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Impedance Matching Network for Ground Eliminated Open-ended Resonant Coil Structure in Distributed Wireless Power Transmission Systems

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***Abstract*— This paper reports a novel technique utilizing a standing-wave node as a virtual ground to implement an impedance matching network and power level tuning in a ground eliminated (GE) open-ended resonant coil structure. This technique with GE open-ended coils can potentially be used in wireless power transmission (WPT) systems, where an unknown metallic, ungrounded, arbitrary environment is used as a signal propagation medium to deliver electric power to several distributed nodes. To satisfy WPT standards the proposed resonant WPT system with the matching network is implemented and tested at 13.56 MHz. A comprehensive study of the GE open-ended resonant coil structure demonstrates ground plane effects and the necessity of an impedance matching network in no-ground signal situations. The experimental results confirm the theoretical analysis presenting 9 % improvements in mismatch efficiency, and 13.1 times in power transmission efficiency at 13.56 MHz when the matching network is deployed.**

***Index Terms*—matching network, virtual ground, ground eliminated open-ended coil, resonance inductive coupling, wireless power transmission, wireless sensor network.**

I. Introduction

Wireless power transmission technology offers a wide range of industrial and biomedical applications and could lead to clean sources of electricity for a variety of users[1]. WPT involves the *transmission* of energy from a *power* source to an electrical load across an air gap, without electrical connectors such as wires. Among different WPT techniques, resonant inductive coupling (RIC) is more popular in mid-range (less than two times of coil's diameter size) applications since it has demonstrated higher efficiency in power transmission for long distances than the inductive or capacitive coupling ones[2]. In RIC methods, the transmitter (Tx) and receiver (Rx) coils are coupled in their resonant mode while the magnetic field between them transfers power from the Tx to Rx coil[2]–[6].

WPT has also demonstrated extensive potential in wireless sensor network (WSN) applications. WSNs have been used in industrial environments and demonstrate impressive performance in applications that require real-time, distributed, multi-parameter measurements. WSN systems have also brought, flexibility, high performance and lower cost to sensing devices and systems[7]–[10].

Since WSN systems have distributed structures, supplying the electric power to the sensor nodes is a limiting factor. Using high capacitive batteries, the widespread primary solution, can provide the required electric energy but the power management required to achieve high sensor node performance is challenging and requires regular maintenance and battery replacement[11], [12].

WPT is an effective technique to deliver permanent electric power to WSN nodes while maintaining a wireless data communication link. The main challenge in WPT systems with distributed receiver loads is the physical distance between the power transmitter and the receiver node, where in large distances less power is received by receiver coil and in very close distances frequency splitting will be the major issue[13]. This becomes more critical and complicated when the number of sensor nodes is increased or when they are widely distributed. The transmitter coils must have access to the permanent electric power source and this increases the complexity of the wiring and, consequently, the cost of the system [14].

We have recently proposed a technique [15]–[18], where non-grounded metallic structures can be used as electric power and signal propagation medium to deliver electric power locally to the receiver nodes when they are in vicinity of the metallic structure (Fig. 1). Disparate, the conventional WPT systems, which require two double-ended resonant coils coupled together, this novel technique requires one double-ended coil coupled to a GE open-ended resonant coil which is locally fed by a metallic structure. In this paper, to maintain an efficient power delivery, an impedance matching technique using virtual ground is presented for GE open-ended resonant coils where no actual ground signal is accessible.

II. Theory Ground Eliminated System

The system-level architecture of the GE WPT system is presented in Fig. 1. As shown in this figure, a signal generator is connected to a non-grounded metallic structure with high electric conductivity [14]. This conductive structure (with a length of less than the quarter wavelength of the operating frequency to prevent radiation) serves as the signal propagation medium for several transmitter nodes. Having access to electric power at any point along this metallic structure is the main advantage of this technique. This technique also provides electric energy from one source to multiple nodes, where the receivers can be positioned at any position in the vicinity of the metallic structure. They can be at great distances from each other or from the main power source.

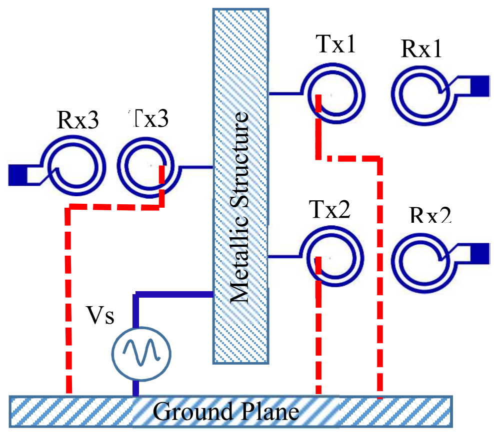

Fig. 1. *Schematic of the proposed WPT system*

To maximize power transmission efficiency for the GE WPT system, each transmitter node and the main power source must have their own independent impedance matching network circuitry.

