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PAPER

Mid-range wireless power transfer: anapoles or magnetic dipoles?

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Abstract

For short-range wireless power transfer (WPT) one recently suggested so-called anapole antennas that practically do not create fields in the far zone, eliminating radiation loss. Enhancements of power transfer efficiency (PTE) compared to traditional WPT systems based on magnetic dipole antennas were claimed for distances of the order of one-tenth of the wavelength or smaller. In this Letter, we theoretically show that a system of two properly engineered magnetic dipole antennas grants a similar PTE for this range of distances and a higher PTE for larger distances. In addition, we demonstrate that at mid-range distances, the radiation from magnetic-dipole-based WPT systems can be made drastically lower than the radiation from a single magnetic dipole antenna. This regime offers an alternative for reduction of far-field radiation.

1. Introduction

Wireless power transfer (WPT) since 1980s [1] has been increasingly becoming an important technology for diverse applications, see e.g. [2–4]. Over the past decade, rapid proliferation of wireless devices has motivated accelerated advancements of wireless powering and charging technologies (see e.g. [5–8]). One of the most critical parameters of WPT systems is power transfer efficiency (PTE), defined as the power delivered to the load of the receiving (Rx) antenna divided by the power accepted by the transmitting (Tx) antenna [5]. One of the loss channels is radiation into the far zone, where it is dissipated into the environment. While conventional near-field WPT devices exhibit negligible radiation loss compared to dissipation in their components, prospective WPT systems operating at several tens or hundreds of MHz may suffer from substantial radiation loss. An important study of the impact of radiation on short-range WPT systems was made in [9]. That paper deliberated on coupling between two coaxial magnetic dipole (MD) antennas beyond the quasi-static limit as a factor determining the spatial distribution of electromagnetic power density. It turned out to be possible to maximize the PTE and minimize the radiated power via optimization of the load impedance for a given distance between the loops.

In other recent works [10, 11], the authors proposed a short-range WPT system based on anapole antennas that create negligibly small far fields and are coupled solely by near fields. Indeed, the short-range WPT (when the transfer distances $d \leqslant 0.1\lambda$, λ is the wavelength in free space) corresponds to the case when the far-zone radiation is a parasitic effect that only results in losses and increased absorption in nearby humans [12]. In this case, it appears reasonable to use anapole antennas instead of conventional loops if they grant the same or higher PTE. In [10] one claimed that the anapole system operating at a few hundred MHz was more advantageous than the MD system for $d \leqslant 0.1\lambda$. This higher PTE was achieved namely due to suppression of the radiation loss.

However, the anapole state implemented in [10] is a superposition of strongly resonant multipoles (see also in [13, 14]). Therefore, this WPT system suffers from resonant loss in the antenna. The comparison between the PTEs of the anapole-based WPT system and the MD-based one which was done in [10], leaves an important question: why instead of a comparison between the anapole WPT system and *an optimized* MD-based WPT system working at the same frequency the authors compared their anapole WPT system with the system *of the same antennas* operating at the frequency of its collective MD resonance? Also, in [10] only distances $d < 0.15\lambda$ were considered. How the efficiencies of the anapole-based system and the *properly designed* MD-based systems differ from one another in a wide interval of distances? This question was not answered. Indeed, the radiation loss is the main factor decreasing the PTE of a properly designed MD-based WPT system operating in the mid-range of distances. For the anapole system, this factor is negligibly small. However, another harmful factor—that of dielectric losses—arises for the anapole system. Therefore, it is unclear *a priori* which of two WPT systems would be more efficient in the mid-range of distances.

In this paper, we perform a comprehensive comparison of MD-based and anapole-based WPT systems aiming at their mid-range operation. Typically, mid-range WPT is defined as the range of the transfer distances that are noticeably larger than the antenna size but still the Rx antenna is not in the far zone of the Tx antenna, which practically means $d < 0.5\lambda$ [15, 16]. In this paper, the mid-range condition can be formulated in terms of the wavelength as $0.1\lambda \leqslant d \leqslant 0.5\lambda$. For both anapole antennas and MD antennas the condition $d > 0.1\lambda$ implies that the distance between the Tx and Rx antennas exceeds their electromagnetic sizes. In other words, we utilize the standard definition of the mid-range WPT. In our study, we show the advantage of the MD-based system compared to the anapole system in what concerns PTE and the advantage of the anapole system in what concerns the radiation into the surrounding environment. In several works on mid-range WPT higher values of PTE were presented, compared to those reported below. However, the results of all these works cannot be used in our comparison study. First, all of them do not consider radiation suppression at all, focusing solely on PTE. Second, those WPT systems cannot be correctly compared to the anapole system: They either include repeaters between the Rx and Tx antennas [17–19] or arrays of Txs instead of a single Tx [20].

