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Measurements and simulations of micron size coplanar waveguides

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Measurements and simulations have been done on a coplanar waveguide, which consists of a pair of slots which taper down to a separation and width of micron size. The purpose of this device is to permit one to concentrate microwaves or millimeter waves on magnetic samples of the order of a micron in order to do ferrimagnetic resonance (FMR) studies on such small samples. The transmission coefficient as a function of frequency found in the simulations agrees quite well with the measurements. The simulations show that the magnetic field at the pinch is about a factor of several thousand larger than the field of the incident wave. Results for the circuit parameters found from the simulations will be compared to the values for these parameters measured for this device, and the prospects for using the device for FMR studies on micron and submicron magnetic particles will be discussed. © 1997 American Institute of Physics. [S0021-8979(97)60808-7]

There is a growing interest in nanoscale magnetic particles due to their unique properties and their potential use in various microwave devices. Standard techniques used in ferrimagnetic resonance measurements, such as cavities, waveguides, and electron paramagnetic resonance (EPR) lack the sensitivity necessary to measure individual nanometer sized particles, or even micron size particles at microwave frequencies. For example, EPR cavity methods require samples with volumes of around 10^{-6} cm³.¹ In this article we will present both measurements and simulations of a slot-line coplanar waveguide transmission line with a pinch of micron size, which can be used to detect ferrimagnetic resonance (FMR) signals from very fine magnetic particles with volumes as small as 85.4×10^{-15} cm³. In contrast, an EPR system, often used in FMR requires that the samples be about 2×10^{-6} cm, containing a minimum of $10^{13} \Delta H$ spins, where ΔH is the resonance absorption linewidth and the input power is 1 mW. Magnetic particles having micron dimensions will possess 10^9 electron spins or less, making FMR measurements on individual micron size particles difficult, if standard cavities are to be used. Recently, microwave cavities have been replaced with planar microwave devices, which have submicrometer size junctions in order to measure FMR on samples of this size. The advantage of using a planar device is that it is ideally suited to magnetic thin film samples.

In this article, we focus on studies of a two-slot planar waveguide, pinched down from millimeter to micron dimensions in the middle, as illustrated in Fig. 1. This device is produced by etching two slots in a metallic coating on a dielectric substrate. The slots are 0.5 mm in width and 0.5 mm apart at the input and output ends of the device. The width and spacing is tapered down to $1 \mu\text{m}$ in the center. The input and output radiation is brought to and from the device by 50Ω coaxial cables. The measured transmission coefficient is shown in Fig. 2 as a function of frequency. As can be seen, there is a high degree of transmission of radiation through the device, especially at frequencies below 10 GHz. As it is well known that SMA coaxial connectors of the type used propagated in multimodes of propagation above 6 GHz, only results below this frequency can be taken to be representative of the behavior of the device. In most of this re-

gime, the transmission amplitude remains quite close to 1, showing that despite the very narrow pinch in the center of the device, most of the incident wave gets transmitted.

We have also simulated the transmission through the device using the three dimensional high frequency structure simulator (HFSS) program, developed by Hewlett-Packard's EEsof division. This program uses the finite element method to solve Maxwell's equations in the geometry of interest. Whereas the pinch in the actual device had a width of $1 \mu\text{m}$, the width of the pinch used in the simulations was $10 \mu\text{m}$ because it becomes very costly in computer time to use a fine enough mesh to simulate a device with a $1 \mu\text{m}$ pinch. Since one expects the behavior of the device to be a function of the ratio of the dimensions of the device to the wavelength of the radiation propagating through it, a simulation done on a device with a pinch of width $10 \mu\text{m}$ should be equivalent to one done on a device with a $1 \mu\text{m}$ pinch and 1/10 of the wavelength (i.e., 10 times the frequency). (Here, we have assumed that the most important dimension in the device is the width of the slots and their separation at the pinch, and

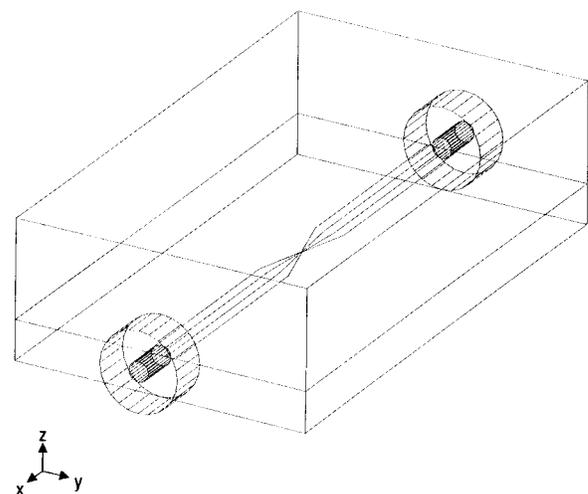


FIG. 1. This is a diagram of the pinched coplanar waveguide considered here. The slot sizes and spacings are 0.5 mm at the input and output ends of the device and about $1 \mu\text{m}$ at the narrowest part of the pinch.

