Microwave Magnetic Envelope Solitons in Thin Ferrite Films

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Research on microwave magnetic envelope (MME) solitons in thin yttrium iron garnet films has revealed important new physics about this important class of nonlinear wave packet excitations. Soliton pulse energy measurements and energy decay have been used to understand the special decay properties for these solitons. The phase profiles of the pulses provide for positive identification of solitons. Threshold power measurements vs. input pulse width yield the soliton order. The soliton velocity is also power dependent, with characteristic plateaus which also relate to soliton order. These MME solitons may be modeled accurately through the nonlinear Schrödinger equation, provided care is taken to use accurate film and excitation parameters and take into account the frequency filtering inherent in the magnetostatic waves which make up the solitons. Special techniques have also been used to observe soliton collisions, generate decay free trains of solitons, and amplify solitons.

Key words: microwave solitons, ferrite films, magnetostatic waves, yttrium iron garnet films, soliton order, phase profiles, nonlinear Schrödinger equation

1. Introduction

Microwave magnetic envelope (MME) solitons in ferrite films were discovered by Kalinikos and co-workers.¹⁾ Since then, work by these authors and others²⁾⁻¹³⁾ has established MME solitons as an important subject area for the study of nonlinear high frequency processes in ferrite thin films. The purpose of this report is to selectively review the work performed at Colorado State University on the basic physics of MME solitons.

2. Soliton basics

Figure 1 shows the microstrip delay line structure which is the basis of the MME soliton experiment. Diagram (a) shows the layout of the yttrium iron garnet (YIG) on gadolinium gallium garnet (GGG) film strip on the input-output antenna structure. Diagram (b) shows the input-output antenna and film setup in more detail. The output antenna is movable, so that the propagation distance can be easily varied. This setup is critical to the device and propagation experiments to be considered shortly.

The nomenclature in Fig. 1 is self explanatory. A microwave pulse applied to the input produces an MME pulse or soliton in the YIG film which propagates down the YIG strip and is detected at the output antenna. The overall nonlinear response is controlled by the input pulse width and the input power. The propagation velocity or MME

Fig. 1 Variable spacing transducer structure for MME soliton pulse measurements.

pulse group velocity v_g is controlled by the film-field geometry, the size of the static field, and the signal carrier frequency. For the case shown, with the static magnetic field H parallel to the propagation direction and antiparallel to the MME pulse carrier wave vector k , one has magnetostatic backward volume waves (MSBVW). The fundamentals of the magnetostatic wave (MSW) excitations which are excited in these experiments and may be used to create MME solitons are reviewed by Chen *et al.* in Ref. 5.

Figure 2 shows a schematic of the typical laboratory instrumentation which has been used for the soliton experiments. The YIG film between the poles of the electromagnet is the key element for the experiment.

Figure 3 shows some representative input and output pulse data from Ref. 5. As the input pulse is made wider, one forms MME solitons which are detected at the output antenna. The output traces shown in (c) and (d) correspond to higher order solitons. These higher order solitons have

Fig. 2 Schematic diagram of MME soliton measurement instrumentation.

Fig. 3 Example from Ref. 5 of single and multi-soliton formation for 5 GHz magnetostatic backward volume wave input pulse signals of different widths.

unique properties which may be exploited for microwave signal processing applications.

References 5, 11, and 12 review the basic properties of MME solitons. The key properties are (1) nonlinear wave packets which do not spread in width as they propagate, (2) a decay in amplitude which is typically twice as rapid as for linear MME pulses, (3) a phase profile which is constant across the pulse, and (4) threshold and velocity characteristics which reflect the soliton order. The first property is the one which makes MME solitons attractive for microwave device applications. Just as optical solitons may be used for robust optical fiber communications, MME solitons may be used for microwave delay and signal processing. The advantage is frequency and time delay agility due to the electronic tunability of the signals.

2.1 Soliton decay

The rapid decay of solitons presents a significant problem for applications. Figure 4 shows two series of MME pulses at (a) low power and (b) in the soliton regime as a function of propagation time. The vertical axes show the detected voltages from the Microwave Transition Analyzer, or "MTA", in Fig. 2. The rapid pulse decay times on the order of 100 ns are clearly evident. Xia *et al.* (Ref. 11) have found that while the amplitude decay rate increased for soliton pulses, the energy decay remains constant and directly related to the intrinsic decay rate for the YIG film.

