High-frequency magnetic microstrip local bandpass filters

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(Received 25 July 2005; accepted 5 October 2005; published online 22 November 2005)

This paper presents results for a compact, local bandpass filter. We fabricated the filter using two different ferromagnetic materials, Fe and NiFe, in a microstrip geometry. The different values of saturation magnetization of the two ferromagnets give rise to different gyromagnetic resonance frequencies and provide a local bandpass region between them. The results show that the center frequency of the filter can be tuned over a wide range by adjusting the magnitude of the bias magnetic field. The filter's bandwidth is almost constant (3.5±0.5 GHz) over the entire tuning frequency range (6–26 GHz). Theoretical calculations are in good agreement with the experimental results. © *2005 American Institute of Physics*. [DOI: 10.1063/1.2138364]

Today, broadband and multiband applications are renewing interest in high frequency (10–50 GHz) filters.[1–12] Modern microwave communication systems, especially in satellite and mobile communications, require high performance bandpass filters having low insertion loss and high selectivity. Usually, these criteria are fulfilled using a waveguide cavity or a dielectric resonator loaded cavity filter because of their low loss. However, in order to reduce size, weight, and cost there has been a growing interest in planar structures.

High frequency signal processing requires alternate approaches. Filters based on yttrium iron garnet (YIG) need very large external magnetic fields to operate in this range. This disadvantage can be overcome by replacing YIG based filters with metallic magnetic thin film filters having a much higher saturation magnetization and therefore a higher frequency of operation. It is to be noted that, when very broad bandwidths are specified, it is then difficult in practice to achieve a return loss of better than 15 dB and 0.2 dB ripple level over the passband by a single filter. Bandpass filters are used where a portion of the rf spectrum is partitioned into small bands.

Recently theoretical[4,5] and experimental[3,6,9] results have shown that microstrip notch filters can be made using metallic magnetic materials. In these filters an external magnetic field sets the resonance frequency of the ferromagnet and a strong absorption of the input signal occurs at the resonant frequency. For a planar structure, this frequency can be calculated by $f=\gamma[H(H+4\pi M_S)]^{1/2}$, where H is the external field, γ is the gyromagnetic ratio, and M_s is the saturation magnetization. The frequency can be adjusted over a wide range by varying the magnitude or/and the orientation of a relatively small bias magnetic field. With this in mind, it is reasonable to see if tunable bandpass filters can be made using a similar technology. To our knowledge there are currently no high-frequency bandpass devices being produced using ferromagnetic metals.

We use a simple idea to create microstrip local bandpass filters—two ferromagnetic metals, Fe and Permalloy (Py), are employed in a single structure as can be seen in Fig. 1. The different values of saturation magnetization in Fe ($4\pi M_s=21$ kG) and Py ($4\pi M_s=10$ kG), gives different resonance frequencies. This results in two different regions in frequency where propagation is not allowed. The frequency between the two transmission dips is effectively a local bandpass region where nearby frequencies are strongly attenuated. There are several critical design issues for realizing practical tunable filters. These include (i) large tunability by a dc magnetic field, (ii) low insertion loss, and (iii) bandwidth considerations. We will show that the local bandpass filter developed here performs reasonably for (i) and (iii) and, although the insertion loss is higher than desired, we will show how it can be improved.

We note that the idea of using two ferromagnetic materials in microwave devices has been used previously, however in a very different application. For example, it has been shown that a dual-ferrite circulator using ferrites with different magnetizations exhibits superior broadband performance.[13]

