Miniaturized Antennas and Planar Bandpass Filters With Self-Biased NiCo-Ferrite Films

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Miniaturized microwave devices are realized by using magnetodielectric substrate comprising thin magnetic films that exhibit both high permittivity and high permeability at gigahertz frequency. We have fabricated and tested miniature circular patch antennas and hairpin bandpass filters with the alumina and Rogers substrate loaded with self-biased NiCo-ferrite films that exhibit excellent uniformity and low loss at frequencies exceeding 1.5 GHz. The measured results of magnetic hairpin bandpass filters have improved the central resonant frequency shift from 1.55 to 1.44 GHz, and a large resonant frequency tunability of about 23%–34% of the -3-dB bandwidth was achieved. For the circular patch antenna, we observed an improvement of 0.8 dB in gain and a large resonance frequency tunability of 100%–320% of the antenna -10-dB bandwidth.

Index Terms—**Bandpass filters, magnetic films, miniaturized filters, self-biased films.**

I. INTRODUCTION

With the continuous growth of wireless communication technologies, design and manufacturing of miniaturized microwave components are among most critical issues in communication systems [1]. In the radio frequency (RF) front-end, patch antennas and bandpass filters [2], [3] with small size and high performance are highly desirable. Planar device size can be minimized by using a substrate with high relative permittivity. However, antennas with high-permittivity substrates result in decreased bandwidth and the excitation of surface waves, leading to lower radiation efficiency and larger element coupling in arrays. It also becomes difficult to achieve impedance matching on high-permittivity substrates, due to large reactance of the coaxial probes used to feed the antenna.

Reducing the size of passive circuit components is generally not an issue because they can be embedded without compromising their performance. However, antenna cannot be placed arbitrarily and its miniaturization is difficult because smaller antennas are plagued by low bandwidth and gain. Achieving relative permeability larger than 1 ($\mu_r > 1$) in antenna substrates can lead to antenna miniaturization, enhanced bandwidth, and tunable radiation frequency [4]–[8]. Bulk ferrite materials [5], [6], composites of ferrite particles in polymer matrix [7], and metal magnetic films [8] have been used in substrates for achieving $\mu_r > 1$. However, bulk magnetic materials or composites and metal films are too lossy to be used at frequencies $>$600 MHz, and need large biasing magnetic fields for improved performance. Besides preventing miniaturization, biasing fields, demanding continuous supply, also drain the available battery power. Metamaterials with embedded metallic circuits are also viable for providing high permeability toward antenna miniaturization [9]. However, they are still too lossy at RF and hard to implement.

The combined high permeability and permittivity of ferrite film materials provides a great opportunity for realizing miniaturized microwave components [10]. In order to be practically feasible in miniature antennas for global positioning system (GPS) applications, it is important for GPS antenna substrates to be composed of self-biased magnetic materials, in which no external bias field is applied. It has been challenging to achieve self-biased magnetic materials in the gigahertz frequency range due to the well-known Snoek limit [11], [12], which leads to limited operating frequency range of the available bulk microwave ferrites. Magnetic thin films provide a unique opportunity for achieving self-biased magnetic substrates with $\mu_r > 1$ at frequencies $>$1 GHz due to the significantly extended Snoek limit, as detailed in Section II. The strong demagnetization field for magnetic thin films $H_{\rm demag} = 4\pi M_s$ allows for self-biased magnetization with high ferromagnetic resonance (FMR) frequencies up to several gigahertz, which are essential for microwave devices.

Recently, we have proposed to use novel magnetoelectric composite substrates for antennas with low-loss magnetic film materials and low-loss high-permittivity dielectric materials [8], [11], [12]. New designs of electronically tunable patch antennas with metallic magnetic films have been investigated [8], which showed that the bandwidth is increased by 50% over the nonmagnetic antennas. Self-biased annular ring antennas at 1.7 GHz with a large bandwidth have been fabricated and characterized with self-biased NiCo-ferrite films [11], which shows great potential for application to mobile handheld wireless communication devices.

In this paper, we discuss the magnetic properties of NiCo ferrite films, which are useful in the design of microwave devices using these films. We present new designs on miniature GPS patch antennas and planar bandpass filters that loaded with self-biased NiCo ferrite films. The films can be deposited on commercially available microwave substrates using low-temperature spin-spray process, essentially creating a magnetodielectric substrate/superstrate for practical applications. The designed magnetic bandpass filters with self-biased ferrite films with the thickness of 2 μm can realize a tuning of 23%–34% of -3-dB bandwidth with a low insertion loss. Measurements on magnetic patch antennas have demonstrated overall improved antenna performance with a large tunability of 100%–320% of the antenna -10-dB bandwidth, and an enhanced gain of 0.8 dB.

