APPLIED PHYSICS LETTERS VOLUME 78, NUMBER 7 12 FEBRUARY 2001

Self-generation of bright microwave magnetic envelope soliton trains in ferrite films through frequency filtering

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(Received 23 October 2000; accepted for publication 14 December 2000)

Resonant ring feedback with frequency filtering has been used for the self-generation of bright soliton trains. The solitons were produced from magnetostatic backward volume spin waves propagated in an in-plane magnetized magnetic film delay line as part of the resonant ring structure. The amplitude and phase time profiles, together with the power spectra of the self-generated pulses, confirm their bright soliton nature. © *2001 American Institute of Physics.*
[DOI: 10.1063/1.1347401]

The self-generation of periodic sequences of envelope solitons through the use of active resonant rings has been recently demonstrated.[1–3] An active resonant ring consists of a ferrite film magnetostatic wave delay line and a microwave amplifier. The self-generation of microwave magnetic envelope (MME) solitons in these rings is achieved through adjustment of the nonlinear and dispersive response characteristics of the delay line and ring. Two feedback techniques were used, synchronized time gating and frequency filtering. For synchronized time gating, a periodic interruption of the feedback timed to match the signal propagation time around the ring was used to produce both bright (Ref. 1) and dark (Ref. 2) MME soliton trains. For frequency filtering (Ref. 3), one modifies the pass band characteristics of the delay line itself to control the number and relative amplitude of the ring resonance modes. Suitable mode configurations in the active circuit at high ring gain can lead to the self-generation of soliton trains. Reference 3 demonstrated the use of this technique to self-generate trains of single fundamental dark MME solitons.

As pointed out in Ref. 3, frequency filtering represents an approach to soliton generation in nonlinear dispersive wave guiding media. This letter reports the application of frequency filtering in a magnetic film delay line resonant ring structure to self-generate output trains of narrow constant phase profile mode locked bright microwave pulses. This particular application, among many, shows that complicated microwave pulse sequences which are needed for modern signal processing applications can be obtained with magnetic structures and frequency filtering in a very simple manner. One may contrast the simplicity of this application with a recent report on a similar mode locked microwave pulse output signal obtained through a fifteen component array of coupled phase locked loops.[4] The present application would be extremely useful when a single ring structure is desired and there is no need for external synchronization. Possible applications include narrow mode locked microwave pulse generators or phase locked microwave frequency comb generators.[5]

The implementation of frequency filtering to yield narrow mode locked output pulse trains in the magnetic film ring structure is a two step process. First, one must fabricate a narrow band yttrium iron garnet (YIG) film delay line with a specific power frequency spectrum which corresponds to the desired single soliton width. Second, one places this structure in a ring circuit to produce phase matching for a particular sequence of frequencies within this pass band. The combination of the delay line pass band and the ring resonances then lead to the self-generation of phase locked frequency harmonics when the feedback gain is increased above the oscillation threshold. When the gain is further increased to the soliton threshold, these phase locked frequency harmonics yield, in the time domain, the mode locked train of bright MME soliton pulses.

Figure 1 shows the resonant ring set up for the self-generation of bright soliton trains by frequency filtering. The ring contains the YIG film delay line, an amplifier, and a variable attenuator. The attenuator is used to control the ring gain. The input and output microstrip lines connect to special two element U-shaped microstrip antennas A_{in} and A_{out} for excitation and detection, respectively. The magnetic field H is in the plane of the film and parallel to the magnetostatic spin wave propagation direction. This is the magnetostatic backward volume wave (MSBVW) configuration. For this arrangement, the nonlinear frequency response and the dispersion have opposite signs and combine to support bright MME solitons in the film. Directional coupler DC1 is used to sample the ring signal. Coupler DC2 allows for the applica-

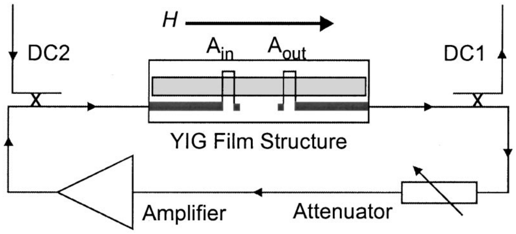

FIG. 1. Diagram of frequency filtering resonant ring structure for the self-generation of bright solitons. The ring consists of the YIG film structure with the special two element U-shaped antennas labeled A_{in} and A_{out}, the attenuator, and the amplifier. The shaded rectangle indicates the YIG film. The DC1 and DC2 elements are directional couplers. The applied magnetic field is labeled H.

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tion of a low power microwave signal for pass band characterization and phase measurements.

