

# Wireless Power Transfer in the Radiative Near-Field Using a Novel Reconfigurable Holographic Metasurface Aperture

Wenyu LUO<sup>†a)</sup>, *Member*

**SUMMARY** In this letter, we propose a novel wireless power transfer (WPT) scheme in the radiative near-field (Fresnel) region, which based on machine vision and dynamically reconfigurable holographic metasurface aperture capable of focusing power to multiple spots simultaneously without any information feedback. The states of metamaterial elements, formed by tunable meander line resonators, is determined using holographic design principles, in which the interference pattern of reference mode and the desired radiated field pattern leads to the required phase distribution over the surface of the aperture. The three-dimensional position information of mobile point sources is determined by machine visual localization, which can be used to obtain the aperture field. In contrast to the existing research studies, the proposed scheme is not only designed to achieve free multi-foci, but also with machine vision, low-dimensionality, high transmission efficiency, real-time continuous reconfigurability and so on. The accuracy of the analysis is confirmed using numerical simulation.

**key words:** *wireless power transfer, metasurface, holographic, binocular location*

## 1. Introduction

As a promising solution, wireless power transfer (WPT) can deliver power without equipping a wiring infrastructure, which can be used for remote, embedded devices, as well as sensors and devices on the move. The near-field magnetic WPT systems are the dominant approach up to now, in which power is transferred with coils coupled at very low frequencies of operation [1]. However, the efficiency of near-field coupling falls off rapidly with the distance between the source and receiver [2].

A promising WPT scheme to achieve the above goal is the radio frequency transmission, in which power can be transferred over relative long distances. The disadvantage of far-field scheme is that beam width from an aperture is limited by diffraction, so that only a minute fraction of power is captured by the receiver. In contrast, near-field WPT can achieve a considerable efficiency levels, because electromagnetic signal energy can be focused at a point where the receiver is positioned by using a large aperture that acts as a lens. Still, although it is possible to provide a high efficiency scheme, these sensors in motion are also difficult to power using near-field WPT [3], which need create a mobile focal spot dynamically. Fortunately, the concept of the metasurface to create a focal spot has successfully been demonstrated in the literature for near-field applications without

phase shifters and amplifiers [4], [5]. However, a major drawback of the applications is that they do not offer the freedom to focus at an arbitrary point dynamically in space, let alone serving multiple users simultaneously.

In this work, we demonstrate a multiple users WPT system based on visual localization in the radiative near-field using a reconfigurable holographic metasurface aperture, which is different from the beacon process in [6] for lower computational complexity. What's more, the details of the metasurface architecture detailed in this paper are not involved in [6]. The reconfigurability enables to achieve varying focusing characteristics for the same aperture. Firstly, the transmitter estimates the three-dimensional spatial coordinate of multiply users base on binocular vision. Secondly, the desired field distribution of the metasurface aperture to create focuses at the position of multiple users is calculated by analyzing three-dimensional spatial coordinate, which equivalents to treat the focused points as some fictitious point sources. Thirdly, by using the coaxial feed into the metasurface aperture, the magnetic field of reference mode can be realized. Lastly, the layout of the metamaterial elements and their tuning states is determined by using holographic design principles, in which the interference pattern of reference mode and the desired radiated field pattern leads to the required phase distribution over the surface of the aperture. This concept above can provide real-time WPT for multiple users simultaneously with higher transfer efficiency, which can be confirmed by the numerical results.

## 2. Dynamically Reconfigurable Holographic WPT System Based on Binocular Location

In this section, we consider a multi-user metasurface aperture system, where a transmitter equipped with  $M$  elements send energy signal wirelessly to  $K$  users. The aperture is center-fed using a coaxial cable, which can obtain uniform plane wave. The holographic aperture concept is illustrated in Fig. 1(a).

The upper of the aperture is discretized into a grid of elements, each subwavelength in dimensions. Each element patterned onto the front surface of the holographic metasurface aperture includes three PIN diode, as depicted in Fig. 1(b,1), for which we assume the circuit model of the PIN diode are modelled as a RL circuit with a negligible forward resistance in parallel with the junction capacitance [7]. The resonance frequency of the element is controlled

Manuscript received February 11, 2019.

Manuscript revised June 14, 2019.

