

Advanced Perspectives on Metamaterial Integration in Wireless Power Transfer: A Review

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Abstract – The field of wireless power transfer (WPT) has recently seen much innovation and improvement and, as a result, there is an ever-increasing need for high power transfer efficiency (PTE) of the WPT systems, as well as enhanced transmission distance for end users. However, some of the currently available WPT systems have a restricted PTE and transfer distance because they use an inductive coupling technique. With this method, the PTE suffers a significant drop as the distance between the transmitter and receiver coils grows. Alternately, magnetic resonance coupling (MRC) is employed as a mid-range WPT solution. For this method, metamaterials (MTMs) are used to increase efficiency by inserting them between the transmitter (Tx) and receiver (Rx) coils. MTMs are artificially manufactured materials that demonstrate unusual electromagnetic properties. These traits include evanescent wave amplification and negative refractive characteristics, both of which have the potential to be employed for the improvement of PTE. This paper offers an in-depth summary of recent research and development in MTM-based WPT systems. In this overview, we examine previously reported MTM-based WPT systems across a range of characteristics, including configuration, operating frequency, size, and PTE. A comparative of the various MTM-based WPT systems is also provided in this paper. PTEs for these systems were also presented against their normalized transfer distances. This study was conducted with the intention of providing a resource for academics studying WPT systems and their practical implementations. This analy-

sis exposes the developments occurring in MTM-based WPT systems.

Index Terms – Inductive power transfer, metamaterials (MTMs), power transfer efficiency (PTE), wireless power transfer (WPT).

I. INTRODUCTION

In today's environment, electronic devices like mobile phones and laptops need wireless power transmission in order to be charged wirelessly. This not only offers protection against interruptions in the power supply but also enables the devices to charge themselves without the need for a conducting line. Wireless electricity is a method that involves the transmission of electrical energy by means of an electromagnetic field between a transmitter and a receiver. It's possible that we'll have access to this kind of technology in the not-too-distant future. Because of this, there is no longer a need for using batteries to power portable gadgets. Radio receivers are necessary for the operation of the system, and the device in question has to be positioned such that it is within range of the transmitter. Electromagnetic connection between the two coils causes the energy to be transferred [1]. The primary operating basis for such systems is the notion of resonant objects efficiently resonating energy while non-resonant things do not.

The history of wireless power transfer (WPT) may be traced back to the latter half of the 19th century and the early part of the 20th century, when various

kinds of wireless energy transfer were initially developed and tested by scientists and engineers. Nikola Tesla is frequently cited as the individual who came up with the concept of WPT for the first time. In the early 1890s, he demonstrated the transmission of high frequency alternating current over short distances without the need of wires. The magnetic resonance approach was yet another early type of WPT. It was initially conceived of by Alexander Popov in the latter half of the 19th century. One of the resonant circuits in this approach acts as the energy generator, while the other acts as the energy receiver. This method includes the transmission of energy between two resonant circuits as shown in Fig. 1 [2].

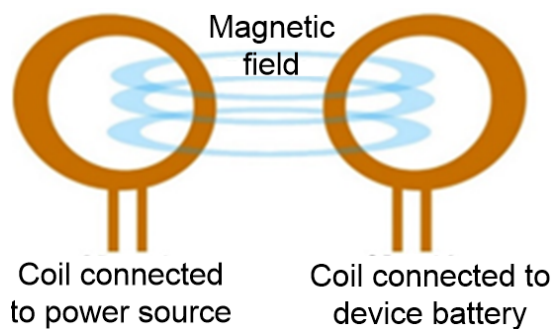


Fig. 1. A simple method of wireless power transfer [2].

In the early part of the 20th century, when inductive charging devices for batteries were being developed, the first commercial uses of WPT were put into practice. These systems move energy from a power source, such as a wall-mounted charging station, to a receiver coil in a battery-powered device, such as a toothbrush or shaver, by use of magnetic induction. Other examples of power sources are solar panels and wind turbines.

The WPT method may be broken down into two different subfields, known as near-field and far-field WPT. WPT systems that have a transfer distance that is shorter than their operational wavelength are said to have a near-field configuration. Magnetic resonance coupling (MRC) and inductive coupling WPT are the two technologies most widely used and correlate most closely to this categorization. Nevertheless, while MRC-based WPT can transfer power across a moderate range (cm to m), extending the transfer distance has the consequence of reducing the magnetic coupling between the transmitter (Tx) and receiver (Rx) coils. Hence, the MRC-based WPT system's transfer distance is limited, and power transfer efficiency (PTE) falls [3]. Radioactive wireless power transfer is a long-range application, better known as far-field energy transfer [4]. In terms of far-field WPT, the microwave energy transfer technique known as radiative WPT falls under this category. Figure 2 shows the

different areas of electromagnetic field in wireless power transfer [5]. The radiative WPT process involves power that is emitted from a transmitter antenna and then travels a great distance via the air as it radiates outward. This electromagnetic (EM) wave may be picked up by a rectenna, a combination of a rectifier and an antenna, and converted into direct current (DC) power. PTE is relatively low since radio waves travel in air in an omnidirectional manner, therefore losses occur during long-distance propagation. Moreover, there are challenges in designing a rectenna, such as overcoming challenges in the design of the feeding network to realize impactful beamforming for high PTE, minimizing mutual coupling among both antenna arrays that degrades rectenna performance, and mitigating high losses associated with array feeding networks.

