Wave-front reversal in a medium with inhomogeneities and an anisotropic wave spectrum

G. A. Melkov, V. I. Vasyuchka, and Yu. V. Kobljanskyj
Faculty of Radiophysics, National Taras Shevchenko University of Kiev, Kiev 01033, Ukraine

A. N. Slavin*
Department of Physics, Oakland University, Rochester, Michigan 48309, USA

(Received 25 May 2004; revised manuscript received 16 September 2004; published 7 December 2004)

The possibility of parametric wave front reversal that involves waves of different nature with substantially different values of group velocity, wave number, and dissipation parameter is demonstrated. This phenomenon takes place in the system of microwave spin waves having anisotropic spectrum and propagating in yttrium-iron garnet films with defects. In our experiment fast input magnetostatic waves (MSW's) having wave vector $k \sim 10^2$ rad/cm and frequency 4.7 GHz were elastically scattered on defects and inhomogeneities of the YIG film and transformed into slow long-lifetime dipole-exchange spin waves (DESW's) of the same frequency having wave vector of the order of $k \sim 10^4$ rad/cm. Then, a short pulse of double-frequency parametric pumping was applied to perform wave front reversal for these DESW's. The reversed DESW's were scattered on the same defects, forming, as a result, an output delayed MSW signal. The dissipation parameter of DESW's was determined experimentally and turned out to be three times smaller than the dissipation parameter of the MSW signal, thus creating a possibility of low-loss delay of microwave pulsed signals.

DOI: 10.1103/PhysRevB.70.224407 PACS number(s): 75.30.Ds, 76.50.+g, 85.70.Ge

INTRODUCTION

The phenomenon of wave front reversal (WFR) under the influence of parametric pumping is well known in both optics and acoustics.[1] WFR was also observed for dipolar spin waves in ferrite films.[2,3] In all the above examples the WFR process involved waves having almost equal magnitudes of frequency, wave number, and velocity. For example, in the experiments[2,3] all the waves participating in the WFR process were backward volume magnetostatic waves (BVMSW's) having wave numbers $k \sim 10^2$ rad/cm.

In this paper we are considering a different situation when the waves participating in the WFR process have equal frequencies ω, but wave numbers k and velocities that could differ by many orders of magnitude. This situation is impossible for optic and acoustic waves since their spectra are practically isotropic, but can be easily realized for spin waves in tangentially magnetized magnetic films where the wave spectrum is substantially anisotropic. The wave number of a spin wave propagating in a magnetic film strongly depends on the direction of the wave propagation. The spin wave spectrum in the ω-$\mathbf{k}$ space forms a zone[4] where every frequency ω corresponds to wide range of wave numbers k starting from $k \leqslant 10^2$ rad/cm [dipolar spin waves or magnetostatic waves (MSW's)] and ending with $k \sim 10^6$ rad/cm (exchange spin waves). The group velocities v_k of spin waves corresponding to the same frequency in this case could vary from $v_k = 10^7$ cm/s (BVMSW's with $k \leqslant 10^2$ rad/cm) to zero at the inflection point of the dispersive curve in the region $k \sim 10^4$ rad/cm, where the negative "dipolar" dispersion is compensated by the positive "exchange" dispersion. Thus, in this region of intermediate wave number values $k \sim 10^4$ rad/cm the spin wave dispersion is influenced by both dipolar and exchange interactions and the waves are called dipole-exchange spin waves (DESW's).

Thus, when a spin wave propagating in a magnetic film experiences elastic (when frequency is conserved) scattering on defects and inhomogeneities that are always present in even the best samples of ferrite [e.g., yttrium-iron garnet or (YIG)] films, not only the direction of the wave propagation is changed (as happens in optics), but the wave itself undergoes a substantial change. As a result, the wave number, group velocity, and dissipation parameter of a new wave created in a scattering process depend on the size and nature of the inhomogeneity. Of course, all these new waves will interact with parametric pumping and will, therefore, substantially change the character of WFR process in ferrite films in comparison to the well known case of WFR involving only similar waves known in optics and acoustics.[1–3,5]

Figure 1 demonstrates one of the possible situations of WFR for spin waves in a magnetized ferrite film (1) with inhomogeneities (2). Antenna (3) (see Fig. 1) at the time $t=0$ excites an input MSW signal having wave number

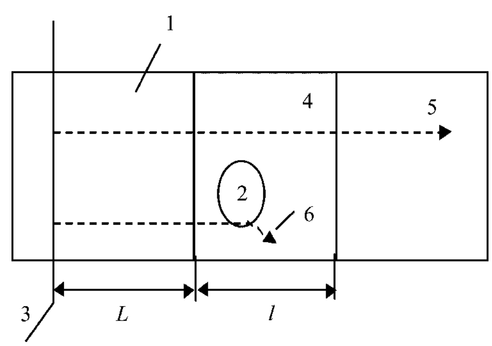

FIG. 1. Propagation and scattering of spin waves in a ferrite film with inhomogeneities: (1) ferrite film, (2) inhomogeneity, (3) stripline antenna that excites MSW signal (dashed lines), (4) shadowed region of parametric pumping localization, (5) the arrow shows the position of the MSW that did not scatter on inhomogeneities, and (6) the arrow shows position of the DESW created as a result of scattering of the MSW signal on the inhomogeneity 2.

