Wireless Power Transfer (WPT) via Dipole-Loop Antenna using AWR

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Abstract: **WPT uses Electro-magnetic wave energy to transfer energy from a power source (transmitters) to load (receiver) wirelessly. The system that incorporates this process is termed as WPT. This particular research area holds a wide range of applications, which includes areas in smartphone technology, electric vehicle, wireless sensor network, medical implants, etc. This project outlines a proof of concept of WPT using AWR as a simulation tool. A simplistic model for near-field coupling was used to demonstrate the process. Furthermore, a comparative analysis between Dipole & Loop antenna was made, to justify which combinations as a transmitter and receiver unit yields a better response.**

Index Terms – Wireless-Power Transfer, EM-propagation, AWR simulation

I. Introduction

WPT is a more general term that denotes many different technologies for physical transmission of the electromagnetic field. Research in WPT dates to 1868, when 'James Clerk Maxwell' merged Ampere's Circuital Law and Faraday's Law of induction. Maxwell equations provide the keystone for current Electromagnetics including Wireless Power Transfer. In 1884, John Henry Poynting presented an EM-field mathematical equation for use in contactless energy transfer. In 1888, Henrich Rudolf Hertz discovered radio waves confirming the forecast of EM-propagation by Maxwell **[6-7]**. The first patent on WPT was observed in 1894, when Hutin and Leblanc devised a power source for the Railway system. However, the first most significant innovation was accomplished by Nikola Tesla. His experiment was based on inductive coupling using Tesla coils which produced high Alternating Currents (AC). Tesla's work contributed to long-distance energy transfer based on radio communication. In 1897, Tesla patented the 'Tesla Tower' built-in Colorado Springs **[7-8]**.

Fig I: Tesla Tower in Colorado Springs

II. Motivation

The motivation of this project was brought about by the work of Dr. Loic Markley **[1-2]**. The objective of **[1]** was to present an MRC WPT system which is an abbreviation for Magnetic Resonance Coupling. This work suppresses power loss when operating in an idle state, but it does maintain high transmission efficiency when operating in active state. This particular research shows that maximum power can be transferred between the transmitter and receiver coils under conjugate matching. A 4-coil MRC system was built to demonstrate the effectiveness of idle power loss suppression. The other literature **[2]** uses Convex Optimization to maximize power efficiency through a cascaded multi-coil wireless power transfer system. An optimal configuration was presented using 20-identical coils that transfer power over 4 cm.

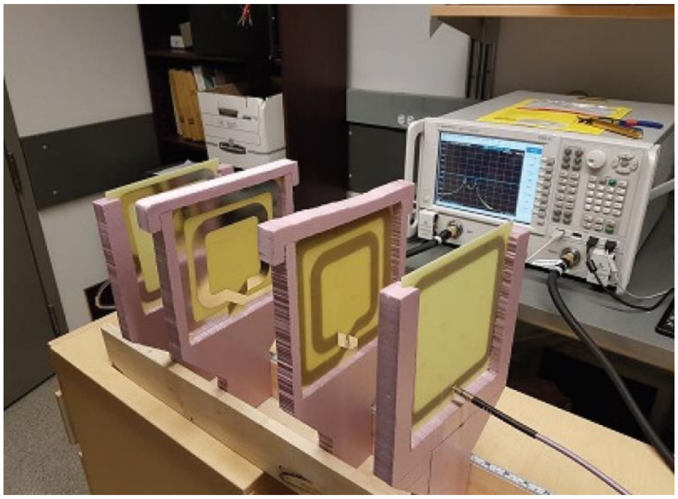


Fig II: A 4-coil MRC system [1]

III. Applications

WPT has a wide range of applications, ranging from small scale to large-scale applications. The most common application is in short-range charging devices, which include smartphones, PCs, audio players, tablets, etc. Electric Vehicles also uses WPT as a charging mechanism to recharge the batteries. WPT has applications in medical devices as well, where it can be used as a power supply for a capsule endoscope for diagnosis **[3].** However, the most intriguing use is on powering UAVs wirelessly. UAV's are used to inspect transmission lines where human intervention is not possible, especially in places which are remote, places where a human cannot be physically present e.g. rough terrain, forests and high altitude. The other uses are in military applications and Sensor Networks.

