Self-Generation of Two-Dimensional Spin-Wave Bullets

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The experimental observation of self-generation of two-dimensional, self-focusing nonlinear spin wave packets — spin wave bullets — in an active ring is reported. The ring is composed of a ferrite film with two antennae for excitation and detection of the wave packets, and a microwave amplifier connecting the antennae and closing the ring. Experimental observation has been made by using the time and space resolved Brillouin light scattering technique. The parameters of spin wave bullets self-generated from noise in an active ring are similar to those of bullets coherently excited by external microwave pulses. The observed self-generation process provides unambiguous evidence that wave bullets are intrinsic excitations of a two-dimensional nonlinear medium with dissipation that is focusing in both directions.

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Theoretical and experimental studies of multidimensional solitons and other nonlinear wave excitations have attracted much interest lately [1–4]. The authors of [1,2] studied the case of two-dimensional magnetic solitons, which was interpreted as a bound state of a large number of magnons. Intensive experimental studies of multidimensional solitons have been performed in nonlinear optics [4,5], in plasma physics [6], and in magnetism [7–9]. In magnetic media two-dimensional self-focusing of nonlinear packets of dipolar spin waves, excited by applying a coherent microwave field to an antenna, has been observed in yttrium-iron garnet (YIG) films [7–9]. This self-focusing leads to the formation of particular two-dimensional nonlinear spin wave packets — spin wave bullets — which in a certain interval of propagation preserve their pulse shape as a result of the competition between the effects of nonlinearity, dispersion, diffraction, and linear dissipation [7]. Further investigations [8,10] have shown that spin wave bullets propagating in wide YIG films (in contrast to *solitons* propagating in narrow YIG film waveguides) are only quasistable, as they do not survive collisions with other bullets. Thus, the question arises as to whether spin wave bullets are intrinsic excitations of two-dimensional magnetic media. The crucial test for the intrinsic character of wave bullets as excitations of a nonlinear plane medium would be an experimental observation of a spontaneous self-generation of such two-dimensional nonlinear excitations from noise when external energy is supplied to the medium.

In this Letter we report the observation of such self-generated two-dimensional spin wave bullets. The bullets are self-generated from noise in a wide YIG film, while the energy is provided by the external amplifier that closes the self-generation ring. The self-generated bullets have a characteristic very similar to the characteristics of spin wave bullets formed from coherent input wave packets [7,8].

The scheme of the active ring structure is shown in Fig. 1. As the medium for propagation we have chosen a relatively large sample (lateral dimensions 26 mm × 18 mm) of a single crystal YIG(111) film with thickness $d = 7\ \mu$m, saturation magnetization $4\pi M_0 = 1750$ G, and full linewidth of the ferromagnetic resonance $2\Delta H = 0.6$ Oe. A standard delay line structure consisting of two parallel microstrip antennae (width 50 μm, length 2.5 mm, separation $l = 6.5$ mm) is placed on the sample. The lateral sizes of the sample are intentionally chosen much larger than the length of the input antenna and the distance between the antennae, thus creating the conditions for the existence of a purely two-dimensional (unrestricted inplane) spin wave process. The applied field is $H_0 = 1735$ Oe. The two antennae are connected through a microwave switch and a high gain, wideband microwave amplifier. The signal from the spin wave

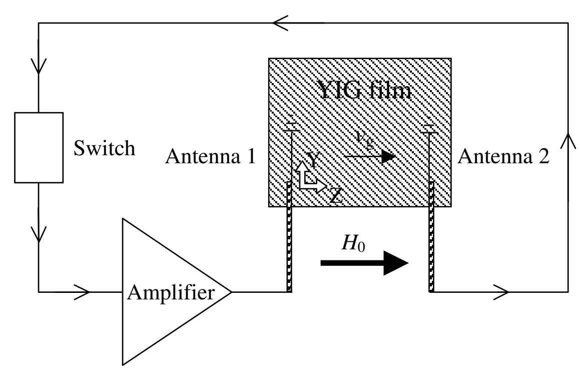

FIG. 1. Experimental setup.

packet is collected at antenna 2 and, after amplification, fed back into the film by antenna 1 closing the ring (see Fig. 1). The microwave switch is used as a mode selector; for details see below.

