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Review Article

A Comprehensive Review of Midrange Wireless Power Transfer Using Dielectric Resonators

Azuwa Ali,[1] **Mohd Najib Mohd Yasin**,[2] **Wan Fahmin Faiz Wan Ali**,[3] **Norsuria Mahmed**,[4] **Muhammad Ramlee Kamarudin**,[5] **Ismahayati Adam**,[2] **Muzammil Jusoh**,[2] **Hasliza Abdul Rahim**,[2] **Shing Fhan Khor**,[1] **Nurulazlina Ramli**,[6] **and Norshamsuri Ali**[2]

[1]*Faculty of Electrical Engineering Technology, Universiti Malaysia Perlis (UniMAP), Pauh Putra Campus, 02600 Arau, Perlis, Malaysia*
[2]*Faculty of Electronic Engineering Technology, Universiti Malaysia Perlis (UniMAP), Pauh Putra Campus, 02600 Arau, Perlis, Malaysia*
[3]*Faculty of Mechanical Engineering, Universiti Teknologi Malaysia (UTM), Skudai, 81310 Johor Bahru, Johor, Malaysia*
[4]*Faculty of Chemical Engineering Technology, Universiti Malaysia Perlis (UniMAP), Taman Muhibbah, 02600 Jejawi, Perlis, Malaysia*
[5]*Faculty of Electrical and Electronic Engineering, Universiti Tun Hussein Onn (UTHM), Parit Raja, 86400 Batu Pahat, Johor, Malaysia*
[6]*Faculty of Engineering and Built Environment (FoEBE), SEGI University, Kota Damansara, 47810 Petaling Jaya, Selangor, Malaysia*

Correspondence should be addressed to Mohd Najib Mohd Yasin; najibyasin@unimap.edu.my

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Magnetic resonant coupling (MRC) is one of the techniques that are widely used in wireless power transfer (WPT) systems. The technique is commonly used for enhancing distance while maintaining power transfer efficiency (PTE). Many studies have investigated new technologies to extend the distance of MRC while maintaining high PTE values. The most promising technique to date in MRC is the addition of a resonator between the transmitter and the receiver coil. The implementation of the resonator varies based on different designs, sizes, and material types, although the outcomes remain unsatisfactory. By introducing dielectric material resonators, PTE can be improved by lowering the ohmic loss which becomes a problem on conventional resonators. This study presents a general overview on the use of dielectric material as a resonator in MRC WPT technology and its technological development. The basic operation of MRC WPT is summarized with up-to-date technical improvements related to dielectric material as a resonator in the field of WPT. An overview of the current limitations and challenges of this technique is also highlighted in this study.

1. Introduction

The magnetic resonant coupling wireless power transfer (MRC WPT) technology uses two electromagnetic systems with the same resonance frequency to transfer power wirelessly at a targeted distance. Generally, both electromagnetic systems can excite strong magnetic resonance if the natural resonance frequency is the same despite the weak coupling at a targeted distance [1]. Prior to magnetic resonance coupling evolution, the most popular and typical technology utilized was inductive coupling (IC). The concept of transferring power over the air was initially founded by Nikola Tesla, leading the experiments and ideas surrounding this concept [2]. Despite its preference, IC could only transfer power within a short distance as compared to MRC as the system efficiency was typically affected by the coil's ohmic resistance and misalignment [2]. In 2007, a researcher from the Massachusetts Institute of Technology (MIT) proved an efficient nonradiative power transfer over a distance of up to 8 times the radius of the coils using a 4-coil system of strongly coupled magnetic resonance that transferred 60 Watts of power with an efficiency of more than 40% and a distance up to 2 meters [3, 4].

Owing to the increasing demand for wireless power transfer systems over the past few years, studies on the application of WPT have also increased significantly. There is a major focus on power transfer efficiency (PTE) as it drops quickly when the separation between the coils increases or when the coils become misaligned [5, 6]. Since consumer applications require extremely efficient end to load wireless power transmission, it is critical to consider methods that achieve maximum efficiency. To attain optimal efficiency, several approaches have been investigated and proposed in previous studies [5–13]. These approaches include impedance matching and control strategies using microcontroller techniques which include the quality (Q) factor and coupling (k) coefficient control, coil structure, and misalignment [14].

The adaptive impedance matching approach was previously introduced [5, 7–13] to improve PTE. Unlike automatic impedance tuning control, the disadvantage of adaptive tuning is the use of the varactor diode in the circuit which introduced additional losses. This reduces the total efficiency of the system. Previous studies have shown that efficiency optimization is achieved by varying the coupling (k) coefficient between the coils [5, 10–13]. This approach was performed by manually adjusting the distance between the coils to achieve a suitable coupling coefficient (k) at a targeted resonant frequency to ensure optimal efficiency. Although the approach yielded good results, the manual adjustment was not a feasible option for its practical implementation.

For the coil structure, several designs ranging from flat printed structured coil (PSC) [15–17] to helix [18–21], square [22–24], and 3D [25, 26] designs have been implemented. Designs ranging from as simple as a circular structure to other complicated designs have been adopted although the efficiency remained below the targeted value. In addition to the inefficient performance, its incompetence as a working device due to the bulky and complex design requires further improvement. For misalignment issues [14], horizontal and angular (azimuthal) misalignment are the two main types of misalignments that can occur. Several attempts have been made to solve this issue by variation of coil structure [27–29] and use of multiple resonators [20]. Variation of the coil structure to address the misalignment issue reduces the target efficiency, and the implementation of multiple resonators is impractical as more than one resonator is used and placed between the transmitter and receiver coils.

Issues pertaining to the MRC WPT system are related to high ohmic losses in the conventional resonator. When the ohmic loss is high, the Q factor automatically decreases, thus reducing the system performance to "hold" the energy for a longer time. Consequently, energy will deteriorate fast when the coils are separated and when there is a misalignment between the coils.

A review of dielectric material as a resonator in the MRC WPT system is presented in this study. The purpose of using a dielectric resonator is to reduce the ohmic loss in the conventional resonator. Studies in the field of material sciences [30, 31] have shown that dielectric material can increase the Q factor through the permittivity characteristic exhibited in the dielectric material. Previous review paper published in 2010 [31, 32] presented an extensive review on dielectric material and design. Therefore, this paper aims to discuss fundamental elements of dielectric material related to WPT and up-to-date developments over the past few years.

2. Working Principle of WPT Systems

WPT systems are classified into two categories based on their transmission technique: far-field and near-field transmissions. Radiative electromagnetic fields are used in far-field procedures, while nonradiative electromagnetic fields are used in near-field techniques. Near-field approaches, such as inductive coupling (IC), magnetic resonant coupling (MRC), and capacitive coupling, are the most prevalent and popular WPT techniques (CC). Table 1 shows a general comparison of the near-field WPT.

The basic operation principle of the WPT system consists of 2 coils: (a) the transmitter at the source and (b) the receiver at the output. Figure 1 shows the block diagram of the basic operation in the WPT system.

For MRC, the basic 2-coiled WPT system consists of two or multiple resonators (usually two) placed between the transmitter and receiver coil, generally known as coils. Figure 2 illustrates the basic operation of the MRC system. The coils and resonators must resonate at the same frequency to achieve optimal efficiency although the distance is varied or misaligned.

The MRC topology is represented by applying the reflected impedance method, in which the compensated capacitances can be determined based on different network topologies such as series-series (SS), series-parallel (SP), parallel-series (PS), and parallel-parallel (PP) [33]. Based on reflected impedance method, SS is the only topology that is independent of the coupling coefficient (k) (changing k does not affect the system) and the load condition since the reflected reactance is equal to zero on the primary side [33]. The SS topology is presented using the circuit analysis as shown in Figure 3.

