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RF Energy Extraction Using Wave Impedance Matching

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Abstract — We present a simple approach that allows a dipole antenna to be mounted over an artificial magnetic conductor for the purpose of extracting RF energy. The method relies on the reactive component of wave impedance in order to remove the need for dipole to diode matching circuitry.

Keywords — AMC; Dipole antenna; Layered Structure; Rectenna; Wheeler Current Sheet.

I. INTRODUCTION

An equivalent circuit model is presented here which yields a simple design approach for scavenging electromagnetic energy without the need for dipole to diode matching circuitry.

The proposed model is shown in Fig. 1, this consists of a three-layer structure. The first layer (Layer 1) represents the closely spaced dipole antenna array including rectifier components used for conversion of the RF input power to the usable dc power. A second-layer (Layer 2) contains of a sheet densely spaced periodic metallic patches, while the third and final layer is a conducting metal sheet separated by a dielectric material of relative permittivity ϵ_r . Layer 2 and Layer 3 form an Artificial Magnetic Conductor (AMC). The overall physical arrangement is akin to the Wheeler sheet [1], but here the purpose is to remove the need for intermediate matching between diode and dipole such that maximum energy can be extracted from a source placed in the quasi-near field of the system.

A conventional rectenna [2] is a combination of receiving antenna, rectifier circuit and a separate matching unit. In this paper we propose a different approach. Here we propose to use the quasi-near field property of a dipole array such that we exploit its reactive component in order to remove the need for extrinsic impedance matching.

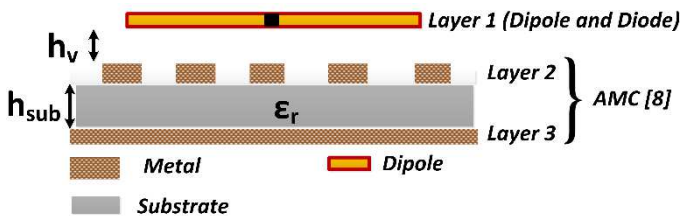


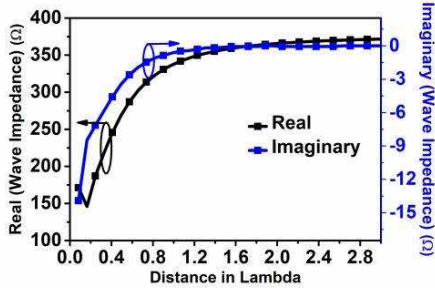
Fig. 1. The proposed structure containing three layers.

II. DESIGN METHOD

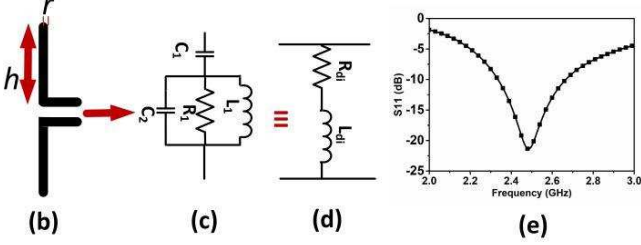
First the wave impedance of a single dipole antenna is established for its near-field and far-field properties using CST microwave studio and benchmarked using 4NEC2. The electric field and magnetic field in the near-field and far-field are simulated and the obtained values of the real and imaginary parts of the wave impedance with distance in units of wavelength are plotted in Fig. 2 (a). Here, an individual Z-directed $\lambda/2$ dipole antenna (28 mm for 2.45 GHz operation, radius 2 mm) is located at the system origin, Fig. 2 (b). The return loss of this dipole antenna, Fig. 2 (e) is better than -10 dB in the frequency range 2.38 GHz to 2.72 GHz. We now consider an equivalent circuit model of the dipole antenna in order to represent its input impedance. The lumped equivalent circuit model reported previously [3, 4] is adopted here, Fig. 2 (c). The equations representing the equivalent components for the antenna are taken from [4] with the h/r ratio selected as 0.125λ . This yields $C_1 = 0.13$ pF, $C_2 = 0.028$ pF, $L_1 = 0.027$ μ H and $R_1 = 4.38$ k Ω . The four-lumped element model can be reduced using circuit theory to a simpler two-element model, Fig. 2 (d). This results in $R_{di} = 68.868$ Ω and $L_{di} = j 47.0116$ Ω .

III. RECTIFIER DIODE IMPEDANCE

The equivalent circuit of the Schottky diode used in this work, HSMS 2820 Avago Solutions, [5], is presented in Fig. 3 (a) as taken from its datasheet. The diode exhibits low junction capacitance and low value of forward voltage (0.34 mV), which ensures the efficient operation for a wide input RF power range. The Schottky diode is a nonlinear device whose impedance changes with the input RF power applied to it as well as its operating frequency. For a diode load resistance of 0.2 k Ω , its input impedance (Z_{diode}) can be obtained and its power contours plotted, Fig. 3 (b) for 2.45 GHz operation. The blue contours represent 20 dBm input power and red contours represent 25 dBm input RF power available at the rectifier diode input port. In this work the chosen value of the rectifier diode impedance is $Z_{diode} = 65 - j45$ Ω at 25 dBm input RF power for the operating frequency of 2.45 GHz. This provides a close conjugate match to the dipole input impedance and yields a converted power of 22.7 dBm, [6, 7].