The system shown in Fig. 1 has the disadvantage of required ground wiring for each transmitter Tx, which increases the cost and complexity of the system and reduces its efficiency and reliability in large scale applications.

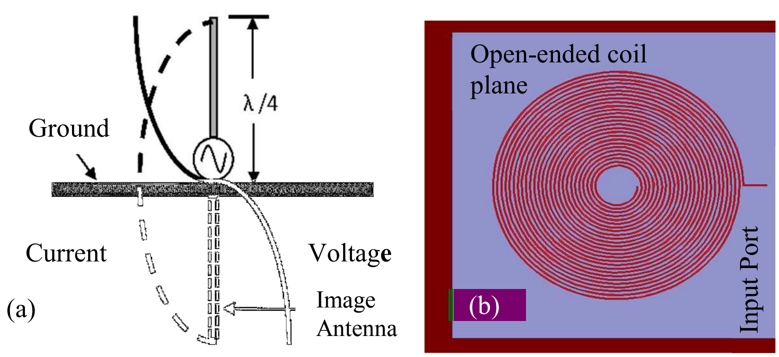

Fig. 2.*(a) Marconi's antenna structure with a length of λ/4, (b) Implemented structure in HFSS with one feed line and one open-ended terminal. The ground plane is considered 100 cm below from the coil plane.*

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To address this issue and eliminate ground wiring for each Tx node, a Marconi antenna structure, which is a modified λ/2 dipole Hertz antenna, is used for the transmitter coils (Fig. 2). This structure, a spiral inductance with wire length of λ/4 of the operational frequency with one signal terminal and one open-ended terminal, has less practical challenges than the Hertz antenna in implementation and satisfies the requirements for low frequency power and signal transmission in midrange applications [18]–[21].

A. GE Open-ended Resonant Coil Structure Design and Simulation

Air core coils with planar structures are considered for the transmitter and receiver nodes, with spiral traces for small size and high performance. The receiver coils are conventional two-terminal coils which are in parallel with a capacitor to maintain a resonant condition. The transmitter coils are open-ended helical resonator with spiral traces and a length of λ/4 at the operation frequency of 13.56 MHz. For an open-ended resonator, the distance between the ground plane and the resonator plays a critical role in the coil's input impedance, which in turn affects the matching network as it works to maintain impedance matching between the coil and the power source. The effect of variations in the distance between the ground and coil planes on the input return loss is shown in Fig. 3. Both coil and ground planes have square shape with size of 15 cm × 15 cm. To perform simulations in HFSS, radiation boundary is used for the vacuum box, which contains the structure. the simulation software is operated on a customized server for electromagnetic simulations with the following specification, "PowerEdge T630 Server,386 G RAM, E5-2680 v3 2.5GHz,30M C,120W Processor". To reduce the simulation time, λ/10 was used as the distance between the object and the boundary for the simulations.

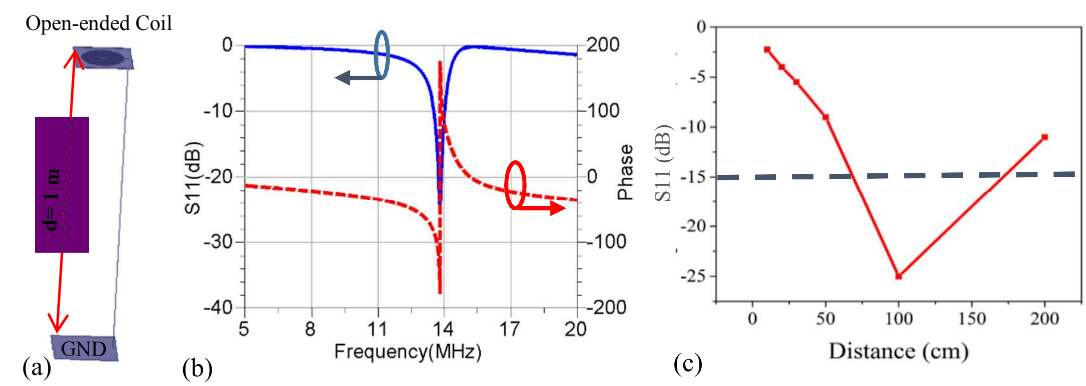


Fig. 3. *(a) Open-ended resonator with single feed, (b) Simulation results of the S_{11} parameter with amplitude and phase at the resonant frequency, (c) S_{11} resonant amplitude for a variant distance between the ground and the coil plane at 13.5 MHz.*

