ENGINEERED META-SUBSTRATES FOR ANTENNA MINIATURIZATION*

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Key Contributions: Antenna miniaturization with enhanced bandwidth and radiation characteristics is a very challenging task in wireless communication systems. The substrate of antenna plays a very important role in achieving the desired antenna parameters. The challenge in this paper is to introduce three types engineered meta-substrates for providing miniaturized antennas having superior performances. These meta-substrates are constructed from (1) magneto-dielectric, (2) embedded-circuit, and (3) reactive impedance surface (RIS) structures. They have the benefit of decreasing the interactions between the antenna and its ground plane and reducing the near field energy stored inside the substrate. Thus, utilizing these functional substrates, one can increase the radiation efficiency and obtain a highly efficient antenna with compact size and wideband characteristics.

MAGNETO-DIELECTRIC

Antenna miniaturization using high permittivity materials as substrates 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 ($\mu_r>\varepsilon_r$). The magneto-dielectric material that is used in this work is a Z-type hexaferrite recently fabricated by the researchers in Trans-Tech Inc.. It has $\varepsilon_r\approx\mu_r\approx 16$, and the dielectric and magnetic loss tangents of about 0.002 and 0.02, respectively. To obtain a magneto-dielectric meta-material with $\mu_r>\varepsilon_r$, a 1-D periodic configuration of dielectric ($\varepsilon_r=2.2$, loss tangent $tg\delta_l=0.001$) and the Z-type hexaferrite (same thicknesses) as shown in Fig. 1 is designed. A patch antenna printed on this engineered meta-substrate (Fig. 2) produces an electric field (E_z) perpendicular to the interface of the layers and a magnetic field (H_x) parallel to the interface. The composite substrate is anisotropic with effective permittivity equal to ε_e and effective permeability equal to μ_o estimated by [3]

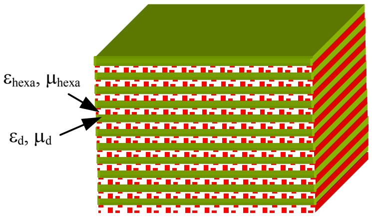

Fig. 1: Composite periodic dielectric and magneto-dielectric structure.

$$\frac{1}{\varepsilon_e}=\frac{1}{2}\left(\frac{1}{\varepsilon_d}+\frac{1}{\varepsilon_{hexaferrite}}\right) \quad , \quad \mu_o=\frac{1}{2}\left(\mu_d+\mu_{hexaferrite}\right). \tag{2}$$

Therefore, we can design $\mu_{or}>\varepsilon_{er}$. Using equal thickness for each layer, $\varepsilon_{er}=3.87$ and $\mu_{or}=8.50$ is obtained. This will provide a miniaturization factor greater than 5 with extremely enhanced antenna bandwidth as will be illustrated next.

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A patch antenna printed on the four layers dielectric and magneto-dielectric materials is depicted in Fig. 2. A Finite Difference Time Domain (FDTD) [4] full wave analysis is applied to characterize the structure. The return loss and radiation patterns are shown in Fig. 3. The antenna resonance is at $f_0 = 277\,MHz$ and it provides a wide bandwidth of about $BW = 3.2\,\%$. The size of the antenna is around $0.09\,\lambda_0$ with a miniaturization factor of 5.4. The directivity of the antenna is $D_0 = 2.9\,dB$ and it has a front-to-back ratio $1.3\,dB$. The antenna efficiency is about $e_r = 67\,\%$. Note that to achieve the same miniaturization factor utilizing only a dielectric material ($\mu_r = 1$) one must use $\varepsilon_r = 23.7$. This reduces the bandwidth to about $BW = 0.5\,\%$ as shown in Fig. 2(a). The efficiency in this case for a dielectric loss tangent of 0.001 is about $e_r = 64\,\%$.

Therefore, utilizing the magneto-dielectric meta-substrate one can offer a miniaturized wideband planar antenna with high efficiency. The antenna bandwidth for the proposed magneto-dielectric substrate is about 6 times higher than that of the dielectric substrate.

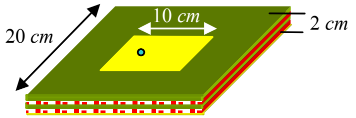
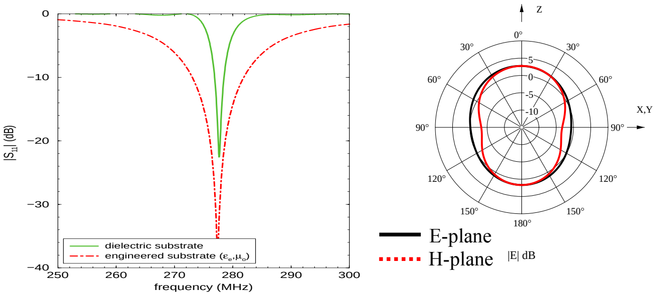


Fig. 2: Patch antenna over the engineered magneto-dielectric meta-substrate.