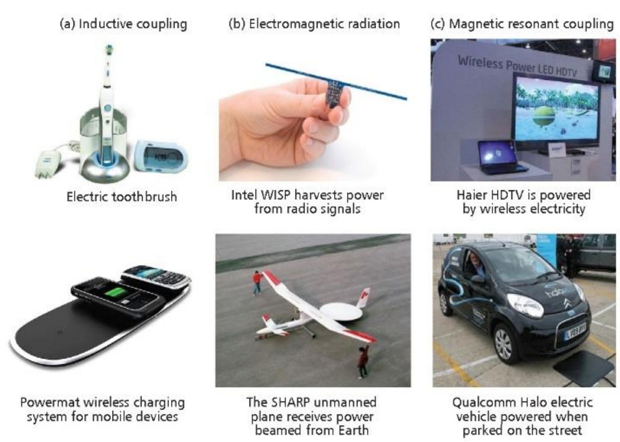


Fig III: Applications of WPT based on different coupling method

IV. Categories of WPT

Broadly, there are two main categories of a WPT-system, Near-field & Far-field. This paper and simulation results focus on Near-field coupling. Near field refers to power transmission within a wavelength of transmitting antenna. It can be further categorized into four sub-groups: a) Magnetic Resonant Coupling b) Inductive Coupling c) Capacitive Coupling & d) Magneto-Dynamic. From the following literature **[3-6]**, uses of 'a-b' were observed to be more popular, due to ease of setup, feasibility and achieving higher efficiency. Transmitting power in Capacitive coupling increases with the value of Capacitance between the plates [3], attaining higher Capacitance value can be infeasible in some cases.

V. Generic Block-diagram of WPT

The figure below shows a simplified generic-block diagram of the WPT system, which includes a transmitter unit that is connected to the main source of power supply. From the figure, we have an oscillator followed by the power source, which converts the input power to the EM-field. The converted EM-field can then be transmitted via the transmitter antenna. In the Receiving unit, the receiver antenna captures the time-varying 'AC-signal' which is converted by the rectifier to a constant DC-voltage. The voltage regulator reduces the pulsating effect and maintains a certain nominal voltage level of the rectified voltage. The purpose of the rectifier & voltage regulator is to supply constant I-V to the load. In general, on the transmitter side, the power and information signal is usually carried by the same RF-carrier. Data information can be retrieved by receiving antenna and energy can be captured by the energy harvest section.

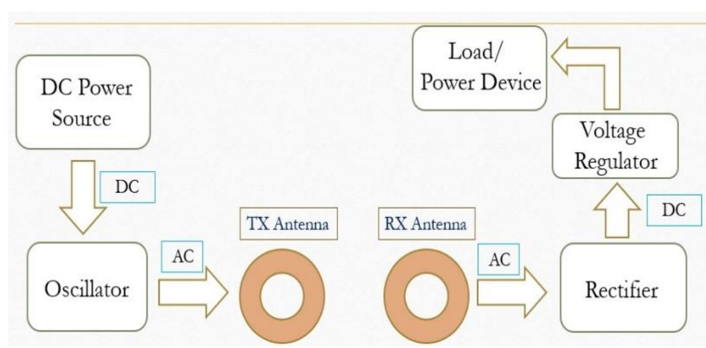


Fig IV: Generic block-diagram of WPT -system

VI. Antenna Constructions: Loop Antenna

The Loop antenna has been constructed in AWR simulation software. At first, an ellipse was drawn and later the shape was modified to make a ring. In figure (V) we have a single loop and figure 'VI' – shows the construction of a circular loop antenna using a single loop. The diameter of the loop antenna used was 20mm. In fig. VI left loop is the transmitter and the right loop is the receiver antenna. The power source is connected to the port-1 of transmitting antenna, hence port-excitation was activated in

Port-1. Port-excitation was disabled in Port-2 of the receiving antenna.

