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5G Magnetic Resonance Coupling Planar Spiral Coil Wireless Power Transfer

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Abstract

Wireless Power Transfer in the 5G frequency band is the most promising technology to power up ubiquitous small electronic devices as well as IoT devices. A strongly coupled magnetic resonance WPT technique that focuses on near-field electromagnetic energy has been proposed in this paper. However, most Magnetic Resonance Coupling Wireless Power Transfer (MRC WPT) applications have been designed in kHz and MHz frequency spectrum. This paper demonstrates Planar Spiral Coil Magnetic Resonance Coupling (PSC MRC) WPT designs at 5G (GHz) frequencies. Also, the transformation technique of the low frequency (kHz and MHz) magnetic resonance circuit model equations to high frequency (GHz) circuit model equations to achieve a high-efficiency power transfer. PSC MRC WPT designs structure antennas are designed at 3.4 - 3.5 GHz in the form of circular and square shapes with 1 turn coil. The proposed antenna structures are firstly being optimized in a full-wave electromagnetic simulator, CST Microwave Studio to resonate at the 3.4 - 3.5 GHz band. Then, the close-loop equations to determine the efficiency of 5G Magnetic Resonance Coupling Planar Spiral Coil Wireless Power Transfer is designed. Lastly, the results are compared with the simulation and calculated parts. The highest efficiency of the PSC MRC circular antenna is 31.58 % when the distance is at 2 mm, and 31.26 and 31.02 % when the distance is at 3 and 4 mm, respectively. The efficiency of circular PSC MRC is found to be 25 % better than the efficiency of square shape design.

Keywords: 5G, Magnetic resonance coupling, Planar spiral coil, Wireless power transfer, Near field coupling

Introduction

Over the past decade, we are surrounded by a plethora of emerging technologies. It includes small and inexpensive communication devices equipped with communication and sensing features. Thus, our future world is predicting the Internet of Things (IoT) paradigm that can access wireless communication systems and artificial intelligence technology. However, some IoT devices do not share common standards and communication requirements. The fifth-generation (5G) is capable to bring together the requirements of IoT devices by integrating multiple heterogenous technologies [1,2]. Furthermore, IoT devices need to be charged and maintained as the network system has massive numbers of sensors. Wireless power transfer is a promising technology to power up IoT devices [3].

Wireless Power Transfer (WPT) is a process in which the system is transmitting an electromagnetic wave (EM) from a transmitter (a power source) to a receiver (electric load). The EM wave is transferred without using any artificial interconnecting conductor [4-6]. Besides, WPT also refers to power transmission (in the form of electrical) at a radio frequency that is much lower than infrared and optical frequencies [4,7]. The concept of WPT has not yet been well finalized. Hence, the research on WPT for the last 2 decades has been developing and focusing on 4 major technological factors: High-density power devices, low power integrated circuits (ICs), high-efficiency antennas or rectennas, and innovative circuit architecture [4,8]. A transmitting antenna with an excellent focusing property and a large receiving antenna are needed to realize an efficient power transfer. It also can avoid energy spillover. Another method is to transmit electromagnetic energy using reactive fields that exist in the proximate open resonator [9].

This paper proposed, a WPT technique based on strongly coupled magnetic resonance which focuses on the near-field electromagnetic energy. This technique can extend the distance of the power transfer between the transmitter and the receiver. Both the transmitting and the receiving coil antenna must resonate at the same operating frequency. The energy is then transferred from the transmitter and the receiver via magnetic resonance. The Magnetic Resonance Coupling (MRC) WPT transmission distance is longer than the IC WPT system. However, there is an optimal distance to transmit the maximum efficiency between the transmitter and the receiver for the MRC WPT system [10]. The transmission efficiency will drop quickly when the receiving coil is shifted away from its optimal distance [11,12]. MRC WPT acquires advantages compared to the Inductive Coupling (IC) WPT due to its reliability for medium-distance applications and high efficiency [13-15]. Furthermore, in MRC WPT, the leakage conductance is compensated by combining the near field magnetic coupling and resonance technique. Thus, the method ensures to improve power flow path wireless transmission energy [13,8].

The Fifth Generation (5G) technology is the next evolution of technology that can provide connectivity for any electrical device, increase the data rate, and has higher energy efficiency. The most important reasons are to utilize these frequency bands for their larger available bandwidth, compact size of the antenna design, higher spatial resolution for a given antenna size, better temporal resolution, and the reusability of frequencies [16,17]. Varieties of 5G enabling technologies have been developed, including extending the wireless communication to the higher frequency band, the advanced development of multi-band antenna, and the wireless power transfer system [18,19]. Also, 5G technology can realize the vision of the Internet of Things/Internet of Everything (IoT/IoE). It supports the significant number of devices connected with a reduced cost per information transfer [4].

Furthermore, the history of RF identification (RFID) Near-Field Wireless Power Transfer for a few decades has applications that operate at low-frequency (LF) ranging from 30 ~ 300 kHz and high frequency (HF) ranging from 3 ~ 30 MHz bands. The LF and HF RFID systems' commercial applications have already been used since the 1990s [20]. Thus, the next 5G generation wireless networks' critical essence is to explore and exploit this new, high-frequency mm-wave band, which ranges from 3~300 GHz frequency band [21-24]. The International telecommunication Union has declared the following spectrum for 5G communication, and the spectrum range is; 3.4 - 3.6, 5 - 6, 24.25 - 27.5, 37 - 40.5 and 66 - 76 GHz frequency bands [25].

There have been several reports on the near-field WPT technology at the GHz frequency band Generally, the proposed designs that are reported are using planar coil, miniature, and fabricated on the silicon wafer [20,26-28]. However, the proposed designs by [20,26-28] are mostly complex and costly, and there is no discussion regarding the theoretical part that has been done comprehensively. The transformation technique of the low frequency (kHz and MHz) magnetic resonance circuit model equations to high frequency (GHz) circuit model equations to achieve a high-efficiency PSC MRC WPT design structure is introduced in this paper. This novel technique can be applied to effectively design PSC MRC Antenna WPT for 5G applications. Most reported Magnetic Resonance Coupling Wireless Power Transfer (MRC WPT) applications have been designed in kHz and MHz frequency spectrum [29-32].

This paper proposed the Planar Spiral Coil Magnetic Resonance Coupling (PSC MRC) Antennas designed at 3.4 - 3.5 GHz frequency band for the Circular and Square shapes with 1 turn. The proposed PSC MRC WPT antennas are firstly designed and optimized to be resonated using their stray or intrinsic capacitance and self-inductance of the coil using the concept of microwave wavelength equation in CST Microwave software 2016. Next, the close-loop equation is proposed to determine the efficiency of Magnetic Resonance Coupling Planar Spiral Coil Wireless Power Transfer in the GHz frequency band. The results are then compared with the simulated and calculated part.

