"Wireless Powered Battery-free Drone Experiment with Novel Flat Beam Forming Technique

KIEES Summer Conference 2023

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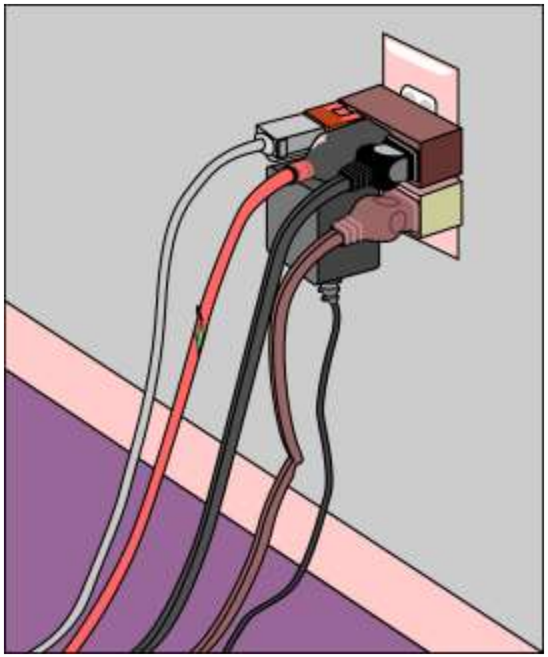
Introduction

What is ‘Wireless Power Transfer’?

Power Transmission + Wireless Communication = **Wireless Power Transfer (WPT)**



Radio

TV

Mobile

- Power transfer from power station to home via wire
- Information transfer from base station to user via radio wave
- Power transfer from transmitter to user via electromagnetic field or radio wave

Energy of Electromagnetic Wave

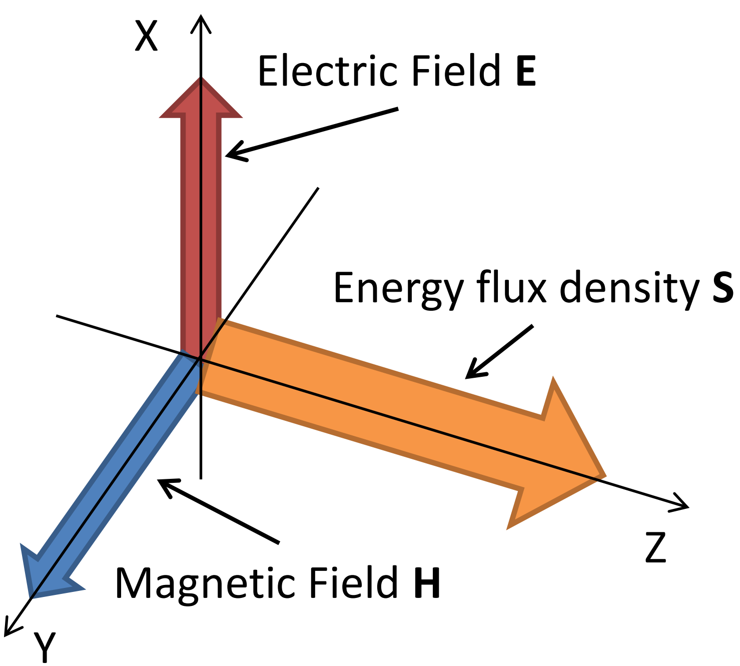
Electromagnetic wave has energy.
We can calculate the power by using poynting vector

$$\mathbf{S} = \mathbf{E} \times \mathbf{H}$$

[W/m^2] [V/m] [A/m]

Microwave Oven
Wave-Energy Conversion to Heat

Poynting vector **S** represents the directional energy flux density of an electromagnetic field



Wave-Energy Conversion
= Frequency Conversion of Carrier Wave
(No Modulation = Continuous Wave)
(MHz, GHz → Hz or DC)
(on same Maxwell's equations)

Report ITU-R SM.2392 (2016,21)

"Applications of wireless power transmission via radio frequency beam",
http://www.itu.int/pub/R-REP-SM.2392

TABLE 3.1

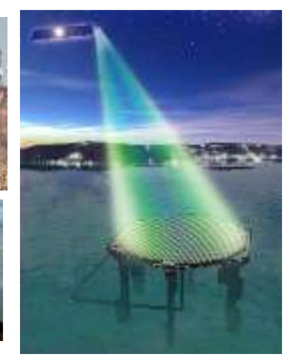
Classification of WPT applications

ID	Application	a) Wide beam to multi-users at short range	b) WPT in closed area	c) Narrow beam to single user at short/long range
a1	Wireless powered sensor network	○		
a2	Wireless charger of mobile devices	○		
b1	Wireless power transfer sheet		○	
b2	MPT in a pipe		○	
b3	Microwave buildings		○	
c1	WPT to moving/flying target			○
c2	Point-to-point WPT			○
c3	Wireless charging for electric vehicles			○
c4	SPS			○

(a) Wide Beam to Multi-Users at Short Distance

- ITU-R Recommendation (2022)
- New Radio Regulation in Japan (2022)
- Many Startup Companies in the World

(c) Narrow Beam to Single User at Short/Long Distance



- Under Discussion
- R&D Phase

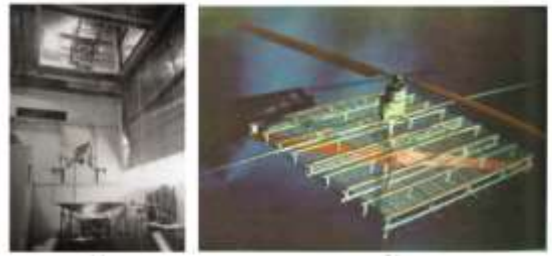
[Today's Topic]

Question → Report → Recommendation → Regulation

History of Narrow Beam WPT to Flying Drone

1959 RAMP in US

1964 Brown's helicopter in US



(b) Brown's wireless-powered helicopter

1987 SHARP in Canada

(b) SHARP experiments.

1992 MILAX in Japan

(c) MILAX

2009 Airship experiment in Japan

2019 Mitsubishi drone experiment in Japan

(d) Mitsubishi drone experiments

2022 in Kyoto Univ.