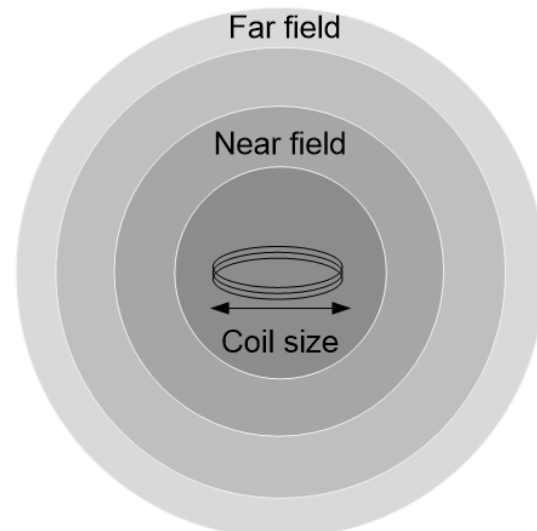


Fig. 2. Areas of the electromagnetic field [5].

WPT has received increased attention as a result of the development of new technologies and applications. Some examples of these developments include wireless charging for mobile phones, electric cars, and medical equipment. As the distance between the transmitter and receiver increase in the wireless power transfer system, the transmission efficiency drops. Transmission efficiency may be improved, and the effective power transfer distance can be extended by increasing coil quality factor and magnetic coupling for both the transmitter and receiver coils [6]. Since near-field energy transfer depends on the coupling of the magnetic fields between the two coils, which accounts for its small range, it is additionally categorized as electromagnetic induction. The near-field energy transfer field shrinks exponentially. Power may be transferred over relatively short distances with a high transfer efficiency using near field

transmission techniques, commonly referred to as non-radiative methods [7]. It consists of magneto-dynamic coupling, resonant capacitive coupling, resonant inductive coupling, and capacitive power transfer [8]. Additionally, far-field energy transfer is categorized as electromagnetic radiation. Long-range applications benefit from it the most. However, because of the power losses, it is less effective in comparison. It uses microwaves and lasers to convey power [9].

William C. Brown's presentation of his capacitive methods study in 1961 was a seminal moment in the field's history. In the study, a systematic approach to transferring power at the microwave level was given. The intrinsic benefit of being able to traverse greater distances may have contributed to the selection of a frequency that is so low as to be practically insignificant. On the other hand, the approach was restricted in that it could only transmit electricity at a low level and had a reduced degree of efficiency. The accompanying misalignment of power transmitter and receiver devices was one of the additional challenges that had to be overcome at this time. This misalignment further contributed to an unpredictable power transfer, which decreased the efficiency of the process.

II. WPT USING INDUCTIVE TECHNIQUES

The utilization of inductive coupling for WPT has garnered considerable attention in contemporary discourse, particularly within domains such as electric vehicle charging, biomedical implants, and consumer electronics [10, 11]. The foundational principle involves the transference of power between two coils, intricately linked through inductive means. In this dynamic, an alternating current within the primary coil engenders a corresponding alternating magnetic field, thereby inducing a current in the secondary coil [12, 13]. The efficiency and efficacy of power delivery are contingent upon a nuanced interplay of factors, including the coupling coefficient, quality factors, operating frequency, coil geometry, and compensation networks [14, 15].

Empirical evidence underscores the pivotal role of resonant compensation networks in optimizing efficiency, yielding a load-independent voltage gain [11, 16]. Prevailing series-series and series-parallel topologies, notably applied in electric vehicle systems, have demonstrated efficiencies reaching 90% [17]. Furthermore, strategies such as achieving zero voltage switching through methodologies like phase shift control contribute substantively to loss mitigation [18]. The scope of inductive coupling extends to wireless battery charging, exemplified by the work of Ragab et al. [19], who devised a photovoltaic charging interface employing inductive coupling and regulating power to the battery through phase control.

Efficiency within the field of magnetic coupling is contingent upon critical parameters. Mutual inductance between coils, dictated by their relative orientation, emerges as a direct determinant of power transfer efficiency [13]. Research findings presented by Shevchenko et al. [20] assert that single-layer coils may manifest superior efficiency in contrast to their double-layer counterparts. Moreover, losses are incurred due to parasitic coupling between non-corresponding coils in multiple input multiple output systems [21]. The ongoing scholarly endeavor is dedicated to optimizing both coupling and compensation mechanisms, thereby augmenting the commercial viability of mid-range inductive WPT. Figure 3 shows a schematic diagram of inductive WPT [22].

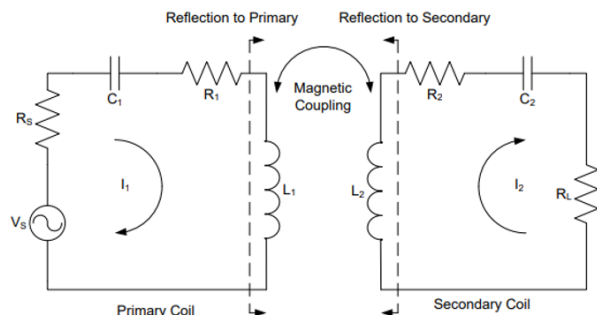


Fig. 3. Schematic diagram of inductive WPT [22].