The PSC MRC Antennas are modeled on the FR4 substrate with thickness and copper thickness of 0.6 and 0.035 mm, respectively, in the CST Software. The parametric evaluation has been done in CST software to find the best performance of S11 (dB) and SRF (GHz) of the proposed PSC MRC Antenna designs to be working at a 5G frequency band. The return loss S11 of each design needs to be below −10 dB to improve the efficiency of the MRC WPT system. Figure 1 below shows the return loss (S11 dB) versus self-resonance frequency (SRF) of the Circular 1-turn PSC MRC Antenna at 3.4 - 3.5 GHz.

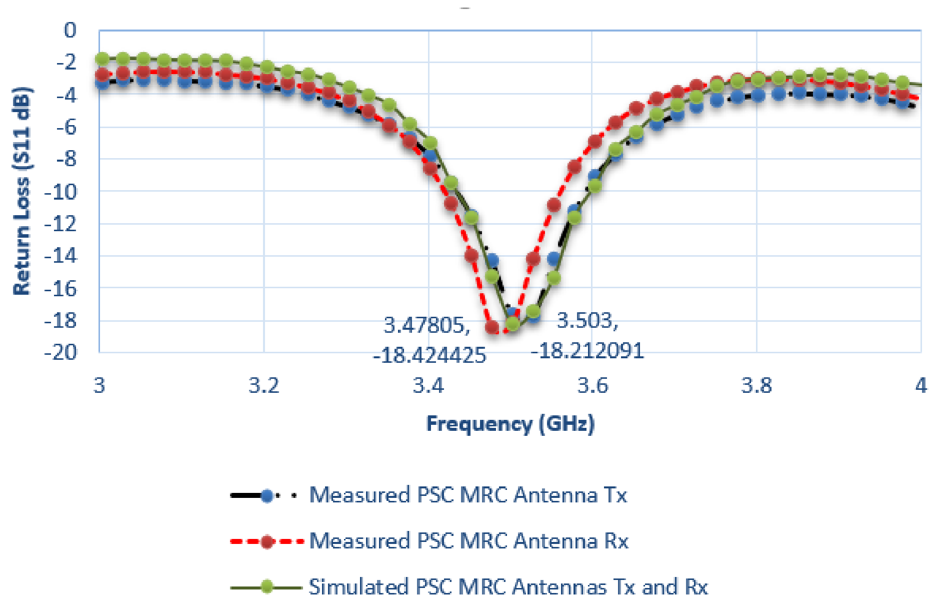


Figure 1 Return loss (S11 dB) versus SRF of the Circular 1-turn PSC MRC Antenna at 3.4 - 3.5 GHz.

5G High-frequency planar spiral coil magnetic resonance coupling wireless power transfer

The High-Frequency Planar Spiral Coil Magnetic Resonance Coupling antenna design's biggest challenge is improving the receiving power efficiency and good WPT charging performance. It has been known that to achieve the same efficiency at transmitter and receiver, the antenna size must be proportional to its operating wavelength. Loop antenna is classified into 2 categories, which are electrically small and electrically large. When the loop's overall circumference is less than 1-tenth of a wavelength ($C\sim\lambda/10$), it will be considered an electrically small loop antenna [33]. However, it will be an electrically large loop antenna when the circumference is about a free-space wavelength ($C\sim\lambda$). Hence, a possible solution to improve the antenna performance and efficiency of a higher frequency system (in this case, GHz), the antenna with the reduced size and the circumference of a free space wavelength, is designed. The circumference of the 1-wavelength loop ($C\sim\lambda$) is always referred to as a resonant loop antenna. The antenna will resonate when C is slightly larger than λ. Since the PSC MRC loop is designed to be a self-resonance frequency, there is no need for an external capacitor to resonate with the antenna. The PSC MRC WPT antennas designed are resonated using their stray or intrinsic capacitance and self-inductance of the coil using the concept of microwave wavelength equation.

The schematic view and dimension for each circular and square PSC MRC Antennas have been demonstrated in **Figure 2**. The PSC MRC Antennas have been designed in CST Software and the dimension is optimized to be operated at the 3.4 - 3.5 GHz frequency band. Also, each PSC MRC Antennae is designed on an FR4 substrate with relative permittivity, ε_r, 4.4, and 1.6-mm thickness. The PSC MRC Antenna is made from copper with a thickness of 0.035 mm and a conductivity value of 5.8×10^7 S/m.

The models are both based on the circular and square PSC antenna architecture design. **Figure 2** beneath proposed the PSC MRC WPT design and the geometrical parameters for both circular-shaped and square-shaped PCS MRC Antenna. *Din* and *Dout* indicate the inner and outer diameter, respectively. Besides, the PCS MRC Antenna's width and spacing are denoted by the *w* and *s*, respectively.

