An Overview of ARL's Low Profile Antenna Work Utilizing Anisotropic Metaferrites

Dr. Gregory Mitchell, *IEEE Member* and Dr. Steven Weiss, *IEEE Member*
U.S. Army Research Laboratory
Adelphi, USA
gregory.a.mitchell1.civ@mail.mil / steven.j.weiss.14.civ@mail.mil

***Abstract*—We present an overview of the U.S. Army Research Laboratory's efforts in developing low profile and wideband antennas for tactical communications. Specifically we utilize an anisotropic magneto-dielectric substrate. This work includes the development of a flared dipole from 200 to 500 MHz, as well as a circularly polarized crossed dipole for satellite communications from 240 to 320 MHz. Each of these antennas are cavity backed with a profile of less than a fortieth of a wavelength. Finally, we give an overview of the theory of anisotropic transverse resonance to be utilized in next generation cavity backed antennas.**

Keywords—low profile; cavity backed antenna, magneto-dielectrics; anisotropic; wideband

I. Introduction

Many military antenna applications require antennas that conform to the surface of a supporting structure. These include airborne and ground based radar, tactical line of sight communications, and satellite communications (SATCOM). Typically, the electrical height between the radiating element and a reflector is approximately $\lambda_o/4$ at the center frequency in free space. This results in a large profile of 375 mm (14.76 inches) at 200 MHz for example. Here we define the profile as the dimension normal to the surface of the supporting structure. We wish to minimize the antenna's profile, to reduce the visual signature of communications platforms. Low profile antennas (LPA) reduce platform visibility to adversaries and decrease antenna weight which also becomes critical for airborne platforms.

Of particular interest are positive index magnetic metamaterials exhibiting low loss in the UHF band [1-2]. Traditionally, magnetic media have high losses above 100 MHz, which makes them unsuitable as substrates for UHF antenna designs [3]. A new class of engineered anisotropic media exists that exhibits positive anisotropic permittivity ($\underline{\underline{\varepsilon_r}}$) and permeability ($\underline{\underline{\mu_r}}$) tensors with low magnetic loss tangents at UHF.

We present an overview of the U.S. Army Research Laboratory's (ARL) work with designing, testing, and measuring LPAs in the VHF/UHF band from 200 MHz to 500 MHz. Specifically we highlight the performance of two LPA prototypes developed and tested under the Battlefield Antenna program in conjunction with Metamaterials Inc., a contractor from Austin, TX. These antennas provide 0 dB to 5 dB of realized gain over a wide bandwidth with profiles of $\lambda_o/40$ and $\lambda_o/25$. The enabling technology for the performance of these antennas is a class of anisotropic magneto-dielectrics fabricated by the same contractor known as Metaferrites. Furthermore, we will show a technique utilizing the theory of anisotropic transverse resonance for a partially loaded cavity that will be used in future ARL LPA development.

II. Antenna Prototypes

This section presents 2 LPA prototypes. The first is a linearly polarized, cavity backed bowtie antenna. The second is a right hand circularly polarized (RHCP) crossed dipole antenna. Both of these antennas have been fabricated and tested in an anechoic chamber. Furthermore, the crossed dipole antenna has also been field tested and compared to commercial satellite communications antennas.

Metaferrites were used to partially load the cavity of the antenna in both cases. The unique low loss magnetic properties of Metaferrites at frequencies above 100 MHz are the enabling technology that provides the necessary impedance bandwidth while allowing the antennas to radiate while maintaining a very small electrical separation from the ground plane. Another important property of Metaferrites is their anisotropy both in permittivity and permeability. We represent this anisotropy as follows

$$\underline{\underline{\mu_r}} = \begin{bmatrix} \mu_x & 0 & 0 \\ 0 & \mu_y & 0 \\ 0 & 0 & \mu_z \end{bmatrix}, \tag{1}$$

$$\underline{\underline{\varepsilon_r}} = \begin{bmatrix} \varepsilon_x & 0 & 0 \\ 0 & \varepsilon_y & 0 \\ 0 & 0 & \varepsilon_z \end{bmatrix}. \tag{2}$$

Note that equations (1) and (2) are diagonal tensors, and therefore the Metaferrites used in the following antennas do not exhibit any gyrotropic phenomena. We wish to further emphasize that these Metaferrites exhibit only positive values of anisotropic permeability and permittivity and do not fall under the classification of double negative (DNG) metamaterials.