$k=k_s \sim 10^2$ rad/cm and group velocity v_s, which propagates towards the region of parametric pumping localization (4) of the width l situated at the distance L from the antenna (3).

A certain part of the MSW signal is scattered on the inhomogeneities (2) and, as a result of this scattering, their wave numbers are changed by the amount $\sim 2\pi/a$, where a is the linear size of the inhomogeneity.[4,6] A typical size of inhomogeneities in high-quality samples of YIG films is of the order of 1 μm, which means that in the scattering process the spin waves having $k \sim 10^4$ rad/cm are created. As it was mentioned above, these waves are slow ($v_k \ll v_s$) dipole-exchange spin waves (or DESW's) (6) (see Fig. 1). Since the number of inhomogeneities in the YIG film sample is not large, the main part of the MSW signal (5) does not interact with them and continues to propagate with its original velocity v_s.

Figure 1 demonstrates positions of the waves at the time $t > t_0 = (L+l)/v_s$, when unscattered MSW (5) have already passed the region of parametric pumping localization (4), while the slow DESW formed as a result of scattering of a part of the MSW on inhomogeneities are still inside this region. If at the time $t=t_p > t_0$ a pumping pulse is supplied to the region (4), the slow DESW will be reversed, will interact again with the inhomogeneity at which they were created, and will be converted in this interaction process into a MSW having wave vector $-\mathbf{k}_s$, frequency ω_s, and propagating towards the input antenna (3). This reversed MSW will excite a delayed electromagnetic signal in the antenna (3) at the time $2t_p$. Note, that the input MSW signal will not be reversed, because at the time $t_p > t_0$ when the pumping is applied this MSW has already passed the region of pumping localization (4). If the pumping is applied at the time $t_p < t_0$, when the MSW signal (5) is still within the region of pumping localization (4), the MSW signal will be reversed as well—such a situation has been described in our previous papers.[2,3] It is clear that in such a situation the DESW's scattered on the inhomogeneities of the sample are also reversed, but their contribution to the total reversed signal is negligible in comparison with the contribution of the reversed MSW signal, thus the DESW's were not taken into account in Refs. 2 and 3.

The elastic scattering of spin waves on inhomogeneities which is necessary for the excitation and reversal of DESW's always takes place in real ferrite samples. In this scattering process (named two-magnon scattering[6]) a primary magnon having the wave vector $\mathbf{k}$ is scattered on an inhomogeneity of the size a, and forms a secondary magnon of the same frequency and the wave vector $\mathbf{k}'$. The probability of two-magnon scattering process $R_{kk'}$ has a maximum value when $k' = k \pm 2\pi/a$,[4,6] and we took this fact into account while evaluating the wave vector of scattered DESW's. Two-magnon scattering is one of the main relaxation processes for spin waves, and very often it makes a largest contribution to the experimentally observed linewidth of the ferromagnetic resonance (FMR) and MSW $\Delta H_s = 2\Gamma_s/\gamma$, where γ is the gyromagnetic ratio for the electron spin and $\Gamma_s = \Gamma_{s0} + \Delta\Gamma_s$ is the relaxation frequency of the MSW signal having the wave number $k=k_s \sim 10^{-2}$ rad/cm and consisting of the contribution Γ_{s0} determined by the eigen-processes of relaxation and the contribution $\Delta\Gamma_s$ determined by the two-magnon relaxation on defects and inhomogeneities.[4,6–8] As a result of two-magnon relaxation a significant part of the energy of the MSW signal is not immediately and irreversibly transferred to the thermal bath, but is transferred into the short-wavelength DESW's instead. This energy in the form of DESW's continues to remain in the film long after the MSW signal is gone from the film, because the group velocity of DESW's having the wave number $k \sim 10^4$ cm^{-1} is close to zero, and the relaxation frequency of DESW (also consisting of two parts $\Gamma_k = \Gamma_{k0} + \Delta\Gamma_k$) is usually 2 to 5 times smaller than the relaxation frequency Γ_s of the MSW signal. Since all the parameters of the inhomogeneities in the film are stochastic, the two-magnon scattering of the MSW signal having $k=k_s$ on the inhomogeneities creates a packet of DESWs having a wide range of wave numbers $k \sim 10^3 - 10^5$ rad/cm and propagation directions. The range of eigenfrequencies of the excited DESWs $\Delta\omega_k$ is inversely proportional to the duration τ_s of the MSW pulse that excited them $\Delta\omega_k \sim \tau_s^{-1}$. Due to the lack of temporal and spatial coherence between the individual waves in the DESW packet, the macroscopic signal created by this packet vanishes very fast (during the time interval that is significantly smaller than Γ_k^{-1}), although the individual waves in the packet continue to have amplitudes significantly exceeding the thermal level. This process of fast vanishing of the macroscopic microwave signal created by a packet of temporally and spatially incoherent DESW having almost the same frequency we shall call "dephasing." The action of parametric pumping on the dephased DESW packet leads to the reversal of the two-magnon relaxation process and results in the restitution of the macroscopic signal from these DESW's. This restituted signal can further be used either in physical experiments or in the microwave signal processing. Indeed, under the influence of a pumping pulse applied at the time t_p after the application of the input signal pulse, all the DESW's (having different wave vectors $\mathbf{k}$) start to move with different velocities $v_{\mathbf{k}}$ towards the scattering centers where they were initially created. The slower DESW's will cover a smaller distance, while the faster DESW's will cover a larger distance, but all of them will reach the corresponding scattering centers simultaneously. As a result of the inverse scattering on these scattering centers (or inhomogeneities) the reversed MSW having wave vector $\mathbf{k} = -\mathbf{k}_s$ and propagating towards the input antenna will be created. After a time interval $2t_p$ this reversed MSW will create a coherent delayed microwave signal at the input antenna.

