Journal of Communications Technology and Electronics, Vol. 48, No. 2, 2003, pp. 185–195. Translated from Radiotekhnika i Elektronika, Vol. 48, No. 2, 2003, pp. 210–221.
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RADIO PHENOMENA IN SOLIDS AND PLASMA

Magnetostatic Spin Wave Solitons in Obliquely Magnetized Yttrium Iron Garnet Films

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Received June 13, 2002

Abstract—Nonlinear propagation of microwave pulses of magnetostatic spin waves (MSWs) in an obliquely magnetized yttrium iron garnet (YIG) film is studied. The dependences of the MSW nonlinear coefficient, dispersion coefficient, and group velocity on the magnetizing field orientation are calculated. The field orientations and frequency intervals corresponding to MSW envelope soliton formation are determined. The dependences of the MSW soliton peak power and duration on the microwave excitation pulse power are analyzed. The possibility of controlling the MSW envelope soliton duration by varying the field orientation is demonstrated.

INTRODUCTION

Magnetostatic spin waves (MSWs) of the microwave spectral range (1–20 GHz) propagating in yttrium iron garnet (YIG) films exhibit a variety of dispersion characteristics and relatively low propagation loss and can easily be excited by microstrip transducers [1, 2]. A nonlinear character of MSW propagation is manifested at power levels of less than 1 mW owing to high nonlinearity of the magnetic subsystem of the ferromagnet [3, 4]. Therefore, MSWs represent a unique subject for the studies of various nonlinear wave phenomena, and their properties ensure the development of new solid-state devices for microwave signal processing [5].

Among the diversity of MSW nonlinearities, note the formation of short microwave pulses with a duration of 1–10 ns by ferrite transmission lines. Both theoretical analysis [6] and experimental data [7] prove that the competition of dispersion and nonlinearity can lead to compression of an MSW packet excited in a ferrite film by a short microwave pulse and formation of the MSW envelope soliton. The formation of these MSW solitons is similar to the formation of optical solitons in nonlinear optical waveguides [8]. Extensive studies [9–26] were aimed at investigation of MSW soliton propagation in perpendicularly [9–11, 15, 16] and in-plane [14, 17] magnetized films. The decay of solitons was studied [12, 20], their propagation velocity was measured [22] and calculated [25], the phase characteristics were analyzed [23], the soliton formation was numerically simulated [13, 18], the interaction of solitons with a continuous wave [26] and parametric pumping [19] were investigated, and the generation of an MSW soliton train in active schemes was demonstrated [21].

However, neither theoretical nor experimental studies (except for [10]) of the nonlinear propagation of MSW pulses in a ferrite film magnetized at an arbitrary angle to the film surface are reported. It is known that the magnetic field orientation governs the MSW dispersion as well as the MSW phase and group velocities [27]. Therefore, variations in the magnetizing field orientation can substantially affect the propagation of nonlinear MSW pulses in a ferrite film.

This study is a pioneering work in theoretical and experimental investigations of the propagation of high-intensity MSW pulses in a ferrite film magnetized at a certain angle to its surface.

In the first (theoretical) section, the nonlinear Schrödinger equation describing the evolution of high-intensity MSW pulses in a nonlinear dispersive medium (a ferrite film) is presented. The transformation of MSW dispersion characteristics in a ferrite film under a variation in the magnetizing field orientation is described. The angular dependences of the MSW dispersion coefficient, nonlinear coefficient, and group velocity, which simultaneously determine the MSW soliton characteristics are calculated. Based on the results of the calculations, the magnetizing field orientations and frequency intervals corresponding to the formation of MSW envelope solitons are predicted.

In the second (experimental) section, the measurement technique is briefly described and the transformation of the frequency response (FR) of MSW transmission line under variations in the ferrite film magnetization angle is studied. Experiments made it possible to determine the conditions of MSW soliton formation in an obliquely magnetized film. The main measured characteristics of MSW solitons are described and the experimental data are compared with the results of calculations. Finally, the main results are summarized and conclusions are made.

1. PROPAGATION OF NONLINEAR MSW PULSES

The Equation of MSW Packet Evolution

At the power levels corresponding to pronounced nonlinearity of the magnetic subsystem of ferromagnet,

the evolution of MSW packet envelope in a ferrite film is adequately described by the one-dimensional nonlinear Schrödinger equation [6]:

$$i\left(\frac{\partial u}{\partial t} + v_g\frac{\partial u}{\partial y} + \eta u\right) + \frac{1}{2}D\frac{\partial^2 u}{\partial y^2} - N|u^2|u = 0. \quad (1)$$

Here, $u(y, t)$ is the packet envelope depending on coordinate y in the propagation direction and time t, $V_g = \partial\omega/\partial k|_{k_0}$ is the group velocity of a wave with frequency ω and wave number k_0, $\omega = \omega(k)$ is the dispersion low, $\eta = \gamma\Delta H$ is the decay constant of a linear wave, γ is the gyromagnetic ratio, ΔH is a uniform ferromagnetic resonance line width, $D = \partial^2\omega/\partial k^2|_{k_0}$ is a dispersion coefficient, $N = \partial^2\omega/\partial u^2|_{k_0}$ is a nonlinear coefficient, $u^2 = m^2/2M_0$ is the normalized wave amplitude, m is the high-frequency component of the magnetization, and M_0 is the ferrite saturation magnetization.

Let us consider the propagation of a short quasi-monochromatic MSW packet in a ferrite film. At any power levels, the wave dispersion results in an increase of the propagating pulse duration. However, the nonlinearity (manifesting itself only at high power levels) may lead to both stretching and compression of the packet. If the Lighthill criterion [8] $D \cdot N < 0$ is satisfied, and the power slightly exceeds a certain threshold [18], the competition of these two processes leads to transformation of the wave packet into the MSW envelope soliton. In the case of the single-soliton mode and low loss, Eq. (1) has an analytical solution for packet envelope $u(y, t)$ of the form [8]

$$u(y,t) = u_0\exp(-2\eta t)\operatorname{sech}\left[u_0\exp(-2\eta t)\sqrt{\left|\frac{N}{D}\right|}(y - V_s t)\right]. \quad (2)$$

The soliton amplitude initially equal to u_0 exponentially decreases at the decay constant 2η, which is two times greater than that of a linear harmonic wave. In the first approximation, the velocity of soliton (2) equals the MSW group velocity, i.e., $V_s = V_g$ [22, 25]. It follows from expression (2) that the MSW packet half-power width is given by

$$\tau = 1.76\frac{\sqrt{|D/N|}}{u|V_g|}. \quad (3)$$

Thus, expressions (2) and (3) imply that the main parameters determining the characteristics of the MSW pulse propagating in a ferrite film are dispersion coefficient D, nonlinear coefficient N, group velocity V_g, and decay constant η.

