

Investigation of spin-electromagnetic wave envelope solitons in a multiferroic layered structure

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Abstract. Hybrid spin-electromagnetic wave (SEW) envelope solitons have been studied both experimentally and theoretically. The solitons were formed during auto-generation of SEWs in an active ring resonator for which the role of the nonlinear dispersive waveguide media was played by a multiferroic layered ferrite-ferroelectric structure. It is demonstrated that the dielectric constant of the structure affects the nonlinear properties of SEWs.

1. Introduction

A nonlinear localized wave packet formed during the propagation of a pulsed excitation as a result of the compensation of the "spreading" effect of the dispersion by the "grouping" effect of the nonlinearity is called an envelope soliton [1]. This is a fundamental physical phenomenon observed in various waveguiding media. The envelope solitons may also be formed via development of a self and induced modulation instabilities during propagation of continuous waves of finite amplitude in a dispersive nonlinear medium [1, 2].

The envelope solitons have been discovered and studied in various media, such as optical fibers, ferromagnetic films, electromagnetic transmission lines, Bose-Einstein condensate, and other media (see, e.g., [1, 3-5]). The soliton phenomena are also being actively studied at present. To last achievements in this field can be attributed the observation of the auto-generation of solitons in metamaterials fabricated on the basis of artificial transmission lines with negative dispersion [6].

In recent years, increased interest has been observed in studies of how magnetic and electric excitations interact in various artificial multiferroic structures [7]. The magnetoelectric interaction in artificial multiferroics can be caused by two effects. One of these is the combination of piezoelectric and magnetostriction effects accompanied by a mechanical deformation of a multiferroic structure in external electric and/or magnetic fields. This is well manifested in artificial structures fabricated from ferromagnetics and piezoelectrics [8]. Another effect is due to the electrodynamic interaction of spin and electromagnetic waves. This effect may give rise to hybrid spin-electromagnetic waves (SEWs) propagating in waveguide multiferroic (ferrite-ferroelectric) structures [9].

Despite that studies of layered multiferroic structures were commenced comparatively long ago [10], nonlinear processes in these structures have been studied insufficiently. For example, the bistability of nonlinear magnetization oscillations in a multiferroic resonator fabricated from a ferromagnetic-piezoelectric planar composite structure was first studied in [11]. The study [12] was concerned with the frequency conversion via a nonlinear magnetoelectric interaction in structures of this kind. The combined wave nonlinearity of SEWs propagating in a multiferroic medium was



theoretically examined in [13] and the formation of bright and dark SEW envelope solitons in a ferrite-ferroelectric layered structure was theoretically predicted in [14]. Then experimental observation of dark envelope solitons was reported in [15].

A review of the literature suggests that envelope solitons studied in detail in various waveguide media have been apparently insufficiently analyzed in multiferroics. The goal of our present study was to examine experimentally and theoretically the spin-electromagnetic wave envelope solitons formed in an artificial multiferroic medium, specifically, in a ferrite-ferroelectric layered waveguide structure.

It is known that one of ways to excite envelope solitons is their auto-generation [6, 16-18]. Therefore, we fabricated for experiments an active ring of ordinary type, in which the planar multiferroic structure served as a nonlinear dispersive medium.

The experiments were performed at room temperature. The multiferroic structure comprised a ferrite and a ferroelectric layers (see figure 1). The ferrite layer was fabricated from an epitaxial film of yttrium-iron garnet (YIG) with a thickness of 5.7 μm , width of 2 mm, and length of 40 mm. The ferroelectric layer had the form of a $5 \times 5 \text{ mm}^2$ barium-strontium titanate (BST) slab with a thickness of 500 μm . Two microstrip antennas serving to excite and receive a traveling wave were situated at a distance of 6.7 mm. The antennas were formed by photolithography on alumina substrates. The receiving antenna was connected with the exciting antenna circuit by a feedback circuit constituted by a wideband microwave amplifier and an attenuator controlling the total gain G in the ring.

