constructed and measured. These very small antennas (λ/5 per λ/9 at low frequency limit) present good radiation performances over bandwidth larger than 115% whatever feeding access is used. These capabilities associated with low production cost, easy integration, and principal feeding line compliance make them good candidates for applications in future UWB systems operating at low frequencies.

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AN EFFICIENT METAMATERIAL-INSPIRED ELECTRICALLY-SMALL ANTENNA

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ABSTRACT: *This article presents an inexpensive, efficient, and electrically-small antenna design that is based on a metamaterial-inspired structure driven by an electrically-small semi-circular loop antenna, which is coaxially-fed through a finite ground plane. The proposed antenna system is linearly scalable over a wide frequency spectrum. The design details and radiation characteristics of the antenna system at 300, 1580, and 6000 MHz are reported.* © 2007 Wiley Periodicals, Inc. Microwave Opt Technol Lett 49: 1287–1290, 2007; Published online in Wiley InterScience (www.interscience.wiley.com). DOI 10.1002/mop.22415

Key words: *metamaterials; electrically small antennas; loop antennas; antenna theory*

1. INTRODUCTION

Recent technological advances in wireless communications and sensor networks have changed the expectations of antenna designs and their performance. The size reduction of state-of-the-art electronic circuits has led to many wireless applications that have conflicting requirements for their antenna systems. In particular, they have exposed the need for electrically-small antennas that are efficient and have significant bandwidths. These requirements, however, are contradictory when standard electrically-small antenna designs are considered, i.e., these radiators are known to be inefficient because they have very large reactances and small resistances and, hence, are very poorly matched to a given source. The design of reactance and resistive matching networks is a challenging task that often introduces additional constraints on the overall performance of the resulting system. An inexpensive, easy to build, efficient, and electrically-small antenna system, that is naturally matched to a source and could be scaled to a wide range of frequencies without any compromise in its performance, would be ideal for many wireless applications.

The introduction of the so-called metamaterials (MTMs), artificial materials that have engineered electromagnetic responses that are not readily available in nature, has provided an alternate design approach that has led to improved performance characteristics of several radiating and scattering systems [1]. Examples include artificial magnetic conductors (AMCs), sub-wavelength resolution lenses, and metamaterial-based electrically-small antennas. These MTM-based antennas have been conceptualized with structures constructed from ideal double negative (DNG) or single negative (SNG) media. For instance, an electrically-small electric dipole and a loop antenna radiating in the presence of, respectively, an isotropic, homogenous lossless, and dispersive electrically-small epsilon negative (ENG) and a μ-negative (MNG) spherical shell have been shown theoretically to produce a radiating element that is impedance matched to a specified source to obtain an efficient electrically-small antenna system [2, 3]. The electrically-small ENG (MNG) metamaterial spherical shell provides the necessary capacitance (inductance) to produce the matching mechanism. The MTMs associated with these designs require unit cells whose sizes are highly sub-wavelength and must be even smaller than the radiating elements. Physical unit cell designs meeting these requirements have been considered.

This research work presents an efficient and electrically-small antenna system based on a three-dimensional (3D) structure that was inspired by these MTM unit cell designs. This element is designed to be resonantly driven by a semi-circular loop antenna fed through a finite-sized ground plane with a 50 Ω coax feedline. The resulting antenna system is naturally matched to the source and acts as a resonant electrically-small magnetic dipole. The performance of this antenna system is characterized with Ansoft's High Frequency Structure Simulator (HFSS).