The structure of this paper is as follows. In section 2, we present simulations of the anapole WPT system [10] and extend its analysis to a wider range of *d*. Considering an alternative MD-based WPT system, we use the dynamic theory [16], in order to stress on the possibility of radiation suppression. In section 3, we investigate radiation suppression for both anapole-based and MD-based WPT systems. Our results are summarized in section 4.

2. Designs and simulations

2.1. Anapole-based WPT system

An anapole antenna developed in work [10] was based on the previous study [21], where it was shown that the so-called colossal permittivity $\varepsilon \sim 1000$ offers great opportunities for the design of an anapole state in the antenna system shown in figure 1(a). Varying the geometric parameters one can create an anapole state and engineer the desired input impedance at its frequency. As shown in figure 1(a), the antenna comprises a circular wire loop arranged coaxially with a dielectric disk whose permittivity $\varepsilon \approx 1000 - j0.25$ is dispersion-free below 1 GHz [10]. The loop radius R_0, the disk radius R, the disk thickness h, and the gap s between the loop and the disk are given in figure 1(a). For the present work, we numerically reproduced the results obtained in [10]. For it we used the full-wave electromagnetic solver Ansys HFSS. The anapole mode is at 408.6 MHz, the magnetic quadrupole moment resonates at 508 MHz, and the magnetic dipole moment resonates at 278 MHz which exactly matches [10]. As well as in [10], in our simulations, the antenna is excited by a 50 Ω voltage source connected to the exciting copper loop. The input impedance of the antenna at its anapole frequency is also equal to 50 Ω (at other frequencies it is different and complex-valued). The Rx antenna in the anapole WPT system is also loaded by $R_L = 50$ Ω. In figure 1(b) we depict the simulated power reflection coefficient of an individual anapole antenna that also agrees with [10]. In the system of two identical anapole antennas shown in figure 1(c), the input impedance of both Rx and Tx antennas changes due to their coupling but this mismatch is compensated by changing the gap s between the loop and the disk. Since in work [10] both theoretical and experimental studies were done and the experimental results matched the theory very well, the selection of the same antenna parameters as in [10] allowed us to enhance the reliability of our simulations. Since we have reproduced the key results of [10], the design parameters of that anapole system formed the reference point for the design of an MD-based WPT system that can be properly compared with the anapole one.

2.2. Magnetic dipole-based WPT system

As an object of comparison, we engineered a WPT system, which is, in accordance with the dynamic theory [16], optimal for both short and mid ranges of distances *d*. The optimum means that at every frequency we achieve an absolute maximum of PTE choosing the load of the Rx antenna in accordance with the dynamic theory developed in [16].

Both loops shown in figure 2(a) with the radii *a* and *b* are electromagnetically small and can be modeled as MDs. Two MDs are coupled solely by near fields, i.e. the regime in which two loops mutually reduce their radiation is desirable [16].

The equivalent circuit of the WPT system is shown in figure 2(b). The two antennas are characterized by their individual input impedances Z_1 and Z_2. The Tx is fed by a voltage source V_G with internal impedance Z_G,

