

Incorporation of Ferromagnetic Metallic Films in Planar Transmission Lines for Microwave Device Applications

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Abstract—We constructed a series of microstrip and co-planar microwave waveguides. These structures use metallic ferromagnets and therefore exhibit strongly frequency-dependent attenuation and phase-shift effects. The lines have maximum attenuation peaks occurring at the ferromagnetic resonance frequency, which increases with applied magnetic field. Such properties are used in band-stop filters. The devices used monocrystalline Fe films grown by Molecular Beam Epitaxy and polycrystalline sputtered permalloy films. For our devices that incorporated Fe the band-stop frequencies ranged from 10–20 GHz for applied fields up to only 80 kA/m (1000 Oersted). For devices using permalloy, the band-stop frequency was in the 5–10 GHz range for applied fields less than 80 kA/m. The maximum power attenuation was about 100 dB/cm, much larger than the previously reported values of 4 dB/cm. The resonance condition also affects the phase of the transmitted wave, strongly changing phase above and below the resonance frequency. The result is a phase-shifter that is tunable with applied magnetic field. We observed phase changes of over $360^\circ/\text{cm}$ with an applied field of less than 40 kA/m.

Index Terms—Coplanar waveguide, ferromagnetic resonance, filter, microstrip, phase shifter.

I. INTRODUCTION

MICROWAVE devices are widely used in both military and civilian communications systems. During recent decades, we have witnessed much progress in high-frequency semiconductor electronics and, in particular, the integration of different electronic components into circuits. An obvious obstacle to the increased use of microwave and millimeter-wave technology is the lack of advances in magnetic structures at high frequencies, for example, from 5–100 GHz.

Insulating ferrimagnetics such as YIG are well established in microwave applications [1]. These materials, however, have one significant drawback; their saturation magnetization, M_s , is low and therefore their operating frequency for moderate applied fields only covers a range of a few GHz. Here we report on the use of ferromagnetic metallic films in microwave transmission lines. These materials have higher M_s and thus have

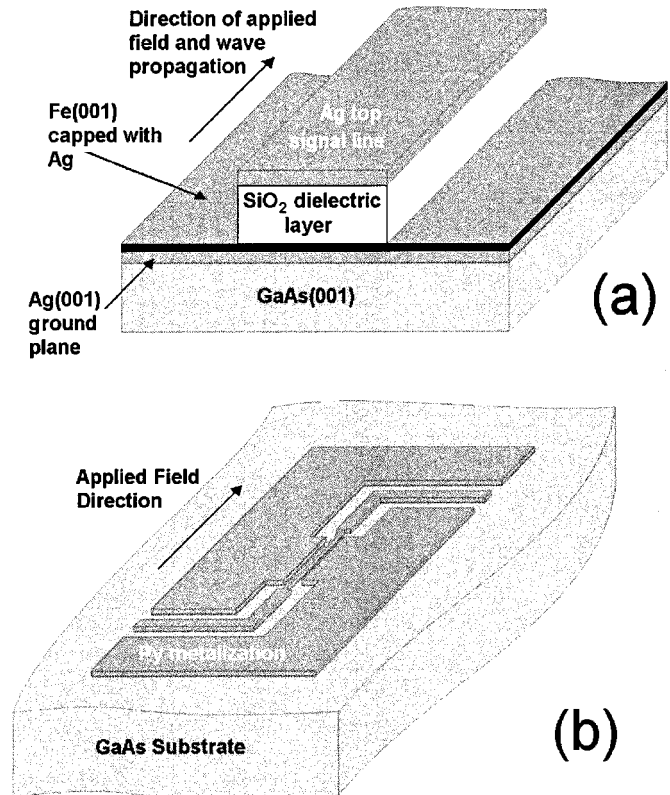


Fig. 1. Schematic diagrams of (a) microstrip and (b) co-planar waveguide structures.

much higher operating frequencies. The theoretical treatment of such devices was explored by Schloemann and co-workers [2], Camley and Mills [3], and Huynen *et al.* [4].

We studied two types of transmission lines, microstrip and co-planar waveguide (CPW). For the microstrip, shown in Fig. 1(a), a ground plane of Ag(001) was grown on GaAs(001) by molecular beam epitaxy (MBE). This provided a template for a Fe(001) single-crystal film (200 nm), which was then capped with a thin Ag layer to prevent oxidization of the Fe [5], [6]. The sample was then transferred to an e-beam evaporation system for deposition of the dielectric layer and signal line. We deposited $4\ \mu\text{m}$ of SiO_2 followed by $2\ \mu\text{m}$ of Ag using a shadow mask to define the strip geometry. The width of our microstrip line ranged from 80 to $120\ \mu\text{m}$.