2. THEORY AND ANALYSIS

The metamaterials (MTM)-inspired element is a 3D extrusion of a planar capacitively loaded loop (CLL) that was previously used as the unit cell inclusion to realize a volumetric artificial magnetic conductor (AMC), which was the enabling technology for a low-profile antenna with interesting operating characteristics [4]. The design specifications of the proposed easy-to-build, efficient, electrically-small antenna with its metamaterial inspired matching/radiating element, the EZ antenna, are illustrated in Figure 1 and are summarized in Tables 1 and 2. The extended capacitive element provides a larger capacitance which allows the resulting CLL to have a lower resonant frequency and finer tuning capability. Moreover, the extended surface provides an effective region that efficiently captures and resonantly magnifies the magnetic flux generated by the electrically-small semi-circular loop antenna that is driving it. The changes in time of this resonantly-large magnetic flux create the induced currents on the extruded CLL structure and produce correspondingly large electric fields across the capacitor gap. These strong electric fields create a capacitance in the system that is sufficiently large to match both the inductance due to the current path formed by the extruded CLL structure and the ground plane, and the inductance of the electrically-small semi-circular loop antenna. Thus, the extruded electrically-small CLL structure is a self-resonant reactive element that can be further matched to the reactance part of the electrically small semi-loop circular

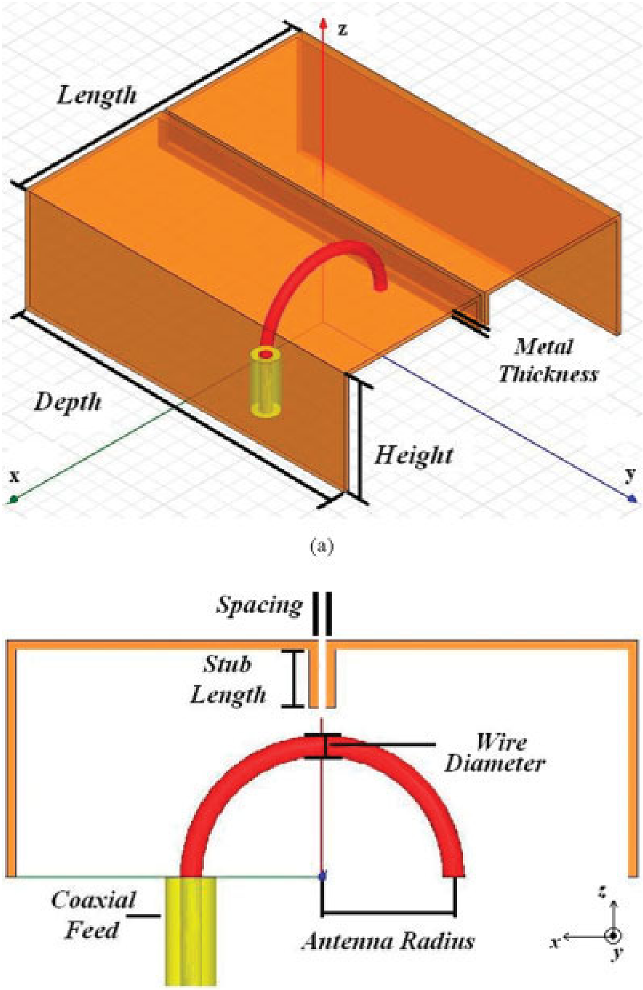

Figure 1 EZ antenna geometry and detailed specifications of each design variable. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

TABLE 1 EZ Antenna Resonant Frequency Specifications, Wire Loop Details, and Ground Plane Dimensions

	Design Frequency (MHz)	Loop Antenna Radius (mm)	Metal Wire Radius (mm)	Ground Plane ($x \times y$) (mm^2)
Design 1[a]	300	1.9	0.3	520 × 520
Design 2	300	2.8	0.3	520 × 520
Design 3	1580	3.1	0.3	135 × 135
Design 4	6000	0.8	0.07	30.34 × 30.34

[a] The copper conductivity value for this design assumed to be 5.8E17 Simens/m.

antenna to create a resonant RLC tank circuit. The bend radius (taking the wire to be electrically-thin) of the semi-circular loop plays a major role in our ability to tailor the resistance of the radiating element to match it to the feedline, thus achieving a resonant behavior of the overall system. In particular, increasing the radius of the semi-circular loop enhances the resonant coupling of the driving antenna to the radiating extruded CLL element and thus, enhances the resulting radiation resistance of the system. The length and height (depth, stub length, and stub spacing) of the metamaterial-inspired element provides the major inductance (capacitance) of this antenna system. The thickness of the wire loop and the metal thickness contribute some to the inductance, but their overall effect to the system is very limited. They do, however, significantly impact the conductor losses in the system.