The impedance mismatch efficiency for a single port device can be calculated as $\eta = 1 - |S_{11}|^2$, [23], where $\boldsymbol{\eta}$ is the transferred power efficiency between the device and the power source, and S_{11} is the amplitude of the S_{11}-parameter at operational frequency. As depicted in Fig.3, ground to coil distance variation can affect the power efficiency and, consequently, the total transferred power to an Rx node.

In addition, having an Rx coil in the vicinity of the transmitter coil can potentially have a loading effect on the Tx coil and degrade its impedance matching with respect to power-source impedance. This effect can be observed in the simulation results, presented in Fig.4. The distance between the Rx and the open-ended Tx coil is an important parameter of the power efficiency between Tx-Rx coils. The power efficiency at the receiver coil in this configuration can be defined as $\eta = |S_{21}|^2$ [23], where $\boldsymbol{\eta}$ is the transferred power efficiency to the receiver coil from the transmitter coil and S_{21} is the amplitude of the S_{21}-parameter at the operation frequency.

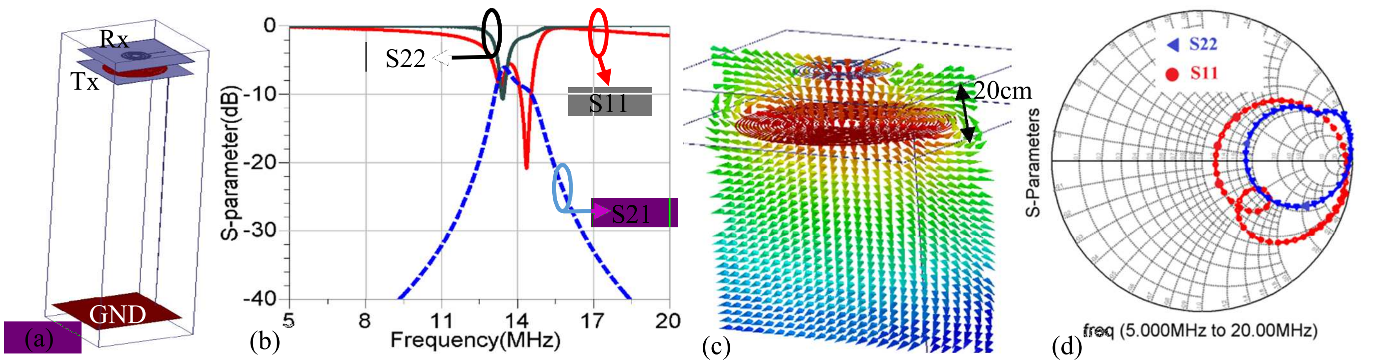


Fig. 4. *(a) Simulated structure, conventional (Rx) Open-ended resonator(Tx), (b) S-parameter of the coupled coils, where S_{21} shows an acceptable level of transmitted power from Tx to Rx at operation frequency of 13.56 MHz, (c) Magnetic field in vector in between the coils and ground plane, (d) Smith chart of the coupled coils.*

These simulations clearly demonstrate the necessity of an impedance matching network for GE open-ended resonator structures, but an inaccessible ground signal makes the design of the matching network for that structure very challenging.

Ground to coil distance and the size of the ground plane are playing a critical role in matching of the open-ended coil structure. Effect of the distance variation between the ground and coil plane and the ground plane size variation are studied and the simulation results are presented in Fig. 5. This parameter plays an important role on the matching network from the power source to the coil and consequently the amplitude of the magnetic field around the coil. The effect of these parameters can be describe considering the input impedance equation (Eq. 1), where the open-ended structure is considered as a monopole antenna, the impedance at the feed point can be presented as Z_{in} [23]:

$$Z_{in} = \frac{Z_{os}}{2} \times \frac{Z_L + jZ_{os} \times tan(\beta l)}{Z_{os} + jZ_L \times tan(\beta l)}, \quad (1)$$

where Z_{os}, β, and l are the characteristic impedance, phase constant, and the length of the line, respectively. These parameters need to be determined using empirical analysis, which are difficult to obtain through an analytical method [22]. As presented in equation 1, the distance from the ground plane and the ground plane area can affect both Z_L and Z_{os}, which result in S_{11} variation (Fig.5 a, b) and input impedance (Z_{in}) consequently.