(a) (b)

Fig. 3: (a) Return loss, and (b) Radiation patterns of the patch antenna over magneto-dielectric meta-substrate.

EMBEDDED-CIRCUIT MEDIUM

It was demonstrated that utilizing a magneto-dielectric material one can noticeably enhance the antenna performance. However, the currently available magnetic materials operate only in the VHF-UHF range and to obtain a material with desired ε and μ at any frequency of interest a composite meta-material must be designed. To accomplish this, a periodic structure of high Q resonant loop circuits embedded in a low dielectric material is introduced in Fig. 4. A unit cell transmission line model of the structure is shown in Fig. 5(a). 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 present 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 transmission line analogy of embedded-circuit structure is shown in Fig. 5(b). It is obtained that the embedded-circuit meta-material offers the following effective permeability and permittivity [5]:

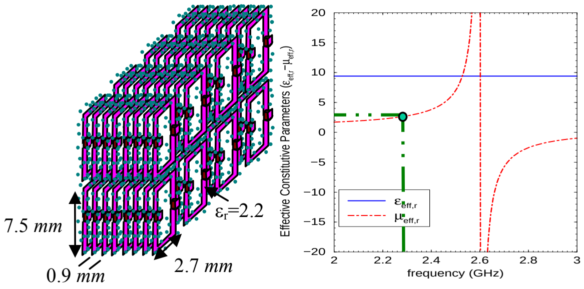
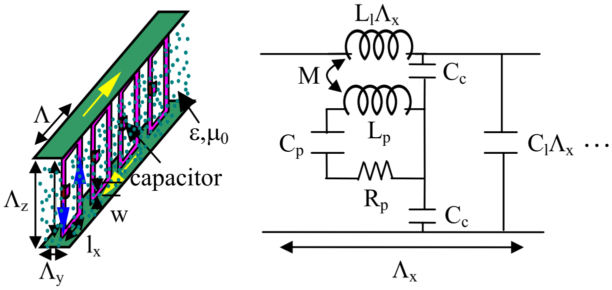


Fig. 4: Embedded-Circuit meta-material and its performance.



(a) (b)

Fig. 5: (a) Transmission line analogy, and (b) Equivalent circuit model for the embedded-circuit medium.

$$\mu_{eff} = \mu_0 \left(1 - \kappa^2 \frac{1}{1 - \omega_p^{\,2}/\omega^2 - j/Q} \right) \quad , \quad \varepsilon_{eff} = \varepsilon \left[1 + \frac{\Lambda_z l_x}{\Lambda_x \Lambda_y} \frac{K(\sqrt{1-g^2})}{K(g)} \right], \tag{3}$$

where $\omega_p = 1\big/\sqrt{L_p C_p}$, $\kappa = M\big/\sqrt{(L_l \Lambda_x) L_p}$, $L_l = \mu_0 \Lambda_z / \Lambda_y$, $L_p = \dfrac{\mu_0 l_x l_z}{\Lambda_y}$, $M = \dfrac{\mu_0 l_x l_z}{\Lambda_y}$, $Q = \dfrac{\omega L_p}{R_p} = \dfrac{4 l_x l_z w}{\Lambda_y (l_x + l_z)\delta}$, and C_p is the value of loop capacitor. Also, K is the complete elliptic integral function and $g = w/(w+h)$.

The FDTD with Periodic Boundary Conditions/Perfectly Matched Layered (PBC/PML) walls [4] is applied to characterize and obtain the effective constitutive parameters of the embedded-circuit medium. The results are shown in Fig. 4. They are in very good agreements with the ones obtained from (3). As determined the meta-material generates the magnetic property in the *GHz* range and consequently one can achieve the antenna miniaturization with enhanced performance in this frequency range by printing the patch on the embedded-circuit meta-substrate. The geometry and return loss of patch antenna printed on the meta-substrate is shown in Fig. 6. It operates at $f_0 = 2.28\,GHz$ and has the miniaturized size $0.075\,\lambda_0$ with a wide bandwidth of about $BW = 1.5\,\%$.

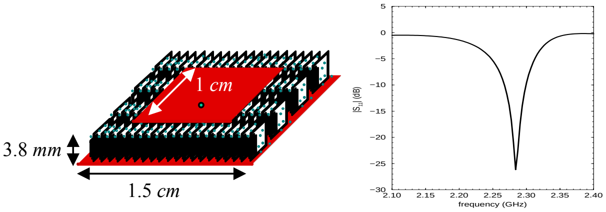


Fig. 6: Patch antenna on the embedded-circuit substrate and its characteristics.

