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Chapter

WPT, Recent Techniques for Improving System Efficiency

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Abstract

Wireless power transfer (WPT) technologies have received much more attention during the last decade due to their effectiveness in wireless charging for a wide range of electronic devices. To transmit power between two points without a physical link, conventional WPT systems use two coils, one coil is a transmitter (Tx) and the other is a receiver (Rx) which generates an induced current from the received power. Two main factors control the performance of the WPT schemes, power transfer efficiency (PTE) and transmission range. Power transfer efficiency refers to how much power received by the rechargeable device compared to the power transmitted from the transmitter; while transmission range indicates the longest distance between transmitter and receiver at which the receiver can receive power within the acceptable range of power transfer efficiency. Several studies were carried out to improve these two parameters. Many techniques are used for WPT such as inductive coupling, magnetic resonance coupling, and strongly coupled systems. Recently, metamaterial structures are also proposed for further transfer efficiency enhancement. Metamaterials work as an electromagnetic lensing structure that focuses the evanescent transmitted power into receiver direction. Transmitting & Receiving antenna systems may be used for sending power in certain radiation direction. Optimizing the transmitter antenna and receiver antenna characteristics increase the efficiency for WPT systems. This chapter will present a survey on different wireless power transmission schemes.

Keywords: capacitive coupling, inductive coupling, intermediate resonators, magnetic resonance coupling, metamaterial structures, power transfer efficiency (PTE), strongly coupled magnetic resonance, wireless power transmission (WPT)

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1. Introduction

With the spreading of mobile phones, portable and wearable electronic devices and changes in the human lifestyle, the need for WPT technology grows to get rid of the inconvenience due to using power cables. On the other hand, there are some applications where WPT probably the only solution or the most efficient solution for their powering for instance implanted biomedical devices, buried sensors, some sensors found in a severe environment such as very high temperatures, and so forth. One of the first trials for WPT was performed by Nikola Tesla a century ago. He wanted to develop a wireless power distribution system. **Figure 1** illustrates a simplified diagram of a WPT system which simply consists of a transmitter that sends the transmitted power through an RF coil or RF resonator. On the receiver

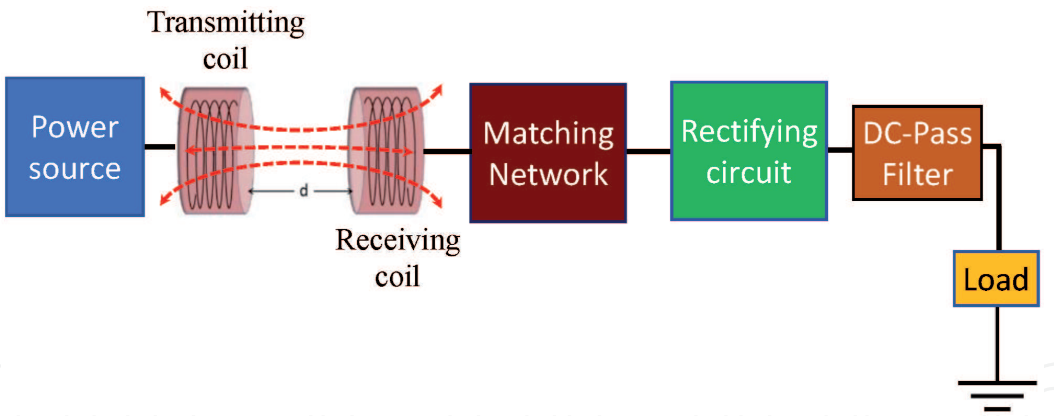


Figure 1.
WPT system.

side, there is a receiving resonator which can be an antenna or coil to receive the incoming wave from the transmitter. Afterward, an impedance matching circuit is inserted to ensure maximum power transfer between the receiving resonator and the rectifying circuit. Then, the rectifying stage is connected. Many combinations could be used for the rectification purpose such as half-wave, full-wave, or any series/parallel diodes combinations. All these rectification circuits are used for converting RF power into DC power. In order to achieve smoothing DC output voltage as well as blocking the higher-order modes, the rectifying circuit is followed by a DC pass filter. The final stage is the device (load) that needs to be charged wirelessly. In this chapter, we will focus on the coupled resonators which is the first stage for WPT systems.

Wireless power transfer technologies can be divided into different categories such as inductive coupling, resonant inductive coupling, capacitive coupling,

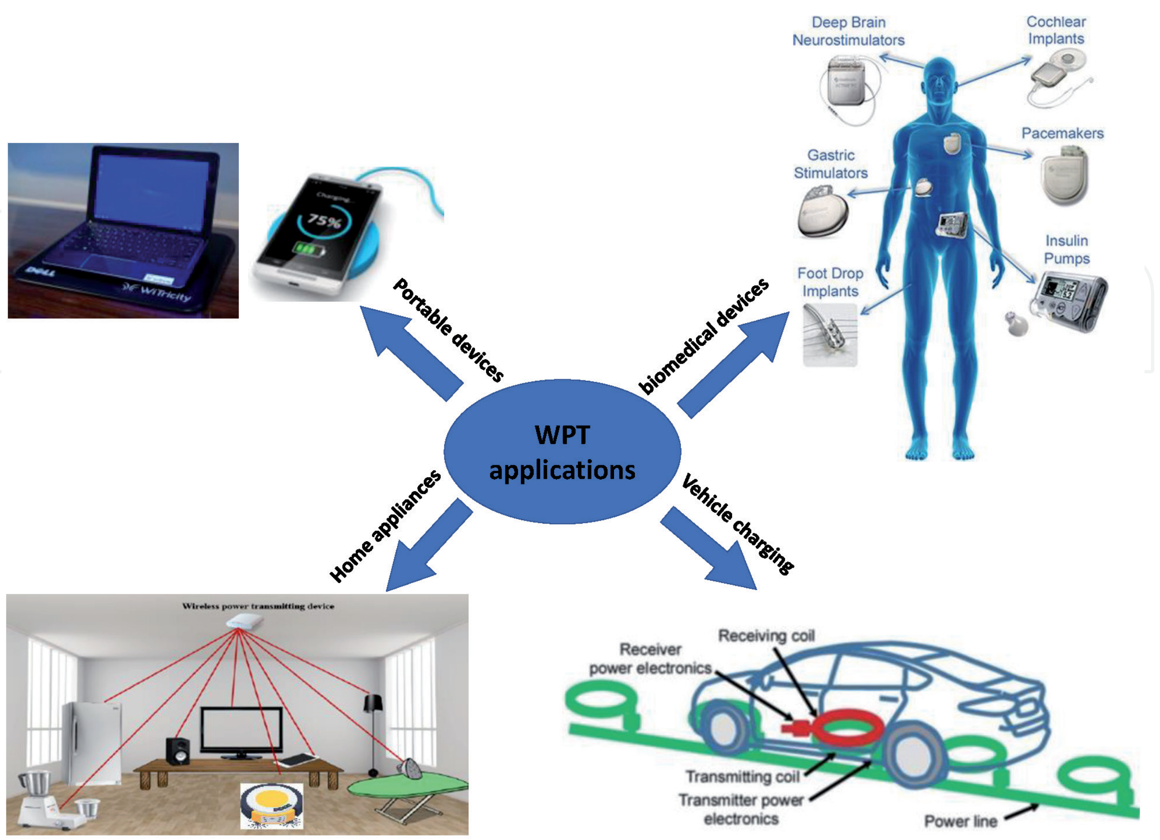


Figure 2.
WPT applications.

microwaves. Through this chapter, we will cover these technologies with highlights on the recent techniques for improving the power transfer efficiency such as using intermediate resonators, applying metasurface structures, and so on. **Figure 2** shows the current and potential applications for WPT systems.

2. Inductive coupling WPT

Conventional coils of wire are the simplest way to transmit a wireless power between transmitter and receiver. In this case, the system can be represented as a transformer where a transmitting coil is analogous to the primary coil, while the received coil is equivalent to the secondary coil as revealed in **Figure 3**. An inductive power transfers between the two coils in a form of a magnetic field. The intensity of the magnetic field follows Ampere's law as in (1), where $\bar{H}$ is the magnetic field intensity that is generated when an electric current, I, passes through an electric closed path with a length of l.

$$\oint \bar{H}.dl = I \tag{1}$$

When the Transmitter has a time-varying current and mounted at an appropriate position from the receiver. Receiver's coil cuts the magnetic field lines, and an induced electromotive force (emf) is generated between the terminals of the receiver's coil as shown in **Figure 3**. The value of the emf depends on the time-varying of the magnetic flux (ϕ) as characterized by Faraday's law as in (2). It is clear that this WPT technology is valid only for short-range applications for example wireless charging pads to recharge cellphones and handheld wireless devices such as laptops and tablets, electric toothbrush, shaver's battery charging, induction stovetops and industrial heaters, charging implanted prosthetic devices such as cardiac pacemakers and insulin pumps [1].

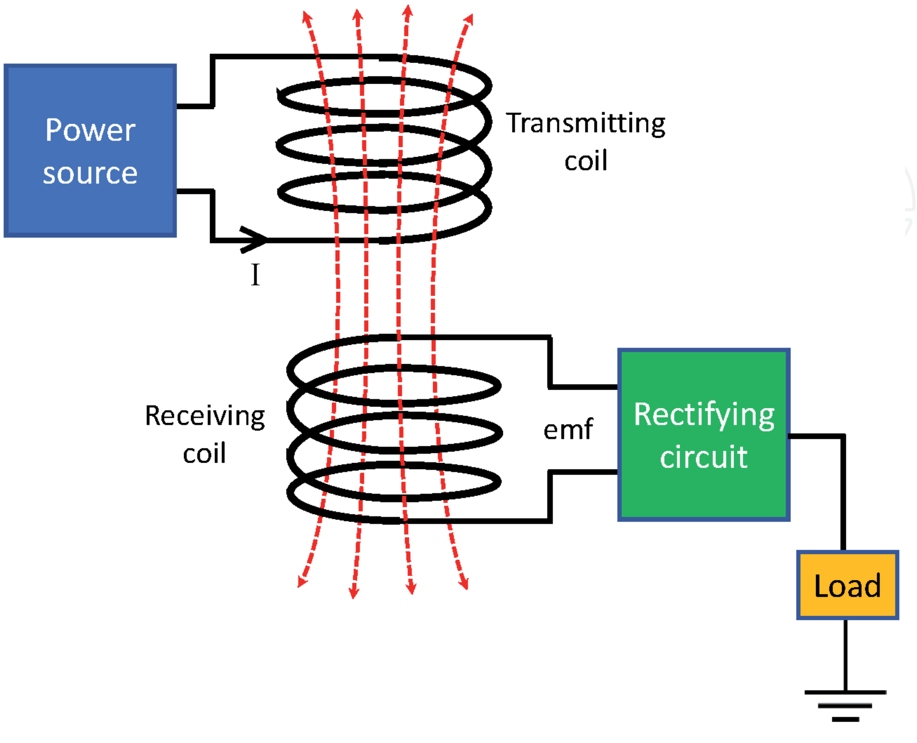


Figure 3.
WPT using inductive coupling scheme.

