The Investigation of Substrate's Dielectric Properties for Improving the Performance of Witricity Devices

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Abstract **─** In designing a better Witricy device, there are several parameters that contribute to the improvement of efficiency. In this article, the substrate characteristics, which gaining less attention despite their potential for the improvement of Witricity performance are thoroughly studied. The characteristics such permittivity and loss tangent that very common in microwave design are investigated. The investigation has proven that RO 3010 substrate composed of ceramic-filled Polytetrafluoroethylene (PTFE) composites is the best material for the optimal Witricity performance, independent of the spiral coil's number of turns. This is due to its high-energy storage capacity obtained from the real permittivity, and roughly low loss factor and tangent loss. Hence, the Rogers RO 3010 substrate is proposed in this study as it performs reliable 50% to 74% coupling efficiency with the varied number of spiral coil turns.

Index Terms **─** Inductive power transfer, strongly coupled magnetic resonance, substrate, wireless power transfer, Witricity.

I. INTRODUCTION

The first experiment on wireless electrical transmission has been conducted by Nikola Tesla since 1890's [1]. However, the work on this wireless power transfer (WPT) was not taken up by scientific community except for some significant experiments [2], such studying a variation of electric potential and its casual fluctuation on a transformer [3]. Then, a more significant and modern experiment has been initiated by a group of researchers in Massachusets Institute of Technology (MIT), by introducing the name of 'Witricity' as a method of WPT that focuses on non-radiative mid-range power transmission. Witricity, which based on reliable and strongly coupled magnetic resonance technique is efficiently lighting up 60 watts light bulbs using 50 cm diameter coils over 2 meter distance in 2007 [4], has gained interests from worldwide researchers. In addition, Intel has also proven the method by an experiment at 60 cm distance with 75% efficiency [5]. Besides Witricity, there are several other methods of wireless power transfer (WPT) including energy harvesting, inductive coupling and capacitive coupling.

A few parameters such as impedance matching [6], coupling [7] and Q-factors [8] are reported to improve WPT efficiency. Study of the substrate thickness, the dimension of the capacitors and the number of turns of the coils is demonstrated in [9] to align the design with a given resonance frequency. However, this work is merely focused on the changing of the substrate thickness of the device concerning only Flame Retarded 4 (FR-4). In addition to thickness, permittivity is one of the important substrate characteristics to be considered in determining the best material that could contribute to the performance improvement of Witricity devices. Therefore, this characteristic needs to be carefully studied and thoroughly discussed. Referring to [10], varying the substrate dielectric property is expected useful in characterizing the resonance frequency of the Witricity device; whereby the lower values of permittivity correspond to higher resonance frequency and vice versa. Furthermore, a study in [11] proves that the increases of the material permittivity result in the increases of the antenna gain for a given resonance frequency. As the gain of antenna related to its efficiency, thus, it is interesting to apply this concept to the Witricity design by studying the effect of the parameter towards its performance, especially in coupling efficiency.

Furthermore, capacitance, C is one of the factors in designing Witricity device as it provides electrical energy storage [9]. The electrostatic energy stored in a parallel plate capacitor measured in the unit of Joules as given by $W = 1/2CV^2$; where V is the voltage difference between two parallel plates. However, the value

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of capacitance strictly depends on the substrate permittivity, ε, the thickness of substrate, d and the area of parallel plates, A as $C = \varepsilon A/d$. Therefore, a significant increase in energy density can be made by either increasing the permittivity, ε of the substrate or the applied field strength, E [12].

In this article, the substrate's dielectric properties are investigated for improving Witricity device performance. A few types of substrates with different permittivity, including Flame Retardant 4 (FR-4), RO4003C, TMM-4 and RO3010 have been measured and compared to CST simulated data. Then, a similar Witricity device design is applied on each substrate to study the permittivity effect towards Witricity performance. The best material is chosen, and the proposed prototype is verified practically.