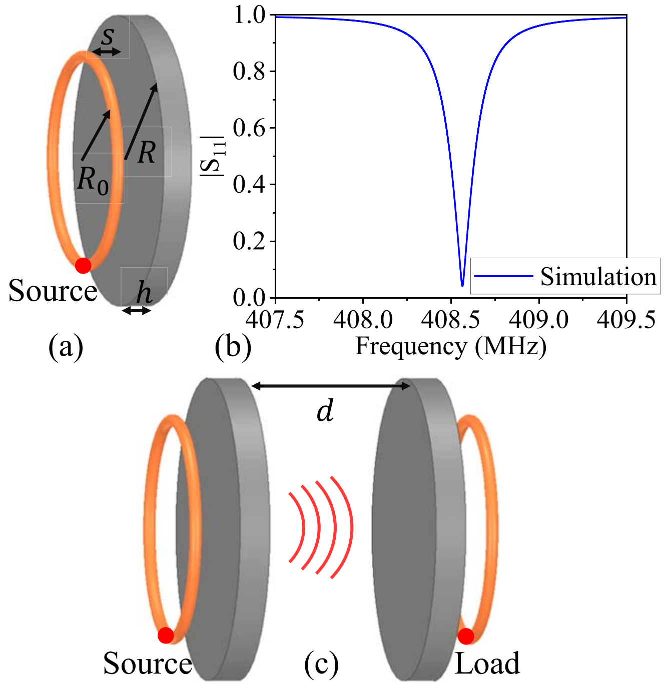

Figure 1. (a) Anapole antenna with the dimensions $R_0 = 36$, $R = 42$, $h = 4.25$, $s = 0.4$ (all in mm) connected to a voltage source. (b) Simulated reflection coefficient of this antenna versus frequency. (c) Anapole-based WPT system.

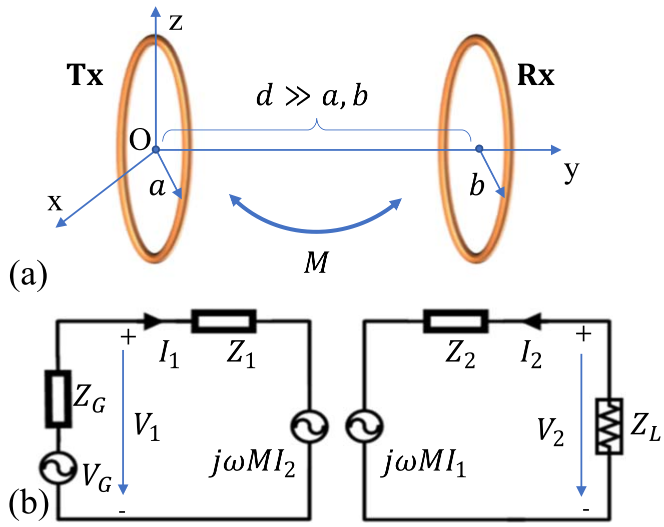

Figure 2. (a) Two magnetic dipoles WPT system, (b) Equivalent circuit model.

and the Rx is loaded by the load impedance Z_L. In the theory [16], we describe the mutual coupling by the complex coefficient $M = M_R + jM_I$, where M_R for small d is equal to the mutual inductance and M_I measures the mutual resistance.

We define the PTE as $\mathrm{PTE} = P_L/P_{in}$, where P_{in} is the power accepted by the Tx antenna and P_L is the power delivered to the load. Note that in this definition, the PTE does not depend on the generator output impedance [5]. The PTE of the WPT system depicted in figure 2 in the case when the load impedance is optimized ($Z_L = Z_{L,opt}$) can be expressed as follows [16]:

$$\mathrm{PTE} = 1 - \frac{2}{1 + \sqrt{\frac{R_1R_2 + \omega^2 M_R^2}{R_1R_2 - \omega^2 M_I^2}}}. \quad (1)$$

Parameters M_R, M_I, R_1, R_2 were found in [16] analytically, numerically, and experimentally. Equation (1) allowed us to find the optimal frequency at which the PTE is maximal under the condition of the optimal load.

For given loop dimensions and a matched Tx antenna, this optimal frequency weakly depends on the distance d [16]. By selecting the optimal load impedance (formulas for $Z_{\mathrm{L,opt}}$ can be found in [16]), we achieve a partial radiation suppression in a certain range of d. In this regime, the currents in the two loops have approximately the same amplitudes and opposite phases. This regime grants the maximum value to PTE of the MD-based system due to decreased radiation loss.

3. Comparisons of WPT Systems

In work [10], the higher efficiency of the anapole-based WPT was claimed based on the comparison of the anapole system shown in figure 1(a) operating at 408.6 MHz with the performance of the same system operating at its magnetic dipole resonance of 278 MHz. As it was mentioned above, this comparison does not allow one to make a valid conclusion about the advantages of the anapole-based WPT. In practice, WPT systems are restricted either by the required frequency range or by the required sizes of the Tx and Rx antennas. Therefore, it would be more relevant to compare the anapole WPT system operating at 408.6 MHz either with an MD-based WPT system designed for this frequency or with an MD system having nearly the same overall sizes of the Rx and Tx antennas and operating at its optimal frequency. With this issue in mind, two MD-based systems are engineered in accordance to the theory [16], and their parameters are simulated using HFSS software.