The characteristics of the magnetic transmitter are obtained by utilizing Kirchhoff's voltage law (KVL) in the first phase of the calculations for the circuit. The impedances of the transmitter and receiver circuits are represented by the following expressions:

$$\begin{aligned} Z_1 &= R_1 + j\omega L_1 + \frac{1}{j\omega C_1}, \\ Z_2 &= R_2 + j\omega L_2 + \frac{1}{j\omega C_2}, \end{aligned} \tag{1}$$

where the mutual inductance, M, depends on the inductances L_1 and L_2 of the transmitter/receiver coils and the

Table 1: Comparison of performance for near-field WPT technique.

WPT characteristic	Near field: Inductive coupling (IC)	Near field: Magnetic resonant coupling (MRC)	Near field: Capacitive coupling (CC)
Frequency	kHz	MHz	MHz
Output power (W)	5	5	1
Distance	cm	m	mm
Efficiency (%)	70–90	40–60	80
Cost	Economical	Economical	Relatively expensive compared to other methods
Application	Wireless charging	Wireless sensor network	Smart card
Safety	Safe from biological point of view	Safe from biological point of view	Safe from biological point of view
Energy transfer	Magnetic fields	Magnetic fields	Electric fields
Enabling power transfer	Coils of wire	Resonant circuits	Conductive coupling plates

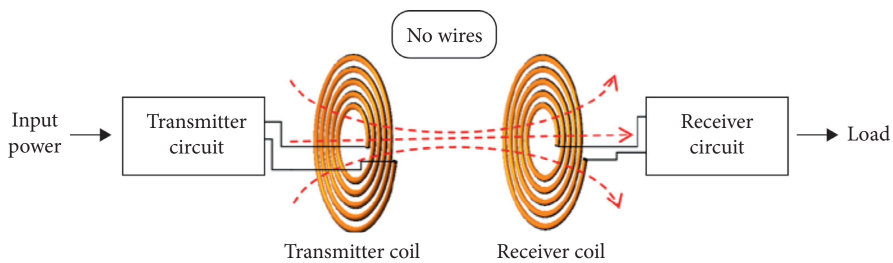


Figure 1: Basic block diagram of WPT.

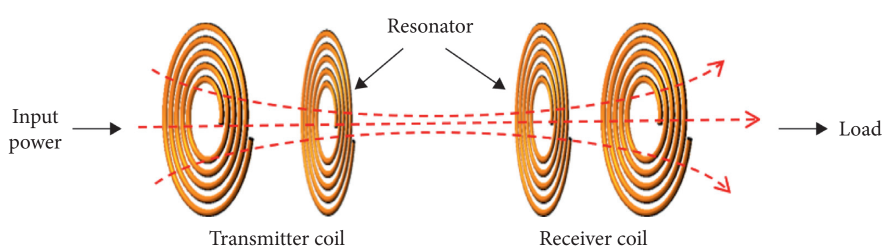


Figure 2: Basic block diagram of the MRC system.

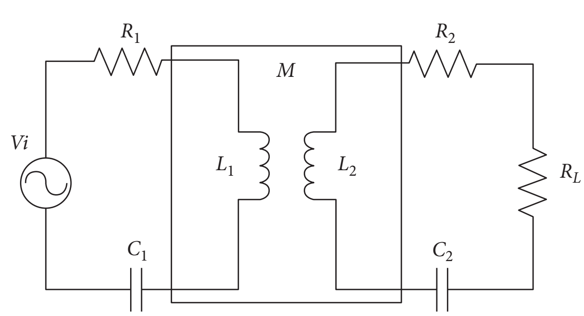


Figure 3: Circuit topology of the MRC system.

coupling coefficient k through the expression shown as follows:

$$M = k\sqrt{L_1 L_2}. \tag{2}$$

Each circuit excites identical mutual inductance on its neighbor which is observed as a feedback mechanism between the two circuits. The net effect is that each circuit modulates the impedance of its neighbor through the coupled magnetic flux and the consequent mutual inductance. At resonance, the reactance of each of the impedances Z_1 and Z_2 is identical to zero, and the resonance equations are obtained as follows:

$$\begin{gathered} \omega L_1 + \frac{1}{j\omega C_1} = 0 \\ \text{or } \omega_0 = \frac{1}{\sqrt{L_1 C_1}}. \end{gathered} \tag{3}$$

At resonance, the two circuits work in near-perfect transfer harmony as indicated by the equation as follows:

$$\omega_0 = \frac{1}{\sqrt{L_1 C_1}} = \frac{1}{\sqrt{L_2 C_2}}. \tag{4}$$

Equation (4) guides the operating frequency of the power transfer system. The inductors and capacitors used do not have to be of the same value. The most important characteristic is that the resonant frequency should be the same for both circuits. The power transfer relationships are the same as in the nonresonant two-coil systems based on the following equations:

$$P_{\text{in}} = \frac{V_s^2 Z_2}{\left[Z_1 Z_2 + (\omega M)^2\right]^2}, \tag{5}$$

$$P_{\text{out}} = \frac{V_s^2 (\omega M)^2 R_L}{\left[Z_1 Z_2 + (\omega M)^2\right]^2}. \tag{6}$$

At resonance, the power factors in each case become one where the input and output power are calculated from the following equations:

$$P_{\text{in}} = \frac{V_s^2 R_2}{R_1 R_2 + (\omega M)^2} = \frac{V_s^2 / R_1}{1 + k^2 Q_1 Q_2}, \tag{7}$$

$$P_{\text{out}} = \frac{V_s^2 k^2 Q_1 Q_2 R_L}{R_1 R_2 \left[1 + k^2 Q_1 Q_2\right]^2}. \tag{8}$$

Therefore, the power transfer efficiency is defined as the ratio of the output power to the input power as follows:

$$\eta = \frac{P_{\text{out}}}{P_{\text{in}}} \times 100 = \frac{k^2 Q_1 Q_2 R_L}{R_2 \left[1 + k^2 Q_1 Q_2\right]} \times 100. \tag{9}$$

The reflection coefficient, S_{21}, and radiation pattern parameters (E-field and H-field) are measured as an outcome of the WPT system performance. The transmitter, receiver coil, and dielectric resonator can be realized by independent equivalent RLC circuits as stated above, with each responding to a certain resonant frequency. The equation as follows is calculated for S_{21} (theoretical) which compromises the value of the Q factor to prove that the Q factor affects the WPT efficiency.

$$\left|S_{21}\right| = \frac{k_{tx}^2 Q_{tx} Q_{rx}}{\left[1 + \sqrt{1 + k_{tx}^2 Q_{tx} Q_{rx}}\right]^2}. \tag{10}$$

Equations (11) and (12) are used to calculate the reflection coefficient in the form of percentage based on the simulation and experimental results. To evaluate the overall WPT system performance, the PTE is calculated using the following equation:

$$S_{21}\,\text{dB} = 20 \log S_{21}, \tag{11}$$

$$n_{21} = S_{21}^2 \times 100\%. \tag{12}$$

The Q factor value is related to an individual reactive component, and it relies on the calculated frequency, which is the resonant frequency of the circuit. The Q value for an inductor with series of loss resistance is the total Q of resonant circuit utilizing that inductor and capacitor as follows:

$$Q_L = \frac{X_L}{R_L} = \frac{\omega_o X_L}{R_L}. \tag{13}$$

Here, R_L must be reduced to a minimum value to increase the value of Q. Therefore, a suitable method to reduce R is by adding a resonator that has a good coupling with the transmitter and receiver coils. Many types of resonators have been adopted, with a range of various designs and wire types and even the use of multiple resonators such as copper coil and metamaterial [34]. Despite using various resonator types and designs, the achieved results were still below the target as indicated in the condition as follows:

$$D > d_m. \tag{14}$$

According to [35], the efficiency deteriorates fast and is less than 50% if the ratio of the distance, D, between the coils is bigger than the coil diameter, d_m. When condition (14) occurs, the PTE drops significantly. Figure 4 show the representation of D and d_m in MRC system.