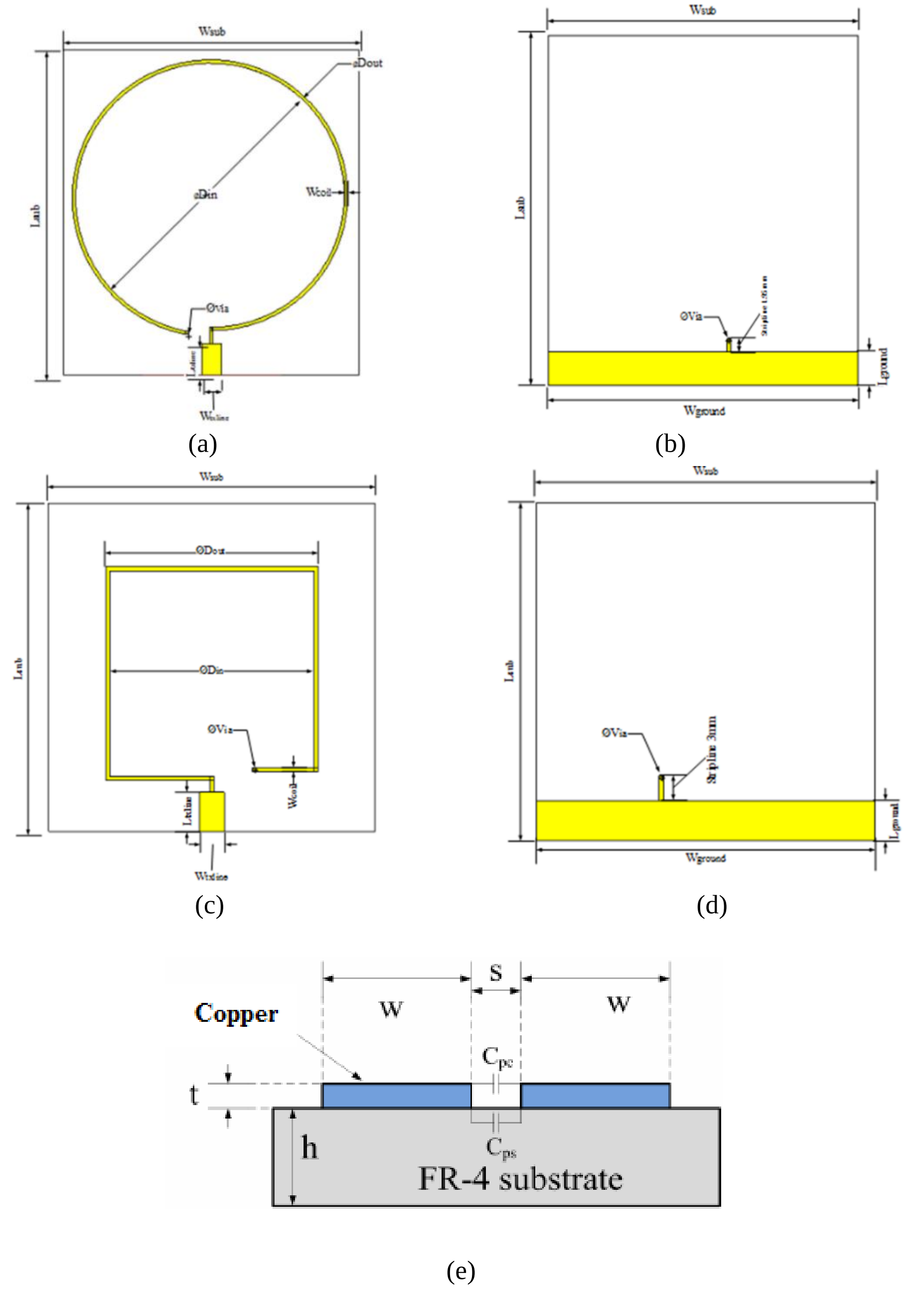


Figure 2 Schematic view of (a) the front view of the self-resonant circular PSC MRC WPT with 1 turn, (b) the back view of the self-resonant circular PSC MRC WPT with 1 turn, (c) the front view of the self-resonant square PSC MRC WPT with 1-turn, (d) the back view of the self-resonant circular PSC MRC WPT with 1 turn, and (e) side view of PSC MRC for a circular and square shape.

The design parameters of the Circular PSC MRC and Square PSC MRC antennas are the width of the planar coil (W), space between the turns of the planar coil (S), the number of turns (N), inner diameter (D_{in}), outer diameter (D_{out}), and the PSC shapes. These parameters will determine the inductor (L) value and the self-resonant frequency (SRF) of the proposed PSC antenna design. The value of the inductor (L) and self-resonant frequency (SRF) will determine the efficiency, η, and performances of the proposed PSC MRC WPT systems.

Table 1 below summarized the optimal dimension of the proposed circular and square PSC MRC WPT antenna structures in **Figure 2**. The substrate for each PSC MRC WPT antenna is 45×45 mm in size for the first design, and then it will differ according to the dimension of the PSC MRC WPT antenna's self-resonance design. The width, Wcoil, and the spacing, Scoil are set to 0.5 mm for optimum results and ease of fabrication. The value of D_{in}, D_{out}, ØVia, Ltxline, Wtxline, Wground, Lground, and Stripline of different designs is summarized according to the self-resonance frequency of the PSC MRC WPT antenna. From **Table 1**, it can be seen that the optimum parameters have been achieved to resonate the PSC MRC WPT antenna for the circular and square designs to be operated at the 3.4~3.5 GHz frequency band. The values are optimum when the frequency is performed at the 3.4~3.5 GHz bands, with the lowest S11 below −10 dB.

Table 1 shows the circular and square PSC MRC WPT antenna design parameters.

Parameters	MRC WPT planar coil antenna 1-turn (*mm*)	
	Circular	**Square**
Substrate Length, *L*	49.75	40
Substrate Width, *W*	45.0	40
Substrate Thickness, *t*	1.6	1.6
Width Coil,*w*	0.5	0.5
Spacing Coil,*s*	0.5	0.5
Diameter In, *Din*	40	25
Diameter Out, *Dout*	41	26
Diameter Via, *ØVia*	0.5	0.5
Length of Transmission Line, *Ltxline*	4.75	4.75
Width of Transmission Line, *Wtxline*	3.0	3
Length of the Ground, *Lground*	4.75	4.75
Width of the ground, *Wground*	45	40

The simulations of the PSCs MRC WPT antenna design are using the computer software CST Microwave Studio 2016. The geometrical of the PSCs antenna is created using the CST modeling tools. The source of the excitation signal and the received signal location is the port attached to the model in **Figure 3**.

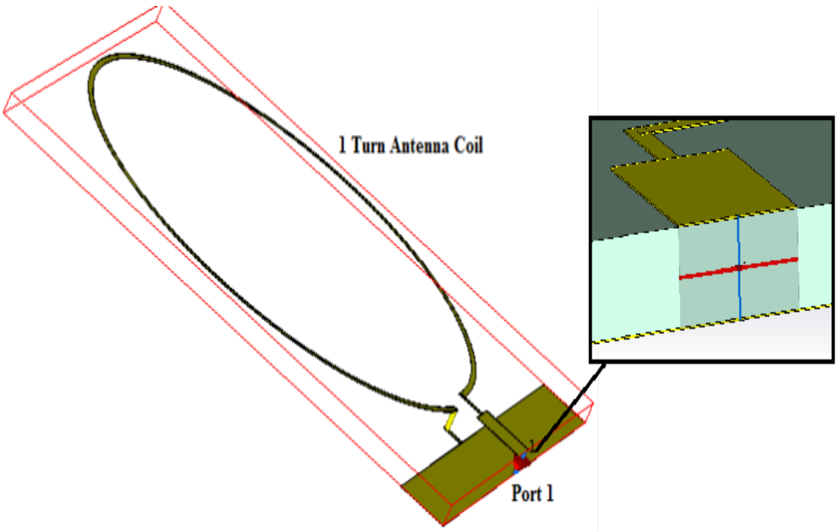
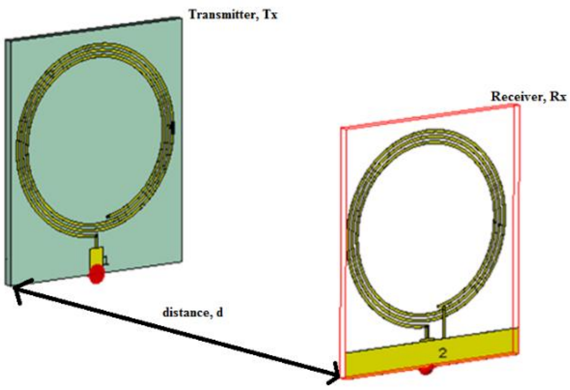


Figure 3 Discrete port 1 for circular 1-turn coil antenna.

