Optical observation of evanescent surface magnons in thin magnetic films

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A new type of nonpropagating surface-wave-like magnon has been detected in yttrium iron garnet films (YIG) in a magnetostatic wave (MSW) device structure using Brillouin light scattering. The measurements were carried out on a YIG film stripline device operated at 2–4 GHz. With an applied magnetic field parallel to the stripline, magnon signals were observed at fields above the surface wave band edge. Theory shows that highly localized, evanescent surface modes can exist at such fields, but only when a ground plane is present; the bandwidth in field or frequency is inversely proportional to the separation between the film and the ground plane. The observed evanescent wave band limits are in good agreement with the theoretical values.

I. INTRODUCTION

In the course of Brillouin light scattering (BLS) measurements on magnetostatic wave (MSW) devices utilizing yttrium iron garnet (YIG) films, a new type of spin-wave excitation was recently observed for fields above the magnetostatic surface wave (MSSW) band edge.[1,2] These modes have now been investigated in detail, both experimentally and theoretically. The excitations consist of highly localized evanescent surface wave (EVSW) modes with a complex wave number. The theory shows that these modes are possibly excited only in the presence of a ground plane and that the bandwidth in field for EVSW excitations is inversely proportional to the separation between the ground plane and the YIG film.

The Brillouin light scattering measurements were performed on a signal-to-noise enhancer (SNE) MSW device structure consisting of a 30-μm-wide stripline in contact with a 26.6-μm-thick YIG film.[3,4] The stripline was on a 625-μm-thick alumina substrate backed by a conducting copper ground plane. The incident laser light was focused onto the YIG film through a small hole in the substrate which was drilled in close proximity to the stripline. Interactions between the incident light and magnetic excitations within the YIG film result in a frequency shift for the scattered light. Direct detection of magnons in the YIG film was accomplished by measuring the intensity versus frequency shift profile for the forward scattered light through the film with a high contrast Fabry–Perot interferometer. Details of the measurement technique are given elsewere.[1,2,5]

The basic evidence for the new EVSW modes is shown in the Brillouin spectrum of Fig. 1. This spectrum was obtained for an in-plane bias field of 600 Oe parallel to the stripline and a YIG film-ground plane separation of 625 μm. Despite the fact that the bias field is well above the surface wave band edge of 492 Oe, one observes pronounced scattering peaks at ± 3 GHz. These peaks disappear when the ground plane is absent.

Intensity profiles and microwave attenuation versus field data are shown in Fig. 2. The YIG-ground plane separation was 625 μm, as for Fig. 1. The data on the intensity of magnon scattered light versus bias field in Fig. 2(a) show the expected scattering due to MSSW excitations within the surface wave region, 150–492 Oe. Strong scattering is also observed *above* the MSSW band edge, up to a field of 625 Oe. The microwave response profile of attenuation in stripline power versus field in Fig. 2(b) shows essentially no power loss above the MSSW band edge, except for a small region of microwave power loss, just above the MSSW band edge, which is due to nonlinear effects associated with the generation of magnons at one half the pump frequency. These results suggest that the observed Brillouin signal above the band edge is due to highly localized evanescent surface-wave-like (EVSW) modes. Such localized modes carry very little microwave power away from the stripline and are not evident in microwave loss measurements.

II. THEORY

This section deals with the theory for the evanescent surface waves. It is found that EVSW modes exist when a

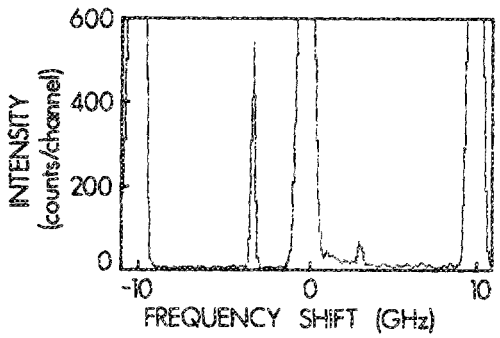

FIG. 1. Brillouin light scattering spectrum for magnetostatic wave signals at 3 GHz in a yttrium iron garnet (YIG) film in a signal-to-noise enhancer (SNE) device structure with a static magnetic field of 600 Oe applied parallel to the stripline in the device. The input power was 40 mW.

