

Axial Magnetic Quadrupole Mode of Dielectric Resonator for Omnidirectional Wireless Power Transfer

Esmaeel Zanganeh, Elizaveta Nenasheva, Polina Kapitanova

Abstract—To achieve omnidirectional wireless power transfer with high efficiency, a high Q-factor transmitter generating homogeneous magnetic field is crucial. Traditionally, orthogonal coils of different shapes are used to realize transmitters. In this paper, we develop an omnidirectional magnetic resonant wireless power transfer system based on a dielectric disk resonator with colossal permittivity and low loss operating at axial magnetic quadrupole mode. The constant power transfer efficiency of 88% at the frequency of 157 MHz over the transfer distance of 3 cm for all angular positions of a receiver is experimentally demonstrated. The possibility of multi-receivers charging is also studied demonstrating a total efficiency of 90% regardless of angular position between two receivers with respect to the transmitting disk resonator. The minimized exposure of biological tissues to the electric and magnetic fields as well as a low specific absorption rate is observed that makes the WPT system safer for charging with higher input power.

Index Terms—Omnidirectional, Magnetic quadrupole, wireless power transfer (WPT), dielectric resonator

I. INTRODUCTION

Wireless power transfer (WPT) technologies are used to charge batteries of different electronic devices [1]–[5]. Among different techniques, the magnetic resonant WPT has attracted great attention for its potential in safe mid-range charging [6]–[10]. However, the power transfer efficiency (PTE) of magnetic resonant WPT systems based on metal coils still suffer from high ohmic and radiation losses and their angular instability [11]–[13]. To reduce the ohmic loss and enhance the PTE, the use of dielectric resonators instead of metallic coils have been recently proposed [14]–[16]. To further enhance the PTE of WPT systems, a dielectric metasurface supporting a quasi magnetic bound state in the continuum was introduced [16]. Another useful feature of the dielectric resonators is the ability to engineer the response by combination of different modes [17]–[19]. Thus, nonradiating sources based on anapole states of dielectric disk resonators can be obtained [20]–[23] bringing a benefit for PTE enhancement of WPT systems due to suppression of radiation losses [24].

This work was supported by the Russian Science Foundation (Project No. 20-72-10090). PK acknowledges the Priority 2030 Federal Academic Leadership Program. EZ acknowledges Dr. Alena Shchelokova for sharing the ceramic hollow disk resonators. (Corresponding author: Esmaeel Zanganeh.)

Esmaeel Zanganeh and Polina Kapitanova are with School of Physics and Engineering, ITMO University, 197101, Saint Petersburg, Russia. (e-mail: esmaeelzanganeh@gmail.com)

Elizaveta Nenasheva is with Ceramics Co., Ltd, 194223, Saint Petersburg, Russia.

To expand charging regions for more convenient utilization, modern WPT systems are required to be insensitive to positional misalignment [25], [26]. Therefore, for WPT to arbitrary spatial position devices, omnidirectional systems have been intensively investigated [27]–[39]. Most of the proposed omnidirectional WPT systems are based on orthogonal transmitting (Tx) coils of different shapes [27]–[30]. Such structures effectively eliminate the cross-coupling effect between multiple coils and generate uniform magnetic field. However, these structures need several power sources to feed each Tx coil and dynamically control the phases and amplitudes of coil currents. Recently, Tx coils fed by a single power source generating uniform magnetic fields were implemented [32], [34]. One of the drawbacks of these systems is the existence of the blind zones with very small electromagnetic coupling to a receiver (Rx) and as a result, low PTE. Another limitation is the safety of omnidirectional WPT systems to the biological tissues. As soon as the shielding techniques could not be applied, the level of electric and magnetic fields created by omnidirectional WPT systems must satisfy the limitations regulated by the standard [40]. Thus, the allowable power transferred by an omnidirectional WPT system could be limited.

In this letter, we propose an omnidirectional WPT system based on a dielectric hollow disk resonator operating at axial magnetic quadrupole mode. We demonstrate that at this mode, the resonator produces a homogeneous magnetic field in the transverse plane which can be potentially used to enable equivalent power transmission to Rx's at any angular position around the Tx. We theoretically and experimentally study the omnidirectional WPT system with single and two Rx's in MHz frequency band. We demonstrate that the advantage of the dielectric resonator with respect to metallic coils is the confinement of the electric field. As a result, the exposure of electric and magnetic fields to biological tissues is minimized. This results in a very low specific absorption rate (SAR), making it a safer option for omnidirectional wireless charging.

