

Planar Annular Ring Antennas With Multilayer Self-Biased NiCo-Ferrite Films Loading

Guo-Min Yang, *Student Member, IEEE*, Xing Xing, Andrew Daigle, Ogheneyunume Obi, *Student Member, IEEE*, Ming Liu, Jing Lou, *Student Member, IEEE*, S. Stoute, Krishna Naishadham, *Senior Member, IEEE*, and Nian X. Sun, *Member, IEEE*

Abstract—With their high relative permeability, magneto-dielectric materials show great potential in antenna miniaturization. This paper presents an annular ring antenna with self-biased magnetic films loading in the gigahertz frequency range. The annular ring antenna was realized by cascading a microstrip ring and a tuning stub. Self-biased NiCo-ferrite films were adopted to load an annular ring antenna on a commercially available substrate that operates at 1.7 GHz. Novel antenna designs with self-biased NiCo-ferrite films on one side and both sides of the substrate were investigated. Antennas with self-biased magnetic films loading working at 1.7 GHz showed a down shift of 2–71 MHz of the central resonant frequency. An antenna gain enhancement of up to 0.8 dB was observed over the non-magnetic antenna.

Index Terms—Annular ring antennas, antenna miniaturization, magnetic films, self-biased ferrite films.

I. INTRODUCTION

THE need for antennas with small size, light weight, and low profile have been continuously growing in modern wireless communication systems [1], [2]. Annular ring antennas have been of great interest to many researchers and engineers in recent years [3]–[7], because annular ring antennas have much smaller circumferences compared to circular patch antennas, and they can radiate a linearly polarized wave or a circularly polarized wave by disturbing the symmetry of the ring. The substrates of planar antennas play a very important role in achieving desirable electrical and physical characteristics. For most cases, antennas can be greatly miniaturized by using a substrate with high relative permittivity [8]. However, antennas with high-permittivity substrates will result in decreased bandwidth and the excitation of surface waves leading to lower radiation efficiency.

Bulk ferrite materials [9]–[13], composites of ferrite particles in a polymer matrix [14], metamaterials [15]–[17], etc. have been used in antenna substrates for achieving $\mu_r > 1$. In [14] ferrite and polymer composite, antenna substrates were produced for the purpose of antenna miniaturization by using their high permeability. It is possible for a ferrite patch antenna to excite

radiation patterns to realize a circularly polarized antenna [10]. A tunable resonant frequency in a patch antenna was obtained by applying an external bias magnetic field to an yttrium iron garnet (YIG) film [12]. It has also been reported that by applying a biasing magnetic field to the ferrite substrate of a patch antenna, two different radiation modes could be observed [13]. However, these materials or composites are too lossy to be used at frequencies >600 MHz under a self-biased condition and large biasing magnetic fields are needed for these ferrites to operate at higher frequencies. Metamaterials with embedded metallic circuits are good candidates for providing a high permeability in antenna miniaturization [15]–[17]. However these metamaterials with embedded metallic circuits need periodic metallic rings and slabs to produce the relatively high permeability, and are not practical in real applications in modern mobile communication systems.

In order to be practically feasible in miniature antenna applications, such as handheld wireless communication devices, it is important for antenna substrates to comprise of magnetic materials without an external bias magnetic field. Magnetic thin films provide a unique opportunity for achieving self-biased magnetic patch antenna substrates with $\mu_r > 1$ at frequencies larger than 1 GHz. The strong demagnetization field for magnetic thin films, $H_{\text{demag}} = 4\pi M_s$, allows for a self-biased magnetization with high ferromagnetic resonance (FMR) frequencies up to several GHz, making these magnetic thin films great candidates for achieving self-biased magnetodielectric antenna substrates working in the same frequency range. Our most recent work on magnetic films loaded patch antennas showed significantly enhanced antenna gain and bandwidth [18]–[20].

In this paper, we present a planar annular ring antenna with self-biased NiCo-ferrite thin films on the top of the antenna and both on top and beneath the ground plane, thus essentially creating a magneto-dielectric substrate/superstrate for practical applications. A large frequency shift of the central resonant frequency of 2 MHz–71 MHz and an enhanced bandwidth were obtained for the designed magnetic ring antennas over the non-magnetic counterparts at 1.7 GHz, which shows great potential for applications in mobile wireless communication systems. In addition, these magnetic antennas can be made conformably at a low cost near room temperature.

II. ANTENNA CONFIGURATION AND CHARACTERISTICS OF NICO-FERRITE FILM

A. Antenna Configuration

Fig. 1(a) and (b) show the schematic view and photograph, respectively, of the annular ring antenna. This antenna consisted of

Manuscript received January 12, 2009; revised August 08, 2009. First published December 28, 2009; current version published March 03, 2010. This work was supported by the ONR and NSF.

G.-M. Yang, X. Xing, A. Daigle, O. Obi, M. Liu, J. Lou, S. Stoute and N. X. Sun are with the Department of Electrical and Computer Engineering, Northeastern University, Boston, MA 02115 USA (e-mail: n.sun@neu.edu; guomyang@hotmail.com).

K. Naishadham is with the Sensors and Electromagnetic Application Laboratory, Georgia Institute of Technology, Atlanta, GA 30332.

Color versions of one or more of the figures in this paper are available online at <http://ieeexplore.ieee.org>.

Digital Object Identifier 10.1109/TAP.2009.2039295

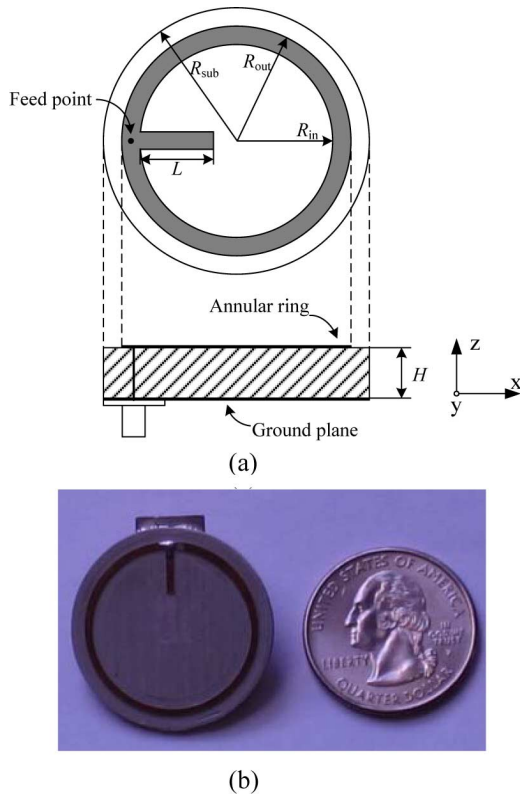


Fig. 1. Geometry of the proposed annular ring antenna. (a) Top view and side view. $R_{sub} = 14$ mm, $R_{out} = 12.4$ mm, $R_{in} = 11.4$ mm, $L = 6.22$ mm and $H = 1.27$ mm. (b) Photograph of the fabricated annular ring antenna without films.