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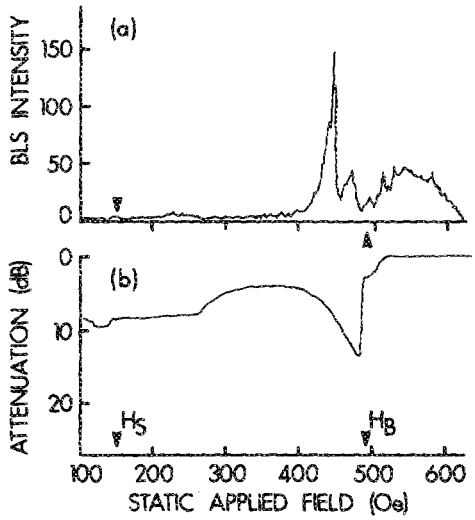

FIG. 2. (a) Profile of scattered intensity vs applied field for MSW signals at 3 GHz in the YIG film in the SNE device. The input power was 40 mW. The arrows indicate the field limits H_S and H_B for magnetostatic surface waves (MSSW) in the YIG film. (b) Data on attenuation in stripline power vs applied field at 3 GHz for the SNE device and an input power of 10 mW.

ground plane is present and that such modes can be supported above the MSSW band edge. The range of fields over which such modes exist is inversely proportional to the separation between the ground plane and the YIG film.

The system under consideration is an in-plane magnetized film of thickness d at a distance l from a metallic ground plane, as shown in Fig. 3. The theory is for magnetostatic waves with a complex in-plane wave number, $\kappa = \kappa' + i\kappa''$, with propagation perpendicular to the in-plane field. The analysis is based on the usual magnetostatic mode formalism.[6] The magnon dispersion has the form

$$f^2 - f_H^2 - f_H f_M - \zeta = 0, \tag{1}$$

where f is the magnon frequency. The parameters $f_H = \gamma H$ and $f_M = \gamma 4\pi M$ express the magnetic field H and the saturation magnetization M in frequency units; γ is a reduced gyromagnetic ratio. The ζ parameter in Eq. (1) is given by

$$\zeta = (f_M^2/4)(1 - e^{-2(\kappa' + i\kappa'')d})(1 + Ae^{-2(\kappa' + i\kappa'')l}) \tag{2}$$

and

$$A = 1 + 2(f + f_H)/f_M.$$

For the case $\kappa'' = 0$, Eq. (1) reduces to the usual dispersion relation for MSSW excitations in the presence of a ground plane. In the absence of a ground plane, i.e., $l \to \infty$, this dispersion reduces to the Damon–Eshbach MSSW dispersion relation.[6] The presence of the ground plane results in an additional set of solutions for which κ'', as well as κ', is nonzero. These solutions correspond to the EVSW modes observed by light scattering.

The complex wave-number solutions for the EVSW modes can be determined from Eqs. (1) and (2). Solutions for κ'' occur near $2\kappa'' l \simeq \pi$ (one can also find more severely localized modes with $2\kappa'' l \simeq 3\pi$, 5π, etc.). Upon setting $2\kappa'' l = \pi + \epsilon$ and assuming the condition $d \ll l$, the ζ parameter can be expressed as

$$\zeta = (df_M^2/4l)[2\kappa' l + i(\pi + \epsilon)] \times \{1 - A[\cos(\epsilon) - i\sin(\epsilon)]e^{-2\kappa' l}\}. \tag{3}$$

Equation (1) then reduces to two coupled equations in κ' and ϵ:

$$2\kappa' l[1 - Ae^{-2\kappa' l}\cos(\epsilon)] - (\pi + \epsilon)Ae^{-2\kappa' l}\sin(\epsilon) - B = 0, \tag{4}$$

$$(\pi + \epsilon)[1 - Ae^{-2\kappa' l}\cos(\epsilon)] + 2\kappa' l Ae^{-2\kappa' l}\sin(\epsilon) = 0, \tag{5}$$

$$B = (4l/d)(f^2 - f_m f_H - f_H^2)/f_m^2. \tag{6}$$

The complex wave number for the EVSW modes as a function of applied field can be determined by solving Eqs. (4) and (5) for κ' and ϵ.

III. RESULTS

The calculated variation of κ' and κ'' as a function of field for the EVSW modes at 3 GHz are shown in Fig. 4. Results on κ' versus field for the MSSW mode are also shown. Two cases are considered. Figure 4(a) is for $l = 1$ cm, that is, a very large film-ground plane separation. In this case the MSSW band extends between field limits H_S and

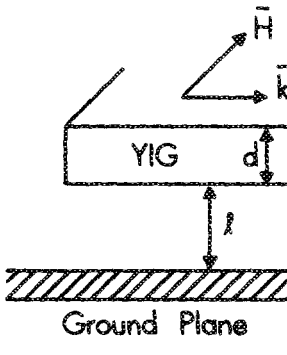

FIG. 3. Schematic diagram of the structure and excitation geometry for surface waves in an in-plane magnetized thin film of thickness d at a distance l from a ground plane.

