NONSTATIONARY RETARDED RERADIATION OF ELECTROMAGNETIC SIGNALS BY FERRITE DURING PARAMETRIC REGENERATION

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Submitted to JETP editor May 7, 1966

J. Exptl. Theoret. Phys. (U.S.S.R.) 51, 1288-1291 (November, 1966)

Nonstationary retarded reradiation (with amplification) of electromagnetic oscillations by parametrically regenerated ferrite has been observed for the first time. It is found that an "active" time interval exists after pumping of frequency f is turned on; the presence of a signal of frequency f/2 in this interval is responsible for the appearance of the reradiation. The "active" interval is found to be retarded with respect to the pumping front (by about 1 to 5 μsec); similarly, the reradiation is retarded with respect to the "active" interval by about 5–50 μsec. These time lags strongly depend on the pumping power. The phenomenon described was observed in yttrium iron garnets of arbitrary shape, including spherical and disc-shaped samples. External elastic forces affect the duration of the "active" interval and the time lags.

OBSERVATION of nonstationary delayed reradiation of electromagnetic signals by a parametrically regenerated ferrite was already reported briefly by the authors earlier.[1] In this article we present a more detailed description of the experiments and the dependence of the time characteristics of the process on the pump power. We also report a strong influence of an external elastic action on the described phenomena.

1. DESCRIPTION OF EXPERIMENT

The experiments were made with single crystal yttrium iron garnet having a saturation magnetization $4\pi M_0 = 1750$ G and a resonance-curve width $2\Delta H = 2-3$ Oe. The ferrite samples had an arbitrary shape—unfinished pieces, discs, spheres—and were placed in a resonator tuned to the pump frequency f = 9340 MHz, having a Q of 500–700. The signal of frequency f/2 = 4670 MHz was applied and picked off with the aid of a coupling loop. The signal was received with a superheterodyne receiver having a sensitivity of approximately 10^{-11} W. Lateral elastic oscillations of 1.0 MHz frequency were applied to the ferrite with the aid of a piezoelectric converter and a metallic concentrator.

At certain definite values of the constant magnetic field, the range of variation of which was in our experiments 1000–2700 Oe, and in a wide range of pump power levels, exceeding the threshold level for parametric excitation of spin waves,[2] we observed nonstationary delayed reradiation of electromagnetic oscillations by the parametrically regenerated ferrite. The time sequence of the occurring processes is shown in Fig. 1. The upper curve shows schematically the envelope of the pump (τ_i —pause interval duration, τ_p—pump pulse duration). In the description that follows, the pump front will be taken to mean the instant of termination of the pause in the pumping.

The cross hatching designates the "active" interval, and the presence of a signal at frequency

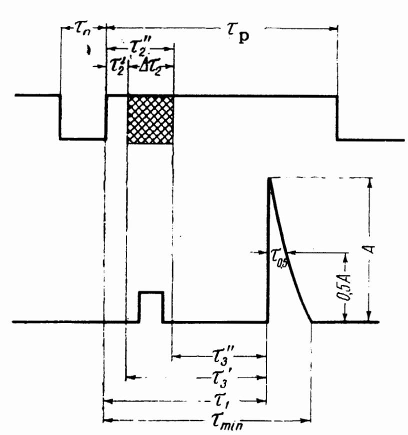

FIG. 1. Schematic representation of the time sequence of the processes. Upper figure—pump envelope, lower figure—envelope of input and reradiated signal pulses.