The YIG film was a 6.9 μm thick, 1.4 mm wide, 45 mm long strip cut from a larger film grown by liquid phase epitaxy. The film had unpinned surface spins and a narrow ferromagnetic resonance linewidth. Each antenna element was 50 μm wide and 2 mm long. The separation between the two elements of each antenna was 0.26 mm. The separation between the facing elements of the two antennas was 2 mm. These dimensions were chosen in order to set the transmission profile of the delay line to approximately the same width as the envelope of the frequency power spectrum for the target bright soliton train. The microwave amplifier had a 30 dB dynamic range, a peak output power of 2 W and a linear response from 2 to 8 GHz. These characteristics insured that the nonlinear response of the active ring was determined solely by the YIG film.

The self-generation of a stable train of bright MSBVW envelope solitons was done in three steps. First, the feedback was set to zero and transmission versus frequency profiles were measured at port DC1 for the YIG film delay line alone with a low power signal applied at DC2 in Fig. 1. These data were used to confirm the desired frequency position and shape of the delay line pass band. Second, additional transmission versus frequency profiles, measured in the same way, were obtained for the entire ring structure and different values of the ring gain. These data were used to (a) confirm the frequency positions of the ring resonances, (b) determine the change in these responses as a function of the gain, and (c) measure the gain threshold for oscillation. In this step, one makes fine adjustments to the field to obtain a profile at high gain with a pronounced spike at the maximum transmission point from Step 1. The other spikes will then fall off more or less uniformly as one moves away from this main spike frequency. Third, the external source at DC2 is disconnected and the gain is now increased above the oscillation threshold. As the gain is increased, one observes an output train of sharp pulses at DC1. This is the bright soliton train. The soliton characteristics can be evaluated and ascertained through measurements of the amplitude and phase profiles and from the frequency power spectrum of the train.

Figure 2 shows two representative output power versus frequency response profiles obtained at $H=1504$ Oe and low input power. Graph (a) corresponds to step one given above with no feedback. Graph (b) corresponds to step two, with feedback in place and the gain set at the oscillation threshold. This threshold point is the gain at which the ring signal breaks into oscillation. For convenience, the ring gain for this condition will be taken as 0 dB.

The profile in Fig. 2(a) is typical of the delay line pass band response for MSBVW excitations,[4] but modified due to the special U-shaped antennas. The pass band extends from 4860 to 4965 MHz and has a broad maximum centered at 4925 MHz. The upper frequency limit is simply the MSBVW cutoff point at wave number $k=0$. The lower frequency cutoff corresponds to a nonzero k and a half wave length π/k which matches the separation between the two elements for each U-shaped antenna. The signals from these two elements are 180° out of phase and interfere destructively for a null output. The maximum in the power frequency spectrum corresponds to the point in k at which these two signals interfere constructively. As mentioned earlier, this portion of the pass band was made slightly broader than the target width of the single soliton power frequency spectrum.

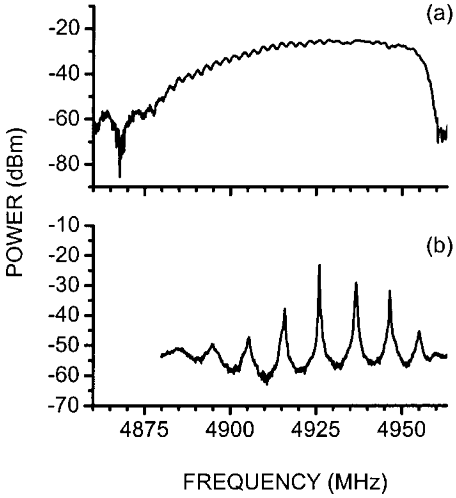

FIG. 2. Power frequency profiles for the delay line ring structure (a) with no feedback and (b) with feedback set at the oscillation threshold 0 dB gain point. The nominal input power was −20 dBm. The static in-plane magnetic field was 1504 Oe.

The profile in Fig. 2(b) shows pronounced spikes which correspond to the resonant frequencies of the ring. At these spike points, the phase matching condition $kL+\phi=2\pi n$ is satisfied, where kL is the phase change for the delay line, ϕ is the electronic phase associated with the rest of the ring, and n is an integer. For the parameters given above, one obtains a spike spacing of about 10.5 MHz. Note the presence of one pronounced spike and several side spikes. The side spikes are smaller by 7 dB or more. The spike spacing, positions, and amplitudes are all a sensitive function of the delay line parameters and the field H. The step two procedure given above was used to match the main spike in Fig. 2(b) to the maximum transmission point in Fig. 2(a). Since the feedback threshold for oscillation in the ring is determined by the spike with the highest power level, the main spike will dominate any linear self oscillation response. This spike provides the seed response for the formation of bright MME solitons when the ring gain is above 0 dB. The filtered MSBVW pass band and the nonlinear MSBVW modulational instability response combine to shape the spectral response to produce the solitons.