For the CPW structures, one of which is shown in Fig. 1(b), we again used GaAs substrates. However, in this case the sample

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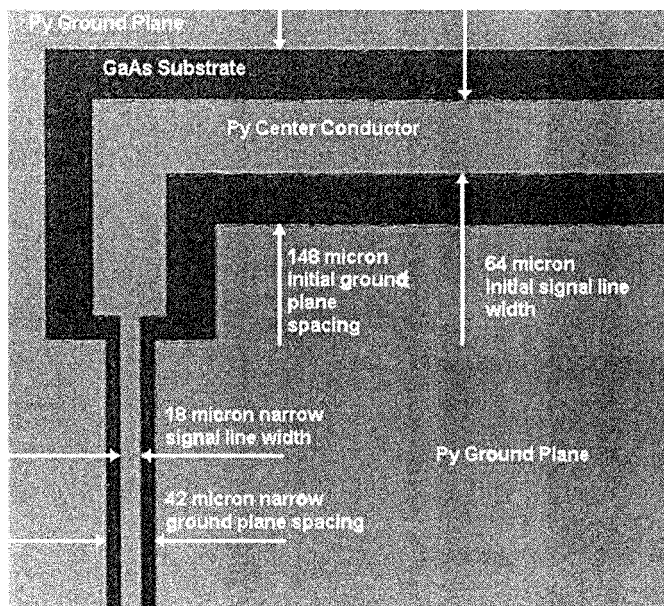


Fig. 2. Photograph of CPW line showing one right-angle bend and width transition.

was prepared in a sputtering system. We deposited a permalloy (Py) film 250 nm on top of a thin Ta adhesion layer. The Py was protected from oxidation with a thin Cu film. The films were patterned by photolithography followed by sputter etching in an Ar atmosphere. The lines were designed for a nominal characteristic impedance of 50 Ω . The waveguides made two right-angle bends to allow probes to contact from the sides, while a field was applied parallel with the length of the line. The lines are wide near the two ends to allow for probing but narrow in the middle to increase the magnitude of the resonance effects. Fig. 2 shows a photograph of one right-angle bend and width transition, including dimensions.

II. THEORY

In our devices, ferromagnetic resonance (FMR) produces absorption and phase-shift effects. The resonance occurs at a frequency given by

$$\omega = \gamma \sqrt{(H + H_a)(H + H_a + 4\pi M_s)} \quad (1)$$

where

- H is the applied magnetic field,
- H_a defines the 4-fold anisotropy field in the direction of the applied field,
- γ is the gyromagnetic ratio, and
- $4\pi M_s$ is the saturation magnetization.

Note that larger M_s values, such as those in Fe and Py, substantially increase the resonance frequency. For reference, the $4\pi M_s$ values for YIG, Py and Fe are 0.175 T, 1 T, and 2.15 T, respectively. Also, the anisotropy field, H_a , in single-crystal Fe is substantial—0.06 T, compared with nearly 0 for YIG and Py.

Consider the magnetic permeability of a ferromagnetic material in an applied field. As Schloemann proposed [2], the “Voigt permeability (μ_{voigt}),” a complex scalar, accurately describes

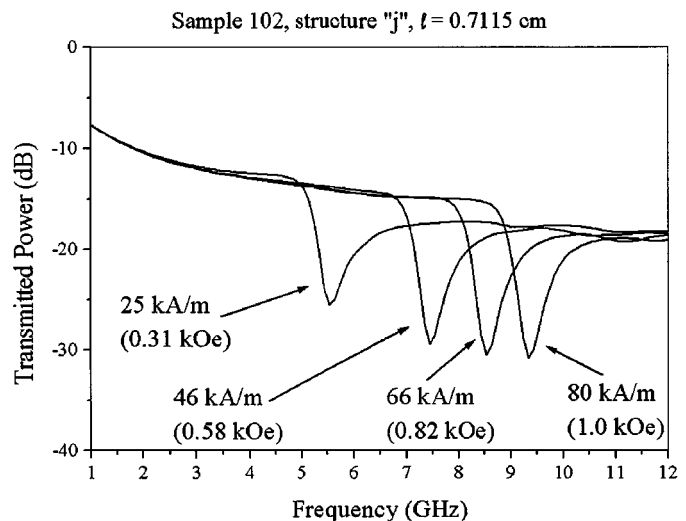


Fig. 3. Tunable band-stop behavior of the Py-based CPW line.

these effects. The relevance of this approach was rigorously confirmed later by Astalos and Camley [7]. At FMR, the imaginary part of μ_{voigt} becomes very large, leading to resonant absorption of microwave power. The real part of μ_{voigt} behaves like the real part of $\epsilon(\omega)$ near resonance, leading to a shift in the phase of a microwave signal.

III. RESULTS AND DISCUSSION

In a previous report [8], we demonstrated a band-stop filter implemented with Fe in a microstrip structure. This device showed large power attenuation at the band-stop frequency—over 100 dB/cm. The filter frequency was tunable over a range from 12–17 GHz by means of applied fields up to 40 kA/m. However, some performance limitations resulted due to our fabrication capabilities at that time. One problem was creating a 50 Ω line for impedance matching. The shadow mask we used to define the strip width created lines too wide for practical dielectric thicknesses, thus creating lines with a characteristic impedance much less than 50 Ω . Another limitation was the large resonance linewidth of our Fe films, which lead to broadening of the band-stop notch. Finally, the microstrip geometry is difficult to construct and to integrate with high-frequency electronics. In order to address these issues, we designed and constructed CPW transmission lines using Py as the magnetic component.

