Wireless Power Transfer and Energy Harvesting Using Metamaterials and Metasurfaces

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Abstract— **In this invited talk/paper, we review and explore the use of metamaterials and metasurfaces for wireless power transfer (WPT) and wireless energy harvesting (WEH) which are two closely related hot topics. The focus is on how to improve the energy conversion efficiency of both systems. It is shown that metamaterials and metasurfaces can indeed achieve a higher RF to DC energy conversion efficiency and operational distance by changing the electromagnetic fields between the transmitter and receiver, and/or making their reception less sensitive to incident wave angle and polarization. They can also be used as either parasitic elements or loading components to improve WEH performance.**

Keywords— Antennas, metamaterials, metasurfaces, wireless energy harvesting, wireless power transfer.

I. INTRODUCTION

WIRELESS power transfer (WPT) and wireless energy harvesting (WEH) are becoming two important topics for the wireless industry [1-6]. WPT is aimed at transmitting power to a desired device/system wirelessly with known frequency and wave polarisation while WEH is meant to harvest electromagnetic energy from the ambient environment without knowing the exact frequency and wave polarisation. They both employ antennas (coils at how frequencies) and rectifiers – their combination is known as *rectenna*. Since rectifiers are non-linear devices and sensitive to power levels and load impedance, it is hard to achieve a high RF to DC *energy conversion efficiency* which is the main figure-of-merit of such a system. Furthermore, the rectenna system energy conversion efficiency is affected by, for example, polarization mismatch, sensitivity to wave incident angle, misalignment, impedance mismatch. How to increase the energy conversion efficiency of a WPT/WEH system is a very challenging task.

Metamaterials (MM) and metasurfaces (MS) have been introduced to realize some special functions which cannot be obtained using normal natural materials [7-10]. They have found a wide range of applications in such as antennas – MS antennas and MS-inspired antennas have been reported and demonstrated their advantages over traditional antennas [10]. Recently, they have been used for WPT and WEH as summarized in a few good review papers [11, 12, 13] which are used as the major references for this talk/paper. In addition, we would like to cover some topics that have not been well studied, including the prospect of using MM and MS for future WPT and WEH applications.

II. HOW TO USE METAMATERIALS AND METASURFACES FOR WPT AND WEH?

To answer this question, we first need to understand WPT and WEH systems. WPT can be divided into two major categories: non-radiative near-field WPT and radiative WPT (which can be near or far-field) as shown in Fig. 1. Non-radiative WPT can be further divided into the capacitive coupling and inductive coupling, the operational distance in these cases is small which is good for some applications (e.g. wireless charger for a toothbrush), but for some other applications, we would like to increase the operational distance (e.g. wireless charging a car/truck). For radiative WPT, we are only interested in microwave WPT in this paper, the distance is much larger than that for non-radiative cases, the receiver is most likely in the far-field of the transmitter although it is possible to be used in the near field.

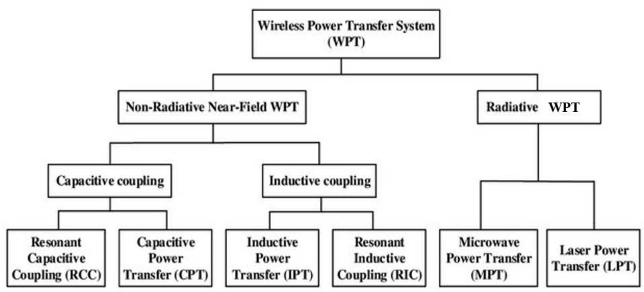

Fig. 1. Classification of WPT (based on [14] with revision)

WEH could happen in the near or far-field of the source – depending on the frequency and distance. For example, to collect the energy from a 50 Hz powerline, the energy harvester would be in the near-field of the source while to harvest the energy for a WiFi system (2.4 and 5 GHz), the harvester would be in its far-field. In most applications, WEH is in the far field and the distance from the source is large and the polarisation may not be well matched.

What MM and MS can do for WPT and WEH? The main job is that they can change the electromagnetic field distribution between the transmitter (the source) and the receiver (the harvester), so more energy/power could be received. Let us take the inductive coupling WPT as an example, as shown in Fig. 2, a transmitting (Tx) coil and a receiving (Rx) coil are separated by a distance d. For the maximum coupling, the Rx coil should be placed very close to the Tx coil – there is an optimum d [15]. But for some applications, we need to increase the distance which means reducing the received power/energy due to less magnetic flux going through the Rx coil. However, if we employ a hybrid metasurface (HMS) slab with zero and negative permeability (which has special reflection, transmission or refraction properties, different from the conventional one), we can change the field distribution between Tx and RX coils to ensure a significant amount of Tx power is delivered to the Rx coil as shown in Fig. 2. The efficiency improvement using this technology is about 20% (from 35% to 42%). Different MM and MS could be employed and placed at the back, middle, or side of these coils to achieve higher power or energy transfer efficiency.