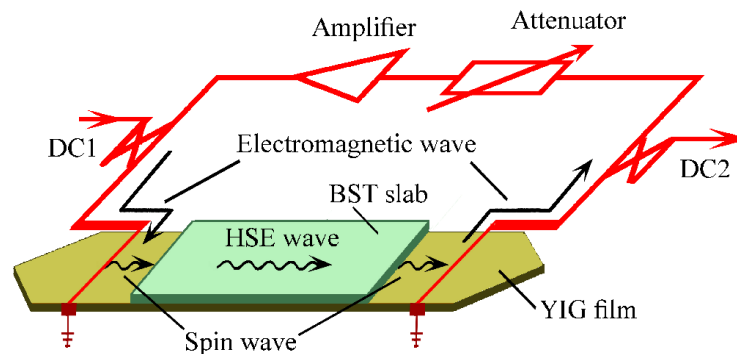


Figure 1. Schematic of the experimental device.

At room temperature, the BST ceramic used in the experiments was in the paraelectric phase. Its permittivity was isotropic and, therefore, the ceramic had no spontaneous polarization. The layered structure was magnetized in its plane perpendicularly to the wave propagation direction. This orientation of the static magnetic field provided conditions for propagation of quasi-surface SEWs [19].

Let us consider the propagation of microwave excitations in the ring (see figure 1). The electromagnetic wave passed through the feedback circuit is converted to the surface spin wave by the input microstrip antenna. This spin wave passes a short distance in the YIG film and enters the multiferroic structure. At the interface with the structure, the spin wave is transformed to a quasi-surface SEW, which then propagates in the YIG-BST structure. Having reached the end of the multiferroic structure, the SEW is converted back to the spin wave, which is received by the output microstrip antenna and converted to the electromagnetic wave. This wave, propagating via the feedback circuit, is amplified and fed to the input microstrip antenna.

In the ring circuit described above, the electromagnetic feedback circuit serves as the active part of the ring resonator, whereas its nonlinearity is mostly determined by the nonlinearity of spin-electromagnetic waves propagating in the multiferroic structure. It is noteworthy that the microwave amplifier had a frequency bandwidth (2-8 GHz) that is wider than that of the multiferroic structure. It is also noteworthy that the propagation time of the microwave carrier signal in the multiferroic structure substantially exceeds its propagation time in the feedback circuit.

The directional couplers DC1 and DC2 with coupling coefficients of -10 dB at the input and output of the waveguide structure were used to input and output the test microwave electromagnetic signal necessary for measuring the ring characteristics below the SEW auto-generation threshold. To observe the shape of the signals generated above this threshold, a small part of the microwave power was extracted from the ring via the output directional coupler.

To control the SEW dispersion by changing the permittivity of the BST slab, chromium electrodes were deposited onto both of its surfaces. The thickness of the metallic electrode situated between the YIG film and BST plate was substantially smaller (~50 nm) than the depth of the skin layer for the microwave signal of the operating gigahertz frequency. This thickness provided an effective hybridization of spin waves localized mostly in the YIG film with electromagnetic waves localized mostly in the BST slab.

According to the theoretical model [20], the eigenmodes of the active ring resonator based on the ferrite-ferroelectric structure have frequencies determined by the phase quantization condition

$$k_{sew}(f)d_{sew} + k_{sw}(f)d_{sw} + \varphi_e = 2\pi n, \quad (1)$$

where k_{sew} and k_{sw} are, respectively, the wave numbers of the spin-electromagnetic waves in the YIG-BST structure and spin waves in the YIG film; f is the frequency of waves; d_{sew} and d_{sw} are the wave propagation lengths; φ_e is the microwave signal phase accumulated in the feedback circuit of the ring; and n is an integer.

In contrast to the magnetic-film active ring resonator, the ring resonator based on a multiferroic structure enables a dual control over wave parameters. This is due to the dependence of the group velocity v_{sew} and wave number k_{sew} of spin-electromagnetic waves on both the permeability and permittivity of the multiferroic waveguide. Thus, the eigenmodes of the ring change their frequencies on varying the magnetic (H) and electric (E) bias fields. In this case, the frequency separation between the modes also changes.