Below, it is demonstrated that the above parameters substantially depend on the magnetizing field orientation, which enables one to control the MSW soliton formation and propagation in obliquely magnetized films.

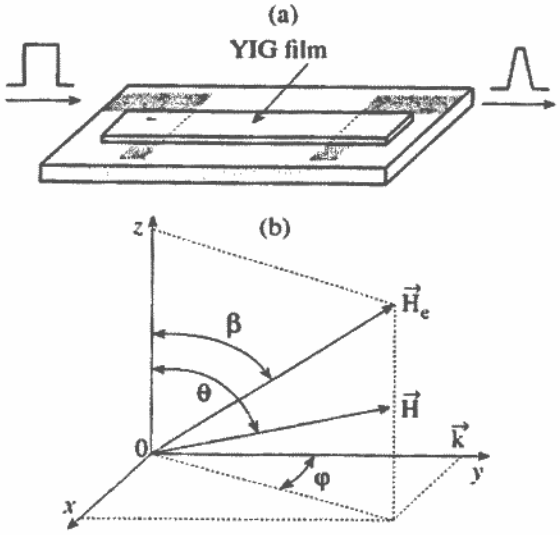

Fig. 1. (a) MSW transmission line and (b) geometry of ferrite film magnetization.

MSW Dispersion Characteristics

Figure 1 shows on MSW transmission line and the ferrite film magnetization geometry. A ferrite film of thickness d represents a narrow strip oriented in the x–y plane and pressed to a dielectric substrate. Two microstrip transducers parallel to the x axis are deposited on the substrate at a distance l from each other. In the film, the input transducer excites an MSW with wave vector $\vec{k}$ directed along the y axis. The output transducer receives the wave that has passed distance l. The entire structure is placed in an external uniform constant magnetizing field $\vec{H}_e$. Field $\vec{H}_e$ is oriented at an angle β to the z axis, so that the projection of the field vector onto the film plane makes an angle φ with the y axis.

Due to demagnetization, internal field $\vec{H}$ inside the ferrite differs from the external magnetizing field $\vec{H}_e$ in both absolute value and direction. Let θ be the angle between the direction of internal field $\vec{H}$ and the z axis. It can be demonstrated that the relationships between the fields $\vec{H}_e$ and $\vec{H}$ are as follows:

$$H_e\sin\beta = H\sin\theta,$$
$$H_e\cos\beta = (H + 4\pi M_0)\cos\theta. \quad (4)$$

These relationships enable one to calculate the value and orientation of the external magnetizing field corresponding to a given value and orientation of the magnetic field inside the film.

Consider more thoroughly two cases of variation in the field orientation that are most interesting from the practical point of view and are studied in experiments.

In the first case, internal magnetic field $\vec{H}$ inside the ferrite rotates in the longitudinal direction in the y–z plane, so that its orientation changes from perpendicular ($\varphi = 0°$ and $\theta = 0°$) to in-plane ($\varphi = 0°$ and $\theta = 90°$) with respect to the film surface. This corresponds to the transition from the propagation of forward volume MSWs (MSFVWs) to the propagation of backward volume MSWs (MSBVWs). In the second case, magnetic field $\vec{H}$ rotates in the transverse direction in the x–z plane, so that its orientation changes from perpendicular ($\varphi = 90°$ and $\theta = 0°$) to in-plane ($\varphi = 90°$ and $\theta = 90°$) with respect to the film surface. This corresponds to the transition from the propagation of MSFVWs to the propagation of magnetostatic surface waves (MSSWs). Note that, in the first case, the projection of field $\vec{H}$ onto the film surface is parallel to wave vector $\vec{k}$ and, in the second case, it is perpendicular to this vector. In both cases, group velocity vector $\vec{V}_g$ is directed along the y axis parallel to wave vector $\vec{k}$. This fact enables one to neglect the anisotropy of wave propagation in the film plane in the experiments and calculations [28].

When field $\vec{H}$ deflects from the normal in the longitudinal (with respect to the wave propagation direction) direction ($\varphi = 0°$), the MSW dispersion in a ferrite film is given by [27]

$$kd = \frac{\mu\sin^2\theta + \cos^2\theta}{\sqrt{-\mu}} \times\left[\frac{\pi n}{2} + \arctan\left(\frac{1+\mu}{\sqrt{-\mu}}\operatorname{sgn}(\mu\sin^2\theta + \cos^2\theta)\right)\right], \quad (5)$$

where $\mu = 1 + (H \times 4\pi M_0)/[(f/\gamma)^2 - H^2]$ is the diagonal component of the ferrite permeability tensor, f is the wave frequency, and $n = 0, 1, 2, \ldots$ is the volume mode number. Figure 2a qualitatively shows the transformation of the dispersion curve for the fundamental MSW mode as angle θ increases from 0° to 90° at the fixed field magnitude $H = 1300$ Oe. It is seen that volume waves exist in the frequency interval represented as $\gamma H = f_1 < f < f_2 = \gamma\sqrt{H(H + 4\pi M_0)}$. The width and boundaries of this interval are independent of the field orientation. At a fixed arbitrary angle θ, MSFVWs and MSBVWs can simultaneously propagate in the film at