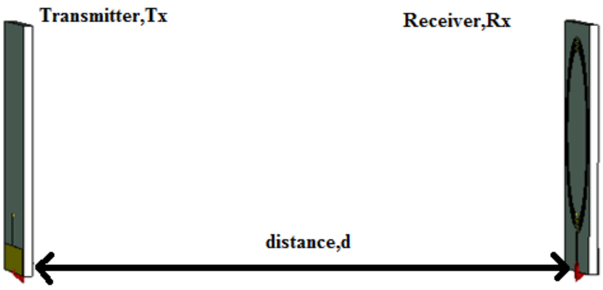
Figure 3 shows how the port is attached to the design models in CST software. The GHz PSC MRC antenna design's biggest challenge is improving the receiving power efficiency and good WPT charging performance. It has been known that to achieve the same efficiency when transmitting and receiving, the antenna size must be proportional to its operating wavelength.

The proposed fully planarized circular and square MRC WPT system with both transmitter and receiver coil antenna is printed on the same side of the FR4 substrate. **Figure 4** shows the PSC MRC WPT antenna is applied to both sides of the transmitter and receiver, respectively. The distance is varied from 0 to 100 mm to investigate the effect of H-field, mutual coupling, and efficiency of the PSC MRC WPT for 5G Applications. The transmitter and the receiver separation should be at least 50 mm to satisfy most WPT applications [34]; the distance of 0 to 100 mm is chosen in this work because to be applied in the PSC MRC WPT working system separation. However, For the high-frequency (GHz), the highest efficiency power transfer is mainly below the 10 mm separation distance between TX and RX [35].

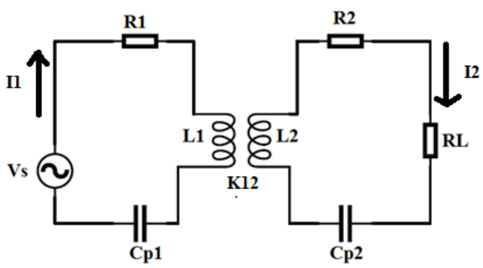
The MRC WPT uses conductor loop coils to generate the alternating magnetic field from the transmitter to the receiver coil. The strength of the field H and mutual coupling eventually decrease as the distance increase. Furthermore, the transfer efficiency decreases dramatically with the increasing distance between the transmitter (Tx) and receiver (Rx).



(a)



(b)



(c)

Figure 4 Schematic view of circular design (a) the perspective view of the proposed PSC MRC WPT system, (b) the side-view of the proposed PSC MRC WPT system, and (c) Equivalent circuit schematic diagram of the MRC WPT from transmitter coil to receiver coil.

Both circular PSC and square PSC architecture are designed to be operated at a high-frequency band which are ranging from 3.4 to 3.5 GHz. The essential design model such as transmitter (TX) and receiver (RX) dimensions, number of turns of the coils, self-mutual inductance, coupling coefficient, and the optimum design is investigated in CST software and MATLAB to compare both design's performances.

The Wireless Power Transfer (WPT) System has been differentiated according to the operating frequency and range, namely, the close coupling, remote coupling, and long-range. A WPT system that is higher than 2.45 GHz is usually known as a backscatter system due to its operational principle of using electromagnetic (EM) waves in the far-field [36]. The PSC MRC Antenna WPT for 5G Applications has been designed to be operated in 3.4 - 3.5 GHz. For passive WPT PSC antennas in this frequency band, the efficiency of converting RF to dc power is very low because the antenna is very small. Thus, our design is not practical to transfer long-distance power transfer. A far-field transfer power transfer is not suitable due to the limited output transmitter coil power. Therefore, the working design is entirely based on near-field WPT using a close coupling method like RFID contactless smart card.

Derivation of efficiency for high-frequency magnetic resonance coupling planar spiral coil wireless power transfer

Following are Eq. (1) until Eq. (22), used in MATLAB that are needed to derive the closed-loop equation to determine efficiency for 5G MRC WPT. The individual model for self-inductance, mutual inductance, and the parasitic component of this work can be illustrated in **Figure 2**.

The efficiency and gain of the system are expressed by the scattering parametersS_{21}, which can be found in Eq. (1) below. According to [8] and [37], Eq. (1) can be applied for low-frequency (kHz and MHz) and high-frequency(GHz) PSC MRC WPT antenna designs.

$$S_{21} = 2\frac{V_0}{V_s}\left(\frac{R_1}{R_2}\right)^2 \tag{1}$$

By incorporating the low-frequency (kHz and MHz) equations with the high-frequency(GHz) equations, the power transfer efficiency (η) for the proposed PSC MRC WPT system by using the general scattering parameters S_{21} can be evaluated as Eq. (2) below [8,38].

$$\eta = |s_{21}|^2 \; X \; 100\% \tag{2}$$

The proposed design precise expression for inductance value, *L*, can be calculated as below. Mostly, Eq. (3) is applied to find the value of PSC inductance for the low-frequency (in kHz and MHz) PSC design and high-frequency (GHz) design. However, in this paper, Eq. (3) has been proposed as the basic equation to derive novel equations to find the precise expression for inductance value, L high-frequency (GHz) designs.

$$L = \frac{\mu_0\, N^2 D_{avg} C1}{2}\left(ln\left(\frac{C2}{\rho}\right) + C3\rho + C4\rho^2\right) \tag{3}$$

The magnetic permeability of free space, μ_0 , is defined as $4\pi\times10^{-7}$ H/m. The fill ration, ρ, is the fill ratio, and the average diameter, D_{avg} can be calculated as Eqs. (4) and (5) below.

$$\rho = \frac{D_{out} - D_{in}}{D_{out} + D_{in}} \tag{4}$$

$$D_{avg} = \frac{D_{in} + D_{out}}{2} \tag{5}$$

The value of the coefficient factors depends on the shapes of the PSC antenna design regardless of low frequency and high-frequency design. The coefficient factors value of $C_1, C_2, C_3\, , and \;\; C_4$ can be found in **Table 2** below [35][38].

Table 2 Shows the coefficient factors for the coil antenna depending on the shapes [39].

