[DRAFT] Proceedings of the IEEE Wireless Power Transfer Conference 2016 (WPTC 2016), pp. 1-4, Aveiro, Portugal, May 5-6, 2016.

Focus Steering in Open-Ended Waveguide Sheet for Efficient and Safe Two-Dimensional Waveguide Power Transfer

Akihito Noda and Hiroyuki Shinoda
Graduate School of Frontier Sciences, The University of Tokyo
5-1-5 Kashiwanoha, Kashiwa-shi, Chiba 277-8561
Email: Akihito_Noda@ipc.i.u-tokyo.ac.jp, hiroyuki_shinoda@k.u-tokyo.ac.jp

***Abstract*—This paper addresses a steerable focus generation scheme for two-dimensional waveguide power transfer (2DWPT). In 2DWPT systems, a receiver coupler put on a waveguide sheet is powered wirelessly by capturing a microwave propagating across the sheet as its non-radiative guided mode. Generating a microwave focus in the waveguide sheet underneath the receiver is desirable for efficient and safe power transfer. In this paper, multiport feeding system for focusing in open-edged waveguide sheet is presented. Measurement results demonstrate that the available power at the focal point is more than 10 times as high as the median value of the available power measured in a 200-mm square region of a 600-mm square sheet.**

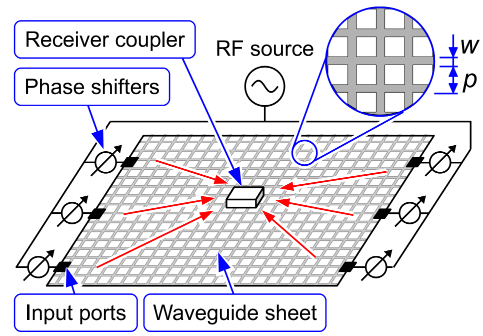
***Index Terms*—Focus steering, two-dimensional waveguide power transfer, wireless power transfer.**

I. Introduction

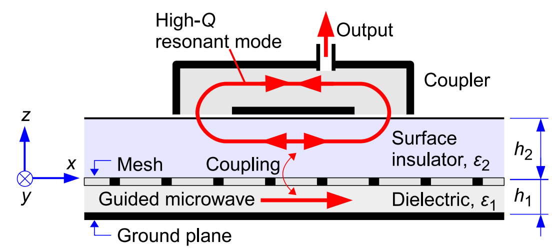
Handling electromagnetic (EM) energy not to diverge in free space but to concentrate at the receiver(s) is one of the most important technical issues in wireless power transfer (WPT) systems. Such techniques enable more efficient and safer WPT, i.e., energy radiated away and lost or absorbed by objects around the WPT system will be suppressed.

For WPT over a long distance, beam antennas and beamforming by phased array have decades of history [1], [2]. Such techniques have enabled WPT systems to transcend the power transmission efficiency determined by the inverse-square law attenuation. For shorter-range WPT, some advanced forms of classical induction coupling between a pair of coils have been developed. By exploiting near-field coupling between high-quality-factor (high-Q) resonators, a large fraction of EM energy concentrates around the resonators and exposure of off-resonant objects to strong EM fields can be avoided [3]. To extend the power transmission range while maintaining high efficiency, cascading multiple resonators is an effective scheme [4]–[6]. Thus, controlling EM field distributions is an essential issue for WPT in terms of efficiency, safety and electromagnetic compatibility (EMC).

This work aims to control EM field distribution in an open-ended two-dimensional waveguide for efficient and safe WPT using the waveguide as a power transmission medium. We refer to such a WPT scheme as two-dimensional waveguide power transfer (2DWPT) [7]. A schematic illustration of a 2DWPT system is shown in Fig. 1. In the system, microwave fed into the sheet travels along the sheet. A special receiver coupler extracts the microwave from the sheet across the surface. For example of its applications, a desktop can be entirely covered with a large single piece of waveguide sheet and electronic devices anywhere on the desktop can be charged wirelessly.



(a)



(b)

Fig. 1. (a) In a 2DWPT system, microwaves fed into the sheet travel along the waveguide sheet. A multiport system enables microwave focusing underneath the receiver. (b) Cross sectional model of coupling between the sheet and the coupler.