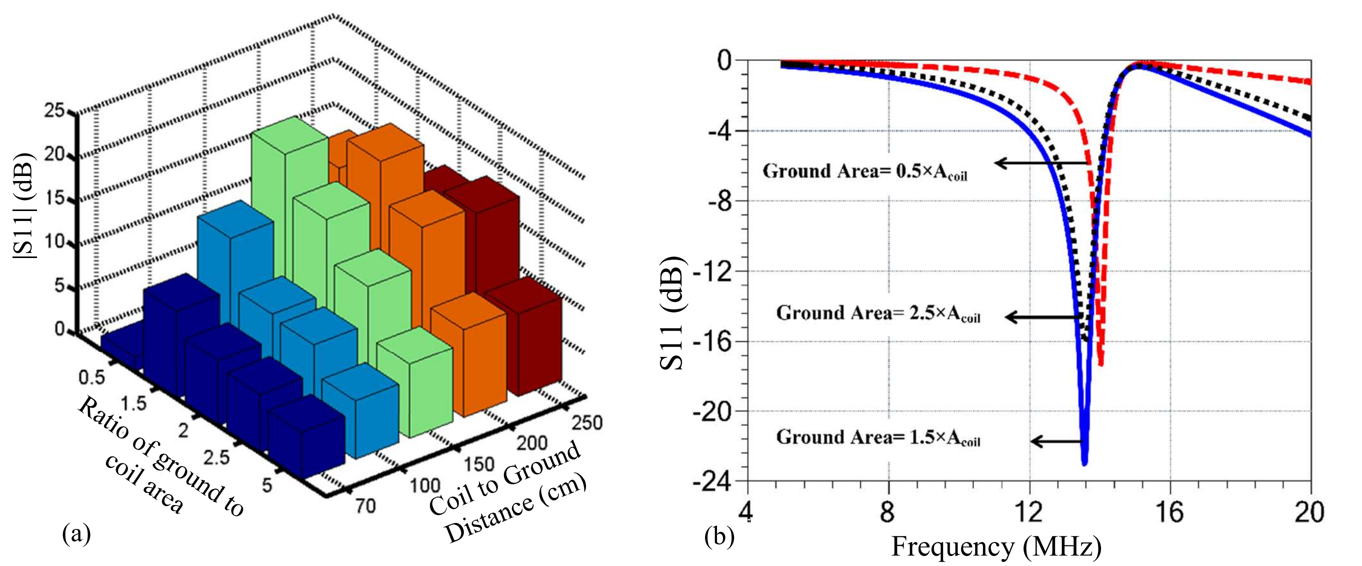


Fig. 5. *(a) Resonant amplitude of S_{11} vs. ground to coil distance and ground to coil area ratio, (b) S_{11} profile for different areas of ground plane at the distance of 200 cm between the ground and coil*

B. Design of Impedance Matching Network for GE Open-ended Resonator

Impedance matching is a common technique in WPT and communication applications to improve the efficiency of the systems. The power transferred to the load can be maximized when Z_{source} is the conjugate of Z_{load} ($Z_{source} = Z^*_{load}$).

The design of a matching network is more challenging when the ground signal is inaccessible. To eliminate the ground signal issue, a virtual ground technique is proposed to be used in standing wave coils. As shown in Fig.6, for a coil with a trace length of L, the resonant frequency occurs at f, as described by c/λ, where f is the main resonant frequency, c is the speed of light and λ is 4×L. Due to its short length, no zero-voltage node from the resonant frequency will appear on the trace that might be used as a virtual ground (VG). The zero-voltage nodes start to appear from the 2nd harmonics and, since the physical size of the coil should be kept small, the second harmonic is used as the operating frequency.

The WPT system in this work is operating at 13.56 MHz, which is the second harmonic of 6.78 MHz. Designed for a resonant frequency of 6.78 MHz, the physical length of the coil is L=11.06 m, the width of the trace is 0.7mm, and the gap between traces is 1.4mm with 35 turns. According to the trace length, the physical location of the virtual ground (VG) is expected at 5.53m from the open-ended side of the coil. The transient response depicted in Fig. 6 clearly demonstrates that the node n_2 can be used as virtual ground and conventional matching networks can be applied using this node.

