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Modelling, Simulation and Investigation of Wireless Power Transfer in Square-loop Chip at UHF Band for Medical/Biomedical Charging

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Abstract: Medical electronics (Implant) devices are important in daily lives of the sick patient with terminal infections. The recent discovery of wireless power transfer (WPT) technology provides a gateway for the noncontact electricity transmission for multiple gadgets and medical implantable devices such as (artificial heart, sphincter, defibrillator and electrical simulator) simultaneously. Wireless power transfer is the transfer of power between a transmitting module and a receiving module of different system. In this work, we designed, modelled and analyzed the effects of orientation, alignment as well as coupling losses of a transmitting and receiving antenna. We designed the antenna by determining the frequency of operation (f_l), dielectric constant of substrate (ε_r), the substrate height (h), loop length, width using the fundamental mode**.** Simulation of the wireless power transfer system was accomplished using the electromagnetic system COMSOL Multiphysics 5.5 model at a frequency domain of 1.8MHz. The model consists of two printed square loop antenna enclosed by an air domain with perfectly matched layer (PML). The etched layer is patterned on 2mm Polytetrafluoroethylene (PTFE) board, the thickness of the copper layer used varies geometrically, but much thicker than the copper skin depth, so that it is modelled as a perfect electric conductor (PEC). Results obtained from the simulation shows a strong coupling at 0, 22.5, 45, 67.5 degrees and a hot coupling around the receiving antenna at angle 90 degrees. These results indicate the device can only be used for direct charging.

Keywords: Biomedical, Substrate, Wireless, COMSOL, Transfer and Noncontact

1. Introduction

The need for noncontact device charging remain the concern for medical embedded systems that require charging while at use and when runs out of charges, the challenge of charging the device without necessarily removing it from the users or not having contact with the charging contact source such as cables and other means remain important that there is serious need to develop a noncontact system for charging. Noncontact electricity transmission method for supplying electricity to an electrical apparatus is based on Faradays law of electromagnetic induction and it's recent (<20 years old) development in the field of household appliances [8]. Wireless Power Transfer (WPT) is well suited for medical applications. The concept of wireless power transfer has been introduced since the 19th century. In 1890's, Tesla demonstrated the first near-field coupling system that wirelessly powered a lamp based on a two-coil system [16]. Resonant circuits were used to enhance the transmission range. Years later the introduction of coil to perform similar experiment [10].

Wireless power transfer technology works on the principle of energy coupling by orientation of the antenna [7, 17]. This technology has ability to charge multiple electronic devices concurrently, over a long distance and through materials such as glass, plastic and wood.

Recently, the introduction of printed loop antenna to the wireless power transfer was experimented and is now being used in electronic gadgets, smart phones, wearable electronics, RFID trackers, medical industry for medical implant to replace power cord or replaceable batteries in heart pumps and hybrid electric vehicles etc. [5]. The wireless power transfer (WPT) technology uses electromagnetic field to transfer energy between two objects. The power source is connected to a power transmitting unit (PTU) which generates magnetic field and the power receiving unit (PRU) converts energy into usable power [11].

A loop antenna is a closed-circuit antenna that is, one in which a conductor is formed into one or more turns so its two ends are close together. Loops can be divided into two general classes, those in which both the total conductor length and the maximum linear dimension of a turn are very small compared with the wavelength and those in which both the conductor length and the loop dimensions begin to be comparable with the wavelength [9]. A "small" loop can be considered to be simply a rather large coil, and the current distribution in such a loop is the same as in a coil. That is, the current has the same phase and the same amplitude in every part of the loop. To meet this condition, the total length of conductor in the loop must not exceed about 0.1. A "large" loop is one in which the current is not the same either in amplitude or phase in every part of the loop. This change in current distribution gives rise to entirely different properties as compared with a small loop.

2. Basic Theory of Wireless Power Transfer (WPT)

When electrical energy from an alternating current (AC) power supply such as a commercial power supply or from a direct current (DC) power supply such as solar cells is converted to high frequency electrical energy by using a high frequency inverter, wireless feeding device (TX) releases electrical energy through a transmission device into space. Then the receiving system (Rx) converts the electrical power into DC in the recipient electrical appliance [8]. A key feature of noncontact electricity transmission is the distribution of electromagnetic energy over space by using an electromagnetic field wave.

