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Nonlinear Ferrite Film Microwave Signal Processing for Advanced Communications—Physics and Devices

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Microwave ferrite devices, including circulators, isolators, and phase shifters, have played a crucial role in the development of radar and other microwave signal processing applications. Recent work has advanced the basic understanding and applications for a wide range of new nonlinear spin wave phenomena in ferrite films. With the help of feedback and parametric pumping interactions, these spin wave phenomena can serve as the basis for phase locked frequency comb generators, wideband chaotic microwave oscillators, and microwave pulse multiplexers, among other devices.

Keywords Ferrite films; microwave signal processing devices; phase locked; frequency combs; chaotic oscillators; pulse cloning

Introduction

Nonlinear effects in ferrite thin films continue to play an important role in high frequency communication signal processing applications [1]. The purpose of this paper is to report (1) the self-generation of broadband chaotic microwave signals in magnetic ferrite film feedback rings and (2) the cloning and trapping of microwave pulses through parametric interactions between spin wave pulses and electromagnetic pumping pulses.

Self-Generation of Chaotic Microwave Signals

Magnetic ferrite film based microwave feedback rings have recently been used to self-generate stationary periodic short microwave pulse sequences in the form of bright, gray, or black spin wave envelope soliton trains [2–4]. In the frequency domain, these pulse sequences correspond to phase locked regular frequency combs. Such short pulse trains and frequency combs have the potential for applications in microwave signal processing devices and systems.

In addition to the stationary waveforms, chaotic microwave signals can also be self-generated in magnetic ferrite film feedback rings. When the ring system works under a relatively high static magnetic field where only four-wave parametric magnon processes

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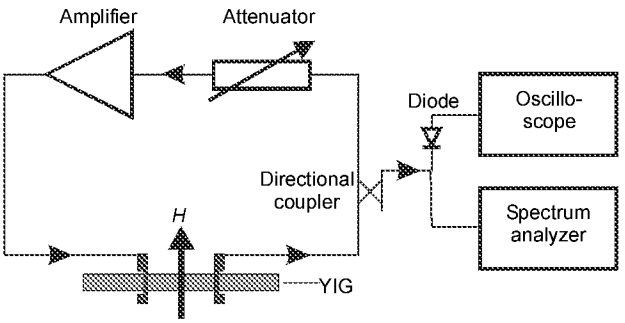

Figure 1. Diagram of magnetic ferrite film based microwave feedback ring.

are allowed, the power spectrum of the self-generated chaotic signal has typical bandwidths of 300 MHz or less. When the ring system works under a relatively low static magnetic field where both four- and three-wave parametric processes are allowed, the generation of chaotic spin wave signals with a bandwidth greater than 1000 MHz is possible. Such a wideband microwave chaotic signal has potential applications for chaotic communication systems. In Refs. [5] and [6], a scheme of direct chaotic communication was proposed. In that scheme, the information components are embedded in the wideband chaotic signal by means of formation of an appropriate stream of chaotic radio pulses. The transmission rate in such a scheme can be as wide as the spectrum of the chaotic signal itself.

This experiment was conducted with the ferrite film based feedback ring as shown in Fig. 1. The ring contained a ferrite thin film delay line, a microwave amplifier, and an adjustable attenuator for gain control. The rectangle strip indicates the single crystal yttrium iron garnet (YIG) thin film. Two microstrip line antennas were positioned over the film strip for excitation and detection of the spin waves in the film. The static magnetic field H was in the plane of the film and perpendicular to the spin wave propagation direction from the input antenna to the output antenna. As the signal circulated in the ring, it was sampled through a directional coupler for spectrum analysis in the frequency domain and detected signal analysis in the time domain. The YIG film strip used for the data shown below was 9.2 μm thick, 1.3 mm wide, and 35 mm long. It was cut from a larger single crystal YIG film grown on a gadolinium gallium garnet substrate. Each microstrip antenna was 50 μm wide and 2 mm long. The antenna separation was 11 mm.

The static magnetic field was about 170 Oe. At this field, both three- and four-wave parametric processes were allowed and wideband chaotic spin wave generation was achieved. At the ring self-generation threshold, a monochromatic spin wave was produced spontaneously in the film. The spin wave frequency corresponds to the ring eigen frequency with the lowest loss. As the ring gain was increased, the other frequency components were generated through the four-wave process. For large gains, the three-wave parametric processes produced rich, chaotic spectra that were still discrete. Then, at very large ring gains, the spectra were chaotic and nearly continuous, with a bandwidth of about 1000 MHz.