Layout	C_1	C_2	C_3	C_4
Square	1.27	2.07	0.18	0.13
Circular	1.00	2.46	0.00	0.20
Hexagonal	1.09	2.07	0.18	0.13
Octagonal	1.07	2.29	0.00	0.19

To design the PSC MRC antenna that can be applied in a high-frequency (GHz) design, each of the parasitic elements of the proposed PSC antenna should be computed. These parasitic elements should be calculated because the self-resonance frequency (SRF) of the PSC MRC antennas cannot be tuned using other external components, such as an external capacitor or external inductor as in the lower frequency model. Therefore, the parasitic equations of high-frequency PSC antennas are integrated into the low-frequency modeling equations, so that suitable modeling equations are achieved to design the proposed PSC MRC antenna. The length of the conductive trace, Lc, and the series resistance denotes the metal loss, R_s, also can be expressed as DC resistance, R_{dc}, at high frequency can be calculated as below.

There are no publications available on the integration of the equations to find the efficiency of the PSC MRC WPT in GHz designs. Firstly, the conductive trace, Lc, in Eq. (6) needs to be computed to find the value of the metal loss, R_s, in the high-frequency (GHz) PSC antenna design

$$Lc = 4ND_{out} - 4Nw - (2N+1)^2(s+w) \tag{6}$$

From Eq. (6), N is the number of turns of the proposed PSC antennas, Dout is the diameter out of the proposed PSC antennas, w is the width of the proposed PSC antenna, and s is the spacing between the planar coil of the proposed PSC antenna. Thus, the metal loss of the high-frequency (GHz) of the proposed PSC antennas can be computed as in Eq. (7) below;

$$R_s = R_{dc} = p_c \frac{L_c}{wt_c} \tag{7}$$

The value of the parasitic self-capacitance, C_p, of the proposed PSC antennas is crucial to determining the SRF of the PSC MRC antennas. Thus, the self-capacitance, C_p , due to the distance between the spiral turns in the FR4 substrate of the high-frequency designs can be calculated in Eq. (9). This equation is applied to find the parasitic element in kHz, MHz and GHz PSC antenna designs. But firstly, the value of the total length of the spiral coil gap, l_g, in Eq. (8) need to be computed to find the value of self-capacitance, C_p.

$$l_g = 4(2\frac{d_{out}}{2} - w \cdot N)(N-1) - 4s \cdot N(N+1) \tag{8}$$

From Eq. (8), N is the number of turns of the proposed PSC antennas, Dout is the diameter out of the proposed PSC antennas, w is the width of the proposed PSC antenna, and s is the spacing between the planar coil of the proposed PSC antenna Consequently, the value of the self-capacitance, C_p, for proposed high-frequency (GHz) PSC antennas can be computed as Eq. (9) below.

$$C_p = C_{pc} + C_{ps} = (0.9\varepsilon_{air} + \varepsilon_{sub})\varepsilon_0 \frac{t}{s} l_g \tag{9}$$

Where, p_c, is the resistivity of the proposed PSC antenna design conductive material, which is copper. Then, t_c , is the thickness of the copper, and w is the width of the proposed PSC antennas. While ε_{air} , is equal to 1 and ε_{sub} , is equal to 4.4 Furthermore, ε_0, is the dielectric constant of the vacuum, which is equal to 8.854×10^{-12} F·m^{-1}.

Thus, the self-resonance frequency, f_{SRF}, of the proposed high-frequency PSC antenna designs can be derived as in Eq. (10) below by integrating the value of inductance, L, from Eq. (3) and the value of the self-capacitance, C_p, from Eq. (9).

$$f_{SRF=}\ \frac{1}{2\pi(LC_p\ )} \tag{10}$$

The mutual inductance, *M*, for the 2 current-carrying planar coils can be calculated using Neauman's equation. According to [39] the equation can be expressed as Eq. (11) below for different axial expressions. The paper only mentioned how to calculate the mutual inductance, M, for the planar coil. Thus, the equations from this paper are used to be integrated into modeling the equations for high-frequency PSC MRC antenna design's efficiency, η. Eq. (11) can be used to calculate any mutual inductance using the planar coil.

$$M = \ \rho \times \sum_{i=1}^{i=\,n_1} \sum_{j=1}^{j=n_2} M_{ij} \tag{11}$$

$$M_{ij} = \frac{\mu_0 \pi a_i^2 b_j^2}{2(a_i^2+b_j^2+d^2)^2}\ (1 + \ \frac{15}{32}\gamma_{ij}^2 + \ \frac{315}{1024}\gamma_{ij}^4) \tag{12}$$

$$a_i = r_{outPSC1} - (n_i - 1)(w_{PSC1} + s_{PSC1}) - \frac{w_{PSC1}}{2} \tag{13}$$

$$b_j = r_{outPSC2} - \left(n_j - 1\right)(w_{PSC2} + s_{PSC2}) - \frac{w_{PSC2}}{2} \tag{14}$$

$$\gamma_{ij} = \frac{2a_i b_j}{\left(a_i^2+b_j^2+d^2\right)} \tag{15}$$

Eqs. (11) - (13) is derived to suit this work's proposed PSC antenna designs for GHz frequency. These equations are then modeled in MATLAB to calculate the mutual coupling of each proposed PSC MRC antenna design.

It can be defined that, $r_{outPSC1}$and $r_{outPSC2}$ are the outer radius of the proposed PSC MRC antenna TX and PSC MRC antenna RX, respectively. The track width for both proposed PSC MRC antenna designs are w_{PSC1} and $w_{PSC2}$and the spacing for both proposed PSC MRC antenna designs are s_{PSC1} and s_{PSC2}. While n_i and n_j , is the number of turns for both TX and RX of the proposed PSC MRC antenna designs. The value of ρ, depends on the shape of the PSC MRC antenna coil. For the circular shape PSC MRC, $\rho = 1$, while the square shape PSC MRC antenna, $\rho = \ (4/\pi)^2$. The mutual coupling, *M*, is essential in determining the efficiency of the MRC WPT system. The mutual coupling, *M*, is directly proportional to the magnetic field strength and the efficiency of the PSC MRC WPT system.