An example of the band-stop behavior of Py CPW lines is shown in Fig. 3. We observed power attenuation of about 20 dB/cm at the resonance frequencies, which were varied from 5–10 GHz with an applied field of up to 80 kA/m. The CPW lines were produced with characteristic impedances within 5 Ω of the desired value of 50 Ω . This is much better than obtained with the microstrip lines, and hence the power transmitted outside of the band-stop region was much higher. The background attenuation observed is due to reflection off the sharp corners and abrupt width change in the line—effects that can be minimized in a real device. The width of the stop band is under 1 GHz, compared with the nearly 3 GHz width observed in the Fe-based microstrip.

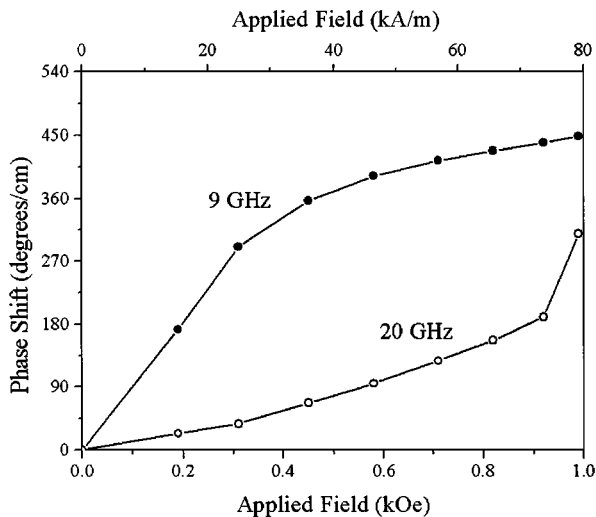


Fig. 4. Relative changes in phase of transmitted microwaves through a Fe-based microstrip versus applied magnetic field for two frequencies.

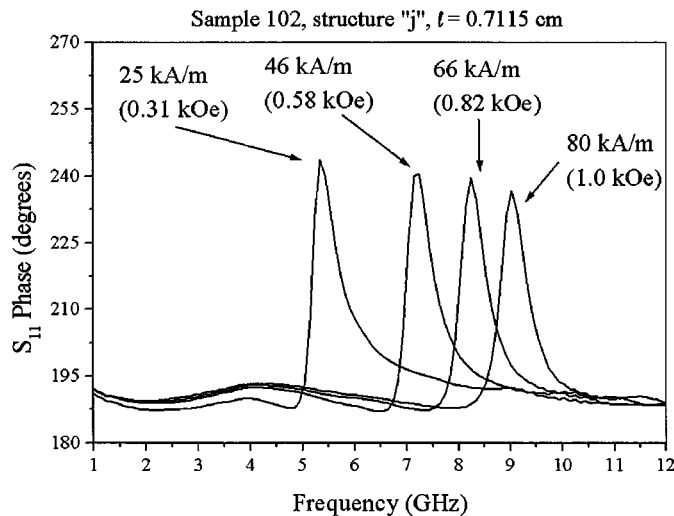


Fig. 5. Phase of reflected signal from a Py CPW line for various fields.

The Fe-based microstrip produced not only the band-stop effect, but also considerable tunable phase-shift effects. Fig. 4 shows the relative changes in phase shift as a function of applied field. For the frequencies of 9 and 20 GHz, we observed phase-shift tuning ranges of 450 and 270°/cm, respectively, as fields of up to 80 kA/m were applied. Note that these two frequencies lie below and above the tuning range of the stop band and therefore correspond to frequencies of low attenuation. For example, at 20 GHz, there is only about 6 dB/cm change in power attenuation over the range of applied field.

In the Py-based CPW lines, the phase-shift tuning of the transmitted signal (30°/cm) was much smaller than the effect observed in the Fe-based microstrip. This is due in large part to the narrower resonant absorption frequency width in Py, which substantially shifts phase only in regions of high attenuation of transmitted power. Fig. 5 shows a significant change in the

phase shift of a reflected signal. Furthermore, there was virtually no change in the magnitude of the reflected power at peak phase changes. In contrast to the continuously-variable phase shift possible in the Fe-based microstrip, the Py structure exhibited abrupt phase shift changes of over 50°. In addition, the magnitude of the effect in the Py structures showed no length dependence, suggesting that such a device could be reduced considerably in size.

IV. CONCLUSIONS

We developed tunable band-stop filters and phase-shifters based on two different ferromagnetic metals, Fe and Py, in microstrip and CPW. For Fe-based microstrip lines, we observed substantial attenuation of over 100 dB/cm and continuously variable phase-shift of over 360°/cm with applied fields of less than 40 kA/m. This attenuation is much higher than previously-reported values of 4 dB/cm [9], [10]. For Py-based CPW devices, we observed attenuation of 20 dB/cm. Changes in transmitted phase-shift are small. However, there are significant phase-shift changes in the reflected signal. These results demonstrate that use of ferromagnetic metallic films in transmission-line structures may have practical application in future microwave devices.

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