(a)



(b)

(c)

(d)

(e)

$$\left[\begin{array}{l} C_1 = \frac{12.0674h}{\log(2h/r) - 0.7245} \text{ pF} \\ C_2 = 2h \left\{ \frac{0.89075}{\log(2h/r)^{0.8006} - 0.861} - 0.0254 \right\} \text{ pF} \\ L_1 = 0.2h \left\{ \left[1.4813 \log(2h/r) \right]^{1.012} - 0.6188 \right\} \mu\text{H} \\ R_1 = 0.41288 \left[\log(2h/r) \right]^2 + 7.4075(2h/r)^{-0.02389} - 7.274 \text{ k}\Omega \end{array} \right]$$

Fig. 2. (a) The Wave impedance of a $\lambda/2$ dipole antenna along boresight from the origin of the antenna. The design model of the dipole antenna; (b) the dipole antenna with $h = 28$ mm, $r = 2$ mm; (c) four element equivalent circuit model of the dipole antenna; (d) resultant input impedance of the dipole antenna and; (e) return loss of the isolated dipole antenna.

A. Artificial Magnetic Conductor (AMC)

To finalise the physical arrangement while accommodating the intrinsic conjugate match of the diode impedance we next realise an AMC. The top layer of the AMC consists of a periodic uniform array of metallic patches with a gap of dimension g in between adjacent square metallic patches, as shown in Fig. 4 (a) and (b). The AMC equivalent circuit model is represented in Fig. 4 (c). The gap capacitance C_{gap} and inductance L_g can be approximated using [8, 9] as

$$C_{gap} = \frac{a\epsilon_0(1+\epsilon_r)}{\pi} \log\left(\frac{8a}{g}\right) \quad (1)$$

$$L_g = \frac{\pi w \mu}{2c \sinh^{-1}(a/g)} \quad (2)$$

where a , g and w are shown in Fig. 4 (a), and ϵ_0 is the permittivity of the free space. Inductor L_d represents the metal backed dielectric slab of thickness H_{sub} and substrate permittivity ϵ_r . From the transmission line model, we find:

$$X_L = jZ_0 \tan(\beta l) \quad (3)$$

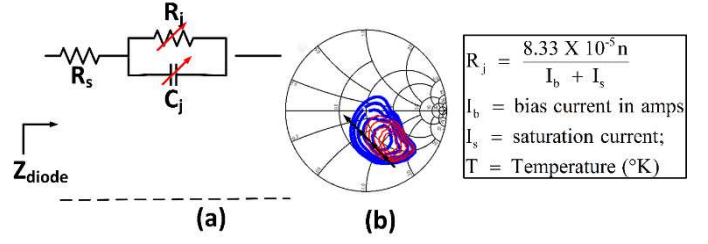


Fig. 3. Diode modelling description: (a) equivalent circuit of the Schottky diode HSMS-2820; (b) the power contour representation of the diode with load resistor is represented on the Smith Chart.

Table 1. Rectifier Diode Equivalent Circuit Values.

Parameter	R_s (Ω)	I_s (nA)	C_{j0} (pF)	n	V_{br} (V)	V_j (V)
Value	6	22	0.7	1.08	15	0.34

Where βl is the electrical length, l is equal to the H_{sub} , along with this the Z_0 , can be written as $120\pi \sqrt{\frac{\mu_r}{\epsilon_r}}$, Yielding $C_{gap} = 2.144$ pF, $L_g = 0.185$ μ H and $L_d = 1.26$ nH.

The overall value of the input impedance Z_{in} can now be obtained, Fig. 5 (a). Here an additional 0.4pF capacitor is connected in between two tightly coupled antennas. This balances their mutual coupling capacitance value. [10, 11]. Hence the input impedance Z_{in} can be represented as:

$$Z_{in} = \{Z_{dipole} + Z_{diode} + (Z_{AMC} // j\omega L_d)\} + \frac{1}{j\omega C_{coupling}} \quad (4)$$

In Eq. (4) Z_{dipole} represents the overall impedance of the dipole antenna incorporating mutual capacitance, Z_{diode} is the equivalent impedance of the Schottky diode used in this process. The final calculated value of the impedance (Z_{in}) for the geometry under consideration here is $134 + j8.50$.

Now under the assumption that the wave is impinging normal to the plane of the designed structure, then for maximum transfer of energy from the incident wave to the diode load, the wave impedance shown in Fig. 2 (a) should be the complex conjugate of the impedance of the structure ($Z_{wave} = Z_{in}^*$). Under this condition the conjugate wave impedance $134 - j8.50 \Omega$ is obtained at $0.16 \lambda_0$ distance.