The geometry of the local band-pass microstrip filter is shown in Fig. 1. The substrate is a 0.35 mm thick GaAs(100) wafer. The structure was grown in a sputtering system with a background pressure maintained at $\sim 2\times 10^{-7}$ Torr. After cleaning the GaAs substrate in an ultrasonic bath, we annealed it to 200 °C inside the vacuum chamber. All the depositions were done at room temperature. First a 5 nm thick Ti layer was deposited for good adhesion to the substrate. This was followed by a 2 micron thick Ag layer, which was used as the ground plane for our device. The next sequence of depositions, Permalloy (NiFe), SiO_2, Fe or Fe/Cu multilayer, and finally 2 microns of Ag, were made through a shadow mask. All depositions were carried out using magnetron sputtering except for the SiO_2 which was grown using an e-gun source to achieve faster deposition rates. We patterned the

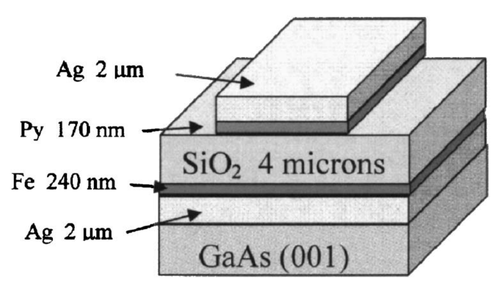

FIG. 1. Geometry of the local band-pass filter with the continuous Fe film.

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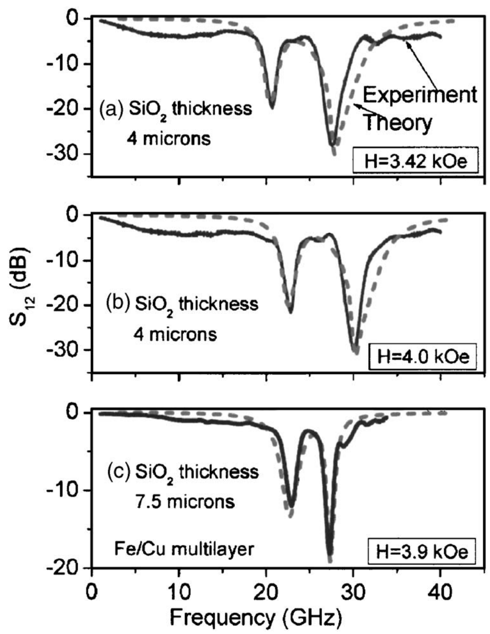

FIG. 2. Transmission response of the local band-pass filter at two different applied fields in (a) and (b). In (a) and (b) the structure has a SiO_2 thickness of 4 microns. (c) shows results for a filter with a SiO_2 thickness of 7.5 microns and with an Fe/Cu magnetic element $[\text{Fe } 5\text{ nm/Cu } 0.8\text{ nm}]_{12}$. The experiment is shown as a solid line and the theory is the dashed curve. In all cases the structure is 3.3 mm long and the microstrip has a width of 18 microns.

film by photolithography and then dry etched to obtain the required strip widths and lengths for the devices. We used a variety of thicknesses for the different layers as will be discussed later.

The device characterization was done by a vector network analyzer along with a microprobe station. Noise, delay due to uncompensated transmission lines connectors, its frequency dependence, and crosstalk have been taken into account by performing through-open-line (TOL) calibration using NIST Multical® software.[14] The dc bias magnetic field is applied along the length of the microstip line. The microstrip operates in a TM mode which ensures the ferromagnetic resonance condition, as the rf magnetic field and the dc magnetic field are perpendicular to each other. The widths of the signal line in our structures are between 12–24 μm and have lengths of 2–6 mm. The microstrips were generally designed to be close to a 50 Ω characteristic impedance.

Figures 2(a) and 2(b) show the experimental S_{12} response of a local bandpass filter with length 3.3 mm and width 18 microns. In this case the thicknesses were: Py, 250 nm; SiO_2, 4 microns; and Fe, 170 nm. In Fig. 2(a) the applied field is 3.42 kOe. The dashed line shows the result of a theoretical calculation for this structure. As discussed above one sees two distinct attenuation regions and in between there is a bandpass region. The position of the notches at either side of the pass band occurs at the frequencies given by the ferromagnetic resonance condition and is tunable with the external field. Figure 2(b) shows the experimental S_{12} response for the same structure at an applied field is 4 kOe. Again, the dashed line shows the result of the theoretical calculation.[4,5,15] Clearly the bandpass region has moved, almost as a single unit, to higher frequencies.