In ordinary long-range WPT systems, if most of the microwave power transmitted is concentrated into the receiver antenna aperture, a significantly high transmission efficiency can be achieved [1]. Similarly, in a 2DWPT configuration where the coupling between the sheet and the coupler is significant, the coupler can capture a large fraction of transmitted power at the focus, even if the sheet edges are terminated with microwave absorbers [8], [9].

Contrarily, in this work, we assume a weak coupling between the sheet and the coupler for safe WPT [7]. The sheet parameters shown in Fig. 1 are the same as those in our previous works [7], [10]: $p = 4.0$ mm, $w = 1.0$ mm, $h_1 = 1.0$ mm, $\varepsilon_1 = 2.1\varepsilon_0$, $h_2 = 4.0$ mm, and $\varepsilon_2 = 1.17\varepsilon_0$, where ε_0 is the permittivity of the free-space. In this configuration, the EM field amplitude at the top of surface insulator layer (at a distance of 4 mm from the mesh plane in the z-axis) is

40-dB smaller than that inside the dielectric waveguide layer (between the mesh plane and the ground plane) [7]. For the weak-coupling condition, resistive termination of sheet edges decreases the efficiency due to the power loss at the edges. This is the reason why focus generation in open-/short-ended sheet is desired.

In this paper, we report on microwave focusing in a 6-port phased array 2DWPT system using an open-ended sheet. Simulated focus generation in a waveguide sheet and measured power transmission efficiency around the focal point will be shown.

II. Focusing in Multiport 2DWPT

Six-port phased array 2DWPT system using a 600-mm square open-ended waveguide sheet is shown in Fig. 2 and Fig. 3. Six radio frequency power amplifiers (RFPAs), designed in [11], are attached to a pair of opposite sides symmetrically with respect to the x- and the y-axes.

For simplicity, the efficiency of power transmission to the receiver coupler is evaluated with a fixed coupler orientation, where the longitudinal axis of the coupler lies in the x-axis. In this configuration, the coupler sensitivity is maximized for the magnetic field vector lying in the y-direction. Hence, in the following discussions, we consider the y-component of the magnetic field.

Let $H_{y,p}(x, y)$ denote the complex amplitude of the magnetic field y-component at (x, y) generated by the pth feeding port. A magnetic field generated by superposition of 6 feeding ports is described as

$$H_y(x, y; \theta_1, \cdots, \theta_6) = \sum_{p=1}^{6} H_{y,p}(x, y) e^{-j\theta_p}, \qquad (1)$$

where θ_p, ranging from 0 to 2π, denotes the phase delay of the microwave supplied from the pth port. Actually, since the relative phases of the ports determine the superposed amplitude, $\theta_1 = 0$ can be assumed without any loss of generality.

The focus generation in the sheet was simulated by CST Microwave Studio. The simulation model constituted of a 600-mm square waveguide sheet and 6 feeding ports. For simplicity, no interaction between the sheet and coupler was considered. The magnetic field patterns $H_{y,p}(x, y)$ were simulated for all the 6 ports.

As shown in Fig. 4, focus generation was calculated with (1) for the following three focal points: $(x, y) = (112.5, 0)$, $(155, -62.5)$ and $(162.5, -167.5)$, where all dimensions are in millimeter. In these cases, the magnetic field intensity is maximized at the intended focal points. On the other hand, some other significant local maximum values can be found, due to the standing waves in the open-ended sheet.