Figure 3 shows representative data on the self-generation of bright solitons when the gain is above the oscillation threshold. The data shown are for a ring gain of 1 dB and other parameters as given above. Graph (a) shows the amplitude versus time signal for the soliton pulse train at point DC1 in Fig. 1. Graph (b) shows the corresponding phase signal. Graph (c) gives the power frequency spectrum for the signal in Fig. 3(a). Except for the phase data, these results are representative of data obtained with no microwave input signal whatsoever. An additional low power 4927 MHz reference signal was used for the phase measurements in Fig. 3(b). This signal had no effect on the soliton response.

The signal characteristics for these data match those ex-

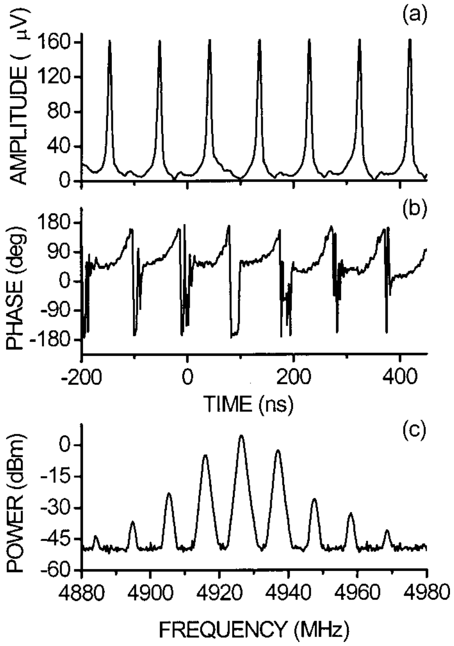

FIG. 3. Bright soliton pulse train characteristics. Graphs (a) and (b) show the microwave voltage and phase profiles, respectively, for the self-generated signal in the ring structure at a ring gain of +0.5 dB. Graph (c) shows the power frequency spectrum of the pulse train in (a).

pected for bright MME envelope solitons. The data in Fig. 3(a) show the sequence of periodic steep and narrow amplitude versus time profiles which characterize the soliton trains generated in the YIG film. These pulses had peak amplitudes of about 160 μV and half amplitude widths of 17 ns. The phase data in Fig. 3(b) show the characteristic regions of constant phase across the central portion of each pulse in Fig. 3(a). These flat phase regions provide the quantitative signature for bright solitons.[5] The power spectrum in Fig. 3(c) shows the multiple frequency harmonics which correspond to the self-generated soliton pulse train in Fig. 3(a). Note that the band width for these harmonics is narrower than the frequency pass band for the low power ring response with no feedback in Fig. 2(a). Note also that the positions of these harmonics for the self-generated bright soliton train match precisely the resonant frequencies of the ring indicated in Fig. 2(c). The 10.5 MHz spacing of these harmonics implies a repetition rate for the temporal pulse train of 95.2 ns. This value closely matches the experimental pulse spacing of 94.3 ns from Fig. 3(a). Taken together, the data in Fig. 3 unambiguously establish the bright soliton nature of these self generated pulses.

Further data show that the pulse trains generated in the ring are stable and can be maintained indefinitely. Stable bright MME soliton self-generation was observed over a range of ring gain values of about 2 dB. At higher gains, the signals changed significantly. The details of these changes under high gain conditions are presently under further study. The main effects appear to be (i) bifurcations and the appearance of extra peaks in the power frequency spectra and (ii) the development of a chaotic signal response at very high values of the ring gain.

In summary, this letter reports the self generation of bright spin wave envelope solitons by a new and general technique. The key to the process is a properly devised filtering response for the nonlinear excitations. The combination of (i) the filtering, (ii) feedback in the resonant ring structure, and (iii) the modulational instability which derives from the nonlinear response produces the soliton signals for a small range of gain values above the oscillation threshold for the ring.

The filtering technique represents an approach to soliton generation in nonlinear dispersive wave guiding media. Previous techniques required either specially shaped input pulse microwave signals or single pulses with some scheme to interrupt the feedback after some limited number of pulses. The frequency filtering eliminates these problems and makes it possible to produce the soliton train for an indefinite time duration without the application of external signals of any kind. From the point of view of applications, the filtering technique provides a way to produce electronically controllable complicated microwave pulse configurations for various microwave engineering applications.[6,7]

This work was supported in part by the U.S. Army Research Office, Grant No. DAAG55-98-1-0430, the National Science Foundation, Grant No. DMR-9801649, the Russian Foundation for Basic Research, Grant No. 99-02-16370, and the International Association INTAS, Grant No. 99-1812.

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