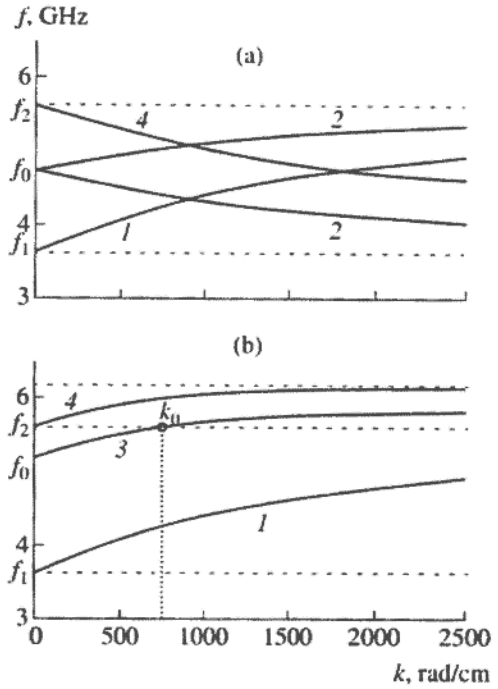

Fig. 2. MSW dispersion characteristics in an obliquely magnetized ferrite film ($d = 8.7$ μm and $H = 1300$ Oe). Field H rotates in (a) longitudinal ($\varphi = 0°$) and (b) transverse ($\varphi = 90°$) directions. Deflection angle equals $\theta = (1)$ 0°, (2) 45°, (3) 60°, and (4) 90°. Volume and surface MSWs exist in the frequency ranges bounded by dashed lines.

different frequencies. The wave numbers of the waves corresponding to both branches of the dispersion characteristic vanish at the transition frequency equal to

$$f_0 = \gamma\sqrt{H(H + 4\pi M_0\sin^2\theta)}. \quad (6)$$

Transition frequency f_0 monotonously shifts from the lower to the upper boundary of the MSW existence interval with increasing angle θ.

When field $\vec{H}$ deflects from the normal in the transverse direction ($\varphi = 90°$), the MSW dispersion in a ferrite film is described by two equations [29].

At any values of deflection angle θ and wave frequencies ranging in the interval

$$f_0 = \gamma\sqrt{H(H + 4\pi M_0\sin^2\theta)} < f < \gamma\sqrt{H(H + 4\pi M_0)},$$

an MSFVW propagates inside the film, and its dispersion relation is written as

$$kd = \sqrt{\frac{\mu\sin^2\theta + \cos^2\theta}{-\mu}} \times\left[\frac{\pi n}{2} - \arctan\left\{\frac{(\mu_a\sin\theta)^2 - \mu(\mu_a\sin^2\theta + \cos^2\theta) - 1}{2\sqrt{-\mu(\mu\sin^2\theta + \cos^2\theta)}}\right\}\right], \quad (7)$$

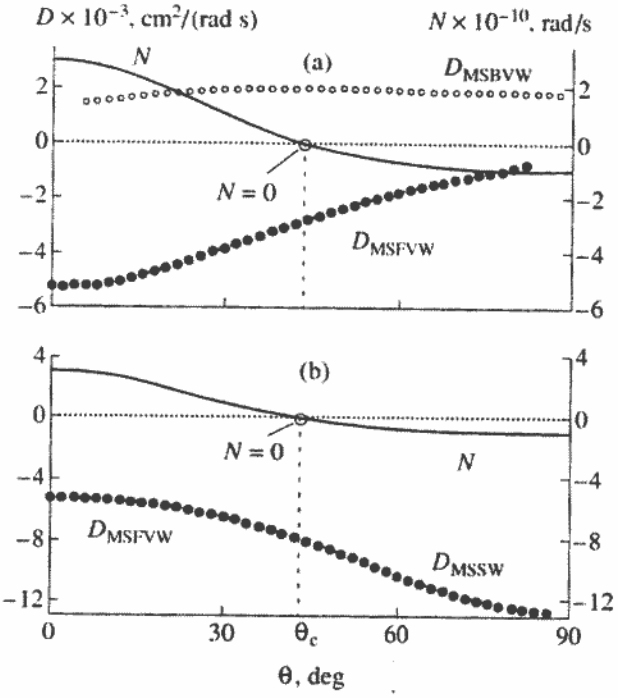

Fig. 3. Angular dependences of dispersion D and nonlinear N coefficients for MSWs in an obliquely magnetized ferrite film. Field H rotates in (a) longitudinal ($\varphi = 0°$) and (b) transverse ($\varphi = 90°$) directions.

where $\mu_a = (f/\gamma)4\pi M_0/[(f/\gamma)^2 - H^2]$ is the off-diagonal component of the ferrite permeability tensor and $n = 1, 2, \ldots$ is the volume mode number.

At deflection angles $0 < \theta < \cot\sqrt{H/4\pi M_0}$ and wave frequencies

$$\gamma\sqrt{H(H+4\pi M_0)} < f < \frac{\gamma H}{2|\sin\theta|} + \frac{\gamma(H+4\pi M_0)\sin\theta}{2},$$

an MSSW propagates in the film. Its dispersion relation is represented as

$$2kd = \sqrt{\frac{\mu\sin^2\theta + \cos^2\theta}{\mu}} \times \ln\left[\frac{\left(\sqrt{\mu\mu\sin\theta^2 + \cos^2\theta} - 1\right)^2 - (\mu_a\sin\theta)^2}{\left(\sqrt{\mu\mu\sin\theta^2 + \cos^2\theta} - 1\right)^2 - (\mu_a\sin\theta)^2}\right]. \quad (8)$$

Figure 2b qualitatively shows the transformation of the MSW dispersion curve as angle θ increases from 0° to 90° at the fixed field magnitude $H = 1300$ Oe. It is seen that the dispersion curve shifts towards higher frequencies with increasing angle θ, so that the section of the dispersion curve corresponding to volume waves diminishes and the section corresponding to surface waves increases. At frequency f_2 of the MSFVW–MSSW transition, the dispersion curve of the volume wave fundamental mode smoothly transforms (at a finite value of wave number k_0) into the dispersion curve of a surface wave. Note that, when the field deflects in the transverse direction, the MSFVW lower boundary frequency corresponding to vanishing wave number k is given by the same formula (6) as frequency f_0 corresponding to the MSFVW–MSBVW transition occurring when the field deflects in the longitudinal direction.

The MSW Dispersion Coefficient, Nonlinear Coefficient, and Group Velocity

Dispersion relations (5), (7), and (8) enable one to calculate the angular dependences of dispersion coefficient $D(\theta)$, nonlinear coefficient $N(\theta)$, and group velocity $V_g(\theta)$ that determine the MSW pulse propagation in a ferrite film under variations in the magnetic field orientation. For further comparison with experimental data, all the calculations were performed for the parameters corresponding to the following experimental conditions: YIG film thickness, $d = 8.7$ μm; saturation magnetization, $4\pi M_0 = 1780$ Gs; wave frequency, $f = 5$ GHz; and wave number, $k \sim 100$ rad/cm. In the calculations, the variation in internal field magnitude H complying with

$$H(\theta) = \sqrt{\left(\frac{f_0}{\gamma}\right)^2 + (2\pi M_0\sin^2\theta)^2} - 2\pi M_0\sin^2\theta \quad (9)$$

was taken into account, which was necessary for maintaining constant frequency $f \approx f_0$ for the waves with $k \longrightarrow 0$ under variations in angle θ.