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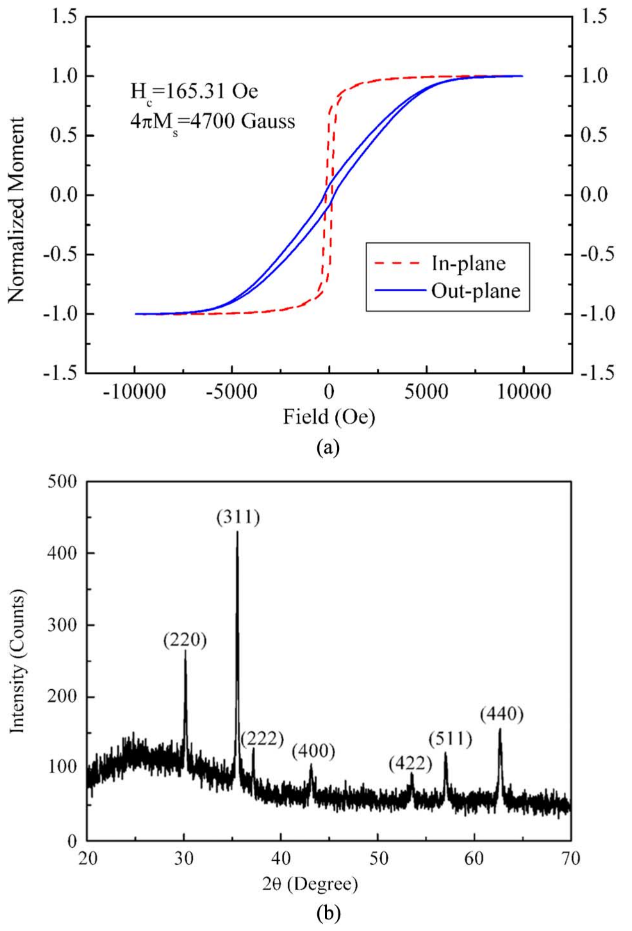


(a)

(b)

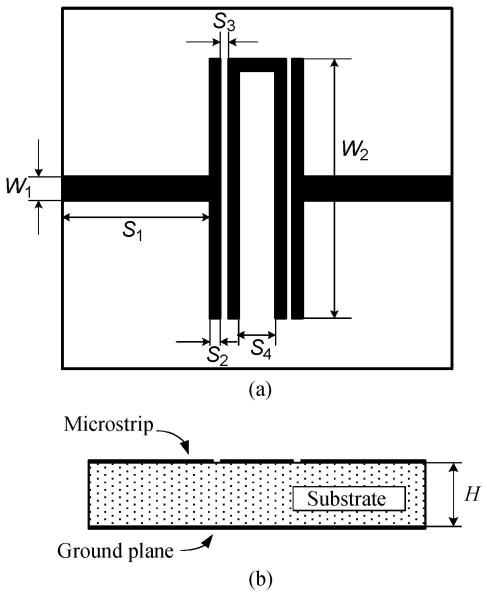
Fig. 1. (a) Hysteresis loop of NiCo-ferrite film. (b) X-ray diffraction for NiCo-ferrite film.

II. CHARACTERISTICS OF NiCo-FERRITE FILMS

In this work, we used the self-biased spinel NiCo-ferrite films fabricated by a low-cost spin-spray deposition process [10], a wet chemical process at a low-temperature of 90 °C. NiCo-ferrite films with composition of $\mathrm{Ni_{0.23}Co_{0.13}Fe_{2.64}O_4}$ can be deposited onto the substrate or the hairpin microstrip. The thickness of ferrite film is about 2 μm. The magnetic hysteresis loops were measured with vibrating sample magnetometer (VSM), as shown in Fig. 1(a). And the XRD pattern is analyzed by copper Ka X-ray diffraction, which is shown in Fig. 1(b). The in-plane resistivity of the film is $5.616 \times 10^3\ \Omega \cdot \mathrm{cm}$, and the coercivity is 165.31 Oe. The relative permittivity of the film is about 13 and the permeability is about 10. The loss tangent of the NiCo-ferrite film is estimated to be about 0.05 at 2 GHz.

