A Novel Artificial Reactive Impedance Surface for Miniaturized Wideband Planar Antenna Design: Concept and Characterization*

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1. Abstract: The concept of a novel substrate for planar antennas, that can miniaturize the size and significantly enhance both the bandwidth and the radiation characteristics of a printed antenna on such substrate, is introduced. Using the exact image formulation for the fields of elementary sources above impedance surfaces, it is shown that a purely Reactive Impedance Surface (RIS) with a specific surface reactance can minimize the interaction between the elementary source and its image (the RIS substrate). A RIS can be tuned anywhere between Perfectly Electric and Magnetic Surfaces (PEC and PMC) offering the unique property to achieve the optimal bandwidth and miniaturization factor. This artificial surface is designed utilizing two-dimensional periodic square patches printed on a metal-backed dielectric substrate. A simplified circuit model describing the physical phenomenon of the periodic surface representing the RIS is developed for simple analysis and design of the proposed artificial surface. Also a Finite Difference Time Domain (FDTD) full-wave analysis in conjunction with the periodic boundary conditions and perfectly matched layer walls is applied to provide a comprehensive study and analysis of complex antennas on such surfaces. An example including a dipole antenna over a RIS substrate is studied and its performance is compared with those of the same antenna over PEC and PMC surfaces.

2. Theory: Fig. 1(a) depicts the geometry of an elementary dipole source **Il** directed in y-direction and located above the impedance plane η. The interaction of EM waves with the impedance surface can be obtained in a closed form representation utilizing the Hertzian vector potential **Π** satisfying

$$\left(\nabla^2 + k_0^2\right)\Pi = j\frac{\eta_0}{k_0}\mathbf{J} \tag{1a}$$

$$\mathbf{E} = \left(k_0^2 + \nabla\nabla\cdot\right)\Pi \quad , \quad \mathbf{H} = j\frac{k_0}{\eta_0}\nabla\times\Pi\cdot \tag{1b}$$

The spectral transformation approach is applied to determine the Hertzian potential **Π** which given by [1]

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

where

$$R_1 = \sqrt{x^2 + y^2 + \left(z - z'\right)^2} \ , \ R_2 = \sqrt{x^2 + y^2 + \left(z + z'\right)^2} \ , \ R_2'(\xi) = \sqrt{x^2 + y^2 + \left(z + z' - j\xi\right)^2} \tag{3a}$$

$$\alpha = \frac{\eta_0 k_0}{\eta} \quad , \quad \beta = \frac{\eta k_0}{\eta_0}\cdot \tag{3b}$$

It is obtained that the EM fields of the elementary source positioned above the impedance plane are in fact the contributions of the source at point z' and a distributed image source in complex z-plane along the $-z' + j\xi$ line (illustrated in Fig. 1(b)). For the conventional PEC and PMC surfaces (zero and infinite impedance planes), the image source is focused at point $-z'$ and hence the surface has the maximum interaction with the dipole above it (significant mutual impedance that can significantly change input resistance and reactance of an antenna). For a purely reactive impedance plane ($\eta = j\nu$) lying between the PEC and PMC the image current is distributed along a line having

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* *Patent is pending.*

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sinusoidal distribution and has a remarkably reduced mutual interaction with the source itself. Thus, utilizing a RIS substrate, one can successfully reduce the antenna back radiation while still a very broad impedance match is achieved. Furthermore, as will be demonstrated later, if the impedance plane has a frequency response varying between PEC and PMC ground planes the resonance frequency can be properly controlled and one will be able to considerably reduce the antenna size.