Figure 2 shows the transmission coefficient of the ring, measured slightly below the autogeneration threshold at $H = 1750$ Oe. In these measurements, a low-power (-20 dBm) signal was fed from the microwave generator to the ring input. It can be seen in figure 2 that the transmission coefficient shows a set of narrow peaks corresponding to the eigenmodes of the ring resonator. The experimental results clearly demonstrate the shift of the eigenmode frequencies of the ring as a result of the decrease in the dielectric constant of the BST layer upon application of an electric field to this layer. In agreement with the theory [20], the resonance frequencies increase at small k_{sew} (which correspond to lower frequencies) and remain nearly unchanged at large k_{sew} (which correspond to higher frequencies). In particular, the eigenmodes of the ring at frequencies of about 7.0 GHz are shifted by several hundred kilohertz.

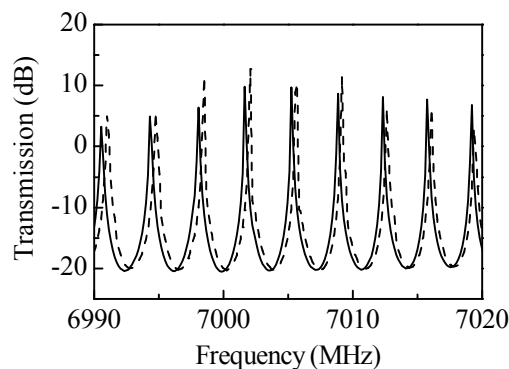


Figure 2. Amplitude-frequency characteristic of the multiferroic ring resonator at bias fields $E = 0$ (solid line) and $E = 12$ kV/cm (dashed line).

Experiments demonstrate that the loss during the propagation of SEWs in a multiferroic structure is a comparatively weak function of the applied bias field E . This results in that the auto-generation of a monochromatic wave in the ring appears at different values of the resultant gain G for different values of E . In these experiments, G was conditionally taken to be 0 dB when auto-generation commenced for the field $E = 12$ kV/cm. Therefore, in the absence of a bias field, the auto-generation appeared at $G = 0.2$ dB. Periodic sequences of solitons started to be formed at $G = 0.25$ dB in the absence of a bias field and at $G = 0.05$ dB in a bias field $E = 12$ kV/cm.

As expected for the nonlinear dispersive medium with "repulsion" type nonlinearity [21], we observed in our experiments the formation of dark SEW envelope solitons. The upper panels of figure 3 show typical experimental results demonstrating the auto-generation of periodic soliton sequences. The experimentally measured sequences are shown by circles. The solid lines in the same figure represent the results of a numerical simulation, discussed below.