II. WITRICITY DESIGN AND THEORETICAL CONCEPT

The proposed Witricity device consists of a transmitter and a receiver, which resonates at similar frequencies. Figure 1 depicts a transmission scheme from the first port to the second port. While, Fig. 2 shows the CST generated layout of the proposed Witricity device and the arrangement in the three-dimensional (3D) simulation tool of CST Microwave Design Studio.

In Figs. 1 and 2, each transmitter and receiver consist of two conducting layers: top and bottom are separated by the air gap. The top layer consists of a rectangular spiral coil inductor (Tx and Rx coil), while the bottom layer has two slotted capacitor plates that are arranged and attached to a single turn coil (Tx and Rx loop). To achieve a simple design workflow, an identical design is implemented in both transmitter and receiver to ensure both devices are always resonating at the same frequency.

The device is designed accordingly to meet the best coupling efficiency, η and impedance matching. Each transmitter and receiver design consists of a substrate with a thickness of 0.635 mm and copper layers on top and bottom layer. On the top layer, a spiral coil of conductive copper, which consists of several numbers of loops that is varied from 10 to 30 turns. The limit of the number of turns is fixed to 30 due to a further increase of turns will lead to a more complicated design and may compromise the precision of the design in fabrication stage. According to the Biot-Savart law in [14], the amount of the induced magnetic field at receiver, H_{Rx} is proportional to the spiral coil's number of turns, n as (1):

$$H_{Rx} = \frac{I \cdot n}{4\pi} \oint \frac{\vec{dl} \times \vec{r}}{r^3}, \tag{1}$$

where, I, n and r are the respective input current, number of turns and distance between the transmitter coil to the receiver. Whilst, dl is the tangential vector around a single loop coil. Accordingly, the spiral coil's number of turns, n is directly influencing the inductance, L value as shown by the modified Wheeler formula in (2) [18]:

$$L = \frac{K_1 \mu_0 n^2 D_{avg}}{1 + K_2 \rho}, \tag{2}$$

where, K_1 and K_2 are the spiral shape dependent coefficients, which equal to 2.34 and 2.75 respectively. Meanwhile, D_{avg} is the average diameter of the rectangular spiral; and ρ is the fill ratio, which defined to 1 for the design. Thus, by varying the spiral coil's number of turns, n will proportionally affect the inductance, L, which then alter the induced magnetic field, H_{Rx} analogously at the receiver. Consequently, the unloaded quality factor, Q of the spiral coil that analogous to $\omega L/R$ will change accordingly.

The overall coupling efficiency of the Witricity device, η can be written as the following Equation (3) [15-16]:

$$\eta = \frac{k^2 Q_1 Q_2}{\left[1 + \left(1 + k^2 Q_1 Q_2\right)^{1/2}\right]^2}, \tag{3}$$

where, Q_1 and Q_2 are unloaded quality factors of the transmitter and receiver coils, respectively, which are equal to $\omega L/R$. While, k is the mutual coupling constant, which has a value ranging from 0 to 1, that closely depending on the distance between transmitter and receiver. Therefore, it is proven in the Equations (1), (2) and (3) that by increasing the spiral coil's number of turns upsurges in the induced magnetic field at the receiver, H_{Rx}, the inductance value of L as well as the overall efficiency of the Witricity device.

As presented in Fig. 2 (b), the bottom layer of the designed Witricity device consists of a single source/load loop is linked to the two 14 x 8 mm^2 slotted rectangular capacitors, which stores electrical charges supplied to the device. The advantages of slotted capacitors over traditional capacitors are the improvement in reflection coefficient and bandwidth [13]. The used substrates in the proposed Witricity are changed to observe the effect of different substrates of FR-4, RO4003C, TMM4, RO3006 and RO3010 that having the relative permittivity in the range of 4 to 11 towards its performance. The information on substrates' properties obtained from the data sheet is listed in Table 1. Table 1 shows the properties of several substrates obtained from the data sheet together with simulated and measured relative permittivity.