The coupling coefficient of the proposed PSC MRC WPT system can be calculated in Eq. (16) below [40]. Eq. (16) can design PSC antenna in low-frequency (kHz and MHz) and high-frequency (GHz).

$$K_{12} = \ M_{12}/\sqrt{L_1 L_2} \tag{16}$$

Figure 4(c) shows that the system's power supply is an AC signal generator. The current in the transmitting coil is I_1, the internal resistance of R_1, the capacitance Cp_1, and the inductance L_1. The current at the receiver side is called I_2, the resistance is R_2, the resistance is R_2, the capacitance is Cp_2, and the inductance is L_2. The coupling coefficient between the coil antennas is called K_{12}. Thus, the related equations which are Eq. (3), Eq. (7), Eq. (10) and Eq. (12), have been integrated and derived as in Eq. (17) below to be used in high-frequency (GHz) PSC MRC WPT designs. The low-frequency (kHz and MHz) equations cannot be used in this proposed calculation.

$$\begin{cases} I_1\left(R_{s1} + \frac{1}{j\omega L_1} + j\omega I_2 M_{12} = \ V_s\right) \\ I_2\left(R_{s2} + \frac{1}{j\omega L_2} + j\omega I_{21} M_{12} = \ 0\right) \end{cases} \tag{17}$$

Then, the impedance of each coil of the proposed PSC antenna designs for high-frequency (GHz) is derived and computed as in Eqs. (18) and (19) below.

$$Z_1 = R_{s1} + j\omega L_1 + \frac{1}{j\omega C_{p1}} \tag{18}$$

$$Z_2 = R_{s2} + j\omega L_2 + \frac{1}{j\omega C_{p2}} \tag{19}$$

Next, Eq. (20) is used to calculate V_0 which is the voltage output.

$$V_0 = I_2 R_2 \tag{20}$$

Thus, the proposed PSC antenna designs for high-frequency (GHz)'s current, I_2, is derived as Eq. (21) below.

$$I_2 = -\frac{j\omega K_{12}\sqrt{L_1 L_2}V_S}{Z_1 Z_2 + \omega^2 K_{12}^2 L_1 L_2} \tag{21}$$

Eqs. (20) and (21) are integrated, and the expression of V_0 of the proposed PSC antenna designs for high-frequency (GHz) is derived as Eq. (22) below. Finally, the efficiency of the proposed 5G PSC MRC WPT can be calculated by incorporating Eq. (22) into Eq. (2).

$$V_0 = -\frac{j\omega K_{12} R_2\sqrt{L_1 L_2}V_S}{Z_1 Z_2 + \omega^2 K_{12}^2 L_1 L_2} \tag{22}$$

Experimental set up of 5G high-frequency planar spiral coil magnetic resonance coupling wireless power transfer

The PSC MRC Antenna experimental setup for the transmission coefficient, S21 (dB) with distance separation from 0 to 100 mm is shown in **Figure 5**. The PSC MRC Antenna circular and square shape in **Figure 2** is fabricated on the FR4 substrate with a thickness of 1.6 mm and a copper thickness of 0.035 mm. The width and the spacing of the planar coil antenna are 0.5 mm. The antenna is designed to be working on a 3.4~3.5 GHz frequency band. The PSC MRC WPT antenna needs to be drilled to create a via from the antenna's front part. Then the via is connected to the ground at the back of the antenna substrate. The SMA connector with 50Ω characteristic impedance is connected to the planar coil antenna's transmission line for the antenna to be working for the testing. **Figure 5** shows the PSC MRC Antenna Set-up for the transmission coefficient, S21 (dB) with distance separation from 0 to 100 mm. The scattering parameters S11 (dB), resonance frequency in GHz, and the transmission coefficient from Port 1 to Port 2, S21 (dB) of the fabricated PSC MRC antennas are measured using a Vector Network Analyzer.

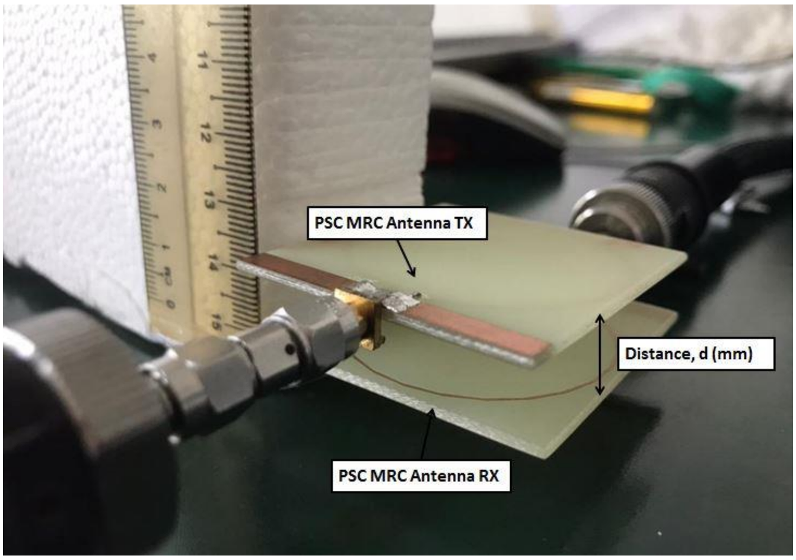


Figure 5 The PSC MRC antenna set-up for the transmission coefficient, S21 (dB) with distance separation from 0 to 100 mm.

In the MRC WPT system, the transmitting coil's design and the receiving coil are critical factors affecting the system's transmission efficiency [41]. The required coil number of turns and inductance decreases as the coil frequency increases to design the GHz frequency MRC WPT Antenna. However, the voltage induced in the Transmitter part is proportional to the frequency. Thus, reducing the number of coil turns hardly affects power transfer efficiency at high frequencies [42]. Also, the MRC WPT technology achieves efficient power transfer through resonance coupling between the resonant coil of the same frequency operations. When the system works at the same resonance frequency, the electromagnetic energy is efficiently transmitted through the magnetic field's conversion to the energy due to the energy transmission channel established between the coil. However, the transmission efficiency will be gradually decreasing as the transmission distance between the TX and RX increases accordingly.

Results and discussion

The mutual coupling *M* depends on the shared magnetic field between the 2 coils or inductors separated by the distance *d*. Any change in axial displacement *d* will affect *M* and eventually affect the WPT system performances. Besides, *M* also depends on the geometric parameters of the inductor coil. The PSC MRC Antenna will have different shapes, turn numbers, coil width, and coil separation. All the parameters need to be varied to get a higher *M* for the WPT system's excellent performance. To calculate *M*, the current PSC MRC Antennas are assumed as continuous current-carrying filaments. **Figure 6** below shows that the PSC MRC Antenna of Circular 1-turn has the highest M than the PSC MRC Antenna of Square 1-turn. As the distance is increasing, the mutual coupling of the PSC MRC is also decreasing. This is because the mutual coupling strength between TX and RX decreases when distance separation is getting bigger. A higher mutual coupling is needed for the best performance efficiency of the WPT system. Thus, it can be concluded that the PSC MRC Antenna of Circular 1-turn has the best performance in mutual coupling as compared to the PSC MRC Antenna of Square 1-turn.