a microstrip ring and a tuning stub. Both the microstrip ring and the tuning stub were realized by patterned copper cladding on the top surface of the underlying dielectric substrate. The feed point was located at the junction of the tuning stub and the microstrip ring with a distance of 0.5 mm to the outer edge of the ring. The radius of the outer ring is 12.4 mm, the radius of the inner ring is 11.4 mm, the length of the tuning stub is 6.22 mm, and the width of the tuning stub is 1 mm. We adopted Rogers RT/duroid 6010, with a relative permittivity of 10.2 and a thickness of 1.27 mm, as the substrate in both simulations and fabrication. The proposed annular ring antenna was designed and simulated with the help of High Frequency Structure Simulator (HFSS 10.0).

B. The Characteristics of NiCo-Ferrite Films

Microwave ferrite ceramics show relatively high permeability of $\mu_r > 1$ and high permittivity ($\epsilon_r \sim 10 \sim 15$), as well as low loss at RF/microwave frequencies. These characteristics are highly desirable for the miniaturization of many different RF/microwave devices, including antennas. The operating frequencies of bulk microwave magnetic materials are limited to less than 600 MHz due to the excessive magnetic loss tangents associated with various loss mechanisms, with FMR being one of the major loss mechanisms. The FMR frequency is therefore the upper frequency limit for antenna substrates for achieving $\mu_r > 1$.

Our recent work on microwave magnetic thin films, including metallic magnetic films and ferrite films, indicates that

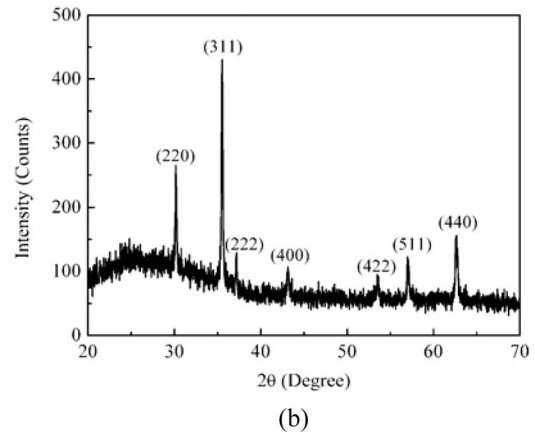
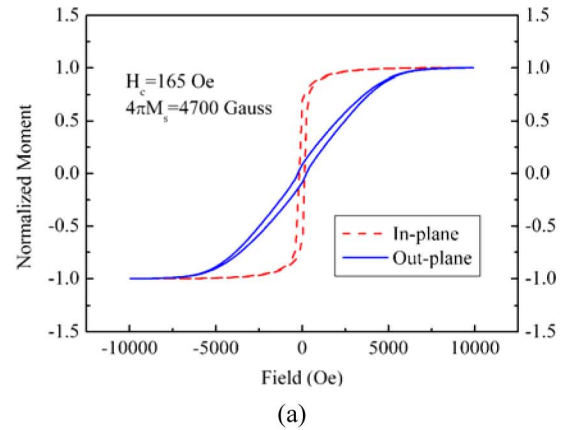


Fig. 2. (a) Hysteresis loop of the NiCo-ferrite film. (b) X-ray diffraction for the NiCo-ferrite film.

these magnetic thin films can readily operate in the gigahertz frequency range under a self-bias condition [21], [22], and have been widely used in RF/microwave devices, including antennas [18]–[20]. In this work, we used self-biased spinel NiCo-ferrite films fabricated by a low-cost spin-spray deposition process [23], a wet chemical synthesis process at a low-temperature of 90°C. NiCo-ferrite films with the composition of $\text{Ni}_{0.23}\text{Co}_{0.13}\text{Fe}_{2.64}\text{O}_4$ were deposited onto a thin transparency. The thickness of ferrite film was about 2 μm . The in-plane and out-of-plane magnetic hysteresis loops of the NiCo-ferrite films were measured with a vibrating sample magnetometer (VSM) with the external magnetic field applied in the film plane, out of the film plane, respectively. The hysteresis loops indicate the dependence of magnetization M on the applied magnetic field H . As shown in Fig. 2(a), the in-plane hysteresis loop shows an in-plane coercivity of 165 Oe as well as the self-biased magnetization of the film under zero applied magnetic fields. There is a huge difference between the in-plane hysteresis and the out-plane hysteresis, indicating that the magnetization stays in the film plane under zero bias magnetic field. The NiCo-ferrite film showed an in-plane homogeneous magnetization with an in-plane relative permeability of ~ 10 . The in-plane resistivity of the NiCo-ferrite film was measured to be $5.6 \times 10^3 \Omega \cdot \text{cm}$.

An X-ray diffraction (XRD) technique was used to reveal the microstructure of NiCo-ferrite films with a copper Ka X-ray source. The X-ray diffraction pattern is shown in Fig. 2(b). It is

clear from the XRD data that the NiCo-ferrite film has a single phase spinel structure without preferential orientation.

The governing equation for magnetodynamics is the Landau-Lifshitz-Gilbert (L-L-G) equation [24], [25]. The in-plane susceptibility spectra of the magnetic films can be expressed by the equation [26]

$$\chi(\omega) = \frac{\omega_m(\omega_m + \omega_k + \omega_{\text{appl}} + j\omega\alpha)}{-\omega^2 + j\omega\alpha\omega_m + \omega_m(\omega_k + \omega_{\text{appl}})} \quad (1)$$

where α is the Gilbert damping constant, $\omega_{\text{appl}} = \gamma\mu_0 H_{\text{appl}}$, $\omega_k = \gamma\mu_0 H_k$ and $\omega_m = \gamma\mu_0 M_s$ (H_{appl} is the applied field, H_k is the in-plane anisotropy field, M_s is the saturation magnetization and γ is the gyromagnetic ratio). The relative permittivity of the NiCo-ferrite film is about 13 and the relative permeability is about 10 at the frequency of 2 GHz, similar to what was reported in [23].