The investigations of the wave front reversal of DESW's formed as a result of scattering of the MSW signal on the film inhomogeneities is of great interest from both fundamental and practical points of view. It is obvious, that using this process it is possible to study the properties and parameters of the spin waves with $k \sim 10^3 - 10^5$ rad/cm. It turns out that these spin waves (DESW's) are the eigenexcitations of microscales- and nanosized magnetic particles and that they determine dynamic properties of magnetic storage devices based on nanostructured magnetic media.[9] From the practical point of view, the transformation of fast signal microwave MSW into slow and long-lifetime DESW's in combination with the possibility of parametric restitution of the MSW signal, means that it is possible to develop a new class of dynamic microwave storage devices capable of storing short microwave pulses and using them later for microwave signal processing.

THEORY

The equations describing the reversal of a wave front of a spin wave (MSW) pulse propagating in a nonideal (i.e., having defects and inhomogeneities) ferrite film subjected to the influence of double-frequency pulsed parametric pumping can be written in the following form:[4,5]

$$\frac{\partial c_s}{\partial t} + i\omega_s c_s + \Gamma_{s0} c_s = -i\gamma h_s e^{-i\omega_s t} - i\sum_{k\neq k_s} R_{k_s k} c_k - iV_{k_s} h_p e^{-i\omega_p t} c^*_{-s}, \quad (1)$$

$$\frac{\partial c_k}{\partial t} + i\omega_k c_k + \Gamma_{k0} c_k = -i\sum_{k'\neq k} R_{kk'} c_{k'} - iV_k h_p e^{-i\omega_p t} c^*_{-k}, \quad (2)$$

where c_s, c_k are the amplitudes of the MSW signal and the scattered DESW's with wave vectors $\mathbf{k}_s, \mathbf{k}$ and frequencies ω_s, ω_k, respectively, h_p is the amplitude of the pulsed microwave magnetic field of the parametric parallel pumping ($\mathbf{h}_p$ is parallel to the bias magnetic field $\mathbf{H}_0$) having carrier frequency twice as large as the carrier frequency of the input MSW signal $\omega_p = 2\omega_s$, V_k is the coupling coefficient of DESW with pumping defined in Ref. 4, and h_s is the amplitude of the microwave magnetic field of the input antenna which excites the primary MSW signal with frequency ω_s and wave number $k = k_s \sim 10^2$ rad/cm.

We shall describe below only the main features of the approximate solution of the infinite system of Eqs. (1) and (2) obtained in Refs. 4–7, while concentrating on the original results obtained for the particular case discussed in the current paper. We shall assume that the probability $|R_{kk'}|$ of two-magnon scattering is much smaller than the relaxation frequencies of the waves $|R_{kk'}| \ll \Gamma_{s0}, \Gamma_{k0}$, and will use this probability as a small parameter. This assumption is justified for high-quality monocrystalline YIG films having very small density of defects and inhomogeneities and ferromagnetic resonance linewidth below 0.6 Oe (see Chap. 11 in Ref. 4 for details on relaxation processes in YIG films). Under this assumption the amplitude c_s of MSW excited by the input antenna is considered to be much larger than the amplitudes of DESW's having $k \neq k_s$ and created in the process of two-magnon scattering $c_s \gg c_k$. Apart from that, we shall omit from the right-hand side part of the Eq. (1) the last term describing the influence of the parametric pumping on the signal wave. This omission is justified if we want to describe only the situation outlined in the Introduction when the pumping is supplied to the film only *after* the primary MSW signal is gone from the region of pumping localization.

Using the above assumptions it is easy to find from Eqs. (1), (2) a contribution of the process of two-magnon scattering to the relaxation frequency of the spin waves[7]

$$\Delta\Gamma_k = \sum_{k'} |R_{k'k}|^2 \frac{\Gamma_{k'0}}{\Gamma_{k'0}{}^2 + (\omega_{k'} - \omega_s)^2}, \quad (3)$$

and to rewrite Eqs. (1), (2) in a simplified form

$$\frac{\partial c_s}{\partial t} + i\omega_s c_s + \Gamma_s c_s = -i\gamma h_s e^{-i\omega_s t}, \quad (4)$$

$$\frac{\partial c_k}{\partial t} + i\omega_k c_k + \Gamma_k c_k = -iR_{kk_s} c_s - iV_k h_p e^{-i\omega_p t} c^*_{-k}, \quad (5)$$

where, as before, $\Gamma_k = \Gamma_{k0} + \Delta\Gamma_k$, $\Gamma_s = \Gamma_{s0} + \Delta\Gamma_s$, $\Delta\Gamma_s \equiv \Delta\Gamma_{k_s}$.