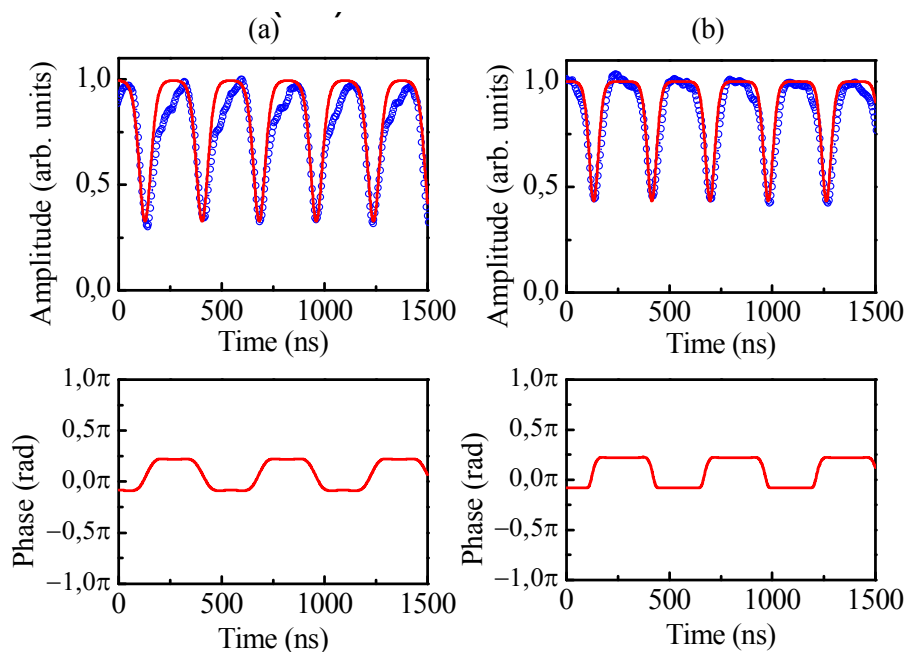


Figure 3. Upper panel: experimental and theoretical profiles of dark spin-electromagnetic wave envelope solitons auto-generated at $E = 0$ (a) and $E = 12$ kV/s (b). Lower panel: the corresponding phase profiles.

The experimental data in figure 3(a) were obtained for the gain $G = 0.3$ dB in the absence of a bias electric field. Under these conditions, dark solitons were formed with duration of 77 ns, repetition period of 273 ns, and carrier frequency of 7000.40 MHz.

Figure 3(b) shows the experimental results obtained at $G = 0.1$ dB and $E = 12$ kV/cm. In this case, the soliton repetition period increased to 282 ns because of the decrease in the SEW group velocity. In this case, the soliton duration decreased to 67 ns. Thus, the experimental results demonstrate that the properties of SEW envelope solitons can be controlled by an electric field.

To confirm the solitonic nature of the observed nonlinear wave excitations, we carried out a numerical simulation. Judging from the physics of formation and circulation of solitons in the active ring, they can be attributed to dissipative solitons [22]. Therefore, we chose as the model equation describing the nonlinear dynamics of spin-electromagnetic waves in a ring resonator the Ginsburg--Landau equation

$$i \left[\frac{\partial u}{\partial t} + V_g \frac{\partial u}{\partial x} + (\omega_r - \alpha) u \right] + \frac{D}{2} \frac{\partial^2 u}{\partial x^2} - (N - i\nu) |u|^2 u = 0, \quad (2)$$

where u is the slowly varying amplitude of the signal circulating in the ring. The coefficients V_g , D , and N denote, respectively, the group velocity and the dispersion and nonlinear coefficients of the model. The coefficients ω_r and ν have the meaning of the linear and nonlinear relaxation frequencies of spin-electromagnetic waves, and the parameter α reflects the amplification process.

The SEW dispersion law was determined for the experimental structure by using formula (1). In this formula, $k_{\text{sew}}(f)$ and $k_{\text{sw}}(f)$ were calculated in terms of the theories for SEWs [19] and spin waves [5]. The dependence of the permittivity of the BST slab on the field E was described by the quadratic function $\varepsilon(E) = 2700 - 4.86E^2$, the coefficients of which were found from the best fit of the theoretical and experimental eigenmode frequencies of the ring resonator by using the least-squares method.

As already noted, the results of the numerical simulation of the soliton auto-generation process are shown in figure 3 by solid lines. The simulation was made for the effective values of the coefficients V_g and D , found from the experiment. For $E = 0$ and $E = 12$ kV/cm, the values of V_g were, respectively, 2.45×10^4 m/s and 2.38×10^4 m/s, and the values of D were, respectively, -0.686 m²/(rad s) and -0.551 m²/(rad s). The values of N were calculated to be, respectively, 1.167×10^{10} rad/s and 1.169×10^{10} rad/s, which is quite reasonable. The solitonic nature of the wave excitations is also confirmed by the occurrence of the fast variation of the envelope phase in the amplitude minimum points of the sequences obtained.

Thus, the results of our calculations confirm the measurement data and support the hybrid-wave nature of the dark envelope solitons auto-generated in the active ring resonator fabricated on the basis of a multiferroic structure.

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