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A. Prabhakar and D. D. Stancil

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Nonlinear microwave-magnetic resonator operated as a bistable device

A. Prabhakar
MKE-Quantum Components, 1450 Infinite Drive, Louisville, Colorado 80027

D. D. Stancil[a)]
Department of Electrical and Computer Engineering, Carnegie Mellon University, Pittsburgh, Pennsylvania 15213

The excitation of large amplitude spin waves causes a shift in the resonance frequency of a ferrite resonator towards higher frequency values. Using this shift, a resonator can be designed to operate in a bistable mode where the history of the input power determines the output power. A theoretical calculation for a resonator with a linewidth of 1.5 MHz, measured at 10 GHz, predicts a discontinuous jump in output power by a factor of about 3.5 as the input power is increased to about 0.7 mW. The phenomenological model that describes the bistability also provides an explanation for the foldover of ferromagnetic resonance curves at high input power levels. An appropriate choice for the operating frequency ensures that the estimated input power required to observe the bistable behavior is below the predicted threshold power for spin-wave auto-oscillations at the main resonance. © *1999 American Institute of Physics.* [S0021-8979(99)35208-7]

I. INTRODUCTION

A variety of microwave devices that use nonlinear spin-wave interactions are found in the literature. Researchers have designed nonlinear devices such as active magnetostatic wave (MSW) delay lines,[1] magnetic envelope soliton train generators,[2] signal to noise enhancers[3] and a bistable microwave device using an external feedback circuit.[4] These devices have possible applications in microwave switching or amplifying circuits.

Anderson and Suhl described an instability mechanism that causes a foldover of the ferromagnetic resonance (FMR) curves for thin film ferrite samples.[5] Seagle, Charap, and Artman suggested that this mechanism can be used to design a device that retains a memory of past microwave power levels.[6] However, experimental observations of the instability have been complicated by parametric spin-wave excitations[7] and thermal effects.[8] We propose a design for a thin film ferrite resonator with a bistable output power below the threshold for spin-wave autooscillations. A phenomenological model similar to Anderson and Suhl's is used to describe a decrease in the demagnetizing field with increasing MSW amplitudes in a perpendicularly magnetized thin ferrite film. The model also draws a parallel between the foldover mechanism for thin film resonators and the observed shifts in the transmission characteristics of propagating forward volume MSWs.[9,10]

The operation of the bistable device is as follows. If the operating frequency is initially higher than the resonance frequency, the MSW excitations are finite but damped. As the input power reaches a threshold value, the resonance frequency moves towards the operating frequency and the damping decreases causing an even further increase in MSW amplitudes. With the output power being proportional to power associated with the MSWs, the output switches from a low value to a high value. Alternatively, a reduction in the input power causes a switch from high to low output values. By tuning the operating frequency, the critical power at which the switching occurs can be made to differ in these two cases causing the device to operate in a bistable mode.

The phenomenological model describes a bistability in output power with an intuitive appeal while yielding theoretical expressions that are similar in form to those obtained from a more accurate canonical formalism.[11,12] A study of the experimental observations of the FMR response of ferrite films does not lead us to the obvious conclusion that the conditions for a bistability in the output power, as we vary input power, match those required to observe a foldover in the FMR resonance curves. Our simulations establish that this is indeed the case. Furthermore, the resonator operates as a bistable device only when the difference between the input signal frequency and the intrinsic resonance frequency exceeds a critical value. This is not apparent from the original formulation of the instability mechanism.[5]

High power MSW devices are susceptible to parametric spin-wave excitations that degrade performance and often result in an auto-oscillatory or chaotic output signal.[13] A bistable response from the ferrite resonator is best observed when the device is tuned such that the critical input power for bistability lies below the threshold for autooscillations at the main resonance.[13,14] Calculations for MSWs excited by a microstrip transducer in a yttrium-iron-garnet (YIG) film indicate that we can establish the desired operating conditions. Such a bistable response was observed recently by Fetisov and Patton.[15]

