An Efficient, Low Profile, Electrically Small, VHF 3D Magnetic EZ Antenna

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A very high frequency (VHF) version of the electrically small, coax-fed, three-dimensional (3D) magnetic EZ antenna was designed and tested. The fabricated antenna was formed by integrating a capacitively-loaded loop (CLL) element with a coaxially-fed, electrically small, semi-circular loop antenna. This low profile antenna (height $\sim \lambda/25$) had an electrical size that was $ka \sim 0.46$ at 105.2 MHz (where $a$ is the radius of an imaginary hemisphere inclosing the antenna). Nearly complete matching to the 50 Ω source and a high overall efficiency (nearly 95 %) were achieved.
Artificial materials are designed and constructed to have desired, but unusual electromagnetic properties that are not generally available in nature. The emergence of metamaterials (MTMs) and their applications for the design of electrically small antennas (ESAs) has provided an engineering methodology to achieve matching, high overall efficiencies, and low Q values. Analytical studies of MTM-engineered electrically small antennas have been reported recently [1]-[4]. It has been demonstrated that a properly-designed homogeneous, isotropic, dispersive spherical shell which surrounds an electrically small antenna can achieve a radiating system that has nearly complete impedance matching to the source and high overall efficiency. More specifically, they were achieved by surrounding small electric or magnetic dipole radiating elements with an ENG (epsilon-negative) or MNG (mu-negative) spherical shell. Moreover, it has been demonstrated that the metamaterial shell acts as a near-field resonant parasitic (NFRP) element, which can be replaced, in essence, by one unit cell of the appropriate metamaterial [5].

Several fabricated and tested variations of a 300 MHz version of the three dimensional (3D) magnetic EZ (easy) antenna [5] have been reported [6]. The 3D magnetic EZ antenna is composed of an electrically small loop antenna that is coaxially-fed through a finite ground plane and that is integrated with an extruded capacitively loaded loop (CLL) element. This 3D CLL structure is designed to be the NFRP element. The measured results for the 3D magnetic EZ antenna demonstrated that for an electrical size, $ka \sim 0.43$, at 300.96 MHz, nearly complete matching to the 50 $\Omega$ source, and a high overall efficiency, i.e., the ratio of the total radiated power to the total input power, was achieved ($> 94\%$). These results and those in [5] demonstrate that CLL-based elements can work from the UHF band to the X band. While negative permeability can not be ascribed to the CLL element itself, it is the inclusion of one unit
cell in an MNG metamaterial. Nonetheless, it is the electrically small NFRP CLL structure that provides the ability to match the electrically small loop antenna to the source. It also enhances the radiation process to achieve high radiation efficiencies. In particular, the CLL element can be engineered to control the strong magnetic flux generated by the small driven loop antenna and convert it into the appropriate currents flowing on the CLL element. Furthermore, this magnetic coupling process between the driven loop and the NFRP CLL element can be adjusted to tune the resonance of the entire antenna system, i.e., with the resonance frequency of the antenna being 
\[ f_{\text{res}} = \frac{1}{(2\pi) \sqrt{L_{\text{eff}} C_{\text{eff}}}} \], its effective inductance \( L_{\text{eff}} \) is determined primarily by the driven loop and the effective capacitance \( C_{\text{eff}} \) is determined primarily by the CLL element [5], [6].

It was desirable to move the magnetic EZ antennas to lower frequencies for several applications. In this paper, we report the design, fabrication and testing of a 3D magnetic EZ antenna at 100 MHz and provide the design for an even lower frequency, 20 MHz. These types of metamaterial-engineered antennas help overcome the loss issues associated with an actual metamaterial-based antenna design [7].

The proposed VHF 3D magnetic EZ antenna is shown in Fig. 1. It is a low profile design, i.e., at its design frequency, 100 MHz, the height 118 mm = \( \lambda/25.4 \). We used the finite element modeling software, ANSOFT’s High Frequency Structure Simulator (HFSS™) for all of the simulations (mention of this product is not an endorsement, but only serves to clarify the software used). Real copper values were used in those simulations, i.e., the conductivity \( \sigma = 5.8 \times 10^7 \) Siemens/m. While the actual antenna with its small ground plane is shown in Fig. 1(c), the ground plane size for the simulations was fixed by the HFSS requirement that the radiation
box walls be a quarter-wavelength (for the lowest frequency considered) away from the radiating elements. A quartz slab was inserted into the capacitive gap region of the parasitic CLL element. The selection of quartz as the dielectric material is not only for its high dielectric constant value (real part of the relative permittivity, $\varepsilon_r = 3.78$) to increase the effective capacitance of the CLL element, but also for its low dielectric loss tangent ($1 \times 10^{-4}$). This choice of quartz for the spacer thus lowers the resonance frequency with little impact on the overall efficiency of the radiating system. It also provides structural stability in the fabricated system [6]. Other low-loss dielectrics could be used as the gap spacer to achieve different resonance frequencies. The resonance frequency can also be changed further by adjusting the stub height or the gap length for a fixed slab permittivity in order to tune the effective capacitance. The antenna, as fabricated by Boeing Research and Technology in Seattle, is shown in Fig. 1(c).