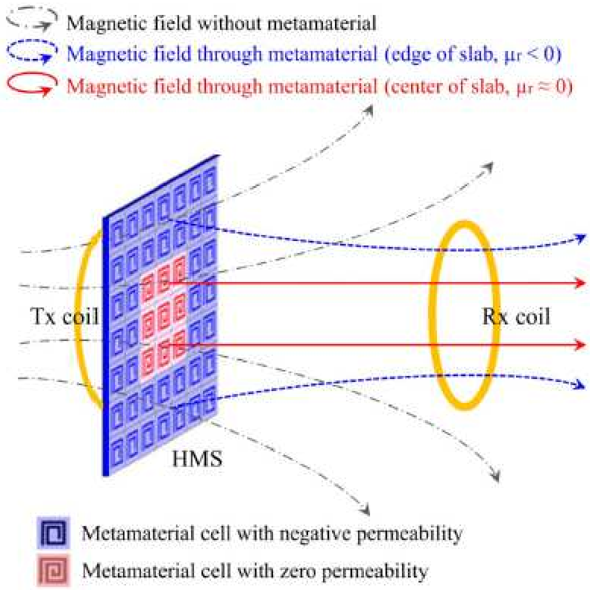

Fig. 2. Magnetic field distribution between a Tx coil and an Rx coil for an inductive WPT system with and without a hybrid metasurface (HMS) [15]

Since there are so many different WPT and WEH systems, their corresponding MM and MS solutions could therefore be very different. Many examples could be found in the literature and some non-radiative WPT designs are selected and summarised in Table I where we can see that the frequency is from 6.06 MHz to 1700 MHz, and the separation between Tx and Rx is from 2.5 to 40 cm. The operational principles could be classified as shielding, focusing, and guiding while the energy conversion efficiency is typically improved over 20%, up to about 50% which is significant.

For radiative WPT and WEH, we can employ MM and MS to receive the electromagnetic energy/waves more efficiently by making it less sensitive to the incident angle and polarisation, or reduce the antenna dimensions, or increase the effective antenna aperture size, so as to improve the overall WPT and WEH system performance.

III. Discussion and Conclusions

In this talk/paper, we have focused on how to use MM and MS for WPT and WEH. We did not discuss impedance matching and rectifying circuits. Generally, they were used in three ways: shielding/reflecting, focusing/concentrating, and guiding/ directing. The main benefits of using MM and MS for WPT and WEH are:

- Energy conversion efficiency improvement;
- Size reduction;
- Improved operational distance;
- Better flexibility.

The drawbacks for MM and MS for WPT and WHE could be the increased cost and complexity of the system. They may also introduce an additional loss.

Further research activities are undertaken worldwide aiming for even higher energy conversion efficiency and improved system performance. MM and MS assisted rectennas and integrated MM/MS-rectenna systems are of great interest. Simultaneous wireless information and power transfer (SWIPT) seems to be an attractive solution for future IoT applications, and reconfigurable intelligent surfaces (RIS) may also be linked to MM and MS for WPT and WEH in the future.

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Table I: Performance comparison of metasurface-based non-radiative WPT systems (Dia denotes diameter).

Ref. (year)	Freq (MHz)	Metasurface Size (cm)	Tx/Rx Size (cm)	Tx/Rx Gap (cm)	Type of Operation	Efficiency Improvement (%)	Notes
[16] (2019)	13.56	36×36	Dia 20/ Dia 20	40	Shield/focusing	36% to 48%	Magnetic field shielding
[17] (2020)	13.56	Dia 22	Dia 22/ Dia 22	12	Shielding	NA	Electric field reduction
[18] (2020)	13.56	18×18	Dia 18/ Dia 18	16	Focusing	5.5% to 32.9%	Electric field reduction
[19] (2020)	100	33×33	Dia 32/ Dia 32	40	Focusing	25% to 42%	Units connected
[20] (2019)	560 1700	3.6×3.6 5.3×5.3	3×3/3×3 5×5/5×5	10 3.6	Focusing Focusing	58.5% 52%	Dielectric resonator
[21] (2019)	472.6	8×8	4×4/ 4×4	36	Focusing	To 60.8%	High permittivity
[22] (2020)	6.06	6×6	Dia 4.2/ Dia 4.2	2.5	Focusing	5% to 12%	Low specific absorption rate
[23] (2019)	14.1	>51×51	Dia 25/ Dia 3	20	Guiding	7.8% to 50.4%	Active metasurface
[24] (2020)	14	>54×54	Dia 6/ Dia 6	3	Guiding	Peak 56.8%	Smart table