Previous studies have noted this condition and aimed to increase the distance and PTE without comparing it with the coil diameter. Table 2 highlights several examples of studies showing that the D/d_m ratio is lower than 1, thus indicating that the coil diameter is larger than the distance. The findings in [35] are supported whereby the PTE is shown to deteriorate when the distance is the same as or higher than the coil diameter value. The main concern lies in producing high PTE without considering the coil size. Subsequently, the system has a big coil but a lower effective distance of PTE. For practical applications, apart from high PTE and longer effective distance, the overall system design should be compact and able to adapt to at least a small misalignment between the coils.

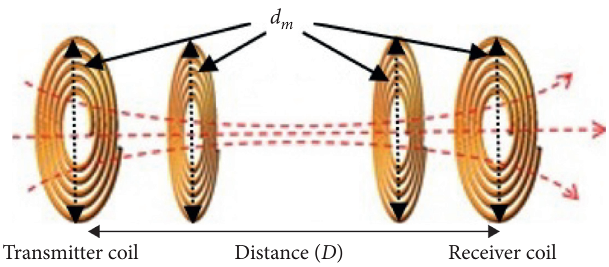


Figure 4: Representation of D and d_m.

Table 2: Calculation of D/d_m based on previous studies.

Reference	Distance, D (cm)	Diameter, d_m (cm)	Efficiency (%)	D/d_m
[12]	30	(31.5, 31.5)	55	0.95
[2]	25	(30, 30)	80	0.833
[3]	0.6	(2, 2)	35	0.3
[4]	0.3	(13.6, 5)	88.11	0.02
[5]	1	(6, 2)	67	0.17

Therefore, an alternative solution proposed for this issue is to replace the conventional resonator in the MRC system with other types such as the use of dielectric material. Studies employing the dielectric resonator in WPT are relatively scarce, and new insights can be unraveled to enhance the overall MRC WPT system.

3. Dielectric Resonators

Dielectric is a poor conductor material but can sustain electrostatic fields. If the movement of current within opposite electric charge poles is retained to a minimum and the electrostatic lines of flux are intact, the electrostatic field will be able to store energy. Most dielectric materials exist as a solid form [32] such as porcelain or ceramics, mica, glass, plastics, and oxides of various metals. Some liquids and gases also act as good dielectric material. Dry air is an excellent dielectric, while distilled water is a fair dielectric. On the other hand, vacuum is one example of an efficient dielectric.

Special and crucial characteristic of dielectric property is its capability to sustain an electrostatic field while releasing minimal energy in terms of heat. Reducing the dielectric loss made the dielectric material more efficient, as the proportion of energy lost as heat is minimal [36]. Another consideration is the dielectric constant which represents the extent to which a substance concentrates the electrostatic lines of the flux. Substances with a low dielectric constant include vacuum and dry air, while moderate dielectric constants include ceramics, distilled water, paper, mica, polyethylene, and glass. High dielectric constants are derived from metal oxides. High dielectric permittivity polarizes more in response to an applied electric field as compared to a material with low permittivity, thereby storing more energy in the material [37]. Therefore, high dielectric permittivity is favorable option for the WPT system to increase PTE and the distance as well as to reduce misalignment issues.

The operating frequency for dielectric resonators depends on the WPT system as previous studies have shown that lower dielectric permittivity (1–100) is often suitable and produces a higher frequency system, whereas higher permittivity (100 and above) is suitable for the kHz and MHz systems. WPT is widely known to operate in MHz range; hence, a dielectric with permittivity of around 1000 is preferable.

By using dielectric material with a suitable dielectric permittivity, it is possible to create a low loss resonator. Low loss resonator exhibits a high refractive index, which resulted in lowering electromagnetic wave movement. In WPT, this characteristic introduces stronger magnetic resonance in the dielectric resonator, thus leading to stronger resonances and higher efficiencies [32, 34]. By using dielectric resonator in WPT, magnetic dipoles are generated due to the interactions between the transmitter and receiver with the source excitation. To increase the transfer efficiency, the quality factor, Q, must be higher than 12. Hence, to obtain a high Q value, the R_L value based on (10) must be very small. To reduce R_L, the resonator is selected and coupled with the transmitter and resonator. The disadvantage of resonators selected in previous studies was that the R_L value was still high, thus resulting in a low Q factor as the coil-type resonators have ohmic resistance.

Therefore, the dielectric resonator is used as there is no additional ohmic resistance in the dielectric material and it is thus considered as a higher order mode of magnetic transfer [37, 38]. The signal reflections and refractions based on boundary conditions and material properties in the dielectric were used to assess the quality factor for the system. The quality factor of the dielectric resonator depends on the dielectric size and dielectric constant value [38]. The echoes formed inside the dielectric can generate a higher order harmonic of fundamental frequency for input excitation. These echoes are known as higher order modes. At any instance, these echoes are a weighted sum or superposition of all the modes present inside the dielectric and thus are termed as dominant modes [37]. Fundamental modes have the lowest resonant frequency, while higher order modes have the highest frequency.

The implementation of the dielectric resonator in the WPT system drives the resonant frequency to the higher order mode. The basic MRC operates at the electric dipole (ED) mode, but when the dielectric resonator is used, other modes known as the magnetic dipole (MD) and magnetic quadrupole (MQ) modes occur [32, 34, 39]. The radiation loss is possibly reduced at a higher mode, thus increasing the system efficiency. Each frequency mode is different in shapes and magnitudes with respect to their magnetic fields. Figure 5 shows the differences between the E- and H-field for MD and MQ as depicted in [39].

Studies have revealed that the WPT efficiency operating at MD mode not only was more efficient but also has higher resistant to the arbitrary orientation of the transmitter and receiver. The higher order modes exist when the value of the refractive index is higher, resulting in reducing ohmic resistance [39]. Therefore, operating at the MD or MQ mode as

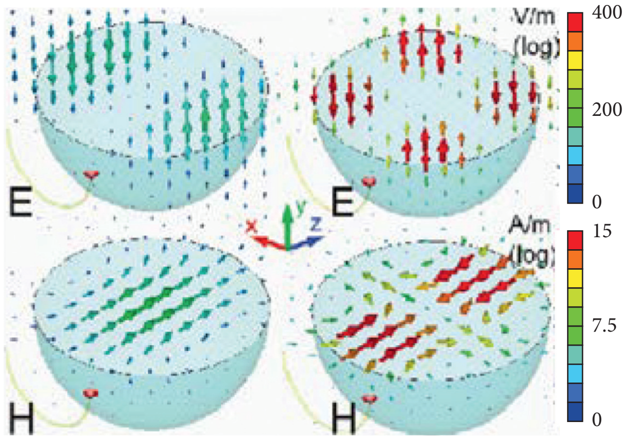


Figure 5: Examples of MD and MQ [39].

opposed to the ED mode produces more efficient WPT system due to the reduction in ohmic and radiation losses.

The theories on magnetic and electric dipole are essential for the understanding of resonant modes in WPT when adopting dielectric material as a resonator. An interesting feature of the dielectric resonator is that it has different radiating modes that are similar to electric and magnetic multipoles known as dipole, quadrupole, and octupole. The radiation pattern can be predicted accurately without using any complicated calculations for a regular shaped dielectric resonator [38].

For example, in the cylindrical dielectric resonator, the $TE_{01\delta}$ mode exists and radiates like a magnetic dipole aligned along its axis as shown in Figure 6. The $TE_{011+\delta}$ radiates as an axial magnetic quadrupole [40]. Equally, the $TM_{01\delta}$ and $TM_{011+\delta}$ modes radiate as an axial electric dipole and a quadrupole, accordingly. The basic form of the radiated fields for the TE and TM modes is independent of the dielectric constant related to the resonator material.