The HFSS model of the EZ antenna consists of three components: (a) a semi-circular loop copper wire antenna connected to the finite PEC ground plane and fed by a 50 Ohm coaxial-cable, (b) an extruded CLL copper structure with its two "J-sheets" being connected to the finite PEC ground plane and with a specified vacuum gap being uniformly held between the capacitor legs of these sheets, and (c) a vacuum radiation box that surrounds the antenna system. The default HFSS electrical properties were assigned for the copper. The radiation box for each design was created using a cube that is at least $\lambda/4$ distance away from the capacitive element per ANSOFT instructions, with one face of the cube being assigned as the finite PEC ground plane. This requirement fixes the size of the ground plane. Initial meshing was applied to improve the convergence of each simulation. The resultant average number of tetrahedra in the final iteration was about 70 K to achieve a simulation with good convergence behavior.

Tables 1 and 2 give the variable specifications of four different EZ antenna designs at three different frequencies: 300, 1580, and 6000 MHz. Table 3 summarizes the HFSS predicted radiation characteristics of these antenna systems. The half-power matched VSWR fractional bandwidth was used to compute the Q value each system at the resonance frequency $f_0 = \omega_0/2\pi$: i.e., $Q_{\mathrm{VSWR}}(\omega_0) = 2/\mathrm{FBW}_{\mathrm{VSWR}}(\omega_0)$ [5]. The ratio, Q_{ratio}, of this Q_{VSWR} value and the Chu limit value $Q_{\mathrm{Chu}} = 1/ka + 1/(ka)^3$, where a is the radius of the minimum enclosing sphere and $ka = \omega_0 a/c$, was obtained using $Q_{\mathrm{ratio}}(\omega_0) = 2/(\mathrm{FBW}_{\mathrm{VSWR}}(\omega_0) \times Q_{\mathrm{Chu}}(\omega_0) \times \eta)$, where c is the speed of light in vacuum and η is the radiation efficiency, respectively. The copper metal used in Design 1 was assumed to have a 5.8E17 Simens/m conductivity, i.e., to model essentially a perfect electric conductor in order to explore the performance of the EZ antenna under these ideal conditions.

The lossless metal 300 MHz scenario, Design 1, produced a perfect radiation efficiency with $ka = 0.11$, which confirms the physical realization of the earlier theoretical predictions [2] of a metamaterial-based electrically small antenna. With realistic metal losses, the radiation efficiency of the antenna system

TABLE 2 EZ Antenna Metamaterial Inspired Structure Dimensions at 300, 1580, and 6000 MHz

	Height Along z-Axis (mm)	Length Along y-Axis (mm)	Depth Along x-Axis (mm)	Spacing Along y-Axis (mm)	Stub Length Along z-Axis (mm)	Copper Metal Thickness (mm)
Design 1[a]	10	20	20	0.03	5.741	0.254
Design 2	10	20	20	0.03	5.76	0.254
Design 3	6.5	17.3	20	0.2	1.57	0.254
Design 4	1.625	4.34	5	0.05	0.459	0.0762

[a] The copper conductivity value for this design assumed to be 5.8E17 Simens/m.

