Two-Magnon Relaxation Reversal in Ferrite Spheres

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Abstract—The reversal of two-magnon relaxation associated with linear scattering of oscillations of uniform magnetization precession from sample nonuniformities is studied theoretically and experimentally in ferrite spheres of yttrium iron garnet (YIG). Relaxation reversal is performed by parametric phase conjugation of dipole–exchange spin waves formed as a result of scattering of uniform precession from inhomogeneities. As a result of two-magnon backward scattering of dipole–exchange spin waves with a certain time delay, magnetization oscillations are renewed with an amplitude that could exceed the initial amplitude of uniform precession. The relaxation reversal is due to crystallographic anisotropy of the sample and is manifest most strongly when a YIG sphere is magnetized along the intermediate axis [110]. Experiments were carried out on YIG spheres of diameter 0.65–1.05 mm for a parallel pumping frequency \( \omega_p/2\pi = 9.4 \text{ GHz} \), which is about twice the uniform precession frequency. The maximal delay time for the restored signal of uniform precession was about 2 \( \mu \text{s} \), while the maximal amplitude exceeded the initial uniform precession amplitude by a factor of about 5. The “latent” relaxation parameters of ferrites, e.g., the natural ferromagnetic resonance linewidth associated with many-particle processes and the linewidth associated with two-magnon scattering at bulk nonuniformities, are determined experimentally. © 2004 MAIK “Nauka/Interperiodica”.

1. INTRODUCTION

The main contribution to the ferromagnetic resonance linewidth \( \Delta H \) even in perfect samples of yttrium iron garnet (YIG) comes from two-magnon relaxation processes connected with two-magnon elastic scattering of magnetization oscillations from bulk and surface nonuniformities in the sample [1]. As a result of two-magnon scattering, uniform precession of magnetization, or a magnon with wavenumber \( k = 0 \), excites a spin wave, or a magnon with wavenumber \( k \neq 0 \) determined by the size \( a \) of the nonuniformity. Waves with \( k' \sim 2\pi/a \), are excited most intensely. For YIG single crystal with a typical size \( a \sim 1 \mu\text{m} \) of nonuniformities, this corresponds to excitation of dipole–exchange spin waves with \( k' \sim 10^4 \text{ cm}^{-1} \) by uniform precession. In addition to the magnetic dipole interaction, the exchange interaction of magnetic moments proportional to \( k^2 \) becomes significant for such waves.

It should be noted that the momentum conservation law rules out two-magnon scattering and two-magnon relaxation associated with it in a perfect infinitely large crystal. This law can be violated only in a crystal containing nonuniformities and boundaries.

Prior to the irreversible transformation into thermal lattice vibrations, the uniform precession energy is transformed by two-magnon relaxation first to a system of dipole–exchange spin waves, where it can exist even after the termination of uniform precession oscillations, since the lifetimes \( T_k = 2/\gamma \Delta H \) of dipole–exchange spin waves are several times longer than the lifetimes \( T = 2/\gamma \Delta H \) of uniform precession. Here, \( \gamma \) is the gyromagnetic ratio for electron spin and \( \Delta H \) is the resonance linewidth of dipole–exchange spin wave with wave-number \( k \). Before the attainment of the thermal level by the amplitude of dipole–exchange waves, the energy of these waves can be transferred back to uniform precession, which causes reversal of two-magnon relaxation and partial restoration of the uniform precession of magnetization.

Several methods for reversal of scattering processes are known. We will use the method of phase conjugation by parametric pumping [2]. As applied to the case considered here, this method consists of the following stages. First, a signal electromagnetic pulse of duration \( \tau_s \) and frequency \( \omega_s \) close to the ferromagnetic resonance frequency \( \omega_0 \) excited uniform precession. As a result of interaction with random nonuniformities in the sample, this precession excites a set of \( n \gg 1 \) dipole–exchange spin waves propagating from these nonuniformities with different wavevectors \( \mathbf{k}_n \), frequencies \( \omega_n \sim \omega_0 \), and group velocities \( v_n \). After the termination of the signal pulse, uniform precession rapidly dies away and spin waves continue to move away from the nonuniformities, attenuating with time at a much lower rate than uniform precession. Then a uniform parametric pump pulse of duration \( \tau_p \) and frequency \( \omega_p = 2\omega_0 \) is supplied at instant \( t = t_p \). Pumping, first, leads to parametric amplification of primary waves (propagating away from nonuniformities) having frequencies \( \omega_n \) and wavevectors \( \mathbf{k}_n \) and, second, excites new idler waves of

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frequency $\omega_i$, whose wavevectors $k_i$ satisfy the energy and momentum conservation laws:

$$\omega_i = \omega_p - \omega_n, \quad k_i = k_p - k_n,$$

where vector $k_p$ is the pump wavevector. In the case of a uniform pumping ($k_p = 0$), we have $k_i = -k_n$; i.e., the idler wave is an reverse wave relative to the primary dipole–exchange spin wave, which propagates along the same path as the primary wave, but in the opposite direction. Such a behavior of the idler wave can be interpreted as phase conjugation (or time reversal) of the primary wave under the action of parametric pulsed pumping [2]. Thus, for all $n$ idler reverse waves, the reverse path to nonuniformities will be the same as for the primary waves and, after the termination of pumping, will take the same time $t_p$ as the time of propagation of primary waves from inhomogeneities to the instant of pump pulse action irrespective of the wave velocity $v_r$. Consequently, over a time $t = 2t_p$ (for $\tau_p \ll t_p$), all idler waves reach the corresponding nonuniformities at which they form a restored signal of uniform magnetization precession as a result of backward two-magnon scattering.