Equations (4), (5) reflect the fact that before the parametric pumping is switched on the amplitude of the primary MSW signal c_s (excited by the microwave signal supplied to the input antenna) is much larger than the amplitudes c_k of dipole-exchange spin waves created due to the two-magnon scattering of this MSW signal on defects. The only influence of the two-magnon scattering on the MSW signal is the renormalization of its relaxation frequency $\Gamma_{s0} \to \Gamma_s = \Gamma_{s0} + \Delta\Gamma_s$ [see Eq. (4)]. In contrast, the influence of the two-magnon scattering on the DESW with $k \neq k_s$ manifest itself not only as relaxation frequency renormalization $\Gamma_{k0} \to \Gamma_k = \Gamma_{k0} + \Delta\Gamma_k$, but also as the appearance in the right-hand side of Eq. (5) of the driving term that is proportional to the amplitude c_s of the primary MSW signal. The amplitude c_s of this MSW signal is calculated using Eq. (4). For the practically important case of a pulsed input signal $h_s(t)$ of the duration $\tau_s \ll \Gamma_s^{-1}$ the amplitude c_s of the primary MSW excited by this signal increases linearly with time and reaches its maximum magnitude A_+ when $t = \tau_s$:

$$A_+ = i\gamma_s \tau_s. \quad (6)$$

After that, using Eq. (5) with vanishing coupling to the pumping $V_k = 0$ and taking into account only the resonance terms with $\omega_k \cong \omega_s$ that give the dominant contribution to the result, it is easy to find the amplitudes of DESW's created as a result of two-magnon scattering of the MSW signal on the inhomogeneities

$$c_k(t = t_p) = -A_+ \frac{R_{kk_s}}{(\omega_k - \omega_s) - i\Gamma_k} e^{-i\omega_k t_p} e^{-\Gamma_k t_p}. \quad (7)$$

These newly created DESW's before the time $t = t_p$ when the pumping pulse is applied to the film will only dephase and dissipate.

The DESW amplitudes $c_k(t = t_p)$ defined by Eq. (7) can be used as initial conditions for the solution of the Eq. (5) at the time after the pumping pulse is applied at the time $t = t_p$. Solving Eq. (5) for $t \geq t_p$ with the initial conditions (7), we find the expression for the DESW amplitude that is increasing in time under the influence of a powerful $(h_p V \gg \Gamma_k)$ parametric pumping pulse of the carrier frequency $\omega_p = 2\omega_s$:

$$c_k = -i\frac{R_{kk_s}}{2\nu_k}\left\{\frac{\nu_k - i(\omega_k - \omega_s)}{\Gamma_k + i(\omega_k - \omega_s)}A_+ e^{-i\omega_k t_p} + i\frac{V_k h_p}{\Gamma_k - i(\omega_k - \omega_s)}A_+^* e^{i\omega_k t_p}\right\} e^{-i\omega_k(t-t_p)}e^{-\Gamma_k t}e^{\nu_k\tau_p}, \quad (8)$$

where $\nu_k = \sqrt{|V_k h_p|^2 - (\omega_k - \omega_s)^2}$ and τ_p is the duration of the pumping pulse.

The first term in the curly brackets in Eq. (8) describes frequency-selective parametric amplification of the DESW's that are moving away from the scattering center (or inhomogeneity), while the second term in Eq. (8) describes the parametric front reversal of DESW's that after the reversal are moving towards the scattering centers. These reversed DESW's at the time $t=2t_p$ will form a phased macroscopic signal: it is clear from Eq. (8) that at $t=2t_p$ the phases of all the reversed waves are the same independently of their eigenfrequencies ω_k. This phased macroscopic signal creates a reversed MSW signal $c_{-s}=A_- e^{-i\omega_s t}$ that moves from the scattering centers to the input antenna and induces in this antenna a delayed output microwave signal. The ratio of the absolute values of the reversed A_- and input A_+ MSW at the signal frequency will give us the coefficient $K=|A_-|/|A_+|$ of the parametric reversal of MSW in nonideal ferrite films caused by the effect of two-magnon scattering on inhomogeneities.

The equation for the amplitude of the reversed MSW at the signal frequency can be obtained from the Eq. (1). Since this equation is essentially linear

$$\frac{\partial c_{-s}}{\partial t} + i\omega_s c_{-s} + \Gamma_s c_{-s} = -i\sum_k R_{k_s k} c_k, \quad (9)$$

where c_k are defined by Eq. (8). In Eq. (9) it was assumed that the parameters of the primary and reversed MSW are the same $\omega_s=\omega_{-s}$, $\Gamma_s=\Gamma_{-s}$.