Figure 3a shows the dependences of dispersion coefficients $D_{MSFVW}(\theta)$ and $D_{MSBVW}(\theta)$ for both volume wave branches in the vicinity of the frequency $f = 5$ GHz calculated for the field deflecting from the normal to the film surface ($\varphi = 0°$) in the longitudinal direction. It is seen that dispersion coefficient D_{MSFVW} for the MSFVW branch is negative and its absolute value monotonously decreases by a factor of almost ten with increasing deflection angle. Dispersion coefficient D_{MSBVW} for the MSBVW branch is positive, and its maximum absolute value is almost 2.5 times less than the maximum value of the coefficient for the MSFVW. If angle θ increases from 30° to 90°, the dispersion coefficient for the MSBVW remains virtually unchanged.

Figure 3b shows the angular dependences of dispersion coefficient $D(\theta)$ in the vicinity of the same frequency $f = 5$ GHz calculated for the field deflecting from the normal to the film plane ($\varphi = 90°$) in the transverse direction. In this case, the dispersion coefficient is always negative, and its absolute value monotonously

increases by a factor of nearly 2.5 with the MSFVW–MSSW transition.

The angular dependence of nonlinear coefficient $N(\theta)$ is calculated using the method proposed in [27]. The value of N slightly depends on the MSW wave number if $kd < 0.1$. This condition is almost always satisfied in experiments on MSFVW and MSBVW wave packet excitation in YIG films as thick as 10 μm. Therefore, expression (6) for f_0 makes it possible to obtain explicit analytical dependence $N(\theta)$ for the waves with $k \longrightarrow 0$. Then, the expression obtained can be applied to the waves with small k. Such an approach yields the expression for $N(\theta)$ used in the calculations:

$$N(\theta) = 2\pi\frac{\partial f}{\partial u^2} = \gamma 4\pi^2 M_0 \frac{1}{\sqrt{1+\frac{4\pi M_0}{H}\sin^2\theta}} \frac{2-\left(1+\frac{4\pi M_0}{H}\right)\tan^2\theta}{1+\left(1+\frac{4\pi M_0}{H}\right)\tan^2\theta}. \quad (10)$$

The angular dependence $N(\theta)$ is the same for both the longitudinal and transverse deflections of the field (the solid lines in Fig. 3). At the operating frequency close to 5 GHz, nonlinear coefficient N is positive for MSFVWs propagating in a perpendicularly magnetized film, so that the wave frequency increases with the wave power. The coefficient is negative for MSBVWs and MSSWs propagating in an in-plane magnetized film, so that the wave frequency decreases with increasing power. It follows from formula (10) that nonlinear coefficient N vanishes at critical deflection angle θ_c complying with

$$\tan^2\theta_c = 2/(1+4\pi M_0/H). \quad (11)$$

If the field is oriented at angle θ_c, variations in the wave power do not lead to a nonlinear shift of its frequency. In the case considered, the critical angle equals $\theta_c = 43°$ at the frequency close to 5 GHz.

It follows from formula (11) that, in the general case, the value of critical angle θ_c monotonously increases with field magnitude H and the operating frequency. Note that, when the field is oriented at angle θ_c, thermal stabilization of the characteristics of linear MSWs in a ferrite film takes place [29]. Temperature variations in magnetization M_0 do not affect the MSW dispersion characteristic.

Figure 4 shows the absolute value of group velocity V_g versus the field orientation in the ferrite film calculated for all of the above types of MSWs using dispersion relations (5), (7), and (8) in the vicinity of the operating frequency $f = 5$ GHz and $k \sim 100$ rad/cm. It is seen that the rotation of the magnetizing field in the longitudinal direction leads to substantial variations in V_g for both forward and backward waves. The absolute value of MSFVW group velocity V_g decreases from its maximum to zero. On the contrary, the absolute value of the MSBVW group velocity increases from zero to its maximum. The rotation of magnetizing field $\vec{H}$ in the transverse direction at the given wave frequency, only decreases the absolute value of the group velocity in the vicinity of the critical angle by no greater than 10%.

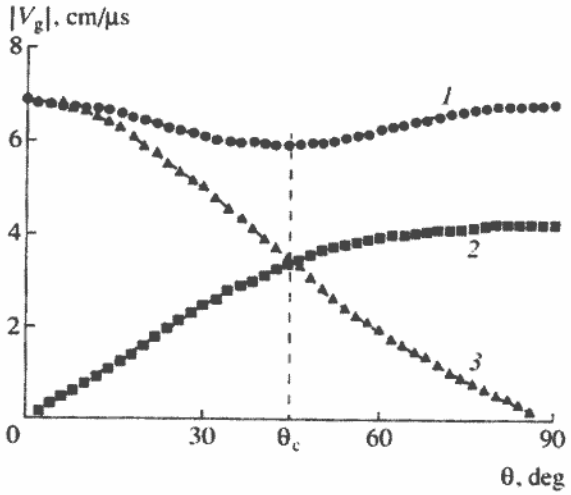

Fig. 4. Calculated angular dependences of the absolute value of the MSW group velocity (f = 5 GHz) in an obliquely magnetized ferrite film. Field H rotates in the (*1*) transverse direction (MSFVW–MSBVW the transition), (*2*) longitudinal direction (MSBVW branch), and (*3*) longitudinal direction (MSFVW branch).

The Ranges of MSW Soliton Formation

The angular dependences of coefficients $D(\theta)$ and $N(\theta)$ (Fig. 3) combined with the Lighthill criterion [8] $N \cdot D < 0$ enable one to predict the ranges of the magnetic field orientation angles and frequencies corresponding to MSW envelope soliton formation in an obliquely magnetized ferrite film.

It follows from the results presented in Fig. 3a that, when field $\vec{H}$ deflects from the normal to the film surface in the longitudinal direction and θ ranges in the interval $0 < \theta < \theta_c$, the solitons can be formed with the MSFVW branch, which corresponds to the frequencies higher than $f_0 = 5$ GHz. For the deflection angles $\theta_c < \theta < 90°$, the solitons can be formed with the MSBVW branch (the frequencies are lower than 5 GHz). In both cases, the Lighthill criterion is satisfied.