3. Dipole Antenna in Free Space and Over the PEC & PMC Surfaces: A $\lambda/2$ dipole antenna in free space has a $73\,\Omega$ input impedance and it can be matched to a normal $50\,\Omega$ line easily. However, in order to reduce the antenna back radiation the dipole can be placed above a PEC ground plane, but according to image theory, the radiated field of the image current cancels the antenna radiation field. That is the radiation resistance goes down and the stored energy in the near field increases significantly. If such antenna can be matched, matching can only be accomplished over a very narrow band. To rectify this difficulty, in recent years considerable efforts have been devoted towards the development of PMC surfaces [2]. In this case although the far field cancellation does not occur, the input resistance is doubled and as before the stored energy in the near field is increased considerably. That is matching is still difficult and expected bandwidth is low. Although PMC is better than PEC for conformal antennas, neither is a good choice for planar antennas. Here we investigate an artificial substrate with a reactive surface impedance to enhance the antenna characteristics noting that the image of an electric current above a RIS is distributed and the mutual impedance between the antenna and its image is reduced.

4. Reactive Impedance Surface (RIS) Substrate: The challenge in this section is to present an artificial reactive impedance surface utilizing the composite periodic structures. The circuit model analytical approach and FDTD numerical method are applied to investigate the characteristics of the impedance plane. The unique properties of the designed RIS in enhancing the antenna performance, namely, size reduction, wide bandwidth, and reduced back radiation are highlighted.

Design of RIS: To present the RIS substrate a periodic structure of metallic square patches printed on a metal-backed dielectric substrate as shown in Fig. 2 is used. The meta-backed dielectric material after the distance d (thickness of substrate) provides an inductance property, which is in parallel with the capacitor existed between the patches. Thus, the periodic medium can be simply represented as a parallel LC model with the desired reactive impedance ($\eta = j\nu$)

$$\eta = Z_{LC} = j\frac{X_L X_C}{X_C - X_L} = jX_{LC} \tag{4}$$

where $X_L = \omega L$ and $X_C = 1/\omega C$ are the reactances of the equivalent inductor and capacitor that are analytically determined. The normalized impedance ν/η_0 of the surface is obtained using equation (4) and is plotted in Fig. 3(a). The FDTD with PBC/PML boundary conditions [3] is also applied to calculate the normal incidence reflection coefficient from which the normalized impedance is extracted and plotted in Fig. 3(a) as well. An excellent agreement between the analytical and numerical approaches is observed. The behavior of the impedance plane for an oblique incident wave is investigated in Fig. 3(b). It is determined that the designed periodic substrate successfully provides an artificial RIS with the unique property between the PEC and PMC.

Antenna Over the RIS: The geometry of the dipole antenna over the RIS substrate is shown in Fig. 4. The FDTD is applied to obtain the input impedance and radiation patterns of the antenna as illustrated in Figs. 5 and 6. In the low frequency range the substrate behaves as PEC (Fig. 3), which further suppresses the dipole radiation and reduces the antenna input impedance. However, as the frequency increases and the substrate goes through the region of reactive property the mutual coupling is reduced and the RIS provides a wideband characteristic as determined by the gentle variation of reactance and resistance near the resonance ($BW = 6.4\,\%$). The spectral variation of RIS lowers the zero cross point of the antenna reactance, which results in antenna miniaturization. In this example the size of the dipole antenna is reduced to 0.35λ. Moreover, the radiation pattern is remarkably enhanced and the directivity of about $6.7\,dB$ with $20\,dB$ front-to-back ratio is achieved.