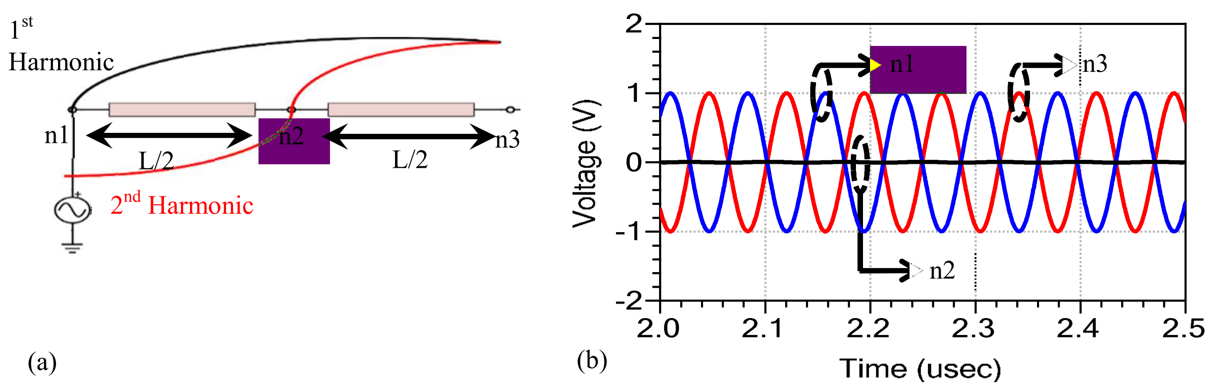


Fig. 6. *(a) Open-ended resonator schematics and voltage propagation profile along the wire for the first and second harmonics, (b) Transient response of the voltage signal at the selected nodes on the coil trace.*

To understand the mechanism of impedance matching an equivalent circuit and model is presented in Fig.7 (a). Considering the structure as a monopole antenna, the impedance at the feed point can be presented as Z_{in} according to Eq. 1.