Figure 2(c) shows the results for a structure where the Py thickness is 300 nm, the SiO_2 thickness is 7.5 microns, and the final element is a Fe/Cu multilayer $[\text{Fe } 5\text{ nm/Cu } 0.8\text{ nm}]_{12}$. There are some important differences between the results in Fig. 2(c) and in Figs. 2(a) and 2(b). First, the insertion loss is much smaller for the structure with the Fe/Cu multilayer. Second, the bandpass region is much narrower in the structure with the Fe/Cu multilayer. We will discuss these differences shortly.

TABLE I. Summary of performance and physical parameters for the local bandpass filters.

Filter with Fe film	Filter with Fe/Cu ML structure
170 nm Fe	$[\text{Fe } 5\text{ nm/Cu } 0.8\text{ nm}]_{12}$
4 microns SiO_2	7.5 microns SiO_2
240 nm Py	300 nm Py
Center frequency: 6–26 GHz	6–25 GHz
Pass-band 3 dB width: 3.5±0.5 GHz	Pass-band 3 dB width: 2.5±0.5 GHz
Pass-band insertion loss: 4±0.5 dB	Pass-band insertion loss: 2.75±0.25 dB
Pass-band ripple ~0.5 dB	Pass-band ripple ~0.3 dB
Pass-band return loss: <−15 dB	Pass-band return loss: <−20 dB

The theoretical calculations involve finding wavelike solutions to Maxwell's equations in each material and then matching the solutions using the boundary conditions of conservation of tangential **E** and tangential **H** at the interfaces between the different materials. The magnetic materials are characterized by a frequency dependent permeability and a frequency dependent dielectric function which results from the metallic conductivity.[4,5]

For the first structure, the linewidth is 150 Oe for Fe and 220 Oe for Py. Normally the Py linewidth would be smaller, however Py is deposited early in the process and we believe it is slightly damaged in the later growth steps leading to a larger linewidth. The g factor is 2.06 for Fe and 2.12 for Py in agreement with typical values. Finally we include small corrections in the Fe permeability to account for the shape anisotropy of the structured Fe microstrip.[9,12] The Py is in the form of an extended film and does not require this additional correction.

In the second structure with the Fe/Cu multilayer, we have used a linewidth of 85 Oe for the Fe/Cu in the theoretical calculations. It is known that such a Fe/Cu multilayer may have much narrower magnetic linewidths than a continuous Fe film.[11] Our calculations show that the reduced insertion loss seen in Fig. 2(c) compared to Fig. 2(a) is partly due to the narrowed linewidth and partly due to increasing the thickness of the dielectric. We have also found that, in order to match the experimental results, $4\pi M_{\text{eff}}=18.6$ kG in the Fe/Cu structure rather than $4\pi M=21.5$ kG used for the thicker Fe film. It is well known that $4\pi M_{\text{eff}}$ may be lower in thin Fe films[16]—the Fe films are only 5 nm thick in the Fe/Cu structure—because of surface anisotropy or alloying. This reduction in magnetization is responsible for the narrowing of the bandpass region, from 3.5 GHz in Figs. 2(a) and 2(b) to 2.5 GHz in Fig. 2(c). This behavior indicates that one could make filters with even narrower bandpass regions by using Fe and Fe/Cu as the two magnetic components.