Usually, the propagation of two-dimensional spin wave packets along the $\hat{z}$ direction in a magnetic film lying in the $(\hat{y}, \hat{z})$ plane is described by the two-dimensional nonlinear Schrödinger equation [7,9]:

$$i\left(\frac{\partial U}{\partial t} + v_g \frac{\partial U}{\partial z}\right) + \frac{1}{2} D \frac{\partial^2 U}{\partial z^2} + \frac{1}{2} S \frac{\partial^2 U}{\partial y^2} - N|U|^2 U = -i\Gamma U, \tag{1}$$

where U is the amplitude of the spin wave packet envelope proportional to the dynamic magnetization in the medium, $v_g = \partial\omega/\partial k_z|_{k_{0z}}$ is the group velocity, $D = \partial^2\omega/\partial k_z^2|_{k_{0z}}$ and $S = \partial^2\omega/\partial k_y^2|_{k_{0z}}$ are the dispersion and diffraction coefficients, respectively, $N = \partial\omega/\partial|U|^2|_{k_{0z}}$ is the nonlinear coefficient, $k_0 = k_{0z}$ is the carrier wave number, $\omega(k_y, k_z, |U|^2)$ is the nonlinear wave dispersion law, and Γ is the combined relaxation parameter, comprising the damping in the film ($\Gamma_f = 5.3 \times 10^6$ rad/s), losses in the antennae, and the parameter characterizing the gain of the amplifier ($\Gamma < 0$). The process of self-focusing in two dimensions requires that both $D \times N < 0$ and $S \times N < 0$. This is satisfied for so-called backward volume magnetostatic waves (BVMSW) [7,11], which propagate in in-plane magnetized ferromagnetic films along the direction of the applied field (here the $\hat{z}$ direction).

Without dissipation the ongoing self-focusing effect would result in a collapse of the self-focusing packet [12]. However, the presence of even a weak linear dissipation in the medium stops the self-focusing and results in the formation of a quasistable spin wave bullet (or bullet of BVMSW) [7]. On the other hand, the dissipation should be small enough to allow for a sufficient time span for developing the nonlinear two-dimensional instability.

The YIG film with the microstrip antennae forms a transmission line for two-dimensional BVMSW wave packets, but (and we stress this again) no external coherent input signal was applied to the antennae. This transmission line plays the role of a resonator in a feedback loop of a standard microwave generator [13]. The resonance frequencies of a ring, like the one shown in Fig. 1, are determined by the phase matching condition

$$k_{nz}(\omega)l + \phi = 2\pi n, \tag{2}$$

where $\hat{z}$ is the propagation direction, n is an integer, l is a distance between the antennae, and ϕ is the additional phase shift associated with the electronic part of the ring.

To achieve stable generation of a pulse sequence, it is necessary to fulfill several conditions [14,15]. First, the frequency passband of the ring (which includes the amplifier and the YIG film transmission line) must be larger than the width of the central lobe of the frequency spectrum of a single generated pulse. Otherwise, the shape of the pulse will be distorted due to the filtering properties of the ring. It is known [7] that the duration of a spin wave bullet formed from a coherent nonlinear input pulse is about $\tau = 15$–20 ns. Thus, a transmission line with a passband of $\Delta F = 150$ MHz is used, providing $\tau\Delta F \geq 2$ [16].

Second, the amplification gain of the external amplifier must be large enough to compensate for the losses in the ring and to allow for self-generation.

Finally, for the generation of substantially nonlinear pulses in the ring, it is necessary to choose the distance l between the antennae larger than the characteristic nonlinear length in the medium $L_{NL} = v_g/(|N|U^2)$ [see Eq. (6) in [17]], thus allowing for the development of the nonlinearity responsible for both longitudinal and transverse focusing. The nonlinearity also provides a phase-locking mechanism for the generated harmonics. All these conditions are fulfilled in the experimental setup shown in Fig. 1.

When the amplification gain of the external amplifier is increased and self-generation in the ring starts, many resonant frequencies are generated simultaneously. To limit the number of generated harmonics and to make the generation of the nonlinear pulse sequence more stable we use the "time-gating" technique by employing a microwave switch (see Fig. 1). The switch is opened once during each propagation period of the packet over the ring ($T_0 = 190$ ns) for a time (about $\tau_b = 20$ ns) that is larger than the expected duration of the generated bullet. For small amplification gains the synchronization of the switch is crucial: a variation of the modulation period, T_0, by more than ± 3 ns leads to a breakdown of the self-generation process.