C. Loading Effects of Magnetic Materials

Applying a superstrate is an effective gain enhancement method for microstrip antennas [27]. Instead of the conventional dielectric material, magnetic materials are adopted as a practical means to coat above the annular ring antenna in this paper. For a rectangular patch antenna with the dominant mode of TM_{010}^z , the resonant frequency of the antenna is a function of its dimension and given by [1]

$$f_{\text{rad}} = \frac{1}{2L\sqrt{\mu\epsilon}} = \frac{c}{2L\sqrt{\mu_r\epsilon_r}} \quad (2)$$

where μ_r is the relative permeability and ϵ_r is the relative permittivity of the substrate, c is the speed of light in free space, L is the effective length of the rectangular patch [1]. Magneto-dielectric materials loaded as superstrates can not only improve the antenna gain, but also miniaturize the antenna by the same factor using moderate values of permittivity and permeability of $n_{\text{mf}} = \sqrt{\mu_r\epsilon_r}$ [28]–[30]. The magnetic films also lead to better wave impedance match between the antenna substrate and air (since $\sqrt{\mu_r/\epsilon_r} \approx 1$), thus mitigating the negative impact on antenna efficiency from wave impedance mismatch between the substrate and air. The wave impedance mismatch at the substrate/free space interface is reduced by the addition of NiCo-ferrite layer with a relative permittivity of $\epsilon_{\text{rf}} \cong 13$ and a permeability of $\mu_{\text{rf}} \cong 10$. If the wave impedances are matched on both sides of the interface, maximum transmission occurs, whereas little energy will be transmitted when the wave impedances are significantly different at the interface. The bandwidth ($\text{VSWR} = 2$) for planar microwave antennas with a magneto-dielectric substrate can be described as [28]

$$\text{BW} = \frac{96\sqrt{\mu_r/\epsilon_r}t/\lambda_0}{\sqrt{2}[4 + 17\sqrt{\mu_r\epsilon_r}]} \quad (3)$$

where t is the thickness of the substrate, and λ_0 is the wavelength at the resonant frequency. Clearly the incorporation of a self-biased microwave ferrite film in antenna substrates leads to an increased permeability of antenna substrates, and thus, a reduced radiation frequency and an enhanced bandwidth.

The impedance behavior of the annular ring antenna can be approximated with the behavior of an equivalent resonant cir-

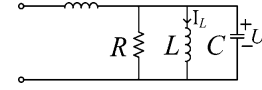


Fig. 3. Equivalent circuit of the annular ring antenna.

cuit [1], [29]. As shown in Fig. 3, the value of capacitor C will increase if we load the antenna with dielectric material, which in turn will shift the resonance frequency. One has to adjust the inductor L to get the resonant frequency in this resonant circuit. If we load the antenna with inductive material (i.e., NiCo-ferrite films), the equivalent value of L will increase. We can then decrease the equivalent capacitor C for a certain frequency. The benefit of the inductive loading can be explained with the variation of stored energy, as shown in (4)

$$\begin{aligned} W &= W_m + W_e \\ &= \frac{C}{2}|U|^2 + \frac{L}{2}|I_L|^2 \\ &= \frac{|U|^2}{2} \left(C + \frac{1}{\omega^2 L} \right). \end{aligned} \quad (4)$$

In the above equation, I_L is the current through the inductor of L , and U is the voltage of the capacitor C . For the annular ring antenna, the source voltage is a constant, thus an increase in C leads to increased stored energy. If magnetic ferrite films were loaded over the ring antenna, the equivalent value of L will be increased, thus we can decrease the equivalent capacitor for a certain frequency. Furthermore, as indicated in (4), the stored energy will be decreased and more energy will be radiated into the free space.

D. The Lossy Effects of NiCo-Ferrite Films on the Antenna Bandwidth

The self-biased spinel NiCo-ferrite films possess a high relative permeability and can be fabricated by a low-cost spin-spray deposition process. The effects of the magnetic loss tangent of the ferrite films could not be neglected when several layers of NiCo-ferrite film were stacked together as a superstrate loading. The relationship between the antenna bandwidth and the lossy effects of substrate and NiCo-ferrite films could be expressed by the maximum achievable fractional bandwidth (FBW), which is given by [31], [32]

$$\text{FBW}_{\text{max}} = \frac{\text{VSWR} - 1}{Q_{\text{total}}\sqrt{\text{VSWR}}} \quad (5)$$

where Q_{total} is the total quality factor of the designed antenna and is given by

$$\frac{1}{Q_{\text{total}}} = \frac{1}{Q_{\text{rad}}} + \frac{1}{Q_{\text{sw}}} + \frac{1}{Q_d} + \frac{1}{Q_m} + \frac{1}{Q_c} \quad (6)$$

where

Q_{rad} is the antenna radiation quality factor.

Q_{sw} is the quality factor due to the surface wave. For the ferrite films loading, the antenna acts as a source of surface waves in the material and the amount of the energy radiate to the excitation of surface wave depends on the thickness of the superstrate. Q_d is the quality factor due to the dielectric losses, and $Q_m =$

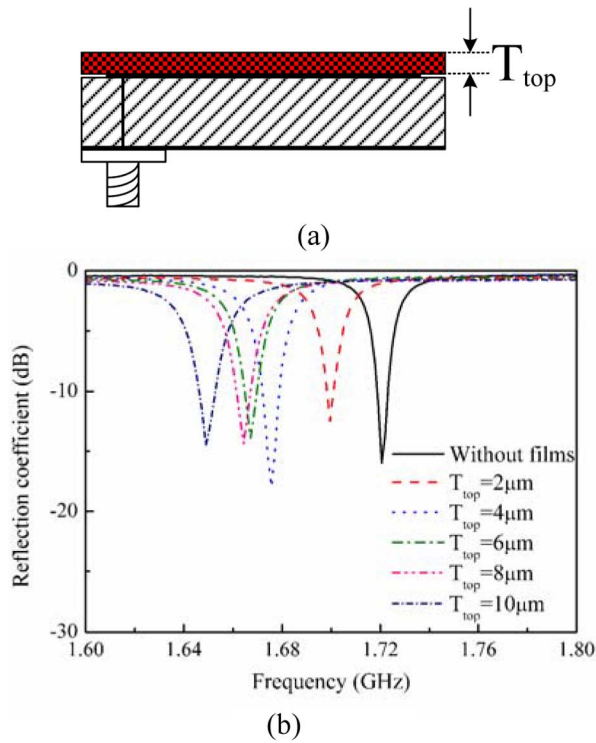


Fig. 4. (a) Annular ring antenna with ferrite films above the ring. (b) Measured reflection coefficient with $T_{\text{top}} = 2, 4, 6, 8, 10 \mu\text{m}$.

