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Cumulative NMR Stimulated Echo in Lithium Ferrite

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Abstract: *The results of the cumulative NMR stimulated echo phenomenon study in lithium ferrite are presented. This echo is generated by the joint action of a train of weak writing radio-frequency pulse pairs and final reading single radio-frequency pulse which exhibits the growth of intensity at increasing the number of exciting radio-frequency pulse pairs.*

Similar effect was earlier observed for the case of cumulative stimulated photon echo. The obtained results could be understood in the frames of a simple theoretical model of cumulative NMR stimulated echo formation.

Keywords: *NMR, lithium ferrite, stimulated echo, cumulative NMR echo, cumulative photon echo.*

1. Introduction

Recently we reported an unusual spin-echo phenomenon a so-called NMR single-pulse echo effect in cobalt and lithium ferrite, when a train of echoes generated by a repeating single radio-frequency (RF) pulse sequence exhibits the growth rather than damping [1].

Similar effect was earlier observed for photon echoes generated by a repeating two RF pulse sequence [2] and called as the cumulative two-pulse photon echoes. In this case also a train of echoes, generated by a repeating two-pulse sequence, exhibits a growth rather than damping.

This method was further developed in [3] where for the first time it was realized other mode of cumulative long-lived optical echo generation –cumulative stimulated photon echo (CSPE), which is clarified in Fig1.

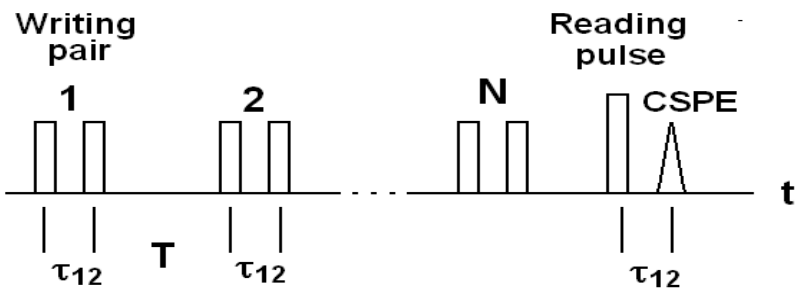

Fig1. *The excitation mode of CSPE with N writing pulse pairs and a final reading pulse.*

Here besides N identical pulse pairs a resonant medium is affected by the additional reading RF pulse.

In Fig.2a the oscillograms are presented illustrating this mode of CSPE excitation and the increase of these echo signals intensity with the increase of the identical pair number. This is also quantitatively shown on the I(N) graph, presented in Fig.2b.

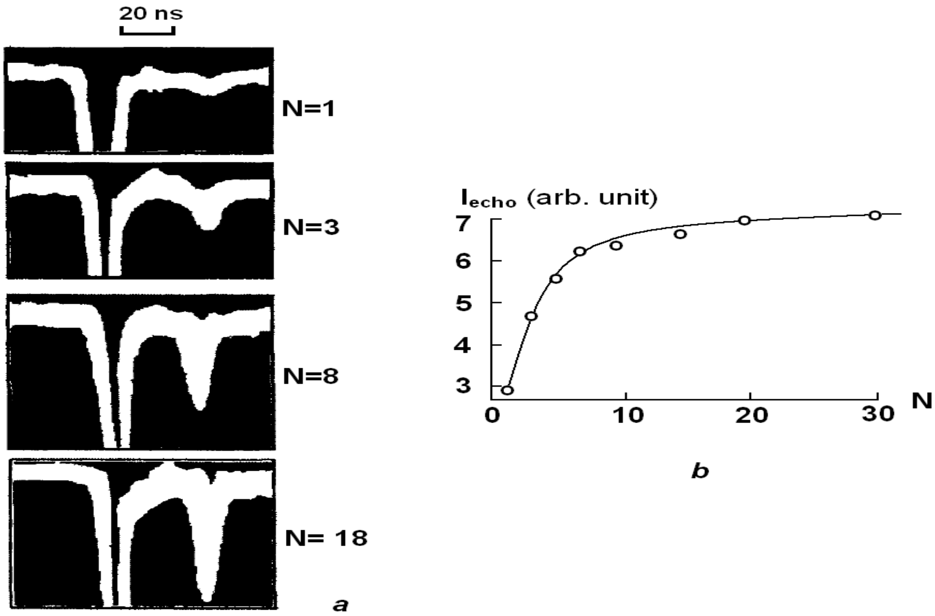

Fig2.a. *oscillograms illustrating the increase of CSPE signals with the increase of the number N of identical pulse pairs in $LaF_{31}Pr^{3+}$ crystal at temperature T=2.2 ; b - The CSPE intensity dependence on the writing pairs number N [3].*

It was shown that, firstly, the cumulative echo effect takes place only at small pulse areas of pulsed pairs ($<\pi/12$). Secondly, at small N the CSPE amplitude grows linearly and then at $N\geq15$ saturates due to the irreversible relaxation.