Figure 2 shows representative results for two different values of the ring gain G, as indicated. The left graphs show the time-domain power profiles, while the right graphs show the corresponding power-frequency spectra. The $G = 0$ reference point was obtained as the gain at which the self-generation of a monochromatic signal just started. The data in graph (a) for $G = 3.5$ dB shows a chaotic signal with a discrete spectrum. When the ring gain

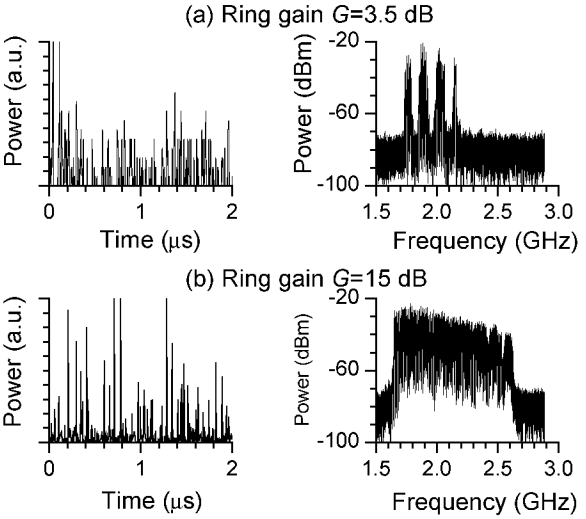

Figure 2. Time-domain power profiles (left) and power-frequency spectra (right) of self-generated chaotic spin waves for different ring gains as indicated.

is increased to $G = 15$ dB, as in graph (b), the spectrum widens to about 1000 MHz and becomes more dense, relative to the $G = 3.5$ dB situation in graph (a). The time-domain signals in both graph (a) and graph (b) have a form of very short chaotic pulse sequences.

Cloning and Trapping of Microwave Pulses

Three-wave parametric pumping [7–9] was used to clone magnetostatic backward volume wave (MSBVW) pulses. In contrast to the broadband chaotic generation discussed above, the cloning and trapping of MSBVW utilizes a three-wave parametric interaction between MSBVW pulses near 5 GHz and electromagnetic pumping pulses near 10 GHz.

The experimental apparatus consisted of a magnetostatic wave (MSW) delay line, an open dielectric resonator (ODR) [10], and three principal signal arms: a 5 GHz signal arm, a 10 GHz pumping arm, and a detection arm, as shown in Fig. 3. The delay line consisted of a long and narrow, 7.1 μm thick single crystal YIG film on a gadolinium gallium garnet substrate. The YIG film strip was placed inside the ODR which was 4.2 mm long, 4.1 mm wide, and 2.3 mm thick, and had relative permittivity $\varepsilon_r \approx 80$ at 10 GHz. Two 20 μm wide microstrip lines were positioned over the YIG film with a separation of 6 mm. The film/ODR structure sit on a flange end of a TE_{10}waveguide, which provides pumping signal to the ODR. A static magnetic field was applied parallel to the long direction of the YIG film strip.

The 5 GHz signal arm consisted of a synthesized sweeper, controlled by a microwave transition analyzer (MTA), a pulse generator with adjustable pulse width and delay, and a microwave switch. The MTA was additionally used as a high frequency sampling oscilloscope. The 10 GHz pump arm consisted of a microwave source, a pulse generator with adjustable pulse width and delay, a microwave switch, and a traveling wave tube amplifier. The pumping pulses were fed into an X-band circulator, and from the circulator into the TE_{10} waveguide.

