Magnetostatic Soliton Propagation at Microwave Frequency in Magnetic Garnet Films

P. De Gasperis, R. Marcelli, and G. Miccoli

Istituto di Elettronica dello Stato Solido del Consiglio Nazionale delle Ricerche, I-00156 Roma, Italy

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The linearity of the power response of yttrium iron garnet films to a microwave pulse having length shorter than the delay time characteristic of the specimen is investigated. In particular, a threshold is found above which output power increases with respect to standard linear trend. The above novel effect, analyzed in some detail on five epilayers of different thicknesses, cannot be explained in terms of usual nonlinear processes. An interpretation in terms of soliton excitation, accounting for the existence in the system of both intrinsic nonlinearity and dispersion, is proposed.

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Presently, solitons are an active field of interest in both fundamental and applied solid-state physics. The mathematical advances in finding out analytical solutions to a certain number of nonlinear dispersive wave functions[1] have given a powerful tool to their study and characterization.

As is well established, a soliton results as a fairly delicate balance between the dispersion (which forces the signal to spread out) and the nonlinearity (which forces the signal to steepen) of the system under investigation. Apart from the interest in basic research, the remarkable applications of soliton propagation in optical fibers,[2] nonlinear transmission lines,[3] and Josephson junctions[4] (just to mention a few of them) seem to justify the search for solitons in media which are inherently both dispersive and nonlinear. Some systems in the field of acoustical[5] and radio-frequency signal transmission are in principle suitable to fit those requirements. Among them, the analysis of possible soliton excitation in a magnetostatic wave (MSW) device such as a dispersive delay line[6] operating at microwave frequency is particularly appealing. From a theoretical standpoint, a dipolar model dealing with the nonlinear properties of nonexchange MSW's propagating in a low-loss magnetic film of yttrium iron garnet (YIG) has been recently developed.[7] To account only for nonlinearities produced by self-action processes, a nonlinear Schrödinger equation describing the evolution of envelope solitons has been derived in the weak nonlinearity approximation. In this way, expected threshold powers for the onset of self-modulation and self-channeling have been derived.

Furthermore, through an analysis of the unique experimental data available in current literature, it turns out that attempts to detect purely magnetostatic solitons in YIG films have been so far unsuccessful.[8] In this framework, some nonlinear phenomena, interpreted in terms of multisoliton excitation as deduced by our analyzing the time envelope of an output pulsed signal,[8,9] have been reported. In order to get that result, the operational frequency had to fall within a few defined regions of the spectrum close to so-called repulsion gaps.[10] According to the theory and experimental findings,[11] resolvable gaps can be observed under specific conditions of spin pinning whenever the dipolar and exchange energy terms are comparable in magnitude. From an experimental standpoint, a correct analysis of the possible propagation of MSW solitons at microwave frequency can be performed by our looking at the power response of the device, i.e., by measuring the output power (P_{out}) as a function of the input power (P_{in}). Hence, dissimilar to the experiment of Ref. 9, the detection and analysis of the output signal envelope in the time domain is not here considered as a reliable technique to achieve unambiguous results. In fact, because of the finiteness of its operational band, the device introduces an amplitude modulation of a pulsed signal passing through it. Thus, especially for devices characterized by a narrow transmission band (i.e., up to 100–150 MHz), the presence of several side lobes hinders the detection of possible satellite peaks or oscillations[8,9] correlated soliton propagation.

In this work, the power response to pulsed microwave signals passing through a standard magnetostatic-wave dispersive delay line tunable in the C band (4–8 GHz) has been analyzed as a function of the film characteristics (i.e., thickness and magnetic losses). As a peculiar result, a novel and unusual nonlinear effect related to the *increase* of the output signal above a defined threshold power has been observed and interpreted in terms of soliton generation. A quantitative comparison with available theory seems to confirm the validity of our basic interpretation.