Similar to the generation of one-dimensional spin wave solitons [14], the presence of the time-gating switch and of the natural four-wave nonlinearity of the YIG film sample creates a mechanism for self-limiting the amplitude of the generated spin wave packets. However, in two dimensions there exists an additional mechanism of self-limitation associated with diffraction and the partial collapse of the strongly self-focused bullet in the middle of the propagation path that manifests itself for large values of the external amplification gain coefficient.

To monitor the propagation of the nonlinear wave packets, the space- and time-resolved Brillouin light scattering technique in the forward geometry is used [18]. It allows us to obtain the two-dimensional distribution of the spin wave intensity $I(y, z)$ (proportional to the squared amplitude of the local dynamic magnetization in the film, $|U|^2$) of the propagating wave packet with a spatial resolution of 0.1 mm and a temporal resolution of 2 ns.

Two series of intensity distributions corresponding to two different values of the external amplification gain are shown in Fig. 2. Within each of the series five wave packet profiles are plotted corresponding to five progressively increasing propagation times, illustrating the dynamics of wave packet propagation between the antennae. Here, the carrier frequency and the carrier wave number of the generated wave packets are $f = \omega/2\pi = 6990$ MHz and $k_{nz} = 150$ rad/cm, respectively, while the group velocity is $v_{gr} \approx -3.5$ cm/μs. The coefficients of dispersion D, diffraction S, and the nonlinear N at this working point are calculated using [19] $D = 1.4 \times 10^3$ cm^2/s, $S = 7.5 \times 10^4$ cm^2/s, and $N = -8.3 \times 10^9$ s^{-1}.

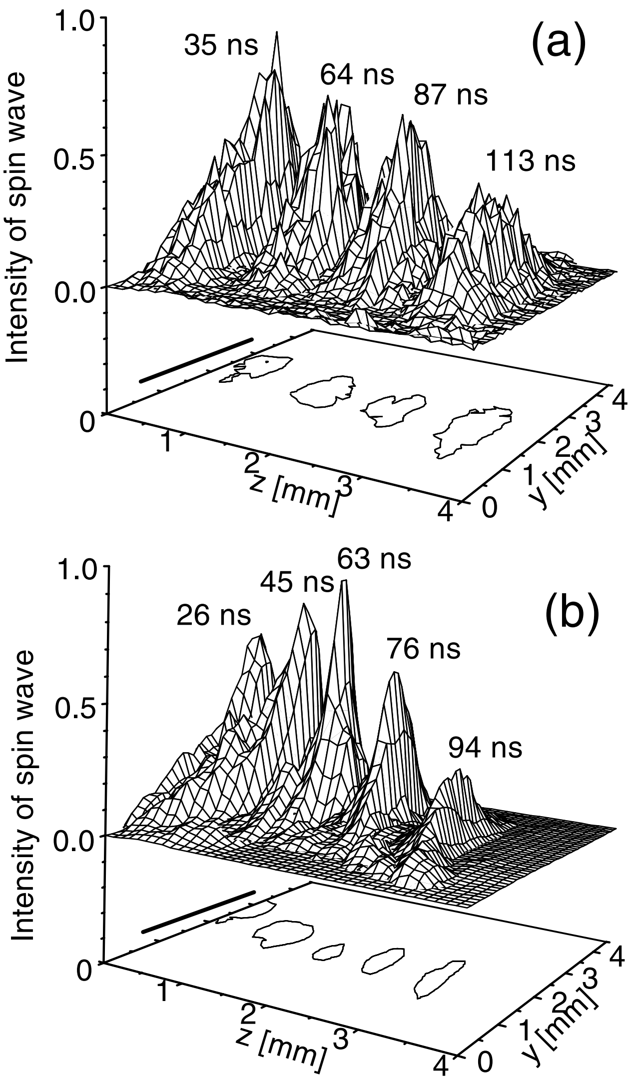

FIG. 2. Nonstationary self-focusing of a two-dimensional self-generated BVMSW packet. The upper part of the panels shows spin-wave intensity distributions in the film, created by the BVMSW propagating packet at successive instants of time, as indicated, after the launch of the packet. The lower part presents the cross sections of the propagating pulse at half maximum power. Panels (a) and (b) correspond to quasilinear ($P_1 = 1$ mW) and strongly nonlinear ($P_1 = 220$ mW) spin wave packets, respectively. The black stripes in the lower frames indicate the position of antenna 1.