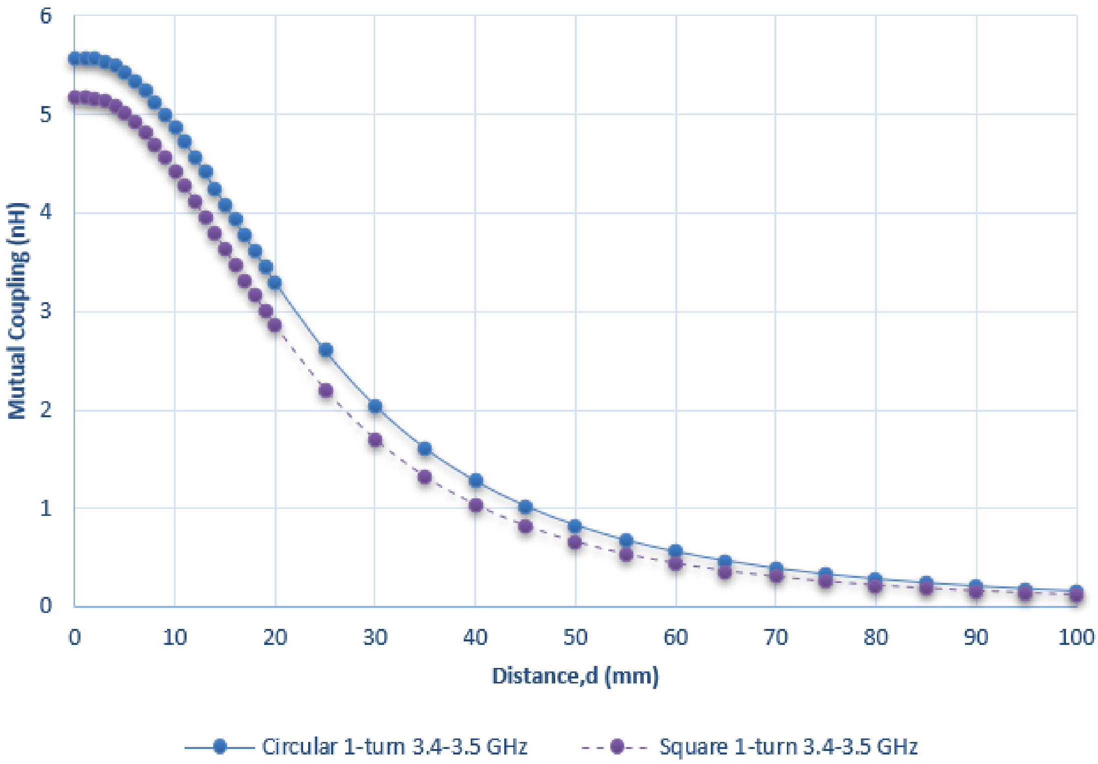


Figure 6 Calculated mutual coupling, M, for PSC MRC of circular 1-turn versus PSC MRC of square 1-turn at 3.4 - 3.5 GHz.

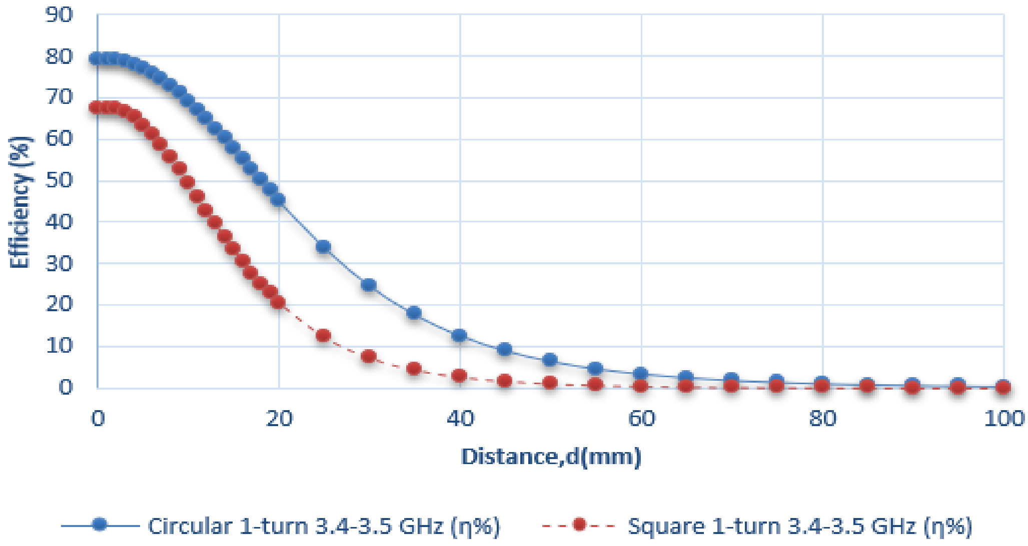


Figure 7 Calculated efficiency for circular PSC MRC at 3.4 - 3.5 GHz versus square PSC MRC at 3.4 - 3.5 GHz.

The power transfer efficiency of the PSC MRC designs is calculated using the circuit theory. Eqs. (1) - (22), have been calculated and modeled in MATLAB to analyze each PSC MRC design's efficiency at 3.4 - 3.5 GHz. Power efficiency is essential in determining the high-power parameters for the WPT system. In conclusion, for the 3.4 - 3.5 GHz calculated design, the PSC MRC Circular's efficiency is better than the PSC MRC Square design's efficiency as shown in **Figure 7**. The mutual coupling must be higher and is crucial to achieving a higher efficiency WPT design. However, some other parameters also affected efficiency, such as the PSC MRC Antenna's geometrical shape. The geometrical configurations of the PSC MRC are the inductance value L, the number of turns, spacing, width, radius in, radius out, and the axial spacing of the WPT. The non-uniform current distribution from various electromagnetic phenomena dramatically affects the coil electromagnetic induction. For example, the edge-effect is occurred by the coil geometry of the PSC.