The unique characteristic of the dielectric resonator to produce various radiation patterns from different excitation radiation modes has not been investigated and appears to be interesting. For instance, the higher order mode $HEM_{21\delta}$ of a dielectric resonator, known as magnetic quadrupole mode, has the capability of sustaining magnetic fields that are less exploited in research related to WPT. Figure 7 shows the differences between the $TM_{01\delta}$ and $HEM_{21\delta}$ modes.

4. Inferences from Literature Review Studies

The manipulation and application of dielectric resonators in WPT began in 2013. However, their potential was hardly explored due to difficulties in producing high permittivity dielectric resonators. Inconsistent and unreliable fabrication processes were some of the challenges faced by researchers for their practical application. Nevertheless, the potential of dielectric resonators in enhancing WPT systems can be further explored, thus enabling the identification of new materials. A summary of publications reported from 2013 to 2019 is shown in Figure 8.

A WPT system based on ceramic material as a dielectric resonator was investigated in [42] as shown in Figure 9. In this study, Nishikawa and Ishizaki used a round shaped ceramic dielectric in their research and avoided the use of conventional resonators as conventional resonators have ohmic losses due to unloaded impedance. The researchers focused on the Q factor, particularly with emphasis on the microwave band frequency. The resonant frequency was set to 2.4 GHz and considered to be quite high for the MRC operating frequency. The dielectric material permittivity and PTE distance were not mentioned in the study.

In 2014, Hotta et al. used water as a dielectric to investigate the efficiency of MRC [43] as in Figure 10. They compared the use of conventional resonators with dielectric resonators. The results revealed that the conventional method produced a 5 to 10% increase in efficiency due to the low permittivity of water.

In another study [44], the authors used water or aqueous solution as a dielectric material, but the dielectric permittivity varied from 80 to more than 2000. The results based on the eigenmode analysis indicated that the higher the permittivity, the higher the Q factor. This observation supports the notion that the low permittivity dielectric observed in [43] is less efficient as compared to the conventional resonator. Therefore, high permittivity is more suitable to be implemented in the WPT system.

The use of higher dielectric permittivity was suggested in [39] as in Figure 11, in which ceramic dielectric with a permittivity of 80 was incorporated into the design. With a higher Q value, the radiation loss is minimized, and the efficiency of the system is increased. The basic principle of the system can be obtained from the Mie Scattering Theory which specifies that the charges bound inside the dielectric resonator interact with an external magnetic field as different orders of magnetic multipolar modes can be formed at different frequency. Therefore, the magnetic dipole (MD) mode is excited at the frequency of 210 MHz while the magnetic quadrupole (MQ) mode is excited at higher frequency of around 300 MHz. These two frequencies were recognized as the operating frequencies with an efficiency of nearly 90% at a 5 cm distance. The efficiency related to (14) was still low as the resonator dielectric was 8 cm and the sphere resonator design was big and bulky, thus deemed unsuitable for practical purposes.

In a follow-up study, the same authors improved the WPT system as proposed in [46, 47] using a dielectric cylinder resonator with colossal permittivity. The dielectric resonator was made from ceramics with a high permittivity of around 1000. The results were quite promising as the resonance frequency shifted from GHz to MHz, thus enabling the WPT operation. The simulation and experimental results were verified with a 50% efficiency which could be maintained within the separation distance of 16 cm (3.8 radius ratio with respect to resonator size) as in Figure 12 and Figure 13.

Several other follow-up studies were also published by the same authors in 2016 [39, 48, 49], 2017 [45, 47, 50], and 2019 [10]. Figure 14 illustrates the WPT system proposed by the authors [48–50]. The effect of using low and high

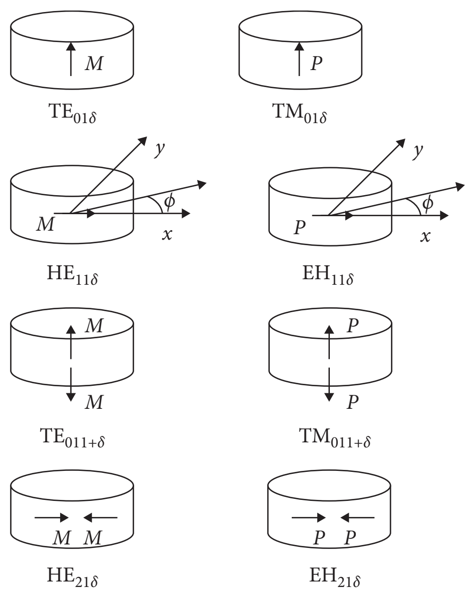


Figure 6: Nature of radiation for different modes of the cylindrical dielectric resonator. M is magnetic dipole and P is electric dipole [40].

permittivity dielectric resonator in the WPT system was investigated using ceramics based on Ba, Sr, and TiO_3 solution doped with Mg. Previous studies were only based on the simulation using the CST software by locating the magnetic distribution within the WPT system.

In 2018 [34], the working prototype was designed and validated for the WPT system using metasurface WPT for mobile charging applications. Figure 14 illustrates the proposed system, where the PTE increased tremendously to 80% at a 25 cm distance.

In addition, several studies [51–54] investigated the dielectric resonator effect in the WPT system. A recent study [35] showed that the WPT system operated at a quadrupole mode is more efficient and more resistant with different orientation of the transmitter and receiver placement. This finding affirms that the use of dielectric resonators can increase the WPT PTE and effective distance as well as reducing the misalignment issue. The effect of the dielectric design or shape was investigated using the dielectric strapping resonator [51] as in Figure 15(a) and dielectric-loaded multimode split cavity resonator (SCR) [52] as in Figure 15(b). The results were quite promising although further investigation of the implementation is required for its practical use. In another study [53], as in Figure 16(a), dielectric resonators from EXXELIA TEMEX E5080 which are composed of the oxide composition of B_m, S_m, and T_i material with a permittivity of 78 were employed. The authors indicated that this ceramic material was quite difficult to source as a ready-made resonator, and it was not easy to fabricate the resonator with a specific permittivity value. As in Figure 17 dielectric resonator is used layer by layer between the transmitter and receiver coil.

As previously indicated, misalignment in the MRC is another issue that must be addressed. There are two main types: lateral (horizontal) misalignment and angular (azimuthal) misalignment [56]. Two authors highlight the issue of misalignment in dielectric resonators for MRC WPT in [53, 57]. Both authors discussed misalignment on the lateral and angular axes. Table 3 shows a summary of previous studies on misalignment using dielectric material.

In contrast, Table 4 summarizes the previous studies on misalignment using conventional resonator. The findings for both types of misalignments using dielectric resonator are fairly good in comparison to previous studies such as [27, 58–62]. In a prior research, the authors used a different coil, resonator, and tracking technique to decrease the influence of misalignment. A precise comparison of performance cannot be done since the idea of misalignment has been defined variously in prior research and is application dependent. For example, in the case of an electric vehicle, lateral misalignment is considered since the charging pad is fixed beneath the vehicle, preventing azimuthal misalignment.