In one of these test WPT systems, the reference loop antenna is optimized for the operation frequency of 408.6 MHz, which is the same as that of the anapole system. In this case, the loop radius is set to $a = b = 14$ mm, i.e. both reference Tx and Rx antennas are identical single-turn loops of copper wire. The Tx loop with a 1 mm gap is connected to the 50 Ω voltage port, and the Rx antenna comprises the optimal loading resistance R_{L} connected through an ideal (lossless and lumped) matching circuit. The reactive component of the output impedance of the Rx antenna is then compensated, whereas R_{L} is chosen to maximize the PTE.

In the second test WPT system, the loop antennas are set to the same dimensions as the loop of the anapole antenna ($a = b = R_0 = 36$ mm). Our previous work [16] has demonstrated that for transfer distances significantly larger than the loop radius, the optimal operating frequency is approximately 160 MHz, which remains the same until the long-range domain $kd \gg 1$. Then, we compare the anapole-based WPT system with two MD-based systems: that operating at the same frequency and that having the same size but operating at 160 MHz. In both cases, the useful load impedance is optimized in accordance with the theory [16]. However, in order to clarify the role of this optimization, we also considered the MD-based system operating at 160 MHz with the 50 Ω load—that of the anapole system. For the MD-based system, this load is higher than the optimal load by two orders of magnitude. Finally, we have studied an MD-based WPT system based on loop antennas that we optimized using the conventional quasi-static model of mutual coupling that replaces the complex coupling parameter M by the real-valued mutual inductance. This comparison illustrates the advantages of the dynamic model developed in [16].

To understand the underlying physics, besides the PTE, we also simulated the power delivered to the loads and lost powers in all components separately: loss in the metal parts, loss in the dielectric disk, and the radiation loss. Moreover, to see the impact of coupling on radiation we simulated radiation from single Tx antennas for three cases: a single anapole antenna, a single loop of radius $a = 36$ mm operating at the same frequency (408.6 MHz), and a single loop of radius $a = 14$ mm operating at 160 MHz. The simulation results are presented in table 1 and figure 3.

Let us first discuss table 1. We see that the radiation of both the anapole antenna and the anapole WPT system is suppressed by three orders of magnitude compared to the single loop of the same size $a = 36$ mm operating at the same frequency. First, we evaluate the loss profile of the anapole WPT system at a short distance $d = 0.1\lambda$. At this position, the anapole still demonstrates effective power transfer to the load with a PTE of approximately 51.7 %, which aligns with [10]. For larger distances, e.g., $d \geqslant 0.1\lambda$, the metal loss is relatively small, but the dielectric loss is of the same order of magnitude as the power radiated by a single loop. This dielectric loss is still the main reason for the low efficiency. It is noteworthy that in the design of the anapole system in [10], the complex permittivity of the disk was optimized for available ceramics. If the dielectric loss tangent of the disk material is reduced compared to present 0.000 25, the efficiency will not increase. On the contrary, it drops because the anapole state bandwidth shrinks and the resonant loss increases in the disk. The MD-based WPT system compared to the anapole system is characterized by a lower radiation suppression, but grants much higher values of PTE for the same range of distances. Table 1 shows that for mid-range WPT, the MD-based systems are much more efficient than the anapole-based system, whose only advantage is the practical absence of far-zone radiation.

Now, let us discuss the efficiencies of all WPT systems under study as functions of the electromagnetic distance $kd \equiv 2\pi d/\lambda$ plotted in figure 3. It is clearly seen that the PTE of both optimized MD-based systems is incomparably higher than that of the anapole system in the mid-range and long-range regions, but they are also