II. EIGENMODE ANALYSIS

A schematic view of the dielectric hollow disk resonator is shown in Fig. 1(a). We start with the eigenmode analysis of the dielectric resonator in CST Microwave Studio 2022, which reveals three modes at the frequencies of 138, 152.5, and 150.2 MHz, respectively. Simulated magnetic field distributions of all modes in both transverse (x - y) and axial (x - z) planes are illustrated in Fig. 1(b-d). For the first mode

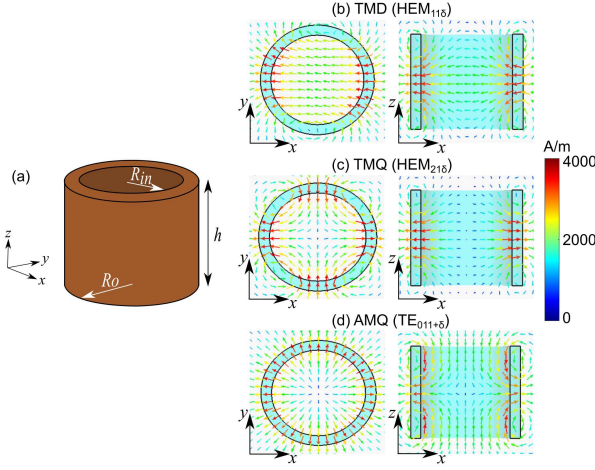


Fig. 1. (a) Schematic view of the dielectric hollow disk resonator with outer radius $R_o = 62.2 \text{ mm}$, inner radius $R_{in} = 50.75 \text{ mm}$, height $h = 100 \text{ mm}$, permittivity $\epsilon = 1000$ and loss tangent $\tan\delta = 4 \times 10^{-4}$. Simulated magnetic field distributions of (b) the TMD (b), TMQ (c), and AMQ (d) resonator modes in the transverse and axial planes.

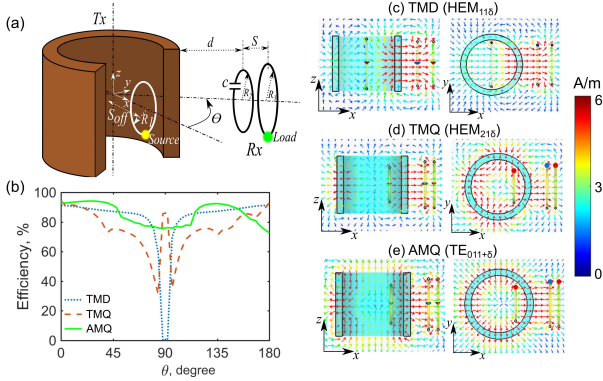


Fig. 2. (a) Schematic view of a WPT system based on the dielectric hollow disk resonator excited by a simple copper loop. The radius of the Rx resonator and load loop is set as $R_2 = R_3 = 40 \text{ mm}$ for systems operating at all three modes under study. Transfer distance is $d = 3 \text{ cm}$. The wire radius is $t = 2 \text{ mm}$. (b) PTE of the WPT systems operating at the TMD, TMQ, and AMQ modes extracted from the simulated S-parameters by Eq(1). Simulated magnetic field distributions of the WPT systems operating at the TMD (c) TMQ (d), and AMQ (e) modes at the transverse and axial planes.

at the frequency of 138 MHz, the magnetic field oscillates along the x -axis (see Fig. 1(b)). From the point of view of traditional dielectric resonators antenna design, this mode is known as $\text{HEM}_{11\delta}$ [41]. For the second mode at the frequency of 152.5 MHz, the magnetic field is oscillating inside of the resonator providing four maximums in the transverse plane as shown in Fig. 1(c). This mode is classified as $\text{HEM}_{21\delta}$ mode. At the frequency of 150.2 MHz, the homogeneous radial magnetic field distribution in the transverse plane together by oscillating fields in z -direction is obtained. This mode is classified as $\text{TE}_{011+\delta}$ mode. However, using Mie scattering theory [42], the obtained $\text{HEM}_{11\delta}$, $\text{HEM}_{21\delta}$, and $\text{TE}_{011+\delta}$ modes can be classified as transverse magnetic dipole (TMD), transverse magnetic quadrupole (TMQ), and axial magnetic quadrupole (AMQ), respectively.