Continuous advancements in magnetic materials, coil structures, and compensation techniques are playing a pivotal role in augmenting the capabilities of inductive WPT systems. A study conducted by Yamada et al. [23] has yielded analytical expressions for mutual inductance in coils featuring ferrite cores, utilizing image theory. The results exhibit a robust alignment with numerical outcomes, facilitating simplified modeling and design considerations. Notably, the field of vehicle charging remains a focal point, with Aziz et al. [24] conducting a comprehensive review of inductive charging developments, encompassing innovations like movable power tracks and methodologies for foreign object detection. These innovations collectively contribute to enabling safe high-power operation.

The significance of compensation networks is underscored in ensuring efficiency across variable coupling and load conditions. In a comparative experimental study by Rehman et al. [25], series-series and series-parallel topologies were assessed, revealing that the latter demonstrated superior efficiency, particularly with larger transmitter coils. Diep et al. [26] further contributed to this discourse by designing an electric vehicle system employing series-series compensation, achieving an impressive average efficiency of 89.5%, even during

dynamic charging scenarios. The landscape of converter architectures has also evolved, as evidenced by the introduction of a novel transformerless multilevel inverter for inductive power transfer by Lee et al. [27], realizing an 84% converter efficiency from input to load.

In the field of multiple-device WPT, Vo et al. [28] developed a technique that enables independent control of load voltages by dynamically tuning the transmitter array. Addressing orientation sensitivity challenges, Roberts et al. [29] delved into conformal resonant magnetic coupling, achieving a notable 60% efficiency over a 100 MHz link through the use of compact high-Q resonators. Compatibility strides, exemplified by Wandinger et al. [30], extended the efficiency of inductive transfer through saltwater, opening up novel applications such as underwater charging. Persistent endeavors in modeling resonant conditions [31], optimizing coil structures [32], estimating system parameters [33], and integrating power management solutions [34] collectively lay a robust foundation for the ongoing innovation in mid-range inductive WPT.

Inductive energy transfer results in the production of dipole fields that are aligned longitudinally. As the transmitter and receiver move apart, these fields become weaker. Therefore, the distance that separates the two coils is one of the parameters that influences the efficiency of the power transfer. As a result, the efficiency increases in proportion to the distance between the receiver and the transmitter [34, 35].

III. METHODS TO ENHANCE EFFICIENCY OF POWER TRANSFER

Many investigations have been carried out with the goal of increasing the distance between the coils without effecting efficiency of power transmission.

A. Type of antenna

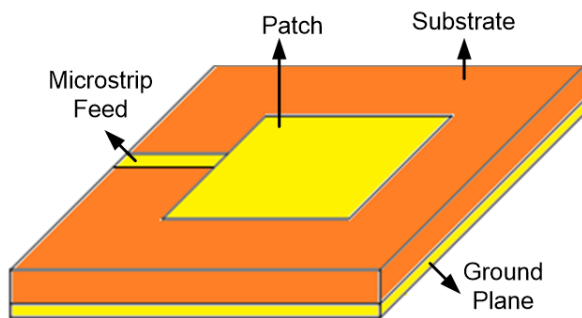


Fig. 4. Microstrip patch antenna [36].

As shown in Fig. 4, the antenna radiates from the patch's width and not its length; the effectiveness of the antenna's radiation is dependent on the patch's width

[36]. Because of this, the length of the patch has no bearing on the antenna's ability to radiate (W). When the value of W is low, the amount of radiation emitted is low, and when the value of W is high, the amount of radiation emitted is high [37]. The antenna's bandwidth is influenced both by the substrate thickness (h) of the dielectric materials and by the value of the parameter W . A greater bandwidth is indicated by a bigger W number. The value of W is one of the factors that determines the gain of the antenna. This value also depends on a number of other characteristics. The greater the value of W , the greater the gain that the antenna provides. The operation of the antenna is determined mostly by the relative permittivity (r) value of the substrate material and, as a result, the h material may be determined.

Research on spiral antennas has been going on for several decades, and these antennas have recently emerged as top contenders for use in applications that need circularly polarized broadband antennas [38]. Spirals can have a single arm or many arms, and they have been implemented both in the form of microstrips and in the form of slots as shown in Fig. 5.



Fig. 5. Example of a microstrip circular spiral coil antenna and square spiral antenna [38].

Mirrors serve as the conceptual foundation for this form of microstrip configuration's use of the radiation principle [38]. The ratio of the front to the rear of the signal grows as the frequency of the signal rises, allowing for the possibility of one-sided radiation.

At a certain frequency, which is determined by the structural properties of the spiral, the direction of the highest radiation will begin to sway in the opposite direction. As frequency continues to increase, the direction of the deflection shifts to both sides of the axis that is perpendicular to the surface of the antenna. Within the dielectric, the height of the slab is stipulated to be around a fourth of the wavelength at the antenna's center frequency [38]. This height is determined by the antenna.

Therefore, height tends to be equal to one-half of the wavelength at the relevant frequencies when considering the higher frequency bands [38]. When it reaches the spiral plane, the phase of the original signal is exactly

the opposite of that of the wave that was reflected by the ground plane. This is because of the phase of the wave that was reflected by the ground plane. Following the superposition of the signals, there is a reduction in the amount of radiation at the broadside, and the main lobe begins to separate.

These antennas have the capacity to resonate in frequencies considerably lower than those that conventional multiband antennas are capable of and, at the same time, they have a very compact size [38]. The extended length of the current route through the conductor area as a result of the spiral shape of this conductor is the critical factor in achieving this level of performance.

