Brillouin Light Scattering Analysis of Ultra Short Microwave Pulse Formation Processes in Yttrium Iron Garnet Films

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Abstract - Wave vector selective Brillouin light scattering has been used to observe directly the half frequency parametric magnons in the three magnon splitting process responsible for ultra short microwave pulse formation from nonlinear magnetostatic surface waves in yttrium iron garnet films. The frequencies and wave vectors of the relevant spin waves and threshold powers for the onset of these processes were quantitatively determined.

INTRODUCTION

Recently, the generation of extremely short microwave pulses as narrow as 2 ns from relatively long magnetostatic surface wave (MSSW) input pulses in yttrium iron garnet films (YIG) at high power has been demonstrated [1]. These short pulses were obtained with a long and narrow YIG film strip in a standard magnetostatic wave delay line structure. This ultra short pulse generation required a frequency below 3.3 GHz, the cut off for three magnon splitting processes in YIG [2].

The model proposed in [1] to explain the pulse formation involves MSSW magnons which split into two approximately half frequency dipole exchange spin wave (DESW) modes with wave vectors on the order of $10^4$ rad/cm. Brillouin light scattering (BLS) techniques have now been used to analyze the generation of these DESW excitations in the above process. The frequencies and wave numbers for these magnons are as expected from the model. The data also give specific threshold power levels for the different DESW magnon pairs involved in the three magnon process.

EXPERIMENT

The microwave measurements were performed in the same way as in [3]. The experiments utilized a microstrip antenna structure with a 2 mm wide, 8.7 μm thick YIG strip with a nominal length of 12 mm. The film was magnetized in-plane by a static magnetic field perpendicular to the long side of the strip and the MSSW propagation direction. The structure consisted of one fixed and one movable 50 μm wide microstrip antenna placed perpendicular to the YIG strip. The fixed antenna was used for input and the movable antenna was used for output. Data were obtained for MSSW carrier frequencies above as well as below the 3.3 GHz three magnon cut off. The detailed BLS three magnon experiments were done for an MSSW frequency $f_2$ of 2.6 GHz. The input pulse width was about 100 ns. The duty cycle of the input signal was kept below 5% in order to avoid heating effects.

The BLS measurements were made with an automated multipass tandem Fabry-Perot interferometer in forward scattering geometry [4]. The wave vector selective measurements were based on the technique given in [5]. Linearly polarized light at 514.5 nm wavelength from an Ar$^+$ ion laser at a 15-20 mW power level is focused by a 50 cm focal length lens onto the YIG film at normal incidence. The low power is needed to eliminate heating effects. The YIG sample was mounted on a 3-axis stepper motor controlled translation stage in order to move the probe beam to different points on the sample. The direct transmitted beam through the semi-transparent film and the forward scattered light are collected by a standard photographic lens. Wave vector selective scattering data were obtained from sequences of measurements for different sized on-axis circular apertures placed after the collection lens. With a precise match-up of the aperture center to the direct beam axis, it was possible to select wave numbers from zero to upper limit $k_{max}$ values up to $4 \times 10^4$ rad/cm. See [5] for further details of the technique.

RESULTS

The most important result from the microwave experiments in [1] was the significant pulse narrowing which occurred for MSSW pulses at high power when the carrier frequency was below 3.3 GHz. Figure 1 shows the typical pulse narrowing microwave response as a function
Fig. 1(a) shows microwave output power vs. time profiles and (b) corresponding Brillouin light scattering spectra. The pairs of graphs from bottom to top are for increasing values of the input peak power $P_{in}$, as indicated.

The results in Fig. 1 provide direct evidence for the parametric excitation of half frequency spin waves as part of the process which leads to the ultra short pulses. These data show that the technique provides an extremely sensitive way to detect the relevant magnons and actually observe the onset of the nonlinear interactions, which produce these magnons.

Detailed measurements over the active region of the YIG film between antennas show that the strength of the parametric $f_s/2$ magnon signal depends on the spatial position, the direction and size of the magnon wave vector, and the power. The full ensemble of these results is beyond the scope of this paper and will be presented elsewhere. The proof that three magnon splitting is the process responsible for ultra short pulse formation in YIG films, however, can be readily demonstrated from selected results on the wave number dependence of the BLS peak response at $\pm f_s/2$ for different powers. These results are presented below.

According to the model in [1], dipole exchange spin wave (DESW) excitations close to $f_s/2$ are parametrically pumped by the low wave number input MSSW signal. The MSSW signal has a wave vector $k$ in the propagation direction and the DESW $k$-values are in the film plane and nearly perpendicular to this direction. Through three magnon confluence processes, these DESW
magnons then combine to produce the wide band spectrum of spin waves centered at $f_s$ which leads to the short pulses.

Wave vector selective BLS measurements have provided a direct way to probe the details of the above processes. Data were obtained with the wave vector selective diaphragm in place and set to different diameters to yield different cut-off wave number $k_{\text{max}}$ limits. For diaphragm diameters below 1 mm, the BLS peak signal at $-f_s$ remained unchanged but the peaks at $\pm f_s/2$ were eliminated. This diameter, therefore, defines a $k_{\text{max}}$ limit of about 1250 rad/cm for the wave number distribution for the MSSW signal. This cut off is consistent with antenna coupling considerations and with the spread in $k$ values expected for the MSSW band of excitations, which make up the narrow pulse at high power.

The threshold power levels for the parametric excitation of the DESW magnons were obtained from further data on the $-f_s/2$ BLS peak intensities as a function of diaphragm diameter and the corresponding $k_{\text{max}}$ wave number limit. Figure 2 shows two representative sets of data on scattering signal vs. $k_{\text{max}}$ for the $-f_s/2$ peak. For each $P_{\text{in}}$ value, one obtains a threshold response for the onset of the DESW half frequency signal. There are distinct step increases in the signal at $k_{\text{max}}$ values of $12 \text{H} \times 10^3$ and $21 \text{H} \times 10^3$ rad/cm for $P_{\text{in}}$ values of 32 mW and 64 $\mu$W, respectively.

The threshold effect shown in Fig. 2 correlates with the allowed DESW wave numbers for three magnon splitting expected from the dispersion curves and energy and momentum conservation considerations. Figure 3 shows the three lowest DESW dispersion branches calculated from [7] for the experimental parameters. The solid circles indicate the two lowest $k$ pairs of magnons for which the splitting is allowed. Note that for each pair, one actually has plus and minus $k$ values for momentum conservation. The $k$ values of $11.6 \text{H} \times 10^3$ and $20.2 \text{H} \times 10^3$ rad/cm for these mode pairs are in good agreement with the threshold $k_{\text{max}}$ values from the data. The results in Fig. 2 also indicate that parametric magnons with higher $k$ values, which derive from higher order DESW branches, have much lower power thresholds.

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**REFERENCES**

[6] To the knowledge of the authors, up to now there has been no satisfactory explanation for the Stokes anti-Stokes asymmetry usually observed in this kind of experiments.

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Fig. 2. Integrated BLS intensity for the $-f_s/2$ peak as a function of the diaphragm cut-off wave number $k_{\text{max}}$ for two input power $P_{\text{in}}$ levels, as indicated.

Fig. 3. Dispersion diagram of spin wave frequency $f_s$ vs. wave number $k$ with the lowest three branches of the DESW dispersion for an in-plane magnetized 8.7 $\mu$m thick YIG film at a field of 340 Oe. The solid circles indicate the allowed pairs of DESW modes for splitting.