<sup>†</sup>The author is with North China University of Water Resources and Electric Power, China.

a) E-mail: luowenyu@ncwu.edu.cn

DOI: 10.1587/transfun.E102.A.1928

by its length parameter  $L$ . As shown in Fig. 1(b,2), when PIN diode 1 and PIN diode 2 are forward-biased and PIN diode 3 is reverse biased, the resonance length parameter is  $L$ . The length decides the phase jump  $\phi_1$ , which is given as an example at 92.5GHz depicted by Fig. 3(e) in [8]. In addition, the resonance length parameter is  $L/2$ , when PIN diode 1 and PIN diode 2 are reverse-biased and PIN diode 3 is forward biased, which prompts that the phase jump is  $\phi_2$  as in Fig. 1(b,3). The equivalent circuits of forward-biased and reverse biased PIN diode are shown as Fig. 1(c). The maximum transmit power is  $P_t$ .

As shown in Fig. 1(a), each user  $k$ ,  $k \in \{1, \dots, K\}$ , cannot send anything, whose position information is confirmed by the two pick-up heads connects by a processor located at the transmitter. Let  $(u_k, v_k)$  denotes the image coordinates of user  $k$ . Then, we can achieve the total transformation matrix  $F$  according to the basic method in [10]. So, the position  $\{x_k, y_k, z_k\}$  of user  $k$  can be estimated according to exterior limit constraint method, which is denoted by  $\mathbf{r}_k$  as (1).

$$\mathbf{r}_k = \begin{bmatrix} x_k \\ y_k \\ z_k \end{bmatrix} = F \begin{bmatrix} u_k \\ v_k \end{bmatrix} \quad (1)$$

In Fig. 1(a), the magnetic field of the metasurface aperture radiated by the coaxial feed into the dielectric substrate can be modelled by means of the Hankel function [7] as follows

$$\mathbf{H}_{ref} = \begin{cases} H_0^1 \left( \frac{Q\mathbf{r}}{\sqrt{\epsilon_r}} \right) \cos \phi, & x\text{-polarization} \\ H_0^1 \left( \frac{Q\mathbf{r}}{\sqrt{\epsilon_r}} \right) \sin \phi, & y\text{-polarization} \end{cases} \quad (2)$$

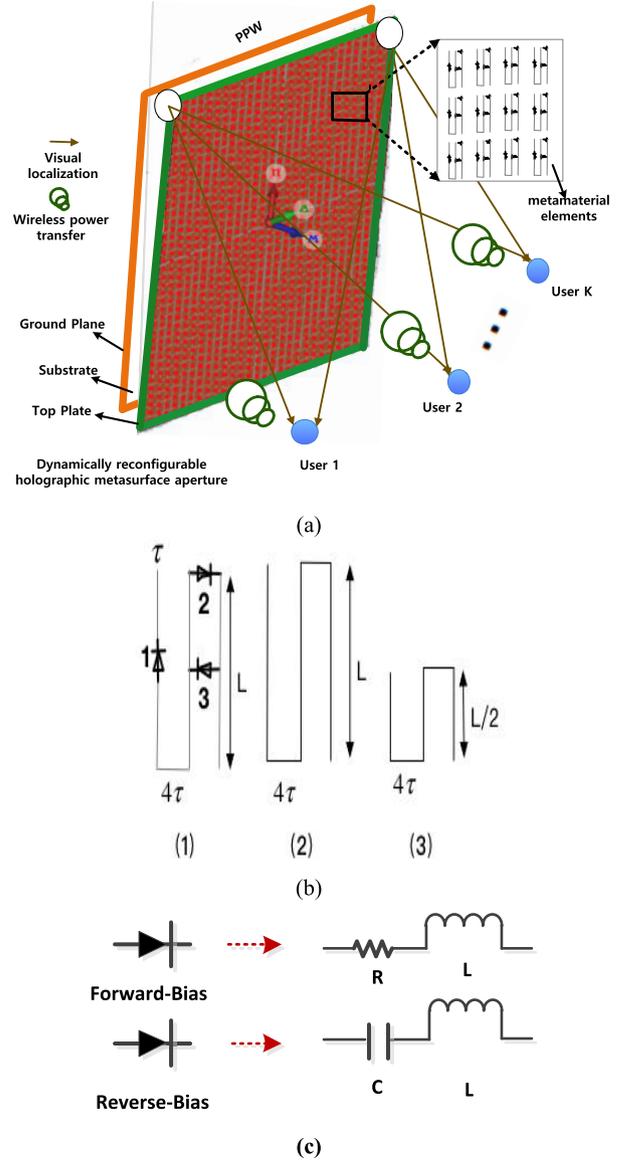
where,  $\mathbf{H}_{ref} \in \mathbb{C}^{\sqrt{M} \times \sqrt{M}}$ ,  $Q$  denotes wavenumber within the vacuum,  $\mathbf{r}$  is the position of the metasurface element on the aperture in Fig. 1(a). And  $\epsilon_r$  is the dielectric constant of the dielectric substrate. So, the desired field distribution to create a focus at the position of user  $k$  is calculated by treating the position as a fictitious point source placed at  $\mathbf{r}_k$  and back-propagating the radiated field from the point source to the aperture can be expressed as