B. Multiple coils

By coupling together many coils and transferring their energy to one another, it is possible to create a WPT system that is effective across a considerable distance [39]. In [40], multiple coils, also known as repeater coils or relay resonators, are utilized to supply energy for the load. These multiple coils are arranged in the shape of a domino [40, 41].



Fig. 6. Experimental setup for multiple coils [39].

Figure 6 shows the experimental setup for multiple coils where the second coil placed at the center is the repeater. The practicability of the system is severely compromised as a result of the presence of a great number of relay coils between the transmitter and the receiver [42]. In addition to this, the efficiency of the system plummets as the relay coils move further away from their intended location.

C. Resonant coupling

Since Kim [43] published their findings, the use of resonant coupling technology has become more significant in the field of wireless power transmission.

In order to create effective methods of wireless power transfer based on Fig. 7, Kim relied on the ideas developed by Nikola Tesla. Interestingly, Kim demonstrated that electricity could be transmitted across lengths of two meters with an efficiency of just 20%. Despite the fact that this efficiency was somewhat poor, the transmitted power could reach up to a notional value of 50 W at

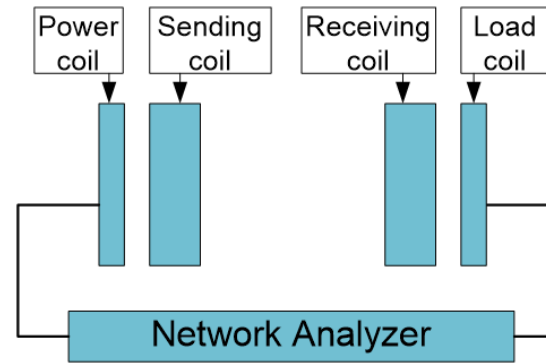


Fig. 7. Schematic diagram of resonant coupling [43].

a radio frequency that covered a range of 9.4 MHz. The enhanced influence of radiation as well as the complexity connected with manufacture both served as limitations on the endeavor.

D. High Q-factor

Under the assumption that there is only a weak coupling between particles, power transfer efficiency may be written as stated in [44]. It is plain to observe that the use of high-Q coils is capable of bringing about significant progress in terms of power transfer efficiency.

In [45], the authors suggest a self-resonant structure that is built on a foil layer and has a Q-factor of 1183, as shown in Fig. 8. This structure obtained a power transfer efficiency of 94% at a relatively wide transfer distance in comparison to the solid or Lize wire. In [46], coils with quality factors ranging from 15 to 1000 were used to obtain a PTE of 10% when the transmission distance was about nine times greater than the radius of the coils. However, a high Q-factor will result in significant voltage pressures being placed on the transfer coils. This is because the reactive current or voltage that the coils are expected to handle should be Q-times the actual power current or voltage that is being carried by the coils.

In addition to this, having a high frequency would result in a narrow band, which in turn would need a precise control technique. Both [47] and [48] have underlined how important it is to have a high Q-factor when building a coil with a high efficiency. This may be accomplished by raising the inductance of the coil while simultaneously lowering its resistance value. The multi-layer coil that was suggested in [49, 50] includes a number of concentric coils whose cross-sectional area grows with the number of coils in the stack [51]. The number of coils in the stack has an effect that causes the internal resistance to decrease [52]. In addition to this, inductance will grow while the diameter of the coil will stay the same, which will contribute to a high efficiency tiny coil design that is appropriate for wireless power transfer operation [51].

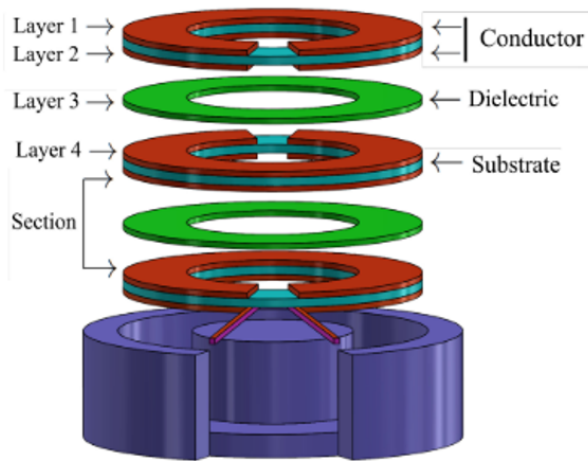


Fig. 8. A self-resonant structure [45].

The ground-breaking research conducted by Zhu and colleagues [53] in 2008 prepared the way for a new technological advance in the area of wireless power transfer. The researchers used the idea of back emf to the receiving coil in their investigation. This idea helped boost the transmission distance and the conveyed power even at a moderate range of radio frequencies. The benefit of electricity being transported over or past barriers was one of the most significant developments made possible by this approach. Despite the fact that this significant milestone has already been reached in the field of signal transmission, wireless power transmission is lagging behind in this area. The generation of eddy currents in the magnetic field that was being transmitted was the consequence of employing back emf, and this restriction was brought about by the presence of metallic objects. The effectiveness of the systems in urban or urbanized areas was greatly hindered as a result of this.

References [49, 53] demonstrate Brooks coil designs. Optimized performance is achieved by a standardized number of stacked layers and a multilayer coil orientation with a square cross-sectional area. As the maximum number of stacked layers varies with coil size, this is done in accordance with those parameters. This kind of design makes it possible to get the maximum possible inductance value with a wire that has a finite length [49].