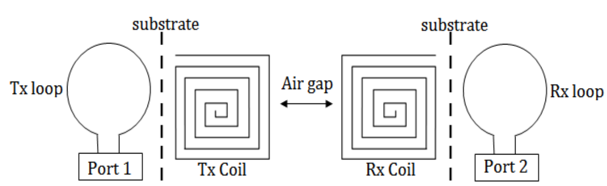

Fig. 1. Witricity device transmission scheme.

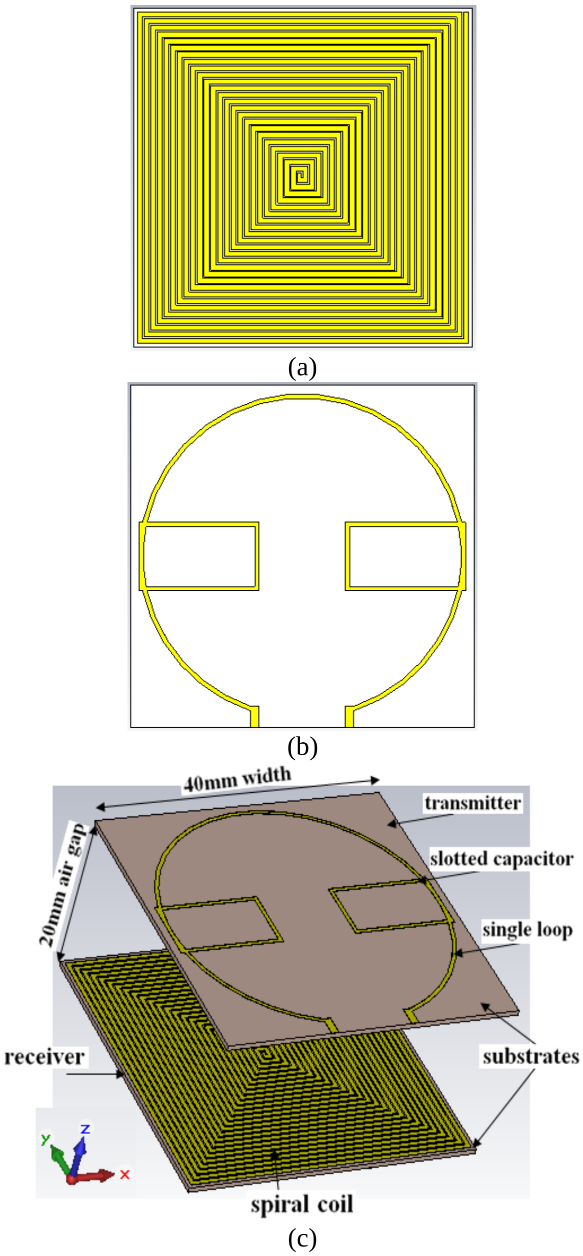

Fig. 2. (a) The top, (b) bottom, and (c) full 3D CST generated layout of Witricity device.

III. RESULTS AND DISCUSSION

The simulation and experimental results, and discussion are divided into two parts; A and B. Section A discusses the respective results obtained related to complex permittivity. Meanwhile, Section B presents the effect of permittivity towards coupling efficiency and the verification of Witricity design with the best substrate.

A. Complex permittivity

The dielectric property is derived from the effective complex permittivity, ε^* of the substrate, which determines its electromagnetic (EM) ability such as the polarization, dielectric losses and conductivity. Compared to ε^*, its complex relative permittivity, ε_r^* as expressed in (4) is used more often as the value is dimensionless and simpler [16]:

$$\varepsilon_r^* = \frac{\varepsilon^*}{\varepsilon_0} = \frac{\varepsilon' - j\varepsilon''}{\varepsilon_0} = \varepsilon_r' - j\varepsilon_r'', \qquad (4)$$

where, ε_0, ε_r' and ε_r'' are the permittivity of free space (8.85×10^{-12} F/m), the real and imaginary part of the complex relative permittivity, accordingly. The real part of ε^*, which is ε' that denotes the ability of a material to store the incident EM energy through the wave propagation. Whilst, the imaginary part of ε^* noted by ε'' represents the degree of EM energy losses in the material. Thus, the respective ε_r' and ε_r'' are also known as the dielectric constant and loss factor. The real and imaginary relative permittivity values of four different types of dielectric materials; RO 4003, FR-4, TMM-4 and RO 3010 are depicted in Table 1.