TABLE 3 **Summary of the EZ Antenna Radiation Characteristics at 300, 1580, and 6000 MHz**[b]

	$F_{resonant}$ (MHz)	*ka*	FBW_{VSWR}(%)	Q_{ratio}	AP (W)	RE (%)	OE (%)	*D*
Design 1[a]	299.69	0.11	0.0123	20.5	1	100	100	2.68
Design 2	299.97	0.11	0.0643	21.1	0.9969	18.73	18.67	2.68
Design 3	1580	0.49	0.6834	28.3	0.9998	96.97	96.95	3.70
Design 4	5997	0.46	0.6735	26.2	0.9939	92.67	92.10	3.16

[a] The copper conductivity value for this design assumed to be 5.8E17 Siemens/m.
[b] *ka*, Maximum electrical size of the antenna system; AP, Accepted Power; RE, Radiation Efficiency; OE, Overall Efficiency; and D, Directivity.

decreases as the ka values decrease from the electrically-small antenna limit, $ka = 0.5$ to zero. A comparison of the Q values of each antenna design reveals that the amount of energy stored in the designed element to provide the necessary capacitance depends on the ka value of the system. As the *ka* value approaches zero, the reactance of the loop antenna also approaches zero. This loop antenna behavior leads to less stored energy being required to provide the requisite matching capacitance [6]. On the other hand, as the *ka* value approaches the 0.5 limit, the reactance of the loop antenna gets more inductive and the antenna system needs to store more energy. A comparison of Designs 3 and 4 clearly shows that the design frequency and component dimension ratio are almost identical. The EZ antenna can be linearly scaled to any desired frequency. We have

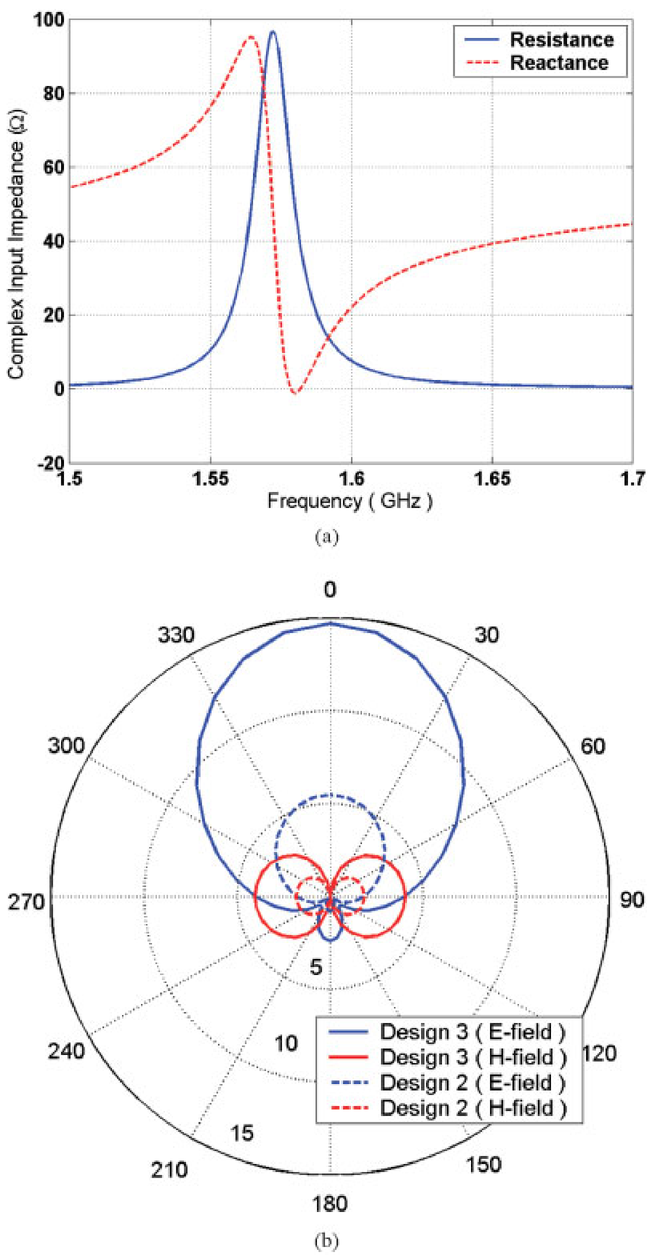

Figure 2 (a) Complex input impedance values for Design 3, and (b) far-field E- and H-field patterns comparisons for Design 2 and Design 3. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