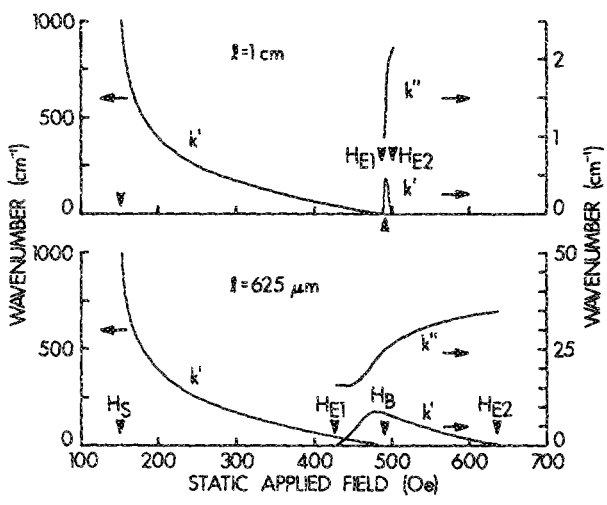

FIG. 4. Calculated variation of the surface magnon wavenumber and the real and imaginary parts of the evanescent wave wavenumber with bias field at 3 GHz in a 26.6-μm-thick YIG film and at a distance (a) 1 cm and (b) 625 μm from a ground plane. The fields H_{E1} and H_{E2} indicate the field limits for the evanescent waves. The field limits for the surface waves are indicated by H_S and H_B.

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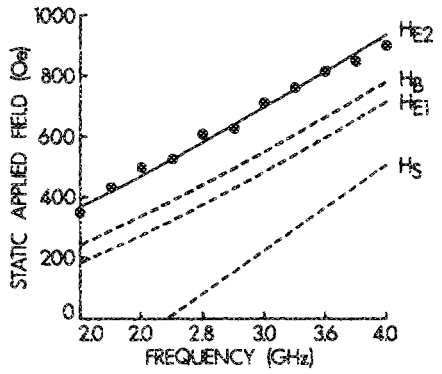

FIG. 5. Variation of the upper cutoff field H_{E2} vs excitation frequency for evanescent waves in the YIG film SNE device. The solid points denote the BLS data and the solid line represents the theory. The dotted lines show the frequency variation of the MSSW band edge, H_S and H_B, and the evanescent wave low-field band edge H_{E1}.

H_B which are very close to the usual Damon–Eshbach values. The EVSW mode solution region is very narrow in this case, and is limited to fields very close to H_B. Figure 4(b) is for a smaller l value of 625 μm which corresponds to the present experimental situation. The essential effect of moving the ground plane closer to the YIG film is to *expand* the interval for EVSW solutions. The low-field EVSW band edge H_{E1} moves well below H_B and the high-field band edge H_{E2} moves well above H_B. For the situation in Fig. 4(b), the band width in field is 209 Oe and the band extends some 145 Oe above the upper MSSW band edge.

One convenient test of the theory is to compare the calculated frequency dependence of the upper EVSW band edge, H_{E2}, with the BLS band-edge measurements at different frequencies. Brillouin light scattering profiles similar to the one in Fig. 2(a) were obtained over the frequency range 2–4 GHz. The resulting experimental EVSW H_{E2} band-edge determinations are shown in Fig. 5, along with the results from the theory. The field limits H_S, H_{E1}, and H_B are shown for reference. Figure 5 shows excellent agreement between data and theory for the upper EVSW band-edge value versus frequency.

In conclusion, a new type of magnetic excitation in thin YIG films has been identified by Brillouin scattering and investigated theoretically; the excitation is an evanescent surface-wave-like (EVSW) mode which can be supported only in the presence of a ground plane. These EVSW modes can transport no power and cannot be observed with microwave loss measurements. The observed cutoff field for such modes agrees well with the theoretical analysis.

ACKNOWLEDGMENTS

The MSW device structure used in these experiments was provided by Dr. J. D. Adam, Westinghouse Research and Development Center, Pittsburgh, Pennsylvania. This work was supported by the Electromagnetics Directorate of the Rome Air Development Center, Hanscom Air Force Base, Massachusetts, Contract No. F19628-85-K-0002. Dr. Booth is with the Department of Pure and Applied Physics, University of Salford, Salford M5 4WT, UK. This work was performed, in part, while Dr. Booth was a Visiting Professor at Colorado State University.

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