Embedded-Circuit and RIS Meta-Substrates for Novel Antenna Designs

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1. Abstract: Antenna miniaturization with enhanced radiation performance is a contemporary problem with application in RF and wireless systems. The substrate and ground plane of antenna play a very important role in achieving the desired antenna characteristics. The focus in this paper is to present the applications of two types of meta-substrates for novel antenna designs, namely, Embedded-Circuit Meta-material (ECM) and Reactive Impedance Surface (RIS) substrates. ECM provides a way to fabricate an ε-μ substrate, allows antenna miniaturization with relatively high bandwidth and efficiency. Also, a novel compact RIS as the ground plane for a dual-band E-shaped patch/slot antenna is proposed to reduce the interaction of antenna with its ground and design a miniaturized wideband antenna system.

2. Magneto-Dielectric Embedded-Circuit Medium: Antenna miniaturization using high permittivity materials as substrate has been attempted in the past [1]. Although miniaturization can be achieved using high dielectric materials, there are two drawbacks. One problem stems from the fact that the field remains highly concentrated around the high permittivity region (field confinement), which results in low antenna efficiency and narrowband characteristics. The second drawback pertains to the fact that the characteristic impedance in a high permittivity medium is rather low which creates difficulties in impedance matching of the antenna. These aforementioned problems can be effectively circumvented if one uses a magneto-dielectric material. Magneto-dielectric materials can also miniaturize the antenna by the same factor however using moderate values of permittivity and permeability ($n=\sqrt{\mu_r \varepsilon_r}$). Therefore, the issue of strong field confinement is minimized and the medium is far less capacitive when compared to the dielectric-only high permittivity material. Furthermore, since the characteristic impedance of magneto-dielectric medium ($\eta=\eta_0\sqrt{\mu_r/\varepsilon_r}$) is close to that of the surrounding medium (η_0) it allows for ease of impedance matching over a much wider bandwidth.

It has been shown by Hansen and Burke [2], that the zero-order bandwidth for an antenna over a magneto-dielectric substrate with thickness t can be approximated by

$$BW \approx \frac{96\sqrt{\mu_r/\varepsilon_r}\; t/\lambda_0}{\sqrt{2}\,[4+17\sqrt{\mu_r \varepsilon_r}\,]}\,. \tag{1}$$

Thus for a given miniaturization factor (constant $\sqrt{\mu_r \varepsilon_r}$) the antenna bandwidth can be enhanced by increasing μ_r/ε_r ($\mu_r > \varepsilon_r$). However, the main engineering question is that "*how one can obtain a magnetic material with relatively large permeability*'. Basically, the naturally available magnetic materials operate only up to lower UHF band.

It was demonstrated in [3] that a periodic structure of high Q resonant tank circuits embedded in a low permittivity dielectric material has the potential to successfully obtain an ε-μ medium at any frequency of interest. In this work we design a compact embedded-circuit structure which is constructed of miniaturized tank circuits made up a wire loop and an interdigated capacitor (see Fig. 1). A unit cell transmission line model of the structure is shown in Fig. 1(b). The magnetic flux linking the transmission line induces a current in the loops in a direction so that the magnetic flux generated by the loops would oppose the transmission line magnetic flux and thus presents an effective magnetic behavior. In addition, the coupling capacitors existing between the wire loops and the conductor of transmission line significantly affect the dielectric property of the background material and produce an effective permittivity. The equivalent circuit model of the

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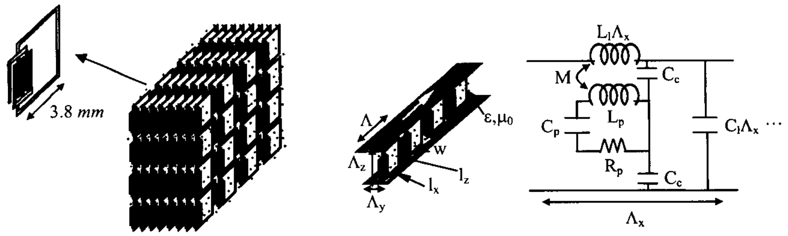
transmission line analogy of embedded-circuit structure is shown in Fig. 1(b). It is obtained from the circuit model that the ECM offers the following effective permeability and permittivity [3]:



(a) (b)

Fig. 1. Embedded-Circuit Meta-material (ECM), (a) 4-Layered periodic structure, (b) Transmission line analogy and its equivalent circuit model.