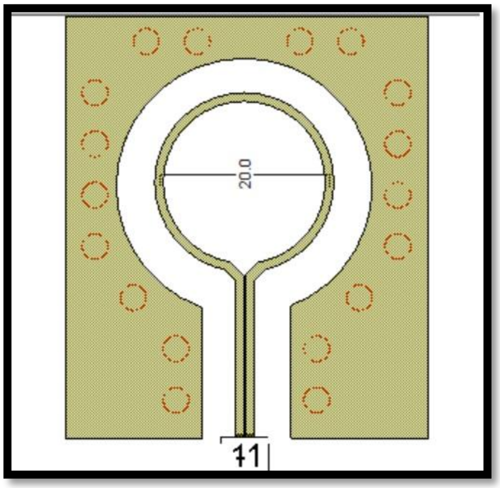
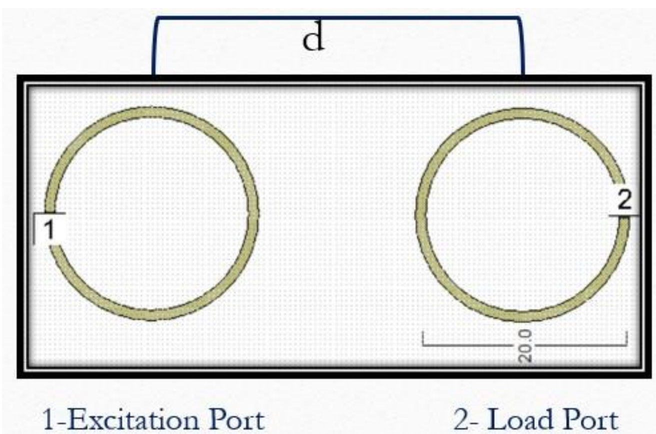


Fig V: Constructions of single Loop Antenna (AWR)



VI: Transmitter and Receiver Loop Antenna (AWR)

VII. MATLAB Simulation: Loop Antennas H-field

Loop antennas typically have low radiation resistance 'Rr' and high reactance value. Hence their impedance is difficult to match to a transmitter. As a result, a loop antenna is more commonly used as a receiving antenna **[5]**. The E-H pattern follows the distribution of 'sin θ' **[10]** giving the radiation pattern like that of a short dipole. The small loop antenna is considered as dual of the loop antenna. If a small dipole had magnetic current flowing as opposed to electric current, the field pattern would resemble that of a small loop. Figure VII shows the dimension of an elliptical loop antenna in a coordinate system. It is evident from the cartesian coordinate system that the diameter is 20mm. A practical loop antenna will not be a perfectly circular ring with a uniform radius. The figure is consistent with the practical design. In fig VIII, we have a 2-dimension H-field pattern only in a positive z-plane direction. The equations were extracted from Balanis. page (233-240). **[10]**.

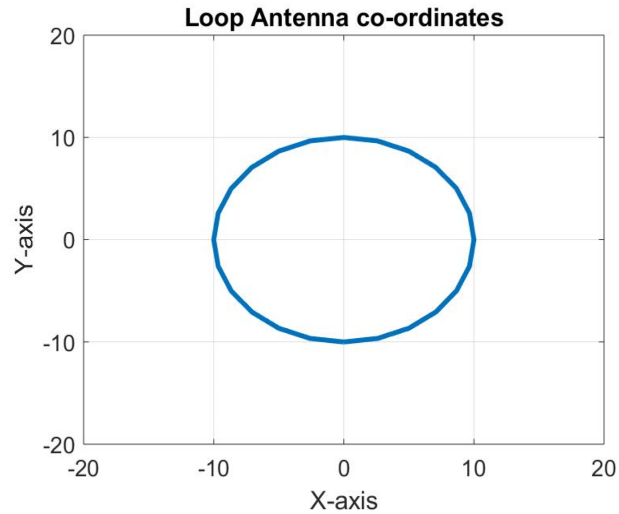


Fig VII: Co-ordinate System of Elliptical Loop Antenna (MATLAB)

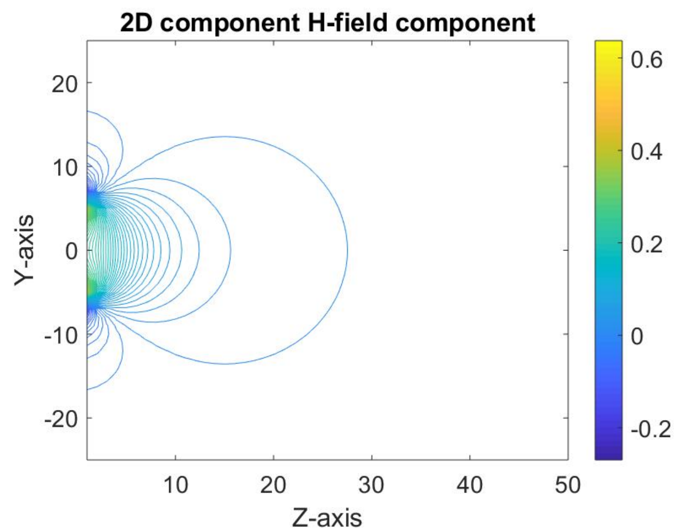


Fig VIII: H-field pattern of Loop Antenna using (MATLAB)