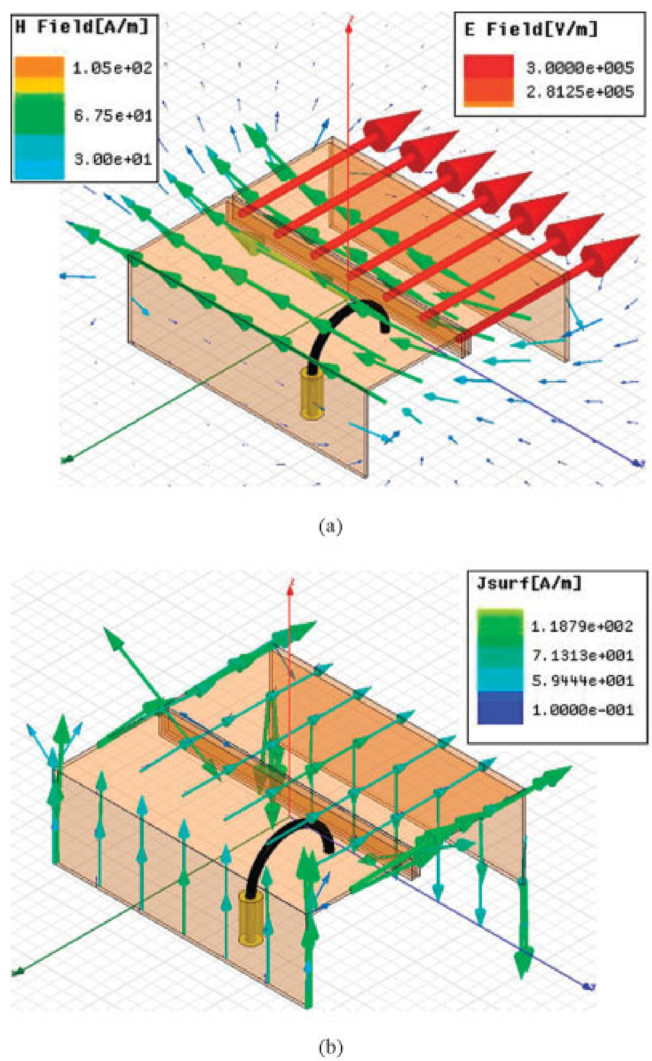

Figure 3 (a) E- and H-field vector plots and (b) magnitude of the surface current vectors on the metamaterial-inspired structure obtained from Design 3 at 1580 MHz. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

achieved this scaled design at 300 MHz as well; however, we choose to report the smaller *ka* design at this frequency to allow a direct connection between these results and those reported in Refs. 2 and 3. The differences between Designs 1 and 2 show that the copper losses significantly impact the radiation efficiency of this resonant system. The performance of the scaled limit case at 300 MHz is essentially the same as its higher frequency versions. The overall efficiencies of these electrically-small-limit systems are very high. The complex input impedance behavior and the far-field radiation patterns for the GPS-frequency Design 3 are shown in Figure 2. The resistance and reactance curves in Figure 2(a) exhibit characteristics analogous to the anti-resonant behavior of an electrically-small circular loop (i.e., a magnetic dipole) antenna [5, 6]. In particular, it is clear from Figure 2(a) that the EZ antenna is anti-resonant and matched to the feedline at the source frequency. Figure 2(b) also demonstrates that the EZ antenna is acting like a magnetic dipole over a PEC ground plane. Figure 3 shows the E-and H-field vector plots using *xy*-plane cuts in the stub and just above the semi-circular loop antenna, respectively, and the current vector plots on the metamaterial-inspired structure. From Figs.3(a) and 3(b), one clearly sees that the metamaterial-inspired radiating structure is acting like a uniformly extruded CLL element.