Solving Eq. (9) and taking into account only the second term in the curly brackets of Eq. (8) responsible for the wave front reversal we get the following expression for the maximum amplitude A_- of the reversed MSW signal at the time $t=2t_p$:

$$A_- = iA_+^*\sum_k \frac{V_k h_p e^{\nu_k\tau_p}}{2\nu_k}e^{-2\Gamma_k t_p} \times \frac{|R_{k_s k}|^2}{[\Gamma_k - i(\omega_k - \omega_s)][\Gamma_k - \Gamma_s + i(\omega_k - \omega_s)]}. \quad (10)$$

We shall evaluate the sum in Eq. (10) approximately using a series of reasonable assumptions. First of all, we shall assume that the parametric pumping strongly amplifies only a spectrally narrow packet of DESW's having frequencies close to the half of the pumping frequency $\omega_p/2$, so the main contribution to the sum (10) is provided by the resonant waves having $|\omega_k - \omega_p/2| < \Gamma_s,\Gamma_k$. Second, we shall assume that the DESW packet is reasonably narrow in the wave vector space, so that we can consider the DESW parameters V_k, ν_k,Γ_k to be independent of the wave vector. Third, based on the data from parallel pumping experiments in YIG (see Chap. 10 in Ref. 4), we shall assume that short-wavelength DESW have substantially larger lifetimes compared to long-wavelength MSW $\Gamma_k \ll \Gamma_s$. Using these assumptions and the previously made assumption of smallness of the probability of two-magnon scattering, it is possible to derive a simple approximate expression for the reversal coefficient of the MSW signal in the nonideal ferrite film

$$K = \left|\frac{A_-}{A_+}\right| = \frac{1}{2}\frac{\Delta\Gamma_s}{\Gamma_s}e^{(h_p V_k \tau_p)}e^{[-2(\Gamma_{k0}+\Delta\Gamma_k)t_p]}. \quad (11)$$

It is clear from Eq. (11) that to achieve a maximum value of the reversal coefficient K it is necessary to have an optimum amplitude of the two-magnon scattering (that is roughly characterized by the magnitude of the additional relaxation $\Delta\Gamma_{s,k}$ caused by two-magnon scattering). When the scattering is extremely small (ideal film with no defects: $R_{kk_s}\to 0$, $\Delta\Gamma_s \to 0$) the front reversal effect is vanishing as the efficiency of the DESW creation on defects is very small. In the opposite limiting case (imperfect film with a large number of defects) the reversal coefficient K is exponentially decreasing with the increase of the probability of two-magnon scattering due to the increase of the DESW relaxation parameter $\Delta\Gamma_k$. It is also clear from Eq. (11) that the reversal coefficient K exponentially increases with the increase of the amplitude and duration of the pumping pulse, and exponentially decreases with the increase of the time interval t_p between the application of the signal pulse and the application of the pumping pulse that causes the reversal process.

So far we have considered only the process of the output signal formation due to the effect of parametric wave front reversal caused by the second term in the curly bracket of Eq. (8). The first term in the curly brackets in Eq. (8) is responsible for the appearance of a macroscopic output delayed signal at the *output* antenna due to the effect of frequency selective parametric amplification of the forward-propagating DESW's.[5] This signal is observed in the case of rather long pumping pulses ($\tau_p \approx \Gamma_k^{-1}$) at a different delay time $t \leqslant t_p + \tau_p$ and at a different place (output rather than the input antenna), and will not be considered below.

EXPERIMENTAL RESULTS AND DISCUSSION

The experimental investigation of the phenomenon of parametric wave front reversal of waves having a strongly anisotropic spectrum was performed on the system of spin waves propagating in a yttrium-iron garnet (YIG) ferrite film [see (1) in Fig. 2]. Our YIG film sample was epitaxially grown on a gallium-gadolinium garnet (GGG) substrate (2), had unpinned surface spins and the following sizes 1.5 mm $\times$20 mm$\times$7.1 μm. The YIG film sample was tangentially magnetized by a constant bias magnetic field $\mathbf{H}_0$ directed along the long side (20 mm) of the sample and parallel to the direction of propagation of the primary MSW signal ($\mathbf{H}_0 \| \mathbf{k}_s$). The MSW signal [backward volume magnetostatic wave[4] (BVMSW)] was excited and received by a microstrip antenna (3) of the width $W=50$ μm. The input pulsed microwave signal supplied to the input antenna to excite the MSW signal had the following parameters: carrier frequency

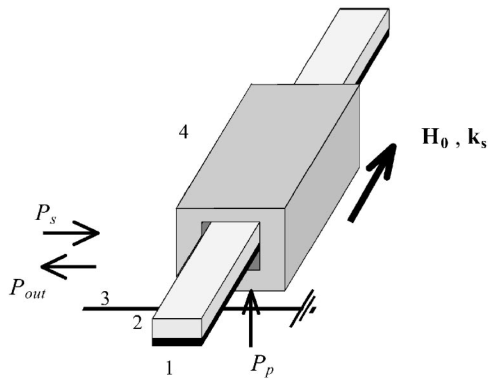

FIG. 2. Experimental setup: (1) ferrite (YIG) film, (2) substrate, (3) input antenna exciting and receiving spin wave signals, and (4) pumping dielectric resonator.