VIII. Resonance Behaviour of Spiral Resonators: MATLAB Antenna Toolbox

The strength of the Magnetic field generated by a transmitting coil (resonator) is quantified by the coupling factor 'k'. The range of 'k' varies from 0 to 1**[6]**. The value of k =1 represents perfect coupling. Coupling is dependent on the distance 'd' between the transmitter and receiver coil and follows the inverse relation with distance 'd'. Figure IX shows a 3-D position plot of Spiral Archimedean Resonators **[9]**. The dimension of the resonators can be interpreted from the 'y-z' axis and the distance ‘d’ can be directly interpreted from the x- position of both the resonators. The response of resonance frequency f_{res} with distance can be visualized from Fig X. It is evident from the 3D-plot that we have a strong localized field in the near-field. Coupling between the two resonators decreases with increasing distance and follows the inverse proportionality as stated below:

$$Coupling \propto \frac{1}{d^3} \qquad \text{eq. (1)}$$

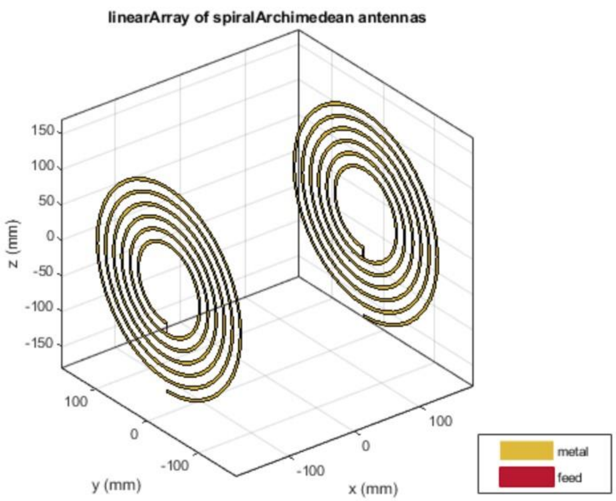


Fig IX: Spiral Archimedean Resonators [7]

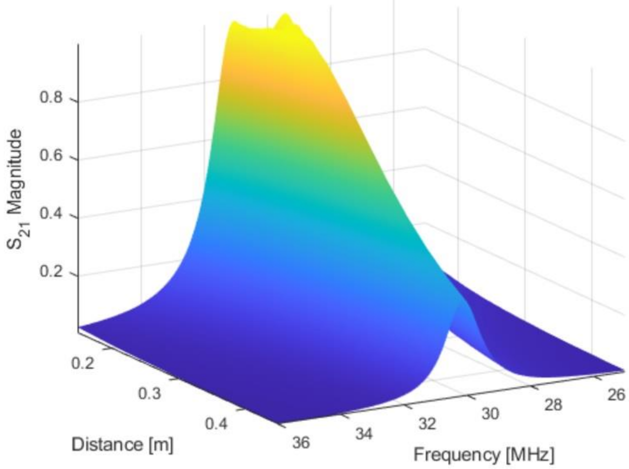


Fig X: 3D -frequency response of the resonators

From figure X, we can see a sharp peak at a frequency of around 30 MHz. This frequency is termed as the resonant frequency f_{res}, which is strongly dependent on the distance between the resonators, type of antenna used and the excitation strength of the source at the transmitter.

IX. WPT System Design: using Dipole & Loop antenna

Dipole antenna acts as an electric near-field coupler and a loop antenna acts as a magnetic near field coupler. There are several factors which affect the effective transmission between these two types of antenna:

a. geometry of transmitting and receiving antenna

b. electrical size of the antenna (l and D relative to **λ**)

c. distance ‘d’ between the antenna.

In general, as the electrical length of both types of antenna increases, the efficiency ‘η’ decreases.

In the literature **[4]** loop system was proven to be superior than the dipole in achieving high ‘η’**-** efficiency. The superiority was due to the Q-factor of the lumped elements in the matching circuits, which can be defined in the practical range only for the loop antenna, in comparison to a dipole.