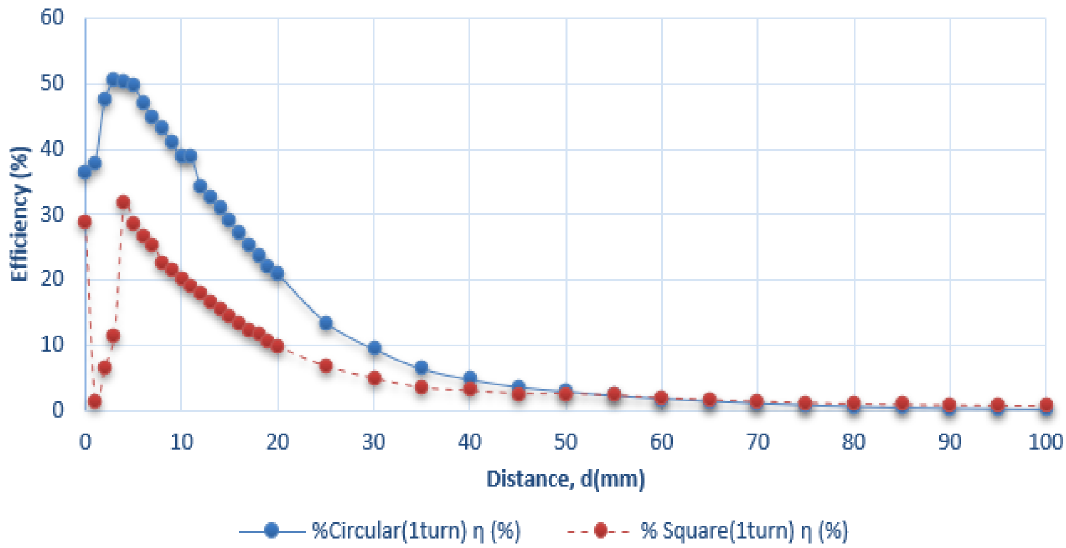


Figure 8 Efficiency (%) CST simulation for PSC MRC circular 1-turn versus square 1-turns at 3.4 - 3.5 GHz.

Figure 8 is the comparison between CST Simulation for PSC MRC Circular 1-turn versus Square 1-turns at 3.4 - 3.5 GHz. It can be seen that the square shape has the lowest efficiency as compared to the circular shape from a distance of 0 to 40 mm. Then, the PSC MRC antenna's efficiency is similar for both, when the distance is 40 to 100 mm. The square design efficiency dropped from highest to lowest when the distance is 1 to 2 mm. Then the efficiency started to increase when the distance is from 3 to 5 mm. It can be concluded that for all the PSC MRC Antenna designs, the circular shape has better efficiency results as compared to the square designs in CST simulation software. The fluctuations of efficiency for the square PSC MRC antenna might be due to the edge effect of the square corners.

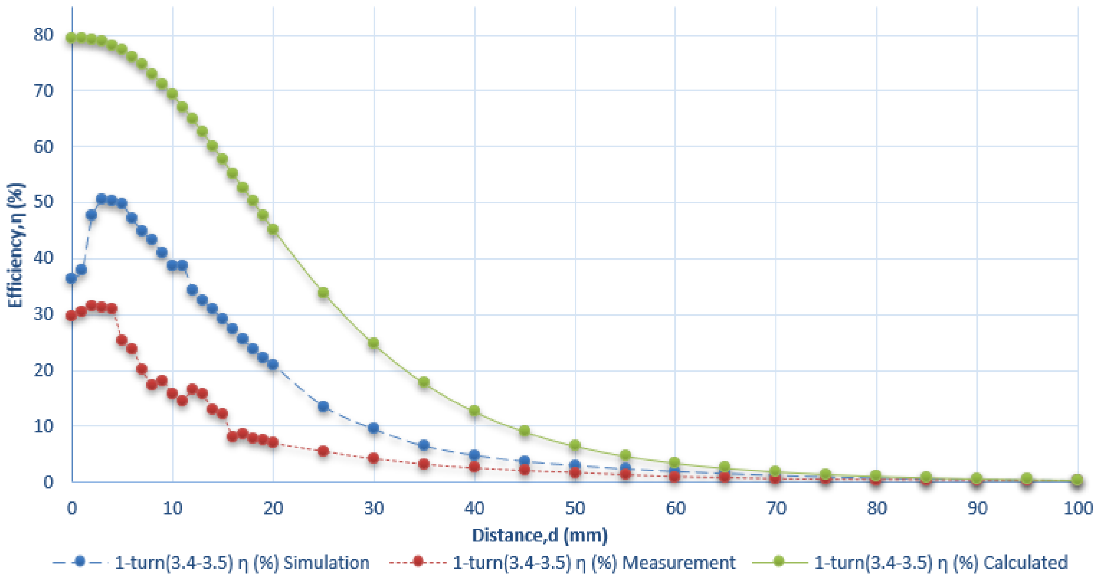


Figure 9 Calculated, Simulated and Measured efficiency (%) for PSC MRC circular 1-turn at 3.4 - 3.5 GHz.

Figure 1 above shows the return loss of the simulations versus fabrication results for Circular PSC MRC 1-turn 3.4~3.5 GHz.The Circular 1-turn PSC MRC Antenna of 3.4~3.5 GHz shows the return loss (S11 dB) of −18.21 dB for both Coil TX and Coil RX. The fabricated antenna is tested to be working at the 3.5 GHz band. This falls in the range of 3.4 - 3.5 GHz in the range of the 5G frequency band. The simulation result showed that the return loss S11 (dB) fall at −18.42 dB at the working frequency of 3.47 GHz. The difference in resonance frequency is only 30 MHz. The return loss of the PSC MRC must be designed below −10 dB due to the loss in the WPT working system. **Figure 9** shows that the results are comparable with the fabrication measurement results because only a minor frequency and S11 shift between simulated and measured results. The Calculated, Simulated, and Measured Efficiency (%) for PSC MRC Circular 1-turn at 3.4 - 3.5 GHz. The results show good agreement in the efficiency percentage trend from a distance of 0 to 100 mm. However, the efficiency is decreased by nearly half when compared to each of the methods.

Conclusions

The proposed closed-loop equation methods have been presented to determine the efficiency for 5G Magnetic Resonance Coupling Planar Spiral Coil Wireless Power Transfer. The transformation technique of the low frequency (kHz and MHz) magnetic resonance circuit model equations to high frequency (GHz) circuit model equations to achieve a high-efficiency PSC MRC WPT design structure has been introduced and applied in MATLAB. This technique can be implemented to effectively design PSC MRC Antenna WPT for 5G applications.

The proposed MRC WPT structures have been theoretically studied, simulated, and experimented within the lab. A circular 1-turn PSC MRC Antenna at 3.4 - 3.5 GHz has been fabricated and it gets better theoretical and simulation results as compared to the Square 1-turn PSC MRC Antenna. The Circular 1-turn PSC MRC Antenna's highest efficiency is 31.58 % when the distance is at 2 mm, and 31.26 and 31.02 % when the distance is at 3 and 4 mm, respectively. The efficiency is starting to get to 0 % as the distance is at 60 mm, which is 0.94 %. The efficiency at 100 m is 0.25 %. This work proposed designs for 5G applications as the operating frequency is designed at the 5G frequency band which is at the 3.4 - 3.5 GHz frequency band.

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