Ordinal Excitation of Three-Magnon and Four-Magnon Processes of Magnetostatic Surface Waves in YIG Films

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Abstract: Ordinal excitations of three-magnon decay, modulation instability and four-magnon decay processes of magnetostatic surface waves propagating in a pure yttrium iron garnet film are investigated in accordance with the relationship between the magnetostatic wave frequency and the internal magnetic field. Onset of the modulation instability is realized as a result of modification of magnetostatic surface wave dispersion characteristics by a metallic ground plane.

1. INTRODUCTION

It is well known that three basic types of magnetostatic waves (MSW), i.e., magnetostatic surface wave (MSSW), magnetostatic forward volume wave (MSFVW) and backward volume wave (MSBVW) can be excited in a ferromagnetic medium with respect to orientation of the external biasing magnetic field. In recent years, nonlinear effects in MSW propagation subject to high power have aroused great interests owing to their importance in science and potential engineering values[1-3], among which the nonlinear MSSW has presented the most peculiar properties. For MSSW, three-magnon decay processes (i.e., the first-order Suhl instability [4]), four-magnon decay processes (i.e., the second-order Suhl instability [4]), and modulation instability have been extensively studied [5-7]

In this paper, ordinal transitions among the different MSSW parametric and modulation instabilities are investigated. Evolution of the nonlinear processes in MSSW propagation is experimentally revealed on the basis of the excitation conditions for these nonlinear phenomena.

2. ORDINAL TRANSITIONS AMONG PARAMETRIC AND MODULATION INSTABILITIES

For a traveling MSSW, conservation in energy and momentum is required both in the three-magnon processes and the four-magnon processes. These conservation laws are expressed as follows:

For the three-magnon processes:

$$\begin{aligned}\omega &= \omega_1 + \omega_2 \\ \mathbf{k} &= \mathbf{k}_1 + \mathbf{k}_2\end{aligned}\quad (1)$$

For the four-magnon processes:

$$\begin{aligned}2\omega &= \omega_1 + \omega_2 \\ 2\mathbf{k} &= \mathbf{k}_1 + \mathbf{k}_2\end{aligned}\quad (1')$$

where ω and $\mathbf{k}$ are the frequency and wave vector of the MSSW, ω_i and $\mathbf{k}_i$ ($i=1,2$) are the frequencies and wave vectors of the parametrically excited MSW. The nonlinear processes described by Eqs. (1) and (1') can not take place simultaneously as onset of the three-magnon processes will simply expel appearance of other higher order nonlinear processes due to its extremely low power threshold. As a basic frequency criterion, it can be considered that when an MSSW frequency is higher than $2\omega_H$, the three-magnon processes are favorable; on the contrary, the four-magnon processes prevail.

For an MSSW, its frequency always falls into the range from $\sqrt{\omega_H(\omega_H + \omega_M)}$ to $(\omega_H + \omega_M)/2$ where $\omega_H = \gamma H_i$, $\omega_M = \gamma 4\pi M_s$, the gyromagnetic ratio γ equals 2.8MHz/Oe for YIG, H_i is the internal magnetic field which is identical to the external magnetic field H_e for the MSSW and MSBVW, $4\pi M_s$ is the saturation magnetization of the ferromagnetic film. For an FM structure that the ferromagnetic medium is grounded by a metallic plane directly, the upper frequency limit can be extended to $\omega_H + \omega_M$. By considering the frequency criterion, it can be found that when $H_i < 4\pi M_s/3$, there always exists possibility for the three-magnon processes; when $4\pi M_s/3 < H_i < 2\pi M_s$, if only the MSSW frequency takes value between $2\omega_H$ and $\omega_H + \omega_M/2$ (again, for the FM structure, the allowed frequency range for the three-magnon processes can be extended up to $\omega_H + \omega_M$),