As shown in Table 5, the form of the dielectric varies across designs, and the size is identical to that of the transmitter and receiver coils. The shape of the dielectric has no discernible influence on the overall system's performance, and according to [65], the dielectric constant is the most critical factor. The greater the dielectric constant is, the longer the dielectric can retain magnetic fields; however, the frequency is shifted to a lower value. As demonstrated in [53], the parametric research employed dielectric constants ranging from 1000 to 2000; however, due to the inaccessibility of the needed dielectric constant, the authors employed 78 dielectric values for experimental verification. The frequency was increased from hundreds of MHz to GHz, which reduced the effective distance (to only a few millimetres) since the system wavelength decreased as the frequency was increased. According to Song et al., the initial research used a spherical shape dielectric to investigate parametric effects on the dielectric constant of a WPT system starting in 2016 [48] and shifted to a slimmer dielectric in 2019 [34] that is disc

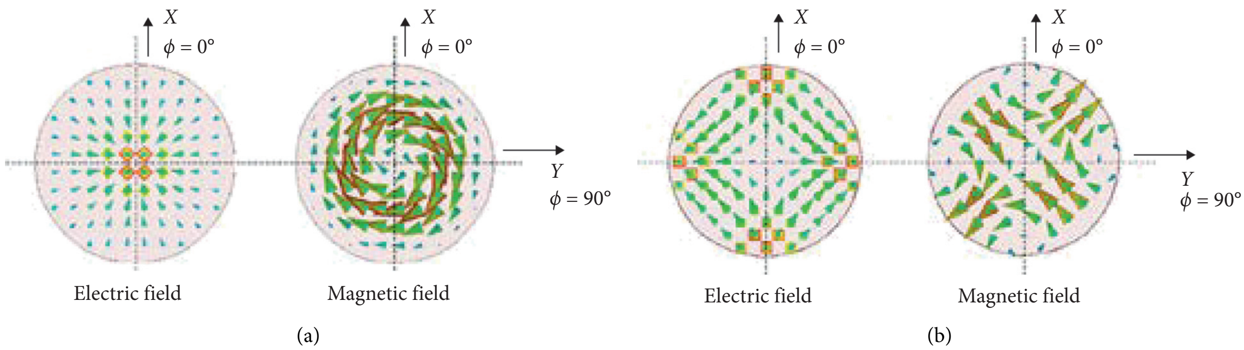


Figure 7: View of the electric and magnetic field intensity using HFSS eigenmode method. (a) $TM_{01\delta}$; (b) $HEM_{21\delta}$ modes [41].

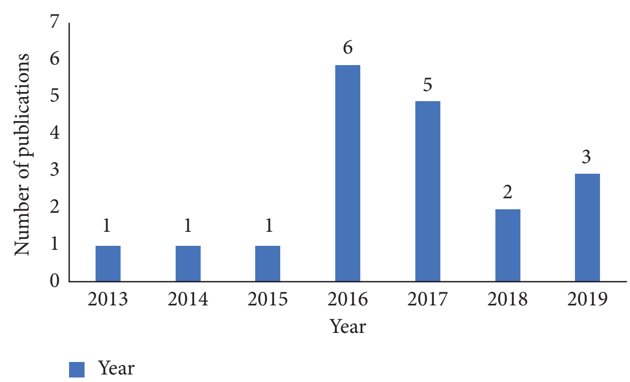


Figure 8: Publications on WPT using dielectric resonators from 2013 to 2019.

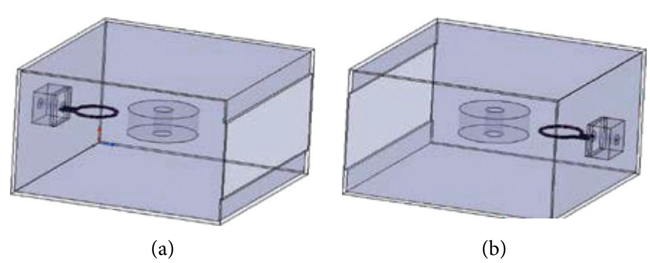


Figure 9: Design of the WPT system as in [42].

ceramics shape because it is more suitable for implementation and commercialization in real applications.

Comparison of the performance of MRC with a dielectric resonator and a conventional resonator is shown in Tables 6 and 7. As shown in the tables, the D/d_m ratio is greater when a dielectric resonator is used, indicating that the dielectric resonator has a substantial influence on the performance of the MRC. On a more positive note, research into dielectric resonators may be expanded and investigated further.

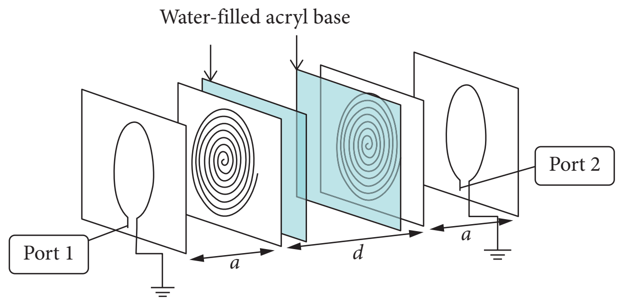


Figure 10: Design of the WPT system as in [43].

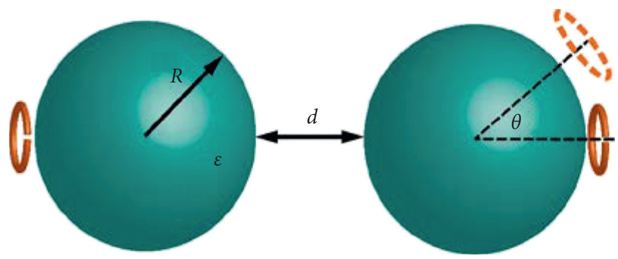


Figure 11: Design of the WPT system as in [39, 45].

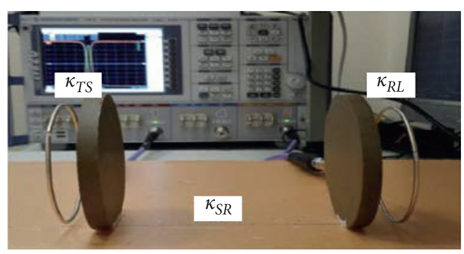


Figure 12: Design of the WPT system as in [46, 47].

Figure 13: Design of the WPT system as in [48–50].

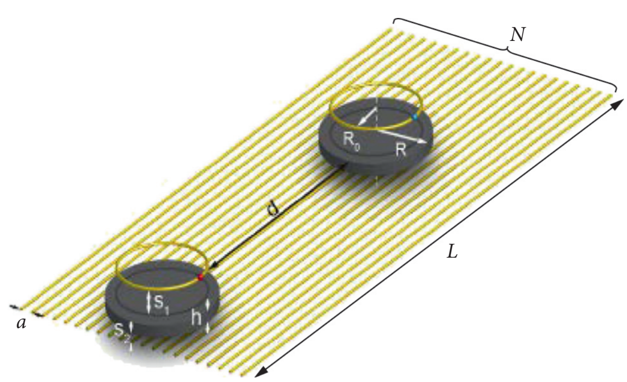
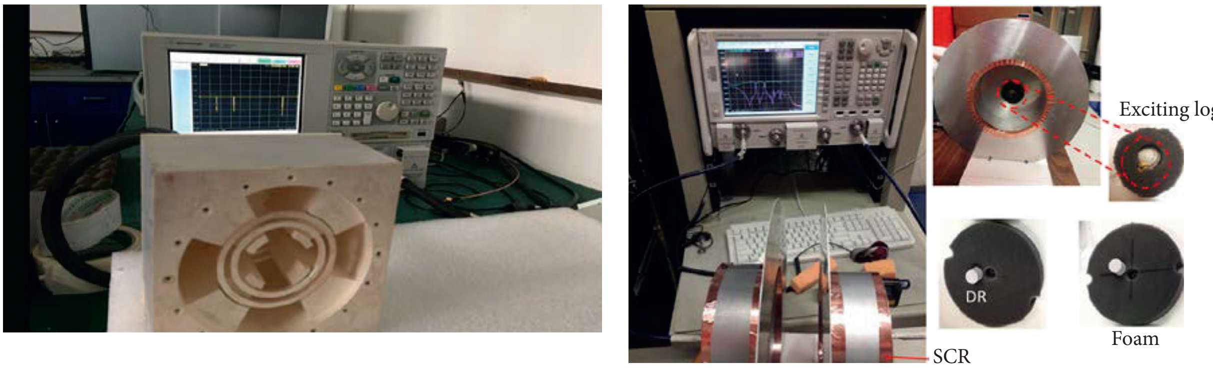
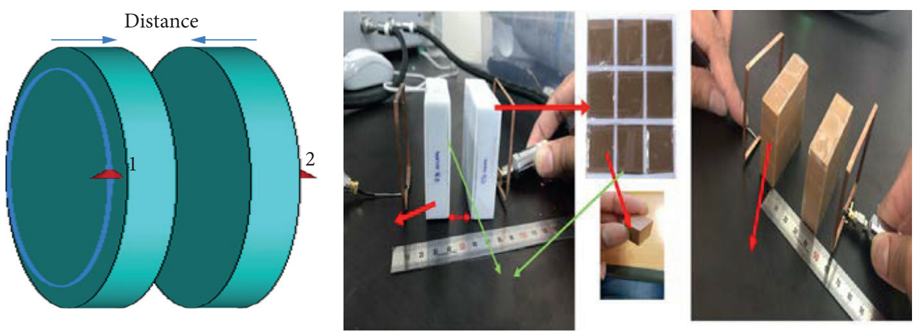


Figure 14: Design of the WPT system as in [34].