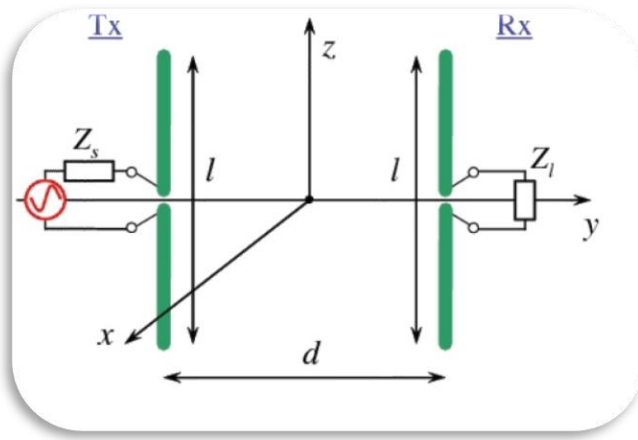


Fig XI: WPT-system using dipole antenna as transmitter & receiver

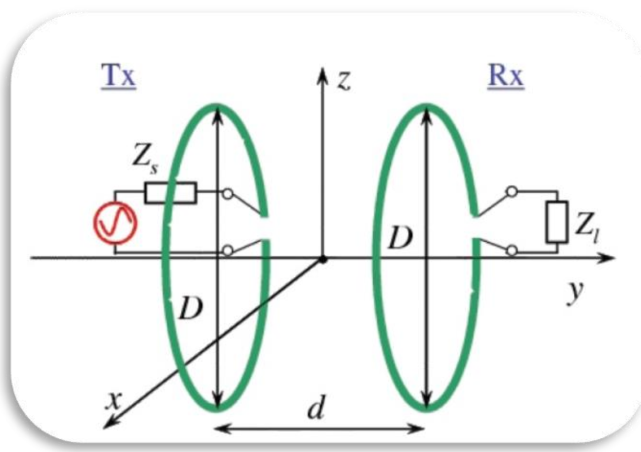


Fig XII: WPT-system using Loop antenna as transmitter & receiver

We can use a simplified model for the WPT-system using a 2-port network. As only a fraction of magnetic flux produced by the first coil enters the second coil, knowing the transmission efficiency is of great importance. Efficiency η can be calculated by the eq. (2-4).

$$We\ know, \qquad \eta\ =\frac{P_{load}}{P_{input}}$$

$$\eta\ =\frac{|S_{21}|^2(1-|\Gamma_l|^2)}{|1-\ S_{22}\Gamma_l|^2\ \ (1-|\Gamma_{input}|^2)} \qquad eq.(2)$$

$$\Gamma_{in}=S_{11}+\frac{S_{12}S_{21}\Gamma_{load}}{1-\ S_{22}\Gamma_{load}} \qquad eq.(3)$$

$$\Gamma_{load}=\frac{Z_{load}-\ Z_{output}}{Z_{load}+\ Z_{output}} \qquad eq.(4)$$

$where,\ \boldsymbol{\Gamma}_l: reflection\ coefficient\ at\ the\ load\ Z_l\ \ and$

$\boldsymbol{\Gamma}_{in}: reflection\ coefficient\ at\ 'Port\ 1'from\ fig.VI$.

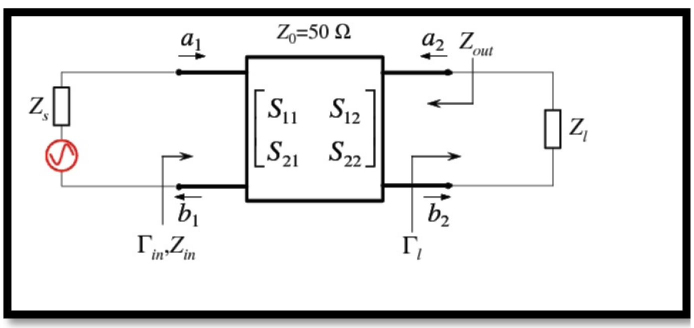


Fig XIII: Two-port equivalent circuit for WPT-system

$Refering\ to\ above\ figure$:

S_{ij} : denotes $S-\ parameter\ \ of\ 2\ port\ Network$;

Z_S: denotes the $internal\ impedance\ of\ Source$;

Z_l: denotes the $internal\ impedance\ of\ load$;