$$\mu_{eff} = \mu_0\left(1-\kappa^2\frac{1}{1-\omega_p{}^2/\omega^2 - j/Q}\right) \quad , \quad \varepsilon_{eff} = \varepsilon\left[1+\frac{\Lambda_z l_x}{\Lambda_x\Lambda_y}\frac{K(\sqrt{1-g^2})}{K(g)}\right], \tag{2}$$

where $\omega_p = 1/\sqrt{L_pC_p}$, $\kappa = M/\sqrt{(L_l\Lambda_x)L_p}$, $L_l = \mu_0\Lambda_z/\Lambda_y$, $L_p = \frac{\mu_0 l_x l_z}{\Lambda_y}$, $M = \frac{\mu_0 l_x l_z}{\Lambda_y}$,

$Q = \frac{\omega L_p}{R_p} = \frac{4l_xl_zw}{\Lambda_y(l_x+l_z)\delta}$, and C_p is the value of loop capacitor. Also, K is the complete elliptic integral function and $g = w/(w+h)$. The effective ε-μ of the medium is plotted in Fig. 2. Note that by controlling the interdigitated capacitors of the loops one can easily change the resonance frequency of structure and successfully tune the performance of material at any desired frequency.

As observed the embedded-circuit material shows the magnetic property in GHz range and thus can be used as the substrate for design of miniaturized antennas with enhanced characteristics in this range. Fig. 3 depicts the geometry of a patch antenna printed on the ECM substrate. A Finite Difference Time Domain (FDTD) technique [4] is applied to comprehensively investigate the interaction of antenna with its composite substrate and obtain the antenna return loss as shown in Fig. 3. The antenna operates at $f_0 = 2.28\,GHz$ and has the miniaturized size $0.075\,\lambda_0$ with a wide bandwidth of about $BW = 1.5\%$.

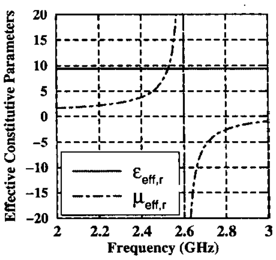


Fig. 2: Effective constitutive parameters of ECM.

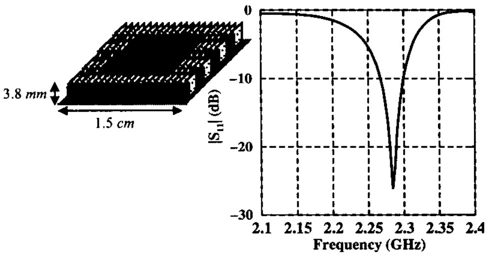


Fig. 3: Patch antenna on the ECM substrate and its return loss.

3. RIS for Compact Wideband E-Shaped Antenna Design: One of the well-known methods for designing a wideband antenna is to generate a multi-resonant characteristic with adjacent resonant frequencies. E-shaped antenna [5] is a typical example in this area that is constructed of a patch with two parallel slots incorporated into its geometry to achieve a dual resonance behavior (see Fig. 4). Fig. 5 shows the resonance performance of E-shaped patch/slot antenna. It is observed that the antenna provides a wide bandwidth of about 23 %. To fully investigate the effects of the patch and slots on the resonance characteristics of E-shaped antenna, surface current distributions at resonant frequencies 2.26 and 2.54 GHz are plotted in Fig. 6. It is illustrated that at the higher frequency ($f_0 = 2.54\,GHz$) the effect of slots are not very significant and the whole structure acts like a conventional patch and radiates. However, at the lower frequency ($f_0 = 2.26\,GHz$) the effect of slots are remarkably dominant. They cancel the contribution of patch in the middle of structure, and present strong surface currents at the edges of patch. Thus one can concludes that the patch controls the performance of antenna at higher resonant frequency and slots control its behavior at the lower resonant frequency.

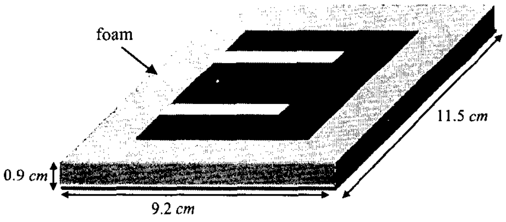


Fig. 4. E-Shaped patch/slot dual resonant antenna.

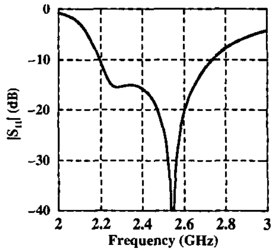
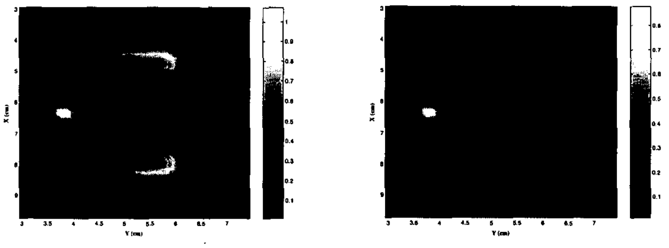


Fig. 5. Return loss of E-shaped antenna.