$$\mathbf{P}_k = \frac{e^{-jk(\mathbf{r}-\mathbf{r}_k)}}{|\mathbf{r}-\mathbf{r}_k|} \quad (3)$$

where,  $\mathbf{P}_k \in \mathbb{C}^{\sqrt{M} \times \sqrt{M}}$ . Based on the superposition of holographic, the desired field distribution for multi-user system can be expressed as follows

$$\mathbf{P} = \sum_k \mathbf{P}_k \quad (4)$$

For the convenience of analysis, in this paper, we adopt a binary algorithm, relying on that it is very difficult to design matched electric and magnetic resonators that simultaneously control impedance for all phase shifts. The element pattern as in Fig. 1(b,2) is selected when the phase difference between the guided mode,  $\mathbf{H}_{ref}$  and back propagated



**Fig. 1** (a) The proposed multi-user WPT system based on reconfigurable holographic metasurface with machine visual localization. PPW stands for parallel-plate waveguide and the white circles above the PPW stand for pick-up heads. (b,1) describes a meander line element with three PIN diodes. When PIN diode 1 and PIN diode 2 are forward-biased and PIN diode 3 is reverse biased, the metasurface element is represented as (b,2). And the resonance length parameter is  $L$ . When PIN diode 1 and PIN diode 2 are reverse-biased and PIN diode 3 is forward biased, the metasurface element is represented as (b,3). And the resonance length parameter is  $L/2$ . The length parameter  $L$  or  $L/2$  decide the phase response of each element of the metasurface.  $\tau$  stands for the width of the meander line. (c) PIN diode equivalent circuit diagram; forward-biased:  $R = 4 \Omega$  and  $L = 0.5 \text{ nH}$ , reverse-biased:  $L = 5 \text{ nH}$ ,  $C = 0.02 \text{ pF}$  [7], [9].

pattern,  $\mathbf{P}$ , remains within a certain threshold, which is selected to be  $\phi_0$  as a result of numerical parametric analyses. Besides, the element pattern as in Fig 1(b,3) will be selected. For more advanced unit cell topologies, such as continuously tunable surface impedance [11], we can design a metasurface with full phase control. The details of the metasurface architecture are beyond the scope of the present

study, but we will study some of the metasurface aperture constraints in the consideration of more realistic implementations in the future.

Next, according to (2), we can obtain magnetic field of the reference wave matrix  $\mathbf{H}_{ref}$  by simulating specific excitation structures in FDTD, which is stable throughout the whole process. Then, the calculated hologram mask can be computed as (5). And the reconfigurable architecture of aperture can be adjustment by the calculated hologram mask.

$$\hat{\mathbf{M}} = \hat{\mathbf{p}} \cdot * \mathbf{H}_{ref}^* \quad (5)$$

where,  $\hat{\mathbf{M}} \in \mathbb{C}^{\sqrt{M} \times \sqrt{M}}$ ,  $\cdot *$  denotes matrix point multiplication.  $\mathbf{H}_{ref}^*$  denotes the complex conjugate of the guided magnetic field matrix  $\mathbf{H}_{ref}$ .  $\hat{\mathbf{p}}$  denotes the estimated field distribution with estimating error for the position of multiply users.