In general, magnetostatic waves are inherently dispersive slow electromagnetic waves generated in a garnet chip magnetically saturated in an external dc field. In principle, the system is also nonlinear as evidenced by a look at the basic equation of the standard theoretical treatment.[12] However, in the usual derivation of the dispersion relation, the nonlinearity is commonly assumed to be small and hence negligible with respect to the linear terms. Although in practice such an approach has been demonstrated to be consistent with experiments, the nonlinear contribution is no longer negligible for input power levels which typically exceed some MSW's in the continuous-wave regime with a consequent signal limitation.[13]

In order to achieve conditions under which practically no magnetoexchange gaps exist (i.e., only the dipolar term is actually relevant), rather thick films have been exploited[14] in the present experiment. In particular, five YIG epilayers having thicknesses of 9, 22, 31, 48, and 107 μm, and different levels of magnetic losses [as quantified by ferromagnetic resonance (FMR) linewidth], have been exploited by our shaping them as rectangular chips of 15×5 mm^2. Because of that choice, the effects due to the exchange energy term can be reasonably neglected (i.e., no resolved magnetoexchange branches are observed). As is commonly done,[15] MSW propagation in the film has been achieved by its placement on two 50-Ω-matched, 10-mm-distant parallel microstrips evaporated on a 254-μm-thick alumina grounded substrate. The frequency of work was around 7.0 GHz while the constant dc field (about $H_0 = 4.20$ kOe) was oriented normal to the chip plane to excite purely forward volume waves. In this way, the operational frequency falls safely outside the region of overlapping among MSW's and half-frequency exchange spin waves[16] where drastic limitations of the rf signal output take place.

During the experiment, rectangular pulses as short as 20 nsec could be launched, while the power, shape, and time delay of the signal were controlled and measured by standard microwave apparatus such as a sampling oscilloscope and sensitive power meters.

In general, the total attenuation affecting the signal passing through the measurement setup and the device is due to both insertion and propagation loss. The former is due to many technical reasons such as matching of transducers,[17] dissipation of cables and connectors, and so on, and it is definitely independent of the length and the power level of the input pulse. On the other hand, the propagation loss is correlated with the intrinsic properties of exploited material,[18] namely delay time and magnetic relaxation.

As a first step, the behavior of the power response to a cw input signal has been tested for a 9-μm-thick film. As a confirmation of an earlier measurement,[19] the relative trend is linear up to input values of the order of 15 mW above which a net saturation of the output signal starts to appear. When pulsed signals with $P_{in} < 15$ mW are exploited, the same linear response is obtained (see the straight line drawn in Fig. 1) for a pulse length (t_p) of the same order or higher than the delay time. For shorter pulses, the output behavior starts to be nonlinear above threshold values (P_{th}) of the order of some hundred microwatts or less where the measured output power is *greater* than that expected from the extrapolation of the initial linear trend, as clearly visualized in Fig. 1 for the specific case $t_p = 30$ nsec. Such an effect,