To design a highly efficient omnidirectional WPT system, one needs to provide a high Q-factor and uniform magnetic field distribution over the angle. The numerically estimated Q-factor is found as high as 2510 for all the modes under consideration. However, the magnetic field distributions of TMD and TMQ modes have blind zones which may lead to weak coupling with Rx. The AMQ mode provides a uniform magnetic field distribution in the transverse plane. Being properly excited, this mode can be used to overcome the blind zone limitation and implement the Tx for an omnidirectional WPT system enabling power transmission to Rx's at any angular position around the Tx.

III. NUMERICAL STUDY

The PTE of WPT systems based on the dielectric hollow disk resonator operating at the TMD, TMQ, and AMQ modes is numerically studied. A schematic view of the WPT system created in the CST is shown in Fig. 2(a). The dielectric resonator excited by a copper source loop with radius R_1 is used as the Tx. The Rx resonator is placed at a transfer distance d with respect to the Tx. The Rx resonator is a simple copper loop with a radius of R_2 terminated by a capacitor C to provide a resonance at the same frequency as the Tx. A load loop made of a copper wire with a radius of R_3 is placed at a distance of S from the Rx resonator. A 50Ω port is inserted in the slits on both source and load loops. The reflection and transmission coefficients for the different angular positions of the Rx are numerically obtained in CST Microwave Studio and used to calculate the PTE as follows:

$$\eta = \frac{|S_{21}|^2}{1 - |S_{11}|^2} \times 100 \%. \quad (1)$$

The geometrical parameters and capacitance value obtained during the numerical optimization of the WPT systems at different modes are listed in Table. I. The PTEs calculated by Eq (1) as a function of Rx angular position are shown in Fig. 2(b). At TMD mode the PTE is zero for the angles around

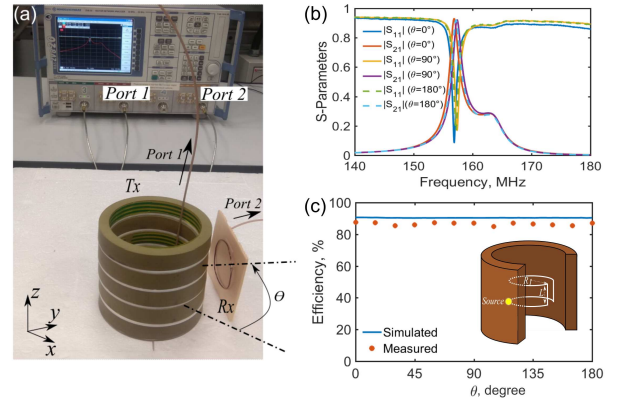


Fig. 3. (a) Photo of the omnidirectional WPT system experimental setup with one Rx. (b) Measured S-parameters of the system for different angular positions of the Rx. (c) Measured and simulated PTE of the omnidirectional WPT system at the frequency of 157 MHz as a function of the Rx angular position θ . The inset shows the design of the Tx with symmetrical excitation shielded loop centered on the hollow disk with a radius of $R_1 = 45 \text{ mm}$ and height $L = 25 \text{ mm}$ and a 2 mm gap between its two vertical sections.

TABLE I
GEOMETRICAL PARAMETERS, CAPACITOR VALUE, AND RESONANT
FREQUENCY OF WPT SYSTEMS OPERATING AT TMD ($\text{HEM}_{11\delta}$), TMQ
($\text{HEM}_{21\delta}$), AND AMQ ($\text{TE}_{011+\delta}$) MODES.

Mode	R_1 (mm)	S_{off} (mm)	C (pf)	S (mm)	f (MHz)
TMD	45	0	7.4	15	138
TMQ	30	30	6.45	12	153
AMQ	30	30	6.7	12	150

90° and the Rx cannot be charged there. The magnetic field of the system working at TMD is oscillating in x direction and is minimum around $\theta = 90^\circ$. For the system working at TMQ mode, there are two blind zones around 80° and 100° angles, where the PTE is around 40%. The magnetic field is oscillating along both x and y axes (Fig. 2(d)). In the system working at AMQ mode, the PTE is over 80% for all angles. The magnetic field provides almost uniform distribution in the transverse plane Fig. 2(e). However, the PTE is not still constant due to the asymmetric excitation of the Tx. To achieve the constant PTE of the WPT system working at the AMQ mode, we come up with a symmetric source loop design, as shown in the inset of Fig. 3(c). The PTE of the WPT system working at the AMQ mode with symmetrical excitation is calculated and shown in Fig. 3(c). The maximal PTE of 90% for all angular positions of the single Rx is achieved numerically.