II. BISTABLE RESPONSE

A resonator is usually classified in terms of its quality factor, Q, and the full width at half maximum, Δ, of its frequency response. The output power, P_{out}, is related to the low power resonance frequency, f_0, the input power, P_{in}, and input frequency, f, as

[a)]Electronic mail: stancil@ece.cmu.edu

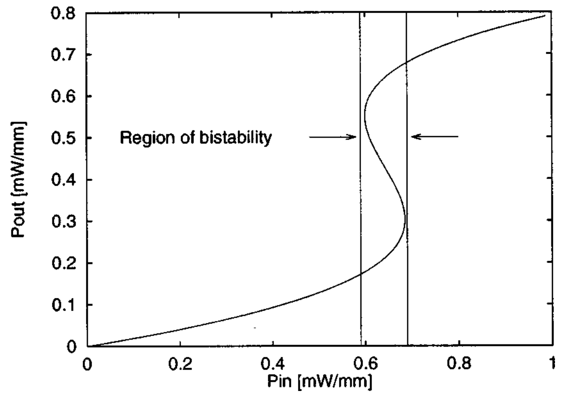

FIG. 1. Estimated response of a thin film ferrite resonator with $A'=1$, $2\Delta=1.5$ MHz, $f-f_0=1.6$ MHz, and $\alpha=2.5$ MHz mm/mW.

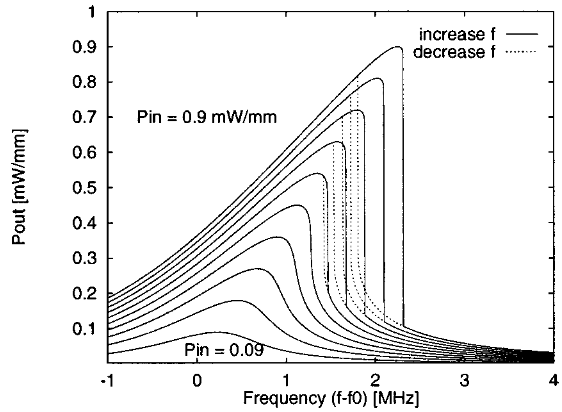

FIG. 2. Simulated fold-over effect in the FMR response of a thin film ferrite resonator with $\alpha=2.5$ MHz mm/mW and $A'=1$. The hysteretic response is obtained by solving Eq. (3) as $f-f_0$ is swept in opposite directions.

$$P_{\text{out}}=\frac{A\,P_{\text{in}}}{[f-f_0]^2+\Delta^2}. \tag{1}$$

Q and the peak power in the resonator are defined by the constants A and Δ such that

$$Q=\frac{f_0}{2\Delta},$$

and

$$\lim_{f\to f_0} P_{\text{out}}\approx\frac{A P_{\text{in}}}{\Delta^2}. \tag{2}$$

Assuming that the output is proportional to the power in the spin-wave excitations P_{SW}, we incorporate the dependence of the resonance frequency on MSW amplitude by re-writing Eq. (1) as

$$P_{\text{SW}}=\frac{A'\,P_{\text{in}}}{[f-(f_0+\alpha P_{\text{SW}})]^2+\Delta^2}, \tag{3}$$

where αP_{SW} represents a linear shift in the observed frequency characteristics and A' represents the efficiency of coupling into the spin-wave system. This linear shift has been well characterized for the case of MSWs in thin film ferrite samples.[9,10,14] A phenomenological model suggests that an increase in MSW amplitude is accompanied by a reduction in the demagnetizing field within the thin film sample.[10] For the case of MSWs excited by a microstrip transducer, P_{in} and P_{SW} refer to the power per unit width. The coefficient α is given by[10]

$$\alpha=\frac{1}{2\pi}\left(\frac{4|\gamma|}{\omega M_s d^2}\right), \tag{4}$$

where $\omega=2\pi f$, $|\gamma|=2\pi(28\text{ GHz/T})$ is the gyromagnetic ratio, $M_s=140$ kA/m is a typical value for the saturation magnetization of the film and d is the film thickness. The cubic relation between P_{in} and P_{SW}, described by Eq. (3), is plotted in Fig. 1.