Some results on amplitude and energy decay from Ref. 11 are shown in Fig. 5, based on pulse data similar to that shown in Fig. 4. Apart from the many details in Fig. 5, the main point is that the energy decay rate β is constant, independent of the input power and the pulse amplitude, and is *precisely* equal to 2η , where η is the amplitude decay rate for linear pulses. The amplitude decay rate α is larger than η at low power because of dispersion broadening for these short pulses. At high power this amplitude decay rate is equal to the energy decay rate, as expected for solitons.

Fig. 4 Example from Ref. 11 of (a) low power and (b) soliton pulse decay vs. time. The carrier frequency was 5 GHz and the transducer separations were changed from 3 to 10 mm to obtain the data.

Graph (b) shows modeling results based on the nonlinear Schrödinger (NLS) equation. It is particularly noteworthy that the various decay rates agree precisely with the measured rates. The good match up of the curves with the scaling shown also yields a calibration between the reduced power parameter u_0^2 in the theory and the actual power in the experiments. The vertical dashed lines in (a) and (b) show the soliton formation region.

Fig. 5 Example results from Ref. 11 on the amplitude decay rate α and energy decay rate β vs. input power for pulse signals of the sort shown in Fig. 4. Graph (a) shows the data. Graph (b) shows theory based on the NLS equation, with u_0^2 as a dynamic magnetization response parameter which scales with input power. The horizontal dashed line labeled η shows the amplitude decay rate for linear pulses.

2.2 Soliton phase

One very important development in the understanding of soliton properties has been in the discovery of the importance of phase profiles. The steepening and narrowing is purely qualitative. Phase profiles are quantitative.

Figure 6 shows one result from the phase profile measurements on MSBVW solitons in Ref. 12. The dashed curves show the usual power profiles vs. time at the output transducer and the solid lines show the phase across the pulse. If the carrier signal inside the pulse envelope maintains a perfect harmonic form, the phase change is zero. When dispersion is acting to broaden the pulse or nonlinear effects are acting to shift the frequency, the phase profile will be concave upward or concave downward, depending on the MSW signal. When dispersion and the nonlinear response are compensated, as for solitons, the phase profile is flat. The region of constant phase across the peak region in (b) and (c), and across the main peak and the secondary peak in (d), show the formation of solitons.

The discovery of phase profiles as an unambiguous and direct indication of soliton formation has proved to be very useful for soliton diagnostics. The soliton pulse trains to be considered below, for example, could be instantly verified to consist of solitons simply from phase profile measurements.

Fig. 6 Experimental phase and power profiles from Ref. 12. These data are for an MSBVW 5 GHz pulse signal as a function of the input power. The solid lines show the phase profiles and the dashed lines show the power profiles.

2.3 Nonlinear power response and soliton modeling

One important result of soliton generation in YIG films is a nonlinear output versus input power response. A typical response is shown in Fig. 7. These responses are clearly nonlinear, with a small but distinct change from a simple linear response for input powers in 50-100 mW range and a turnover in the peak output power above 300-500 mW, depending on the frequency.

While the solid curves in Fig. 7 are a guide to the eye only, modeling based on the nonlinear Schrödinger equation has proved to be quite accurate, if proper attention is paid to the careful determination of the MSW parameters and the frequency response of the MSW normal modes are taken into account. Such modeling has been successful, not only for the decay properties already discussed, but also for power profiles of the sort in Fig. 7 and actual pulse profiles as well. Some representative comparisons between measured pulse profiles and modeling results are shown in Fig. 8. The operating point frequency of 4.90 GHz was far enough from the MSBVW cut-off frequency of 5.04 GHz that filtering of the model response was not needed. The profiles show that the NLS equation provides a satisfactory basis for the modeling of MME solitons. If the operating point frequency is close to the band edge, so that the Fourier components of the microwave pulse signal extend beyond that band edge, this natural filtering must be included in the NLS model calculations.