Today's Topic

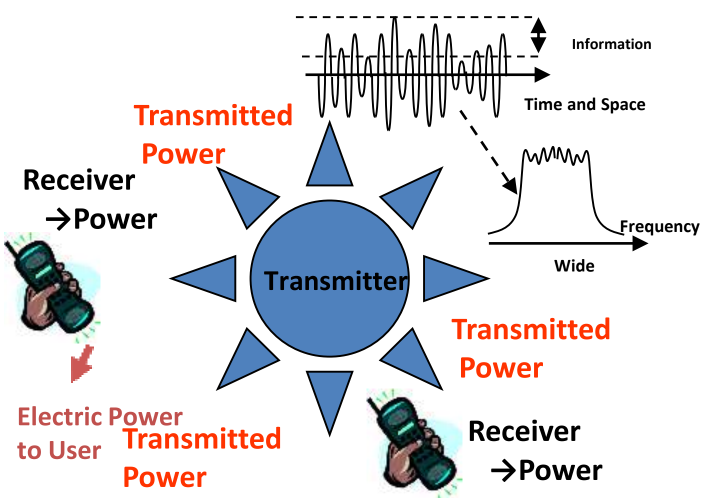
Key Technology
- High Beam Efficiency and Beam Forming -

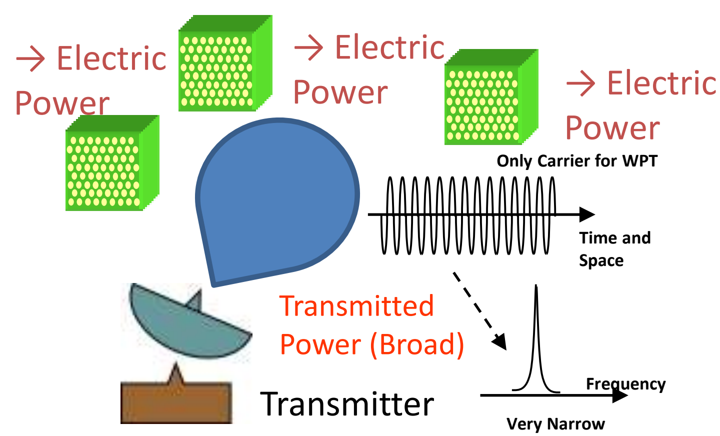
Theoretical Beam Efficiency for Energy Harvesting and Ubiquitous WPT

Friis' Transmission Formula (in Far Field)

$$\eta = \frac{P_r}{P_t} = \frac{G_t A_r}{4\pi d^2} = \frac{A_t A_r}{\lambda^2 d^2} = \frac{\lambda^2 G_t G_r}{(4\pi d)^2}$$

P_t : Tranmitted Power, P_r : Received Power, d : Distance
G_t : Transmitting Antenna Gain, A_t : Effective Aperture of Tx Antenna
A_r : Effective Aperture of Rx Antenna, λ : Wave Length





Beam Efficiency and Total Efficiency of WPT and MPT

Beam Efficiency by
Friis' Transmission Formula
in Fraunhofer Region (Far Field)
(with Assumption of Plane Wave)

$$\boxed{\eta = \frac{P_r}{P_t} = \frac{G_t A_r}{4\pi d^2} = \frac{A_t A_r}{\lambda^2 d^2} (= \tau)}$$

Beam Efficiency by
(Exact) Friis' Transmission Formula
in Fresnel Region
(without Any Assumption)

$$\boxed{\eta = \frac{P_r}{P_t} = 1 - e^{-\tau^2}}$$

[How to increase beam efficiency of WPT and MPT]

1. Large τ
   a. Higher Frequency (Shorter Wavelength l)
   b. Larger Antenna Aperture (A_t, A_r)
   c. Shorter Distance (d)
2. Amplitude Tapering with Flat Phase
3. Phase Optimization with Flat Amplitude by Phased Array

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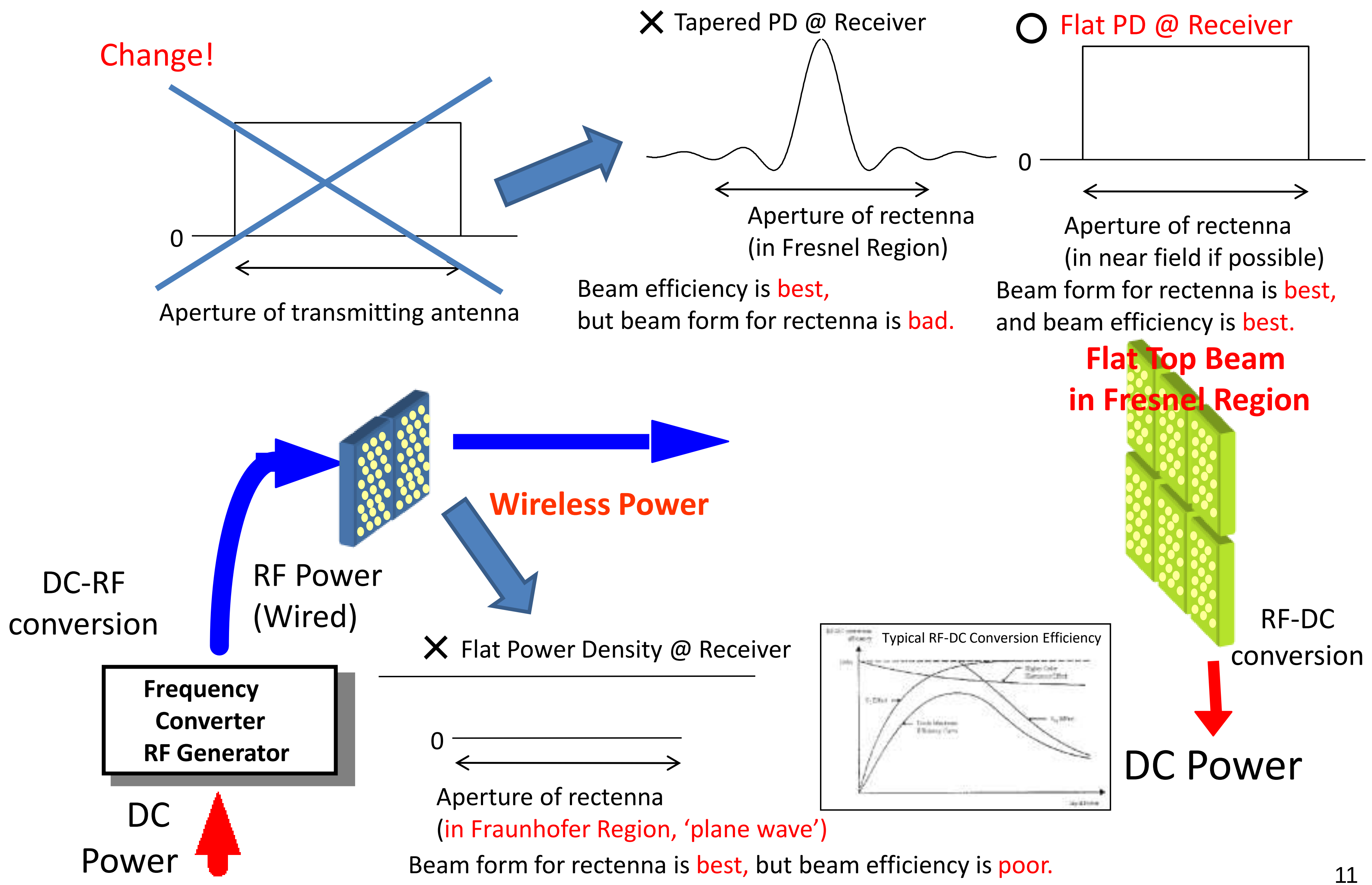
(Total Efficiency of WPT and MPT) = (Beam Efficiency)
x (Circuit Efficiency at Tx, Rx)