A region of bistability is well defined when we obtain real values of P_{SW} that satisfy

$$\frac{\partial P_{\text{in}}}{\partial P_{\text{SW}}}=0\,. \tag{5}$$

Combining Eqs. (3) and (5), we solve for the real roots of

$$3(\alpha P_{\text{SW}})^2-4\alpha P_{\text{SW}}(f-f_0)+\Delta^2+(f-f_0)^2=0 \tag{6}$$

to obtain the following condition for observing bistability,

$$f>f_0+\sqrt{3}\Delta\,. \tag{7}$$

III. FMR RESPONSE

To establish the similarity between the foldover of the FMR response and a bistability in the output power of the resonator, Eq. (6) is solved for the two cases: (a) increasing and decreasing input power at a fixed input frequency and (b) sweeping input frequency up and down while keeping input power fixed. Both calculations yield identical results and the latter case is shown in Fig. 2. A bistability in P_{SW} occurs for values of $f-f_0$ that lie between the solid and dashed vertical lines.

IV. LIMITATIONS ON THRESHOLD POWER

Spin-wave auto-oscillations above the Suhl instability threshold at the main resonance can severely degrade the performance of the proposed bistable ferrite resonator. Experimental observations for the case of forward volume MSWs excited by a microstrip transducer appear to support the theoretical predictions for the auto-oscillation threshold power levels.[14,16] We compare the predictions for the input power at the onset of auto-oscillations with those for the onset of bistability. The comparison yields an operating region where we expect to observe bistability but not auto-oscillations.

The threshold power per unit width for auto-oscillations (AOs) at the resonance frequency, $\omega_0=2\pi f_0$, is given by[14]

$$P_{\text{AO}}=\frac{\omega_0\omega_M\eta_0 d^2}{2|\gamma|^2\mu_0}, \tag{8}$$

where μ_0 is the permeability of free space, $\omega_M = |\gamma|\mu_0 M_s$ and the intrinsic loss parameter $\eta_0 = 2\pi\Delta$. At the onset to bistability, the critical power P_c is calculated using Eq. (6) as

$$P_c = \lim_{f \to f_0 + \sqrt{3}\Delta} P_{\mathrm{SW}} = \frac{2\Delta}{\sqrt{3}\alpha}. \tag{9}$$

To ensure bistability below the auto-oscillation threshold, we require $P_c < P_{\mathrm{AO}}$. Substituting Eq. (4) in Eq. (9) the inequality can be expressed as

$$f < \sqrt{3} f_0. \tag{10}$$

Typically, $f_0 \sim 1$ GHz and Eq. (10) can be satisfied over a wide range of operating frequencies. It is important to note that Eqs. (4) and (8) are valid for propagating waves and are therefore only accurate to within a factor of 2 for a resonator. However, the condition of Eq. (10) is based on the ratio $P_{\mathrm{SW}}/P_{\mathrm{AO}}$ and should thus be independent of such a correction factor.

V. CONCLUSION

Simulations reveal that the bistability in output power and the foldover effect in the FMR response curve at high input power levels are two manifestations of the same physical process.[5] Furthermore, the foldover effects in the FMR response of a ferrite resonator[7,8,11] is analogous to a shift in the microwave passband of MSW delay lines.[9,10] In both cases, the excitation of large amplitude spin waves causes a decrease in the demagnetizing field in the film leading to a shift in the resonance frequency. For a thin film resonator, this effect can be exploited to achieve bistability in the output power. We evaluated the design for a typical yttrium-iron-garnet film and determined a frequency regime where the resonator would exhibit a bistable output signal. We expect a degradation of the bistable behavior after the onset of auto-oscillations. Our calculations indicate that for the case of forward volume MSWs it is possible to tune the device to achieve bistability below the auto-oscillation threshold at the main resonance.[14,16] While recent observations have confirmed the existence of bistability,[15] further experiments are required to fully validate the theory.

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