As shown in Table 1, the measured data of real relative permittivity between the dielectric materials have no significant differences with either simulated data obtained from CST and data sheet. Thus, it can be drawn that the Rogers RO4003 has the lowest ε_r' comparative to FR-4, TMM-4 and RO 3010. The FR-4 ε_r' is slightly higher than RO 4003 but almost similar to TMM-4 followed by RO 3010 that has the highest ε_r' with more than two-time values of the others. Considering from this aspect only, thus, the lowest energy transfer efficiency is expected from RO 4003 due to the less EM energy storage ability that related to lowering real permittivity and followed by FR-4, TMM-4 and RO 3010.

N onetheless, there is another factor that contributes to the efficient energy transfer, which is substrate's loss tangent, tan δ can be expressed as (5) [17]:

$$\tan\delta = \frac{\omega\varepsilon_r'' + \sigma}{\omega\varepsilon_r'}, \qquad (5)$$

where, ω and σ are angular frequency and conductivity loss, respectively in conditions of $\varepsilon_r'' \geq 0$ and $\varepsilon_r' \gg \varepsilon_r''$. At high frequency as considered in this proposed work, the substrate's loss tangent, tan δ can be simplified to $\varepsilon_r''/\varepsilon_r'$. It is also known as the dissipation factor that describes the angle difference between capacitance current and voltage. As noted from Table 1, the highest value of the loss tangent belongs to FR-4, followed by RO 3010, RO 4003, and the lowest belongs to TMM-4. Thus, concludes the FR-4 and TMM-4 have the respective highest and lowest loss.

By having the information of the loss tangent, the imaginary relative permittivity, ε_r'' in Table 1 is obtained by multiplying the real relative permittivity, ε_r' and the loss tangent. The imaginary relative permittivity, ε_r'' presents the loss factor that portraying the efficiency of energy transfer. Therefore, higher loss factor (imaginary relative permittivity, ε_r'') leads to the least efficient energy transfer. The results show a significant difference between FR-4 and other substrates. It can be deduced that FR-4 have the largest loss factor with almost three-time values of RO 3010 and more than six-time of the other substrates. However, RO 4003 that has the lowest ε_r'' will have the smallest loss factor that expected to contribute for better energy transfer.

By considering both real and imaginary relative permittivity, it can be deduced that a substrate must have small loss factor (imaginary relative permittivity) and large real relative permittivity to store more energy from incident EM wave. As a result from both real and imaginary relative permittivity, the smaller value of loss tangent is important in determining the best material for Witricity device.

Table 1: The substrate properties obtained from the data sheet, CST and measured relative permittivity

Substrate	Data Sheet			CST	Measurement	Calculated
	Material Composition	Real Relative Permittivity (ε_r')	Loss Tangent	Real Relative Permittivity (ε_r')	Real Relative Permittivity (ε_r')	Imaginary Relative Permittivity (ε_r'')
FR-4	Epoxy resin	4.4-4.7	0.014-0.017	4.41	4.30	0.06-0.07
RO4003C	Glass reinforced ceramics	3.55	0.0021	3.56	3.55	0.0075
TMM-4	Ceramic thermoset	4.70	0.002	4.51	4.50	0.0090
RO3010	Ceramic-filled PTFE	11.20	0.0022	10.22	10.20	0.0224

B. Coupling efficiency

The concerned coupling efficiency of the Witricity device, η expressed in (3) is analogous to $|S_{21}|^2$. The comparison of the proposed Witricity device's coupling efficiency performance that designed using different dielectric materials, including FR-4, RO 4003, TMM 4, and RO 3010 are obtained via CST Microwave Studio simulation. It is to study the relationship between the complex permittivity and loss tangent toward coupling efficiency performance. The effect of varying the spiral coil's number of turns in the Witricity design for the different dielectric materials is shown in Fig. 3, while the corresponding coupling efficiency of their optimal design is shown in Fig. 6.