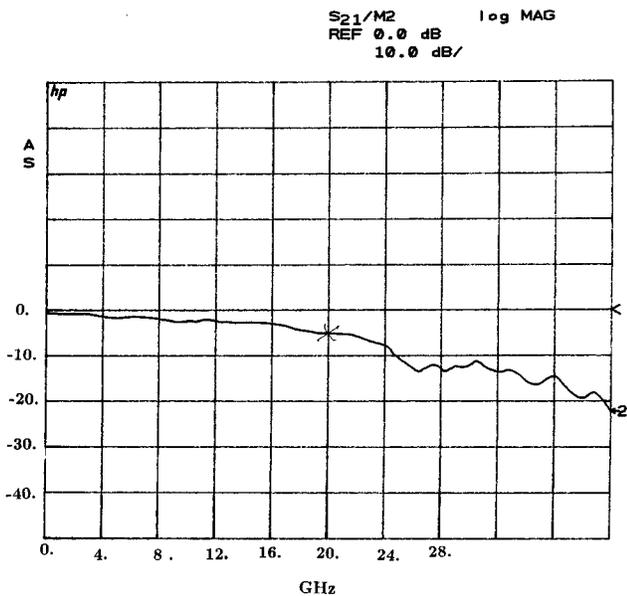


FIG. 2. S_{12} the transmission amplitude in dB [defined as $10 \log(E/E_0)$], where E is the electric field at the output end and E_0 is the field at input vs frequency in GHz. Each square in the vertical direction is 10 dB and each square in the horizontal direction is 4 GHz.

that the other dimensions of the device are less important for determining the propagating fields in the device.) The results are shown in Figs. 3 and 4. In Fig. 3, the calculated transmission coefficient is shown as a function of frequency. A comparison to experimental results shown in Fig. 3 shows that the simulation produces results that are qualitatively similar to those of the actual device. The magnitude of the magnetic field of the electromagnetic wave found in the simulation for a typical run is shown in Fig. 4. As can be seen, the field gets multiplied by over an order of magnitude at the pinch (which is equivalent to two orders of magnitude in the power). Similar results are found at other frequencies. This implies that this device should be quite effective in

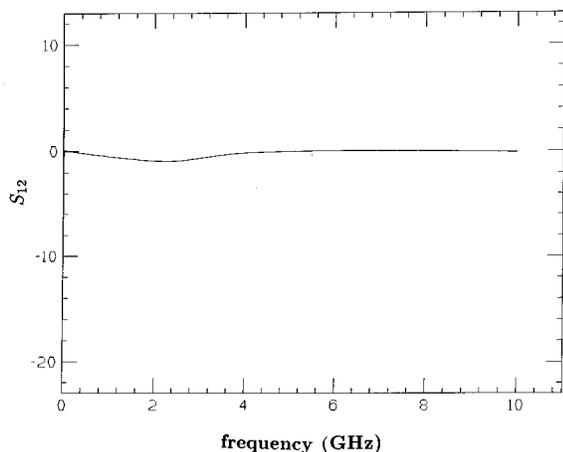


FIG. 3. The calculated transmission amplitude (dB scale) is plotted vs frequency in GHz.

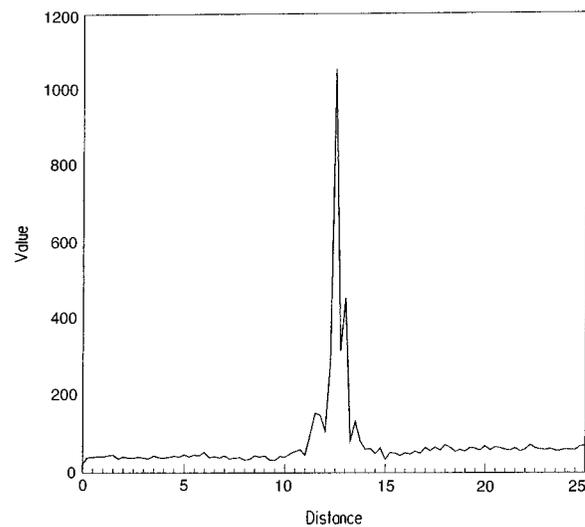


FIG. 4. The magnitude of the magnetic field (in arbitrary units) at the center (i.e., the symmetry axis) of the device is shown as a function of distance along the device in mm for a frequency of 2 GHz, which has a $10 \mu\text{m}$ pinch. (It should be representative of the results for 20 GHz for a device with $1 \mu\text{m}$ pinch.)

concentrating radiation in very small samples for the purpose of doing FMR and other studies on such small samples.

The pinched coplanar waveguide described in this article was used to perform ferromagnetic resonance (FMR) on micron size magnetic samples. The samples were etched from a 105-nm-thick $\text{Fe}_{80}\text{B}_{15}\text{Si}_5$ film on a quartz substrate. The film was deposited on fused quartz by ion beam sputtering. Figure 5 shows results of FMR measurements taken on a $4 \mu\text{m}$ disk of this material at various frequencies. Improved results are forseen if higher dielectric substrates and better transmission line impedance matching are obtained as the lines narrow. These modifications should yield higher microwave fields at the junction, further increasing the device sensitivity. Such refinements may make this technique a valuable

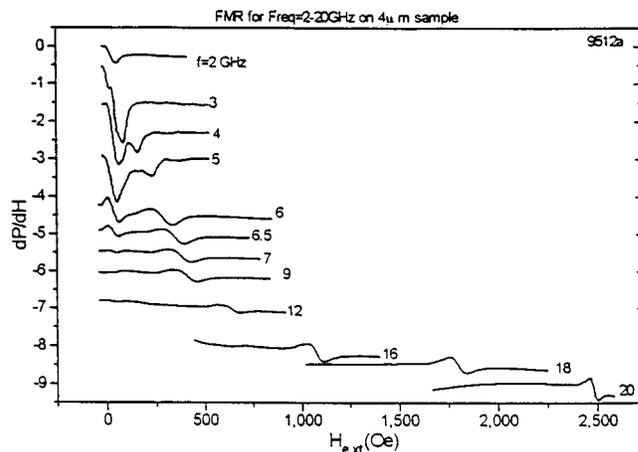


FIG. 5. Measured FMR for a $5 \mu\text{m}$ disk at several different frequencies. The differential power dP/dH is in arbitrary units and the dc field is in Oe.

tool for understanding the properties of nanostructured materials and perhaps even for small biological samples.

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