$1/\tan\delta_{\epsilon,\text{eff}}$, here $\tan\delta_{\epsilon,\text{eff}}$ is the effective dielectric loss tangent of the composite structure of the Rogers material and the ferrite films.

Q_m is the quality factor due to the magnetic losses, and $Q_m = 1/\tan\delta_{\mu,\text{eff}}$, here $\tan\delta_{\mu,\text{eff}}$ is the effective magnetic loss tangent of the composite structure of the Rogers material and the ferrite films. The thickness of the ferrite film is only several microns, which is less than one percent of the total thickness of the substrate. The effective magnetic loss tangent would therefore not be a dominant factor to the antenna fractional bandwidth.

Q_c is the quality factor due to the copper losses.

With (5) and (6), we can see that the antenna fractional bandwidth is tightly linked to the material losses (both dielectric and magnetic losses). High material losses lead to large antenna fractional bandwidth but at the cost of the radiation efficiency at the same time. The self-biased spinel NiCo-ferrite film is a low-loss thin film at gigahertz frequencies with a very small thickness fraction, which leads to enhanced antenna bandwidth and improved antenna gain.

E. Experimental Results for Single-Sided Ferrite Films Loading

To investigate the loading effects of magnetodielectric materials as antenna's superstrate, five annular ring antennas with ferrite films were designed and fabricated as follows. First, one layer of ferrite thin film with thickness of $2 \mu\text{m}$ was introduced above the microstrip ring, as indicated in Fig. 4(a), in which $T_{\text{top}} = 2 \mu\text{m}$. In addition, magnetic antennas with several layers of the NiCo-ferrite film loading on one side were designed with the thickness of ferrite films varied with $T_{\text{top}} = 4, 6, 8, 10 \mu\text{m}$, and shown in Fig. 4(a). In order to compare the

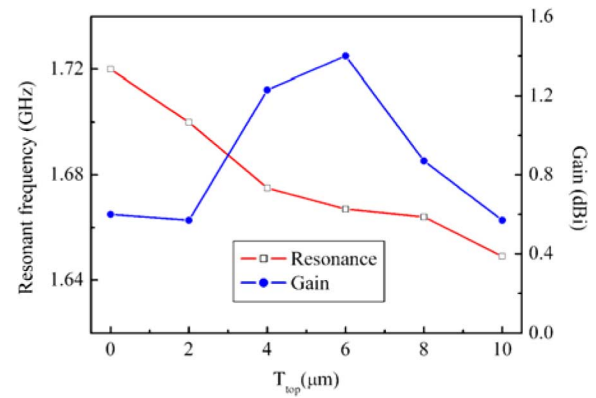


Fig. 5. Measured resonant frequency and antenna gain with single-sided ferrite films loading.

results with the non-magnetic antenna, the measured reflection coefficient of five magnetic antennas along with that of non-magnetic ring antenna were plotted and analyzed. The reflection coefficient curves in Fig. 4(b) were measured with all the geometrical dimensions of the antenna unchanged, except the ferrite film thickness.

From Fig. 4(b) we can see that the central resonant frequency of the non-magnetic antenna is about 1.72 GHz, and the -10 dB bandwidth is 5 MHz. When a ferrite film with thickness of $2 \mu\text{m}$ is added above the ring; the resonant frequency shifts down to 1.70 GHz. This indicates a frequency down shift of 20 MHz relative to the non-magnetic antenna. When the thickness of the ferrite film is $4 \mu\text{m}$, the resonance shifts down to 1.675 GHz, a frequency shift of 45 MHz, or is equivalent to five times of the antenna bandwidth of non-magnetic ring antenna. The resonant frequencies are 1.667 GHz, 1.664 GHz, and 1.649 GHz, when the thicknesses of the ferrite film are 6, 8, 10 μm , respectively. The antenna gains are 0.57 dB, 1.23 dB, 1.4 dB, 0.87 dB and 0.57 dB, respectively, for the antenna loaded with 2, 4, 6, 8 and 10 μm thick ferrite film. Clearly, ferrite films loading can lead to miniaturized antennas by downward shift of the resonance frequency. A summary of the variation of resonant frequency and antenna gain with ferrite films loading is shown in Fig. 5.

The antenna gain and the radiation patterns of E-plane and H-plane were measured in the anechoic chamber and plotted in Fig. 6(a) and (b), respectively. In order to compare the experimental results with the numerical results, the simulated E-plane and H-plane of the annular ring antenna are also given in the same figure. The gain comparison technique was used to determine the gain of the antenna. As shown in Fig. 6(a), when the thickness of ferrite films is $4 \mu\text{m}$ or $6 \mu\text{m}$, the upper half pattern is almost the same, while the bottom half pattern shrank. This can also be observed in Fig. 6(b). This shows that as an inductive loading acts as a superstrate, more energy will be radiated into forward free space. A maximum antenna gain of 1.4 dBi was obtained when the thickness of ferrite films was $6 \mu\text{m}$ and coated above the ring. All the measured gains were plotted in Fig. 5. However when the thickness is more than $6 \mu\text{m}$, the antenna gain begins to decrease. From the radiation patterns of E-plane, we can see that more energy may be radiated between the elevation angles of 60° – 120° and 240° – 300° . The main reason for this may be that with an increase in the thickness of ferrite