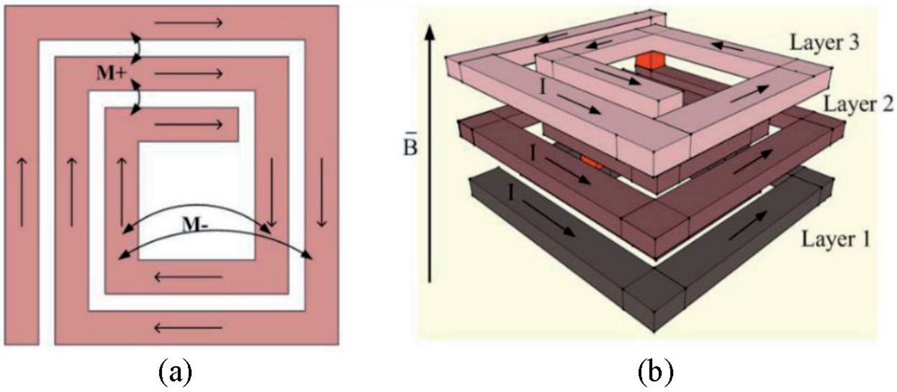
$$emf = -\frac{d\phi}{dt} \tag{2}$$

WPT system performance can be estimated by the power transfer efficiency (PTE) which depends on the KQ product. K is the coupling coeffect between transmitter and receiver, it is a ratio and varies from 0 to 1 as a maximum value at totally power coupling. Q is the unloaded quality factor of the transmitter's or receiver's coil; Q can be calculated from the coil inductance as in (3), where ω is the angular frequency, L is the coil inductance, and R the loss resistance of the coil. While PTE is calculated from (4) [2]. It is clear that increasing the transfer efficiency needs a high value of the KQ product.

$$Q = \frac{\omega L}{R} \tag{3}$$

$$PTE = \frac{k^2 Q_t Q_r}{\left[1 + \sqrt{1 + k^2 Q_t Q_r}\right]^2} \times 100\% \tag{4}$$

Numerous studies were introduced in the inductive coupling approach [3–9]. In [10], a multi-layer spiral inductor is proposed for biomedical applications at a frequency of 13.56 MHz which is the license-free industrial, scientific, and medical (ISM) band. It uses a stacked structure to achieve a compact WPT, where the stacked inductors occupying an area of 10 mm × 10 mm with 1 cm separation between transmitter and receiver. The inductance is further increased by stacking the printed spiral inductors on top of each other in such a way that the flow of the current always takes the same direction as shown in **Figure 4**. In [8], a pair of printed spiral coils, as illustrated in **Figure 5**, used in biomedical implanted microelectronic devices to maximize the inductive power transmission efficiency. Zixuan et al. [6] introduced an analysis of alternative-winding coils for getting high-efficiency inductive power for mid-range WPT. Alternative-winding coils structure is demonstrated in **Figure 6**.



(a) (b)

Figure 4.
Multi-layer stacked inductor; (a) top view (b) 3D geometry [10].

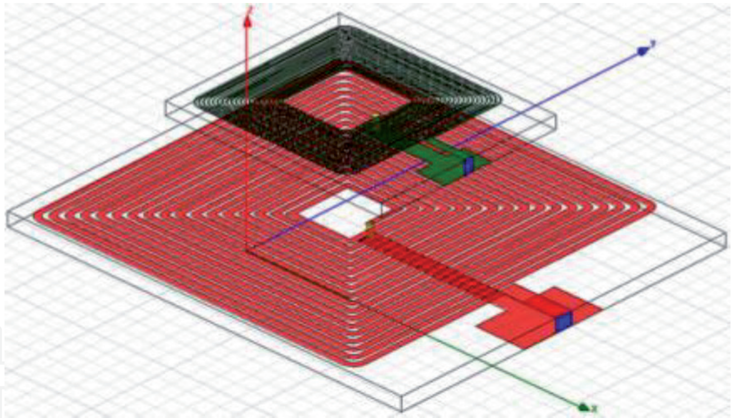


Figure 5.
Design of a pair of printed spiral coils [8].

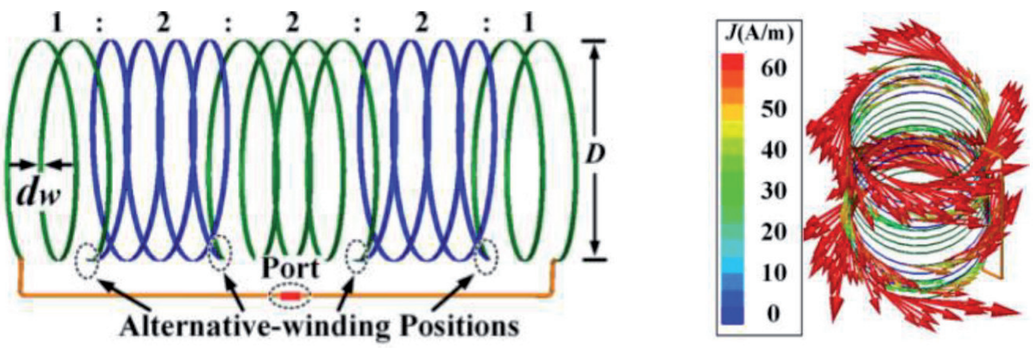


Figure 6.
Alternative-winding coils geometry and its current distribution [6].

3. Resonant inductive coupling WPT

Resonant inductive coupling or magnetic resonance coupling is another form of the WPT technologies in which power is transferred between two tuned resonant circuits, one in the transmitter and the other tuned circuit in the receiver as depicted in **Figure 7**. Each resonant circuit comprises an inductor connected to a capacitor to resonate and couple the transmitted power at their resonance frequency. This resonance is responsible for emphasizing the quality factor (Q-factor) for the resonant circuit. Therefore, the coupling and the power transfer efficiency between the transmitter and receiver increase due to the directly proportional relationship between them. Magnetic resonance coupling scheme is applied in mid-range applications such as charging electric vehicles, charging portable devices, biomedical implants, powering busses, trains, RFID, smartcards.

Several studies have invested the resonant inductive coupling technique for enhancement the power transfer efficiency of WPT systems [11–13]. In [14], we proposed dual open-loop spiral resonators (OLSRs) to improve the magnetic field for WPT system. OLSRs are fed through Metal–Insulator–Metal (MIM) capacitive coupling using a 50 Ohm microstrip transmission line as shown in **Figure 8**. A series resonance model is used to achieve resonant inductive as illustrated in the equivalent circuit model in **Figure 9**. The open-loop spiral resonator (OLSR) includes the series combination between the MIM capacitor and the spiral-loop inductor. Dual OLSRs are used instead of a single OLSR to strengthen the surface current on the spiral resonators. Therefore, it helps to intensify the electromagnetic

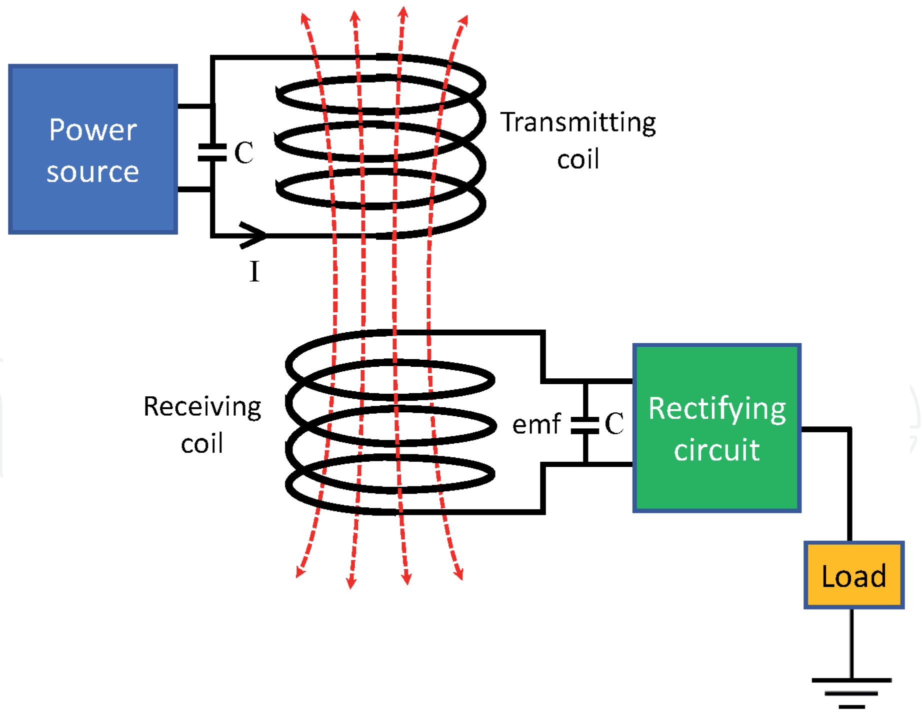


Figure 7.
Resonant inductive coupling WPT structure.