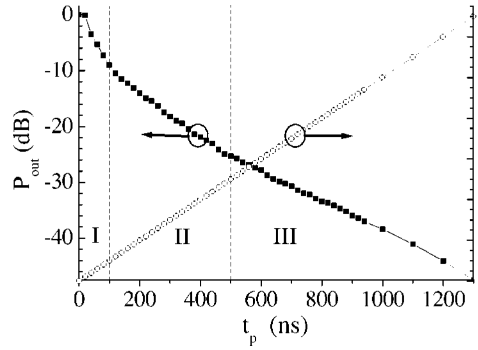

FIG. 3. Dependence of the power P_{out} and the delay time t_d of the output signal on the time t_p at which the pumping pulse was supplied to the YIG film. The input/output antenna was situated in the immediate vicinity of the dielectric resonator ($L=0$, see Fig. 1) and the bias magnetic field was $H_0=1092$ Oe.

$\omega_s/2\pi \cong 4.7$ GHz, pulse duration $\tau_s=30$ ns, power $P_s < 0.3$ mW. This input electromagnetic pulse excited in the film a packet of BVMSW signal having the carrier wave number $k_s \cong 10^2$ rad/cm and group velocity $v_s \cong 3 \times 10^6$ cm/s.

To supply pulsed microwave pumping magnetic field (carrier frequency $\omega_p \cong 2\omega_s$) to the ferrite film, the film sample was placed inside a rectangular opening in a pumping dielectric resonator (4) (see Fig. 2) made of thermostable ceramics having a dielectric constant $\varepsilon \cong 80$. The length of the resonator [determining the size of the pumping localization region along the direction of the MSW propagation (see Fig. 1)] was $l=3.5$ mm while the oscillation type in the resonator was $H_{11\delta}$ (for details see Ref. 10). The microwave magnetic field of this oscillation type is parallel to the axis of the resonator opening and has a maximum magnitude in this opening. Pumping pulses of duration $\tau_p=50$ ns and power $P_p=4.5$ W were supplied to the dielectric resonator (4) from a magnetron generator via a standard rectangular waveguide. The microwave pumping magnetic field of the dielectric resonator $\mathbf{h}_p$ was parallel to the bias magnetic field $\mathbf{H}_0$, i.e., the case of parallel pumping (see Chap. 11 in Ref. 4) described by Eqs. (1), (2) was realized in our experiment.

Under the influence of the input signal of the power P_s and the pumping of the power P_p a reversed MSW signal of the amplitude A_- (10) was formed in the YIG film. This reversed MSW induced in the microstrip antenna (3) an output signal of the power P_{out} (see Fig. 2) which was transmitted via a circulator to a measurement circuit.

The results of the experimental measurements of the output power P_{out} and the delay time t_d of the output signal as functions of the time t_p at which the pumping pulse was switched on are shown in Fig. 3. It is clear, that in accordance with the theory presented in the previous section, we see the exponential decrease of the output power with the increase of t_p. Three distinct regions I, II, and III having different slopes can be clearly seen on the curve $P_{out}(t_p)$ shown in Fig. 3. According to the theoretical expression (11) these slopes are determined by the relaxation frequency Γ_k of waves making the dominant contribution to the output signal. The region I in Fig. 3, where $t_p < t_0 \cong 100$ ns is caused by a well-known effect of wave front reversal of the MSW signal. Similar effect was studied in detail in our previous paper.[3] Although other waves (and, in particular, DESW's created due to the MSW scattering on inhomogeneities) also contribute to the output signal in the region I ($t_p < 100$ ns), the contribution of the fast MSW signal is dominant due to the high efficiency of MSW excitation by the input antenna.[11] The MSW relaxation frequency $\Gamma_s = \gamma \Delta H_s/2$, determined from the slope of the curve in the region I in Fig. 3 is $\Gamma_s = 5.5 \times 10^6$ s^{-1} ($\Delta H_s = 0.65$ Oe), which agrees very well with the experimentally measured ferromagnetic resonance linewidth ($\Delta H_0 = 0.6$ Oe) of our YIG film sample.

When $t_p > t_0 = 100$ ns, as it was mentioned in the Introduction, the parametric pumping cannot directly interact with the MSW signal, as by the time when the pumping pulse is switched on the MSW has already left the region of pumping localization. Thus, the pumping can interact only with the "trace" which the MSW signal left in the region of the YIG film inside the dielectric resonator. As it was explained earlier, we assume that this "trace" consists of slow secondary DESW's created in the process of two-magnon scattering of the primary MSW signal on the defects and inhomogeneities of the YIG film. The wave vectors and amplitudes of these secondary DESW's are determined by the parameters of the defects and can vary in a wide range $k \sim 10^3 - 10^5$ rad/cm. The same statement applies to the dissipation parameter of secondary DESW's, but, as a rule, the dissipation parameter of short-wavelength DESW's is still substantially smaller than the similar parameter of the MSW signal $\Delta H_k < \Delta H_s$.[4] The region II in Fig. 3 (100 ns $< t_p <$ 500 ns) is caused by the front reversal of the DESW's having $\Delta H_k \sim 0.3$ Oe, while the main contribution to the output signal in the region III is caused by the DESW's having $\Delta H_k \sim 0.18$ Oe. To the best of our knowledge, this last value of the relaxation parameter in the region III is the lowest of all experimentally measured dissipation parameters of spin waves in YIG films. This value is close to the value of the spin wave dissipation parameter measured in bulk YIG samples for spin waves $k \sim 10^4$ rad/cm by means of parallel pumping.[4] It is safe to assume that in our current experiment in a YIG film we also deal with the similar DESW. The initial amplitudes of these DESW's are smaller than the amplitudes of other spin waves