It follows from the results presented in Fig. 3b that, in the case of the transverse deflection of field $\vec{H}$ from the normal to the film surface at the angles $0 < \theta < \theta_c$, the solitons can be formed with the volume section of

the MSW dispersion characteristic branch at frequencies higher than $f_0 = 5$ GHz, where the Lighthill criterion is also satisfied. As the orientation angle approaches critical value θ_c, nonlinear coefficient N tends to zero. This hampers the formation of MSW solitons and, in particular, leads to a higher threshold power of soliton formation, growth of the distance covered by the wave packet prior to soliton formation, and a significant increase in soliton duration τ. The formation of MSSW solitons with the envelope given by expression (2) is impossible in a free transversely magnetized ferrite film.

The case when field H deflects in the longitudinal direction (Fig. 3a) should be focused on. Then, for the MSBVW branch, wide-range variations in angle θ virtually do not affect dispersion coefficient D, whereas the absolute value of nonlinear coefficient N monotonously decreases from its maximum to zero. This can be used for experimental studies of soliton formation and propagation in a medium with a controlled nonlinear coefficient.

2. EXPERIMENTAL STUDIES

Experimental Setup and Measurement Technique

The experiments employed a model MSW transmission line whose diagram is shown in Fig. 1a. A YIG ferrite film was grown by liquid-phase epitaxy on a gadolinium gallium garnet substrate. Its thickness, width, and length were 8.7 μm, 2 mm, and 25 mm, respectively. The saturation magnetization of the film was $4\pi M_0 = 1780$ Gs, and the line width of the uniform ferromagnetic resonance at 5 GHz was $\Delta H = 0.6$ Oe. The film was pressed to the substrate with two microstrip transducers. The width and length of these transducers placed at the distance $l = 4$ mm from each other and shorted at the free end were 50 μm and 2 mm, respectively. The transmission line was mounted on a turntable with two degrees of freedom. The system was placed between the poles of an electromagnet. The orientation of the external magnetic field relative to the sample plane could be varied with an accuracy up to 0.5°. An HP83650A synthesizer was used as a microwave signal source. The signal was amplified by a GaAs semiconductor amplifier with an output power as high as 1 W within a frequency range of 2–8 GHz. A semiconductor modulator formed microwave excitation pulses with a duration of 5–100 ns, leading edge less than 2 ns, and modulation depth greater than 30 dB. The transmission line FR (insertion loss L versus frequency f for a continuous signal) and time characteristics of the excitation and output microwave pulses were measured using an HP70004A Microwave Transition Analyzer interfaced with a computer.

To avoid the effect of irregularity of the microwave FR, we performed all the measurements near the same operating frequency of 5 GHz. To this end, each variation in the orientation of the delay line was accompanied by adjustments of the external magnetizing field magnitude (H_e) and orientation (angle β) providing for the required values of internal magnetic field magnitude H and orientation (angle θ) in the ferrite film. Field magnitude H_e and angle β for each measurement were calculated by formulas (4).

MSW Solitons in a Longitudinally Magnetized Film

Figure 5 shows typical FRs of the MSW transmission line measured in the continuous-signal mode at a low-level excitation signal for longitudinal deflection of field $\vec{H}$ from the normal ($\varphi = 0°$).

In a perpendicularly magnetized film, when $\theta = 0°$ and the minimum insertion loss was –17 dB, the bandwidth of MSFVW FR was about 500 MHz at an attenuation level of –50 dB. At deflection angles θ exceeding 10°, the FR is split into two parts with a dip between them as deep as –50 dB (Fig. 5a). The low- and high-frequency sections of the FR correspond to the MSBVW and MSFVW branches of the dispersion curve, respectively. If the deflection angle increases to $\theta = 45°$, the FR represents a symmetric curve with a dip in the middle (Fig. 5b), which corresponds to the symmetric dispersion curve shown in Fig. 2a. The width of each section of the FR is about 200 MHz, and the minimum insertion loss is about –20 dB. Further growth of angle θ leads to a decrease (increase) in the MSFVW (MSBVW) bandwidth (Fig. 5c). In an in-plane magnetized film, the MSBVW FR bandwidth was about 500 MHz and the minimum loss was –15 dB at $\theta = 90°$.

In pulse measurements, 12-ns-long rectangular microwave excitation pulses with a peak power as high as 200 mW were applied to the transmission line input. For each field orientation, the pulse carrier frequency was close to 5 GHz (in the frequency range corresponding to the minimum insertion loss observed in the FR). The insets in Fig. 5 show typical envelopes of the MSW transmission line output pulses. In agreement with the theoretical predictions, nonlinear pulse compression takes place only when the Lighthill criterion is satisfied: $\theta < 43°$ for MSFVWs (Fig. 5a) and $\theta > 43°$ for MSBVWs (Fig. 5c). The compression of the output pulses was not observed if the field is oriented at angles close to the critical one $\theta_c = 43°$, where nonlinear coefficient N tends to zero (Fig. 5b).

Figures 6 and 7 demonstrate the results obtained in more thorough studies of the dependence of output pulse peak power P_{out} and minimum duration τ on input pulse peak power P_{in} for various orientation angles θ of