The wireless power transfer model analyses the energy coupling between two circular loop antennae [7, 14]. The model describes the wireless power transfer technology by evaluating the shape of the loop antennae energy coupling tuned for UHF RFID frequency. The antenna is designed by reducing its size using chip inductors. S-parameters are investigated for proper coupling by configuring the transmitting antenna as fixed type, while the receiving antenna is rotating type. The model designed a perfect electric conductor (PEC), the antennas are made of a material polytetrafluoroethylene (PTFE) board and have a thin copper layer on top. Each of the antennas is featured as a lumped inductor and a lumped port that can resonate or terminate the loop antenna [1, 6]. The antennas are perfectly shaped to perform inductive coupling.

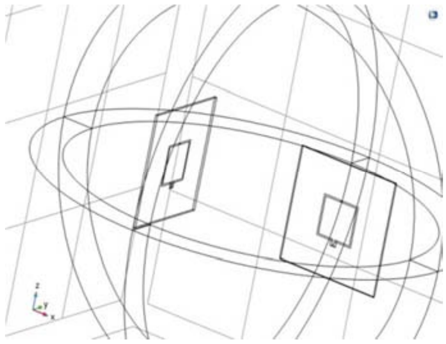

Figure 1. *Geometry of the proposed System.*

Considering ampere circuital law, loop integral of the $\vec{B}$ field equals the net current I enclosed in a loop.

$$^{\varphi}\vec{B}.\vec{dl}=\mu i \tag{1}$$

Where $\vec{B}$=magnetic flux density, I=net current and μ =permittivity

According to Biot-Savart Law,

$$dB = \frac{\mu \times i \times dl \times \sin\theta}{4\pi r^2} \tag{2}$$

dl=infinitesimal length of the conducting material carrying electric charge (i)

r=distance from the length element dl to the field point P.

Magnetic flux is expressed by equation (3):

$$\varphi_s = \iiint_0^A B d\vec{A} \tag{3}$$

Where A is the area enclosed in the given loop.

Solving the differential in (2)

$$\varphi_s \varphi \frac{dl}{\mu A \times \ell} \equiv i \tag{4}$$

Amperes law in term of reluctance is given by:

$$\varphi_s = \frac{i}{Rm} \tag{5}$$

Where,

Rm is the reluctance of the magnetic loop.

$$\left[\frac{\mathrm{A}}{W_b}\right]\left[R_m = \varphi \frac{dl}{\mu \mathrm{A} \times l}\right] \quad (6)$$

Considering the Faradays law,

$$\varphi \mathrm{E}.dl = \frac{d\varphi_B}{dt} \quad (7)$$

$\vec{\mathrm{E}}$ Is the electromotive force (emf), φ_B is the magnetic flux.

The coil voltage is given by;

$$v_1(t) = L_p \frac{di_1(t)}{dt} + \mathrm{M}\frac{di_2(t)}{dt} \quad (8)$$

$$v_2(t) = L_s \frac{di_2(t)}{dt} + \mathrm{M}\frac{di(t)}{dt} \quad (9)$$

Coupling coefficient k along with the inductance ratio is given by:

$$k = \frac{\mathrm{M}}{\sqrt{L_p L_s}} \quad (10)$$

$$n = \sqrt{\frac{L_s}{L_p}} \quad (11)$$

2.1. Loop Design

The antenna was designed by determining the frequency of operation (f_1), dielectric constant of substrate (ϵ_r), the substrate height (h), loop length, width using the fundamental mode**.** Dielectric constant of substrate material plays important role in the printed antenna design. Substrate with a high dielectric constant reduces the dimensions of the patch also affects the antenna performance. There is always relationship between the patch size and the performance of the system [2, 6, 14].

The loops parameters are determined by considering the following equations, peak value V_L of coil terminal voltage is expressed by [13].

$$V_L = 2\pi f_s L I_p \quad (2)$$

Where peak voltage value is given as V_L, f_s are the switching frequency which is taken as 1.85MHz, L is the inductance and I_p is current amplitude. The maximum value of loop/coil terminal voltage is determined by dielectric strength between the input and output terminals and voltage of the resonant inductor. The coil structure, inductance and flux density at the loop central point, targeting the optimal loop structure for the laboratory generation of magnetic field.