IV. EXPERIMENTAL STUDY

Next, we experimentally study the performance of the WPT system operating at the AMQ mode. The fabricated prototype of the WPT system is shown in Fig. 3(a). It comprises of a dielectric hollow disk resonator excited by a symmetric source loop as the Tx, and an Rx resonator coupled to a load loop. Due to some technical limitations, we could not fabricate the disk with the parameters used in simulations. Thus, we stack it of five hollow disks with the following dimensions: the inner radius of $R_{in} = 50.75$ mm, the outer radius of $R_o = 62.2$ mm, and the height of $h_d = 20$ mm. The hollow disks are made from BaSrTiO₃, including Mg-containing compositions and have the permittivity of $\epsilon = 1000$ and $\tan\delta = 4 \times 10^{-4}$ (at 1 MHz) [43]. Since the ceramic disks are fragile, several thin hollow spacers made of plexiglas with relative dielectric permittivity around 3.5 and electrical conductivity of 0.02 $S m^{-1}$ and height of 3 mm are used between them. The symmetric source loop is a shielded loop made of a coaxial cable [44]. The Rx resonator is made of copper wire with radius $R_2 = 34$ mm and wire diameter $t = 1$ mm. To provide the resonance at the frequency of 157 MHz, the Rx is matched by $C = 6.8$ pf capacitor. The load loop radius is $R_3 = 30$ mm. The end of the source and load loops are connected to the 50 Ω ports of a Vector Network Analyzer (VNA) by coaxial cables.

The S-parameters of the WPT system as a function of the Rx angular position with the step of 15° are measured and several of them are shown in Fig. 3(b). Then, the PTE is calculated using Eq.(1) and compared to the simulated PTE in Fig. 3(c). An equivalent PTE above 88% for all Rx angular positions is achieved.

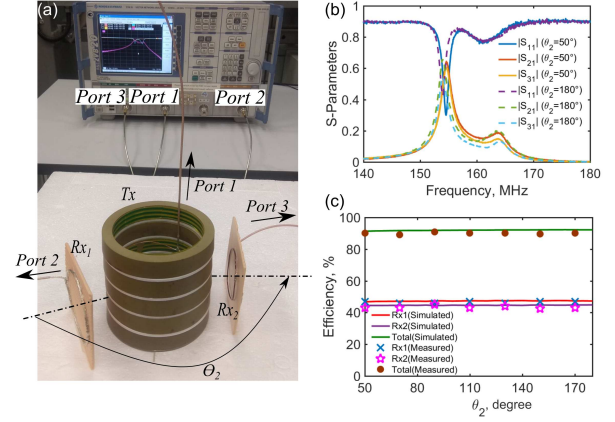


Fig. 4. (a) Photo of the omnidirectional WPT system experimental setup with two Rx's separated by angle θ_2 . (b) Measured S-parameters of the omnidirectional WPT system for $\theta_2 = 50^\circ$ and $\theta_2 = 180^\circ$. (c) Measured and simulated PTEs of Rx_1 , Rx_2 and total PTE of the omnidirectional WPT system at the frequency of 154 MHz as a function of θ_2 . Note that the angles between 0° to 50° are not feasible due to the receivers' size restrictions.

V. MULTI-RECEIVER OMNIDIRECTIONAL WPT

We also experimentally study the system with two Rx's. An identical second Rx (Rx_2) is added to the system with the angular position of θ_2 with respect to the Rx_1 as shown in Fig. 4(a). The S-parameters of the system as a function of the θ_2 with the step of 20° are measured and several of them are depicted in Fig. 4(b). One can see that not only the operational frequency is stable for all angular positions, but also the transmission and reflection coefficient magnitudes are at the same level. The PTEs of Rx_1 and Rx_2 are calculated from the measured S-parameters using Eq (1). The total PTE is calculated as the sum of the first and second Rx PTEs.

The variation of the Rx_1 , Rx_2 , and total PTEs concerning the angle between the Rx_1 and Rx_2 , (θ_2), are compared to the simulated results in Fig. 4(c). One can see the total PTE remains almost 90% regardless of the addition of the Rx_2 , or its position. Also, the PTEs of Rx_1 and Rx_2 remain stable and almost equal for all angles. Therefore, it is clear that the WPT system operating at AMQ can be applied to omnidirectional WPT with multi-receivers.