3. CONCLUSIONS

This research work introduced an efficient electrically-small antenna design methodology in which a self-resonant capacitive structure that is driven by an electrically-small semi-circular loop antenna coaxially-fed through a finite ground plane was obtained. These designs realized an inexpensive, easy-to-build, efficient, and electrically-small antenna. The proposed antenna system is linearly scalable to a wide range of frequencies. The overall efficiency of the antenna system depends on the choice of overall electrical size. Highly electrically-small versions exhibit large conductor losses because of their resonant nature. The type of metal used for the designs can be selected to improve this characteristic. Electrically-small-limit versions were shown to be highly efficient. Preliminary proof-of-concept experiments have confirmed these results and will be reported elsewhere.

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SPATIAL DIVERSITY ANTENNA FOR WLAN APPLICATION

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ABSTRACT: *This article presents a novel printed diversity planar monopole antenna integrated on a PCMCIA network card with minimized the mutual coupling for WLAN application at the 5 GHz bands (5150–5350 and 5725–5875 MHz). The proposed diversity antenna is printed on FR-4 substrate and small size enough to be embedded in the laptop computer. Optimizing the separation distance and antenna parameters with use of two slots on a ground, the good isolation performance (less than −20 dB) between the two printed monopole antennas is achieved. The proposed diversity antenna has an impedance bandwidth of 2360 MHz ranging from 4520 to 6889 MHz ($S_{11} < -10$ dB). There is a good agreement between the simulated and measured results.* © 2007 Wiley Periodicals, Inc. Microwave Opt Technol Lett 49: 1290–1294, 2007; Published online in Wiley InterScience (www.interscience.wiley.com). DOI 10.1002/mop.22414

Key words: *spatial diversity antenna; WLAN application; slots*

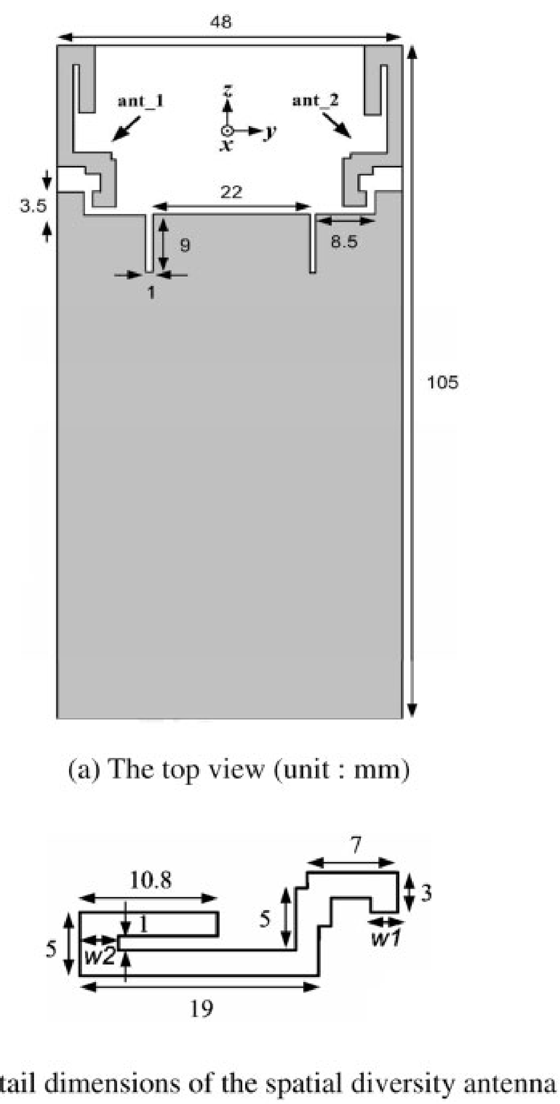

Figure 1 Configuration of the proposed spatial diversity antenna (a) The top view (unit : mm) (b) Detail dimensions of the spatial diversity antenna