A. Low Profile, Cavity Backed Flared Dipole (Bowtie)

Originally, ARL wished to design a low profile, cavity backed antenna which maintained a positive realized gain and a return loss of -10 dB or better from 200 MHz to 500 MHz. The aperture of the antenna should be planar and not exceed 0.186 m^2 (2.0 ft.^{2}). Furthermore, the profile should not exceed 50.8 mm (2 in.). From the beginning, ARL targeted the use of Metaferrites as the enabling technology for this type of antenna. Metamaterials Inc. was chosen both to design an antenna prototype as well as fabricate and measure the Metaferrite material used in the design.

The resulting A133 antenna is the slotted bowtie antenna shown in Fig. 1. The bowtie antenna yields wider bandwidth than a typical dipole. The 2 arms of the bowtie are fed with equal amplitude and 180^o out of phase. A commercial 180^o degree hybrid coupler provides the necessary phase shift. The profile of the A133 antenna is established by a rectangular metallic cavity, shown in Fig. 2 that is 38.1 mm (1.5 in.) thick. This is approximately equal to λ_o/40 at 200 MHz.

The cavity is partially loaded with Metaferrite material underneath the dipole arms. The rest of the cavity is filled with a dielectric material representative of free space to provide structural support. The Metaferrite tensors have the values μ_x=15, μ_y=1, μ_z=1, ε_x=17, ε_y=17, and ε_z=3. The loss tangent of μ_x varies from 0.05 to 0.2 across frequency while the other 5 tensor components have a loss tangent on the order of 0.02 or less. The orientation of the tensors is such that the dominant value of $\underline{\boldsymbol{\mu}}_r$ (in this case μ_x=15) is aligned with the direction of the magnetic field in the cavity.

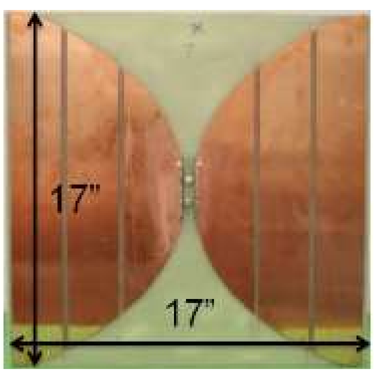

Fig. 1. Top view of the low profile, cavity backed A133 antenna. (Figure courtesy of Metamaterials, Inc. – Austin, TX)

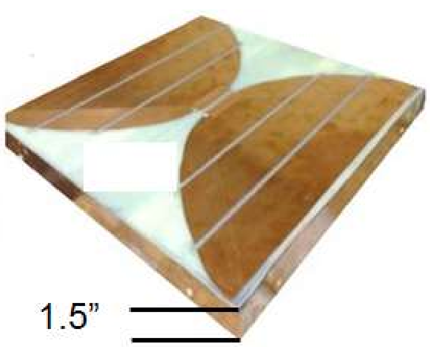

Fig. 2. Perspective view of the low profile, cavity backed A133 antenna. (Figure courtesy of Metamaterials, Inc. – Austin, TX)

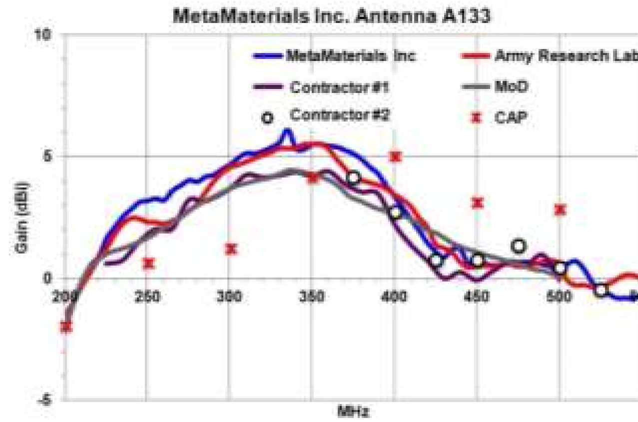

Fig. 3. Measured realized gain versus frequency at antenna broadside. (Figure courtesy of Metamaterials, Inc. – Austin, TX)