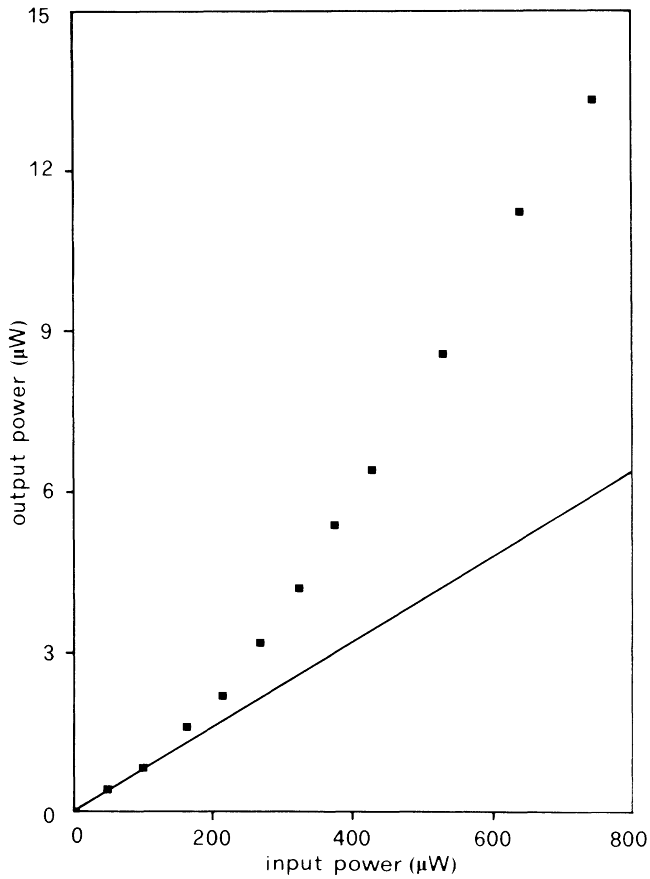

FIG. 1. Typical nonlinear response of the output power P_{out} as a function of the input power P_{in} (both given in microwatts) taken on film No. 1 (9 μm thick) at 7 GHz and with $t_p = 30$ nsec. When a rf pulse having $t_p \gtrsim T_d$ or a cw signal is exploited, measured values fall on the drawn straight line. Analogous plots have been obtained for every couple of pulse-length and thickness values.

just opposite to what is observed when a signal limitation occurs, can be interpreted in terms of a decrease of the propagation loss inside the magnetic film for $P > P_{th}$.

By extension of the above investigation to the other four specimens, analogous responses have been observed for pulse lengths ranging between 20 and 60 nsec. As a graphical résumé of those results, the inferred values of threshold power as a function of inverse squared pulse length are plotted in Fig. 2 for all five samples. As is evidenced, higher values of threshold power are related to shorter pulses and to thinner films even if, for the two thickest films, the trends are not experimentally resolvable.

As mentioned, the above results cannot be definitively explained within the framework of standard nonlinear processes such as interaction with exchange spin waves[16] and multimagnon or phonon confluence.[20] On the other hand, the observed loss reduction above the threshold is

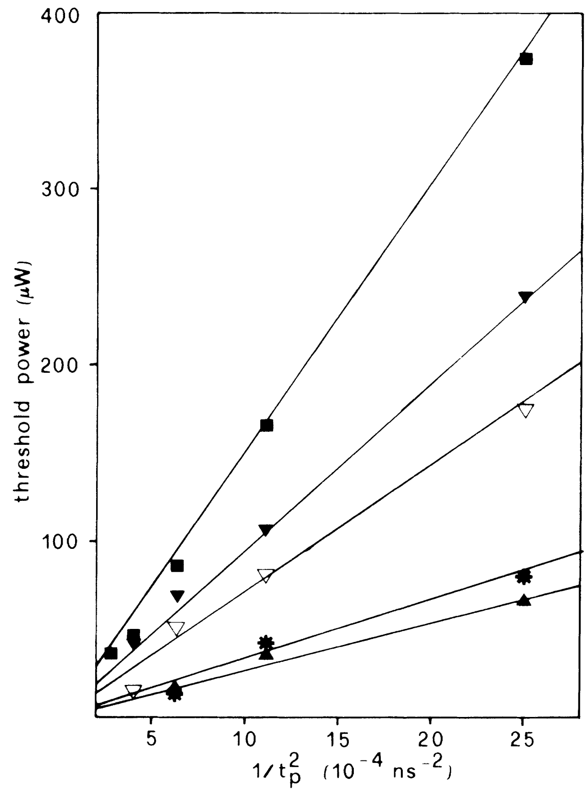

FIG. 2. Experimental values of threshold power P_{th} (given in microwatts) as a function of the inverse squared pulse length t_p for films: squares, No. 1 (9 μm); inverted filled triangles, No. 2 (22 μm); inverted open triangles, No. 3 (31 μm); filled triangles, No. 4 (48 μm); asterisks, No. 5 (107 μm). P_{th} values have been already corrected for the linear loss affecting pulse at the time $t \leq t_p$ (see text). As a comparison, for each film the expected curve calculated according to the $1/t_p^2$ trend is also drawn.

explainable by our accounting for the excitation of a soliton resulting from the balance between the inherent nonlinearity and dispersion of the magnetostatic system.