REACTIVE IMPEDANCE SURFACE

As mentioned earlier, to improve the antenna characteristics one needs to decrease the interaction between the antenna and its ground plane. An antenna close and parallel to a PEC or PMC substrate has a strong coupling with that surface and cannot radiate properly. To conceptually investigate the effect of the antenna's ground plane on its performance let's consider an infinitesimal dipole over a general impedance plane η. The Hertzian vector potential for the dipole is given by [6]

$$\Pi = -\frac{j\eta_0 Il}{4\pi k_0}\left[\hat{y}\left(\frac{e^{-jk_0R_1}}{R_1}+\left(\frac{e^{-jk_0R_2}}{R_2}-2\alpha\int_0^\infty e^{-\alpha\xi}\,\frac{e^{-jk_0R_2'(\xi)}}{R_2'(\xi)}\,d\xi\right)\right)-\hat{z}\,\frac{2}{k_0}\,\frac{\eta/\eta_0}{1-(\eta/\eta_0)^2}\,\frac{\partial^2}{\partial y\partial z}\int_0^\infty\left(e^{-\alpha\xi}-e^{-\beta\xi}\right)\frac{e^{-jk_0R_2'(\xi)}}{R_2'(\xi)}\,d\xi\right], \quad (4)$$

where $R_1 = \sqrt{x^2+y^2+(z-z')^2}$, $R_2 = \sqrt{x^2+y^2+(z+z')^2}$, $R_2'(\xi) = \sqrt{x^2+y^2+(z+z'-j\xi)^2}$, $\alpha = \dfrac{\eta_0 k_0}{\eta}$, $\beta = \dfrac{\eta k_0}{\eta_0}$.

It is observed that for the PEC (zero impedance) and PMC (infinite impedance) surfaces the image current is focused at one point and has the maximum interaction with the antenna; however, for a reactive impedance surface (RIS) with $\eta = jv$ the image current has a sinusoidal distribution along the line $-z' + j\xi$. Therefore, an RIS with moderate value of v can drastically improve the antenna performance. To provide a surface with reactive impedance characteristics a periodic structure of metallic patches printed on a PEC backed dielectric material is designed in Fig. 7. A unit cell building block of the structure is in fact represents an *LC* circuit with reactive impedance property. The behavior of RIS is shown in Fig. 7.

A 0.1λ patch antenna printed on the RIS, as shown in Fig. 8, has the superior characteristics as $BW = 6.7\,\%$, $G = 4.5\,dBi$, and $e_r = 90\,\%$. Note that the inductive behavior of the RIS substrate effectively mitigates the capacitive property of the antenna bellow its resonance and considerably reduces the size of antenna.

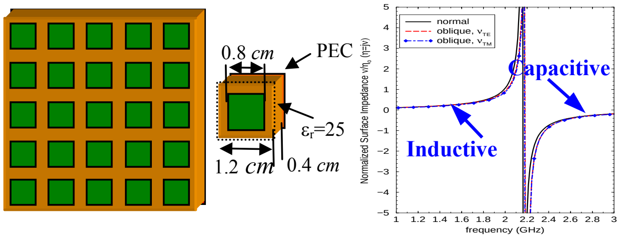


Fig. 7: RIS and its impedance behavior.

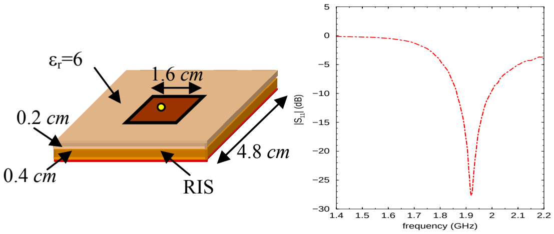


Fig. 8: Patch antenna over the RIS and its return loss.

REFERENCES

[1] J. S. Colburn and Y. Rahmat-Samii, *IEEE Trans. Antennas Propagat.,* vol. 47, no. 12, pp. 1785-1794, Dec. 1999.

[2] R. C. Hansen and M. Burke, *Microwave and Opt. Tech. Lett.*, vol. 26, no. 2, pp. 75-78, July 2000.

[3] H. Mosallaei and K. Sarabandi, "Magneto-Dielectrics in Electromagnetics: Concept and Applications," *Accepted for publication in IEEE Trans. Antennas Propagat,* 2003.

[4] H. Mosallaei and Y. Rahmat-Samii, *Electromag. J.*, vol. 23, no. 2, pp. 135-151, Feb.-Mar. 2003.

[5] K. Sarabandi and H. Mosallaei, "Novel artificial embedded circuit meta-material for design of tunable electro-ferromagnetic permeability medium," *IEEE International Microwave Symposium*, Philadelphia, Pennsylvania, June 8-13, 2003.

[6] H. Mosallaei and K. Sarabandi, "A novel artificial reactive impedance surface (RIS) for miniaturized wideband planar antenna design: Concept and characterization," *IEEE AP-S International Symposium and USNC/CNC/URSI National Radio Science Meeting*, Columbus, Ohio, June 22-27, 2003.