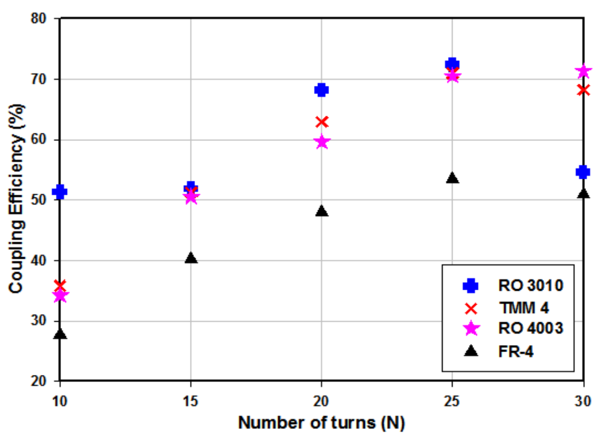

Fig. 3. Coupling efficiency of Witricity device with diferent substrates and varied number of spiral coil turns between 10 and 30.

Based on Fig. 3, at the low number of turns, there are significant results shown between each material with RO 3010 has the best coupling with approximately 50% followed by TMM 4, RO 4003 and FR-4. The result complies with the sequence of ε_r' from the highest to the lowest as shown in Table 1, except for FR-4, which has greater ε_r' compared to RO 4003 but has lower coupling efficiency performance. This result deduces that the real part of complex relative permittivity is important in achieving high capacitance value of the Witricity device, which enabling high-energy storage at the transmitter and receiver. Likewise, the imaginary part of the complex relative permittivity is also an important factor as it represents the energy loss in the material. The lower value reflects a low-energy loss due to absorption of the material. Therefore, the performance of FR-4 is the worst among all the substrates as it has low real relative permittivity, but highest imaginary, which results in lower coupling efficiency. At the highest number of turns, most of the substrates show a significant drawback, especially by RO 3010 yet better than FR-4, which has the largest imaginary relative permittivity and tangent loss. However, RO 4003 performs almost similar result with 25 turns even at higher turns as it has the lowest loss factor. Both phenomena prove a stronger dependency of imaginary permittivity compared to the real permittivity for the number of turns higher the optimal 25. This is, on the contrary, for a number of turns that less than optimal 25, which shows stronger dependency on the real permittivity compared to the imaginary.

Referring to the obtained results, Witricity device with RO 3010 substrate and optimal 25 number of turns is fabricated. The fabricated prototype is shown in Fig. 4. The 25 number of turns is chosen as an optimum as most of the substrates show best coupling at this number.

The measurement setup used to validate the performance of this proposed Witricity device is shown in Fig. 5. The results of the coupling efficiency of their optimal design are shown in Fig. 6.

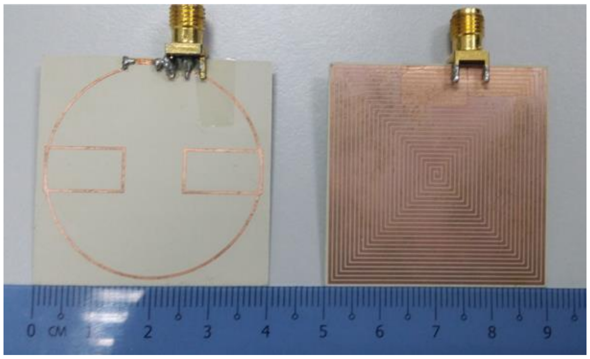

Fig. 4. Prototype of Witricity device with optimal 25 number of spiral coil turns using RO3010 substrate.