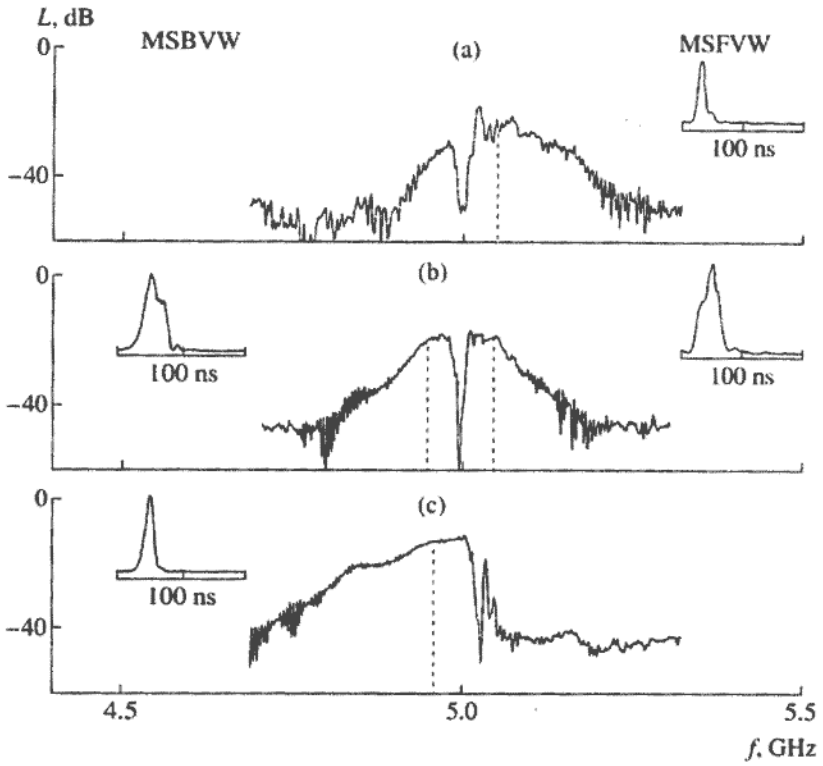

Fig. 5. MSW FRs for a longitudinally magnetized YIG film at various orientation angles of internal magnetic field H: θ = (a) 16°, (b) 45°, and (c) 65°. Insets show MSW pulses having passed the transmission line. The vertical dashed lines show carrier frequencies of MSBVW and MSFVW pulses.

the internal field. The half-power output pulse duration was measured.

Figure 6 corresponds to the MSFVW branch of the dispersion curve. It is seen that, in the perpendicularly magnetized film, a typical nonlinear compression of the MSFVW pulse takes place at $\theta = 0°$ (curve *1*). Output pulse power P_{out} nonlinearly increases and duration decreases from 12 to 3.5 ns as the input pulse power increases to $P_{in} \sim 70$ mW. The shortest single output pulse whose envelope is adequately described by formula (2) is obtained at $P_{in} = 70$ mW. If the excitation pulse power exceeds 70 mW, the output pulse is split into two and, then, into three overlapping pulses typical of the multisoliton mode. Note that the duration of the first pulse remains equal to 3.5 ns. At the internal field orientation angle $\theta = 40°$ (curve *3*) close to the critical angle $\theta_c = 43°$, the output pulse power P_{out} almost linearly increases and the corresponding duration slightly decreases (from 12 to 8.5 ns) with the increasing excitation pulse power owing to diminishing coefficient N. Finally, at the value $\theta = 50°$ (curve *4*) exceeding the critical angle, only broadening of the output MSFVW pulse with increasing P_{in} is observed. Such a behavior of MSFVW pulses is in agreement with the results of calculations (Fig. 3), predicting compression of MSFVW pulses only when the field deflects from the

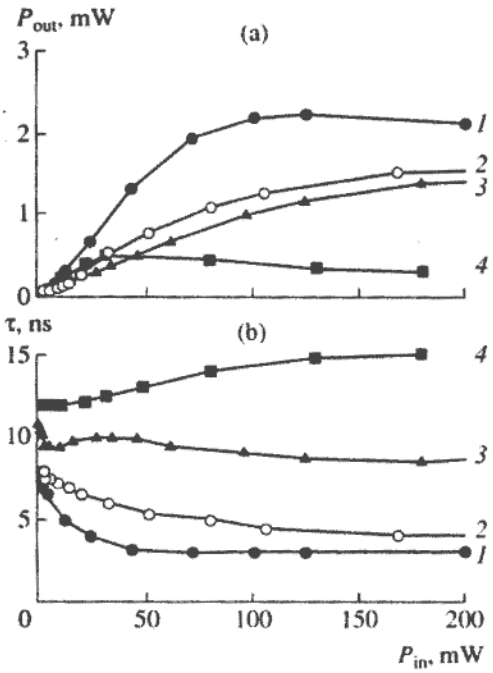

Fig. 6. Plots of MSFVW pulse (a) peak power P_{out} and (b) duration τ vs. excitation pulse peak power P_{in} at various orientations of the field: θ = (*1*) 0°, (*2*) 30°, (*3*) 40°, and (*4*) 50°.

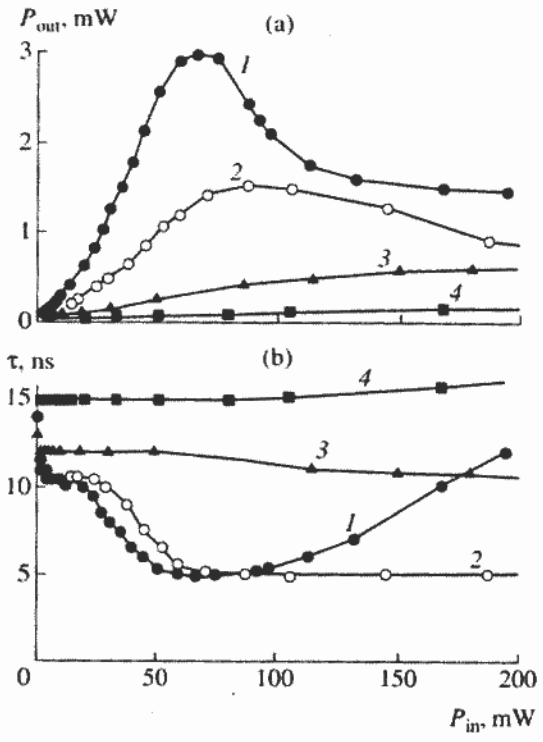

Fig. 7. Plots of MSBVW pulse (a) peak power P_{out} and (b) duration τ vs. excitation pulse peak power P_{in} at various orientations of the field: θ = (*1*) 90°, (*2*) 60°, (*3*) 50°, and (*4*) 40°.

normal to the film plane at an angle less than critical value θ_c.

Figure 7 corresponds to the MSBVW branch of the dispersion curve. For an in-plane magnetized film, at θ = 90° (curve *1*), the nonlinear compression of the output pulse is observed, which leads to formation of a single MSBVW soliton at the same input signal power $P_{in} \approx 70$ mW. Further growth of P_{in} results in diminishing P_{out} and output pulse broadening owing to the formation of the second soliton. At the field orientation angle θ = 60° (curve *2*), the compression of the output pulse typical of the MSBVW soliton formation is also observed. If the orientation angle θ = 50° (curve *3*) is close to the critical value, *N* tends to zero but the Lighthill criterion is still satisfied, the output power monotonously grows, and the output pulse duration slightly decreases (from 12 to 11 ns). In the case when the field deflection angle θ = 40° (curve *4*) is less than the critical value, only the broadening of the output MSBVW pulses is observed, which is in agreement with the theoretical predictions.