References

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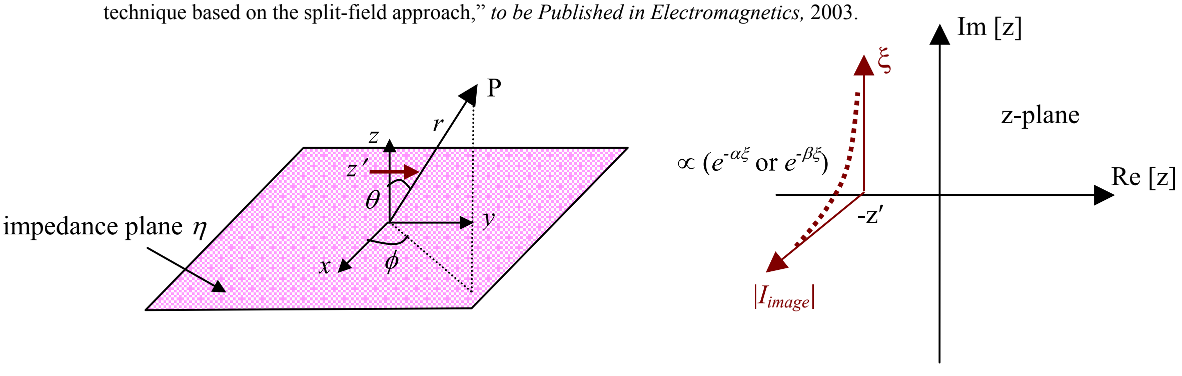
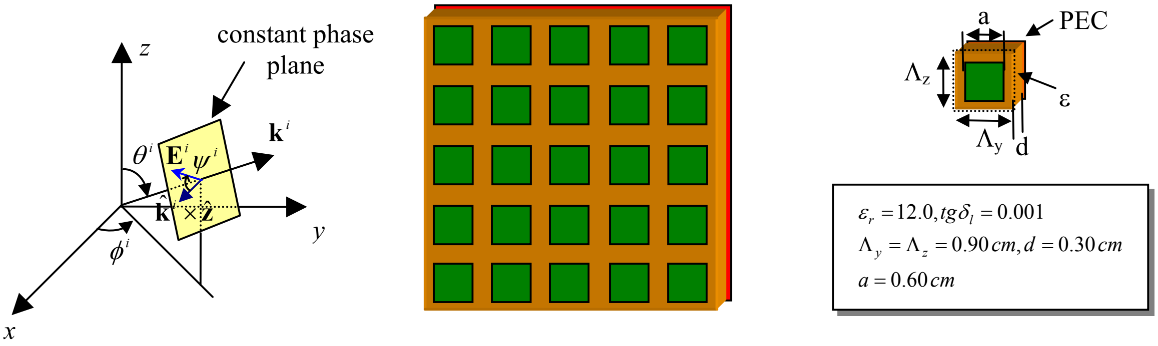
[3] H. Mosallaei and Y. Rahmat-Samii, "Broadband characterization of complex periodic EBG structures: An FDTD/Prony technique based on the split-field approach," *to be Published in Electromagnetics,* 2003.



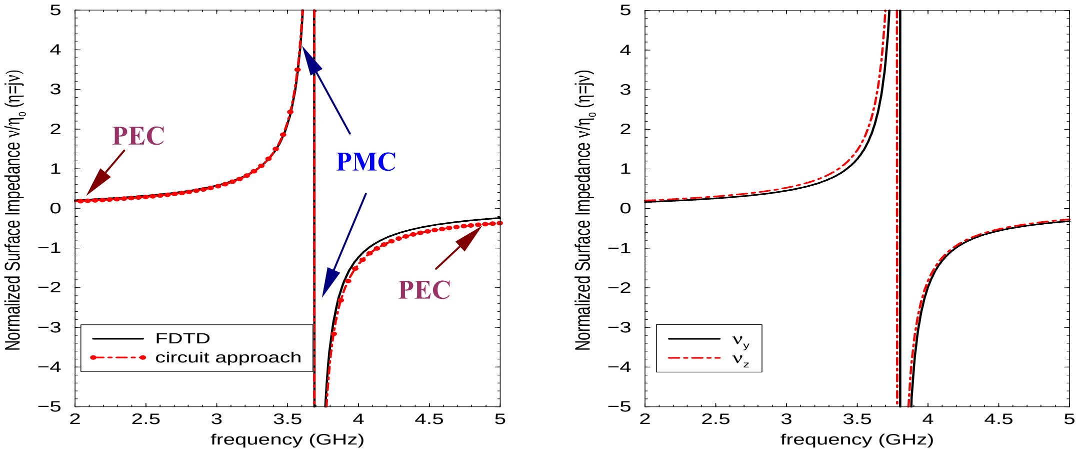
(a) (b)

Fig. 1. (a) Dipole antenna over the impedance plane η, (b) Distributed image source in the complex z-plane along the line $-z' + j\xi$.