$Z_o\ is\ the\ characteristics\ impedance\ which\ usually\ have\ a$ value of '**50Ω**'

X. Simulation results AWR (a): Dipole-Dipole WPT System

Figure XIV below shows simulation results for the dipole antenna as both transmitter and receiver of the WPT system. From the fig. XIV (a) we have an impedance plot which decreases as we sweep across the frequency. In XIV (b) we have the radiation pattern which differs from the donut shape pattern of a dipole as 2-dipole was placed parallel to each other. In XIV (c) we have a response for return loss (R-L). This parameter indicates efficiency $'\eta'$. The bottom brown-graph of 'R–L' is for the 2- dipole and the top-pink graph is for a single-dipole response. We can deduce from the plot that the single dipole has greater 'R-L' than the 2-dipole.

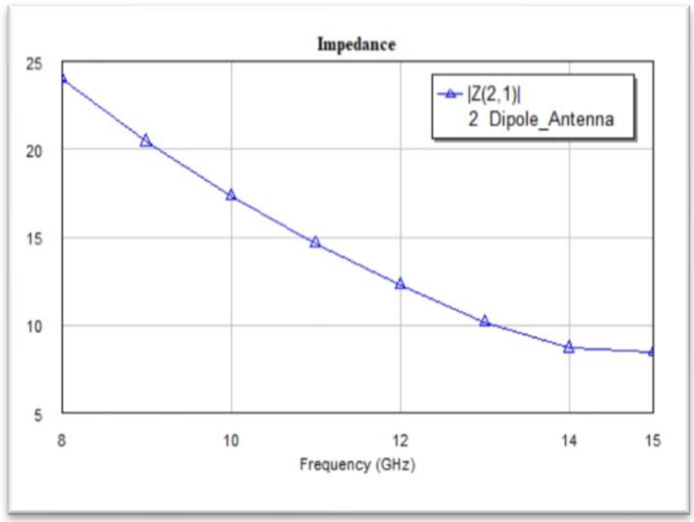


Fig XIV (a) : Impedance Vs Frequency

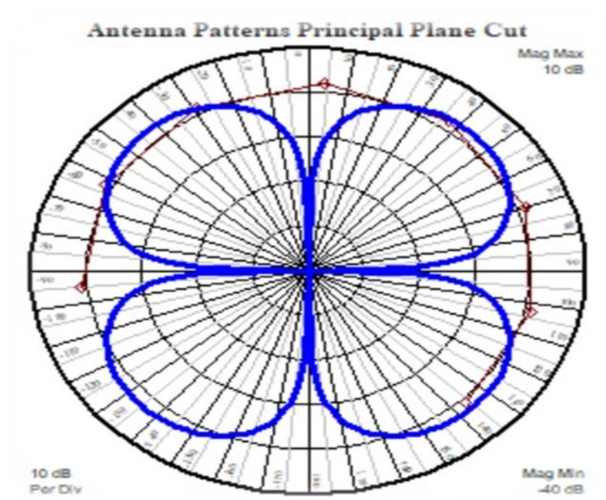


Fig XIV (b) : Radiation Pattern of 2-dipole (for receiver)

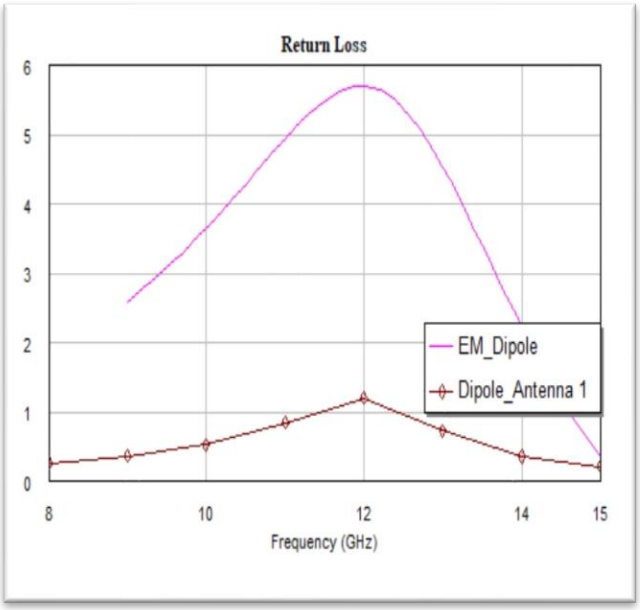


Fig XIV (c): Return Loss for a single dipole and 2-dipole

X. Simulation results AWR (b): Loop-Loop WPT System

In fig 'XV (a)'. we have far-field pattern obtained moving the loop antenna beyond the far-field condition. In fig 'XV (b)', we have a far-field pattern at different frequency sweep. We have a frequency response in fig XV (c), the center frequency gives a sharper peak if we bring the loop antenna closer to each other.