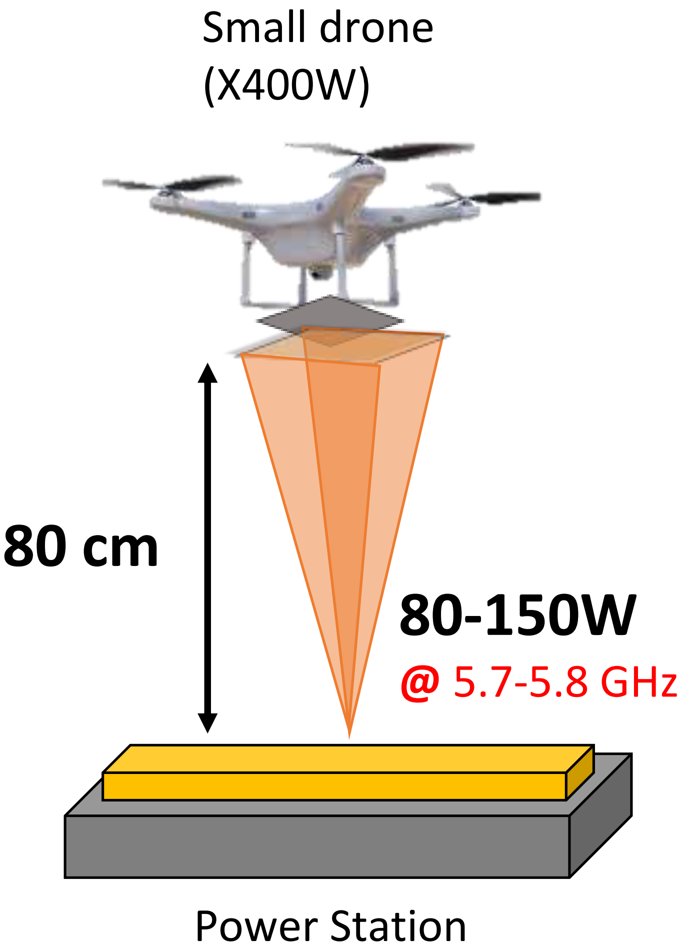
4. Optimization of Amplitude and Phase with consideration of efficiency of rectenna

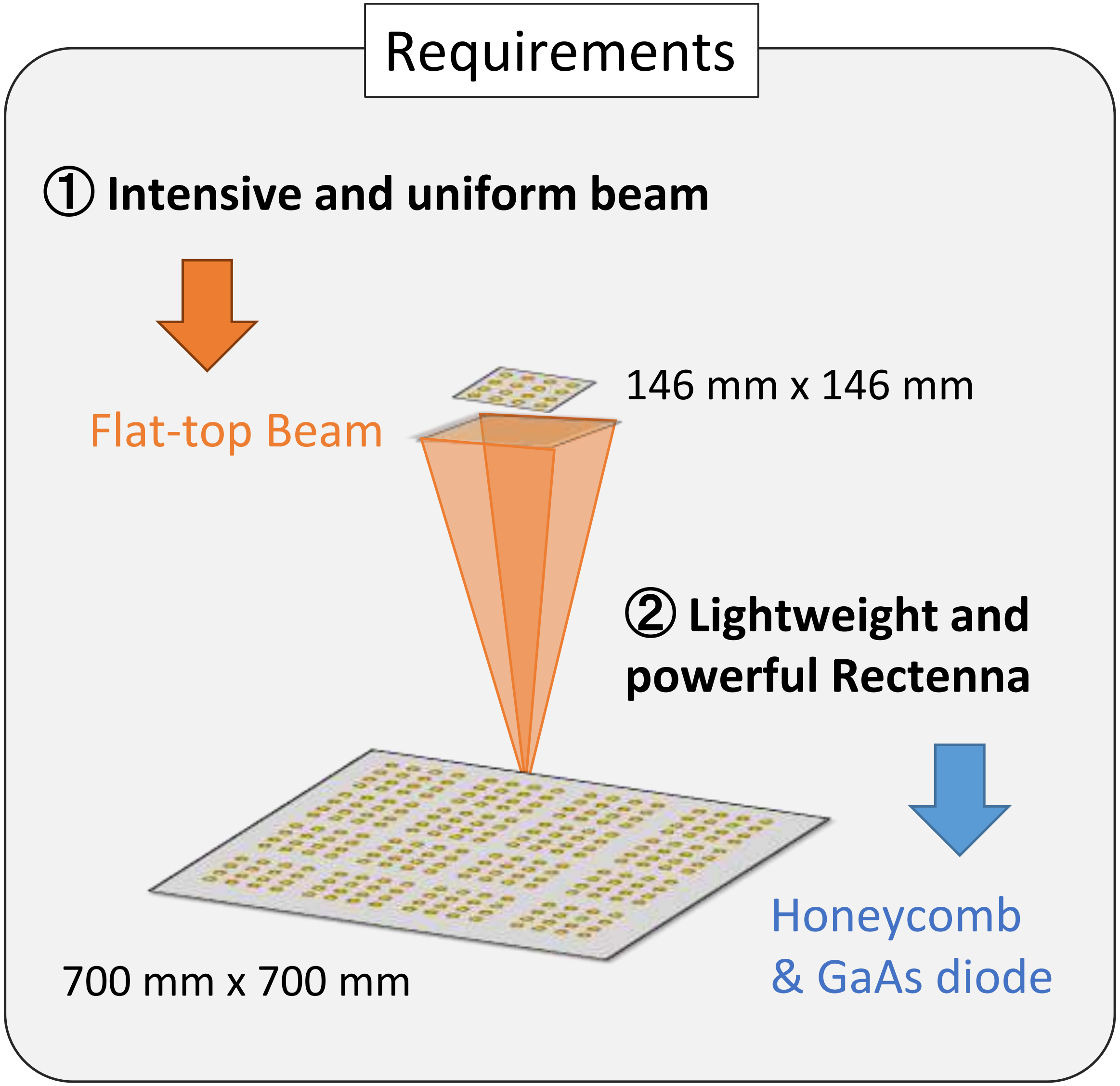
Optimization of Amplitude and Phase with consideration of efficiency of rectenna