Fig. 3 shows the realized gain to broadside of the A133 antenna versus frequency. These measurements were made in anechoic chambers by multiple entities and 4 out of the 5 all show good agreement within 1.0 dB across frequency. While, we do not show the S-parameters for the two port input, the return loss is included as part of the calculation of the realized gain. We can infer, that while we need a good return loss in order to maintain a positive realized gain at a λ_o/40 profile (calculated at 200 MHz), we probably are not maintaining a -10 dB return loss across the whole frequency. This is especially apparently at either end of the frequency band where there is an appreciable dip in realized gain.

B. Low Profile, Cavity Backed Crossed Dipole

As a follow up to the success of the A133 antenna, ARL wished to design a low profile, cavity backed RHCP antenna with similar radiation characteristics or better for a tactical satellite communications antenna. The bandwidth requirements were only to cover the tactical satellite band of 240 MHz to 320 MHz. We also wanted a similar volumetric footprint for the antenna as for the A133. Metamaterials Inc. was again chosen to design an antenna prototype as well as fabricate and measure the Metaferrite material used in the design. We did not require that the new antenna utilize the same Metaferrite as in the A133.

The resulting A145 antenna is the slotted crossed bowtie antenna shown in Fig. 4. We see that the crossed bowtie antenna of Fig. 4 shows a linear taper, while that of Fig. 1 shows an elliptical taper. This alteration was made to better accommodate the reduced area available for each of the 4 crossed dipole arms. The 4 arms of the bowtie are fed with equal amplitude in phase quadrature to provide the required RHCP polarization. A cascade of a commercial 90^o coupler and 2 180^o degree couplers provides the necessary phase shift. The profile of the A145 antenna is established by a rectangular metallic cavity 50.8 mm (2.0 in.) thick. This is approximately equal to λ_o/25 at 240 MHz. Fig. 5 shows the A145 antenna covered by a radome. The dimensions are now 0.46 m x 0.46 m x 0.05 m (18 in. x 18 in. x 2.0 in.)

Again the cavity is partially loaded with Metaferrite material underneath the dipole arms with the dominant axis of $\underline{\boldsymbol{\mu}}_r$ aligned with the direction of the magnetic field in the cavity. However because we now have 2 dipoles producing orthogonal fields, the orientation of the Metaferrite under the vertical arms and horizontal arms is rotated 90º with respect to each other. The Metaferrite tensors under the horizontal arms have the values μ_x=50, μ_y=1, μ_z=1, ε_x=100, ε_y=16, and ε_z=3.4. The Metaferrite tensors under the vertical arms have the values μ_x=1, μ_y=50, μ_z=1, ε_x=16, ε_y=100, and ε_z=3.4. The loss tangent of the dominant $\underline{\underline{\mu}}_r$ axis varies from 0.05 to 0.2 across frequency while the other 5 tensor components have a loss tangent on the order of 0.02 or less.

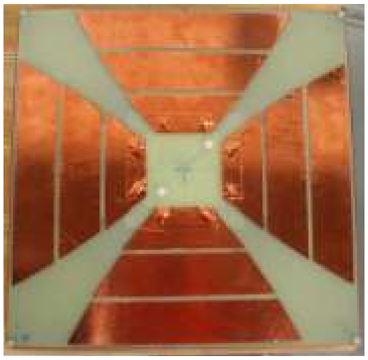

Fig. 4. Top view of the low profile, cavity backed A145 antenna. (Figure courtesy of Metamaterials, Inc. – Austin, TX)