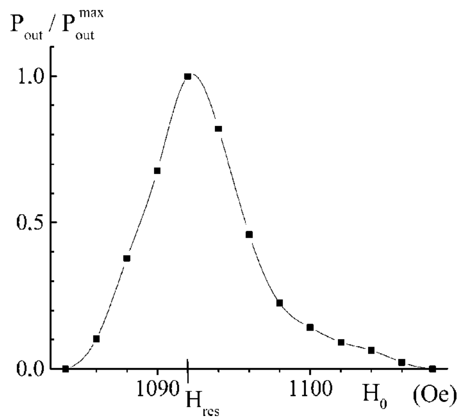

FIG. 4. Dependence of the relative magnitude of the output signal power P_{out}/P_{out}^{max} on the bias magnetic field H_0 in the case when $t_p=500$ ns and $L=0$.

creating the output signal in the regions I and II (see Fig. 3), but due to their very small dissipation parameter they outlive all the other waves and provide a dominant contribution to the output signal at large values of t_p (see region III in Fig. 3). The excitation of these weakly dissipative DESW's allowed us to obtain a large delay of the input microwave pulsed signal $t_d=2.6$ μs with total insertion loss of 47.5 dB (see Fig. 3). These parameters are substantially better than all the published characteristics of delayed signals obtained in devices based on MSW propagation in YIG films.[11,12]

The dependence of the signal delay time t_d on the time t_p when the pumping pulse is supplied in all the three above described regions I, II, and III is a straight line with the slope equal to 2. Moreover, it turned out that the signal delay t_d does not depend on the distance L between the antenna and the dielectric resonator (see Fig. 1). The increase of L led only to the decrease of the amplitude of the output signal leaving the signal delay constant. This experimental fact supports our assumption, that the delay time is independent of the group velocity of waves taking part in the wave front reversal process. It also demonstrates that the pumping pulse reverses fronts of all the waves (MSW's and DESW's) excited in the YIG film. The decrease of the output signal amplitude with the increase of separation L between the antenna and the resonator is caused by the increase of the time interval during which the signal propagates in the form of fast-decaying MSW. Thus, the best characteristics of the signal delay (shown in Fig. 3) were obtained when the dielectric resonator was situated in the immediate vicinity of the input/output antenna.

We also measured the dependence of the output signal P_{out} on the magnitude of the bias magnetic field H_0 in the case when the time of pumping pulse application t_p corresponded to the boundary between regions II and III in Fig. 3 and the output pulse was mostly formed by reversed long-lifetime DESW's. This choice of t_p allowed us to obtain a reasonably large reversed signal in a wide range of bias magnetic field values. The dependence $P_{out}(H)$ is shown in Fig. 4, and it can be seen, that this dependence demonstrates a "resonance" behavior with the linewidth of only several oersteds and the maximum corresponding to the field of uniform ferromagnetic resonance H_{res}. This quasiresonance behavior of the output signal takes place, most probably, due to a well-known property of two-magnon scattering in ferrites: this process has maximum efficiency in the case when the frequency of the scattered signal coincides with the upper boundary of the spin wave spectrum in the experimental sample.[4,6] In our experimental case of a tangentially magnetized ferrite film the upper boundary of the spin wave spectrum coincides with the FMR frequency, and it is natural to expect a maximum of two-magnon scattering at this point. In contrast, in the experiments where wave front reversal of propagating MSW takes place and the contribution from the two-magnon scattering is insignificant (see Ref. 3 and regime I in Fig. 3 of this paper) the dependence $P_{out}(H_0)$ has a nonresonant character, and the maximum of the output signal corresponds to the maximum of the transmission-loss characteristic of the experimental setup.

The "resonance" behavior of the field dependence of the output signal power shown in Fig. 4 clearly demonstrates the important role of the two-magnon scattering in the formation of the output signal. It is also known, that the efficiency of two-magnon scattering could be significantly increased by the roughening of the surface of the experimental sample.[4] In our experiments it turned out, however, that the surface roughening leads to the increase of the output reversed signal only in the case of relatively thick ferrite films having thickness $d \geqslant 30$ μm. For these "thick" films the roughening of the film surface resulted in the increase of the output signal of up to 10 dB and in the broadening of the field dependence of the output power (see Fig. 4) to several tens of oersteds around the FMR magnetic field H_{res}. For the relatively thin YIG films $d \leqslant 10$ μm the roughening of the film surface led, for the most part, to the decrease of the output signal. This decrease in the output signal could be connected with the fact that, according to Eq. (11), an optimum efficiency of the two-magnon scattering is required to achieve the maximum value of the wave front reversal coefficient K. When the probability of two-magnon scattering $R_{kk'}$ increases above this optimum, the output signal starts to decrease exponentially due to the increase of the additional dissipation for DESW's caused by the two-magnon scattering $\Gamma_k=\Gamma_{k0}+\Delta\Gamma_k$. For example, in a YIG film of the thickness 5.9 μm surface of which has been treated with the abrasive paste having the grain size of 1 μm for large values of t_p corresponding to the region III in Fig. 3 we observed the increase of the slope of the dependence of $P_{out}(t_p)$. This slope increase corresponded to the increase of the effective dissipation parameter of the DESW's from 0.34 to 0.41 Oe. Thus, it seems that in relatively thin films the number of defects naturally present in the volume and on the surface of the sample is either close to optimum or exceeding it, so that the additional defects created by the surface roughening only decrease the amplitude of the reversed signal. The difference in the behavior of thick and thin films could be understood if we use analogy with the well-developed theory of two-magnon scattering in ferrite spheres, where it was established that the contribution of surface defects to the dissipation parameter is proportional to the ratio of the sample surface to its volume.[4] It is clear, that in the thick films this ratio is smaller, and the contribution of two-magnon scattering at the surface is also smaller, so that by roughening the sample surface we could reach the optimum number of defects in the sample.