WPT Powered Drone Experiment in Kyoto University

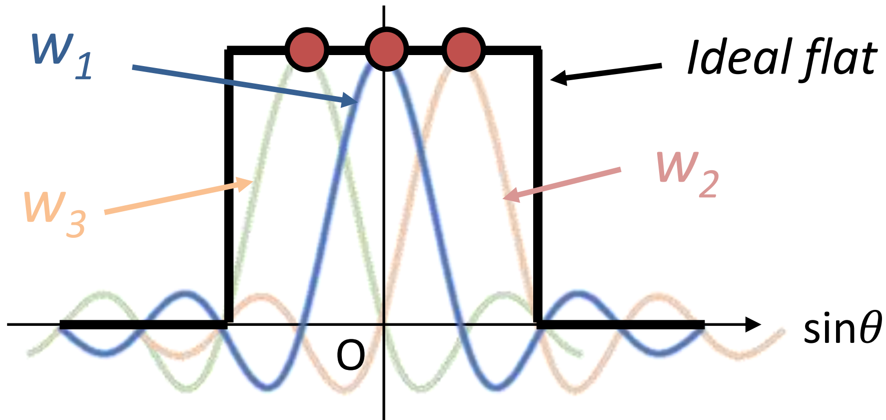
WPT Powered Micro-Drone in Kyoto Univ.





Flat Beam by Woodward Lawson method (WLM)

(***Flat pattern*** imitated by ***superposition of sinc function***)



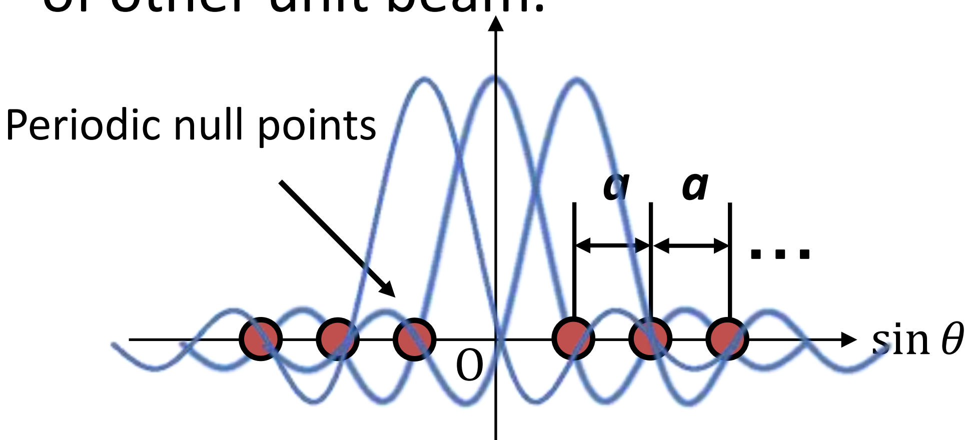
3 samples

$$w_{flat} = w_1 + w_2 + w_3$$

*w_1, w_2, w_3, w_{flat} is array weight.

Increasing the number of samples means high reproducibility.

⇩ Each unit beam (sinc function) can be positioned only at null points of other unit beam.



$$a = (N \bullet d/\lambda)^{-1}$$

λ : Wavelength

N : Number of elements

d: Interval between elements

Smaller ***a*** is preferred in terms of Increasing sampling points

P. M. Woodward, " A method of calculating the field over a plane aperture required to produce a given polar diagram, " Proc. IEE, part IIA, vol.93, pp.1554-1555, 1947.

P. M. Woodward and J. P. Lawson, " The theoretical precision with which an arbitrary radiation pattern may be obtained from a line source of finite size, " Proc. IEEE, vol.95, p1, pp.362-370, 1948.

Pre-Experiment of Total Efficiency by Flat Top Beam

Uniform Beam Pattern at Rectenna Array by Simulation

< Uniform 1 >

Selected

		21.6	27.7	21.1		
	37.4	83.1	108.2	82.5	36.5	
22.7	84.1	183.0	235.5	182.4	82.8	22.0
28.9	108.3	233.8	300.0	233.2	107.3	28.3
22.1	82.1	179.6	231.2	179.2	81.6	21.8
	35.6	79.9	104.3	79.7	35.6	
		20.4	26.5	20.6		

Unit: [mW]