There are a number of methods to parameterize the performance of our local bandpass filters. The key parameters for the two filters are listed in Table I. It is important to note that the local bandpass filter can be tuned to different fre-

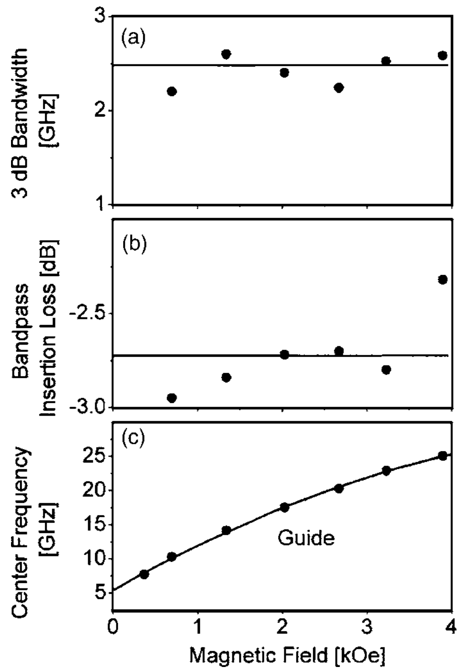

FIG. 3. Characteristics of the local bandpass filter with the Fe/Cu structure as a function of applied field. (a) Shows band-width; (b) shows insertion loss, and (c) shows the central frequency as a function of applied field.

quencies without substantially changing the width of the bandpass region. Filters with constant bandwidth have practical applications where a number of different center frequencies are needed.

We give additional parameters for the local bandpass filter with the Fe film below. The frequency tunability of the filter is defined as

$$\frac{f_c(\text{max field}) - f_c(\text{zero field})}{f_c(\text{zero field})} \times 100\,\%,$$

where f_c is the center frequency of the filter. As the bias magnetic field is varied from 0.03 to 4 kOe the center frequency varies from 6 to 26 GHz giving a maximum frequency tunability of 500%. The reflected signal is small, S_{11} is less than -15 dB at the pass-band region. The filters exhibit clean pass-band response and high out-of-band rejection in the frequency range near the pass band region. The maximum low-frequency rejection for Py is >60 dB/cm and the high-frequency rejection for Fe is >90 dB/cm.

The "rate of rejection" of this filter is very high and is similar on both the lower and higher cutoff sides. The "slope of the local bandpass filter," i.e., the rate of attenuation where the signal is 3 dB down from f_c, is ~ 10 dB/GHz for all measured fields. The shape factor of our filter (defined as the ratio of a filter's pass-band width plus the transition region width over the pass-band width) is about 1.54. (The transition region width is measured as the width from the 3-dB points to the lowest transmission on either side of the pass-band.) For an ideal filter the shape factor is 1. The external quality factor, $Q_{\text{ext}} = f_c/\Delta f$, ranges from 5 to 7 as the center frequency changes from 18 GHz to 26 GHz. The value of Q_{ext} can be easily increased by choosing different magnetic materials with saturation magnetizations that are closer to each other; in fact the Q_{ext} value is about 10 found for the filter with the Fe/Cu structure.

Figure 3 shows the 3-dB bandwidth, pass-band insertion loss and center frequency as a function of the biasing magnetic field for the filter with the Fe/Cu structure. The pass-band insertion loss is 2.75 ± 0.25 dB. Although this insertion loss is not as low as is normally desired for typical applications it should be possible to further reduce the insertion loss by further reductions in the linewidth and reductions in thickness of the magnetic materials. Figure 3(c) shows that the center frequency f_c of the filter mimics the usual dependence of frequency on magnetic field. The solid line is a guide to the eye.

In summary, we have developed a wide-band local band-pass filter. The use of Fe and permalloy in the same device demonstrates the feasibility of magnetically tunable local band-pass planar microwave filters. The devices operate from 6 to 26 GHz in fields up to 4 kOe. The pass-band region is nearly constant over the entire frequency range. Filters with a constant bandwidth over a wide frequency range have numerous practical applications such as phased array radar where a number of different center frequencies are needed.

The authors acknowledge support from the DOA Grant No. W911NF-04-1-0247 and US ARO Grant No. DAAD19-02-1-0174.

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