In spite of Brooks coil and multilayer coil design, the use of a magnetic core for the WPT coil design proved ineffective due to core saturation [49] and a detrimental influence [51] on wireless devices in the nearby area. As a result of this, [49, 51] have shown that the use of an air core, which is efficient and does not influence inductance with an increase in current, is warranted. As a result, careful attention must be given to the frequency of operation in conjunction with the number of stack layers,

and the application of core in coil design is of the utmost importance.

Furthermore, the efficiency and reliability of WPT systems are significantly influenced by capacitor stability. The efficient transmission of energy is dependent on a continuous state of resonance between the transmitter and receiver coils, which is facilitated by capacitors in resonant circuits [54]. Nevertheless, capacitor instability can result from factors such as temperature fluctuations, dielectric degradation, and ageing, which can result in changes in resonance frequency and a decrease in efficiency over time [55]. Applications that necessitate consistent power levels for extended periods are particularly susceptible to this instability. The enhanced resilience to temperature fluctuations and reduced dielectric losses of advanced materials, such as polymer and ceramic capacitors, have been investigated, rendering them suitable for WPT systems in high-temperature or long-duration environments. Recent research indicates that the utilization of these stable capacitors can improve the durability of the system, thereby assuring a more sustained PTE by reducing the frequency detuning that is frequently caused by capacitor instability [56].

E. Metamaterials for WPT systems

The word "meta" in metamaterials (MTMs) comes from the Greek meaning "beyond" MTMs are defined as man-made materials that exhibit unusual and exotic properties that cannot be quickly identified in naturally occurring materials, allowing them to overcome limitations associated with using conventional materials in microwave and optical systems [5, 57]. Veselago presented the first theoretical analysis of MTMs in 1968. He postulated the wave particle duality of materials with simultaneously negative electric permittivity and magnetic permeability, which are characteristics of MTMs. This inquiry was the first of its kind.

Materials can be divided into four zones based on the polarity of permittivity and permeability since these two parameters indicate the electromagnetic properties of materials [58]. Permittivity and permeability are two factors that reflect the electromagnetic characteristics of materials, making this possible. The materials are classified as double-positive (DPS) materials, which are the typical materials, since their permittivity and permeability polarities are both positive at the same time, as shown in Fig. 9.

The materials are considered to be epsilon-negative (ENG) if their permittivity values are below zero and their permeability values are above zero ($\epsilon < 0$, $\mu > 0$). The materials are considered to be mu-negative (MNG) when their permittivity is positive, but their permeability is negative ($\epsilon > 0$, $\mu < 0$). In particular, when it is designed to have both of these characteristics be negative, the

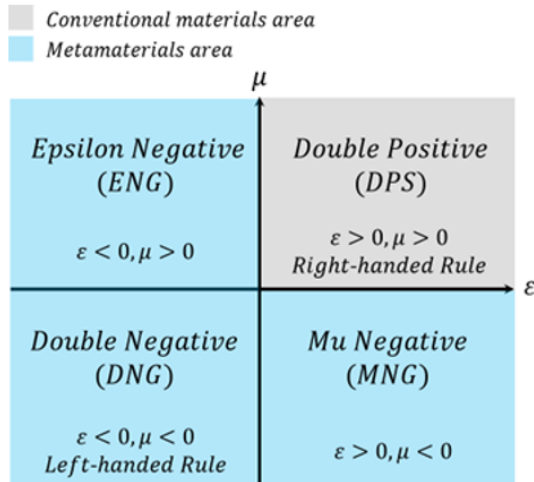


Fig. 9. Types of metamaterials based on permeability (μ) and permittivity (ϵ) values [58].

material in question is referred to as a double-negative material (DNG) and, in general, MTMs are recognized to be the material of choice. When ENG and MNG materials display such peculiar traits at frequencies where typical materials do not, they can also be classified as MTMs. This is the case when the materials display MTMs characteristic.

Electromagnetic waves can travel through a medium if the values of both its permittivity and its permeability are in a state that is either positive or negative at the same time. The right-handed rule is followed by the electric, magnetic, and wave vectors in typical (DPS) media. The Poynting vector, on the other hand, is parallel to the wave vector, indicating that energy is lost together with the wave's movement. The electric, magnetic, and wave vectors all follow the left-handed rule when it comes to MTMs (DNG) media. Energy flow is also anti-parallel to the source's phase propagation direction since the Poynting vector has the opposite direction of wave propagation [59]. Because of this, MTMs are also sometimes referred to as left-handed materials [60] or backward-wave media [34].

In addition to this, the negative permittivity and permeability values of the DNG materials cause the electromagnetic wave that is travelling through the medium to have a negative refractive index. The electromagnetic phenomena known as the refractive index takes place between two different kinds of materials. Snell's law, which describes the connection between the incidence angle and the consequent refracted angle of EM wave transmission at the interface of two materials, is adhered to by both the DPS and DNG materials. This law indicates that DPS and DNG materials behave in the same manner.

MTMs are notable for a number of key qualities, one of which is evanescent wave amplification. This is in addition to the negative refraction property. Rong [35] published their findings on evanescent wave amplification features in 2000.

As was noted earlier, near-field WPT systems have attracted a significant amount of attention due to the fact that they may be utilized in a variety of settings. However, because they rely on inductive coupling as their primary method of power transmission, the vast majority of today's WPT systems have limitations when it comes to the efficiency of power transfer and the distance it can cover. MRC-based WPT is an alternative that might be considered. When Tx and Rx coils are tuned to resonate at the same frequency [61], the MRC-based WPT system may be constructed and put into operation.