Inductance of magnetic generation loop consists of internal inductance L_{in} and external inductance L_e and the inter-winding mutual inductance M. the equations below explain the analysis parameters to determine the internal inductance, wiring length and the permeability of the vacuum [13].

$$L_{in} = \frac{\mu_o I}{8\pi} \quad (13)$$

Equation 14 gives the external inductance L_e of a single turn coil, where D is the distance to coil tangent and r is the conductor axis:

$$L_e = \mu_o R\left(\log 8\frac{D+r}{r} - 2\right) \quad (14)$$

Mutual inductance M from the vertical point of a square loop a and b on the same axis at distance d:

$$M = \mu_o \sqrt{ab}\left(\left(\frac{2}{k} - K\right)K(k) - \frac{2}{k}E(K)\right) \quad (15)$$

$$K^2 = \frac{4ab}{(a+b)^2} + d^2 \quad (16)$$

The size and other parameters were obtained using the patch design

$$\epsilon_{reff} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2}\left[1 + 12\frac{h}{W}\right]^{-\frac{1}{2}} \quad (17)$$

Length

$$\Delta L = 0.142h\frac{(\epsilon_{reff} + 0.3)\left(\frac{W}{h} + 0.264\right)}{(\epsilon_{reff} - 0.258)\left(\frac{W}{h} + 0.8\right)} \quad (18)$$

The actual length of the patch

$$L = \frac{1}{2f\sqrt{\epsilon_{eff}\sqrt{\mu_0 \epsilon_0}}} - 2\Delta L \quad (19)$$

Effective length is given as:

$$L_{eff} = L + 2\Delta L \quad (20)$$

Width

$$W = \frac{1}{2f_r\sqrt{\mu_0 \epsilon_0}}\sqrt{\frac{2}{(\epsilon_r + 1)}} \quad (21)$$

For square printed loop the perimeters are equal

$$\mathrm{L=W} \quad (22)$$

Figure 2. *Proposed Square loop.*

The loop inductance is determined by using the equation:

$$L_{Square} = \frac{2n^2\mu a}{n}\left(ln\frac{a}{d} - 0.774\right) \quad (23)$$

Where
n- number of coils,
d - wire diameter,
a - length of the patch and
L – Inductance where the inductor used for this work is obtained to be 0.006514nH

The inductive coupling method is based on electromagnetic induction and was developed by Michael Faraday in 1831 [12]. The lumped inductor inserted here was to reduce the size of the loop and to distribute the energy equally round the loop.

Magnetic field and electric field are inductively generated in the space near a frequency power supply (e.g. KHz – MHz range). Receivers received power wirelessly through magnetic and electric fields; this is called inductive coupling WPT [16].

The power received in the radiative near field is given in Equation 24, when r is sufficiently small.

$$P_t = \left(1 - e^{-r^2}\right) P_t \quad (24)$$

$$r^2 = \frac{A_t A_r}{(\lambda d)^2} \quad (25)$$

The mutual inductance between the transmitter and receiver is obtained using Equation 26:

$$M = k \times \sqrt{(L_1 \times L_2)} \quad (26)$$

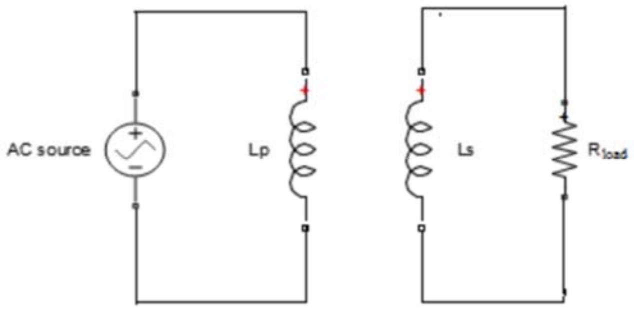

Figure 3. *Basic circuit diagram of WPT using inductive coupling [14].*

2.2. COMSOL Multiphysics 5.5

COMSOL Multiphysics is a cross platform finite element analysis solver and Multiphysics simulation software. It allows conventional physics-based user interfaces and coupled systems of Partial Differential Equation (PDE). COMSOL provide IDE and unified workflow for electrical, mechanical, fluid, acoustics and chemical applications [1, 4].

3. Model Definition and Simulation

The modeling and simulation were conducted using COMSOL Multiphysics 5.5 which is general modeling software suitable for electromagnetic systems simulation. The model consists of two printed square loop antenna enclosed by an air domain with perfectly matched layer (PML). The etched layer is patterned on 2mm Polytetrafluoroethylene (PTFE) board, the thickness of the copper layer varies geometrically, but much thicker than the copper skin depth, so it is modelled as a perfect electric conductor (PEC).