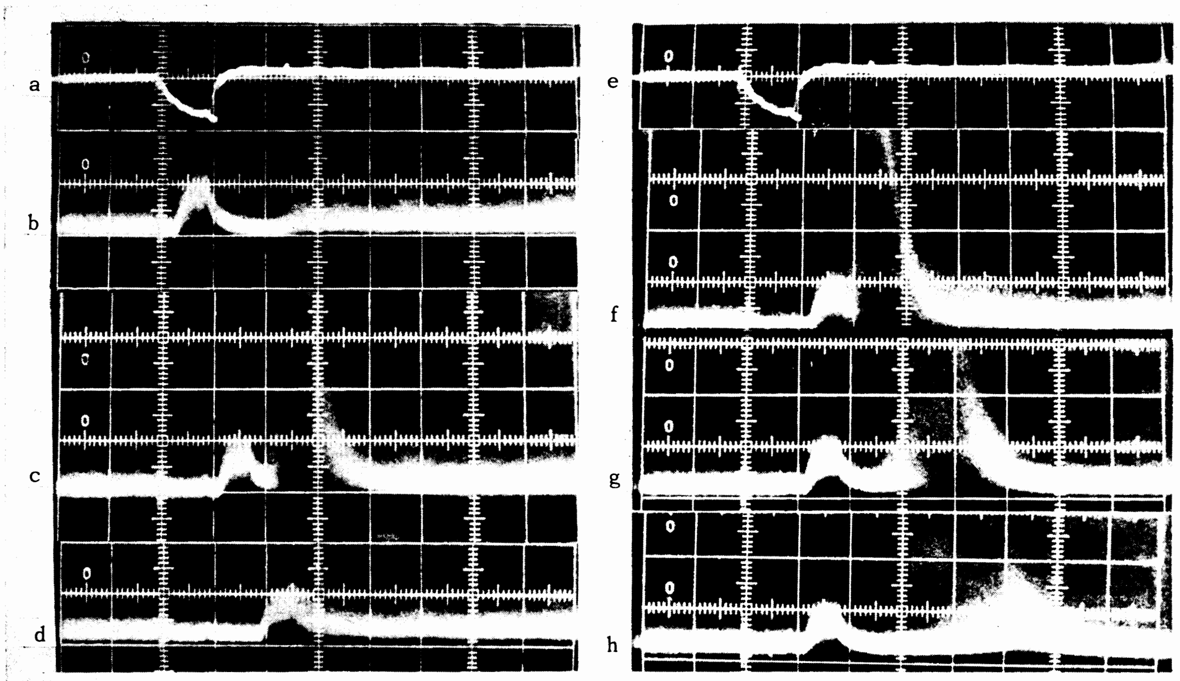

FIG. 2. Oscillograms of the processes. Each horizontal scale division is 10 μsec. a–Pump envelope, b, c, d–oscillograms illustrating the presence of an "active" interval (in photographs b and d the input pulse is outside the "active" interval and there is no reradiation, in photograph c the input pulse is in the "active" interval and the reradiated pulse can be seen); f, g, h–oscillograms illustrating the decrease in the delay time of the reradiated pulse with increasing pump power (the pump power increases in the upward direction from 0.2 to 1.3 W).

f/2 in this interval gives rise to the reradiation phenomenon. If the input signal is outside the "active" interval, then the described effect is not observed. Reradiated oscillations have the form of radio pulses whose duration at the 3 dB level ($\tau_{0.5}$) changes little when the duration of the input pulse changes from 3 μsec up to a continuous signal. If we measure the time from the pump front, then τ_2' means the start of the "active" interval, and τ_2'' its end. The delay time of the reradiated pulse relative to the pump front was designated in Fig. 1 by τ_1. The duration of the "active" interval $\Delta\tau_2 = \tau_2'' - \tau_2'$, and also its shift relative to the pump front (τ_2' and τ_2''), depends strongly on the pump power. The oscillograms of Fig. 2 illustrate the foregoing effects.

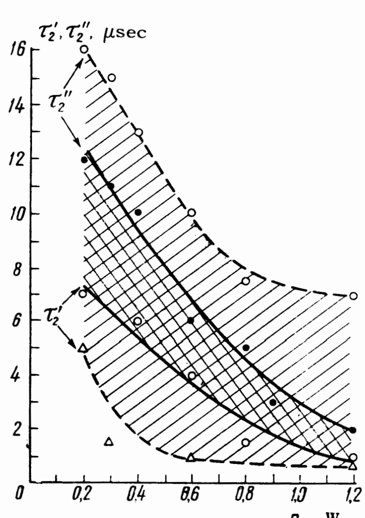

FIG. 3. Dependence of τ'_2 and τ''_2 on the pump power: solid line–in the absence of a lateral elastic force, dashed–in the presence of same.

The dependence of τ_2' and τ_2'' on the pump power is shown in Fig. 3. In the same figure, the dashed lines show analogous relations; but in the presence of an external elastic action (here and throughout we use the elastic-action intensity which has been the maximum attainable in our ex-

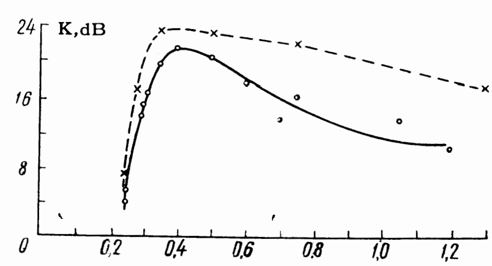

FIG. 4. Dependence of the coefficient of amplification on the pump power: solid line–in the absence of a lateral elastic force, dashed–in the presence of same.

periments). The reradiation delay time relative to the pump front (τ_1) increases from 5 to 50 μsec with decreasing pump power from 1.3 to 0.2 W. A lateral elastic force causes τ_1 to increase by 2–10 μsec. The times $\tau_3' = \tau_1 - \tau_2'$ and $\tau_3'' = \tau_1 - \tau_2''$, which determine the time shift between the "active" interval and the reradiated pulse, depend on the pump power in a manner similar to τ_2' and τ_2''.

It must be noted that the amplitude of the reradiated pulse exceeds the amplitude of the input signal, i.e., amplification takes place. The dependence of the power amplification coefficient (by which is meant the ratio of the peak powers of the reradiated pulse and the input signal) on the pump power is shown in Fig. 4, which shows also the influence of the lateral elastic force. The amplification coefficient depends little on the time position of the amplified pulse in the "active" interval. The amplification band is changed little by the pump and amounts to approximately 1.5–2.0 MHz. The upper limit of the dynamic range of the amplification at the 3 dB level relative to the maximum amplification coefficient is 10^{-8} W. Attention is called to the steep leading front of the reradiated amplified pulse, as can be seen from the oscillograms of Fig. 2. The duration of the leading front of the reradiated pulse does not depend on the duration of the leading front of the amplified pulse.