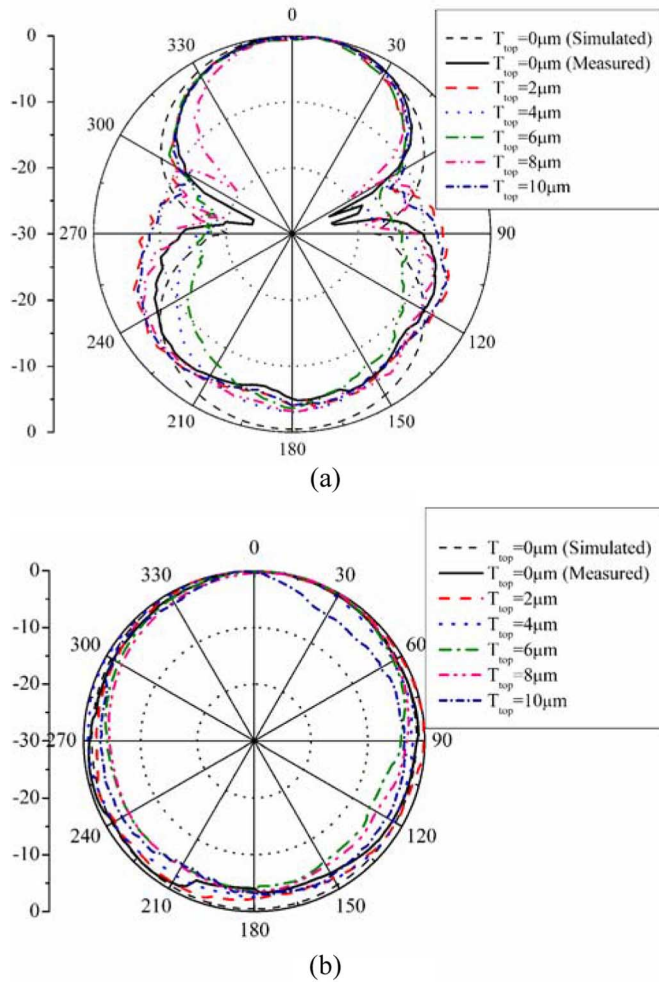


Fig. 6. Normalized radiation patterns of annular ring antennas loaded with ferrite films. Simulated results with $T_{\text{top}} = 0 \mu\text{m}$ only and measured results with $T_{\text{top}} = 0, 2, 4, 6, 8, 10 \mu\text{m}$, respectively. (a) E-plane. (b) H-plane.

films, the surface wave may radiate more energy, which resulted in decreased antenna gain.

The designed annular ring antenna is a linear polarization antenna. From the measured radiation patterns [Fig. 6(a) and (b)] we can clearly see that the radiation patterns are approximately the same shape, which indicates that self-biased NiCo-ferrite films can not excite two near degenerate orthogonal modes with equal amplitude and 90 degree phase difference. However, by applying a biasing magnetic field to the ferrite substrate of an antenna, one may get a circular polarization antenna.

F. Experimental Results for Double-Sided Ferrite Films Loading

As the radiation pattern of E-plane of the ring antenna is very similar to the shape of the digit “8”, which means the ring antenna will radiate into both forward and backward directions at the same time, it is necessary to investigate the magnetic antenna with ferrite films on both sides. For this purpose, we designed magnetic antennas with ferrite films loaded on both sides of the antenna, with one layer under the ground plane ($T_{\text{bottom}} = 2 \mu\text{m}$) and one to four layers of ferrite films above the ring ($T_{\text{top}} = 2, 4, 6$ and $8 \mu\text{m}$, respectively), as shown in

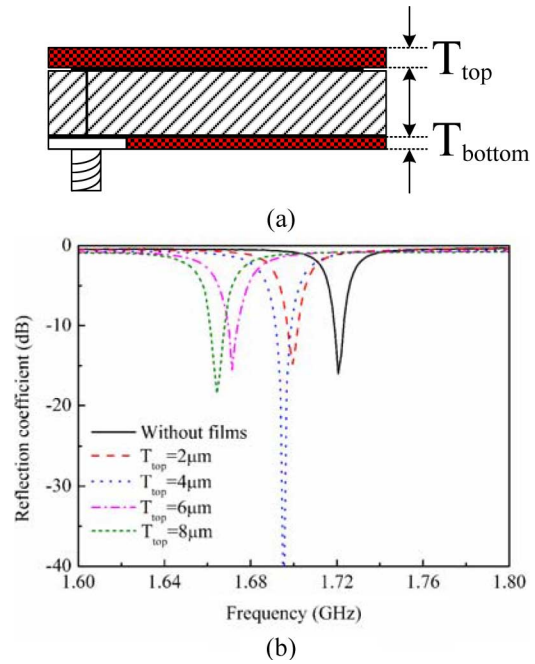


Fig. 7. (a) Annular ring antenna with several layers of ferrite film above the ring and one layer of ferrite film under the ground plane. (b) Measured reflection coefficient with $T_{\text{top}} = 2, 4, 6, 8 \mu\text{m}$; $T_{\text{bottom}} = 2 \mu\text{m}$.

Fig. 7(a). In order to compare the results with the non-magnetic antenna, the measured reflection coefficient of five antennas were plotted and analyzed. The reflection coefficient curves in Fig. 7(b) were measured under the condition that all the geometrical dimensions of the antenna were kept unchanged, and only the ferrite films were added at different positions.

When one layer of ferrite film was added above the microstrip ring and one under the ground plane at the same time, the resonant frequency moved down to 1.70 GHz with a reflection coefficient magnitude of -15 dB. When two layers of ferrite film were added above the ring and one layer under the ground plane, the resonance shifted down to 1.695 GHz with the minimum reflection coefficient of about -47 dB, a frequency shift of 25 MHz compared to the non-magnetic substrate. The bandwidth was 7 MHz with the addition of the ferrite film, an increase of 40% relative to non-magnetic antenna's bandwidth. As shown in Fig. 7(b), the ferrite film loading led to an enhanced bandwidth and an improved matching. It is notable that as we have analyzed in the Section II, the bandwidth improvement could be partially attributed to the lossy effects of the ferrite films (i.e., the loss tangent of the magnetic material). Also the antenna gain of this case is 1.23 dB. The addition of the three layers of ferrite film above the ring and one layer underneath the ground plane tunes the resonance down to 1.671 GHz. The resonant frequency shift is 49 MHz compared with the non-magnetic antenna. The antenna gain of magnetic antenna with top 3 layers and bottom 1 layer of ferrite film is 1.33 dB. Adding four layers of ferrite film above the patch shifts the resonance down to 1.664 GHz, with the reflection coefficient of -18.5 dB. We observe a central frequency shift of about 56 MHz.