These experiments showed the possibility to increase of the maximum intensity with the increase of pairs number on the several orders in respect to the ordinary three pulse stimulated echo signal. This makes it possible to obtain the intensive CSPE signals using packets of small intensity pair pulses what essentially improves the energetic of optical memory operation on the basis of long-lived CSPE effect.

This method could be useful also in NMR and QMR allowing one to improve sensitivity of these techniques due to possibility of obtaining intensive cumulative echo signals using small power RF pulses, in particular, it could be used to improve sensitivity for the remote detection of explosives using QMR [4].

For experimental observation of three-pulse NMR cumulative stimulated echo (CSE) signals we use lithium ferrite due to its long spin-lattice relaxation times as compared with other magnets [5].

2. Experimental Results and Their Discussion

A standard phase-incoherent spin-echo spectrometer was employed for measurements in frequency range 40-400 MHz at temperature 77 K. In frequency range 40-220 MHz a standard self-excitation RF oscillator has been used. The frequency of oscillator could be gradually retuned by using a number of circuits with different inductance coils and adjustable capacities. In the frequency range 200-400 MHz it was used a commercial manufactured oscillator based on the two-wire Lekher-type line including two coils with different numbers of turns. For pulse lengths ranging between 0.1 and 50 μs a maximum RF field produced of the sample was estimated to be about 3.0 Oe, while the rise and fall times of RF pulse fronts were no more than 0.15 μs. The recovery time of the spectrometer characterizing the transient loss of its sensitivity following the RF burst, was about ~ 1 μs. For investigation of lithium ferrite the resonant system of spectrometer was modified similar to described in work [6] allowing us to increase sharply its sensitivity as compared with one in work [5].

In Fig.3 the block-scheme of modernized pulsed NMR spectrometer for observation of cumulative SPE effect is presented. The spectrometer was supplemented by the ATMEGA328P-PU (1), where the formation of the required RF pulse package takes place. The number of RF pulses belonging to a packet could be arbitrary. The repetition rate of packet spans range from the single triggering to the hundreds kilohertz ones.

The controller controls the pulse generator G5-7A (2) by the trigger input. Video-pulses generated by generator (2) are supplied to the pulse-amplifier and modulator (3) which sends high-voltage pulses to RF generator (4) then to the sample under investigation. The NMR echo signals formed in the samples are supplied to the receiver of the NMR spectrometer (5) where the additional enhancement and detection of signals takes place. The detected echo signal is finally sent to the digital oscilloscope (6) LeCroy 9410 for the final processing of signal.

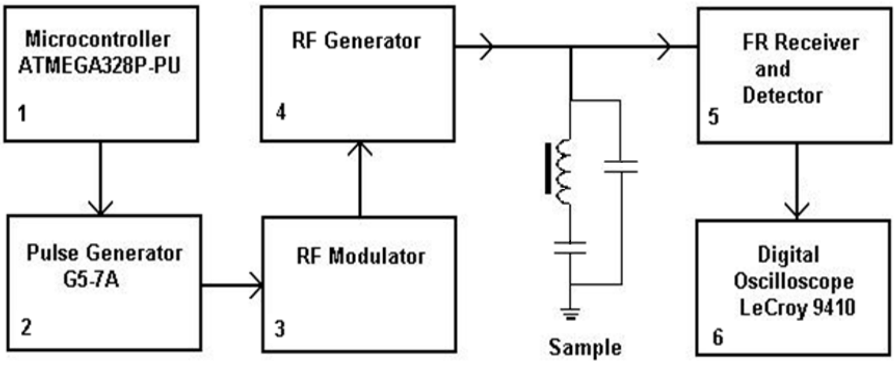

Fig3. *The block-scheme of noncoherent pulsed NMR spectrometer*

The circular discs of dielectric lithium ferrite and its solid solutions with zinc $Li_{0.5}Fe_{2.5-x}Zn_xO_4$ ($0\leq x \leq 0.25$) enriched by isotope ^{57}Fe (96.8 %) were used.

Measurements were carried out at liquid nitrogen temperature T=77 K to obtain the intensive echo signals and long spin-lattice relaxation times T_1 ~ 13ms. The echo intensity values were taken directly from the oscilloscope screen.