VI. DISCUSSION

To understand the benefits of the proposed WPT system, we compare its characteristics with other implementations reported in the literature (Table. II). The proposed omnidirectional WPT system operates at the frequency of 157 MHz and achieves 88% of the PTE to a single Rx over 3 cm transfer distance. This PTE is comparable to the systems reported in [6], [14], [15], [24] that do not offer omnidirectionality. Compared to the omnidirectional WPT systems reported in [31]–[34], [36], the proposed WPT system provides the highest PTE over a larger distance without any blind zone. For instance, our proposed system outperforms the metal coil-based system in Ref. [34] in both efficiency (88% vs. 65.4%) and operation distance normalized to wavelength (0.016 vs. 0.004). This demonstrates the superior performance of our proposed WPT system.

TABLE II
COMPARISON OF OMNIDIRECTIONAL AND DIRECTIONAL MAGNETIC RESONANT WPT SYSTEMS BASED ON METALLIC AND DIELECTRIC RESONATORS.

Ref.	Frequency	Tx resonator type	PTE(%)	Blind zone	Distance/ λ	Tx size/ λ
[6]	10 MHz	Metal coil	94	Yes	0.025	0.02
[14]	232 MHz	Dielectric disk	90	Yes	0.03	0.0649
[15]	2.4 GHz	Dielectric sphere	80	Yes	0.05	0.8
[24]	408 MHz	Dielectric disk	92	Yes	0.055	0.1142
[31]	535 KHz	Orthogonal coils	78	No	0	5.35×10^{-4}
[32]	13.56 MHz	Cubic Metal coil	60	No	0.0136	0.009
[33]	20 KHz	Orthogonal coils	11.5	No	4×10^{-6}	2×10^{-5}
[34]	13.56 & 27.12 MHz	Metal coil	61.6 & 65.4	No	0.004	0.0072
[36]	6.78 MHz	Metal coil	74.2 (DC-DC)	No	4.5×10^{-4}	0.0034
This work	157 MHz	Dielectric disk	88	No	0.016	0.065

To ensure the safety, it is crucial to examine the field exposure to biological tissues and SAR [40]. The electric and magnetic fields of the proposed WPT system's Tx with symmetric excitation are compared with fields of the metal Txs of omnidirectional WPT systems reported in Ref. [34] and Ref. [36]. The central cross sections of the electric and magnetic field distributions simulated in CST Microwave Studio are compared in Fig. 5(a) and (b), respectively. The magnetic field of the proposed Tx based on dielectric disk resonator has the highest amplitude at short distances d in comparison to the magnetic fields provided by the designs reported in Ref. [34] and Ref. [36]. Its magnitude decays faster as d increases (Fig. 5(a)), indicating strong accumulation of the magnetic field in proximity of the dielectric resonator. The electric field of the proposed Tx (see Fig. 5(b)) is negligible compared to electric fields of the metal Txs reported in Ref. [34] and Ref. [36]. Therefore, the proposed omnidirectional WPT system based on the dielectric resonator offers the strong confinement of the electric field providing less exposure of the electric field [40] to surrounding biological tissues compared to WPT systems based on metal Txs.

To perform SAR analysis, we employ CST Microwave Studio and a computer-aided-design model of the front part of a human arm as depicted in Fig. 5(c). The model consists of the main biological tissues of the arm characterized by their corresponding electromagnetic properties. The distance between the Tx and the arm is 4 cm. For the input power of 0.5 W, the maximal calculated SAR is 0.034 W/kg, averaged over 1 g of tissue (see Fig. 5(c)). There are no nonlinear effects in the WPT system, and the maximal SAR for different input powers can be obtained by scaling up these results. According to the IEEE safety regulation [40], which specifies the maximum SAR value for limbs and pinnae as 4 W/kg, a maximal input power of 117 W is allowed.

VII. CONCLUSION

We proposed the omnidirectional WPT system based on a dielectric hollow disk resonator operating at AMQ mode. A uniform radial magnetic field in the transverse plane of the Tx resonator is generated helping to avoid the blind zone. A symmetric excitation loop to achieve a constant PTE over all angular positions of the Rx is proposed. With respect to the experimental data, the omnidirectional WPT system provides 88% of PTE over all angles at the transfer distance of 3 cm to