2.4 Soliton order and soliton velocity

Although not evident from the power profiles in Fig. 7, one may use these types of data to determine input power threshold values for the onset of the nonlinear response and soliton formation. A careful examination of the response data in Fig. 7, for example, would yield well defined input power values for the departure from a strictly linear response. As shown in Ref. 8, these threshold power values hold important information on the order of the soliton which will eventually be produced at high power. This soliton order loosely corresponds to the number of peaks evident in

Fig. 7 Output pulse peak power P_{out} vs. input pulse peak power P_{in} for three operating point frequencies, as indicated. The inset graphs show the three sets of data separately. The solid lines are a guide to the eye. The MSBVW input pulse width was 13 ns and the film thickness was 10.2 μ m.

Fig. 8 The solid and dashed curves show measured and computed output power vs. time profiles, respectively, for the indicated input pulse peak power P_{in} values. The parameters were the same as for Fig. 7 and the operating point frequency was 4.90 GHz.

the pulse profile, as in Fig. 3, for example.

While the details of the analysis are based on inverse scattering theory and beyond the scope of this report, the results on soliton order as a function of the input pulse width are particularly striking. Some representative results are shown in Fig. 9. These results were obtained from measurements of the input power threshold for the onset of soliton formation as a function of the input pulse width. The data show that the soliton order parameter n moves from an initial value of 1 at the lowest pulse width shown to a plateau at $n = 2$, and then approaches $n = 3$ at very large pulse widths. These experiments were the first to demonstrate the quantitative experimental connection between soliton power thresholds

The soliton order also appears to be manifested in a recently discovered power dependent soliton velocity. In contrast with the above results on decay and threshold power, a power dependent soliton velocity is not predicted by either the NLS equation or the inverse scattering formalism. The experimental results are shown in Fig. 10. The three graphs in the figure are for different input pulse widths. The various horizontal dashed lines labeled $n = 1$, $n = 2$, and $n = 3$ correspond to predicted velocities for different order solitons based on an ad hoc model which equates soliton thresholds and modulational instability thresholds. The vertical dashed line separates the nonlinear

Fig. 9 Experimental 5.8 GHz MSBVW soliton number parameter n versus input pulse width from Ref. 8, as obtained from power threshold measurements and inverse scattering theory.

Fig. 10 Soliton velocity as a function of power for different input pulse widths.

from the linear response regimes. A real theory for this effect has yet to be developed.

The data show that at the shortest input pulse width of 13 ns, the measured soliton velocity shows a linear increase with power. There may be a small plateau at the $n = 1$, but the data are too coarse to define such a plateau clearly. The 25 ns and the 36 ns data, however, clearly show velocity plateaus at the $n = 2$ and $n = 3$ velocity levels, respectively.

2.5 Soliton reflection and collision

One of the fundamental and most appreciated properties of solitons is in the ability of two such pulses to pass through each other without modification. While such an ability is expected for linear signals because of superposition, it does not usually extend to nonlinear systems. Solitons represent an important exception.

Figure 11 demonstrates the experiment and the observed results of soliton collision. The upper diagram shows the distance vs. time trajectories for the single and the double pulse experiment with reflection of the pulses off the far edge of the film. When two properly timed pulses are used, one achieves a collision between the two solitons roughly midway between the film edge and the pick-up transducer. It is clear from the data in Fig. 11 that the collision does not affect the soliton shape or amplitude.

The results in Fig. 11 are for order one solitons generated at modest power levels above threshold but well below the turnover point in Fig. 7, for example. Figure 12 shows a striking collision effect for substantially higher powers close to the turnover point and in the regime for which second order solitons are produced. The data in graph (a) show that when only one pulse is propagated, the shape upon reflection is deteriorated somewhat but the order two soliton character is preserved. Graph (b) shows that the second

Fig. 11 Representative trajectories and soliton pulse profiles for the single and double pulse experiments in the backward volume wave configuration for the 5.1 μm thick YIG film strip and a carrier frequency of 5.779 GHz, after Ref. 9.

pulse, even before collision, is modified by the passage of the first soliton. Pulse F2 in (b) shows only a single peak. These data show a new “wake” effect. The first soliton produces a wake. The second soliton following close behind is modified by this wake. Clearly, there is more to soliton interactions that one might expect from theoretical considerations and the data in Fig. 11

3. Soliton feedback and soliton trains

In addition to the study of soliton properties for single propagation paths, or with reflection as in Figs. 11 and 12, feedback techniques have been used to cycle the MME soliton pulses through the YIG film for multiple passes. Under proper conditions, it is possible to produce decay free soliton trains and to use mode locking to spontaneous soliton modes in the YIG film without any input microwave pulses whatsoever. Both effects present important new aspects of soliton physics. They also hold profound device implications.