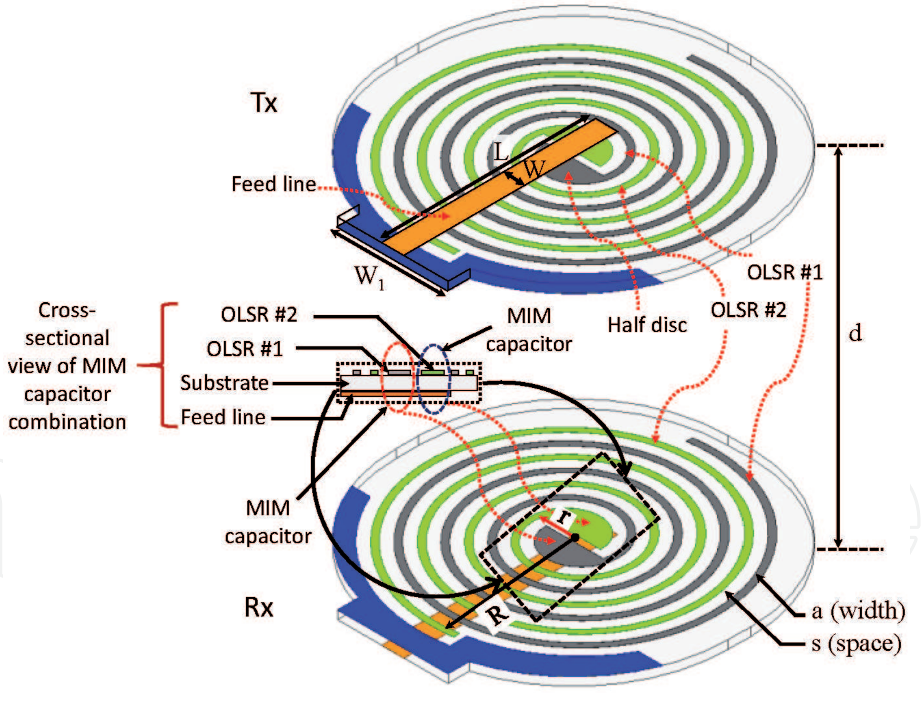


Figure 8.
OLSR WPT geometry [14].

field in order to get a high transmission distance or higher power transfer efficiency. **Figure 10** displays a comparison between the power transfer efficiency for using a single and double OLSR. The results show the improvement in PTE in double OLSR. The OLSRs WPT system operates at 438.5 MHz with a measured PTE of 70.8% at a transmission distance of 31 mm and a design area of 576 mm^2. While PTE for a single OLSR is 56% at 487 MHz at the same transmission distance.

A printed spiral coil with a planar interdigital capacitor is proposed in [15] as shown in **Figure 11**. It studies the misalignment issues between transmitter and

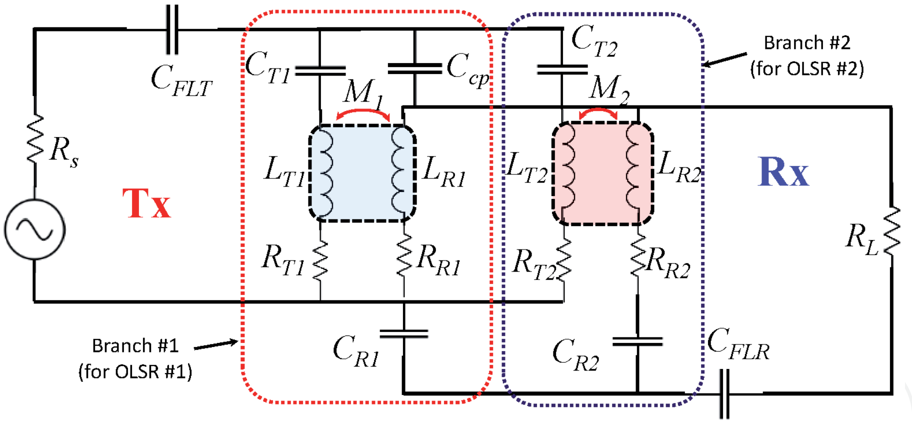


Figure 9.
Equivalent circuit model for OLSR [14].

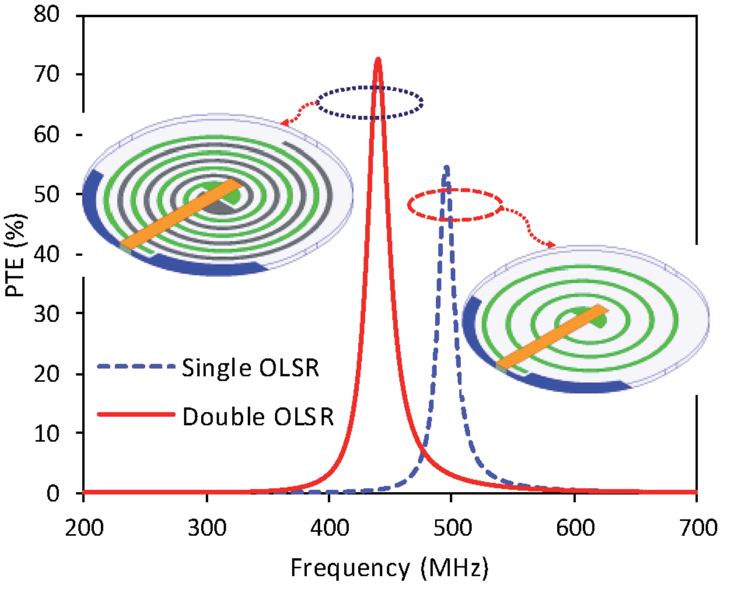


Figure 10.
PTE versus frequency of a single and double OLSR [14].

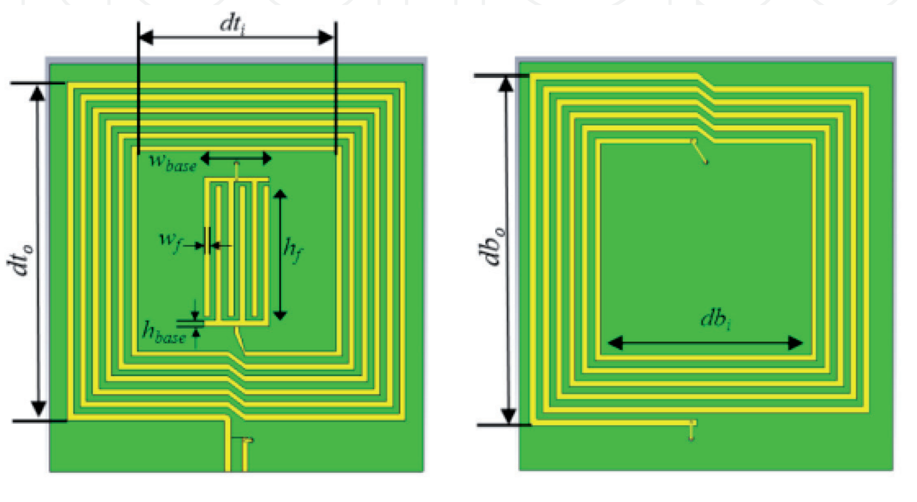


Figure 11.
Geometry of a printed spiral coil with planar interdigital capacitor [15].

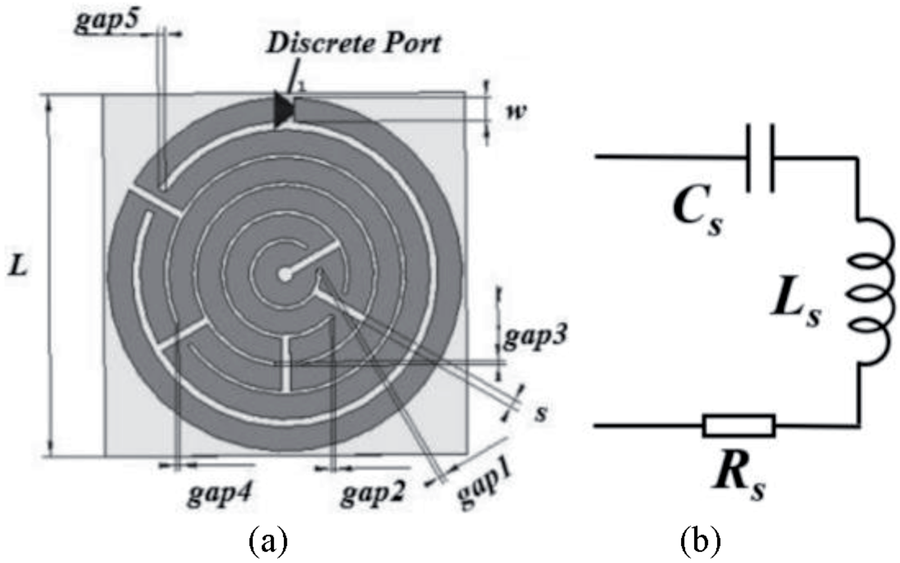


Figure 12.
(a) Conformal split-ring loop self-resonator, (b) equivalent circuit [16].

receiver. Under a perfect alignment, WPT offers a maximum measured transfer efficiency of 71.84%. This research uses the integration between the interdigital capacitor and the spiral coil to get a magnetic resonant resonator with high immunity for the misalignment instances. Wang *et al.* [16] proposed a conformal split-ring loop self-resonator which has a self-resonant frequency and its equivalent circuit is a series resonant circuit composed of an inductor-capacitor series connection as displayed in **Figure 12**. This resonator introduces a high transfer efficiency of 87.9% at a transfer distance of 22 mm. A resonant inductive link for