(a) (b)

Figure 15: Design of the WPT system from reference studies: (a) [51]; (b) [52].



(a) (b)

Figure 16: Design of the WPT system from reference studies: (a) [55]; (b) [53].

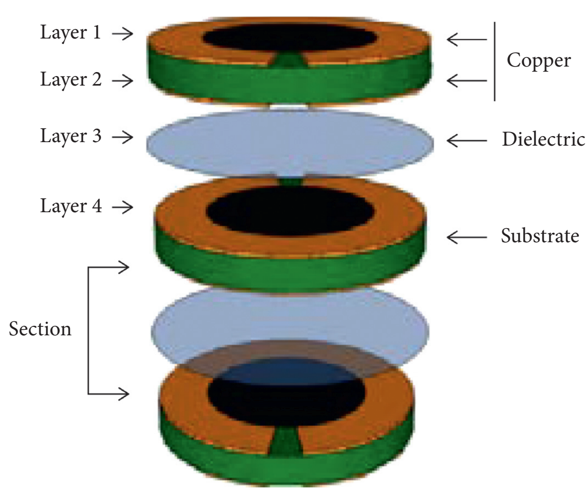


Figure 17: Design of the WPT system as in [54].

Table 3: Summary of previous studies on misalignment using the dielectric resonator.

Reference	Diameter (cm)	No misalignment (distance, efficiency)	Lateral (distance, efficiency)	Angular (degree, efficiency)
[57]	8.4	16 cm, 50%	7 cm, 5%	60°, 10%
[53]	3.6	3.6 cm, 52%	3.6 cm, 50%	60°, 70%

Table 4: Summary of previous studies on misalignment using the conventional resonator.

Reference	Diameter (cm)	No misalignment (distance, efficiency)	Lateral (distance, efficiency)	Angular (degree, efficiency)
[58]	60	65 cm, 70%	30 cm, 60%	—
[59]	24	—	10 cm, 50%	—
[60]	24	—	10 cm, 50%	—
[27]	20	—	3 cm, 70%	60°, 65%
[61]	6	1 cm, 78%	1 cm, 60%	6°, 50%
[62]	7.4	—	3.5 cm, 73.6%	90°, 21.9%

Table 5: Overall summary of previous studies using a dielectric material.

No.	Author	Dielectric types	ε_r	Distance, D (cm)	Efficiency (%)	D/d_m	λ
1	Song et al. [34]	Disk, ceramics	1000	25	70~80	2.98	0.25
2	Song et al. [35]	Spherical, ceramics	1000	4	90	2	0.03
3	Kapitanova and Belov [47]	Disk, ceramic	1000	10	90	1.19	0.13
4	Guo et al. [51]	Strapped, ceramic	—	3.5	70	0.76	0.11
5	Elnaggar et al. [44]	Rectangular, aqueous solution	81–2365	—	—	—	—
6	Zyga [63]	—	—	—	—	—	—
7	Song et al. [46]	Disk, ceramic	1000	16.5	50	1.96	0.12
8	Das et al. [53]	Rectangular, ceramic	78	5	50	1.67	0.1
9	Nishikawa and Ishizaki [42]	Round, ceramic		5	90	2	0.4
10	Belov et al. [39]	Sphere, ceramic	80	5	90	0.31	0.05
11	Kapitanova et al. [49]	Sphere, ceramic	1000	7	50	0.83	0.05
12	Song et al. [50]	Sphere, ceramic	80	1	82	0.5	0.08
13	Song et al. [64]	Sphere, ceramic	80	5	80	0.31	0.1
14	Song et al. [55]	Disk, ceramic	1000	12	98	1.42	0.12
15	Hotta et al. [43]	Rectangular, water	—	12	76.62	0.45	0.008
16	Elnaggar et al. [52]	Loaded multimoded split cavity resonator (SCR)	25	7	70	0.19	0.028
17	Kapitanova et al. [48]	Sphere, ceramic	80	16	50	1.9	0.12
18	Stein et al. [54]	Disk, ceramic	—	6.5	90	0.98	0.002

Table 6: Summary of previous studies using the dielectric resonator.

Reference	Distance, D (cm)	Diameter, d_{m} (cm)	Efficiency (%)	D/d_m
[34]	25	(8.4, 8.4)	70~80	2.98
[51]	3.5	(4.6, 4.6)	70	0.76
[53]	5	(3, 3)	50	1.67
[42]	5	(2.5, 2.5)	90	2
[52]	7	(36.8, 36.8)	70	0.19

Table 7: Summary of previous studies using the conventional resonator.

Reference	Distance, D (cm)	Diameter, d_m (cm)	Efficiency (%)	D/d_m
[66]	1	(6.55, 2.05)	79.8	0.15
[3]	0.6	(2, 2)	35	0.3
[4]	0.3	(13.6, 5)	88.11	0.02
[67]	5	(18, 19) (12, 15)	30	0.26
[68]	2	(2, 2)	35	1

5. Conclusion

Owing to the high potential of the WPT system, many industry practitioners are eager to adopt this system in their applications. Various studies have been performed to solve the problems related to the WPT system, particularly concerning the distance of PTE as well as misalignment issues. The manipulation of dielectric resonators previously used for antenna applications for high frequency has been adopted in the WPT system to provide a better solution for the current issues. However, the fabrication of the dielectric resonator with targeted permittivity is difficult to source, and the cost of the dielectric material is high. Therefore, a suitable design for the WPT system integrated with dielectric material is required to ensure its practical implementation.

Data Availability

Data are available from the corresponding author on request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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References

[1] L. Gao, W. Hu, Z. Wu et al., "Magnetic coupling resonant wireless energy transmission coil quantitative relation modeling and simulation research," in *Proceedings of the 2013 10th IEEE International Conference on Control and Automation (ICCA)*, pp. 202–207, Hangzhou, China, June 2013.

[2] S. Park, H. Kim, J. Cho, E. Kim, and S. Jung, "Wireless power transmission characteristics for implantable devices inside a human body," in *Proceedings of the 2014 International Symposium on Electromagnetic Compatibility*, pp. 1190–1194, Gothenburg, Sweden, 2014.

[3] B. T. Nukala, J. Tsay, D. Y. C. Lie, J. Lopez, and T. Q. Nguyen, "Efficient near-field inductive wireless power transfer for miniature implanted devices using strongly coupled magnetic resonance at 5.8 GHz," in *Proceedings of the 2016 Texas Symposium on Wireless and Microwave Circuits and Systems*, Waco, TX, USA, 2016.

[4] D. Lie, "Wireless power transfer (WPT) using strongly coupled magnetic resonance (SCMR) at 5.8 GHz for biosensors applications: a feasibility study by electromagnetic (EM) simulations," *International Journal of Biosensors & Bioelectronics*, vol. 2, no. 2, 2017.