It is important to emphasize that in order to observe the described effect it is necessary that the pump be present continuously during the time from the pump front to the end of the reradiated pulse (τ_{min} in Fig. 1). No reradiation is observed when $\tau_1 < \tau_p < \tau_{min}$, corresponding non-inertial decrease in the duration of the reradiated pulse is observed, and if $\tau_p < \tau_1$. Reradiation vanishes also if in the time interval from zero to τ_1 one makes an arbitrarily small additional pause in the pump.

The duration of the reradiated pulse $\tau_{0.5}$ depends strongly on the pump power, increasing from 6 to 16 μsec when the pump power decreases from 1.3 to 0.2 W. An external lateral force increases $\tau_{0.5}$ by 3–6 μsec. In the absence of an external signal, a "peaked" electromagnetic radiation[3] was observed from the ferrite at a frequency f/2, delayed relative to the front of the pump. Oscillograms of this phenomenon, which apparently is related to the nonstationary reradiation of the external signal, are shown in Fig. 5.

It must be noted that an external elastic force exerts a strong influence on all the processes listed above, and an increase in the intensity of the elastic action was equivalent in most cases to a decrease in the pump power. This is attributed to the decrease in the parametric regeneration due to the modulation of the constant magnetic field by an additional high-frequency magnetic field produced in the ferrite by magnetostriction.[4] In many cases, however, no complete equivalence of the increase in the amplitude of the elastic signal and the decrease in the pump power was observed; for example, the presence of an elastic force has a much stronger influence on the broadening of the "active" interval than a decrease in the pump power. The degree of surface finish and the dimension and shape of the sample exerted no noticeable influence on the observed phenomena.

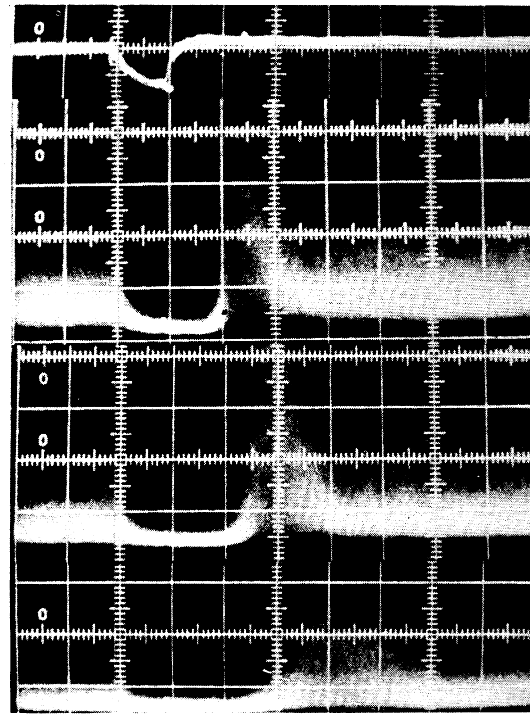

FIG. 5. Oscillograms of "peak" electromagnetic radiation. Each horizontal scale division is 10μsec. On the top is shown the pump envelope. The pump power increases in the upward direction from 0.2 to 1.3 W.

2. DISCUSSION OF RESULTS

In conclusion we shall discuss briefly the features of the effect described above.

The pump power level was in our experiments somewhat higher than the threshold of parametric excitation of spin waves and appreciably lower than the threshold of excitation of magnetostatic oscillations in the ferrite.[5] Therefore the observed amplification can be regarded as spin-connected. The coupling between the electromagnetic and the spin oscillations is ensured in this case essentially by nonlinear spin-phonon interaction occurring in nonlinear ferromagnetic resonance, and not the presence of an inhomogeneous demagnetizing field,[6] inasmuch as the effect is observed also in samples of spherical form. However, individual essential features of the described effect cannot be uniquely interpreted at present, and call for additional study.

Thus, the existence of an "active" interval, i.e., a unique time selection, is unusual. Also striking is the large delay between the input and reradiated signals. The delay does not depend on the dimensions and shape of the sample and is apparently not connected with the relaxation processes, since: 1) the reradiation is observed only in the presence of a pump signal that remains continuous from the instant of its switching-on to the end of the reradiated pulse, and 2) turning off the pump during the reradiation process leads to an instantaneous cessation of the reradiated pulse.

In the experiments of Sparks and Higgins,[7] who observed a peak nonstationary amplification of elastic waves, there was no "active" interval, nor was there a dependence of the delay time on the pump power. The delay time calculated from the speed of propagation of the elastic waves through the sample agreed well with the values measured by them.

The authors thank Professor V. V. Migulin for continuous interest and useful advice, and also B. M. Mikhaĭlov for help with the experiment.

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Translated by J. G. Adashko
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