(a) (b) (c)

Fig. 2. RIS artificial surface. (a) Plane wave illumination and its corresponding coordinate system, (b) Periodic structure ant its, (c) Building block unit cell.



(a) (b)

Fig. 3. Impedance behavior of the RIS plane. (a) Normal incidence (notice to the excellent agreement between the circuit model and FDTD method), (b) Oblique incidence ($\theta^i = 90^\circ$, $\phi^i = 120^\circ$, $\psi^i = 50^\circ$).

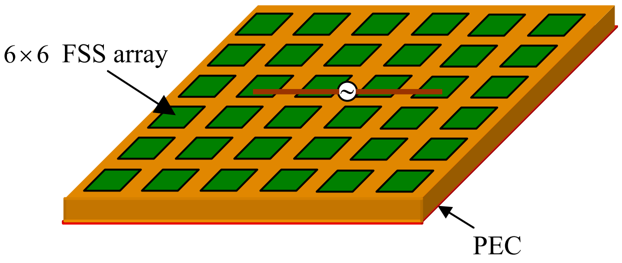
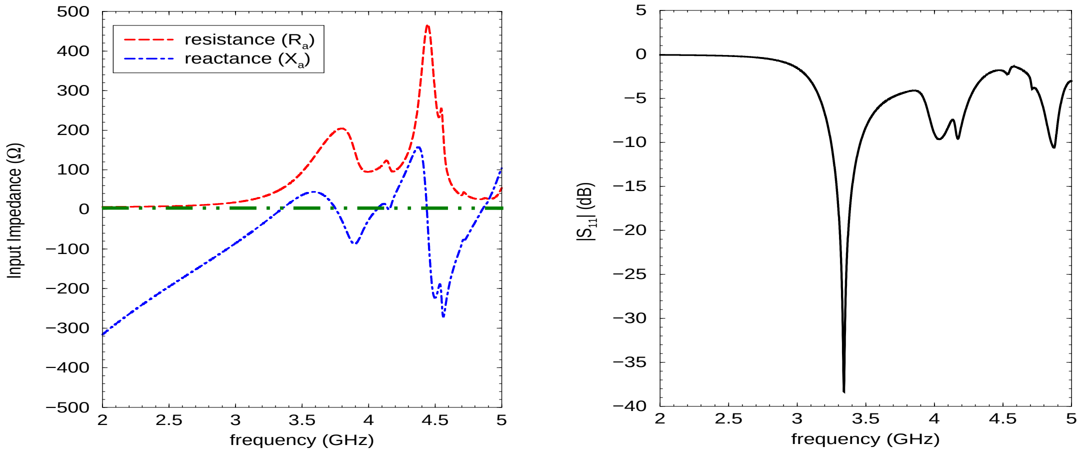


Fig. 4. Dipole antenna over the RIS substrate.



(a) (b)

Fig. 5. Input impedance of the dipole antenna over the RIS. (a) Input resistance and reactance, (b) Return loss.

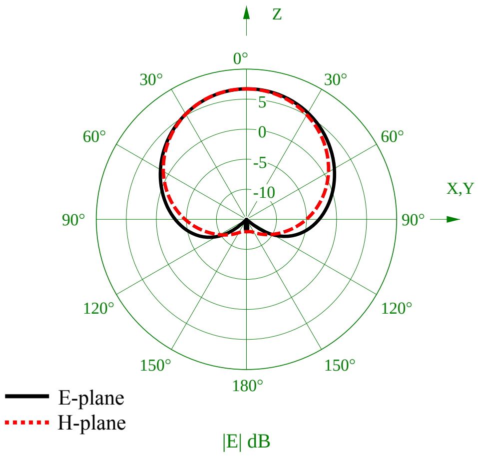


Fig. 6. Radiation patterns of the dipole antenna over the RIS.