Both sides (top and bottom) of ferrite films loading effects are summarized in Fig. 8. From this figure we can see that with a $2 \mu\text{m}$ thick layer of ferrite film beneath the antenna, the resonant

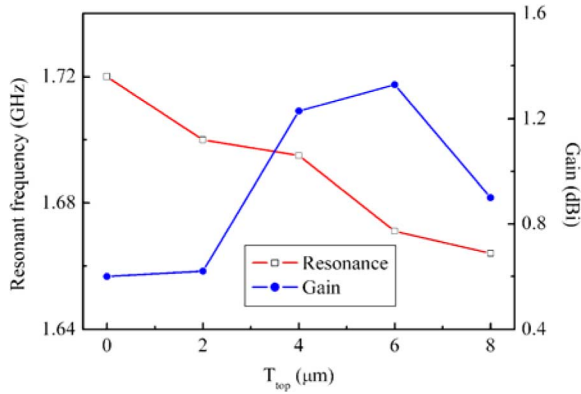


Fig. 8. Measured resonant frequency and antenna gain with double-sided ferrite films loading.

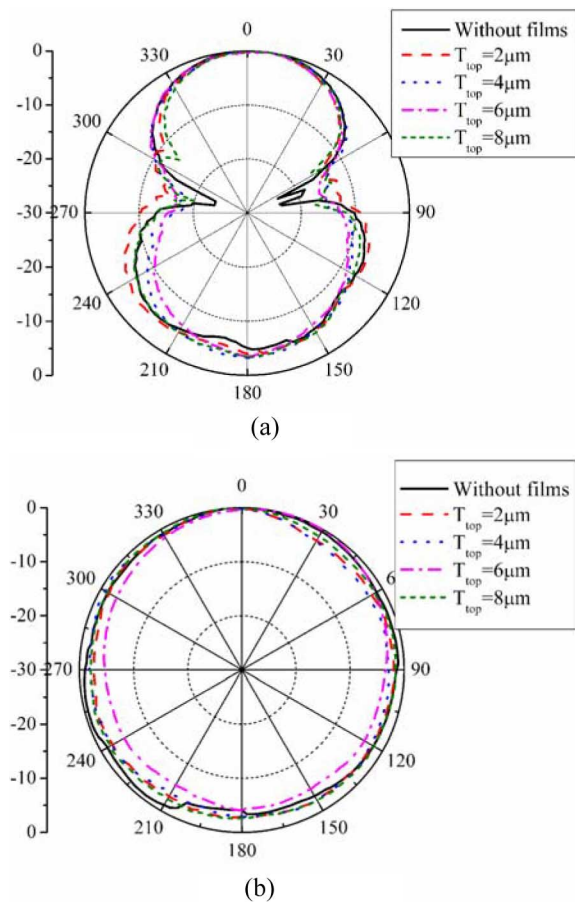


Fig. 9. Normalized radiation patterns of annular ring antennas loaded with ferrite films. (a) E-plane. (b) H-plane.

frequency decreased drastically with the increase of ferrite films loaded on top. Furthermore, an interesting phenomenon is that an enhanced bandwidth are observed with both sides loading, and the maximum antenna bandwidth was obtained in the case of top 2 and bottom 1, which showed a 40% enhanced -10 dB bandwidth over the non-magnetic counterparts.

The normalized radiation patterns of E-plane and H-plane are plotted in Fig. 9(a) and (b), respectively. As shown in the figure of the E-plane, when T_{bottom} is $2 \mu\text{m}$ and T_{top} are $4 \mu\text{m}$ and $6 \mu\text{m}$, the bottom half patterns are a little bit smaller than that

of without films, which means more energy will be radiated into free space. The measured antenna gains are also summarized in Fig. 8. The measured antenna gain increases first and with the increase of the thickness of ferrite films. Then the gain decreases when the thickness is more than $6 \mu\text{m}$. The main reason for this phenomenon may be the problem of surface waves and the lossy effects of the ferrite film, which may have resulted in decreased antenna gain when the thickness is more than $6 \mu\text{m}$.

III. CONCLUSION

NiCo-ferrite films were successfully introduced into antenna substrates, leading to miniaturized magnetic annular ring antennas with enhanced performances at 1.7 GHz. These spin-spray deposited NiCo-ferrite films are not as lossy as bulk ferrites materials, due to the strong demagnetization field of the magnetic thin films as well as the large in-plane anisotropy field of the magnetic films in the range of hundreds of Oe. These magnetic antennas show a great promise for achieving miniaturized microstrip antennas on magneto-dielectric superstrate/substrate with enhanced bandwidths, improved gains, and high efficiencies. In addition, these magnetic antennas can be made conformably at a low cost with low-temperature physical vapor deposition method, making these ring antennas with ferrite films very promising for real applications. Measurements on magnetic antennas demonstrated that the central resonant frequency could be varied downward over a range of 50% to 1420% of the antenna bandwidth ($VSWR = 2$), which indicates the self-biased magnetic films do lead to minimized antennas by shifting down the resonance frequency. A maximum enhancement of antenna gain up to 0.8 dBi was obtained with ferrite films loading over the non-magnetic antenna. Antennas with self-biased ferrite films loading show significant improvement in antenna efficiency, gain and omnidirectional performance in gigahertz frequency range.

ACKNOWLEDGMENT

The authors would like to thank Prof. A. Farhat for allowing the use of the measurement facility. The authors would also like to thank several anonymous reviewers for their constructive and detailed comments which led to important improvements to this paper.