An investigation was done employing a system with two coils [62]. However, the two-coil system's transfer efficiency rapidly decreased as the transmission distance increased. Additionally, transfer efficiency was strongly impacted by changes in load, and transfer distance that could be practically accomplished with the two-coil WPT system was restricted. Several alternative methods, such as a three-coil system [49], a four-coil system [63], adaptive methodology [64], frequency adaptive matching technique [65], coupling optimization approach [66], and multi-resonator relay approach [67], have been researched in order to enhance transfer efficiency and distance.

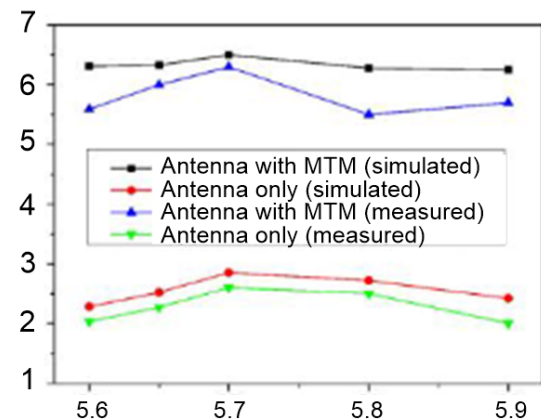


Fig. 10. Comparison of gain at 5.7 GHz [69].

Because regular materials do not possess the EM characteristics that metamaterials have, the difficulties outlined previously can be overcome by employing metamaterials [68]. It enhances transfer efficiency and distance by manipulating the electromagnetic waves that are generated by a microwave device [69]. It has been shown that placing a metamaterial over a patch antenna can lower the surface waves, leading to an increase in

both the gain and the bandwidth of the antenna [68–70] as shown in Fig. 10. If the antenna is able to fulfil the requirements of the conventional resonance cavity, then the reflected wave will be able to go through the metamaterial unit cell with the same phase. In turn, the antenna's gain will improve as a result of this.

Alternately, [71] explored the use of the MTM slab in the MRC-based WPT system a few years ago, which resulted in a significant improvement in the transfer efficiency of the WPT. The MTM slab, which included a near-field WPT system based on MRC, has since been the subject of intensive study employing a wide range of methodologies. Often, one or more MTM slabs are placed between the transmitter and receiver coils. This helps to concentrate the magnetic field on the receiver coil, which in turn results in a large improvement in PTE. In addition to this widely used design, there have been reports of a wide variety of alternative structures.

MTM slabs are integrated into WPT systems in a variety of different ways to achieve high PTE. This is accomplished by making use of the one-of-a-kind qualities of MTMs, which include negative refraction and evanescent wave amplification. The magnetic field that is produced by a Tx coil in a WPT system, such as the one shown in Fig. 11, displays its flux lines in a symmetrical pattern around the coil. If the Rx coil is placed in the area where the flux lines from the Tx coil reach then, according to Faraday's law, the magnetic flux that is crosslinked inside the Rx coil will cause current flows in the Rx coil, resulting in the wireless transmission of power. There is a problem caused by the fact that the magnetic flux cre-

ated by the Tx coil is not entirely caught by the Rx coil, which results in a low PTE and leakage.

A conceptual schematic representing the MTM-based WPT's underlying idea can be seen in Fig. 12 (a). Figure 12 (b) illustrates what happens when an MTM slab is placed between Tx and Rx, due to the fact that the MTM slab has a negative refraction index. Since it can concentrate the magnetic field lines directly on the Rx, it can boost power transmission efficiency. Using this idea of MTM-based WPT MTMs, a variety of structures have been examined. These architectures have varying dimensions, and the MTM slabs are located in a variety of different places.

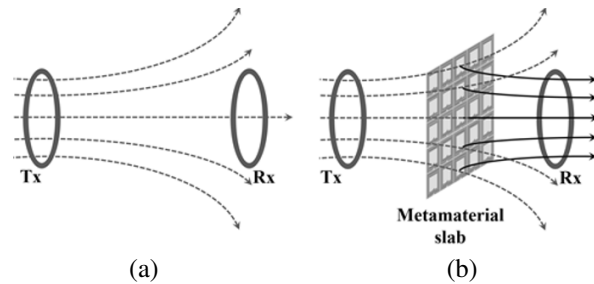


Fig. 12. Concept MTM based on WPT.

The effectiveness of MTM structures in WPT applications is significantly influenced by their design and geometry. Liu [72] conducted a study that highlighted the significance of the geometry and structure of the MTM unit in WPT systems. The study introduced a practical model for MTMs. Research showed that the efficacy of the system is significantly impacted by the resonance frequency and quality factor of MTMs, which are determined by their geometric configuration. The study highlighted the importance of precise MTM design for optimal functionality by providing a circuit-based model to predict the performance of MTM-enhanced WPT systems.

Lee [73] conducted an additional study that concentrated on the optimization of low-frequency magnetic MTMs to improve the efficiency of WPT. The research emphasized the critical role of the shape and arrangement of MTM units in attaining the desired magnetic properties, which in turn enhances PTE. The experimental results presented in the study demonstrated a substantial increase in PTE as a result of the implementation of optimized MTM designs, thereby validating the theoretical models that were proposed.