III. Efficiency Measurement around Focal Point

This section presents actual efficiency of power transmission measured around the focal point. In the measurement setup shown in Fig. 3, stimulus signal from a vector network analyzer (VNA) is supplied to the primary RFPA, while

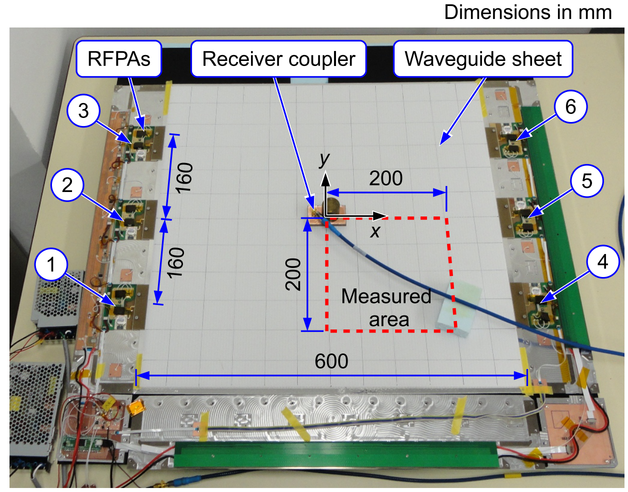


Fig. 2. Six-port phased array 2DWPT system using a 600-mm square waveguide sheet.

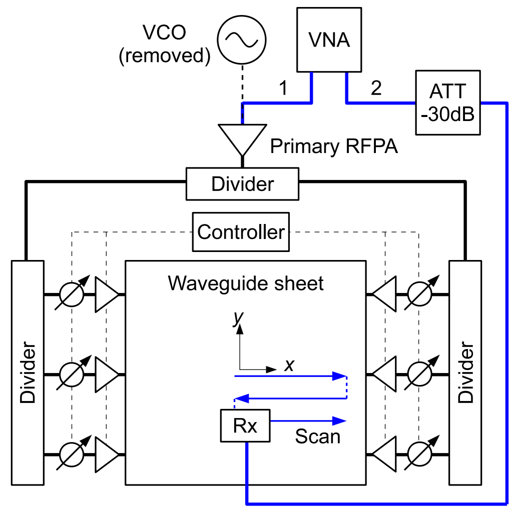


Fig. 3. Schematic diagram of a 6-port 2DWPT system for efficiency measurement.

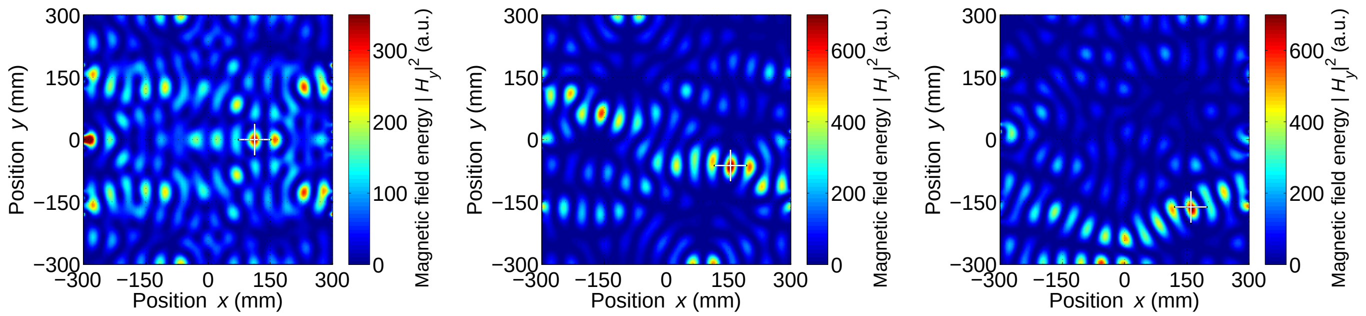
2.496-GHz RF source signal supplied in the actual power transmission setup is removed. The stimulus power of VNA, P_{stim}, is set to be equal to the original signal power, +2-dBm.

The power transmission efficiency is defined as the ratio of the RF output P_{out} to the RF input P_{in} and calculated as

$$\eta \equiv \frac{P_{\mathrm{out}}}{P_{\mathrm{in}}} = \frac{|S_{21}|^2 P_{\mathrm{stim}}}{P_{\mathrm{in}}}. \qquad (2)$$