REFERENCES

- [1] C. A. Balanis, *Antenna Theory: Analysis and Design*. Hoboken, NJ: Wiley, 2005.
- [2] K. L. Wong, *Planar Antennas for Wireless Communications*. Hoboken, NJ: Wiley, 2003.
- [3] H. Nakano, H. Yoshida, H. Mimaki, J. Yamauchi, and K. Hirose, "Printed loop array antenna radiating a circularly polarized wave," in *Proc. 9th Int. Antennas Propag. Conf.*, Apr. 1995, vol. 1, pp. 504–507.
- [4] R. L. Li, N. A. Bushyager, J. Laskar, and M. M. Tentzeris, "Determination of reactance loading for circularly polarized circular loop antennas with a uniform traveling-wave current distribution," *IEEE Trans. Antennas Propag.*, vol. 53, no. 12, pp. 3920–3929, Dec. 2005.
- [5] F. Qureshi, M. A. Antoniadis, and G. V. Eleftheriades, "A compact and low-profile metamaterial ring antenna with vertical polarization," *IEEE Antennas Wireless Propag. Lett.*, vol. 4, pp. 333–336, 2005.
- [6] E. Ojefors, H. Kratz, K. Grenier, R. Plana, and A. Rydberg, "Micromachined loop antennas on low resistivity silicon substrates," *IEEE Trans. Antennas Propag.*, vol. 54, no. 12, pp. 3593–3600, Dec. 2006.
- [7] A. L. Borja, P. S. Hall, Q. Liu, and H. Iizuka, "Omnidirectional loop antenna with left-handed loading," *IEEE Antennas Wireless Propag. Lett.*, vol. 6, pp. 495–498, 2007.

- [8] A. Hoorfar and A. Perrotta, "An experimental study of microstrip antennas on very high permittivity ceramic substrates and very small ground planes," *IEEE Trans. Antennas Propag.*, vol. 49, pp. 838–840, May 2001.
- [9] D. M. Pozar and V. Sanchez, "Magnetic tuning of a microstrip antenna on a ferrite substrate," *Electron. Lett.*, vol. 24, pp. 729–731, Jun. 1988.
- [10] H. How, T. Fang, and C. Vittoria, "Intrinsic modes of radiation in ferrite patch antennas," *IEEE Trans. Microw. Theory Tech.*, vol. 42, pp. 988–994, Jun. 1994.
- [11] R. K. Mishra, S. S. Pattnaik, and N. Das, "Tuning of microstrip antenna on ferrite substrate," *IEEE Trans. Antennas Propag.*, vol. 41, pp. 230–233, Feb. 1993.
- [12] P. J. Rainville and F. J. Harackiewicz, "Magnetic tuning of a microstrip patch antenna fabricated on a ferrite film," *IEEE Microw. Guided Wave Lett.*, vol. 2, pp. 483–485, Dec. 1992.
- [13] H. How, P. Rainville, F. Harackiewicz, and C. Vittoria, "Radiation frequencies of ferrite patch antennas," *Electron. Lett.*, vol. 28, pp. 1405–1406, Jul. 1992.
- [14] T. B. Do and J. W. Halloran, "Fabrication of polymer magnetics," in *Proc. IEEE Int. Symp. Antennas Propag.*, Jun. 2006, pp. 1709–1712.
- [15] K. Buell, H. Mosallaei, and K. Sarabandi, "A substrate for small patch antennas providing tunable miniaturization factors," *IEEE Trans. Microw. Theory Tech.*, vol. 54, pp. 135–146, Jan. 2006.
- [16] H. Mosallaei and K. Sarabandi, "Design and modeling of patch antenna printed on magneto-dielectric embedded-circuit metasubstrate," *IEEE Trans. Antennas Propag.*, vol. 55, pp. 45–52, Jan. 2007.
- [17] K. Sarabandi, A. M. Buerkle, and H. Mosallaei, "Compact wideband UHF patch antenna on reactive impedance substrate," *IEEE Antennas Wireless Propag. Lett.*, vol. 5, pp. 503–506, 2006.
- [18] N. X. Sun, J. W. Wang, A. Daigle, C. Pettiford, H. Mosallaei, and C. Vittoria, "Electronically tunable magnetic patch antennas with metal magnetic films," *Electron. Lett.*, vol. 43, no. 8, pp. 434–435, Apr. 2007.
- [19] G. M. Yang, A. Daigle, M. Liu, O. Obi, S. Stoute, K. Naishadham, and N. X. Sun, "Planar circular loop antennas with self-biased magnetic film loading," *Electron. Lett.*, vol. 44, pp. 332–333, Feb. 2008.
- [20] G. M. Yang, X. Xing, A. Daigle, M. Liu, O. Obi, J. W. Wang, K. Naishadham, and N. Sun, "Electronically tunable miniaturized antennas on magnetolectric substrates with enhanced performance," *IEEE Trans. Magn.*, vol. 44, no. 11, pp. 3091–3094, Nov. 2008.
- [21] S. X. Wang, N. X. Sun, M. Yamaguchi, and S. Yabukami, "Sandwich films: Properties of a new soft magnetic material," *Nature*, vol. 407, pp. 150–151, Sep. 2000.
- [22] J. Lou, R. E. Insignares, Z. Cai, K. S. Ziemer, M. Liu, and N. X. Sun, "Soft magnetism, magnetostriction and microwave properties of FeGaB thin films," *Appl. Phys. Lett.*, vol. 91, p. 18254, Oct. 2007.
- [23] K. Kondo, S. Yoshida, H. Ono, and M. Abe, "Spin sprayed Ni-(Zn)-Co ferrite films with natural resonance frequency exceeding 3 GHz," *J. Appl. Phys.*, vol. 101, p. 09M502, 2007.
- [24] L. Landau and E. Lifshitz, "On the theory of the dispersion of magnetic permeability in ferromagnetic bodies," *Physik Zeits. Sowjetunion*, vol. 8, pp. 153–169, 1935.
- [25] T. L. Gilbert, "A Lagrangian formulation of the gyromagnetic equation of the magnetization field," *Phys. Rev. B*, vol. 100, pp. 1243–1255, 1955.
- [26] N. X. Sun, S. X. Wang, T. J. Silva, and A. B. Kos, "Soft magnetism and high frequency behavior of Fe-Co-N thin films," *IEEE Trans. Magn.*, vol. 38, pp. 146–150, Jan. 2002.
- [27] D. R. Jackson and N. G. Alexopoulos, "Gain enhancement methods for printed circuit antennas," *IEEE Trans. Antennas Propag.*, vol. 33, pp. 976–987, Sep. 1985.
- [28] R. C. Hansen and M. Burke, "Antenna with magneto-dielectric," *Microw. Opt. Technol. Lett.*, vol. 26, pp. 75–78, Feb. 2000.
- [29] P. M. Ikonen, K. N. Rozanov, A. V. Osipov, P. Alitalo, and S. A. Tretyakov, "Magneto-dielectric substrate in antenna miniaturization: Potential and limitations," *IEEE Trans. Antennas Propag.*, vol. 54, pp. 3391–3399, Nov. 2006.
- [30] P. M. Ikonen, S. I. Maslovski, C. R. Simovski, and S. A. Tretyakov, "On artificial magnetodielectric loading for improving the impedance bandwidth properties of microstrip antennas," *IEEE Trans. Antennas Propag.*, vol. 54, pp. 1654–1662, Jun. 2006.
- [31] K. R. Carver and J. W. Mink, "Microstrip antenna technology," *IEEE Trans. Antennas Propag.*, vol. 29, pp. 2–24, Jan. 1981.
- [32] E. Belohoubek and E. Denlinger, "Loss considerations for microstrip resonators," *IEEE Trans. Microw. Theory Tech.*, vol. 23, pp. 522–526, Jun. 1975.