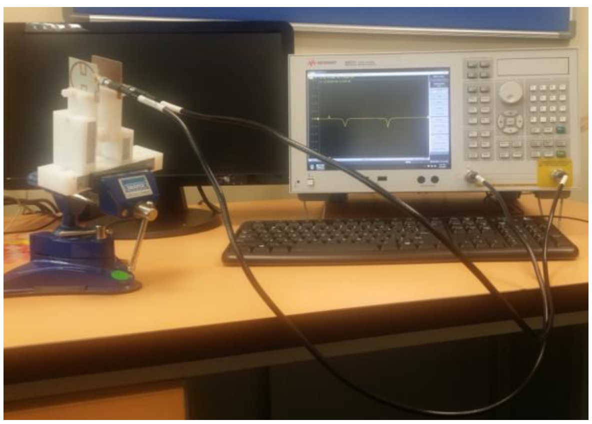

Fig. 5. Measurement setup using Keysight Vector Network Analyzer (VNA).

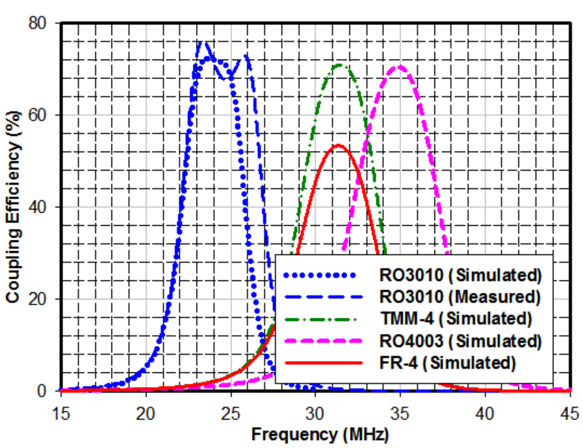

Fig. 6. Coupling efficiency results Witricity device using different materials having optimal 25 number of spiral coil turns.

At the optimal 25 number of turns, the coupling efficiency results in Fig. 6 show the lead taking by the design using RO 3010 with comparable simulated and measured performance of 72.3% and 76.2%, respectively at approximately 24 MHz. While, the design using FR-4 has performed worse coupling efficiency with 53.4% at a higher frequency of 31.5 MHz. However, other materials perform at the almost similar level between 70.5% to 71.0% due to the nearly close loss tangent about 0.002-0.0022, which is about eight times lower than FR-4 of 0.014-0.017.

By considering different substrates of various real relative permittivities, the distinct values of capacitances are expected in each design as the number of spiral coil turns are kept at a constant of 25 turns. This has led to different operating frequency for each design, where the lowest frequency obtained by the highest real relative permittivity substrate. This contrasts to the design with the lowest real relative permittivity material that has the highest operating frequency. Consequently, the operating frequency of the designed Witricity device is inversely proportional to capacitance and real relative permittivity of the chosen substrate.

IV. CONCLUSION

The performance of the Witricity device can be improved by selecting an appropriate dielectric material or known as a substrate in the design process. The dielectric properties of substrate involve in designing Witricity device is shown by investigating the effect of complex permittivity to the device performance. The study shows that the high real relative permittivity, which also branded as dielectric constant results in great coupling performance, especially for the spiral coil's number of turns from 10 to 25. RO 3010 has the widest range of the tunable number of coil turns as it has been greater than 50% efficiency for 10-30 turns, followed by TMM-4 and RO 4003 that achieve more than 50% efficiency at 15-30 turns. Meanwhile, FR-4 needs at least 25 turns to perform well. The study also has shown a great performance of Witricity device with a high real relative permittivity substrate from a low number of coil turns up to the optimal of 25. Afterward, the performance has strongly affected by the value of imaginary permittivity as been noted by the design using RO 3010 substrate compared to others at 30 number turns.

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