Figure 13 shows a schematic feedback configuration which served as the basis for an active delay line, as discussed in Ref. 14. The output pulse train is generated from the single input pulse. As the pulse circulates around the feedback loop, one output pulse is generated for each pass. With simple feedback as shown in Fig. 13, the overall loop gain must be kept fairly low in order to avoid oscillations. Nevertheless, it was possible to achieve pulse decay rates which were significantly smaller than those shown in Fig. 4. The simple feedback scheme in Fig. 13 has not yet been successfully applied to solitons.

However, refinements to this scheme have been applied to solitons. The first such application was in the form of an “interrupted” soliton feedback generator.¹⁰⁾ The circuit was more complicated than in Fig. 13, but the basic change was

Fig. 12 Representative pulse profiles from Ref. 9 for single and double pulse experiments, as in Fig. 11, but at an input power level well above the soliton threshold.

simply to add a fast microwave switch in series with the attenuator in the feedback loop. This switch was normally closed so that the feedback could work to generate the series of output pulses shown in Fig. 13. It was found, however, that by using the switch to *interrupt* the feedback, one could use this break in the feedback to suppress the oscillations which commence for loop gains of unity or higher. With the input power and other conditions adjusted to produce soliton propagation in the YIG film, the interrupted feedback made it possible to operate the device with a loop gain of unity and produce a very long train of decay free soliton pulses. The maximum time between interruptions which could be used before oscillation set in was about 40 μs .

The second such application was in the form of a mode locked “spontaneous” soliton generator.¹⁵⁾ In this scheme, the switch in the first scheme was used as a modulator and the feedback loop was opened for about 10 ns once every cycle. If the modulation was synchronized to the loop cycle time for the MSW pulse, it was found that solitons could be generated *spontaneously*. That is, the decay free train of solitons could be produced through mode locking to the modulation and *without any input trigger pulse whatsoever!*

Figure 14(a) shows a representative soliton pulse output train for the mode locked experiment from Ref. 15. Even though only nine pulses are shown, the actual train of soliton pulses extends indefinitely. Keep in mind that the gain of

Fig. 13 Schematic diagram of the active magnetostatic wave (MSW) delay line with an attenuator, an amplifier, and a passive MSW YIG film delay line in a feedback loop, and with directional couplers for input and output, from Ref. 14.

Fig. 14 Graphs (a) and (b) show detected microwave voltage and phase for spontaneously generated MSBVW solitons in the mode locked modulated feedback scheme.

the feedback is set at unity and the MSW pulse propagation conditions are carefully adjusted to support soliton propagation in the YIG. Figure 14(b) shows companion phase profiles for the pulse amplitude profiles in (a). The flat phase regions which occur just at the positions of the amplitude peaks in (a) provide a direct confirmation that solitons are being generated through this mode locking process. The pulse trains generated through the interrupted scheme look similar to the sequences in Fig. 14, except that the interrupted train can only be maintained for a maximum of about 40 μ s.

4. Parametric amplification of solitons

The feedback techniques presented above provide one way to maintain the soliton pulse amplitude over many pulse cycles and for long, electronically tunable delay times. A second way to eliminate the problem of soliton decay is to develop some means of direct amplification of the propagating MSW pulse signals. A new parametric technique to accomplish such amplification has recently been developed.¹³⁾ The structure is similar to the structure in Fig. 1, except for the additional center element. This element consists of a microstrip line coupled to a microstrip resonator element positioned midway between the input and output transducers. The pump pulse signal consists of a microwave pulse at approximately twice the carrier frequency of the input MME pulse signal. This pulse is timed to occur just as the signal pulse passes over the resonator element. Parametric coupling between the microwave signal from the resonator to the propagating magnetostatic wave pulse leads to a boost in the amplitude of the signal pulse. Details may be found in Ref. 13. The

maximum gain in the soliton peak power at the output is about 7 dB. Lower power pulses in the linear regime could be pumped to gains exceeding 20 dB.

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