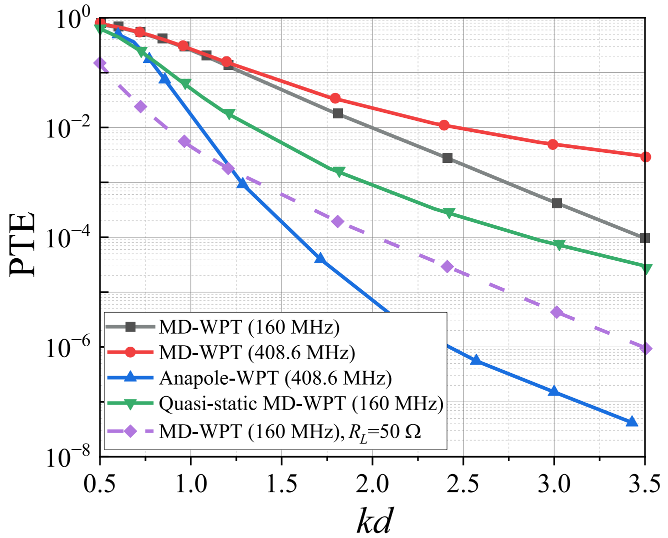

Figure 3. Comparison of PTEs calculated for three MD-based WPT systems (1—same size and optimal load, 2—same operation frequency and optimal load, 3—same size and 50 Ω load) and for an anapole-based WPT system (50 Ω load).

Table 1. Parameters comparison between anapole- and MD-based WPT devices.

Antenna	Freq. (MHz)	Radius (cm)	Distance (cm)	Metal Loss (mW)	Dielectr. Loss (mW)	Rad. Pow. (mW)	P_L (mW)	PTE
MD Single	408.6	3.6	—	33	—	967	—	—
Anapole Single	408.6	3.6	—	149.96	848.94	1.09	—	—
Anapole WPT	408.6	3.6	7.3 (0.1λ)	71.482	408.949	2.105	517.464	0.517
Anapole WPT	408.6	3.6	18 (0.25λ)	150.558	848.134	1.155	0.153	1.5×10^{-4}
MD Single	160	3.6	—	593	—	407	—	—
MD WPT	160	3.6	18 (0.1λ)	219	—	242	539	0.539
MD Single	408.6	1.4	—	653	—	346	—	—
MD WPT	408.6	1.4	18 (0.25λ)	658	—	288	54	0.054

noticeably higher in the range $kd = 0.5 - 0.7$ where $d \approx 0.1\lambda$. The MD-based system loaded by the 50 Ω resistance, which is not optimal for it and optimal for the anapole-based system fails the contest with the anapoles for $kd \leqslant 1.2$ but for larger distances becomes more efficient. Finally, the WPT system in which the load was chosen using the conventional model of inductive coupling has the same efficiency in the range $kd = 0.5 - 0.7$ and higher efficiency for $kd > 0.7$. The results clearly show that for the mid-range WPT, the MDs are advantageous compared to anapoles because the coupling of two anapole antennas drastically drops when $d > 0.1\lambda$. As to the range of distances $d \sim 0.1\lambda$, in this case the efficiency of the properly designed MD system is not lower than that of the anapole system because the dielectric loss of the last one has the same order of magnitude as the radiation loss of the MD system.

Now let us see how the radiation loss can be reduced in an MD-based WPT system compared to a single MD antenna. In accordance with table 1, the radiation of this system is partially suppressed due to coupling of antennas separated by the electromagnetic distance $kd > 0.6$. According to [16], the maximal suppression of radiation of an MD-based WPT system is achieved at $kd = 0.4 - 0.6$. Below we compare the radiation of the MD-based WPT system and that of the anapole system for this range of d. To ensure a fair comparison of the radiation suppression in the MD-based system and in the anapole-based system, we choose the distance between the Tx and Rx to be equal $d = 5a = 5b$. For both WPT systems, it corresponds to $kd \approx 0.4$. Here, we optimize the load impedance of the MD-based WPT system, and the anapole WPT system is redesigned to achieve impedance matching and maximal efficiency for the chosen distance. This short-range design procedure is described in [10]: one varies the parameters s and h to take into account strong coupling of anapole antennas and to keep the 50 Ω load optimal.