Just keeping the stability of the reference wave matrix, multiple focus points will present at the positions of users based on holographic reconstruction. The received energy signal at user  $k$  is given by

$$R_k = f_k \left( \sqrt{P_t} \hat{\mathbf{p}} \cdot * \mathbf{H}_{ref}^* \cdot \mathbf{H}_{ref} \right) \quad (6)$$

where  $f_k(\cdot)$  denotes the mapping function from the radiated field of aperture to the location of user  $k$ , which equals to forward-propagating the radiated field from the aperture to a point. Therefor  $R_k$  is a scalar representation, which can be calculated by using numerical integration based on Poynting theorem. The corresponding harvested power at user  $k$  is denoted by

$$Q_k = \eta_k |R_k|^2 \quad (7)$$

where  $0 \leq \eta_k \leq 1$ , denotes the RF-to-direct current (DC) energy conversion efficiency, which is a constant and thus omitted in the sequel for brevity.

*Lemma 1:* With massive metasurface elements, the harvested power at user  $k$  given in (7) converges almost surely to

$$Q_k \rightarrow \eta_k P_t \frac{\cos(2k\Delta_k)}{|r_{0k} - r_k|^4} \left( \frac{\pi^2}{6} - \frac{1}{2} \right)^2 \quad (8)$$

*Proof:* Applying (4) and (6) to (7), we can obtain (9) as follow

$$Q_k = \eta_k P_t \left( \sum_M \left[ \left( \sum_k \left( \frac{e^{-jkr - (r_k + \Delta_k)}}{r - (r_k + \Delta_k)} \right) \right) \frac{e^{jkr - r_k}}{|r - r_k|} \right] \right)^2 \quad (9)$$

where,  $\Delta k$  denotes estimated position error. Let  $r_{0k}$  represents a point on aperture with the same x coordinate and y coordinate as  $r_k$ . With  $M \gg K$ , (9) can be derivate as

$$Q_k = \eta_k P_t \frac{\cos(2k\Delta_k)}{|r_{0k} - r_k|^4} \left( \sum_M \left[ \frac{1}{1 + r_m^2} \right] \right)^2 \quad (10)$$

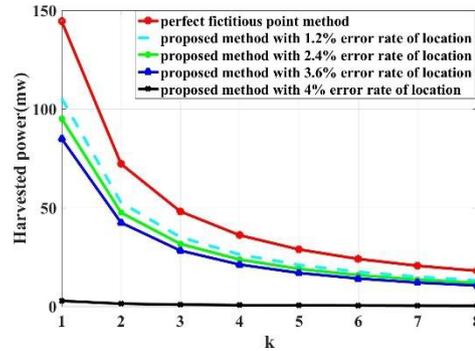


Fig. 2 The harvested power of user  $k$  by various user number.

where,  $r_m$  represents the distance between the current element and  $r_{0k}$ . Without loss of generality, we assume that  $r_m$  increases by unit. According to Vieta theorem and Eulerian theories, we can obtain (8). So, the estimated error of position for user can also affect the received power. For  $\Delta_k = 0^\dagger$ , (8) becomes  $\eta_k P_t \frac{1}{|r_{0k} - r_k|^4} \left( \frac{\pi^2}{6} - \frac{1}{2} \right)^2$ . This can be shown to be the maximum power that can be harvested with the position of user  $k$ . The harvested power at user  $k$  is a strictly increasing function of the total transmitter power  $P_t$ , but a strictly decreasing function of the fourth power of the distance.

### 3. Numerical Results

We present simulation results to validate the performance of our proposed method. We set  $M = 32 \times 32$ ,  $K = 4$ ,  $P_t = 30 \text{ dbm}$ ,  $f_c = 20 \text{ GHz}$  and  $\eta_k = 0.9$ ,  $k \in \{1, 2, 3, 4\}$ . In addition, each pick-up head is located at the one top corner of the aperture at intervals of 15 cm, corresponding to an electrical size of  $10\lambda$  at 20G,  $\tau = 0.12 \text{ mm}$ . The parameter length  $L$  of the element is 15 mm.  $\phi_0 = 0$ ,  $\phi_1 = \pi/3$  and  $\phi_2 = -\pi/3$  can be obtained by simulations with CST. We begin our analysis with the above WPT scenario. Figure 2 depicts the harvested power of user  $k$  by various user number with different error rate of location by 1.2%, 2.4%, 3.6% and 4%. It is observed that the smaller error rate of location is, the higher the energy collected by the receiver is. What's more, the error rate of location is too high to collect effective energy because the position of the receiver deviates from the focus area. In brief, the proposed method has vital performance loss than the perfect fictitious point method. However, the proposed method can support for real-time mobile WPT for multiply users and has low actual cost. From the figure, we also can obtain that the effect of error rate of location is weakening with the increase of  $K$ , which because of energy dispersion for multiply users.