For a uniformly magnetized sphere, the FMR frequency is linearly proportional to the net magnetic field H_{net}, with the gyromagnetic constant, γ being close to 2.8 MHz/Oe. Large bias fields of the order of 1000 Oe are needed for the FMR frequency to reach gigahertz range, and allow device operation in that range. The relative permeability of the magnetic sphere can be described by

$$\mu_{sr} = \frac{4\pi M_s}{H_{s\mathrm{net}}} + 1 \tag{1}$$



(a)

(b)

Fig. 2. Geometry of the hairpin bandpass filter. (a) Top view: $W_1 = 1.18$ mm, $W_2 = 18.1$ mm, $S_1 = 9.0$ mm, $S_2 = 0.23$ mm, $S_3 = 0.07$ mm, and $S_4 = 1.2$ mm. (b) Side view: $H = 1.28$ mm.

which is inversely proportional to the net uniformly magnetic field $H_{s\mathrm{net}}$. We can therefore readily reach the Snoek limit [13], [14]

$$f_{\mathrm{FMR}} \cdot (\mu_{sr} - 1) = \gamma \cdot 4\pi M_s \tag{2}$$

i.e., the product of the FMR frequency and the relative permeability is a constant that is determined by the saturation magnetization of the magnetic medium.

The permeability of the ferrite in the film plane is still $\mu_{fr} = (4\pi M_s / H_{f\mathrm{net}}) + 1$ with $H_{f\mathrm{net}}$ being the net in-plane field, while the FMR frequency is increased to be

$$f_{\mathrm{FMR}} = \gamma \sqrt{H_{f\mathrm{net}} \cdot (4\pi M_s + H_{f\mathrm{net}})} = \gamma H_{f\mathrm{net}} \sqrt{\mu_{fr}}. \tag{3}$$

The FMR frequency of magnetic films is therefore boosted to $\sqrt{\mu_{fr}}$ times of that of uniformly magnetic spheres, allowing self-biased FMR frequency as well as the operation frequency of magnetic films in the gigahertz range. Similarly, the product

$$\mu_{fr} \cdot f_{\mathrm{FMR}} = \gamma \cdot 4\pi M_s \cdot \sqrt{\mu_{fr}} \tag{4}$$

is also boosted to $\sqrt{\mu_{fr}}$ times of that of the magnetic spheres, indicating a significantly boosted Snoek limit for magnetic films.

III. BANDPASS FILTERS WITH NiCo-FERRITE FILMS

Fig. 2(a) and (b) shows the layout of top view and side view of the hairpin bandpass filter. This bandpass filter consists of a U-shaped quarter-wave resonator and two quarter-wave resonators with tapped-line input and output. All these resonators and a tapped line are realized by patterned copper cladding on the top surface of the underlying dielectric substrate. The width of the quarter-wave resonator is 0.23 mm and the length is 18.1 mm as we adopted Rogers R3010 as the substrate in both simulations and fabrications, which has a relative permittivity of 10.2 and a thickness of 1.28 mm. All the parameters are listed in the caption of Fig. 2. The proposed hairpin bandpass

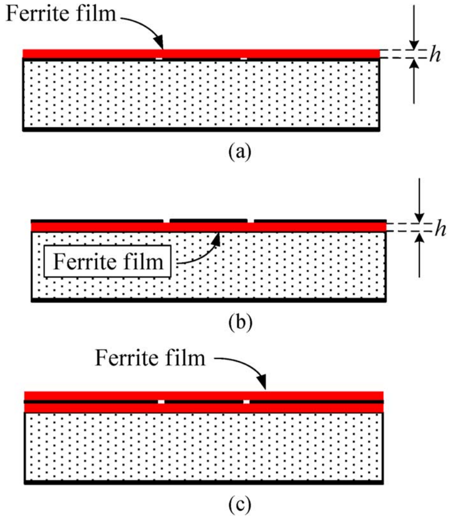


Fig. 3. (a) Bandpass filter with ferrite film above the microstrip. (b) Bandpass filter with ferrite film under the microstrip. (c) Bandpass filter with ferrite films both above and under the microstrip. The thickness of the film is h = 0.002 mm.

filter is designed and simulated with the help of high-frequency structure simulator (HFSS 10.0).

As indicated in Fig. 3(a)–(c), three hairpin bandpass filters with ferrite films are designed as follows. First, the ferrite film with the thickness of 2 μm was covered over the hairpin microstrip. Second, the ferrite film was added under the hairpin microstrip bandpass filter. Finally, two lays of ferrite films were added in our simulation: one is under the hairpin microstrip and another is just over the hairpin microstrip. In order to compare the results with the nonmagnetic bandpass filter, the s-parameters of ferrite-loaded filters are plotted and analyzed next.