The first series of profiles [Fig. 2(a)] corresponds to a relatively low value of the amplification gain yielding a peak power of the generated wave packet at the input antenna of about $P_1 = 1$ mW. This power is not sufficient to cause a pronounced transverse nonlinear self-focusing of the generated wave packet, and a spin wave bullet is not formed. Nevertheless, the propagating wave packet is almost stationary for the most part of its propagation path. Here the regime of nonlinear compensation of the dispersive and diffractive spread of the wave packet is achieved. Note that such a propagation regime was not observed for the coherent excitation of BVMSW packets [7] where the propagating packet was either self-focusing or exhibited a relatively strong diffraction spreading. We believe that the multiple-pass circulation of the packet in the ring is responsible for the observed stabilization of the wave packet size in this weakly nonlinear regime.

The second series of profiles [Fig. 2(b)] corresponds to a relatively high value of the amplification gain yielding a peak power of the generated wave packet at the input antenna of $P_1 = 220$ mW. Here the generated wave packet is clearly self-focusing in both in-plane directions, and a bullet is formed. The experimentally measured parameters of this bullet (width, length, peak power) are very close to the parameters of a BVMSW bullet formed under coherent excitation by an external input microwave pulse [7]. For example, the minimum transverse size of the bullet observed here is 0.65 mm, as discussed below, which compares to 0.6 mm obtained in [7].

The time evolution of the transverse width $L_y(z)$ of the self-generated spin wave packets of Fig. 2 is shown in Fig. 3, where curves corresponding to three different values of the amplification gain (characterized by the measured power at the input antenna P_1) are presented. It is clear that for the case of the weak nonlinear regime, $P_1 = 1$ mW [see Fig. 2(top)], after a small initial self-focusing of the packet taking place for $t < 45$ ns, the

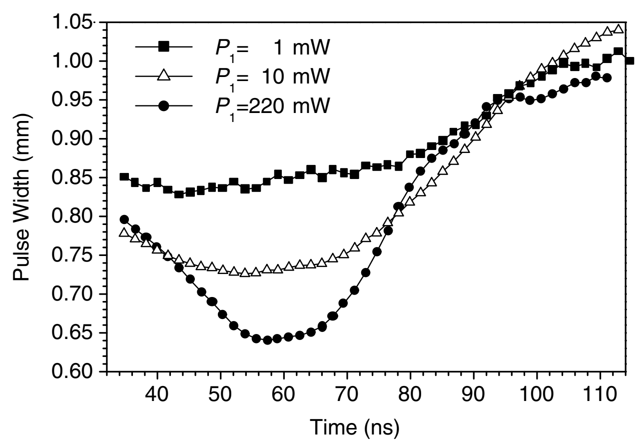

FIG. 3. Evolution of the transverse width of the spin-wave packet L_y with propagation time t.

packet is only weakly spread by diffraction in its further propagation.

In contrast, in the strongly nonlinear regime, just before the onset of the chaotic behavior, when $P_1 = 220$ mW [corresponding to the profiles given in Fig. 2(b)], a significant transverse self-focusing is observed for $t < 52$ ns. For $55 < t < 70$ ns the wave packet propagates as a well-formed bullet exhibiting an almost constant transverse width of about 0.65 mm. This is the region where the self-focusing two-dimensional spin wave packet becomes quasistationary (i.e., it becomes a wave bullet) due to the loss of energy to linear dissipation. With the further increase of the propagation distance dissipation continues to reduce the bullet's amplitude (thus reducing the focusing action of nonlinearity), and, in the end, diffraction uncompensated by nonlinearity spreads the wave packet in the transverse direction and causes the increase of the width L_y. The dispersion acting in the direction of propagation has a similar (but weaker) effect on the packet's length L_z. This behavior of the self-generated spin wave bullet is very similar to the behavior of coherently excited spin wave bullets [7].

In conclusion, the observed self-generation of spin wave bullets proves that two-dimensional self-focusing wave packets (wave bullets) are intrinsic nonlinear excitations of a nonlinear medium where two-dimensional nonlinear self-focusing is competing with substantial linear dissipation. Together with the self-generation of one-dimensional spin wave envelope solitons observed previously in narrow YIG film waveguides [14] these results complete the physical picture of the self-generated nonlinear excitation in one- and two-dimensional magnetic media.

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