Guo-Min Yang (S'07) was born in Zhejiang Province, China, in 1979. He received the B.S. degree (with honors) in communication engineering from Xi'an University of Technology, Xi'an, China, in 2002 and the M.S. degree in electronic engineering from Shanghai Jiao Tong University, Shanghai, China, in 2006. He is currently working toward the Ph.D. degree in electrical and computer engineering at Northeastern University, Boston, MA.

His current research interests include antenna miniaturization, magneto-dielectric materials, metamaterials, frequency selective surfaces, UWB filters, UWB antennas, computational electromagnetics and inverse scattering problems in EM. He has authored 12 journal publications and 10 conference papers.

Mr. Yang is a member of the Editorial Board of the IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES. He was the recipient of National Graduate Student Scholarship in 2006.



Xing Xing received the B.S. degree in physics from Nanjing University, China, in 2006 and the M.S. degree in electrical engineering from Northeastern University, Boston, MA, in 2009. She is currently working toward the Ph.D. degree in electrical and computer engineering at Northeastern University, Boston, MA.

Her research interests include magnetic materials and devices.

Andrew Daigle received the B. S. and M. S. degree in electrical engineering from Northeastern University, Boston, MA, in 2007 and 2009, respectively, where he is currently working toward the Ph.D. degree.



Ogheneyunume Obi (S'09) was born in Benin City, Edo State, Nigeria, in 1979. She received the B.Eng. degree in electrical and electronics engineering from the University of Benin, Benin City, in 2004 and the M.S. in electrical engineering from Northeastern University, Boston, MA, in 2009, where she is currently working toward the Ph.D. degree.

Her principle research interest is fabrication of magnetic thin films for microwave devices.

Ogheneyunume is a member of Eta Kappa Nu (HKN).



Ming Liu received the B.S. degree in mathematical physics from Inner Mongolia University, Baotou, Inner Mongolia, China, in 1999 and the M. S. degree in chemical physics in Dalian Institute of Chemical Physics, Chinese Academy Sciences, Dalian, Liaoning, China, in 2004. Currently, he working toward the Ph.D. degree at Northeastern University, Boston, MA.

His current research interests are on Processing and characterization of magnetic, ferroelectric, and magnetolectric materials and the demonstration of composite microstructures and functional coupling.



Jing Lou (S'08) was born on January 20, 1981, in China. He received the B.S. degree in physics from Nanjing University, Nanjing, China, in 2003 and the M.S. degree in physics from Northeastern University, Boston, in 2005, where he is currently working toward the Ph.D. degree.

His main research interests include synthesis, microstructure, and properties of magnetic and magnetoelectric materials for applications in RF and microwave devices. Novel devices based on magnetoelectric concept are also his focus.

Stephen Stoute is currently working toward the B.S. degree at Northeastern University, Boston, MA.



Krishna Naishadham (M'87–SM'94) received the M.S. degree from Syracuse University, and the Ph.D. from the University of Mississippi, both in electrical engineering, in 1982 and 1987, respectively.

From 1987 to 1999, he served on the faculty of Electrical Engineering, as an Assistant Professor at the University of Kentucky, Lexington, and as an Associate Professor (tenured) at Wright State University, Dayton. He taught courses in electromagnetics (EM) and antennas, and performed research on microwave circuits, computational EM and

microwave characterization of novel electronic materials. From 1999–2002, he was at Philips, working on advanced RF system architectures for broadband mixed signal distribution. From 2002–2007, he was a Research Scientist at MIT Lincoln Laboratory, and contributed to hybrid asymptotic techniques for

electromagnetic modeling of large bodies containing small features, and to RCS characterization using spectral estimation methods. In 2008, he joined Georgia Institute of Technology as a Research Faculty and a Principal Research Scientist at the Sensors and Electromagnetics Laboratory. His current research focuses on multifunctional antenna arrays, co-site interference in arrays, antenna miniaturization, and mitigation of parasitic effects in wearable antennas. He published four book chapters and several papers in professional journals and conference proceedings on topics related to antennas, computational EM and wave-oriented signal processing.

Dr. Naishadham is a Member of URSI Commission B. He served the IEEE as Member of the Technical Program Committee for Antennas and Propagation Symposium (1992–1995), and International Microwave Symposium (1994–2005). He was Chair of the IEEE Dayton Joint Chapter of AP and MTT Societies from 1994 to 1999.



Nian X. Sun (S'99–M'02) received the Ph.D. degree from Stanford University in 2002.

Previously, he was a Scientist at IBM and Hitachi Global Storage Technologies between 2001 to 2004. Currently, he is an Associate Professor in the Electrical and Computer Engineering Department, Northeastern University, Boston, MA. His research interests include novel magnetic, ferroelectric and magnetoelectric materials and devices, such as antennas, phase shifters, filters, circulators, etc., magnetic sensors; material and device properties at RF/microwave

frequencies; energy harvesting materials and devices; micro/nanotechnologies for biomedical magnetic sensing, etc. He has published over 70 technical papers, more than 20 US patents and patent disclosures.

Dr. Sun was the recipient of the NSF CAREER Award in 2008, the ONR Young Investigator Award in 2007, and the 1st Prize IDEMA Fellowship in 2000.