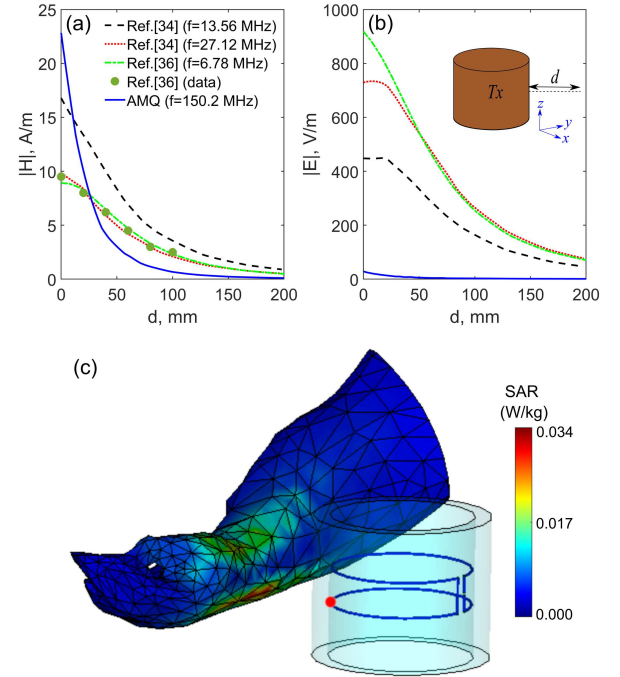


Fig. 5. Simulated (a) magnetic and (b) electric fields of the proposed omnidirectional WPT Tx as a function of the distance d compared to the Tx of the omnidirectional WPT systems based on metallic coils reported in Refs [34] (square coil) and [36]. To verify the correctness of our simulations with the results presented in Ref. [34] we made sure that the reflection coefficient coincides with Fig. 12(a) in Ref. [34]. Magnetic field data presented in Fig. 2 of Ref. [36] is added to panel (a), which coincides with the recalculated magnetic field of the Tx. (c) Simulated SAR of the omnidirectional WPT Tx in an arm located at a distance of 4 cm.

a single Rx. The possibility of charging multi-receivers is also experimentally verified. The results showed a stable and high efficiency of 90% regardless of the angle between two Rxs. Examination of the safety issues of the proposed WPT system revealed minimal exposure of the electromagnetic fields to biological tissues, resulting in a very low SAR. These findings establish the proposed WPT system as a safer option for omnidirectional wireless charging.

REFERENCES

- [1] M. Song, P. Jayathurathnage, E. Zanganeh, M. Krasikova, P. Smirnov, P. Belov, P. Kapitanova, C. Simovski, S. Tretyakov, and A. Krasnok, "Wireless power transfer based on novel physical concepts," *Nature Electronics*, vol. 4, pp. 707–716, 10 2021.