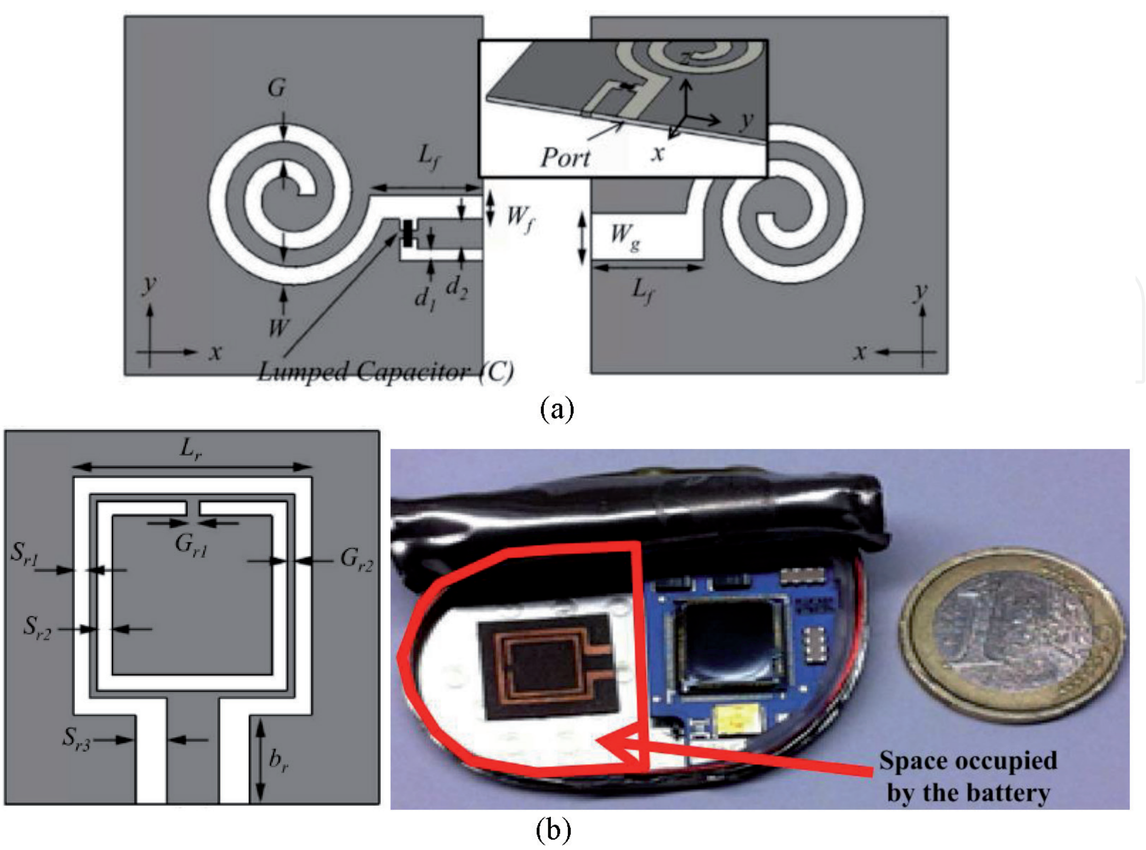


Figure 13.
Spiral coil integrated with lumped capacitor design (a) Transmitter's resonator, (b) Reciever's resonator [17].

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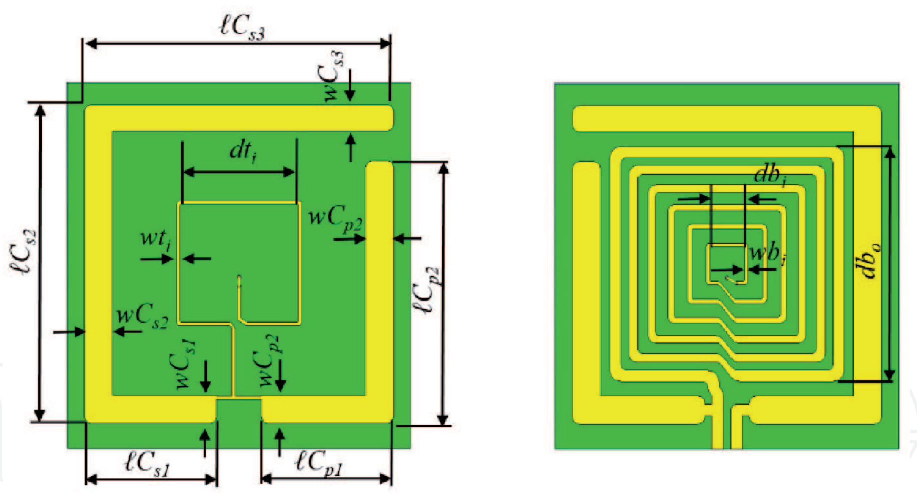


Figure 14.
Capacitive compensated plates design [18].

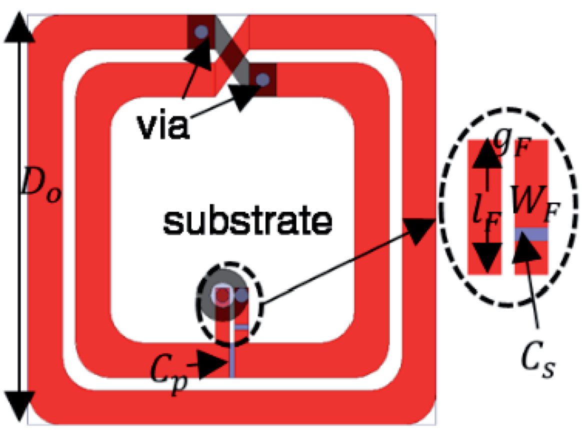


Figure 15.
Planar view of the transmitter/Reciever [19].

powering pacemakers was presented in [17]. The transmitting resonator consists of two spirals printed on the top and bottom face of the Arlon substrate as illustrated in **Figure 13**. A surface-mounted capacitor is inserted in a shunt with the printed spiral to tune the resonance frequency at the desired value. On the other hand, the receiving resonator is a square split-ring resonator. Series–parallel capacitive plates are employed with a printed spiral resonator [18] to get satisfactory tolerance toward angular and lateral displacement. **Figure 14** shows capacitive compensated plates, C-shaped and mirrored L-shaped capacitive plates are formed on the top and bottom layer of the substrate. **Figure 15** presents an asymmetric resonant inductive coupled WPT system [19]. This system has a measured power transfer efficiency of 75% at a transmission distance of 38 mm.

4. Strongly coupled magnetic resonance WPT

Strongly coupled magnetic resonance refers to inserting intermediate resonators with a high-quality factor (Q) in the transmission path between transmitter and receiver as revealed in **Figure 16**, these intermediate resonators are used to emphasize the transferred magnetic power. This technology is categorized as mid-range WPT. In 2007, a group of researchers at the Massachusetts Institute of Technology proposed an experiment using a strongly coupled magnetic resonance technique [20].

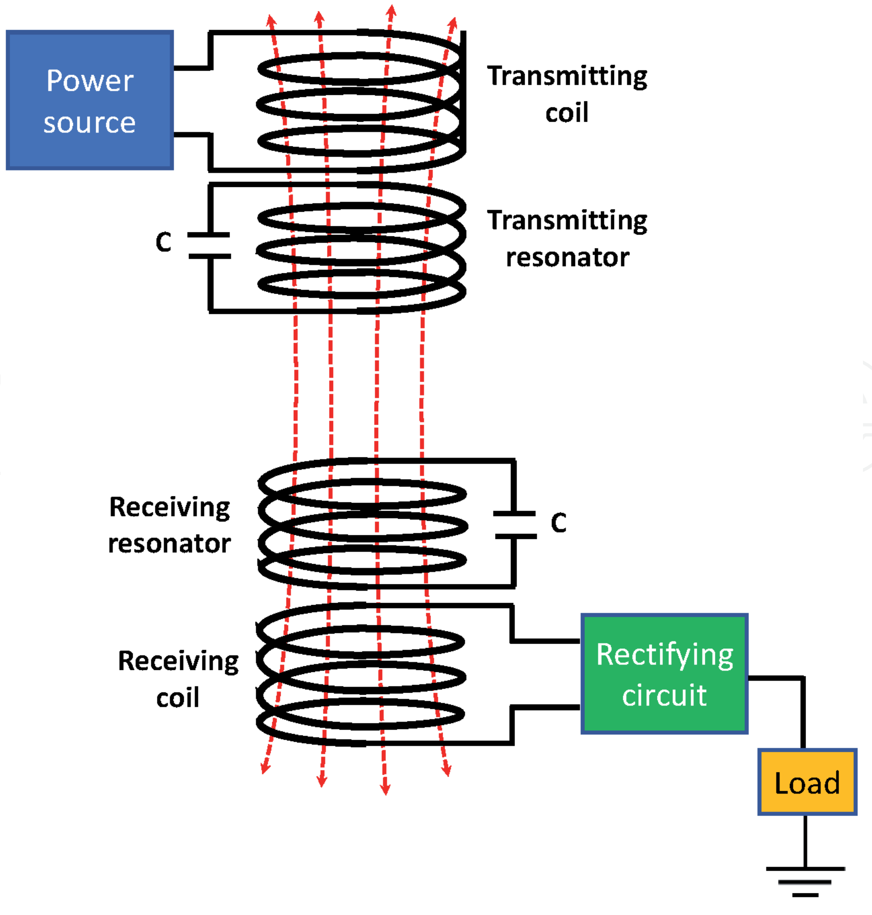


Figure 16.
Strongly coupled magnetic resonance WPT.

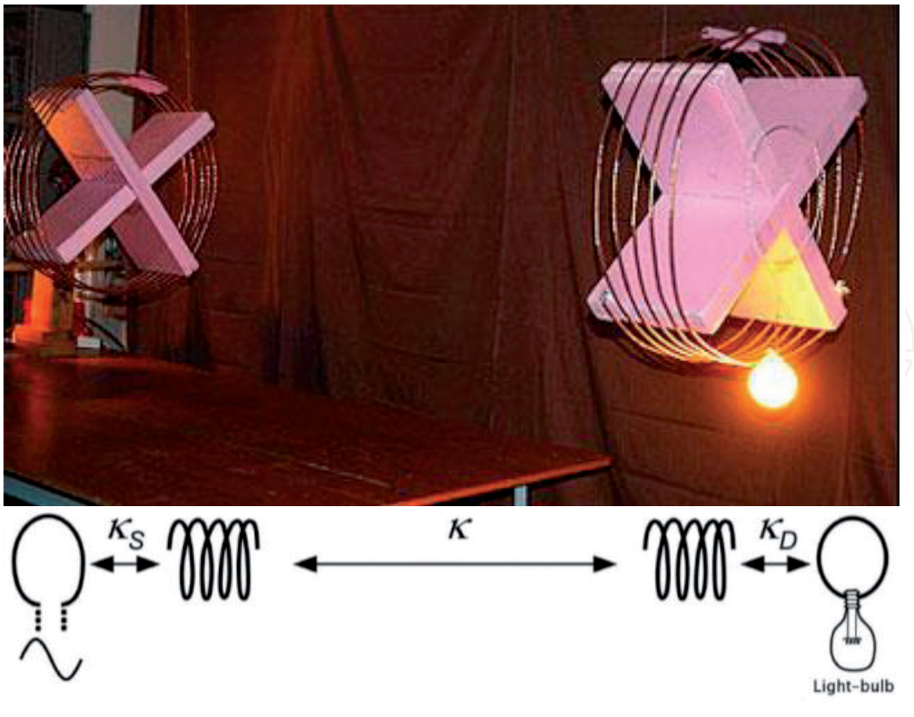


Figure 17.
Setup of MIT researchers group experiment [20].