Flat Top Beam Pattern at Rectenna Array in Experiment

< Flat 2 >

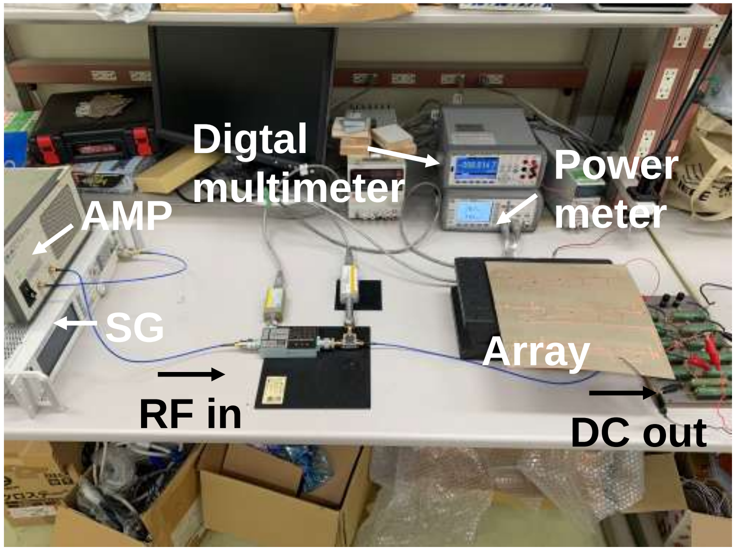
Selected

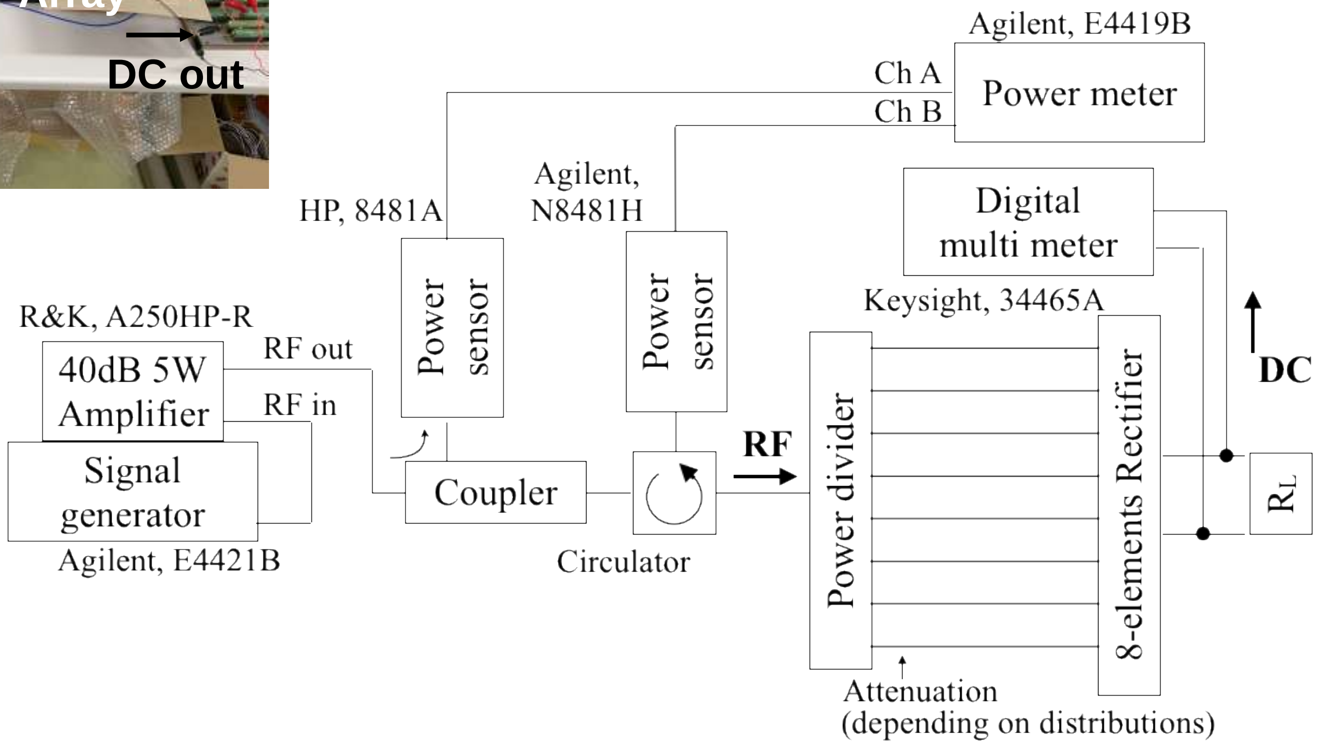
		87.5	138.4	106.9		
	96.2	131	189.7	161.1	94.4	
91.9	140.3	183.7	250.1	208.5	161.5	115.9
119.2	165.6	222.4	300	230.7	163.4	146.6
88.1	144.6	188.9	239.4	181.6	143.9	103.1
	88.1	146.6	175.8	144.9	93.8	
		96.4	145.6	95.7		

Unit: [mW]

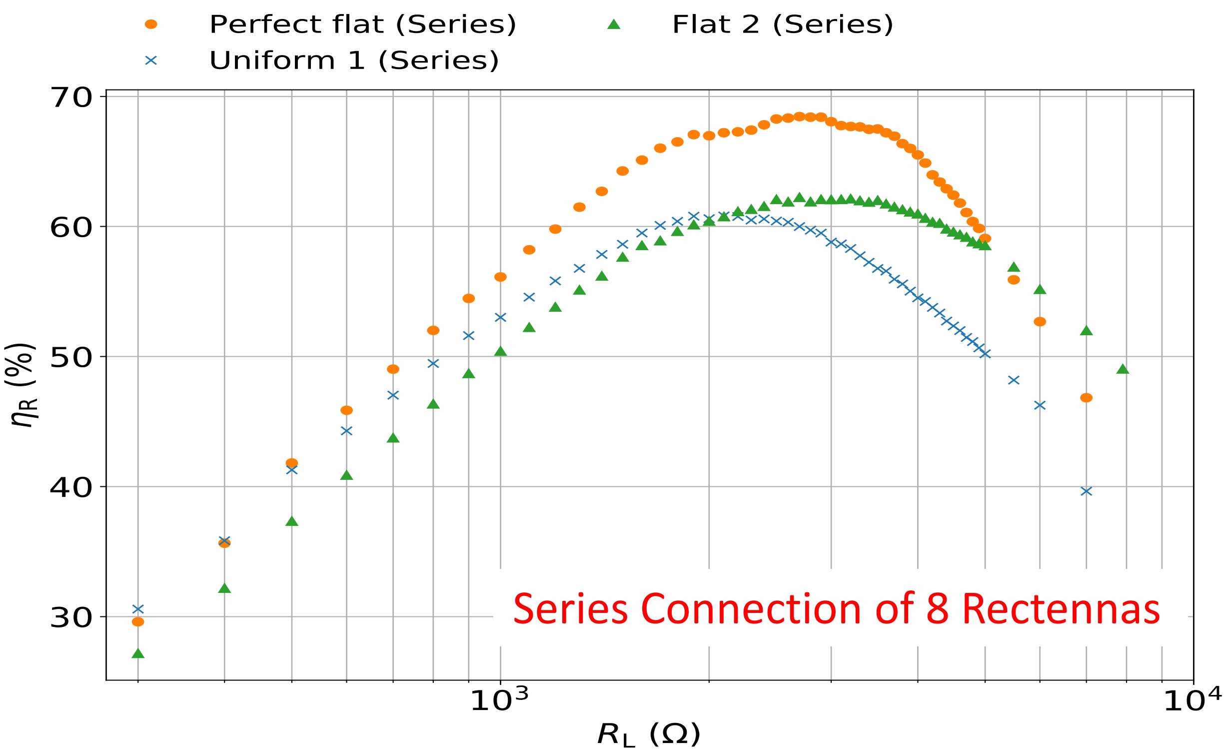
< Perfect flat > Assumption of Equal 300 mW Input MW to Each Rectenna Element

Experimental Setup





Measured Efficiency



[9] K. Needham, "Plans for first Chinese solar power station in space revealed," The Sydney Morning Herald, February 2019, https://www.smh.com.au/world/asia/plans-for-first-chinese-solar-power-station-in-space-revealed-20190214-p50xtg.html

[19] Y. Fujino, "A rectenna for milax," in Proc. of 1st Wireless Power Transmission Conference, 1993, pp. 273-277