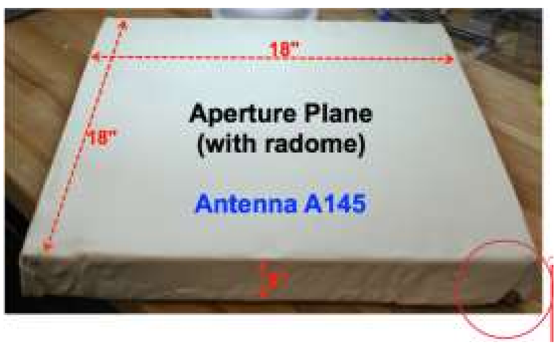

Fig. 5. Perspective view of the low profile, cavity backed A145 antenna. (Figure courtesy of Metamaterials, Inc. – Austin, TX)

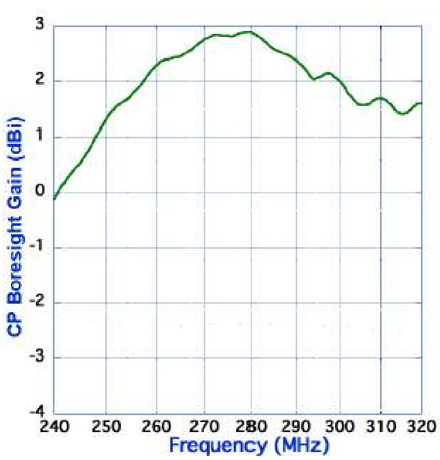

Fig. 6. Measured realized gain versus frequency at antenna broadside. (Figure courtesy of Metamaterials, Inc. – Austin, TX)

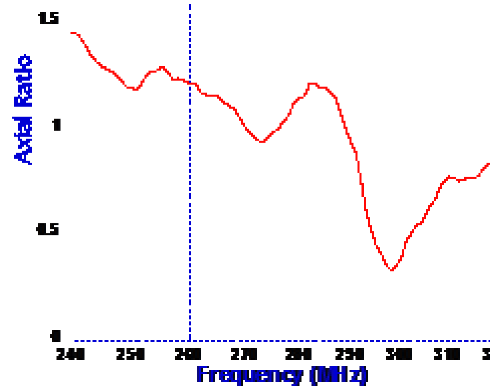

Fig. 7. Axial ratio versus frequency at antenna broadside. (Figure courtesy of Metamaterials, Inc. – Austin, TX)

Fig. 6 shows the realized gain to broadside of the A145 antenna versus frequency. These measurements were made in an anechoic chamber by JEMS Engineering. We see a slightly reduced performance to the A133 from 240 MHz to 320 MHz. Fig. 7 shows the measured axial ratio of the A145 antenna. In order, to maintain communication with a satellite a 3.0 dB or lower axial ratio is required. We see that the A145 antenna maintains a good axial ratio between 0 dB to 1.5 dB across the required frequency range.

III. Anisotropic Transverse Resonance

In a parallel effort, ARL also initiated a study into anisotropic electromagnetic theory to gain a better understanding of how anisotropic media might be best utilized in a cavity backed antenna to provide wideband performance. As a result, we developed a theory of anisotropic transverse resonance for a partially filled rectangular cavity. By maintaining a constant resonance within the cavity at a given frequency, we show that we can achieve a voltage standing wave ratio (VSWR) of better than 2:1 and a realized gain of 4.0 dB to 8.0 dB from 200 MHz to 500 MHz. Furthermore, we gain insight into what tensor values are the most important and how their interaction varies the performance of a cavity backed LPA. We note that this technique was not utilized by Metamaterials Inc. in the design of the A133 or the A145 LPAs. Furthermore, we present the most interesting results here, but more detailed derivations and designs are given by Mitchell and Wasylkiwskyj in references [4] and [5].

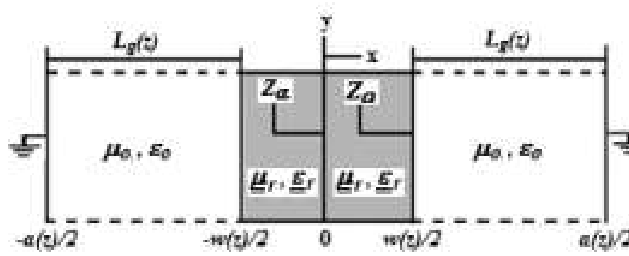

Fig. 8. Transmission line representation of a partially loaded rectangular cavity bounded by two perfectly conducting walls at $x = +/- a(z)/2$ [5].