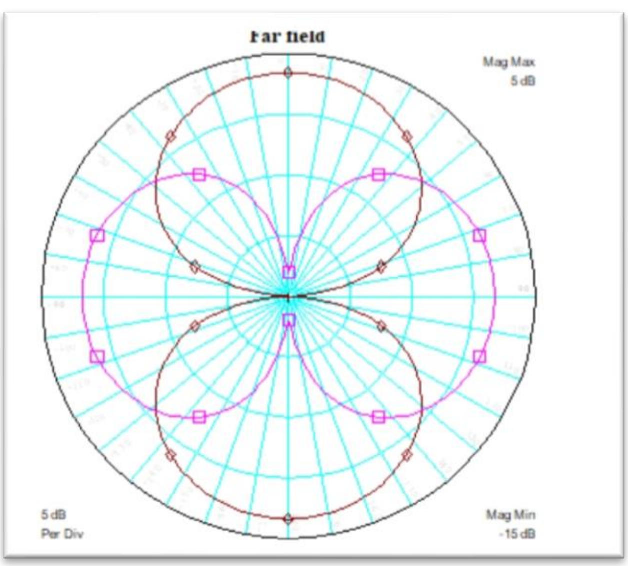


Fig XV (a): Far-field Pattern at a single frequency

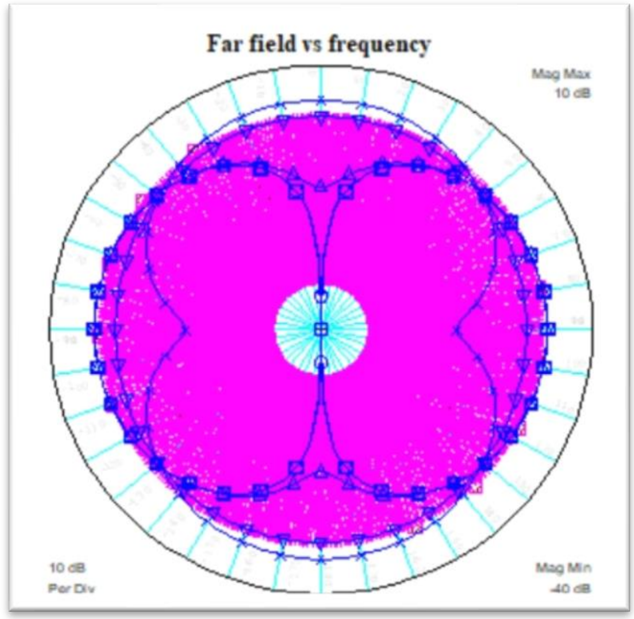


Fig XV (b): Far-field Pattern at different frequency sweep

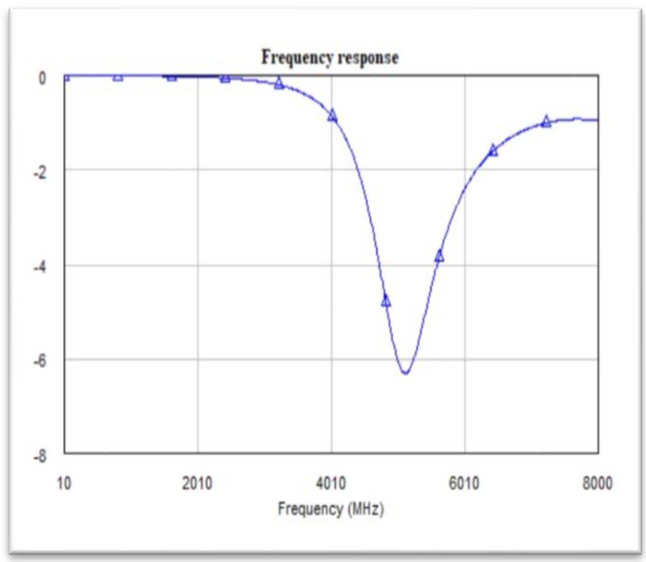


Fig XV (c): Frequency response with resonance freq at around 5200 MHz

X. Simulation results AWR (c): Dipole - Loop WPT System

In fig XVI (a), we have an antenna pattern when dipole was placed as a receiver. In fig XVI (b), we have linear total power for φ = 0 & 90 degree. As we change the distance between the antenna, we can have an intuitive sense of efficiency from these patterns.