These processes follow the procedures for modeling a perfectly conducting system, electromagnetics wave and the frequency was set to 1.8MHz, geometry of the loop was drawn using the work plane where the square point was taken and drawn at the center of the graphics plane following the perimeter obtained for the loop antenna. These processes were followed for the inner patch. The receiving loop was mirrored to form exact antenna of the same structure and size placed inside a perfectly conducting sphere to form a layer around the modelled systems.

Modeling Equations are as follows:

Frequency domain equation for the simulation is as follows:

$$\nabla\, X\, \mu_r^{-1}(\nabla X E) - k_0^2\left(\varepsilon_r - \frac{j\sigma}{w\varepsilon_0}\right) \in = 0 \quad (27)$$

and Perfect Electric:

$$n\, X\, E = 0 \quad (28)$$

Lumped port:

$$Z = \frac{V_1}{j_1} \quad (29)$$

Table 1. *Parameters for circular and square analysis.*

Switching Frequency	9 x 10^{-3}kHz
Impedance	5.0Ω
Coil inductance	58.9μH
Wire inductance	3.0μH
Resonant Frequency	1.8MHz

Table 2. *Simulation Parameters.*

Loop	L_e (cm)	L_{in} (cm)	Position (xy, xy) cm
Square ring 1	3.6	3.6	0, 0
Square ring 2 (inner ring)	3.3	3.3	0, 0
Inductor	0.2	0.125	0, -2.1875
Feed Point	0.2	0.125	0, 1.724
Feed line 1	0.2	0.6	0.1, -2.25
Feed line 2	0.2	0.6	-0.1, -4

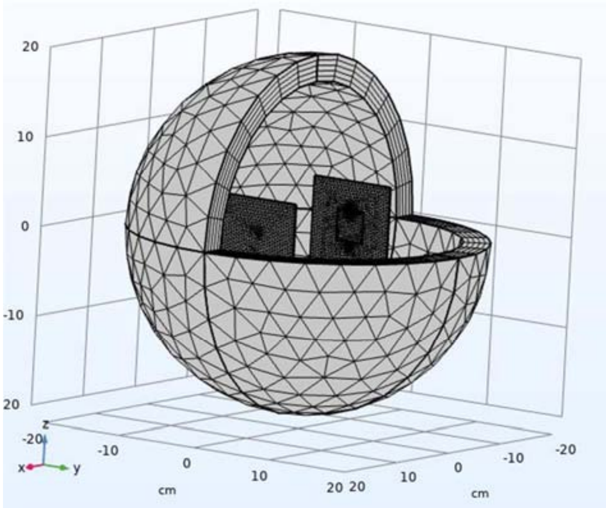

Figure 4. *Meshed system.*

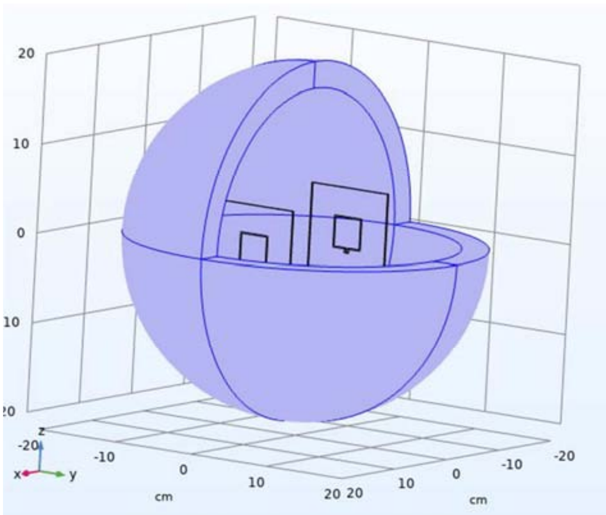

Figure 5. *Perfectly conducting region.*

4. Results and Discussion

The Electric field normalization of the wireless power transfer printed square-loop antenna were simulated on COMSOL Multiphysics 5.5 software tool where the S-parameters was obtained to determine the coupling capacity of the system, Figure 4 shows the meshed system for applying the physics controlled principle for the calculations, Figure 5, shows the perfectly conducting region of the chip loop, Figure 6 to Figure 10 display the radiating coupling power at different varying angles where their S – parameters shows the power presented in Table 3, S_{11} is below -20dB regardless of the receiving antenna orientations, while the S_{21} is tabulated with angles respectively. Figure 11, shows the S parameters graph against the angles in degrees while Figures 12 and 13 are smith chart and surface admittance graph respectively as shown in Table 4. The smith evaluations display the frequency abilities, perfect impedance matching and admittance for proper applications in the considered field.

