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An active resonator based on magnetic films for near field microwave microscopy

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An active resonator perturbation method is introduced as a sensitive and versatile way to probe material properties in near field microwave microscopy. An active ring microwave oscillator based on magnetostatic excitations in a yttrium iron garnet thin film has been developed with a coaxial near field probe connected directly to the resonator ring. The probe tunes the resonator’s emission frequency, and the high Q-factor of the magnetostatic oscillations allows for a very sensitive spatially resolved probe of surface impedance and material properties with a much larger dynamic range than conventional resonant probes for microwave microscopy. © 2012 American Institute of Physics. [doi:10.1063/1.3672081]

INTRODUCTION

Numerous recent implementations of scanning near-field microwave microscopy in the 1–10 GHz frequency range have been based on resonators perturbed by a local probe scanned over a surface of interest.1 Such resonators, typically designed with a coaxial geometry2 or with a planar transmission line geometry integrated into an AFM probe3 to take advantage of existing fabrication technologies, can also be considered passive resonators due to the fact that they are fed by an external microwave source. Typical measurements involve bringing a sharp tip protruding from the resonator close to a sample of interest, scanning the surface, and measuring shifts in resonant frequency in order to deduce material properties of the surface of the sample.1,4 Shifts are typically small compared to the linewidth of a passive resonator, even in the case of a high quality resonant probe.5 These shifts are usually measured not by acquiring an entire spectrum at each pixel of an image, but by exciting the resonator at a frequency of maximum slope in its spectrum and measuring changes in intensity reflected from the cavity. The sensitivity of the system is thus related to the resonator’s linewidth, and the frequency range over which the system can produce meaningful results must be smaller than the linewidth.

An alternative approach introduced in this work is to use an active resonator tuned to a frequency of interest, perturb the resonator with a near field probe close to a sample, and measure directly the emission frequency with a frequency counter, allowing for a much larger frequency range to be measured and thus allowing for a much larger range in the material parameter being measured. For this purpose, a resonator based on magnetostatic surface waves (MSSW) in a yttrium iron garnet (YIG) film provides a natural solution. Not only can MSSW’s be highly monochromatic within a resonator, but are also tunable over a large frequency range using an external magnetic field.

In this work we report on results from an original implementation of a near filed microwave microscope where an active resonator based on magnetostatic excitations in a YIG thin film is coupled to a near filed scanning probe, and compare our results with a conventional passive resonant probe microwave microscope.

EXPERIMENT

An active ring resonator6 was implemented by coupling a 7.3 μm thick YIG thin film in the shape of a ferromagnetic waveguide, grown on a gallium gadolinium garnet (GGG) substrate by standard liquid phase epitaxy, with an external amplifier as shown in Fig. 1. The two coupling antennas were comb-shaped with equal period to impose a wavenumber of 500 cm−1 and to ensure excitation of a highly monochromatic MSSW, and one of these antennas was connected to the output of the circuit. The ferromagnetic resonance half-power linewidth of the YIG film was estimated to be about 0.3 Oe at 5 GHz, with a saturation magnetization 4πMs = 970 G. A variable external bias magnetic field was applied using two identical moveable parallel permanent magnets a few millimeters from the film. With a bias field measured to be 240 Oe, this system oscillated at about 1.8 GHz with one detectable mode and emitted approximately 10 mW of power. This was easily detected using a spectrum analyzer or a frequency counter, and the linewidth was estimated to be less than 1 KHz. Note that the narrow linewidth is a result of the fact that the resonator amplifies only a small fraction of the allowed wavenumber values of magnetostatic surface waves, thus producing a highly monochromatic excitation in the ferromagnetic waveguide. The
emission frequency was found to be tunable within a range of about 200 MHz with careful control over the bias magnetic field.