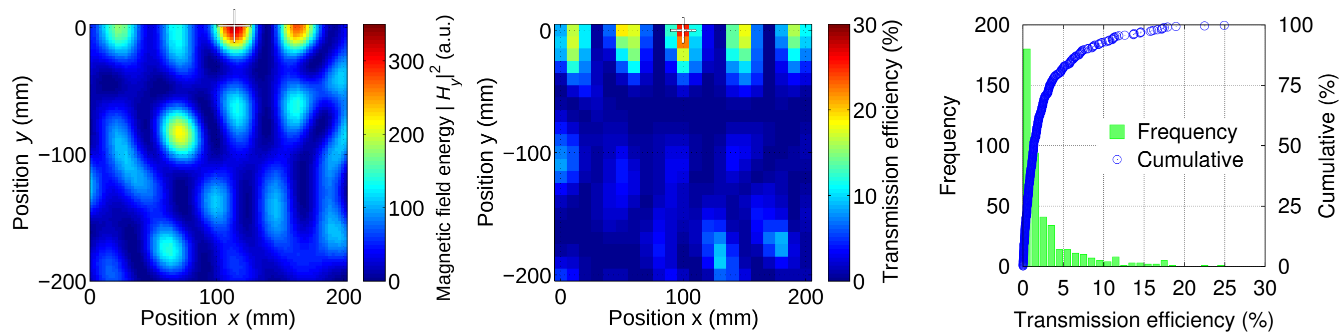
S_{21} is obtained from the measured transmittance between two ports of VNA by compensating the attenuation due to the atteuator and coaxial cables. The RF input into the sheet, P_{in}, was preliminarily measured and was 1.0 W for each port [11], therefore 6.0 W for the 6-port system.

The efficiency η was measured at 21×21 points in a 200-mm square area shown in Fig. 2. The receiver coupler was moved by a motorized XY stage. Measured results for three different focal points are shown in Fig. 5. For each focal position, simulated magnetic field is also shown.

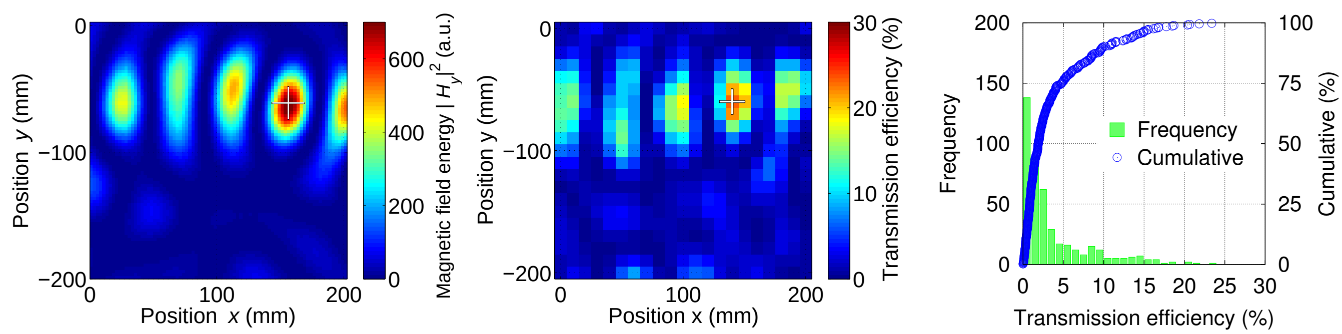


(a) (b) (c)