[5] T. P. Duong and J.-W. Lee, "Experimental results of high-efficiency resonant coupling wireless power transfer using a variable coupling method," *IEEE Microwave and Wireless Components Letters*, vol. 21, no. 8, pp. 442–444, 2011.

[6] T. C. Beh, M. Kato, T. Imura, S. Oh, and Y. Hori, "Automated impedance matching system for robust wireless power transfer via magnetic resonance coupling," *IEEE Transactions on Industrial Electronics*, vol. 60, no. 9, pp. 3689–3698, 2013.

[7] K. E. Koh, T. C. Beh, T. Imura, and Y. Hori, "Impedance matching and power division using impedance inverter for wireless power transfer via magnetic resonant coupling," *IEEE Transactions on Industry Applications*, vol. 50, no. 3, pp. 2061–2070, 2014.

[8] C. J. Chih-Jung Chen, T. H. Tah-Hsiung Chu, C. L. Chih-Lung Lin, and Z. C. Zeui-Chown Jou, "A study of loosely coupled coils for wireless power transfer," *IEEE Transactions on Circuits and Systems II: Express Briefs*, vol. 57, no. 7, pp. 536–540, 2010.

[9] J. Lee, Y.-S. Lim, W.-J. Yang, and S.-O. Lim, "Wireless power transfer system adaptive to change in coil separation," *IEEE Transactions on Antennas and Propagation*, vol. 62, no. 2, pp. 889–897, 2014.

[10] S. Y. R. Hui, W. Zhong, and C. K. Lee, "A critical review of recent progress in mid-range wireless power transfer," *IEEE Transactions on Power Electronics*, vol. 29, no. 9, pp. 4500–4511, 2014.

[11] H. Hoang, S. Lee, Y. Kim, Y. Choi, and F. Bien, "An adaptive technique to improve wireless power transfer for consumer electronics," *IEEE Transactions on Consumer Electronics*, vol. 58, no. 2, pp. 327–332, 2012.

[12] D. Ahn and S. Hong, "A transmitter or a receiver consisting of two strongly coupled resonators for enhanced resonant coupling in wireless power transfer," *IEEE Transactions on Industrial Electronics*, vol. 61, no. 3, pp. 1193–1203, 2014.

[13] Y. Zhang, Z. Zhao, and K. Chen, "Frequency-splitting analysis of four-coil resonant wireless power transfer," *IEEE Transactions on Industry Applications*, vol. 50, no. 4, pp. 2436–2445, 2014.

[14] M. Abou Houran, X. Yang, and W. Chen, "Magnetically coupled resonance WPT: review of compensation topologies, resonator structures with misalignment, and EMI diagnostics," *Electronics*, vol. 7, no. 11, p. 296, 2018.

[15] J. Zhang, X. Yuan, C. Wang, and Y. He, "Comparative analysis of two-coil and three-coil structures for wireless power transfer," *IEEE Transactions on Power Electronics*, vol. 32, no. 1, pp. 341–352, 2017.

[16] A. P. Sample, D. A. Meyer, and J. R. Smith, "Analysis, experimental results, and range adaptation of magnetically coupled resonators for wireless power transfer," *IEEE Transactions on Industrial Electronics*, vol. 58, no. 2, pp. 544–554, 2011.

[17] K. Chen and Z. Zhao, "Analysis of the double-layer printed spiral coil for wireless power transfer," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 1, no. 2, pp. 114–121, 2013.

[18] C. Yang and K. Tsunekawa, "A novel parallel double helix loop resonator for magnetic coupled resonance wireless power transfer," in *Proceedings of the PIERS Proceedings*, pp. 466–470, Guangzhou, China, August 2014.

[19] Y. Zhang, T. Lu, Z. Zhao, K. Chen, F. He, and L. Yuan, "Wireless power transfer to multiple loads over various distances using relay resonators," *IEEE Microwave and Wireless Components Letters*, vol. 25, no. 5, pp. 337–339, 2015.

[20] K. Lee and D.-H. Cho, "Diversity analysis of multiple transmitters in wireless power transfer system," *IEEE Transactions on Magnetics*, vol. 49, no. 6, pp. 2946–2952, 2013.

[21] Y. Zhang, Z. Zhao, and T. Lu, "Quantitative analysis of system efficiency and output power of four-coil resonant wireless power transfer," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 3, no. 1, pp. 184–190, 2015.

[22] J. Deng, W. Li, T. D. Nguyen, S. Li, and C. C. Mi, "Compact and efficient bipolar coupler for wireless power chargers: design and analysis," *IEEE Transactions on Power Electronics*, vol. 30, no. 11, pp. 6130–6140, 2015.

[23] F. L. Cabrera and F. R. De Sousa, "Achieving optimal efficiency in energy transfer to a CMOS fully integrated wireless power receiver," *IEEE Transactions on Microwave Theory and Techniques*, vol. 64, no. 11, pp. 3703–3713, 2016.

[24] S. Moon and G. W. Moon, "Wireless power transfer system with an asymmetric four-coil resonator for electric vehicle battery chargers," *IEEE Transactions on Power Electronics*, vol. 31, pp. 6844–6854, 2016.

[25] N. Ha-Van, H. Le-Huu, M. T. Le, K. Park, and C. Seo, "Free-positioning wireless power transfer using a 3D transmitting

coil for portable devices," *Journal of Electromagnetic Engineering and Science*, vol. 20, no. 4, pp. 270–276, 2020.

[26] T. Hou, J. Xu, W. S. Elkhuizen et al., "Design of 3D wireless power transfer system based on 3D printed electronics," *IEEE Access Digital Object Identifier*, vol. 7, pp. 94793–94805.

[27] J. Wang, J. Li, S. L. Ho et al., "Lateral and angular misalignments analysis of a new PCB circular spiral resonant wireless charger," *IEEE Transactions on Magnetics*, vol. 48, no. 11, pp. 4522–4525, 2012.

[28] D. Liu, H. Hu, and S. Georgakopoulos, "Misalignment sensitivity of strongly coupled wireless power transfer systems," *IEEE Transactions on Power Electronics*, vol. 32, pp. 5509–5519, 2016.

[29] F. Kong, Y. Huang, and L. Najafizadeh, "A coil misalignment compensation concept for wireless power transfer links in biomedical implants," in *Proceedings of the 2015 IEEE Wireless Power Transfer Conference*, Boulder, CO, USA, 2015.

[30] Y. Zhang, T. Yoshikawa and T. Kitahara, "A quantitative analysis of coupling for a WPT system including dielectric/magnetic materials," *Progress in Electromagnetics Research Letters*, vol. 72, pp. 127–134, 2018.

[31] S. B. Narang and S. Bahel, "Low loss dielectric ceramics for microwave applications: a review," *Journal of Ceramic Processing Research*, vol. 11, no. 3, pp. 316–321, 2010.

[32] A. A. Ward, *Dielectric Materials for Advanced Applications*, 2016.

[33] R. S. Yaduvanshi and G. Varshney, *Nano Dielectric Resonator Antennas for 5G Applications*, Taylor & Francis Group, Abingdon, UK, First edition, 2020.

[34] M. Song, K. Baryshnikova, A. Markvart et al., "Smart based on a metasurface for wireless power transfer," *Physical Review Applied*, vol. 11, no. 5, p. 1, 2019.

[35] A. Petosa and A. Ittipiboon, "Dielectric resonator antennas: a historical review and the current state of the art," *IEEE Antennas and Propagation Magazine*, vol. 52, no. 5, pp. 91–116, 2010.

[36] P. D. Terekhov, K. V. Baryshnikova, Y. A. Artemyev, A. Karabchevsky, A. S. Shalin, and A. B. Evlyukhin, "Multipolar response of nonspherical silicon nanoparticles in the visible and near-infrared spectral ranges," *Physical Review B*, vol. 96, no. 3, Article ID 035443, 2017.