Utilizing new spin spray technology, we were able to coat these substrates with a 2-μm NiCo ferrite. Once this had been completed, we deposited a 3-μm copper layer with the use of our physical vapor deposition system (PVD). Photolithography was then used to develop this copper into our desired hairpin bandpass filter shape. Four hairpin bandpass filters with/without NiCo-ferrite film are fabricated and tested. As plotted in Fig. 4(b), the central frequency of the filter without ferrite film is about 1.552 GHz; when the ferrite film is added above the microstrip, the resonant frequency shifts down to 1.475 GHz. This indicates a tuning range of 77 MHz, which is equivalent to approximately 23% of the -3-dB bandwidth. When the ferrite film is added just under the microstrip, we observed that the resonant frequency is 1.465 GHz, and the insertion loss is about -0.64 dB. When two ferrite films are added under and above the microstrip at the same time, the resonant down shifts to 1.441 GHz, and a frequency shift of 111 MHz was obtained, which is also equal to approximately 34% of the -3-dB bandwidth. In summary, we note that the hairpin bandpass filter loaded with ferrite film can indeed miniaturize the geometrical dimensions effectively, as demonstrated by shifting down the resonance.

IV. DESIGN OF GPS ANTENNAS WITH/ WITHOUT FERRITE FILMS

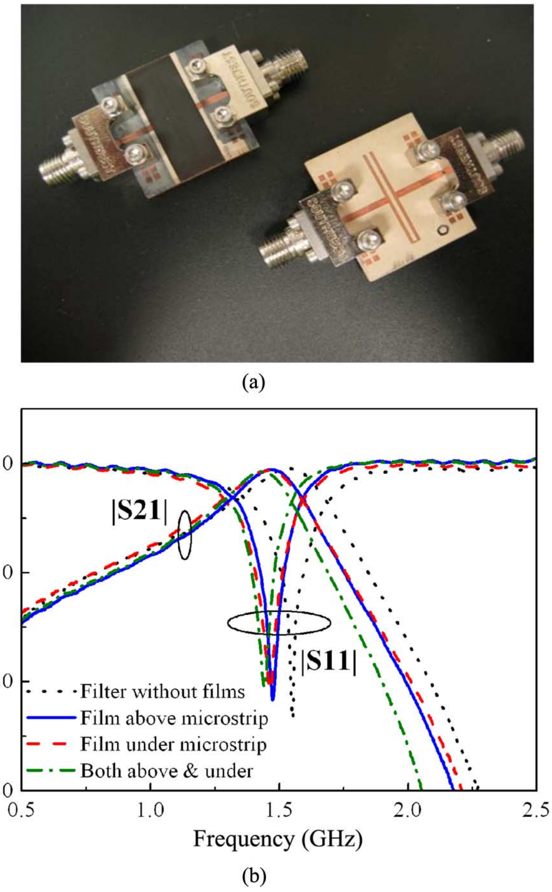


Fig. 4. (a) Fabricated hairpin bandpass filter with/without NiCo-ferrite films. (b) Measured results of bandpass filter with/without ferrite films.