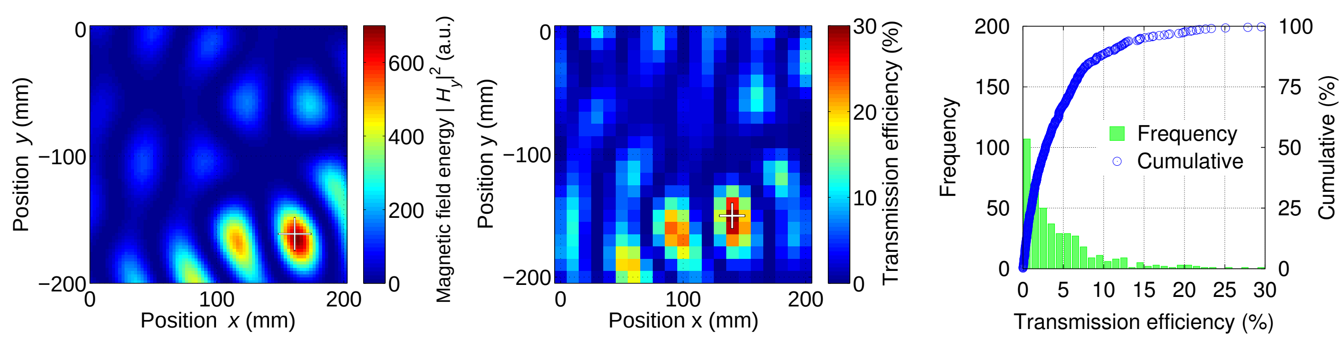
Fig. 4. Simulated magnetic field energy $|H_y|^2$ distribution in the waveguide sheet. The input ports are located at $(x, y) = (-300, -160)$, $(-300, 0)$, $(-300, 160)$, $(300, -160)$, $(300, 0)$ and $(300, 160)$. Target focal positions are (a) $(x, y) = (112.5, 0)$, (b) $(x, y) = (155, -62.5)$ and (c) $(x, y) = (162.5, -167.5)$. Each focal position is indicated with a white cross.



(a)

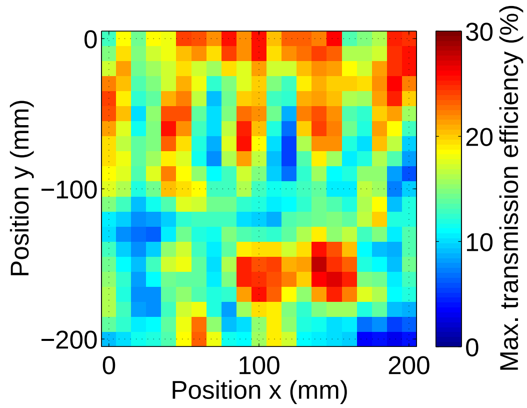


(b)

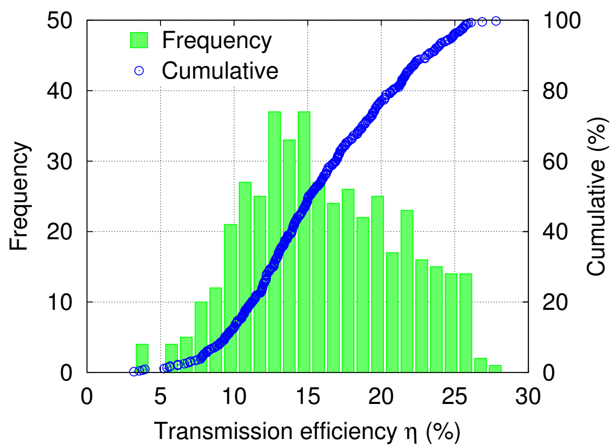


(c)

Fig. 5. Square of the y-component of simulated magnetic field $|H_y|^2$ (proportional to the magnetic field energy density) and measured power transmission efficiency. Each three graphs in (a), (b) and (c), from left to right, show: simulated $|H_y|^2$ in the xy-plane, measured efficiency in the xy-plane, and the histogram of the measured efficiency. The intended focal positions (x, y) of simulation and measurement are: (a) $(112.5, 0)$ and $(100, 0)$; (b) $(155, -63.5)$ and $(140, -60)$; and (c) $(162.5, -167.5)$ and $(140, -150)$, respectively. Each focal position is indicated with a white cross. The simulated $|H_y|^2$ in (a), (b) and (c) are the magnified views of Fig. 4(a), (b) and (c), respectively.



(a)



(b)

Fig. 6. Measured efficiency of power transmission. (a) Heatmap of efficiency maximized at each position, by tuning the phase delay of every port. (b) Histogram of the efficiency maximized at every position.