They effectively powered a light bulb wirelessly using a power source located 2 m away from the light bulb. They obtained a power transfer efficiency of about 40%. The experiment is demonstrated in **Figure 17**, the intermediate resonators are self-resonant.

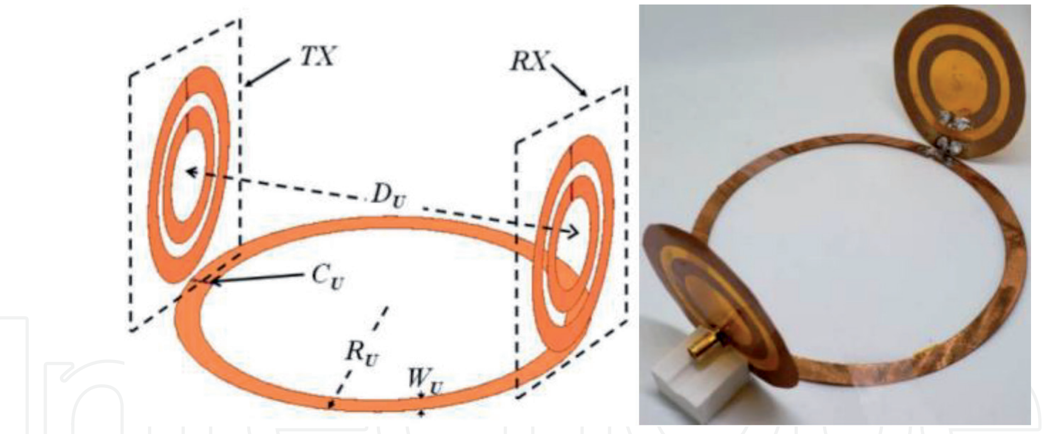


Figure 18.
Conformal strongly coupled magnetic resonance system [26].

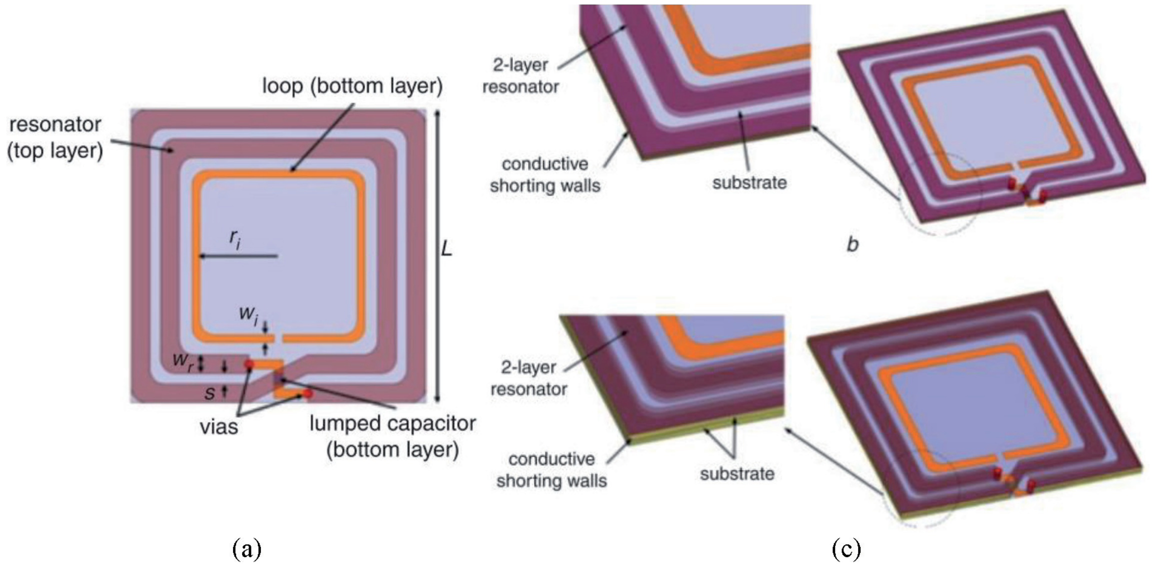


Figure 19.
(a) Geometry of a printed spiral coil, (b) two layers using conductive shorting wall, and (c) three layers using conductive shorting wall [23].

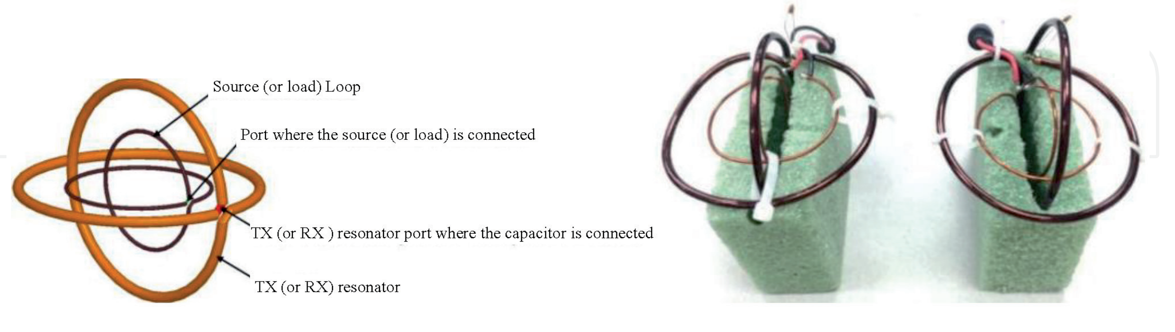


Figure 20.
3-D strongly coupled magnetic resonance WPT [22].

Recently, several authors [21–27], have utilized from the strongly coupled magnetic resonance scheme to enhance the transmission properties of WPT systems. Barreto et al. [26] proposed a conformal strongly coupled magnetic resonance system for range extension by using U-loop as an intermediate resonator as shown in **Figure 18**. It provides a high transfer efficiency reach 70% at a transfer distance equal to the diameter of the U-loop (48 cm). Also, this WPT system can maintain efficiencies greater than 60% regardless of the angular position of the receiver around the U-loop. A multilayer

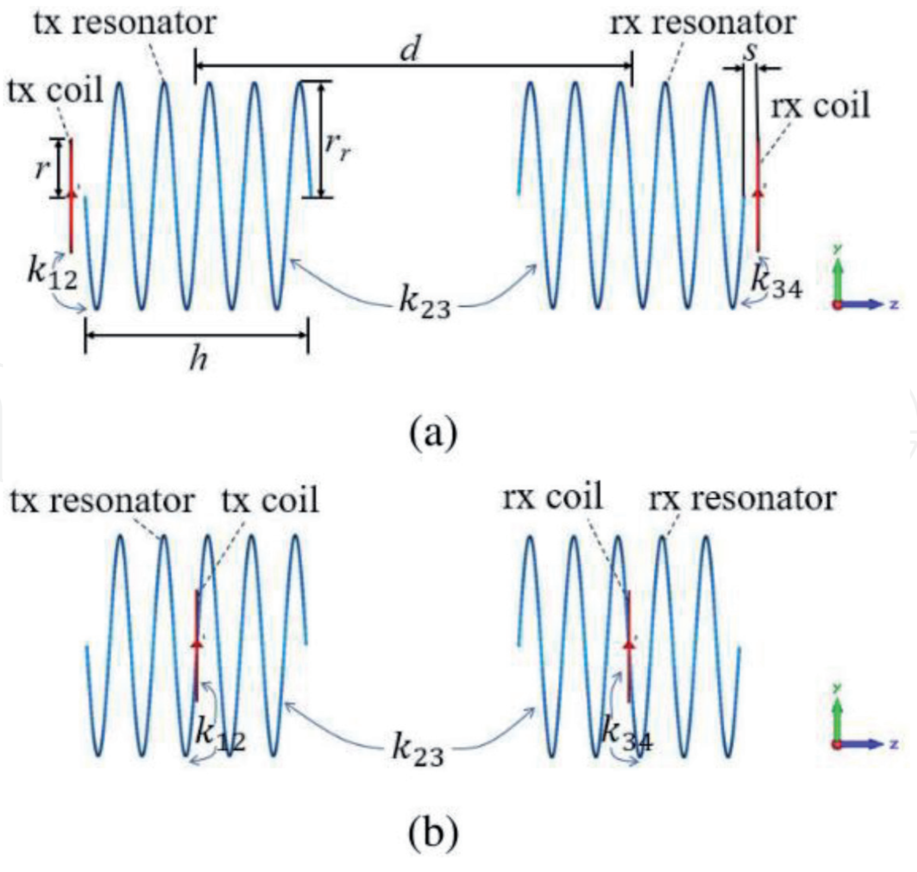


Figure 21.
(a) Conventional four-coil system with the transmitter/receiver coils outside the resonators. (b) Wideband four-coil system with the transmitter/receiver coils at the center of resonators [24].