In addition, Li [74] conducted a thorough examination of MTM-based WPT systems, which included a discussion of the efficacy of the systems and the various MTM configurations. The review emphasized that certain MTM geometries, including Swiss roll structures

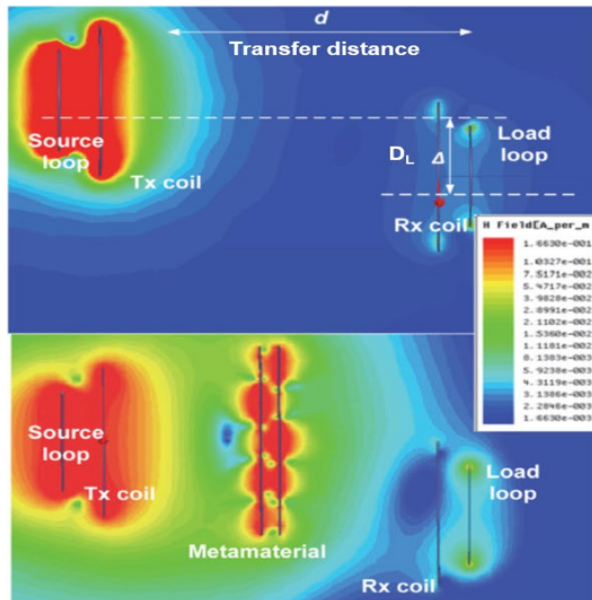


Fig. 11. WPT magnetic field distribution [71].

and split-ring resonators, are effective in enhancing PTE and focusing magnetic fields. The authors emphasized the necessity of meticulous MTM design to address the challenges associated with efficiency and alignment in WPT systems.

IV. THE DIFFICULTIES OF MTMS ON WPT SYSTEMS

Integrating MTMs into WPT systems has the potential to greatly boost both the PTE and transmit distance of such systems. The reason for this is that MTMs have properties that contribute to the enhancement, specifically negative refraction and evanescent wave amplification. The introduction of MTMs will unquestionably speed up the development of WPT systems. However, research into the applications of MTM-based WPT systems is still in its preliminary stages. As a result, a number of viewpoints and difficulties associated with MTM-based WPT systems are reviewed here with a view towards future advancement.

Prior to any other consideration, the insertion loss of the MTM slab needs to be minimized as much as possible since PTE is one of the most important merit factors of the WPT system. Despite the inserted MTM slab making the PTE of the WPT systems better, it will invariably suffer from insertion losses in WPT systems that are used in the real world. Chabalko [75] measured Tx and Rx insertion losses with and without MTM slabs and a single-turn resonator. They showed that the PTE of the WPT system may be significantly increased by using a single turn resonator, much more so than by employing an MTM slab, under certain conditions. The insertion loss of the MTM slab is much larger than that of the single turn resonator due to the MTM's complex construction and the MTM's non-optimized raw material choices. The previously reported phenomena may be traced back to this root cause.

A superconductor-based MTM slab with minimal conductor loss was shown by Wang [76]. It has been demonstrated that the reduced loss qualities of the superconductor, when combined with the properties of MTMs, may significantly increase the PTE of WPT systems in an efficient manner. Furthermore, it has been hypothesized that such cumbersome structures aren't necessary to create the negative refraction effect [77]. This is an interesting development. Because a thick substrate might cause an increase in the amount of substrate loss, it is best to utilize an MTM slab with a smaller thickness in order to reduce the amount of insertion loss caused by the MTM slab. Because the MTM slab's insertion loss has a direct impact on the PTE of the WPT systems, it should be one of the design priorities to minimize it. This is because reducing it has the potential to provide significant improvements to the PTE of the WPT systems,

which is why it should be investigated further. When it comes to the final applications, there are other losses that might have an impact on the PTE. Power supplies, amplifiers, resonators, rectifiers, DC-DC converters, loads, and other parts comprise the MRC-based WPT systems as a whole. The end-to-end PTE is significantly impacted by the losses that occur in each step as well as the unpredictability of changes to the parameters (weight, transfer distance, orientation) that occur in WPT environments. Hence, it is vital to enhance the efficiency of each phase in the procedure in MTM-based WPT systems, and the entire WPT system must be able to respond to a broad range of WPT circumstances.

Despite the fact that MTMs, because of their one-of-a-kind features, are able to boost the PTE of WPT systems, the development of MTM-based WPT systems for real-world use remains in its infancy. Although WPT system development is being aggressively pursued in a wide range of industries and uses, including the recharging of handheld electronic gadgets, it is clear that this technology has applications in transportation apparatuses or vehicles that run on electricity [78, 79] and medical device replacements [50, 80, 81]. The development of workable MTM-based WPT systems requires substantial investment of time and resources. Most of the observed MTM slabs have a bulky and thick build, which restricts the applications for which these slabs may be used. It is possible that it would not be viable to do so if the additional hefty MTM slab were to be put in the route of the power transmission. The WPT systems' reduced usefulness and adaptability would make them even less appealing than the more traditional wire charging methods. The following is an outline of the several potential solutions to these problems. To begin, the MTM slab has the potential to be included into the WPT systems. In the near future, research has to be done to determine how best to optimize the location of the MTM slab when it is embedded using this strategy. Second, it can involve incorporating the MTM into intermediary items in a way that does not disrupt the consumers' experience. In the future, in preparation for real-world deployments, it will be necessary to do more research on MTM-based WPT systems that make use of embedded methods.