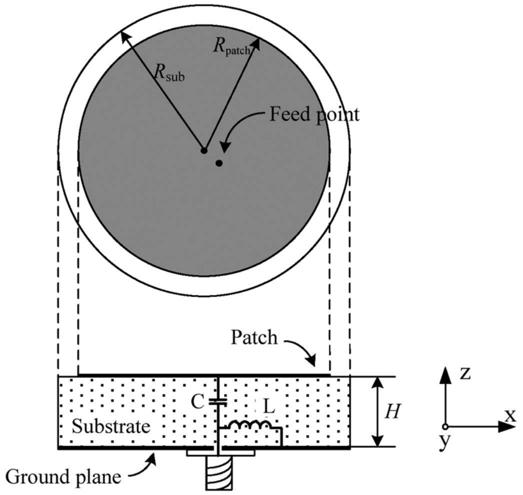
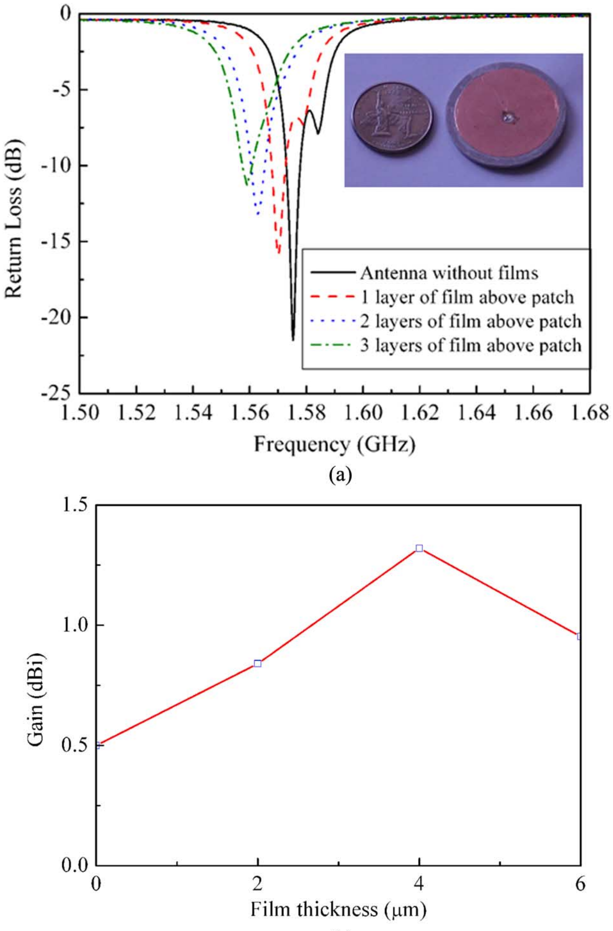


Fig. 5. Geometry of the proposed circular patch antenna. (Top view and side view) $R_{\rm sub}$ = 18 mm, $R_{\rm patch}$ = 15.25 mm, H = 1.28 mm.

Fig. 5 shows the layout of the circular patch antenna. The designed antenna consists of a circular patch and an LC (where L is an inductor and C is a capacitor) impedance matching circuit. Three circular patch antennas with ferrite films are designed and fabricated as follows.

First, a ferrite thin film of thickness 2 μm is introduced above the patch. Second, one more 2-μm-thick ferrite film is added above the patch, which means that the thickness of the ferrite films is 4 μm. Finally, we design an antenna with three layers



(a)

(b)

Fig. 6. (a) Measured return loss against frequency for the four different cases of circular patch antenna. (b) Measured gains of four antennas.

of ferrite film above the patch and each layer of ferrite film is 2 μm. In order to compare the results with the nonmagnetic antenna, the measured return losses of four antennas are plotted and analyzed. The return loss curves in Fig. 6(a) are measured under the condition that all the geometrical dimensions of the antenna are kept unchanged, and only the ferrite films are added at different position.

From Fig. 6(a), we can see that the central resonant frequency of the nonmagnetic antenna is about 1.575 GHz. When a ferrite film is added above the patch antenna, the resonant frequency shifts down to 1.570 GHz. This indicates a tuning range of 5 MHz relative to the nonmagnetic antenna, or equivalent to approximately 100% of the -10-dB bandwidth. When two layers of ferrite film are added above the patch, we observe that the resonant frequency is 1.563 GHz, a shift about 240% of the antenna bandwidth relative to the nonmagnetic circular patch antenna. When three layers of ferrite films are added above the microstrip patch, it moves the resonant frequency further down to 1.56 GHz. This is a tunability of 320% of the antenna bandwidth relative to nonmagnetic antenna. Clearly, the antenna loaded with ferrite film can indeed miniaturize the geometrical dimensions effectively as demonstrated by shifting down the resonance. The antenna gain was measured in the anechoic chamber and shown in Fig. 6(b). The gain of nonmagnetic antenna is 0.5 dBi, while for the later magnetic antennas with one layer, two layers, and three layers, the antenna gains are 0.84, 1.32, and 0.95 dBi, respectively.

V. CONCLUSION

NiCo-ferrite films are successfully introduced for incorporation into circular patch antennas and bandpass filters, leading to significantly enhanced performance at gigahertz. Measurements on magnetic patch antennas have demonstrated overall improved antenna performance with a large tunability of 100%–320% of the antenna bandwidth, and an enhanced gain of 0.8 dB. Four hairpin bandpass filters with/without ferrite films were designed and analyzed in this paper. The designed magnetic bandpass filters with self-biased ferrite films with the thickness of 2 μm can realize a tuning of 23%–34% of -3-dB bandwidth with a low insertion loss. This result demonstrated that the self-biased magnetic films lead to miniaturized bandpass filter without compromising the insertion loss. Therefore, in the design of microwave devices, we can design relatively small geometry devices and get the desired working frequency by loading NiCo-Ferrite films.

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