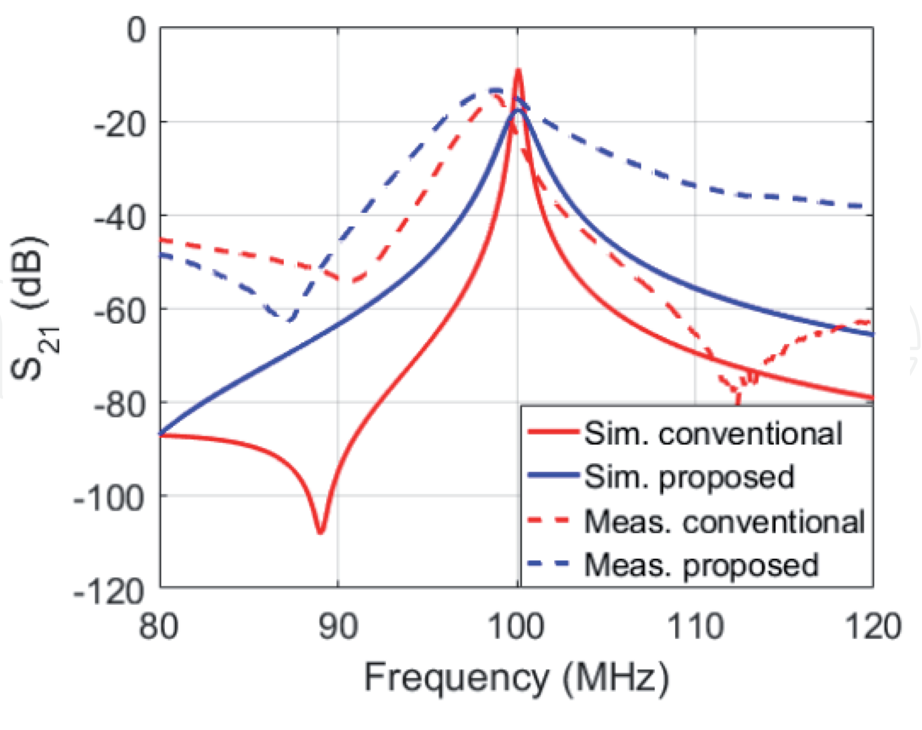


Figure 22.
S_{21} versus frequency [24].

resonator is discussed in [23], where extra layers of printed spiral coils are inserted in the transmitter/receiver resonators to enhance the Q factor and power transfer efficiency. Conductive shorting walls are employed for the connection between the

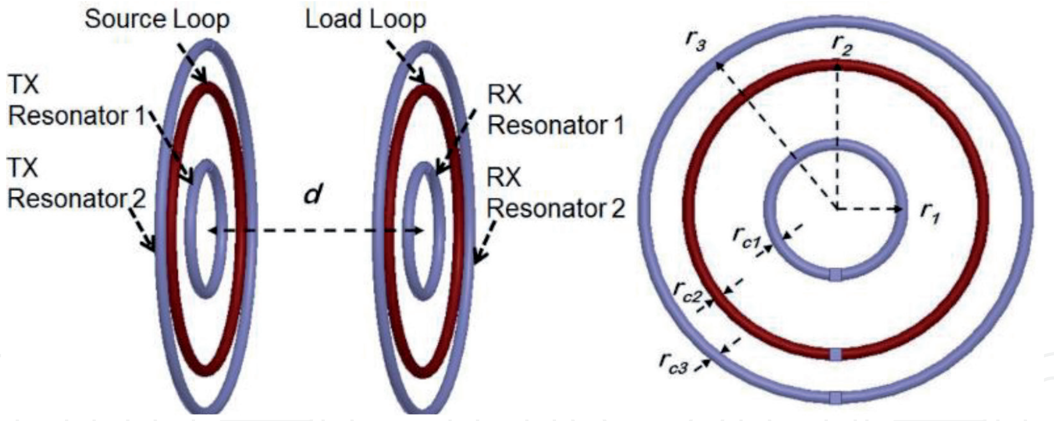


Figure 23.
Configuration for a dual-band conformal strongly magnetic coupling [25].

multilayer resonators as illustrated in **Figure 19**. Liu et al. [22] reduced the misalignment sensitivity of strongly coupled WPT systems by applying two orthogonal coils together in a 3-D model instead of using planar coils as shown in **Figure 20**.

Using strongly coupled magnetic resonance WPT systems leads to getting a high quality factor (Q). Nevertheless, this also results in limiting the system bandwidth. Therefore, Zhou *et al.* proposed a wideband strongly coupled magnetic resonance WPT system [24] to overcome the shifting problems of the resonance frequency that occurs in some practical applications, this, in turn, alleviates the decline in the efficiency caused by this shift in the resonant frequency. **Figure 21** shows the proposed technique, the transmitter and receiver coils are fixed at the center of their corresponding intermediate resonators. In this manner, the leakage of magnetic flux can be mitigated, and the bandwidth is broadened as shown in **Figure 22**. Broadband and multi-band WPT system using conformal strongly coupled magnetic resonance technique is introduced in [25]. A multi-band can be obtained by using multiple pairs of loop resonators with various dimensions to resonate at different frequencies, for example, in **Figure 23**, the source loop and load loop are placed between two resonators (resonator 1 and resonator 2). Each resonator resonates at a different resonance frequency to give a dual-band WPT. The broadband operation can also be achieved by merging between the resonance frequencies, this can be obtained using different values of the capacitance of the loop resonators or use resonators with size near each other. Many designs for multi-band and wideband WPT systems are proposed in [28–35].

5. WPT utilizing meta-surface structures

Metasurface structures are also used to boost the PTE by confining the magnetic field in a narrow channel between transmitter and receiver by combing the evanescent waves from the Transmitter and redirect them into receiver direction due to the negative relative permeability characteristics of some kinds of the metamaterial surfaces. Metamaterials are artificial periodic structures that have negative reflective index characteristics. Metamaterials are classified into three types depending on the polarity of the relative permeability and relative permittivity of the structure: double negative (DNG), ε negative (ENG), and μ negative (MNG), as shown in **Figure 24**.

The inductive, resonance inductive, and strongly coupled magnetic resonance WPT systems rely on the magnetic field coupling between the transmitter and receiver. Thus, the MNG metamaterial category is used with WPT. When the magnetic field travels from the transmitter coil and incident on a metamaterial with MNG, the

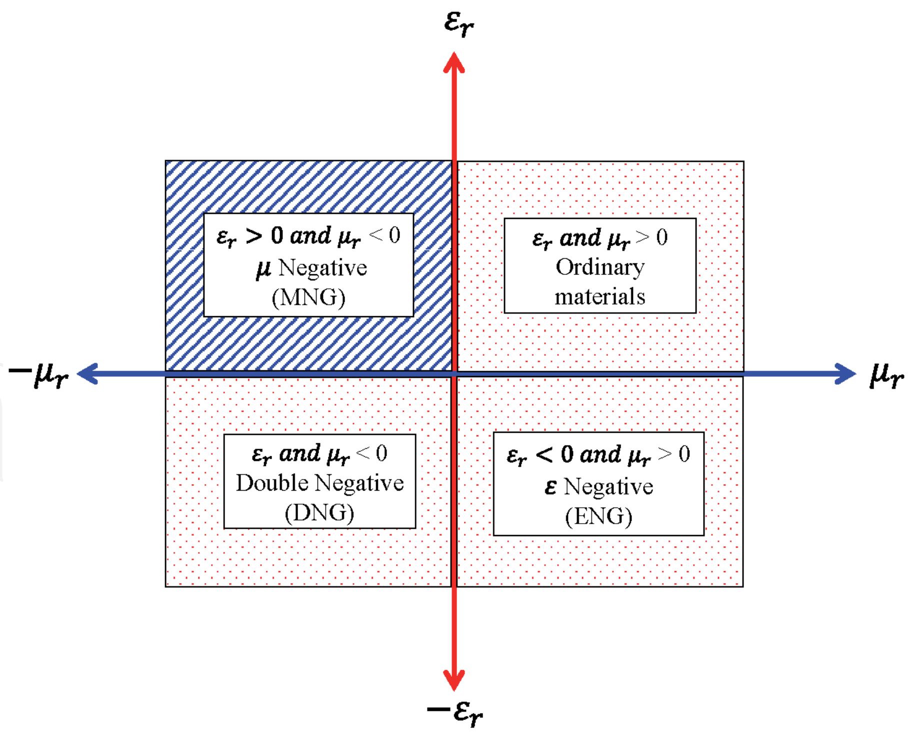


Figure 24.
Metamaterials categories.