[37] A. B. Evlyukhin, T. Fischer, C. Reinhardt, and B. N. Chichkov, "Optical theorem and multipole scattering of light by arbitrarily shaped nanoparticles," *Physical Review B*, vol. 94, Article ID 205434, 2016.

[38] P. Belov, M. Song, I. Iorsh, and P. Kapitanova, "Application of High-Q dielectric resonators for wireless power transfer system," in *Proceedings of the SBMO/IEEE MTT-S International Microwave and Optoelectronics Conference Proceedings*, Porto de Galinhas, Brazil, Decemember 2015.

[39] K. Rajesh, Mongia, and Bhartia, "General design relations for resonant frequency and bandwidth," *International Journal of Microwave and Millimeter-Wave Computer-Aided Engineering*, vol. 4, no. 3, pp. 230–247, 1994.

[40] A. K. Ojha, R. Jain, and P. Kumar, "Magnetic quadrupole mode excitation of a cylindrical dielectric resonator antenna using planar feed," *Microwave and Optical Technology Letters*, vol. 62, no. 3, 2019.

[41] K. Nishikawa and T. Ishizaki, "Microwave-band wireless power transfer system using ceramic dielectric resonators," in *Proceedings of the 2013 IEEE Wireless Power Transfer*, pp. 175–178, Perugia, Italy, May 2013.

[42] M. Hotta, A. Nobu, T. Haruyamab, T. Yuki, and M. Hano, "Effect of water and/or dielectric materials for resonant type," *The Japanese Journal of the Institute of Industrial Applications Engineers*, vol. 2, pp. 2187–5146.

[43] S. Y. Elnaggar, C. Saha, and Y. M. M. Antar, "An electromagnetic induced transparency like scheme for wireless power transfer in contained aqueous solutions," in *Proceedings of the 2018 IEEE Wireless Power Transfer Conference*, Montreal, Canada, 2018.

[44] M. Song, P. A. Belov, P. V. Kapitanova, and C. R. Simovski, "Wireless power transfer through multipole coupling in dielectric resonators," in *Proceedings of the Progress in Electromagnetics Research Symposium*, pp. 1632–1635, St. Petersburg, Russia, May 2017.

[45] S. A. Y. Elnaggar, C. Saha, and Y. M. M. Antar, "Wireless power Transfer via dielectric loaded multi moded split cavity resonator," 2019, http://arxiv.org/abs/1901.06684.

[46] M. Song, P. Belov, and P. Kapitanova, "Wireless power transfer based on dielectric resonators with colossal permittivity," *Applied Physics Letters*, vol. 109, no. 22, 2016.

[47] F. F. Guo, S. Ding, and B. Z. Wang, "Wireless power transfer system based on strapping resonators," *Applied Sciences (Switzerland)*, vol. 8, no. 12, 2018.

[48] P. Kapitanova and P. Belov, "Numerical study of magnetic wireless power transfer system based on magnetic modes of dielectric disk resonator," in *Proceedings of the 2017 IEEE International Conference on Microwaves, Antennas, Communications And Electronic Systems, COMCAS 2017*, Tel-Aviv, Israel, November 2017.

[49] P. V. Kapitanova, M. Song, and P. A. Belov, "Wireless power transfer system based on high-index dielectric resonators," in *Proceedings of the International Conference Days on Diffraction, DD*, pp. 202–206, St. Petersburg, Russia, July 2016.

[50] M. Song, P. A. Belov, and P. V. Kapitanova, "Dielectric resonators for mid-range wireless power transfer application," in *Procedings of the 2017 Wireless Power Transfer Conference*, Taipei, Taiwan, May 2017.

[51] M. Song, P. Belov, and P. Kapitanova, "Wireless power transfer inspired by the modern trends in electromagnetics," *Applied Physics Reviews*, vol. 4, no. 2, Article ID 021102, 2017.

[52] R. Das, A. Basir, and H. Yoo, "A metamaterial-coupled wireless power transfer system based on cubic high-dielectric resonators," *IEEE Transactions on Industrial Electronics*, vol. 66, no. 9, pp. 7397–7406, 2019.

[53] A. L. F. Stein, P. A. Kyaw, and C. R. Sullivan, "High-Q self-resonant structure for wireless power transfer," in *Proceedings of the IEEE Applied Power Electronics Conference and Exposition-APEC*, pp. 3723–3729, Tampa, FL, USA, March 2017.

[54] A. M. Jawad, R. Nordin, S. K. Gharghan, H. M. Jawad, and M. Ismail, "Opportunities and challenges for near-field wireless power transfer: a review," *Energies*, vol. 10, no. 7, p. 1022, 2017.

[55] M. Song, P. Belov, and P. Kapitanova, "Multipolar modes in dielectric disk resonator for wireless power transfer," in *Proceedings of International Conference on Metamaterials and Nanophotonics (METANANO-2017)*, pp. 10–13, Vladivostok, Russia, 2017.

[56] D. Xu, Q. Zhang, and X. Li, "Implantable magnetic resonance wireless power transfer system based on 3D flexible coils," *Sustainability*, vol. 12, no. 10, p. 4149, 2020.

[57] S. Khan and G. Choi, "Analysis and optimization of four-coil planar magnetically coupled printed spiral resonators," *Sensors*, vol. 16, no. 8, p. 1219, 2016.

[58] M. Song, P. A. Belov, and P. V. Kapitanova, "Colossal permittivity resonators for wireless power transfer systems," in

Proceedings of the 2017 11th European Conference on Antennas and Propagation (EUCAP), Paris, France, March 2017.

[59] Z. Dang, C. Yuan, A. Jaber, and Q. Abu, "Reconfigurable magnetic resonance coupled wireless power transfer system," *IEEE Transactions on Power Electronics*, vol. 30, no. 11, pp. 6057–6069.

[60] Y. Li, J. Zhao, Q. Yang et al., "A novel coil with high misalignment tolerance for wireless power transfer," *IEEE Transactions on Magnetics*, vol. 55, no. 6, 2019.

[61] P. Gao, Z. Tian, T. Pan, J. Wu, and W. Gui, "Transmission efficiency analysis and optimization of magnetically coupled resonant wireless power transfer system with misalignments," *AIP Advances*, vol. 8, no. 8, Article ID 085016, 2018.

[62] T.-C. Yu, W.-H. Huang, and C.-L. Yang, "Design of dual frequency mixed coupling coils of wireless power and data transfer to enhance lateral and angular misalignment tolerance," *IEEE Journal of Electromagnetics, RF, and Microwaves in Medicine and Biology*, vol. 3, no. 3, 2019.

[63] L Zyga, "Scientists propose high-efficiency wireless power transfer system," 2016, https://phys.org/news/2016-01-scientists-high-efficiency-wireless-power.html.

[64] P. Kapitanova, M. Song, and P. Belov, "Experimental investigation of wireless power transfer systems based on dielectric resonators," in *Proceedings of the 2016 46th European Microwave Conference (EuMC)*, pp. 755–758, London, UK, 2016.

[65] M. Song, I. Iorsh, P. Kapitanova, E. Nenasheva, and P. Belov, "Wireless power transfer based on magnetic quadrupole coupling in dielectric resonators," *Applied Physics Letters*, vol. 108, no. 2, 2016.

[66] K. M. Krishna, J. Chakraborty, L. Matani et al., "Dielectric materials for power transfer," US Patent 12/778,166, 2015.

[67] S. Khan and G. Choi, "Analysis and optimization of four-coil planar magnetically coupled printed spiral resonators," *Sensors*, vol. 16, no. 8, p. 1219, 2016.

[68] M. F. Mahmood, S. L. Mohammed, S. K. Gharghan, A. Al-Naji, and J. Chahl, "Hybrid coils-based wireless power transfer for intelligent sensors," *Sensors*, vol. 20, no. 9, p. 2549, 2020.