### 4. Conclusion

In this paper, we investigated a novel WPT scheme based on

<sup>†</sup>This hypothesis can be applied to some scenarios, such as short-range high-precision positioning and known user location, etc.

machine vision and reconfigurable holographic metasurface aperture in the Fresnel region. It has been shown that the proposed scheme has the same effect as traditional method. However, the proposed method can transmit energy for multiply mobile users simultaneously without any information feedback. The analytical results demonstrate the ability of proposed method to exhibit high fidelity effect even when serving multi-users.

### Acknowledgments

This work was supported by National Natural Science Foundation of China (U1804148).

### References

- [1] H. Sun, H. Lin, F. Zhu, and F. Gao, "Magnetic resonant beamforming for secured wireless power transfer," *IEEE Signal Process. Lett.*, vol.24, no.8, pp.1173–1177, Aug. 2017.
- [2] G. Lipworth, J. Ensworth, K. Seetharam, D. Huang, J.S. Lee, P. Schmalenberg, T. Nomura, M.S. Reynolds, D.R. Smith, and Y. Urzhumov, "Magnetic metamaterial superlens for increased range wireless power transfer," *Sci. Rep.*, vol.4, 3642, 2014.
- [3] D.R. Smith, V.R. Gowda, O. Yurduseven, S. Larouche, G. Lipworth, Y. Urzhumov, and M.S. Reynolds, "An analysis of beamed wireless power transfer in the fresnel zone using a dynamic, metasurface aperture," *J. Appl. Phys.*, vol.121, p.014901, 2017.
- [4] F. Tofigh, J. Nourinia, M. Azarmanesh, and K.M. Khazaei, "Near-field focused array microstrip planar antenna for medical applications," *IEEE Antennas Wireless Propag. Lett.*, vol.13, pp.951–954, 2014.
- [5] M. Ettorre, M. Casaletti, G. Valerio, R. Sauleau, L.L. Coq, S.C. Pavone, and M. Albani, "On the near-field shaping and focusing capability of a radial line slot array," *IEEE Trans. Antennas Propag.*, vol.62, no.4, pp.1991–1999, 2014.
- [6] W. Luo and L. Xu, "Wireless power transfer in the radiative near-field using a reconfigurable holographic metasurface aperture," 2018 *IEEE International Conference on Communications (ICC)*, pp.1–5, Kansas City, MO, 2018.
- [7] O. Yurduseven, D.L. Marks, J.N. Gollub, and D.R. Smith, "Design and analysis of a reconfigurable holographic metasurface aperture for dynamic focusing in the Fresnel zone," vol.5, pp.15055–15065, 2017, DOI: 10.1109/ACCESS.2017.2712659
- [8] G. Lipworth, N.W. Caira, S. Larouche, and D.R. Smith, "Phase and magnitude constrained metasurface holography at W-band frequencies," *Opt. Express*, vol.24, no.17, pp.19372–19387, 2016.
- [9] MACOM MA4AGBL912 PIN Diode, <https://cdn.macom.com/datasheets/MA4AGBLP912.pdf>
- [10] Z. Zhang, "A flexible new technique for camera calibration," *IEEE Trans. Pattern Anal. Mach. Intell.*, vol.22, no.11, pp.1330–1334, 2000.
- [11] F. Liu, O. Tsilipakos, A. Ptilakis, A.C. Tasolamprou, M.S. Mirmoosa, N.V. Kantartzis, D.-H. Kwon, M. Kafesaki, C.M. Soukoulis, and S.A. Tretyakov, "Intelligent metasurfaces with continuously tunable local surface impedance for multiple reconfigurable functions," *Phys. Rev. Appl.*, vol.11, no.4, p.044024, 2019.