A comparison of the measured and HFSS-predicted values of $|S_{11}|$ for the antenna shown in Fig. 1 is given in Fig. 2. The predicted resonance frequency was $f_{\text{res}} = 100.2$ MHz, while the measured value was $f_{\text{res}} = 105.2$ MHz, where $|S_{11}| = -18.8$ dB. The slight upshift in the resonance frequency is due to the smaller ground plane size of the measured antenna (the simulation assume a infinite large ground plane). The measured radiation efficiency values as a function of the frequency are shown in Fig. 3. The measured results presented in Figs. 2 and 3 were obtained in the reverberation chamber at NIST, Boulder. The NIST chamber used two rotating paddles in order to reduce the uncertainties in the measurements to 1.0 dB or less. Similar measurements for another antenna are discussed in [6]. A log-periodic dipole array antenna was used as the reference; the relative radiation efficiency of the 3D magnetic EZ antenna was measured. The values shown in Fig. 3 were then generated by taking into account the accepted power values for
each antenna, The measured radiation efficiency was approximately 95% at \( f_{\text{res}} = 105.2 \text{ MHz} \) (this efficiency number is an approximation and the uncertainty is still being evaluated). At that resonance frequency one has \( ka = 0.46 \); the measured fractional bandwidth (based on the half-power VSWR bandwidth) was 1.52 % and the corresponding Q ratio was \( Q_{\text{ratio}} = Q/Q_{\text{lb}} = 11.06 \), where the lower bound on \( Q, Q_{\text{lb}} \), equals the radiation efficiency times the Chu lower bound [8], [9]. The gain patterns are shown in Fig. 4(a); the maximum gain value was 5.94 dB. Because the gain patterns are symmetric, it is immediately inferred that the surface currents induced on the electrically small cylindrical CLL element by the flux of the driven semi-loop antenna are uniform and symmetric. This behavior is verified with the HFSS-predicted vector surface current distributions shown in Fig. 4(b). This current distribution also demonstrates that this electrically small antenna system is radiating as a magnetic dipole over a finite ground plane.

One can scale the 3D magnetic EZ antenna design to other frequencies simply by changing the effective capacitance and inductance values. The simplest way to change the resonant frequencies without altering the physical dimensions is by varying the \( C_{\text{eff}} \) values. In particular, the effective capacitance of the CLL element can be varied simply by changing the spacer in the capacitive gap. To illustrate this potential, we replace the quartz spacer with a K-100 dielectric material which has high dielectric constant value (real part of the relative permittivity, \( \varepsilon_r = 100 \)) and low dielectric loss tangent (9×10^{-4}). One would then expect the resonant frequency to be around 20 MHz since the ratio of the relative permittivity between the quartz and K-100 is about 26.4. The HFSS-predicted \(|S_{11}|\) values and gain patterns for this antenna are given in Fig 5. The resonance frequency was 22.86 MHz where the minimum \(|S_{11}| = -32.8 \text{ dB} \). The predicted overall efficiency and fractional bandwidth were, respectively, 11% and 0.25%. The reason why the
overall efficiency drops to the lower value is because we did not change the physical size of the antenna and only replaced the quartz with the K-100 material. The electrical size is now much smaller, i.e., \( k\alpha = 0.1 \) at 22.86 MHz. To illustrate this size dependence of the radiation efficiency, the HFSS-predicted radiation efficiencies versus \( k\alpha \) values are presented in Fig. 6. For \( k\alpha \) values at and slightly below 0.4, the radiation efficiency remains in excess of 90%. However, it diminishes quickly and goes below 10\% when the \( k\alpha \) value was decreased below 0.1. This behavior was expected because we know that the radiation resistance of a small loop antenna with \( kr_\ell < 0.5 \) is proportional to \( (kr_\ell)^4 \) [10], where \( r_\ell \) is the radius of the loop. Consequently, if one would like to have a high radiation efficiency EZ antenna, the simplest way is to increase the \( k\alpha \) value in order to obtain the desired radiation efficiency. Note that one can obtain straightforwardly an electrically small antenna working even in the high frequency (HF) band or even at lower frequencies that has a high radiation efficiency by utilizing this design concept.

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REFERENCES


Fig. 1. Detailed design specifications of the 3D magnetic EZ antenna. (a) XZ plane; (b) XY plane. All dimensions are in mm: W = 116.25, G = 4.5, H1 = 118, H2=11, R1 = 1, R2 = 1.016, T=1.016, R_{wire}=1, R_{antenna}=54, and D=250. (c) The fabricated 3D magnetic EZ antenna.

Fig. 2. Measured and simulated values of $|S_{11}|$ for the 3D magnetic EZ antenna.
Fig. 3. Measured radiation efficiency for the 3D magnetic EZ antenna.
Fig. 4. (a) Simulated gain patterns (in dB) in the yz-and xz-planes, (b) simulated vector current distribution at 100.2 MHz for the 3D magnetic EZ antenna.

Fig. 5. HFSS-predicted $|S_{11}|$ values and gain patterns at 22.86 MHz.
Fig. 6. Radiation efficiency versus ka values for the 3D magnetic EZ antenna with the K-100 spacer in the capacitive gap of the CLL element.