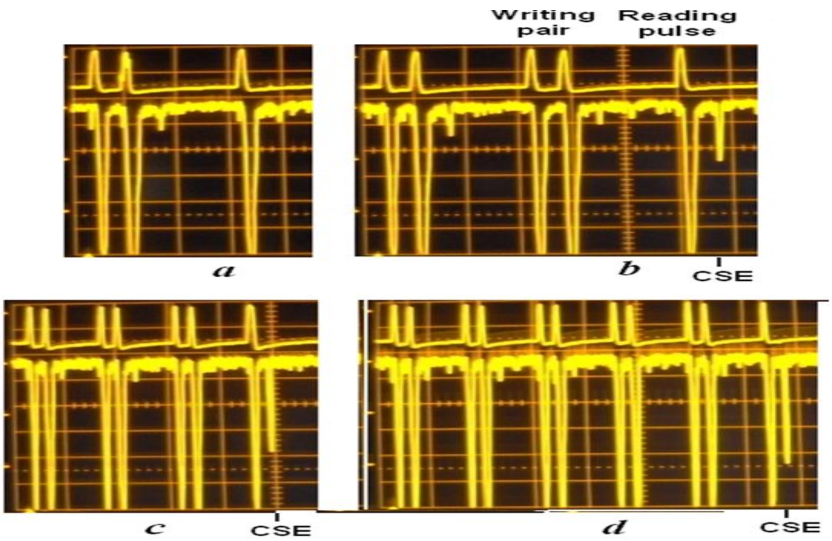

Fig4. *Cumulative NMR stimulated echo CSE in lithium ferrite: the echo amplitude grows as the number N of the writing pairs increase. RF pulses durations are* $\tau_1=\tau_2=\tau_3=\ldots 2\ \mu s$*; time interval between two writing RF pulses is* $\tau_{12}=20\mu s$*, time interval between writing pairs is* $T=100\ \mu s$*, RF pulse packet repetition frequency is* $F_p=10$ *Hz,* $f_{NMR}=71$ *MHz,* $T=77$ *K.*

The upper beam shows the signal from a video-detector monitoring the RF pulse position, amplitude and duration.

In fig.4 it is shown a set of oscillograms illustrating the stimulated echoes cumulative process realization and the increase of the intensity of these echo-signals with the increase of the number of identical pairs. This increase is quantitatively reflected on the graph I(N), presented in fig.5.

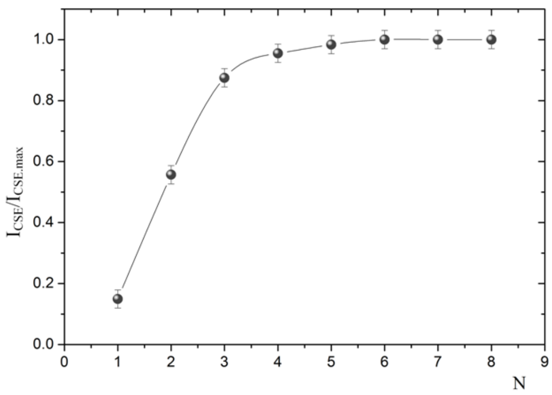

Fig5. *Cumulative NMR stimulated echo intensity dependence on the number of packets N in lithium ferrite.*

Let us account for I(N) dependence by the simple model of cumulative stimulated echo formation. In the case of small deviation of nuclear magnetization m_Z from the equilibrium direction under the action of three equal RF pulses $\alpha=\alpha_i=\gamma\eta h_1\tau_i$ we get the following expression for the three pulse stimulated echo amplitude [7]:

$$m_{\perp SE}(t) = \frac{1}{2} m_o \alpha^3 e^{-[(T/T_1)+(2\tau_{12}/T_2)]} \int g(\Delta\omega) e^{-i\Delta\omega(t-T-2\tau_{12})} d\Delta\omega$$

Using this expression for the stimulated echo and allowing for only the longitudinal relaxation processes and neglecting m_z changes under influence of following RF pulses one could obtain an expression for the amplitude of cumulative NMR stimulated echo by summing up all stimulated echo signals formed by the each pulse pair in the sequence allowing for its corresponding relaxation:

$$m_{\perp CSE}(t) = \frac{1}{2} m_o \alpha^3 \frac{1-e^{-NT/T_1}}{1-e^{-T/T_1}} \int g(\Delta\omega) e^{-i\Delta\omega(t-NT-2\tau_{12})} d\Delta\omega$$

Function to $F(N) = \frac{1-e^{-NT/T_1}}{1-e^{-T/T_1}}$

Is similar to F(n) in [2] and describes the influence of spin-lattice relaxation processes on the cumulative stimulated echo amplitude.

It has limiting values

$$F(N) = const$$
$$N \to \infty$$

And

$$F(N) \sim N$$
$$N \to 0$$

- In the qualitative agreement with the experiment.

It should be noted also that in the previous consideration we assumed according to the corresponding experimental verification that spin-lattice relaxation times for the stimulated echoes contributing in the resulting cumulative echo signal are not changed due to the influence of previous RF pulse pairs at used values of RF pulse powers.

3. Conclusion

We report on the cumulative NMR stimulated echo phenomenon in lithium ferrite which is generated by the joint action of a train of weak writing RF pulse pairs and final reading single RF pulse which exhibits the intensity growth at increasing the number of exciting RF pulse pairs. Similar effect was earlier observed for cumulative stimulated photon echoes. Obtained results could be understood in the frames of a simple theoretical model of cumulative NMR stimulated echo.

Acknowledgments

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