Note that, for field orientation angles close to the critical one $\theta_c = 43°$, the passband for both MSFVW and MSBVW is two–three times narrower and the insertion loss is higher than those for the limit cases θ = 0° and 90°. This limits the pulse spectrum width and additionally impedes the formation of short MSW pulses.

MSW Solitons in a Transversely Magnetized Film

Figure 8 shows typical MSW transmission line FRs for field *H* transversely deflecting from the normal (φ = 90°) measured in the continuous-signal mode at low excitation levels. In a perpendicularly magnetized film (θ = 0°), the same MSFVW FR as in the above case is observed (see Fig. 5). If deflection angle θ increases, the FR width remains virtually constant (500–600 MHz) (Figs. 8a–8c). The minimum insertion loss monotonously decreases from –17 dB at θ = 0° to –9.5 dB at θ = 90°, except for the angles $35° < \theta < 45°$. For these angles close to the critical value (at the given frequency, $\theta_c = 43°$), a developed irregularity of the FR and the abrupt growth of the insertion loss to –40 dB are observed (Fig. 8b).

Pulse measurements similar to the above experiments show that the nonlinear compression of the input pulses takes place when the field deflects from the normal at angle by θ not exceeding 30° (see inset in Fig. 8a). In this case, the Lighthill criterion is satisfied (Fig. 3). If the deflection angle is close to the critical one $\theta_c = 43°$, a significant broadening of the output pulse accompanied by distortions of its shape (see inset in Fig. 8b) is observed. If θ > 42°, the duration of low-intensity pulses having passed the transmission line remains virtually unchanged. An increase in the excitation pulse power results in broadening of the output pulses and distortions of their shape. The Lighthill criterion is not satisfied for these magnetic field orientation angles.

Figure 9 shows measured output peak power P_{out} and minimum output pulse duration τ versus input pulse peak power P_{in} at various orientation angles θ of the internal field.

In a perpendicularly magnetized film, MSFVW solitons with the minimum duration of about 3.5 ns are formed at θ = 0° (curve *1*) when the excitation power is about 70 mW. Nonlinear compression of the input pulses is still observed at the field orientation θ = 30° (curve *2*), when the Lighthill criterion is still satisfied but the value of coefficient *N* decreases. At the angle θ = 50° (curve *3*) close to the critical one, when the compression of MSW pulses is impossible but coefficient *N* is still small, the output pulse duration equals 10 ns and appears to be virtually independent of the input power. Finally, a nonlinear broadening (almost by a factor of two) and distortion in the output pulse shape for MSSW pulses propagating in an in-plane magnetized film (θ = 90°, curve *4*) are observed when the input power increases.

MSW Soliton Duration

The above results enable one to minimize the microwave pulse duration using a nonlinear MSW transmission line by varying the orientation of the magnetizing field. Figure 10 shows minimum duration τ of the transmission line output pulses versus orientation angle θ of the magnetic field inside ferrite. These curves were constructed using the data presented in Figs. 6, 7, and 9. Figures 10a and 10b correspond to the fields deflecting in the longitudinal and transverse directions from the direction of the wave propagation, respectively. In all the cases, the input pulse duration was 12 ns. It is seen that the minimum duration (3.5 ns) of the output microwave pulse is attained for an MSFVW soliton formed in a perpendicularly magnetized film. The minimum duration of the MSBVW soliton in an in-plane magnetized film was greater by a factor of approximately 1.4 (5 ns). If the deflection angle is close to the critical one θ_c = 43°, and nonlinear coefficient N vanishes, a sharp broadening of the output pulse takes place.

The solid lines in Fig. 10 show the dependences of the half-power MSW pulse width on the orientation angle calculated by formula (3). The angular dependences of coefficients $D(\theta)$ and $N(\theta)$ and group velocity $V_g(\theta)$ were calculated from Eqs. (5), (7), and (10) using the experiment parameters. The dimensionless amplitude $u = 0.035$ of the wave is used as a fitting parameter providing the best agreement between the calculated and measured MSFVW soliton durations in a perpendicularly magnetized film. The wave amplitude can also be calculated by the known formulas [6] taking into account the harmonic distribution of the MSFVW fundamental mode intensity across the width of the ferrite waveguide. An estimate for the excitation power $P_{in} = 70$ mW yields the value $u = 0.031$, which agrees well with the above amplitude. In the calculations of the pulse duration, a possible dependence of u on the field orientation was ignored. However, even in this case, the theory adequately describes variations in the MSW soliton duration with the magnetic field orientation. Note that Eq. (2) and formula (3) are not applicable if the orientation angle is close to the critical one. In this case, the calculations of the MSW soliton duration involve dispersion and nonlinear coefficients of a higher order [30].