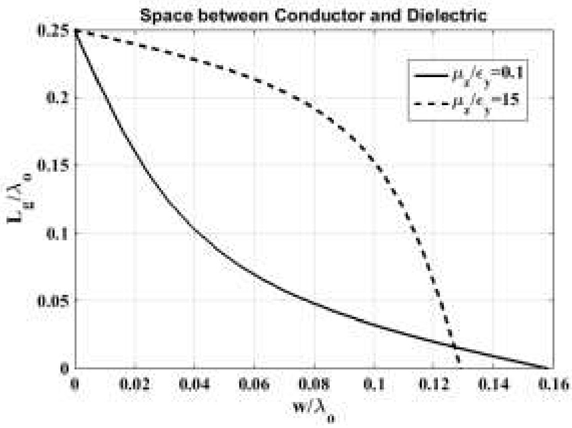

Fig. 9. Plot of the taper defined by the relationship of L_g versus w given by equation (5) [4-5].

Fig. 8 shows a transmission line representation of a partially filled rectangular cavity. The short circuits at either end represent the metallic walls of the cavity where the electric field goes to zero. Furthermore, if $2*L_g+w=a$, then $a=\lambda_{eff}/2$, where λ_{eff} is the effective wavelength at the frequency of resonance, w is the width of the anisotropic medium inside of the cavity, and L_g is the air-filled space between the anisotropic medium and the cavity wall. By implementing the anisotropic time harmonic representation of Maxwell's equations

$$\nabla \times \underline{E} = -j\omega\mu_o \underline{\underline{\mu_r}} \cdot \underline{H}\ , \quad (3)$$

$$\nabla \times \underline{H} = j\omega\varepsilon_o \underline{\underline{\varepsilon_r}} \cdot \underline{E}\ , \quad (4)$$

Mitchell and Wasylkiwskyj show that the relationship between L_g and w that maintains a constant frequency of resonance within the cavity is given by [4-5]

$$\frac{L_g}{\lambda_o} = \frac{1}{2\pi}\tan^{-1}\left[\frac{\sqrt{\mu_z/\varepsilon_y}}{\tan\left(\pi w\sqrt{\mu_z\varepsilon_y}/\lambda_o\right)}\right]. \quad (5)$$

Equation (5) shows that for the particular orientation of Fig. 8 the transverse resonance of the cavity is determined solely by the frequency of resonance, μ_z, and ε_y. This means we are free to optimize the other 4 tensor elements to improve the performance of the antenna without affecting the frequency of resonance. Fig. 9 shows the relationship between L_g and w. Take note that as we vary the width of the anisotropic medium in the cavity, the shape of the cavity walls must correspondingly taper to maintain resonance. This tapering is proportional to the ratio of μ_z to ε_y.

A. Tapered Cavity Antenna

Based on equation (5), we can design a tapered cavity, partially loaded with an anisotropic medium that maintains a constant transverse resonance. This is turn will provide a stable impedance match over at least the first octave of bandwidth above resonance. For this section we make some idealized assumptions about our anisotropic medium such as $\varepsilon_x=\varepsilon_y=\varepsilon_z=1.0$ and that both $\underline{\underline{\varepsilon_r}}$ and $\underline{\underline{\mu_r}}$ are lossless. Our $\underline{\underline{\mu_r}}$ values are $\mu_x=15$, $\mu_y=1$, $\mu_z=15$.

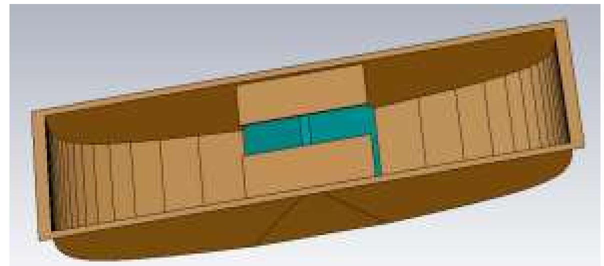

Fig. 10. Tapered cavity antenna based on the anisotropic transverse resonance equation *(patent pending)* [5].