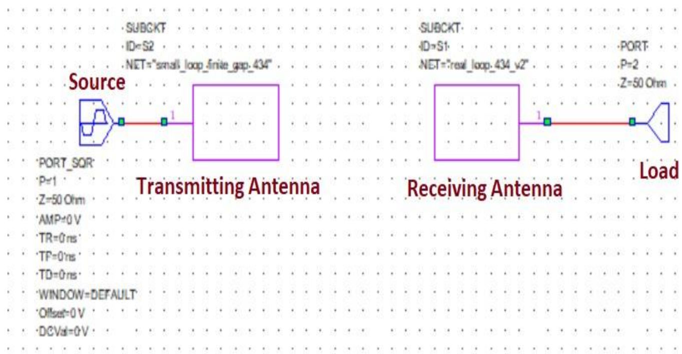


Fig XVII (a): Circuit Schematics of a simple WPT system in AWR

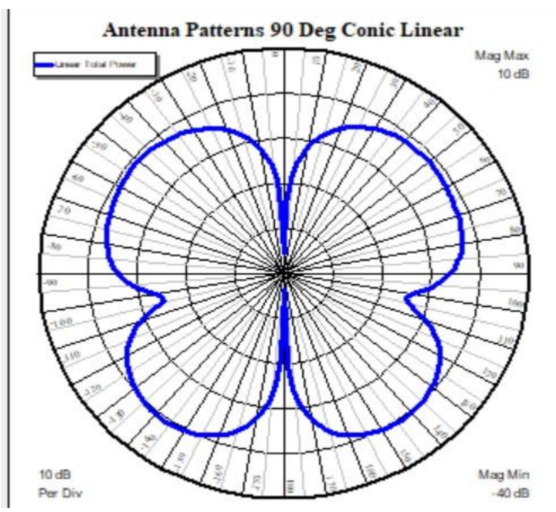


Fig XVI (a): Linear Power of Dipole as Receiver

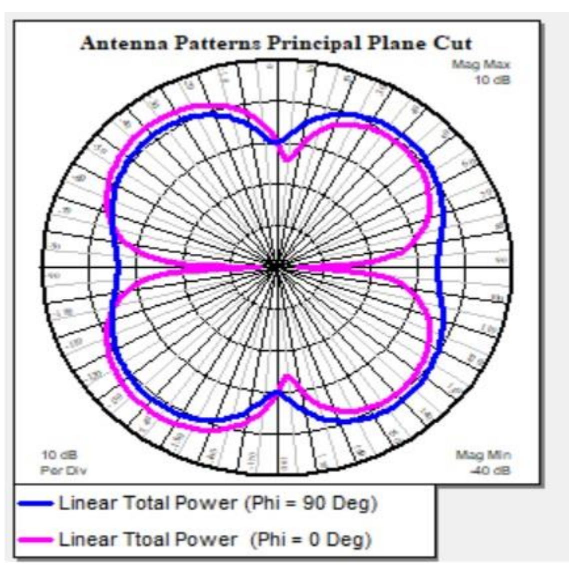


Fig XVI (b): Linear Total power at two different φ

XI. Conclusion

The objective of this project was to demonstrate power transmission between two common antenna types dipole and loop. This project could have been improved if the plots in AWR were shown with the variance of distance. SWPVAR seems to work with schematics only, and in schematics using a sub-circuit model of antenna appeared to have yielded no response for voltage-current, power at the receiving end. However, using an intermediate connection between the transmitting and receiving antenna through a microstrip wire or any electronic components showed a notable response for received power at the load port. Since it would not have served the title objective of this project. Hence, the responses were not reflected in this paper. The circuit schematics could be further enhanced using a 'balun' which would reduce mismatch and give higher efficiency. WPT has a promising potential in many areas of research. In the future, we might see its uses in high-density power devices, low-powered IC's and high-end circuit architectures.

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