B. Load Termination

Fig. 5 (b) and (c) shows the simulated input RF to dc power conversion power and efficiency as a function of diode load termination as observed at the circuit terminals of the rectenna. The highest value (darkest region) obtained from both plots is satisfied for 0.2 k Ω load value, where the peak RF to dc converted power is simulated as 345 mW for 30 dBm input RF power. The proposed structure can be extended using orthogonally connected dipole antennas in order to make it polarisation agnostic, the resultant structure is shown in Fig. 6, where interdigital capacitors remove the need for lumped capacitors. From Fig. 6 it can be seen that the dipoles representing ports BB' and DD' are in series to each other

IV. CONCLUSION

This paper introduced a simple equivalent circuit method for the extraction of energy from a closely positioned wave source impinging upon a dipole-based Wheeler sheet. The approach given here dispenses with the need for external device matching circuitry as the dipole arrangement is intrinsically conjugate matched to wave impedance for a specific distance from the source.

ACKNOWLEDGMENT

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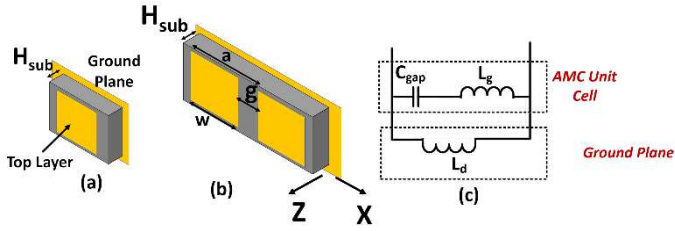


Fig. 4. (a) Single unit cell of the AMC; (b) interaction of two-unit cells where a is periodicity, g is gap in between two square patches and w the width of one metallic patch; (c) equivalent circuit model of the unit cell. Substrate TLY-5A ($\epsilon_r = 2.17$) 0.5 mm thickness is used.

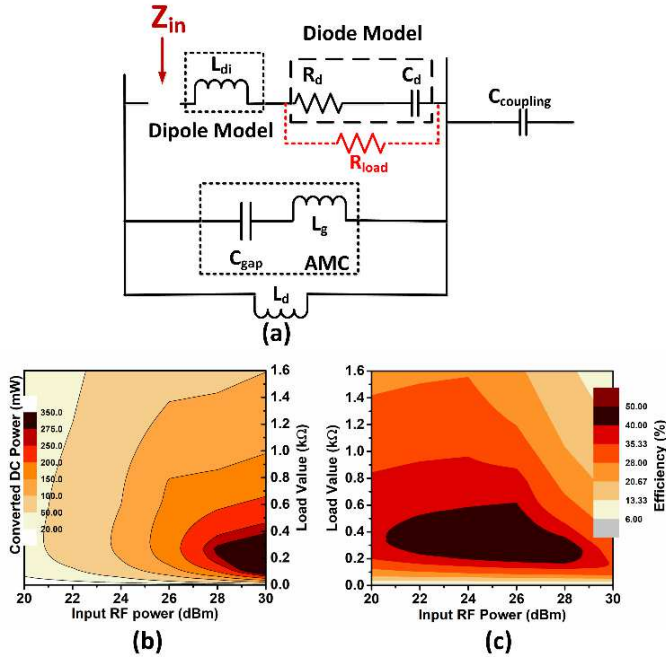


Fig. 5. (a) Equivalent circuit model of the proposed structure. Simulation results of single rectenna; (b) converted RF to dc power; (c) RF to dc conversion efficiency of rectenna with load resistance and input RF power level at 2.45 GHz normal incident power.

while parallel to AA' and CC'. Therefore, extension to an $N \times N$ array will result in same input impedance as was calculated for the single dipole rectenna. Here the optimal wave impedance location will vary from the single dipole case as aperture size will have increased.

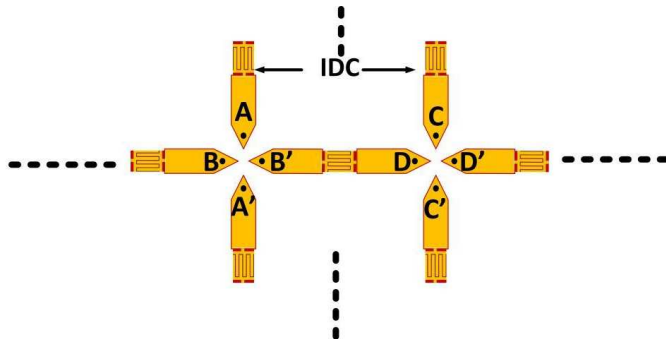


Fig. 6. Plan view of the array structure combination of orthogonally connected dipole antennas and interdigital capacitors.