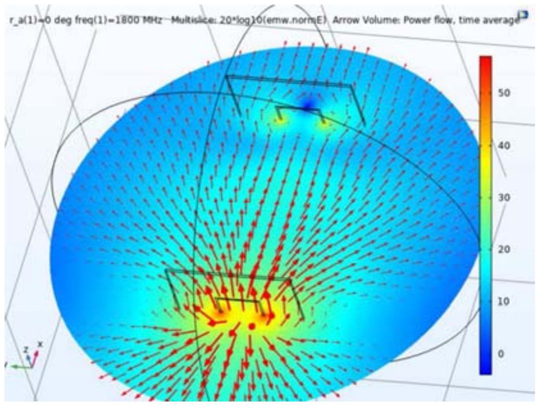

Figure 6. *Multislice Power flow at 0 degrees.*

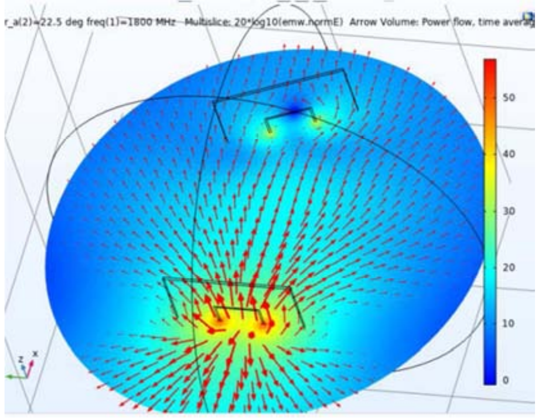

Figure 7. *Multislice Power flow at 22.5 degrees.*

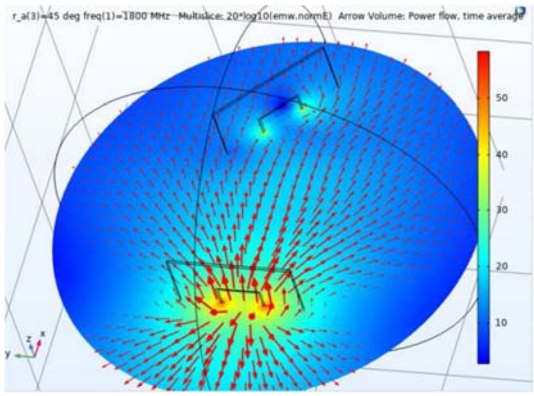

Figure 8. *Multislice Power flow at 45 degree.*

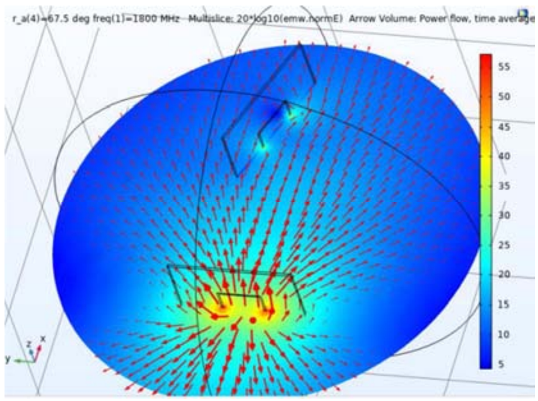

Figure 9. *Multislice Power flow at 67 degree.*

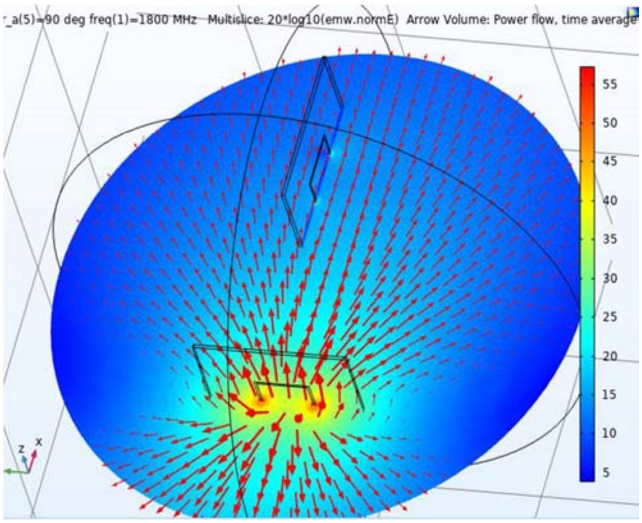

Figure 10. *Multislice Power flow at 90 degree.*

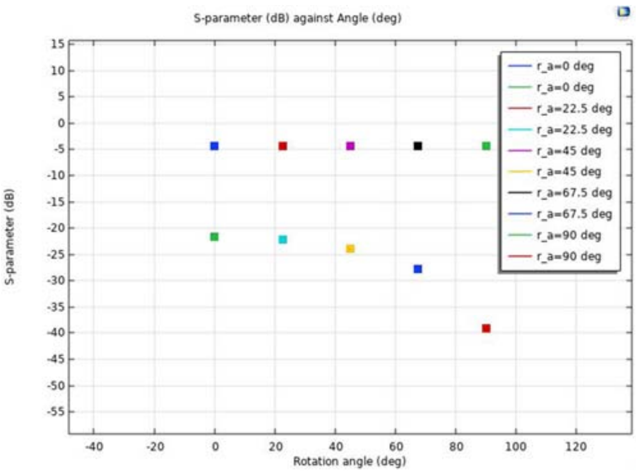

Figure 11. *Sparameter graph for S11 and S21.*

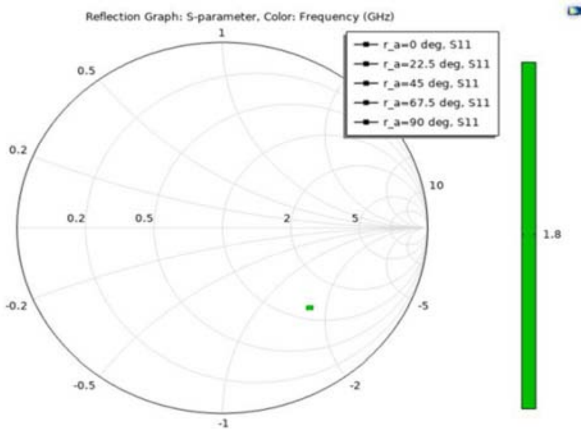

Figure 12. *Smith Chart.*

Table 3. *S-Parameters as function of angle.*

ANGLE (DEGREE)	0	22.5	45	67.5	90
S_{21}(dB)	-21.9	-22.0	-24.0	-26.0	-39.01

Table 4. *Smith Evaluation.*

Reflection	Impedance	Admittance
0.30455 – 0.37273i	1.2341 – 1.1974i	0.41740 + 0.40497i

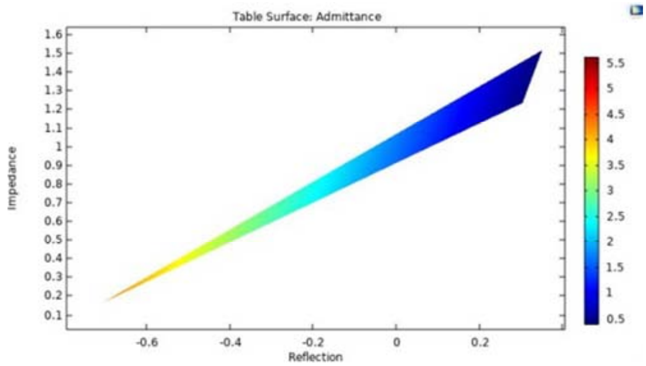

Figure 13. *Surface Admittance.*

5. Conclusion

The simulation focused on power transfer by analyzing the energy and power coupling between two printed square-loop antennas carried on the COMSOL Multiphysics 5.5. The antenna design was accelerated on the software using the geometry and other details based on theory of electromagnetic principles. Four different angles were considered to determine the reception power and identify the coupling energy at exact ranges. Printed Square-loop antenna chips designed to radiate at UHF frequency (1.8MHz) provides inherent inductive coupling by their shape. Perfect coupling configuration was examined in terms of S-parameters by varying the angle of rotation (degrees). Fixed state energy coupling transmitting antenna was improved and a receiving printed antenna chip fixed the rotating state. The square-loop antenna performed excellently well at 0, 22.5, 45, 67.5 and 90 degrees with effective coupling and reception at all angles. This square-loop antenna chips could be applied in biomedical and medical devices charging through the UHF frequency system.

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