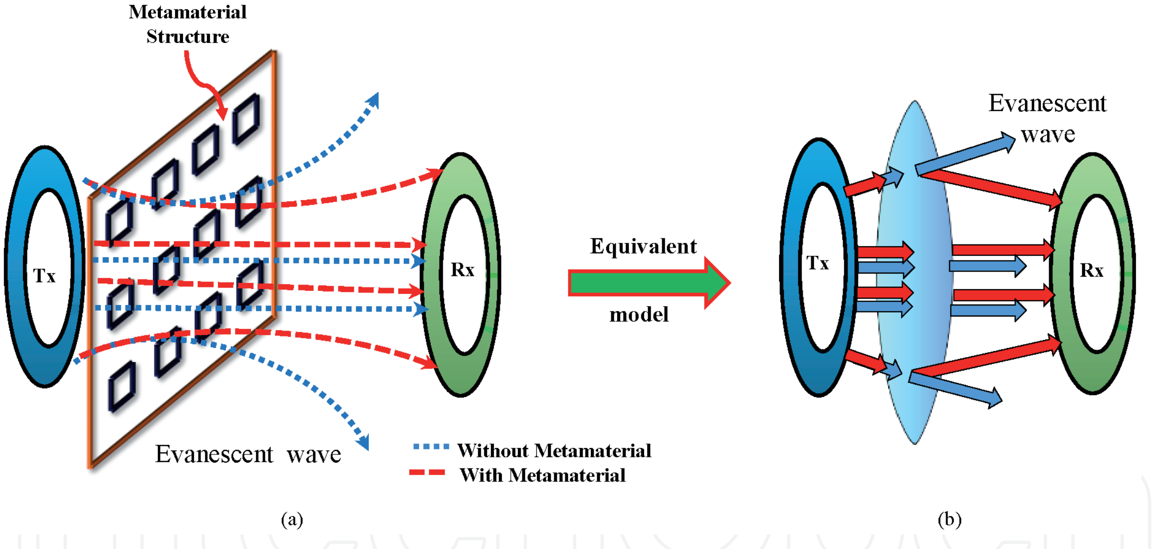
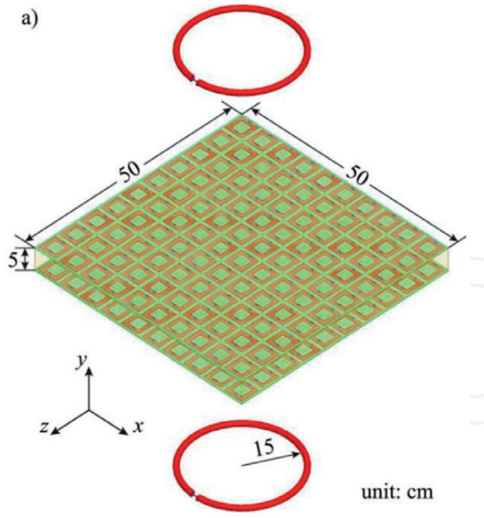
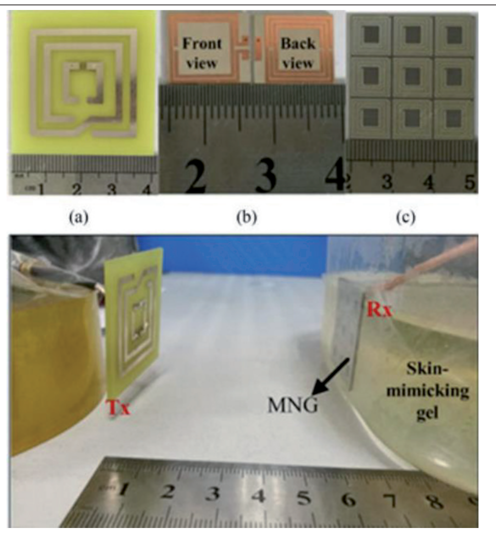
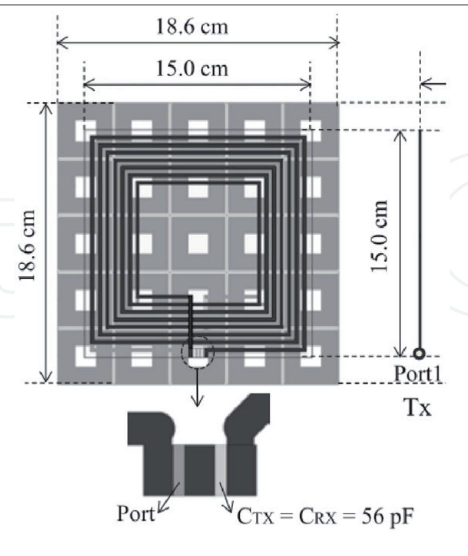
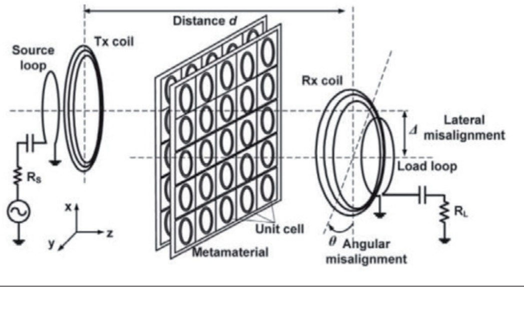


Figure 25.
(a) Metamaterial-based WPT system. (b) equivalent circuit model of applying metamaterial structures with WPT.

outgoing magnetic fields are bent back toward the receiver coil, this increases the field strength between the two coils as revealed in **Figure 25**. Thus, the efficiency is enhanced, and the EMF leakage is reduced due to applying these metamaterial surfaces in the path between the transmitter and receiver coils. **Table 1** summarizes different metamaterial structures that are used in WPT systems [36–40].

6. Capacitive coupling WPT

Capacitive coupling is a kind of coupling that depends on the electric field coupling between two plates, so it is also named electric coupling. Capacitive coupling

Reference	Geometry	Notes
[36]		• A thin metamaterial slabs • Study of three types of metamaterials is presented: the double negative material (DNG), the isotropic μ-negative material (MNG), and indefinite material (IM).
[37]		• An efficient wireless power transfer system integrating with negative permeability (MNG) metasurface is proposed for biological applications. • By using metasurface structure, a coupling enhancement of 15.7 dB is obtained.
[38]		• Metamaterials using a dual-layer printed circuit board (PCB) with a high dielectric constant substrate is proposed for enhancing system efficiency and reduced emf leakage in WPT systems • 44.2% improvement in the PTE and 3.49 dBm reduction in the electromagnetic field leakage at 6.78 MHz and separation distance of 20 cm is obtained.
[39]		• A study of using metamaterial structure to compensate the degradation in the power transfer efficiency due to the misalignment issues between the Tx and Rx.

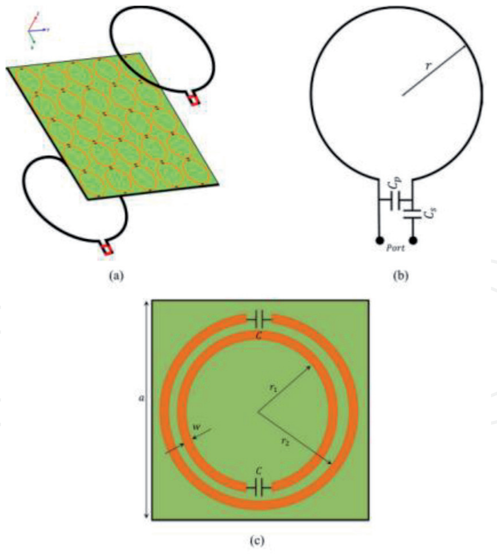
Reference	Geometry	Notes
[40]		• A closed-form and analytical expressions are obtained for efficiency improvement with metasurface.

Table 1.
Different metamaterial structures used in WPT systems.

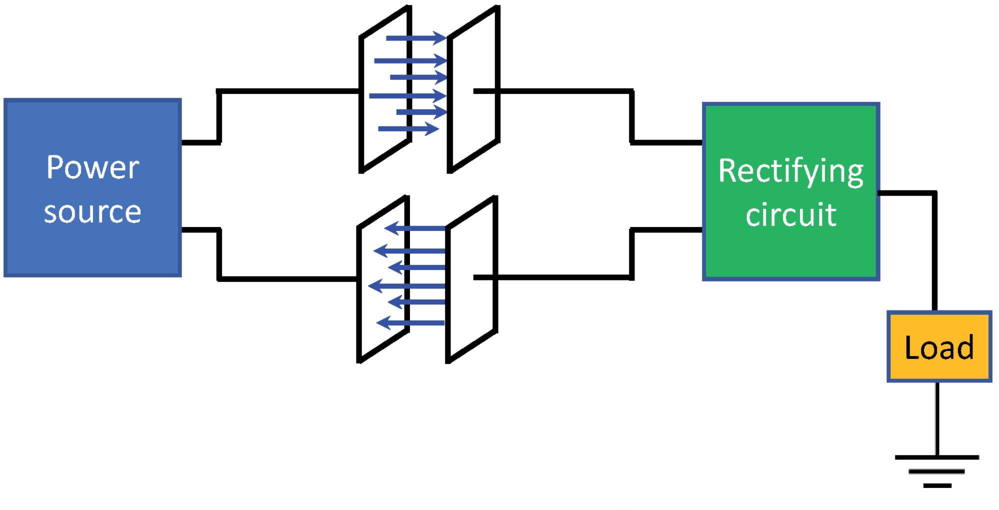


Figure 26.
capacitive wireless power systems.

acts as a capacitor where its metal plates one is in the transmitter and the other in the receiver and the medium in between represents the dielectric. The power can transfer between the two plates in form of a displacement current. **Figure 26** shows the WPT system for the capacitive coupling technique. As a result of electric field interacts with many different materials as well as capacitive coupling method needs very high voltages. Hence, capacitive coupling has only a few practical applications. Capacitive coupling has some special privileges over inductive coupling. The magnetic field is largely confined between the capacitor plates, reducing interference, and higher immunity for the misalignment issues between the transmitter and receiver. Therefore, capacitive coupling can be used in charging portable devices, smartcards, and transferring power between the layers of a substrate in RF integrated circuits. **Figure 27** illustrates an experiment for capacitive coupling that is executed by Nikola Tesla in 1891 [42]. He performed this experiment before his induction WPT demonstration.

In [43], a high-frequency capacitive coupling WPT using dielectric glass layers is introduced to reduce the coupling impedance and increase the coupling

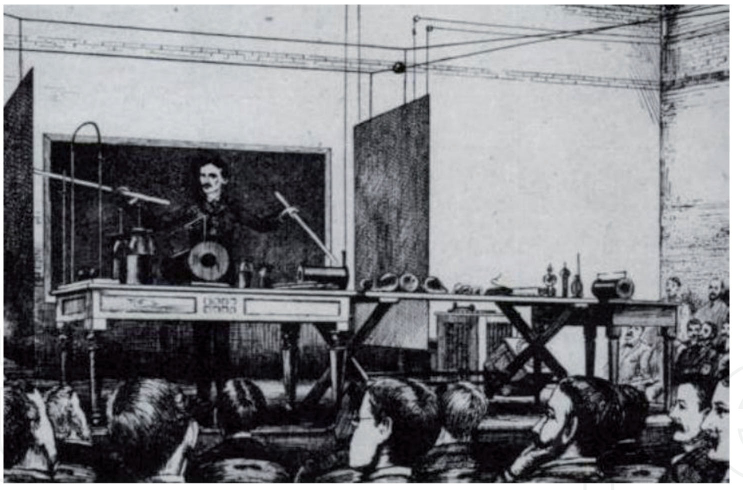


Figure 27.
Tesla demonstrating wireless power transmission using capacitive coupling, New York, in 1891 [41].

capacitance. Thus, it transfers power easily with high efficiency. Regensburger *et al.* introduced a high-performance capacitive WPT system for electric vehicles charging by using interleaved-foil coupled inductors [44]. This system used a kilowatt-scale large air-gap to achieve high power transfer density and high transfer efficiency at the operating frequency (13.56 MHz). Interleaved-foil air-core inductors provide a better quality factor; this makes them are useful at kilowatt-scale power at high frequencies. In [45], multi-loop control that is used to regulate the power transfer in capacitive wireless systems by applying variable matching networks is discussed. An adaptive multi-loop controller combines continuous frequency tracking and matching networks tuning to regulate a current/power to the receiving side at the optimal power transfer conditions. In [46–50], hybrid structures that combine inductive coupling and capacitive coupling WPT in the same system were proposed.