By reference to a typical plot as in Fig. 1, the following interpretation can be figured out. When a rf square pulse is used as input, it propagates in the film with an intrinsic linear propagation loss (L) (in decibels) between microstrips of[18]

$$L = 10\log_{10}[\exp(-\gamma \Delta H\, T_d)] \quad (1)$$

(where γ is the gyromagnetic ratio, ΔH is the FMR full linewidth in oersteds, and T_d is the characteristic delay time in seconds) until reaching the region of nonlinear behavior due to soliton formation. Since we are dealing with a threshold effect, a well-defined energy value is needed to excite a soliton. Thus, in principle, it cannot be generated instantaneously by use of a square pulse of power P (i.e., providing an energy $E = Pt_p$), but at the time $t = t_p$ when the condition $E_{th} = P_{th} t_p$ can be satisfied. In practice, however, the time profile of the rf signal is changed passing through the film during the time $t \leq t_p$, thus reducing the energy available at the time $t = t_p$. If that energy is sufficient to excite a soliton (i.e., $E \geq E_{th}$), the measured values of threshold power have to be corrected for the effect of propagation loss in the interval $0 \leq t \leq t_p$, by use of Eq. (1) where t_p replaces T_d. In this framework, for $P \geq P_{th}$, the total attenuation measured at the end of the device is due both to the insertion loss and to the propagation loss affecting the input pulse before the soliton formation. From a physical standpoint, because of the intrinsic properties of solitons, it means that for $t > t_p$ the rf signal travels in the film with no propagation loss.

TABLE I. Comparison between the values of the D factor inferred (i) by use of the differences in slopes as deduced from Fig. 1 and equivalent plots (D_{prop}) and (ii) by utilization of Eq. (3) after the measurement independently of the FMR linewidth and delay time (D_{FMR}).

Film No.	Thickness (μm)	D_{prop}	D_{FMR}	T_d (ns)
1	9	1.10	0.90	200
2	22	1.08	0.99	112
3	31	0.60	0.62	104
4	48	0.32	0.41	76
5	107	0.58	0.41	54

The above picture can be quantified by an analysis of the available experimental results. In fact, the output power in the linear and nonlinear regions can be written as

$$P_{out}^{(L)} = P_{in}\exp[-(\Gamma + \gamma\Delta H T_d)], \quad \text{for } P < P_{th},$$
$$P_{out}^{(NL)} = P_{in}\exp[-(\Gamma + \gamma\Delta H T_d)]\exp(+D), \quad \text{for } P \geq P_{th}, \quad (2)$$

where

$$D = \gamma \Delta H (T_d - t_p) \quad (3)$$

is the factor of loss reduction due to the soliton excitation in the nonlinear region, and Γ is the insertion loss of the device. Thus, according to the present interpretation, two different approaches are available to infer numerically the factor D: (i) by means of Eqs. (2), through the analysis of the difference in slopes between regions below and above the threshold power, as deduced from the data of Fig. 1 (and of equivalent graphs drawn for all the exploited values of thickness and pulse length); and (ii) by means of Eq. (3), after the measurement of delay time and FMR linewidth.

Since it is based on two independent methods of derivation, the comparison of the D values achieved through the above approaches represents a test of validity of the basic assumption concerning the soliton excitation. As shown in Table I, within the limit of the sensitivity of propagation measurements, such a comparison is satisfactory.

Theoretically, an expression for the threshold power can be derived by means of a general approach dealing with a nonlinear Schrödinger equation.[7] In practice, the related analytical development is very difficult, especially when boundary conditions accounting for experimental occurrences such as nonvanishing wave-vector values, pinning of spins at film surfaces, and beam-steering effects are introduced. In this framework, however, according to the basic assumption of the MSW soliton model, the threshold power is a complicated function of nonlinearity and dispersion but it depends on a simple inverse square law with respect to the pulse length.[7] The validity of such a statement is easy to verify by the comparison of experimental results to a t_p^{-2} trend; as shown in Fig. 2, a good agreement for all specimens has been found. Presently, attempts are in progress to achieve a complete analytical model accounting for all experimental conditions.

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