To generate each focus, the phase delay combination of the 6 ports were preliminarily tuned as follows. First, the receiver coupler position was fixed at the point to be focused and only RFPA #1 was turned on. Others were turned off and an isolator in each RFPA absorbed the microwave flew into them from the sheet. Next, RFPA #2 was turned on and its phase delay was tuned to maximize $|S_{21}|$. RFPAs #3, #4, #5 and #6 were turned on and their phase were tuned one by one, to maximize $|S_{21}|$. For the three focal points $(x, y) = (100, 0), (140, -60)$ and $(140, -150)$, the maximum power transmission efficiency at the focuses were 24.9%, 23.4% and 29.5%, respectively. The median values of the efficiency measured at 21×21 points were 1.3%, 1.9% and 2.8%, respectively. Thus, the efficiency at the focuses were more than 10 times higher than the median values. Objects at off-focal positions will not be exposed to significant EM field.

The simulated magnetic field pattern and the measured efficiency show reasonable agreement. Thus, design optimization of the port location will be possible through the simplified simulation where no interaction between the waveguide sheet and receiver coupler is involved.

Efficiency maximized at each of all the 21×21 positions by following the procedure above described is shown in Fig. 6. As shown in Fig. 6(a), the maximum efficiency strongly depends on the receiver position, due to standing waves generated by a fixed boundary condition. The top 10 percent of high-efficiency receiver position achieved maximum efficiency more than 23%, while the bottom 10 percent were less than 10% as shown in the histogram, Fig. 6(b).

IV. Conclusion

In this paper, an efficient and safe 2DWPT scheme by generating a steerable microwave focus in a waveguide sheet was presented. For high efficiency, the sheet edges should be open- or short-ended. Six-port phased array 2DWPT system using open-ended sheet was presented as an example. The power transmission efficiency at the focal point was more than 10 times as high as the median value of efficiency measured in a 200-mm square area. Thus, efficient and safe 2DWPT was demonstrated with the system.

On the other hand, the maximum efficiency strongly depended on the receiver position. Reducing efficiency fluctuations over the entire sheet surface will be one of our future works.

Acknowledgment

This work was supported in part by the MIC/SCOPE #155103003.

References

[1] W. C. Brown, "The history of power transmission by radio waves," *IEEE Transactions on Microwave Theory and Techniques*, vol. MTT-32, no. 9, pp. 1230–1242, September 1984.

[2] N. Shinohara and T. Ishikawa, "High efficient beam forming with high efficient phased array for microwave power transmission," in *Proc. 2011 ICEAA*, September 2011, pp. 729–732.

[3] 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, pp. 83–86, July 2007.

[4] I. Awai, T. Komori, and T. Ishizaki, "Design and experiment of multi-stage resonator-coupled wpt system," in *Proc. 2011 IMWS-IWPT*, May 2011, pp. 123–126.

[5] M. Dionigi and M. Mongiardo, "Magnetically coupled resonant wireless power transmission systems with relay elements," in *Proc. 2012 IMWS-IWPT*, May 2012, pp. 223–226.

[6] Y. Narusue, Y. Kawahara, and T. Asami, "Impedance matching method for any-hop straight wireless power transmission using magnetic resonance," in *Proc. 2013 IEEE Radio and Wireless Symposium*, January 2013, pp. 193–195.

[7] A. Noda and H. Shinoda, "Selective wireless power transmission through high-Q flat waveguide-ring resonator on 2-D waveguide sheet," *IEEE Transactions on Microwave Theory and Techniques*, vol. 59, no. 8, pp. 2158–2167, August 2011.

[8] B. Zhang, A. O. Lim, Y. Kado, H. Itai, and H. Shinoda, "An efficient power supply system using phase control in 2D communication," in *Proc. 6th INSS*, Pittsburg, USA, June 2009.

[9] T. Matsuda, T. Oota, Y. Kado, and B. Zhang, "An efficient wireless power transmission system using phase control of input electrode array for two-dimensional communication," in *Proc. 13th ICACT*, February 2011, pp. 610–615.

[10] A. Noda and H. Shinoda, "Waveguide-ring resonator coupler with class-F rectifier for 2-D waveguide power transmission," in *Proc. 2012 IMWS-IWPT*, Kyoto, Japan, May 2012, pp. 259–262.

[11] ——, "Edge-mount 1-watt RF amplifier for 2-D waveguide power transmission," in *Proc. SICE Annual Conference 2014*, Sapporo, Japan, September 2014, pp. 1941–1945.