- [2] A. Mahesh, B. Chokkalingam, and L. Mihet-Popa, "Inductive wireless power transfer charging for electric vehicles—a review," *IEEE Access*, vol. 9, pp. 137 667–137 713, 2021.
- [3] Z. Zhang, H. Pang, A. Georgiadis, and C. Cecati, "Wireless power transfer—an overview," *IEEE Transactions on Industrial Electronics*, vol. 66, no. 2, pp. 1044–1058, 2019.
- [4] M. Song, P. Belov, and P. Kapitanova, "Wireless power transfer inspired by the modern trends in electromagnetics," *Applied Physics Reviews*, vol. 4, 2017.
- [5] C. Jiang, K. Chau, C. Liu, and C. H. Lee, "An overview of resonant circuits for wireless power transfer," *Energies*, vol. 10, no. 7, p. 894, 2017.
- [6] A. Kurs, A. Karalis, R. Moffatt, J. D. Joannopoulos, P. Fisher, and M. Soljačić, "Wireless power transfer via strongly coupled magnetic resonances," *science*, vol. 317, no. 5834, pp. 83–86, 2007.
- [7] M. Dionigi, A. Costanzo, F. Matri, and M. Mongiardo, "Magnetic resonant wireless power transfer," in *Wireless Power Transfer*. River Publishers, 2022, pp. 157–197.
- [8] S. Niu, H. Xu, Z. Sun, Z. Shao, and L. Jian, "The state-of-the-arts of wireless electric vehicle charging via magnetic resonance: principles, standards and core technologies," *Renewable and Sustainable Energy Reviews*, vol. 114, p. 109302, 2019.
- [9] X. Mou, D. T. Gladwin, R. Zhao, and H. Sun, "Survey on magnetic resonant coupling wireless power transfer technology for electric vehicle charging," *IET Power Electronics*, vol. 12, no. 12, pp. 3005–3020, 2019.
- [10] M. Song, P. Smirnov, E. Puhtina, E. Zanganeh, S. Glybovski, P. Belov, and P. Kapitanova, "Multi-mode metamaterial-inspired resonator for near-field wireless power transfer," *Applied Physics Letters*, vol. 117, no. 8, p. 083501, 2020.
- [11] F. Liu, Y. Yang, D. Jiang, X. Ruan, and X. Chen, "Modeling and optimization of magnetically coupled resonant wireless power transfer system with varying spatial scales," *IEEE Transactions on Power Electronics*, vol. 32, no. 4, pp. 3240–3250, 2017.
- [12] E. Shamonina, L. Solymar, and V. Kalinin, "On wireless power transfer between coils in the presence of radiation," *Journal of Physics D: Applied Physics*, vol. 54, no. 40, p. 405502, 2021.
- [13] T. Sasatani, A. P. Sample, and Y. Kawahara, "Room-scale magnetoquasistatic wireless power transfer using a cavity-based multimode resonator," *Nature Electronics*, vol. 4, no. 9, pp. 689–697, 2021.
- [14] M. Song, P. Belov, and P. Kapitanova, "Wireless power transfer based on dielectric resonators with colossal permittivity," *Applied Physics Letters*, vol. 109, no. 22, p. 223902, 2016.
- [15] 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, p. 023902, 2016.
- [16] Y. Xie, Z. Zhang, Y. Lin, T. Feng, and Y. Xu, "Magnetic quasi-bound state in the continuum for wireless power transfer," *Phys. Rev. Applied*, vol. 15, p. 044024, Apr 2021.
- [17] H. K. Shamkhi, K. V. Baryshnikova, A. Sayanskiy, P. Kapitanova, P. D. Terekhov, P. Belov, A. Karabchevsky, A. B. Evlyukhin, Y. Kivshar, and A. S. Shalin, "Transverse scattering and generalized kerker effects in all-dielectric mie-resonant metaoptics," *Physical review letters*, vol. 122, no. 19, p. 193905, 2019.
- [18] A. E. Miroschnichenko, A. B. Evlyukhin, Y. F. Yu, R. M. Bakker, A. Chipouline, A. I. Kuznetsov, B. Luk'yanchuk, B. N. Chichkov, and Y. S. Kivshar, "Nonradiating anapole modes in dielectric nanoparticles," *Nature communications*, vol. 6, no. 1, pp. 1–8, 2015.
- [19] V. E. Babicheva and A. B. Evlyukhin, "Resonant lattice kerker effect in metasurfaces with electric and magnetic optical responses," *Laser & Photonics Reviews*, vol. 11, no. 6, p. 1700132, 2017.
- [20] E. Zanganeh, A. Evlyukhin, A. Miroschnichenko, M. Song, E. Nenasheva, and P. Kapitanova, "Anapole meta-atoms: Nonradiating electric and magnetic sources," *Physical Review Letters*, vol. 127, no. 9, p. 096804, 2021.
- [21] P. Kapitanova, E. Zanganeh, N. Pavlov, M. Song, P. Belov, A. Evlyukhin, and A. Miroschnichenko, "Seeing the unseen: experimental observation of magnetic anapole state inside a high-index dielectric particle," *Annalen der Physik*, vol. 532, no. 12, p. 2000293, 2020.
- [22] A. A. Basharin, E. Zanganeh, A. K. Ospanova, P. Kapitanova, and A. B. Evlyukhin, "Selective superinvisibility effect via compound anapole," *Physical Review B*, vol. 107, no. 15, p. 155104, 2023.
- [23] E. Zanganeh, M. Song, A. Evlyukhin, and P. Kapitanova, "Electromagnetic anapole states of nano-disks," in *AIP Conference Proceedings*, vol. 2300, no. 1. AIP Publishing LLC, 2020, p. 020138.