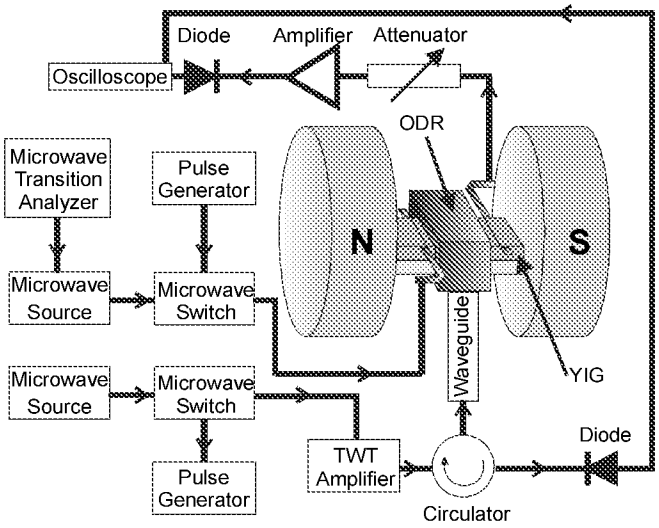

Figure 3. Experimental setup for cloning and trapping microwave pulses.

Due to the nature of the parametric pumping interaction, the pumping pulse frequency must be twice that of the signal pulse frequency to be cloned. The input microwave pulse frequency, and hence the MSBVW pulse frequency, was 4.935 GHz. The pumping pulse frequency was 9.870 GHz.

With four 10 ns wide high power pumping pulses at 9.87 GHz, three microwave output pulses, one parent and two clones, were generated from a single low power microwave input pulse. Figure 4(a) shows three typical output pulses at three different pumping powers. The

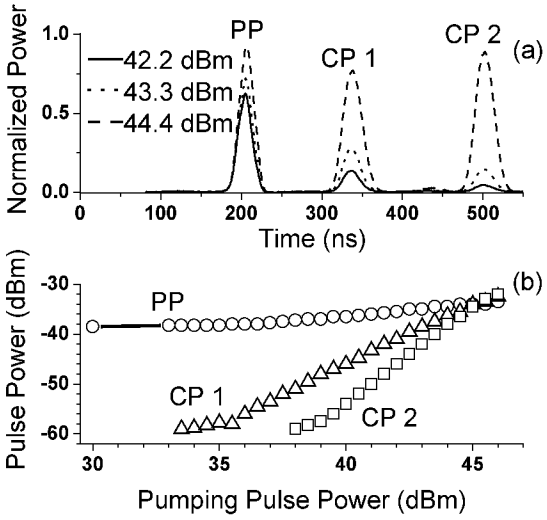

Figure 4. Graph (a) shows three typical output power profiles for pumping powers of 42.2 dBm (16.6 W), 43.3 dBm (21.4 W), and 44.4 dBm (27.5 W). Graph (b) shows output pulse peak power as a function of pumping power.

delay times of the parent pulse (PP), first clone pulse (CP1), and the second clone pulse (CP2) are about 200 ns, 330 ns, and 500 ns. The delay time of the CP2 is 300 ns longer than that of the PP as well as that of a typical 5 GHz delay line [11]. The FFT of the sampled output pulses in Fig 4(a) showed that each pulse had the same carrier frequency spectrum with a width of about 35 MHz.

The peak power of the output pulses was primarily controlled by the pumping power. Larger pumping powers cause larger output powers. This fact can be seen in Fig. 4(b), which shows output pulse peak power versus pumping pulse power. The output pulses were in the linear regime, below a peak output power of 0.5 mW, even for the largest pumping power available, 40 W. Each clone has a different threshold, the first clone appeared near 2 W of pumping pulse power, and the second near 6 W. The peak power of each output pulse increases at different rates with respect to the pumping power due to the fact that each output pulse experiences a different number of pumping pulses. All three output pulses nearly have the same peak power at a pumping power of 31.6 W (45 dBm). The convergence of all three output pulse powers is somewhat arbitrary. The pumping pulse temporal widths and delay were tuned so that at a given power all three output pulses had the same peak power. Had the pump pulse temporal widths or positions been different, each output pulse would have had different gain curves than shown in Fig. 4(b).

Conclusion

This paper reports two new nonlinear spin wave phenomena in ferrite films. Broadband chaotic microwave signals have been self-generated in ferrite film based active feedback ring systems. The frequency bandwidth was about 1000 MHz. Such broadband chaotic signals have possible applications in chaos based communications. With the help of parametric pumping interactions, spin wave pulses were cloned during their propagation in ferrite films. The cloned pulses have the same temporal and spectral characters as the parent pulse. This cloning phenomenon can serve as the basis for novel microwave signal processors, such as microwave pulse multiplexers.

Acknowledgments

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