occurrence of the three-magnon processes is still favorable; when $H_e > 2\pi M_s$, the three-magnon process is forbidden and other nonlinear processes can take place. Therefore, when H_e is chosen in the range between $4\pi M_s/3$ and $2\pi M_s$, all the nonlinear processes can be excited respectively in the frequency range between $2\omega_M/3$ and ω_M provided that the MSSW power exceeds the power threshold corresponding to each instability process. Parametric instability of a traveling MSSW exhibits itself as appearance of a pair of discrete sidebands. Fig. 1 shows the experimental measurements of the power threshold that corresponds to appearance of the first pair of satellite peaks in the spectrum as a function of the MSSW frequency f when the external magnetic field is chosen as 720 Oe. In the experiments, a cw microwave signal is input by a synthesized sweeper to an MSSW delay line which consists of a $28\mu\text{m}$ -thick and 0.4cm -wide yttrium iron garnet (YIG) film and a pair of identical $50\mu\text{m}$ -wide and 1.3cm -apart transducers on a $254\mu\text{m}$ -thick alumina which are shorted by connecting to a metallic plane. The output of the delay line is sent to a spectrum analyzer. In Fig. 1, the dashed line $f_c = 4.03\text{GHz}$ that is $2\omega_H$ divides the measured frequency range into two parts. In part II where $f > f_c$, according to the preceding analyses, the appeared satellites subject to the measured power threshold represent the onset of the three-magnon processes. Compared with the experimental results shown in part I, those in part II are much lower, which is consistent with the theoretical evaluations for the three-magnon processes[8]. It is noteworthy that the power threshold measured at $f = 4.02\text{GHz}$ is strikingly lower than the others measured in part I of Fig. 1. This phenomenon is attributed to a transition from the four-magnon processes to the modulation instability whose power threshold is lower than that of the former nonlinear processes. As introduction of a metallic ground plane with a certain distance to the YIG film can improve the MSSW dispersion characteristics so considerably that in a limited frequency range, the necessary condition for the MSSW modulation instability[7,8], i.e., $(\partial^2\omega/\partial k^2) \times (\partial\omega/\partial|\phi|^2) < 0$, is satisfied ($|\phi|$ is the MSSW amplitude), onset of the MSSW modulation instability is possible if only the MSSW power reaches the corresponding threshold. It is shown in Fig. 2 that for the involved experimental configuration, when the MSSW frequency is between 3.98GHz and 4.04GHz, $\partial^2\omega/\partial k^2 > 0$, and thus, the above-mentioned condition is fulfilled because $\partial\omega/\partial|\phi|^2$ is always less than zero for the MSSW. Excluding the frequency range from 4.03GHz to 4.04GHz for the three-magnon processes, it is possible to activate the MSSW modulation instability only in the frequency range between 3.98GHz and 4.03GHz. It explains the reason why a dramatic decrease in the power threshold occurs at 4.02GHz after the previous measurement at 3.98GHz.

In contrast with Fig. 1, a transition from the three-magnon processes to the four-magnon processes via the modulation instability is observed when the MSSW frequency f is fixed at 3.5GHz, and the external magnetic field increases from 427 Oe to 647 Oe. A magnetic field H_c which equals $f/2\gamma$ ($=625\text{Oe}$) divides the measured field range into two parts. About 20dBm difference in the power thresholds between the two parts can be seen in vicinity of 625 Oe. In part I where $H < H_c$, the first-magnon processes are activated; in part II where $H > H_c$, the higher-order instability processes take place.

3. CONCLUSION

The transitions between the three-magnon processes and the four-magnon processes via the modulation instability can be realized by (a) fixing the external magnetic field H_e and scanning the MSSW frequency through the critical frequency $2\gamma H_e$; and (b) fixing the MSSW frequency f and varying the biasing magnetic field through the critical field $f/2\gamma$; involvement of the modulation instability as a middle stage in such transitions depends on the MSSW dispersion characteristics.

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Fig. 1 Measurement of power threshold for the first appearance of the satellites peaks as a function of the MSSW frequency.

Fig. 2 The dispersion term $\partial^2\omega/\partial k^2$ versus the MSSW frequency

Fig. 3 Experimental power threshold for the first appearance of the satellites peaks versus the external biasing magnetic field when the MSSW frequency is 3.5GHz.