- [24] E. Zanganeh, M. Song, A. C. Valero, A. S. Shalin, E. Nenasheva, A. Miroschnichenko, A. Evlyukhin, and P. Kapitanova, "Nonradiating sources for efficient wireless power transfer," *Nanophotonics*, vol. 10, no. 17, pp. 4399–4408, 2021.
- [25] J. Kim, D.-H. Kim, and Y.-J. Park, "Free-positioning wireless power transfer to multiple devices using a planar transmitting coil and switchable impedance matching networks," *IEEE Transactions on Microwave Theory and Techniques*, vol. 64, no. 11, pp. 3714–3722, 2016.
- [26] E. Zanganeh, A. Sayanskiy, S. Kosulnikov, and P. Kapitanova, "Extreme metasurfaces enable targeted and protected wireless energy transfer," *Advanced Materials Technologies*, p. 2202133, 2023.
- [27] J. Feng, Q. Li, and F. C. Lee, "Load detection and power flow control algorithm for an omnidirectional wireless power transfer system," *IEEE Transactions on Industrial Electronics*, vol. 69, no. 2, pp. 1422–1431, 2021.
- [28] Z. Ye, Y. Sun, X. Liu, P. Wang, C. Tang, and H. Tian, "Power transfer efficiency analysis for omnidirectional wireless power transfer system using three-phase-shifted drive," *Energies*, vol. 11, no. 8, 2018.
- [29] Z. Zhang and B. Zhang, "Angular-misalignment insensitive omnidirectional wireless power transfer," *IEEE Transactions on Industrial Electronics*, vol. 67, no. 4, pp. 2755–2764, 2020.
- [30] J. Feng, Q. Li, F. C. Lee, and M. Fu, "Transmitter coils design for free-positioning omnidirectional wireless power transfer system," *IEEE Transactions on Industrial Informatics*, vol. 15, no. 8, pp. 4656–4664, 2019.
- [31] D. Lin, C. Zhang, and S. R. Hui, "Mathematic analysis of omnidirectional wireless power transfer—part-ii three-dimensional systems," *IEEE Transactions on Power Electronics*, vol. 32, no. 1, pp. 613–624, 2016.
- [32] N. Ha-Van and C. Seo, "Analytical and experimental investigations of omnidirectional wireless power transfer using a cubic transmitter," *IEEE Transactions on Industrial Electronics*, vol. 65, no. 2, pp. 1358–1366, 2017.
- [33] H. Han, Z. Mao, Q. Zhu, M. Su, and A. P. Hu, "A 3d wireless charging cylinder with stable rotating magnetic field for multi-load application," *IEEE Access*, vol. 7, pp. 35 981–35 997, 2019.
- [34] C. Lu, X. Huang, X. Tao, X. Liu, C. Rong, Y. Zeng, and M. Liu, "Design and analysis of an omnidirectional dual-band wireless power transfer system," *IEEE Transactions on Antennas and Propagation*, vol. 69, no. 6, pp. 3493–3502, 2020.
- [35] J. Li, Y. Yang, H. Yan, C. C. Liu, L. Dong, and G. Wang, "Quasi-omnidirectional wireless power transfer for a sensor system," *IEEE Sensors Journal*, vol. 20, no. 11, pp. 6148–6159, 2020.
- [36] N. Ha-Van, Y. Liu, P. Jayathurathnage, C. R. Simovski, and S. A. Tretyakov, "Cylindrical transmitting coil for two-dimensional omnidirectional wireless power transfer," *IEEE Transactions on Industrial Electronics*, vol. 69, no. 10, pp. 10045–10054, 2022.
- [37] T. Feng, Z. Zuo, Y. Sun, X. Dai, X. Wu, and L. Zhu, "A reticulated planar transmitter using a three-dimensional rotating magnetic field for free-positioning omnidirectional wireless power transfer," *IEEE Transactions on Power Electronics*, vol. 37, no. 8, pp. 9999–10015, 2022.
- [38] J. Feng, Q. Li, and F. C. Lee, "Load detection and power flow control algorithm for an omnidirectional wireless power transfer system," *IEEE Transactions on Industrial Electronics*, vol. 69, no. 2, pp. 1422–1431, 2022.
- [39] P. Jayathurathnage, X. Dang, C. R. Simovski, and S. A. Tretyakov, "Self-tuning omnidirectional wireless power transfer using double-toroidal helix coils," *IEEE Transactions on Industrial Electronics*, vol. 69, no. 7, pp. 6828–6837, 2022.
- [40] I. C. 1, "Ieee standard for safety levels with respect to human exposure to electric, magnetic and electromagnetic fields, 0 hz to 300 ghz," *The Institute of Electrical and Electronics Engineers New York, NY*, 2019.
- [41] R. K. Mongia and P. Bhartia, "Dielectric resonator antennas—a review and 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.
- [42] C. Bohren and D. Huffman, *Absorption and Scattering of Light by Small Particles*. John Wiley & Sons, New York, 2008.
- [43] E. Nenasheva, N. Kartenko, I. Gaidamaka, O. Trubitsyna, S. Redozubov, A. Dedyk, and A. Kanareykin, "Low loss microwave ferroelectric ceramics for high power tunable devices," *Journal of the European Ceramic Society*, vol. 30, no. 2, pp. 395–400, 2010.
- [44] C. F. Carobbi and L. M. Millanta, "Analysis of the common-mode rejection in the measurement and generation of magnetic fields using loop probes," *IEEE Transactions on Instrumentation and Measurement*, vol. 53, no. 2, pp. 514–523, 2004.