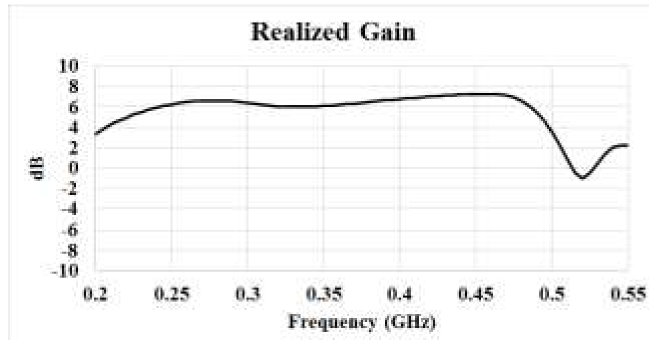

Fig. 11. Simulated realized gain to boresight versus frequency plot for the antenna model shown in Fig. 10 [5].

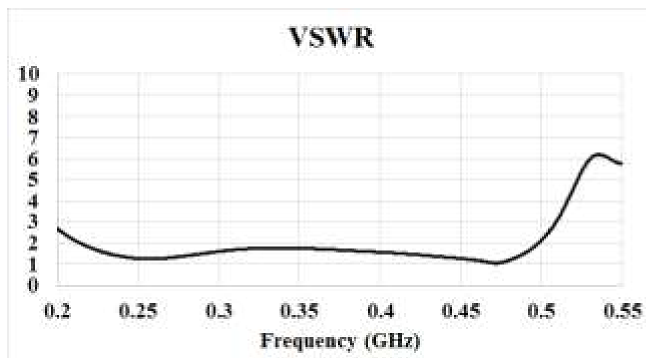

Fig. 12. Simulated VSWR versus frequency plot for the antenna model shown in Fig. 10 [5]. [5]

Fig. 10 shows how the bold solid curve in Fig. 9 corresponds to the tapered cavity of Fig. 10. The anisotropic medium is linearly tapered. Note that we have increased the value of μ_x to 15 since the magnetic field in the cavity is oriented in that direction. We feed the cavity with two rectangular probes that act to tune the impedance seen at the two input ports. These two ports are fed 180° out of phase. The cavity opening acts as the radiator and the dimensions of the antenna are $0.5\lambda_o$ x $0.22\lambda_o$ x $0.04\lambda_o$ at 200 MHz. The normalized depth corresponds to 83.82 mm (3.3 in.).

Fig. 11 shows the realized gain to broadside versus frequency. We see a much flatter gain curve in this case than in Fig. 3 or Fig. 6. The gain varies from 3.3 dB to 7.2 dB from 210 MHz to 505 MHz, but for the majority of this bandwidth the realized gain stays within 6.0 dB to 7.0 dB. The flatness of this realized gain corresponds to the flatness of the VSWR curve in Fig. 12. We see that the VSWR stays below 2:1 over this bandwidth as well. The stability of the VSWR curve can be attributed to the constancy of the transverse resonance within the cavity which is established by equation (5).

IV. CONCLUSIONS

This paper gives an overview of metamaterial work undertaken at ARL over the last several years. Specifically, the focus has been on low profile and wideband antennas that utilize Metaferrites as the enabling technology. Two prototypes that were designed and fabricated for ARL by Metamaterials Inc. shows positive realized gain from 210 MHz to 500 MHz for a cavity backed slotted bowtie antenna with a profile of $\lambda_o/40$ and a RHCP tactical satellite antenna from 240 MHz to 320 MHz with a profile of $\lambda_o/30$. We also show a novel tapered cavity design method to maintain a constant resonance in a partially loaded anisotropic cavity. This technique yields a very high and stable realized gain for a cavity profile of $\lambda_o/25$.

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