CONCLUSION

The effect of parametric wave front reversal (WFR) for spin waves propagating in YIG films with inhomogeneities and defects has been studied both theoretically and experimentally. In contrast with the previous studies of wave front reversal in optics and acoustics, in our case the spin waves with very different values of wave number (from purely dipolar MSW having $k=10^2$ rad/cm to DESW's having $k=10^4$ rad/cm) take part in the reversal process. This wide distribution of the spin wave wave numbers contributing to the reversal process is possible due to the anisotropy of the spin wave spectrum in ferrites.

In our experiment the input electromagnetic pulse of the carrier frequency $\sim$4.7 GHz was supplied to a microstrip antenna that converted it into a packet of propagating MSW signal having the carrier wave number $k\sim 10^2$ rad/cm and dissipation parameter of the order of 0.6 Oe. Due to the scattering on the defects and inhomogeneities, present in the YIG film, these MSW's were transformed into slow and long-lifetime DESW's having $k\sim 10^4$ rad/cm and much smaller dissipation parameter of the order of 0.1–0.2 Oe. Then, application of a pulse of double-frequency parametric pumping initiated a wave front reversal process in which the DESW's experienced inverse scattering on the same defects and created a reversed MSW at the signal frequency propagating towards the input antenna and exciting there a delayed output microwave pulse. Due to the small group velocity and low insertion loss of DESW's we were able to obtain delay times for microwave pulses (carrier frequency of 4.7 GHz), that exceed 2.6 μs with insertion loss lower than 47.5 dB.

The maximum output signal was observed when the external bias magnetic field was close to the characteristic field of FMR in the sample because at this bias field the efficiency of transformation of MSW's into DESW's and back has a maximum. It was shown both theoretically and experimentally, that the efficiency of two-magnon scattering in the YIG film should have an optimum magnitude, because the excessive two-magnon scattering leads to the increase of the dissipation parameter for the created DESW's which, in its turn, leads to the exponential decrease of the efficiency of transformation of the input signal into the output signal. It was also shown, that our experiments allow us to measure the dissipation parameter of spin waves participating in the wave front reversal process and, in particular, the dissipation parameter of short-wavelength DESW's.

ACKNOWLEDGMENTS

This work was supported in part by Ukrainian Foundation for Fundamental Research, grant no. 2.07/16, the MURI grant W911NF-04-1-0247 from the U.S. Army Research Office, the Oakland University Foundation, and Science and Technology Center in Ukraine.

*Electronic address: slavin@oakland.edu

[1] B. Ya. Zel'dovich, R. F. Pilipetskii, and V. V. Shkunov, *Principles of Phase Conjugation* (Springer, Berlin-Heidelberg, 1985); A. Brysev, L. Krutyansky, and V. Preobrazhensky, Phys. Usp. **41**, 793 (1998).
[2] A. L. Gordon, G. A. Melkov, A. A. Serga, V. S. Tiberkevich, A. V. Bagada, and A. N. Slavin, JETP Lett. **67**, 913 (1998).
[3] G. A. Melkov, A. A. Serga, V. S. Tiberkevich, A. N. Oliynyk, A. V. Bagada, and A. N. Slavin, JETP **89**, 1189 (1999).
[4] A. G. Gurevich and G. A. Melkov, *Magnetization Oscillation and Waves* (CRC Press, New York, 1996).
[5] G. A. Melkov, Yu. V. Kobljanskyj, A. A. Serga, V. S. Tiberkevich, and A. N. Slavin, Phys. Rev. Lett. **86**, 4918 (2001).
[6] M. Sparks, *Ferromagnetic Relaxation Theory* (McGraw-Hill, New York, 1964).
[7] E. Schlomann, J. J. Green, and U. Milano, J. Appl. Phys. **31**, 3865 (1966).
[8] M. J. Hurben and C. E. Patton, J. Appl. Phys. **83**, 4344 (1998).
[9] K. Y. Guslienko, R. W. Chantrell, and A. N. Slavin, Phys. Rev. B **68**, 024422 (2003).
[10] A. Okaya and L. F. Barash, Proc. IRE **50**, 2081 (1962).
[11] Yu. V. Kobljanskyj, G. A. Melkov, V. S. Tiberkevich, V. I. Vasyuchka, and A. N. Slavin, J. Appl. Phys. **93**, 8594 (2003).
[12] J. D. Adam. Proc. IEEE **76**, 159 (1988).