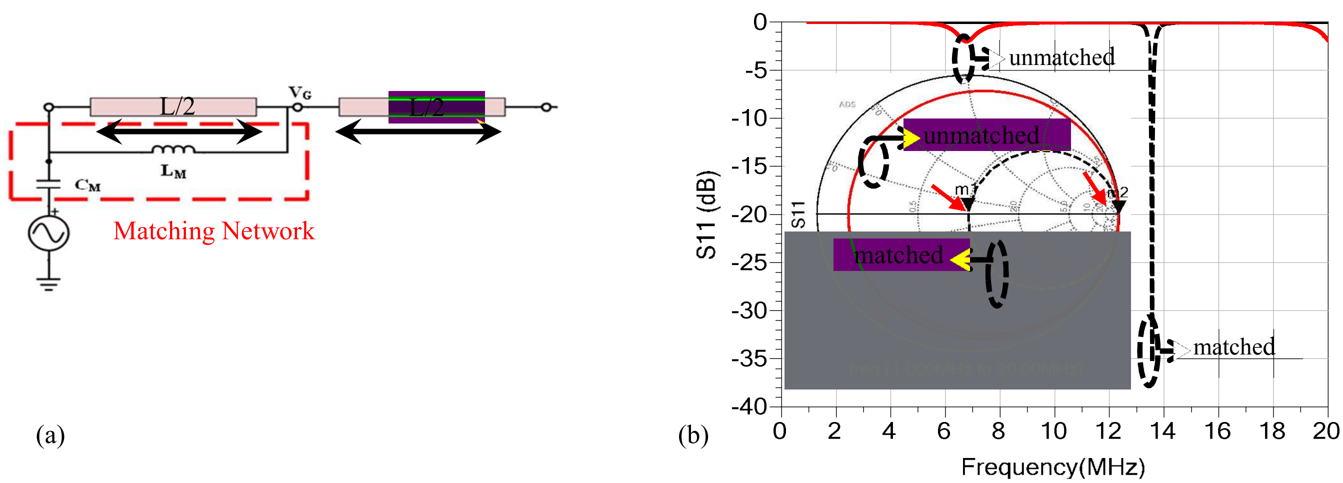


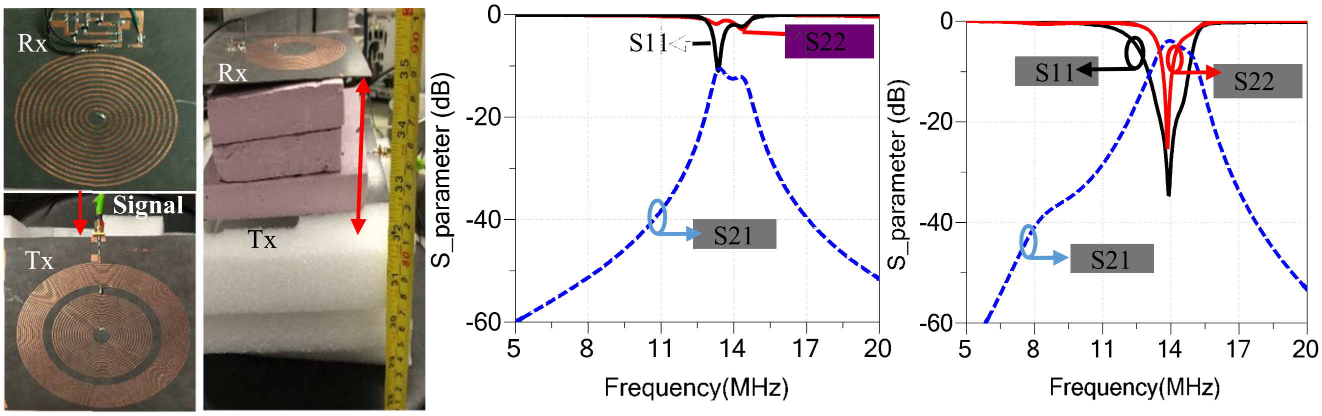
Fig. 7. *(a) A LC matching network using virtual ground for open-ended coil, (b) S_{11} parameters for matched and unmatched open-ended coil.*

An impedance matching configuration (other configurations also can be used) is shown in Fig.7 (a) where LC matching components are used and the node $n_2(V_G)$, at half the coil-length, performs as the virtual ground.

A comparison between the S_{11}-parameters in matched and unmatched condition, using the virtual ground technique, is presented in Fig. 7(b). A Smith chart for matched and unmatched conditions is also shown as an inset.

III. Measurement Results and Discussions

A GE open-ended resonant spiral coil is implemented on an RT 5880 board from Rogers. The fabricated open-ended coil has 35 turns, an inner diameter of 30mm, a trace width of 0.7mm and spacing between the traces of 1.4mm. The signal pin of a source is connected to one-end while the other end of the coil is remained unconnected. Based on these parameters the length of the coil is 11.38m which is equal to λ/4 at 6.78MHz. To perform the experimental measurements, one port of VNA is used and a SMA cable is connected to the loop antenna. The ground signal of the SMA cable is connected to the electrical ground which is placed in different distanced from the open-ended coil.



(a) (b) (c)

Fig. 8. *(a) Implemented GE open-ended Tx coil and a conventional Rx coil with distance of 6 cm, the electrical ground plate is 79cm away from the Tx coil, (b) Measured S-parameters for open-ended Tx and conventional Rx resonant coils in unmatched condition, (c) S-parameter of the system in matched condition.*

To demonstrate the effectiveness of the proposed technique, the measured S-parameters of an open-ended unmatched-coil with Rx receiver at 13.56 MHz is recorded (Fig. 8 a). Having an Rx-coil in distance of 6 cm from the Tx coil, affects the S_{11} parameter of the Tx coil and its matching to the power source, by employing the described impedance matching technique, and using the standing wave virtual ground, a T-type impedance matching network is implemented to enhance the impedance matching at the operating frequency of 13.56 MHz and increases the transmitted power from source to the Tx and consequently Rx coil (Fig. 8b). The received power at the Rx side is 15 mW, where a good impedance matching is established between the transmitter and receiver, while the transmitter transmits 50mW power. Measured results demonstrate a strong correlation between the theoretical analysis and simulations.

IV. Conclusion

This work reported the study of a GE open-ended resonant coil structure as a transmitter coil in a distributed WPT system. FEM simulation and experimental results have demonstrated the dependency of the transmitted power efficiency to ground-plane size and distance from the coil. The main challenge in the design of the matching system was the inaccessibility of the ground signal for the transmitter coil, which was fed through a metallic structure. With no ground signal, matching network design using conventional well-known techniques was very challenging and problematic. To address this issue, virtual grounds and common nodes, which were implemented using a standing wave system, was used to enable employment of conventional LC circuits for matching purposes. Power efficiency, from the source to coil, had an improvement of 15.48 dB on S_{11} and 5.6 dB on S_{21} amplitudes at 13.56 MHz when the matching was applied.

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