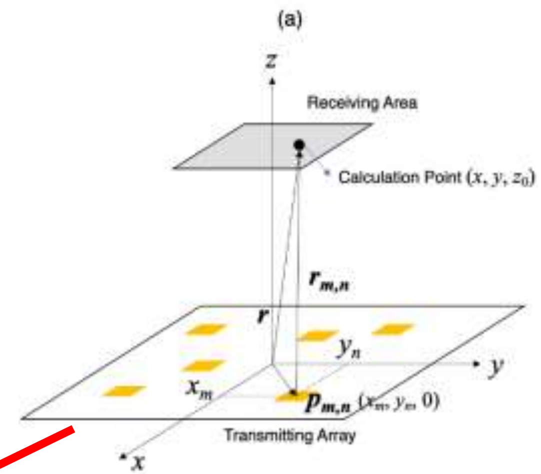
[20] Y. Homma, J. Nishihara, and T. Katase, "Wireless power transmission technology for unmanned aerial vehicles in flight," in Mistubishi Electric Corporation Tech. Rep., vol. 94, no. 2, 2020, pp. 36-40

	[9]	[19]	[20]	Our work
Frequency (GHz)	2.45	2.45	2.45	2.45
Element number	12	72	4	8
Array efficiency (%)	N/A	51.1	77.2	68.2
Output power (W)	2.28	7.1	0.0978	1.64
Output power per element (mW)	190	98.6	24.4	205

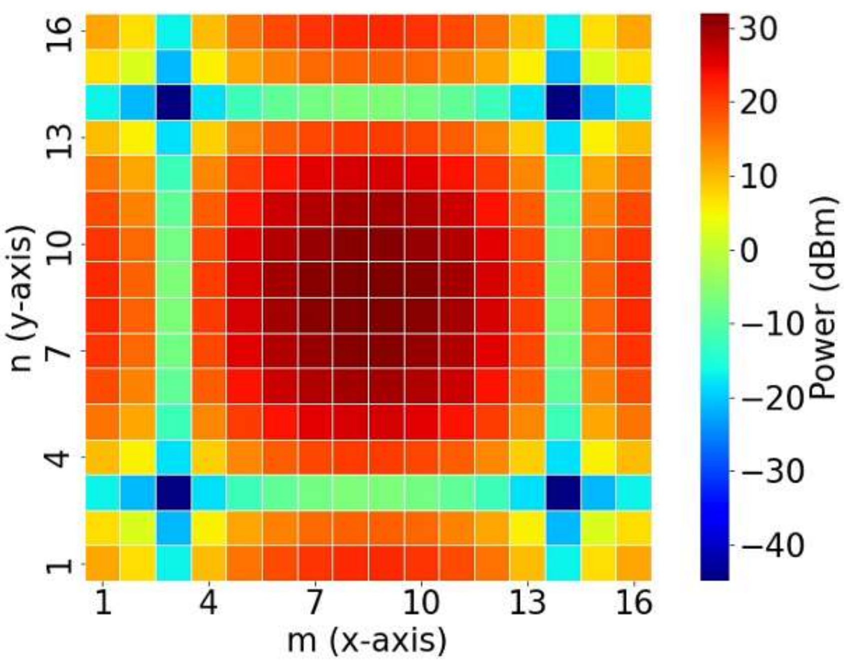
Designed Flat Top Beam for WPT-Drone (1/2)

Parameters for Flat Top Beam

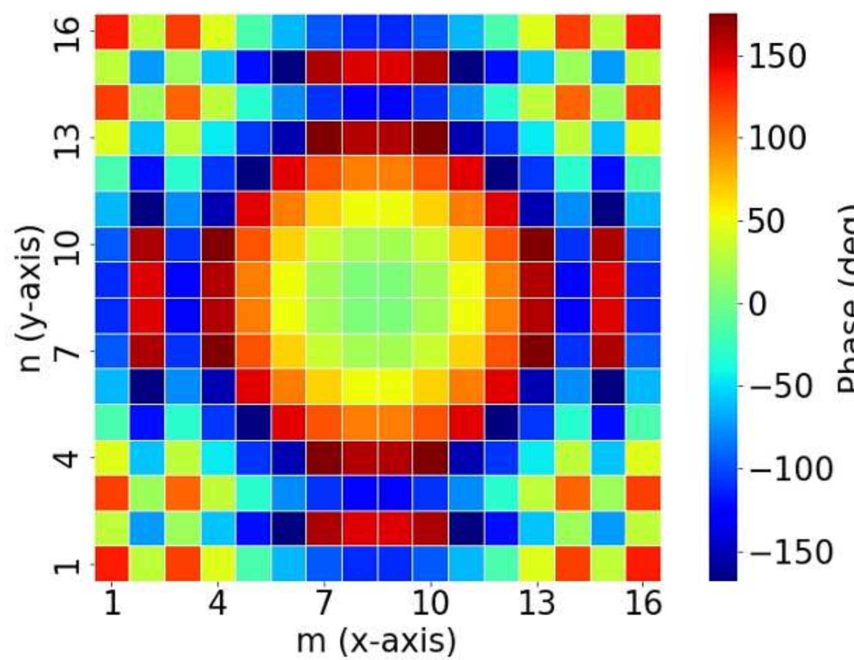
Frequency (GHz)	5.74
Element Number	16 x 16
Element Interval (λ)	0.82
Element Gain (dBi)	7.3
Radiated Power (W)	50
Transmission Distance (m)	0.8