This active resonator was coupled to a probe (Fig. 1), which consisted simply of a rigid coaxial cable whose central conductor was terminated with a sharp point and the outer conductor capped at the end to minimize loss. In this configuration, the probe is itself a passive resonator whose length is approximately the distance between the coupling point C and the tip, so that the system can be thought of as two strongly coupled resonators. When the probe is brought close to the sample, its effective length is slightly modified and the active resonator suffers a small frequency shift. The probe was mounted onto a vertical positioning system and brought close to a sample mounted on a scanning x-y stage. The output of the active resonator was measured with a frequency counter with 100 Hz resolution and used to form images with appropriate control software.

Since this system was highly sensitive to magnetic field (a field of the order of a few tens of nT produced a frequency shift of about 1 KHz), it was enclosed in a ferromagnetic shield, which made the system insensitive to the presence of lightly magnetized objects. The temperature of the system, especially of the bias magnets, was allowed to stabilize to within a tenth of a degree centigrade and the frequency drift settled to less than the 10 KHz level.

RESULTS AND DISCUSSION

As indicated by the arrow in Fig. 1, the length \( L_p \) of the passive probe resonator is important: interference between the microwave signal reflected from the tip and the microwave signal within the active resonator ring determines the sensitivity of the output frequency to perturbations in the passive resonator. Indeed, we found that at some resonator lengths, there was no measurable frequency response when the tip was brought close to a metallic surface. By varying the length of the coaxial cable between the passive resonator and the active one, an approximately optimal coupling was achieved between the resonators. A scan over a copper-printed circuit board interface, with the tip-sample distance adjusted to less than 100 \( \mu \)m then produced the response shown in Fig. 2, with a frequency shift of 50 KHz at 1.8 GHz. We note that this frequency shift is comparable to measurements made with conventional passive resonant probes.\(^5,7\) In the case of passive resonators, however, this shift is much smaller than the typical linewidth of 100 KHz–1 MHz, whereas it is significantly larger than the \( \sim 1 \) KHz linewidth of our active resonator.

A similar scan was performed over a line of graphite marked on a glass surface (Fig. 3), and a strong frequency shift of about 300 KHz was observed primarily due to absorption in the graphite. Here, we also observed a strong dependence of the response on the tip height, including a change in the direction of the frequency shift. This differs from the response we observed from the same sample measured with a conventional passive probe (which is described in Ref. 7), where no change in the direction of the shift was
detected. The magnitude of the frequency shift, however, was comparable to the shift of about 600 MHz at 7 GHz in the conventional probe. This suggests that the active probe system can extract phase information from the tip-sample interaction. This phase sensitivity is likely to be a result of the fact that the probe signal interferes with a highly monochromatic signal produced by the magnetostatic surface waves in the YIG film. In other words, the coupled resonator system serves as a sensitive interferometer between the tip-sample system and the signal produced by the magnetostatic surface waves in the YIG film, and this phenomenon clearly calls for further investigation.

Figure 4(a) shows a two-dimensional scan over the same graphite feature on a glass surface. Although the acquisition time for this image was several minutes, we see that drift effects inherent to the MSSW system are small and mostly corrected for by normalizing each line scan at its first point. The image itself is not a replica of the image formed by a passive resonator probe (Fig. 4(b)) or by an optical microscope, which indicates again that the active probe system is sensitive to effects other than simple absorption of radiation by the graphite. Furthermore, the active probe system clearly produces images of higher resolution with a tip of approximately the same sharpness.

CONCLUSIONS

An active magnetostatic surface wave resonator for microwave microscopy has been shown to produce images of metal/dielectric and graphite/dielectric structures. This active probe system has two important advantages: its sensitivity is much greater than that of a conventional system by virtue of a linewidth two to three orders of magnitude smaller, and its dynamic range (the range of detectable frequency shifts) is larger, of the order of 200 MHz compared to ~1 MHz for conventional systems. This probe system therefore has the potential to image material parameters with greater resolution over a greater range of the parameter of interest. We also find that the active probe system has a phase sensitivity that allows us to distinguish new details in our image, an effect that calls for further investigation. The inherent disadvantage of this active probe system over conventional systems is that it suffers from a very significant temperature- and magnetic field-related drift. This effect has been corrected for in the images presented, and can potentially be reduced using an identical resonator as a reference and making a differential measurement.

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