7. Microwave power transfer (MPT)

Microwave power transmission refers to far-field directive powering, where the power transmission occurs in the far-field using a well-defined directional transmitter. Microwave power transmission depends on the propagation of electromagnetic radiative fields where it is preferred in long-range WPT applications. This sort of WPT is useful for space-based solar power satellites (SPS) applications or with intentional powering such as using a dedicating source with a well-known direction to power a network of wireless sensors, each sensor has its built-in rectenna. One of the first applicable trails of MPT was conducted by William Brown et al. in 1965 by powering an aircraft using a MPT at an altitude of fifty feet for ten continuous hours [51].

There are many challenges regarding RF-to-DC power conversion efficiency, matching circuit design, the dependence of the DC output voltage as well as the conversion efficiency on the input power, load impedance, and operating frequency. In order to solve these issues, many rectennas have been introduced [52, 53]. Several single frequency band rectennas were used for energy harvesting [54, 55], and dual and multiband rectennas were discussed in [56–58]. In [59, 60] we proposed a dual-band rectenna using voltage doubler rectifier and four-section matching network. An enhanced-gain antenna with Defected Reflector Structure (DRS) is integrated with the rectifying circuit for increasing the rectenna capability for scavenging. A voltage doubler circuit is used for the rectification. Moreover, a four-section

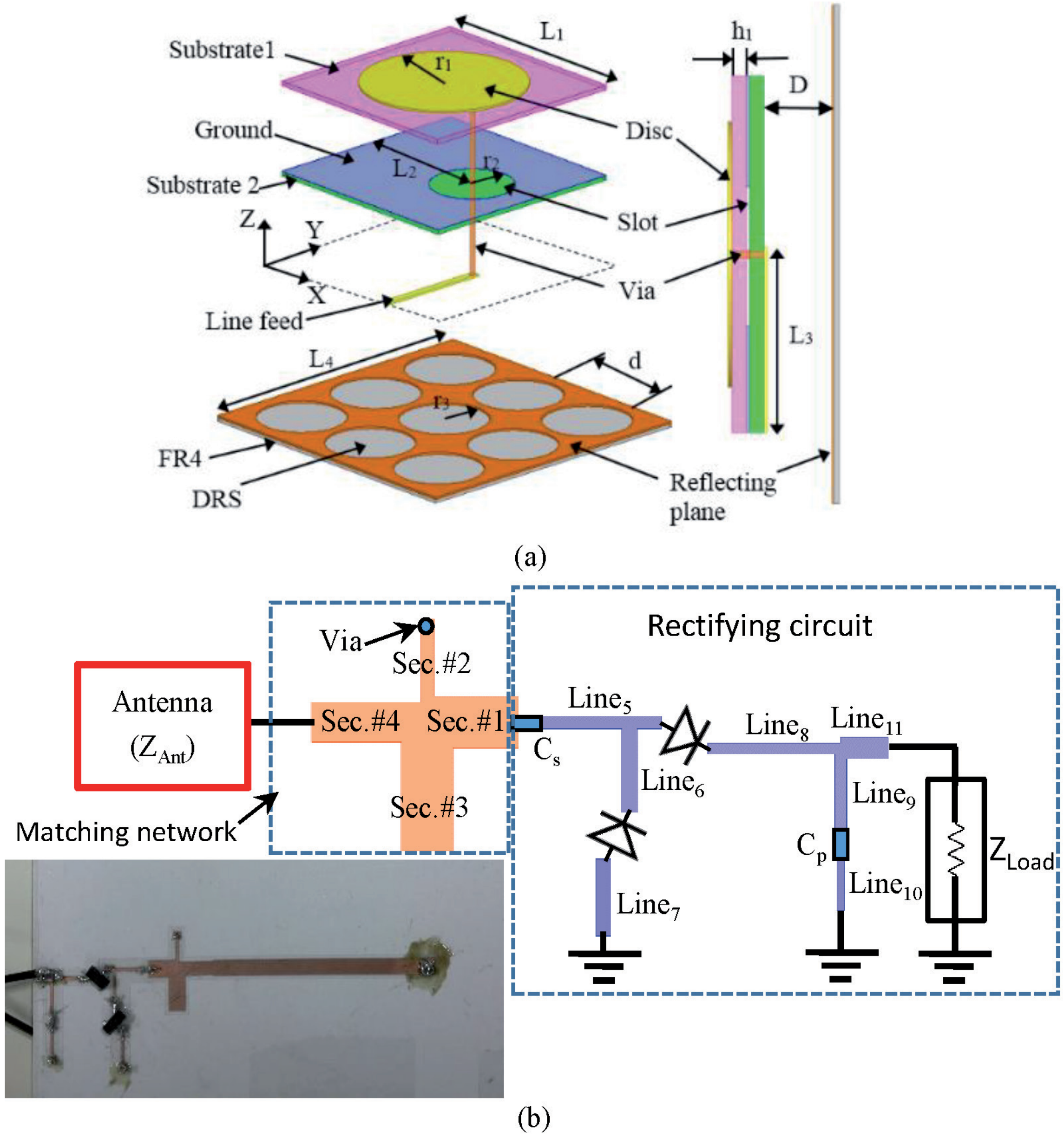


Figure 28.
Dual-band rectenna using four-section matching network, (a) high-gain received antenna, and (b) integration between the receiving antenna and the rectifying circuit [59, 60].

matching network is employed for the matching between the antenna and the rectifier circuit. This matching scheme is used to match between a complex and frequency dependent rectifier input impedance and a real impedance of the antenna (Z_{Ant}) by using different sections (Sec.#1, Sec.#2, Sec.#3, and Sec.#4) as shown in **Figure 28**.

Also in 2020 [61], we proposed a dual-band rectenna for low power applications. The rectenna is comprised of a co-planar (cpw) rectifier integrated with a rectangular split ring antenna loaded by a meandered strip line. A single diode series connection topology is used to miniaturize the losses at low input power operation. For maximum power transfer between the antenna and the rectifying circuit, the matching circuit that consists of a spiral coil in addition to two short circuit stubs is used as shown in **Figure 29**. The proposed rectenna operates at low input power with relatively high measured RF-DC conversion efficiency up to 74% at an input power of −6.5 dBm at the first resonant frequency f_1 = 700 MHz and 70% at −4.5 dBm at the second operating frequency f_2 = 1.4GHz with a resistive load of 1.9 K.

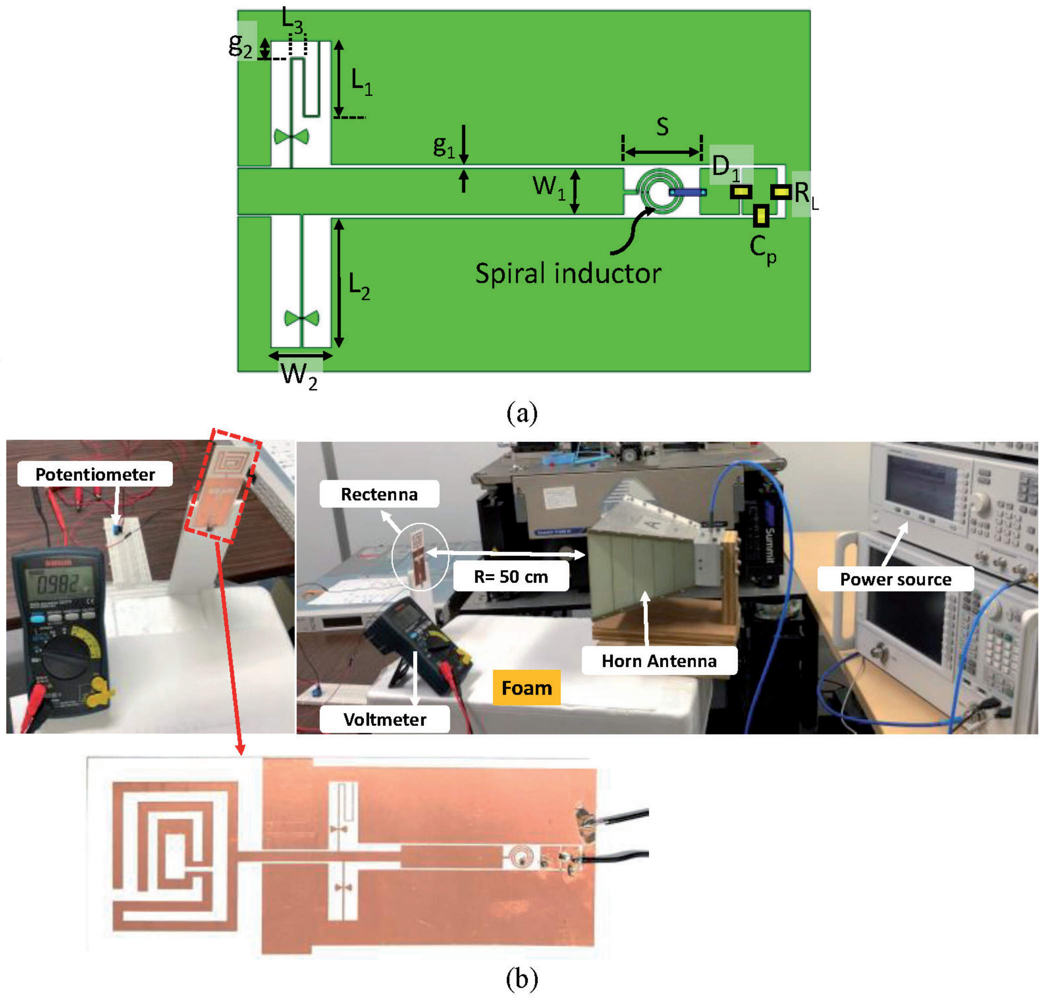


Figure 29.
Low power rectenna, (a) rectifier geometry, and (b) measurement setup [61].

8. Conclusion

This chapter presents a study of wireless power transfer technologies. A survey of employing several techniques such as inductive coupling, **resonant inductive coupling,** strongly coupled magnetic resonance, and capacitive coupling for increasing the power transfer efficiency for WPT systems. Metasurface-based WPT systems are also discussed. Many recently published WPT designs are listed with a highlight for the used techniques. Microwave Power Transfer (MPT) also introduced, and two rectenna designs are described.

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