Power Distribution @ Tx



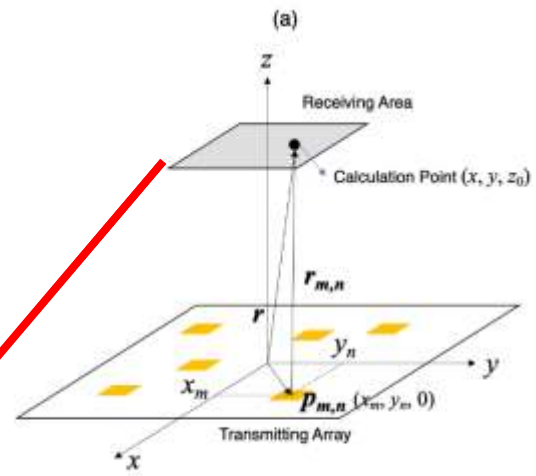
Phase Distribution @ Tx

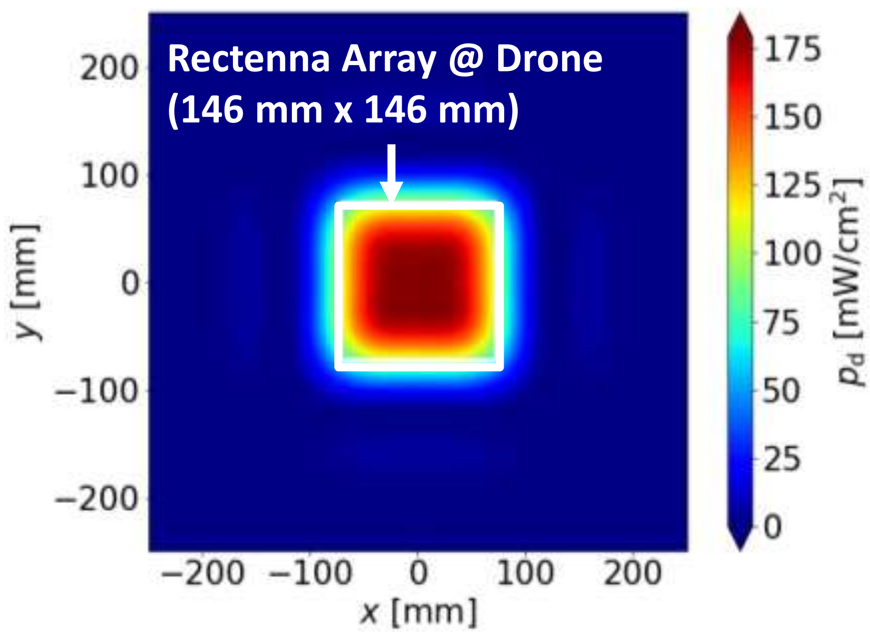


Designed Flat Top Beam for WPT-Drone (2/2)

Parameters for Flat Top Beam

Frequency (GHz)	5.74
Element Number	16 x 16
Element Interval (λ)	0.82
Element Gain (dBi)	7.3
Radiated Power (W)	50
Transmission Distance (m)	0.8





Average Power Density (mW/cm^2)	144
Beam Efficiency (%)	61.9
CV	0.20

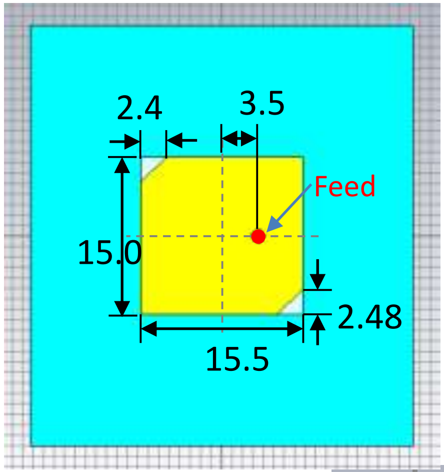
- Beam efficiency

$$= \frac{\text{Illuminated power on Rx}}{\text{Radiated power from Tx}}$$

- CV

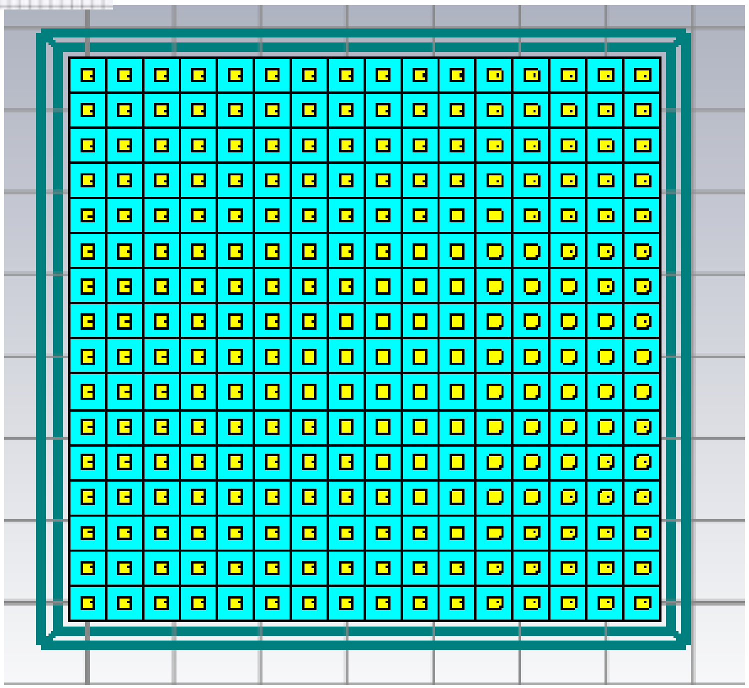
$$= \frac{\text{Standard deviation of power density on Rx}}{\text{Average of power density on Rx}}$$

Developed Tx Antenna for Flat Top Beam

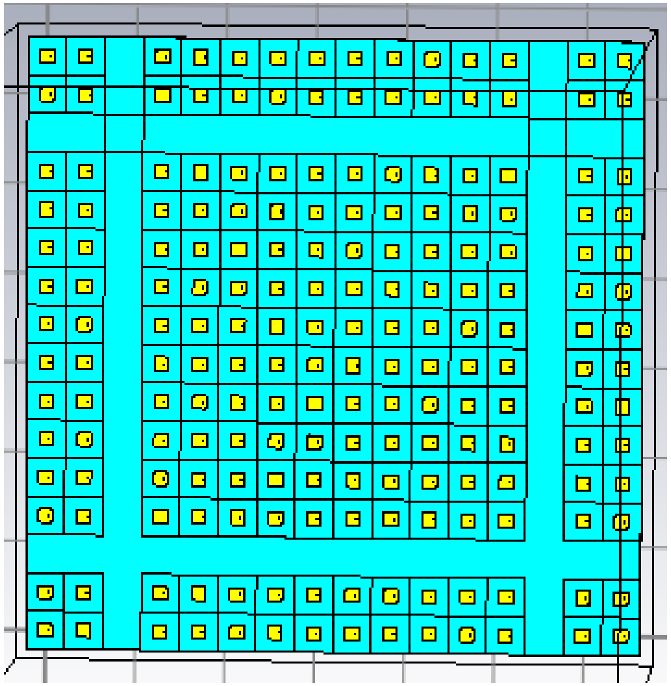


<- Antenna element
(Right-handed circular polarized MSA)

16 x 16 phased array (Original)