(a) (b)

Fig. 6. Surface current distribution of E-shaped patch/slot antenna at (a) lower resonant frequency 2.26 GHz and, (b) higher resonant frequency 2.54.GHz.

Although E-shaped antenna can present a wideband operation, it cannot be considered a miniaturized antenna. For a wireless system one needs to have a compact size in addition to the wide bandwidth characteristic. One way to reduce the size, as mentioned earlier, is to print the antenna on a high dielectric material. However, with this design there will exist a strong coupling between the antenna and the PEC ground plane which makes the antenna highly capacitive and thus matching becomes narrowband. To overcome these problems one may increase the substrate thickness, however this will increase the surface waves and degrades the antenna performance. In addition, matching the antenna is more difficult in this case. In recent years, use of PMC ground plane instead of PEC to enhance the antenna characteristics has been proposed, however, PMC also has a strong coupling with the antenna with similar problems that limits the bandwidth.

A Reactive Impedance Surface (RIS) with impedance property η=jv provides performance superior to PEC and PMC when it is used as the ground plane for antenna [6]. Basically, the image of a point source located above an RIS is a line with sinusoidal distribution and thus there is a minimum coupling between the source and its image. The coupling behavior as a function of surface impedance v/η_0 is illustrated in Fig. 7. It is clearly observed that the minimum coupling occurs for a surface with reactive impedance η=jv between the PEC and PMC planes.

To practically design an RIS, a periodic array of crossed dipole coupled through the interdigitated capacitors printed on a dielectric material backed PEC is proposed in Fig. 8(a). Note that the unit cell of structure has a miniaturized size. The FDTD with PBC/PML walls [4] is applied to characterize the structure. The reflection phase and impedance characteristics of the meta-surface are demonstrated in Figs. 8(b) and 8(c). The reflection coefficient from the RIS is equal to *1*. It is observed in Fig. 8(c) that the RIS shows inductive and capacitive behaviors below and above its resonance frequency. This unique property has the significant advantage for antenna miniaturization.

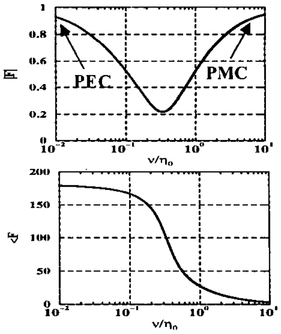
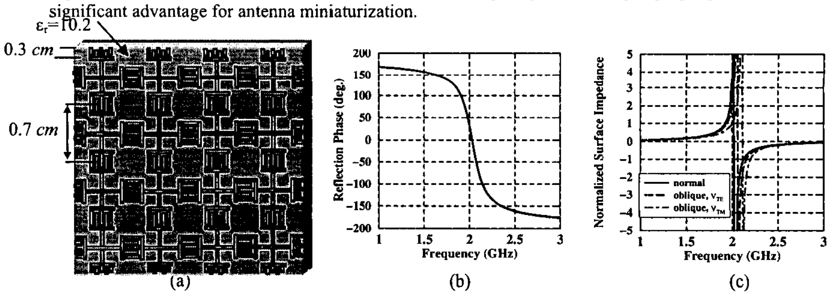


Fig. 7. Coupling between an infinitesimal dipole and impedance plane η=jv.



(a) (b) (c)

Fig. 8. Reactive Impedance surface, (a) Periodic structure, (b) Reflection phase, (c) Surface impedance.

Fig. 9 presents a compact E-shaped antenna printed over the RIS meta-substrate. Reactive impedance surface provides three desired characteristics: 1) total reflection power or enhancing the antenna front-to-back ratio, 2) reducing the interaction between the antenna and its ground plane and thus improving the bandwidth and efficiency, and 3) tuning the inductive property of surface with the capacitive behavior of antenna bellow its resonance and therefore miniaturizing the size. The whole size of antenna with its ground plane is about 2.8 cm and a relatively wide bandwidth of about 7 % between 1.74-1.88 GHz is provided.

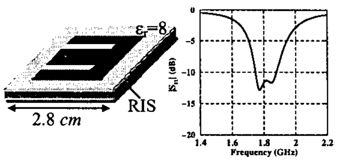


Fig. 9. E-shaped antenna over RIS.

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