A comparison of the Poynting vector distributions simulated for the MD-based system and for the anapole system is presented in figure 4. Poynting vector is typically employed to represent the directional power flux of

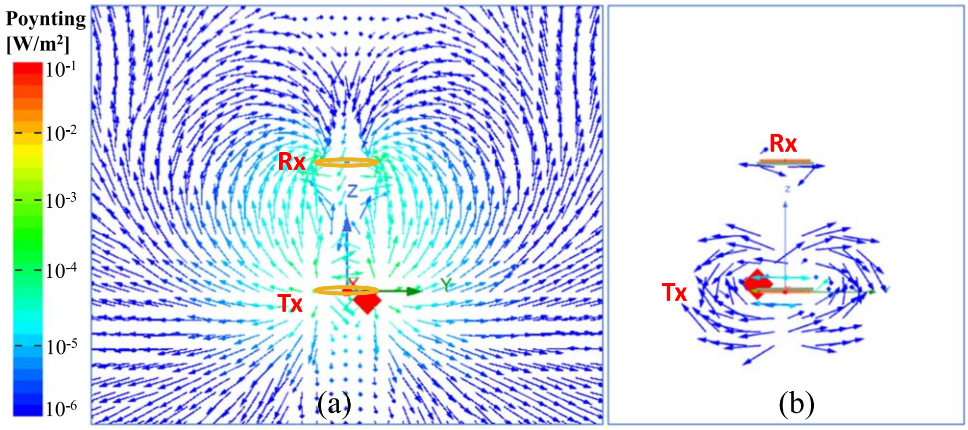

Figure 4. Time-averaged Poynting vector of the WPT system based on (a) two optimally loaded MDs; (b) two anapoles.

an electromagnetic field, describing the rate of energy transfer per unit area and unit time, indicating the direction and magnitude of electromagnetic energy flow. In the case of MDs, we see that almost all power flux lines originating from the Tx loop terminate on the Rx. The power flux concentrates in the vicinity of the two loops creating an effective 'bubble' in which the energy flow is confined. Inside this bubble, there exists a null spot in which the magnetic fields of the two loops mutually cancel out. The field outside the bubble is considerably weaker compared to that in the central area, i.e. the radiation is noticeably suppressed. For the anapole WPT system, power flow is strong only in a small area around the Tx antenna. This radiation suppression is not due to antenna coupling but due to practical absence of radiation from an anapole. In contrast, for two MD antennas at $kd = 0.4$ the dipole radiation of the system is suppressed because the currents in the two coupled loops have nearly the same absolute values and opposite phases [16]. Thus, the whole system forms a magnetic quadrupole whose radiated power is lower by three orders of magnitude than that of an individual loop with the same current. Also, radiation brings a nonzero contribution to power transfer: though the loops are small and coaxial, they are not exactly two collinear MDs.

In full-wave simulations for $kd = 0.4$, the radiation of the MD-based WPT system is suppressed nearly three times compared to that of a single loop. This effect is more pronounced than that presented in table 1. Therefore, WPT is more efficient: we obtained PTE =65.4%. However, in the anapole system, the radiation is lower than that of a single MD of the same size by three orders of magnitude (see in table 1). In specific cases when the efficiency is not as important as the radiation suppression, the use of anapole-based WPT devices may be reasonable.

4. Conclusions

This paper provides a comprehensive comparison of conventional WPT systems based on loop antennas with anapole-based WPT systems for mid-range distances—from 0.1λ to 0.5λ, assuming that the overall antenna size is smaller than 0.1λ. We show that the conventional systems are more efficient for this range of distances and explain the reasons for this. Additionally, the present study demonstrates the advantage of the dynamic model for the proper design of WPT systems, providing the proper choice of loading impedance (i.e. ensuring a drastic gain in the power transfer efficiency).

As to the radiation from the WPT system to the surrounding space, this harmful effect can be significantly suppressed in a conventional WPT system for a certain mid-range distance. However, this radiation suppression is not comparable with the suppression granted by the anapole systems. The anapole-based WPT utilized for mid-range distances is advantageous in what concerns radiation suppression, whereas the MD-based WPT is much more efficient than the anapole one.

This conclusion is, to our opinion, general. Though in this paper we report only a few numerical examples corresponding to the design parameters from table 1, this selection was made to enhance the reliability of our results. The present work is theoretical, and it was important for us to reproduce the experimental results of [10] in our simulations. After that we designed an MD-based WPT system which was a correct analogue of the anapole system from [10]. In the comparative analysis, we have numerically shown that the efficiency of the MD-based system is much higher than that of the anapole system, whereas the anapole system is better in radiation suppression. Ohm's loss of the conventional system is smaller than its radiation loss, but this radiation loss is much smaller than the resonant dielectric loss inherent to the corresponding anapole system. Indeed, these conclusions will not change if we engineer an anapole WPT system physically similar to that suggested in [10] but operating at a different frequency and re-design our MD-based system for the same frequency.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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