Parametrically enhanced dipole–exchange waves propagating from inhomogeneities can also make a contribution to restoration of uniform magnetization precession [3]. Prior to parametric pumping, the phases of all spin waves, $\varphi_n = \omega_nt - 1/\tau_s < \omega_n < \omega_n + 1/\tau_s'$, are uniformly distributed with time over an interval from 0 to $2\pi$, consequently, their total contribution to uniform magnetization precession is equal to zero in view of backward two-magnon scattering. After the pumping is switched on, the process of amplification of primary spin waves begins. If the pump pulse is long enough ($\tau_p \leq T_s$) and, hence, has a narrow frequency range, parametric amplification of spin waves caused by this pulse is characterized by a narrow band: from the entire set of dipole–exchange spin waves, only waves with frequencies close to half the pumping frequency $\omega_p/2$ will be selectively amplified. Thus, the coherence of the system of dephased spin waves will be partially restored and their contribution to uniform precession will differ from zero [3]. This contribution will increase during the operation of a phasing pump pulse and attains its maximal value at the instant of its termination, i.e., for $t = t_p + \tau_p$ and not for $t = 2t_p$, as in the case of phase conjugation for dipole–exchange spin waves. After the termination of the pump pulse, misphasing of dipole–exchange spin waves again comes into play and the contribution of these waves to uniform precession will decrease until it vanishes completely after the attainment of a uniform phase distribution of spin waves (in a time on the order of $1/\tau_s$).

We will confine our analysis to reversal of two-magnon relaxation processes to two-magnon relaxation associated with the effect of parametric phase conjugation of dipole exchange spin waves. In accordance with the above arguments, we will use short ($\tau_p \ll T_s$, $t_p$) signal and pump pulses. First, we will derive theoretical relations describing the process of two-magnon relaxation reversal, which will be verified experimentally using parametric pumping of $3$-cm waves at small ferrite spheres with a diameter from $0.65$ to $1.05$ mm.

2. THEORY

Oscillations of uniform precession and dipole–exchange spin waves coupled by crystal nonuniformities in the presence of parallel parametric pumping can be written in the form [3, 4]

$$\frac{\partial c_0}{\partial t} + i\omega_0 c_0 + \Gamma_0 c_0$$

$$-i\sum_{k \neq 0} R_{0k} c_k = -i\gamma h_c \exp(-i\omega_c t),$$

$$\frac{\partial c_k}{\partial t} + i\omega_k c_k + \Gamma_k c_k$$

$$-i\sum_{k' \neq k} R_{kk'} c_{k'} = -iV_k h_p \exp(-i\omega_p t)c^*_k,$$  

where $c_0$ and $c_k$ are the amplitudes of uniform precession and dipole–exchange spin waves with natural frequencies $\omega_0$ and $\omega_k$, respectively. Here, $h_p$, $h_c$ and $\omega_p$, $\omega_0$, $\omega_c$ are the amplitudes and frequencies of varying magnetic field of parallel pumping and the signal exciting uniform precession, respectively, and $V_k$ is the coupling coefficient of dipole–exchange spin waves with parallel pumping $[1]$; for uniform precession, such a coupling is absent $[1]$ in Eq. (1); $R_{kk'}$ is the probability of scattering of a spin wave (or oscillation) with wavevector $k'$ from a nonuniformity followed by its transformation into a new spin wave (or oscillation) with wavevector $k \neq k'$. It was mentioned earlier that the scattering probability depends on linear size $a$ of a nonuniformity; probability $R_{kk'}$ has the maximal value for $|k' - k| \sim 2\pi/a$.

Finally,

$$\Gamma_0 = \gamma \Delta H/2$$

$$\Gamma_k = \gamma \Delta H_{0f}/2$$

are the parameters of natural relaxation of uniform precession and spin waves, respectively, taking into account only intrinsic multimagnon and magnon–phonon relaxation processes, including those with participation of optical branches. The contributions from two-magnon processes to relaxation, which will be denoted by $\Delta \Gamma_0 = \gamma \delta H_{0f}/2$ and $\Delta \Gamma_k = \gamma \delta H_{f}/2$ for uniform precession and spin waves, respectively, should be determined from system of equations (1) and (2). As a result, we obtain the total frequencies of relaxation and total linewidths in the form

$$\Gamma = \Gamma_0 + \Delta \Gamma_0,$$

$$\Delta H = \Delta H_0 + \delta H_0.$$