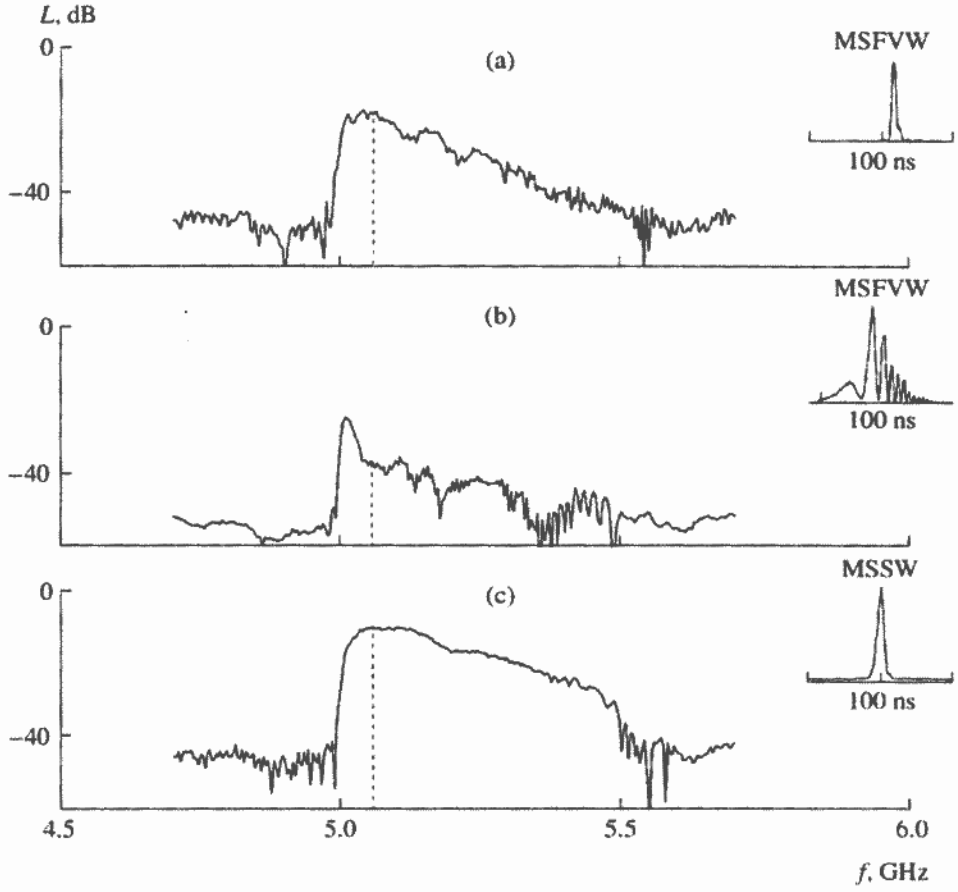

Fig. 8. MSW FRs for a transversely magnetized film at various orientations of magnetizing field H: θ = (a) 20°, (b) 40°, and (c) 60°. Insets show MSW pulses having passed the transmission line. The vertical dashed lines show the carrier frequencies of MSFVW and MSSW pulses.

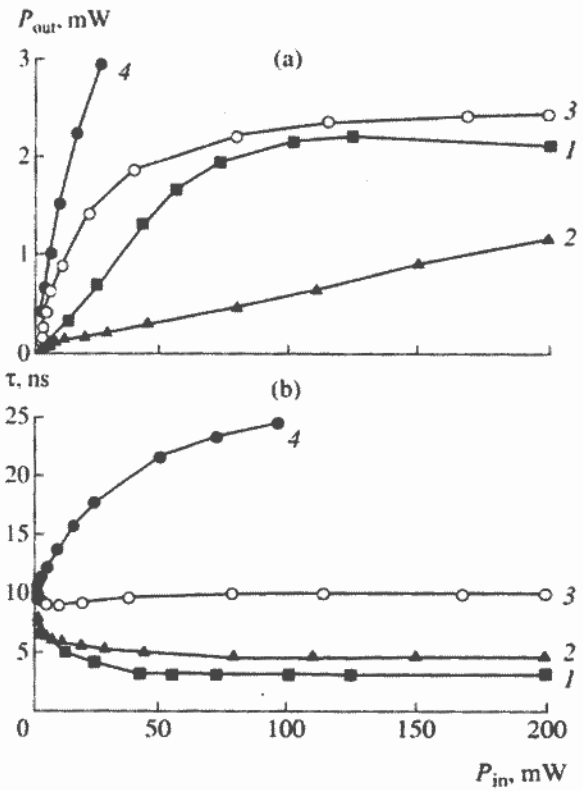

Fig. 9. Plots of (a) peak power P_{out} and (b) duration τ of an MSW pulse in a transversely magnetized film vs. excitation pulse peak power P_{in} at various orientations of the field: θ = (*1*) 0°, (*2*) 30°, (*3*) 50°, and (*4*) 90°.

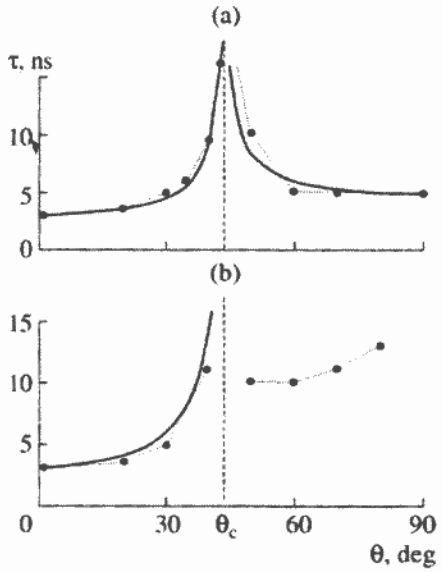

Fig. 10. Plots of the duration of MSW pulse having passed the transmission line vs. the field orientation in (a) longitudinally and (b) transversely magnetized film: (dots) experimental data and (solid lines) results of calculations using formula (3).

CONCLUSION

Both theoretical and experimental studies demonstrate the formation of MSW envelope solitons in the case of nonlinear propagation of high-intensity MSW pulses in an obliquely magnetized YIG ferrite film. When the magnetic field deflects from the normal to the film plane in the longitudinal (relative to the direction of wave propagation) direction, both MSFVW and MSBVW solitons may be formed in the film. MSFVW (MSBVW) solitons exist at small (large) deflection angles, and their frequency is close to the upper (lower) boundary of the volume wave frequency range. At a fixed duration and power of the microwave excitation pulse, MSFVW solitons in a perpendicularly magnetized ferrite film appear to be the shortest ones. The duration of MSBVW solitons in a longitudinally magnetized film is approximately 1.4 times greater. When the magnetic field deflects from the normal to the film plane in the transverse direction, only MSFVW solitons can be formed. They exist in a finite interval of deflection angles, and their frequency belongs to the volume wave frequency range. When the film is magnetized at an angle close to the critical one (in this case, the MSW nonlinear coefficient vanishes), the duration of MSW pulses which have passed the ferrite transmission line sharply increases. The dependence of the MSW soliton duration on the magnetizing field orientation is adequately described by the one-dimensional nonlinear Schrödinger equation. The results obtained clearly show that one can use a nonlinear ferrite transmission line to form microwave pulses with a duration of 3–10 ns and to control pulse duration by varying the magnetizing field orientation.

ACKNOWLEDGMENTS

We are grateful to V.T. Synogach for assistance in the measurements and discussion of the results. This work was supported by the USA National Science Foundation, grant DMR9801649; International Science and Technology Center, grant no. 1522; and NATO, grant PST.CLG.978-96.

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