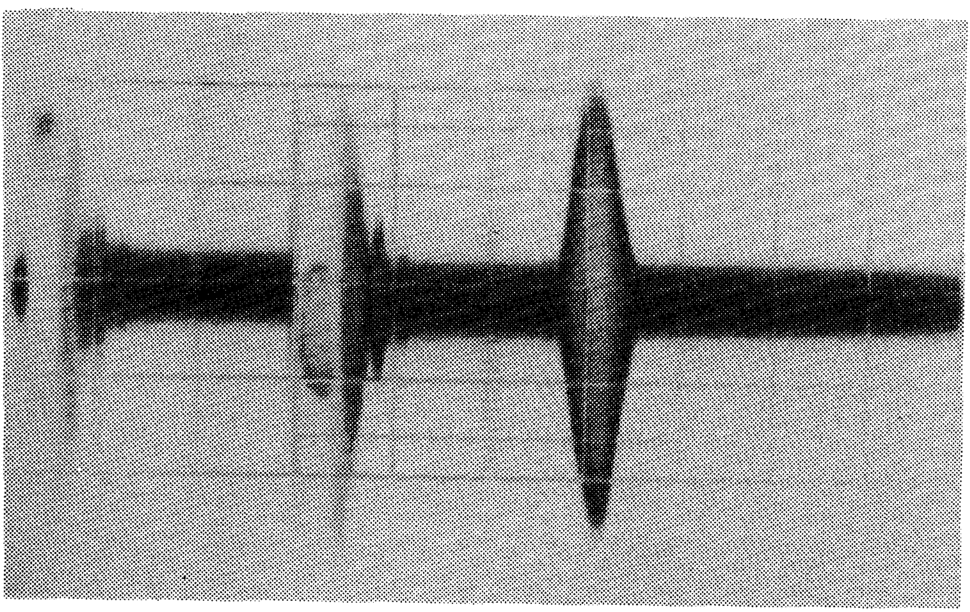

FIG. 2. Echo signal in lithium ferrite obtained as a result of a combined excitation by the fifth subharmonic (14 MHz) and the third subharmonic (23.3 MHz). The pulse duration $\tau_1 = 3$ μsec and $\tau_2 = 4$ μsec. The sweep duration is 10 μsec/cm.

A combined excitation of the echo signals makes it possible to combine the controlled delay of the signal with the frequency multiplication (with conversion to the NMR frequency). The subharmonic transmission of the delayed signal decreases the constraints imposed on the duration and power of the signal modified by the saturation effects and makes it possible to reproduce the shape of a longer signal at the same power level.

To verify the generality of the described effect for the magnetically ordered materials, we performed analogous experiments using thin cobalt films (NMR frequency 213 MHz). By exciting the spin system by the third subharmonic (71 MHz) at the NMR frequency, we were able to observe the echo signals comparable in intensity to those of the ordinary nuclear spin echo. We also observed echo signals due to a combined excitation at the frequencies of 71 and 213 MHz.

Excitation of the nuclear spin system of a magnetically ordered material using *multiple frequencies also produces a nuclear spin echo signal.* Thus, for example, we observed echo signals in lithium ferrite at the frequency of 70 MHz as a result of a combined excitation at the frequencies of 210 and 70 MHz. However, the intensity of these echo signals is much weaker than that produced as a result of subharmonic excitation.

The mechanism for excitation of the nuclear spin echo in magnetically ordered materials using subharmonics and multiple frequencies is not clear yet. Apparently, it differs from the Hahn mechanism[1] and from the parametric-echo mechanism,[2,3] in which the dynamic frequency shift plays the key role. Additional experiments must be performed to determine the role of the parametric and nonlinear effects in this mechanism.

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