Alternatively, one might take into account the current trend of MTM devices. Recent research [82] has focused on active MTMs that may adapt their characteristics in accordance with the information received from the environment. Conventional MTMs, also known as passive MTMs, contain characteristics that are fixed after the device has been manufactured, which restricts the uses of MTM devices. Because they used passive MTMs, the majority of earlier research found that once the MTMs had been constructed, their characteristics could not be altered in any way. Additionally, the MTM

Table 1: Different techniques to enhance WPT system

Ref.	Type of Antenna	Size of Antenna	Metamaterial Shape	Frequency	Distance	Transfer Efficiency
[63]	Single-turn square coils	100×100 mm	2-sided spiral square coil - 5 turns	6.78 MHz	40 cm	24%
[69]	Hexagonal patch	35×25 mm	Hexagon	5.7-10.3 GHz	17.53 mm	90.63%
[70]	Microstrip slot	-	Rectangular Sierpinski fractal	1.38 GHz	-	34%
[73]	Spiral coils	R=50 mm	YBCO spiral-coil structure - 13 turns	58.8 MHz	20 cm	13.58%
[83]	Circular coils	-	2-sided square helical coil - 10 turns	1 MHz	100 mm	9%
[87]	Loop coil antenna	R=20 cm	2-sided square spiral - 3 turns	24 MHz	50 cm	47%
[88]	Loop coil antenna	Tx=4.5 cm Rx=2 cm	2-layer square spiral - 13 turns	4 MHz	10 cm	22%
[89]	Spiral coils	15×15 cm	Hybrid metamaterial slab design - 14.5 turns	6.78 MHz	20 cm	47%
[90]	Spiral coil	R=15 cm	Honeycomb hexagon-shaped spiral copper - 9 turns	6.4 MHz	20 cm	51%
[91]	Square coil	13×13 cm	1-sided spiral coil - 5 turns	13.56 MHz	30 cm	36.4%
[92]	Square coil	D=10 cm	Square spiral coil copper - 11 turns	13.56 MHz	30 cm	13.4%
[93]	Circular coil	D=40 cm	Circular spiral coil - 3 turns	6.5 MHz	100 cm	15.1% (1-sided), 34.4% (2-sided)
[94]	Circular coil	D=500 mm	1-sided square spiral coil - 3 turns	2.8 MHz	160 cm	18.58%
[95]	Square coil	13×13 cm	1-sided square spiral - 5 turns	13.56 MHz	30 cm	41.7%
[96]	Circular coil	R=20 cm	1-sided meander line	27.4 MHz	20 cm	10.7%

slab's operating frequency will remain constant for the same reason. Several studies in the field of MTM-based WPT systems have focused on active MTMs [83]. An active MTM has been developed by Ranaweera [82] as a method for dynamically field localizing WPT systems. Using this technique, electricity may be sent selectively and under control directly to the desired area (hot zone). Using defect cavities with tunable resonant frequencies that are created on MTM unit cells, it is possible to realize the hot zone. It is possible to increase both PTE and safety by bringing about upgraded fields on the desired region. However, due to the fact that they have been using non-resonant loops for both the Tx and Rx coils, the transmission distance has been restricted.

In addition, there has been no extensive research carried out on transfer distance, which is one of the key characteristics that determine the effectiveness of WPT systems. There is a need for greater investigation into active MTM-based WPT systems, despite the fact that

they have proven the active MTM's value in the field of WPT.

In particular, research that has been done on the active MTMs' capacity to exhibit negative refraction might be one of the options. With the ability to manipulate the MTM slab's negative refraction, the WPT's magnetic fields may be redirected depending on their location. If the Rx coil is not lined with the Tx coil, for example, the active MTM slab's negative refraction index can be adjusted to re-direct the electric flux to the Rx.

The receiving efficiency in WPT systems is influenced not only by distance but also by the angle at which the receiving coil is positioned relative to the transmitter. Misalignment in the angle affects magnetic coupling, as angular deviation reduces the effective magnetic flux linkage between coils. This misalignment can significantly decrease transfer efficiency, especially in near-field applications like wearable devices and consumer electronics [84]. Prior research highlights that angular

deviations lead to reduced magnetic coupling, causing a notable drop in PTE. Because of this, the MTM slab is able to correct the alignment issue. Addressing these angle-related losses, recent studies have explored implementation of MTMs strategically within WPT systems to improve PTE despite angular misalignments. Placing MTM slabs at specific points in the system can enhance electromagnetic wave control, allowing the magnetic field to be effectively redirected and, thus, mitigating efficiency losses due to angular displacement [85]. If the MTM unit cells' negative refraction property can be altered, it would be possible to obtain a higher degree of flexibility in MTM-based WPT systems, which will lead to a wider range of applications for these systems. It is anticipated that the active MTMs would open up new possibilities for the implementation of MTM-based WPT systems in a variety of settings, including misaligned circumstances and asymmetric WPT environments, among other potential scenarios [86]. These placements can improve PTE by broadening angular tolerance, a significant step forward for stable and efficient WPT across diverse applications.

Table 1 shows a summarization of various techniques for transfer efficiency enhancement. This review aims to provide a quick reference for people engaged in WPT research and shed light on the evolving nature of MTM-based WPT system technologies. Additionally, the prospects and difficulties associated with MTM-based WPT systems have been explored in relation to the development of the technology in general as well as the applications that make use of it.

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