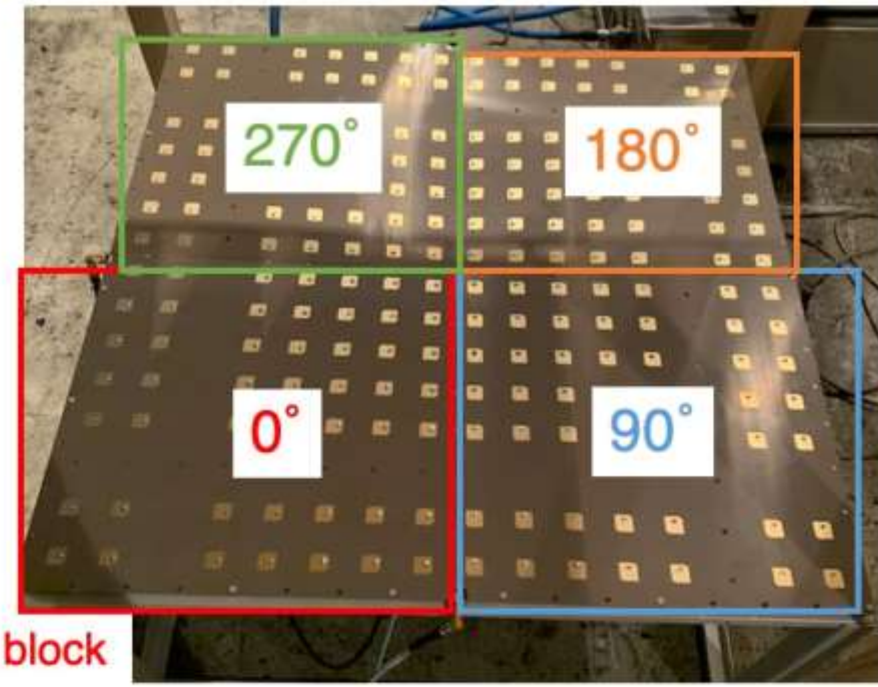


14 x 14 phased array (Revised)



Developed Tx Antenna for Flat Top Beam

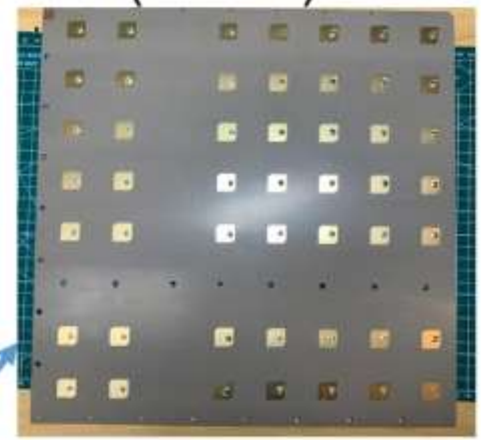
196-element
(Sequential Array)



1 block

Divided into four subarrays
Physically rotated by each group.

49-element
Front (antenna)



Back (Distribution circuit)

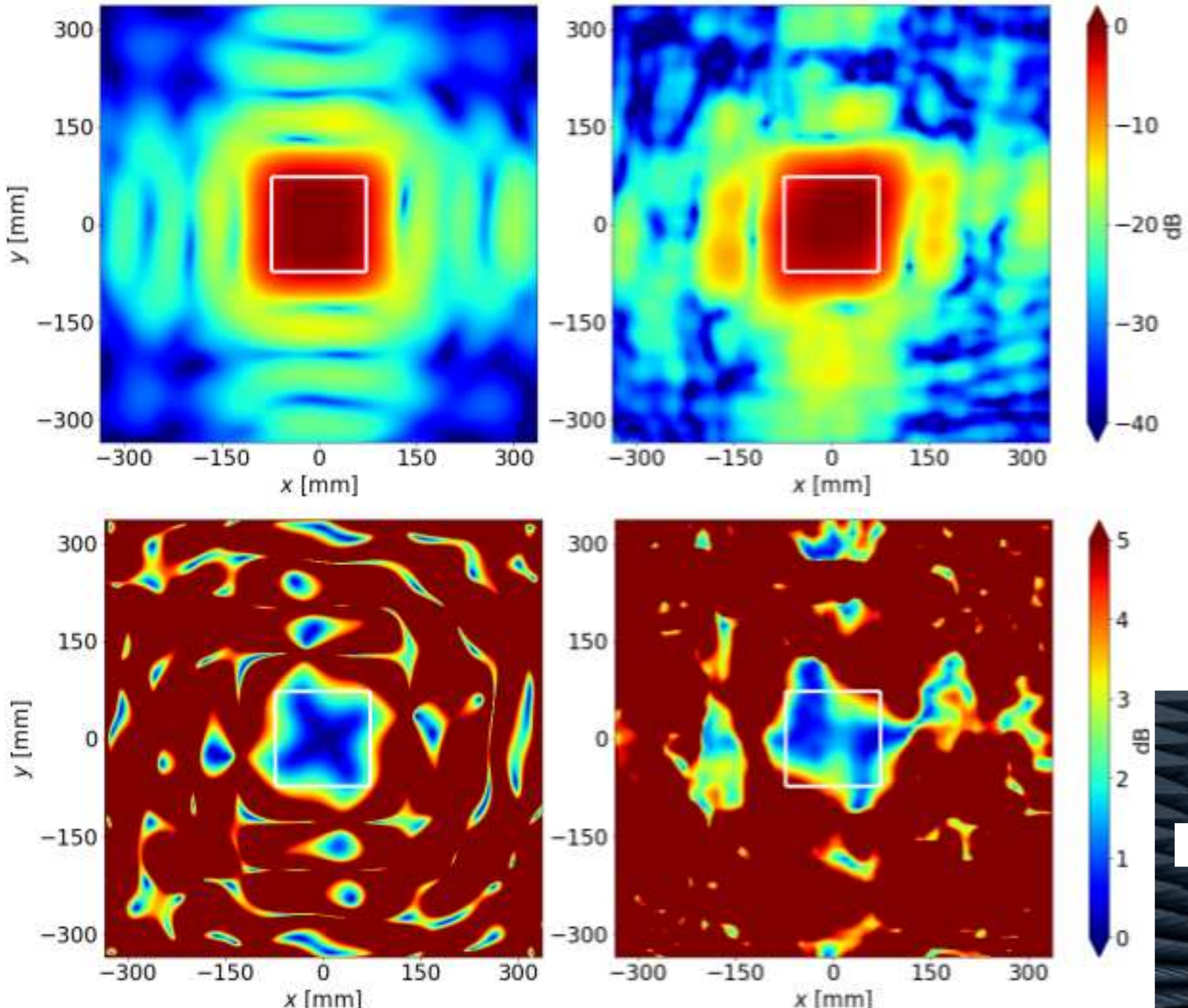
Input

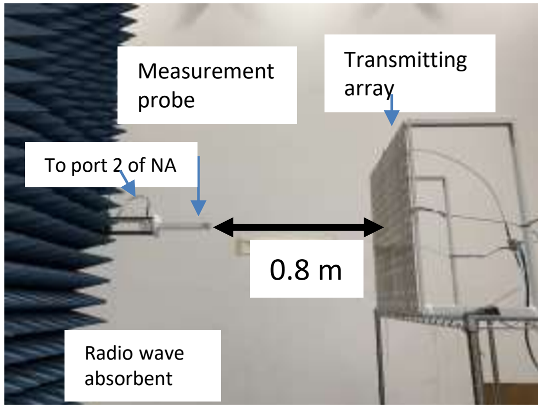
Measured Beam Pattern

< Simulation > < Measurement >

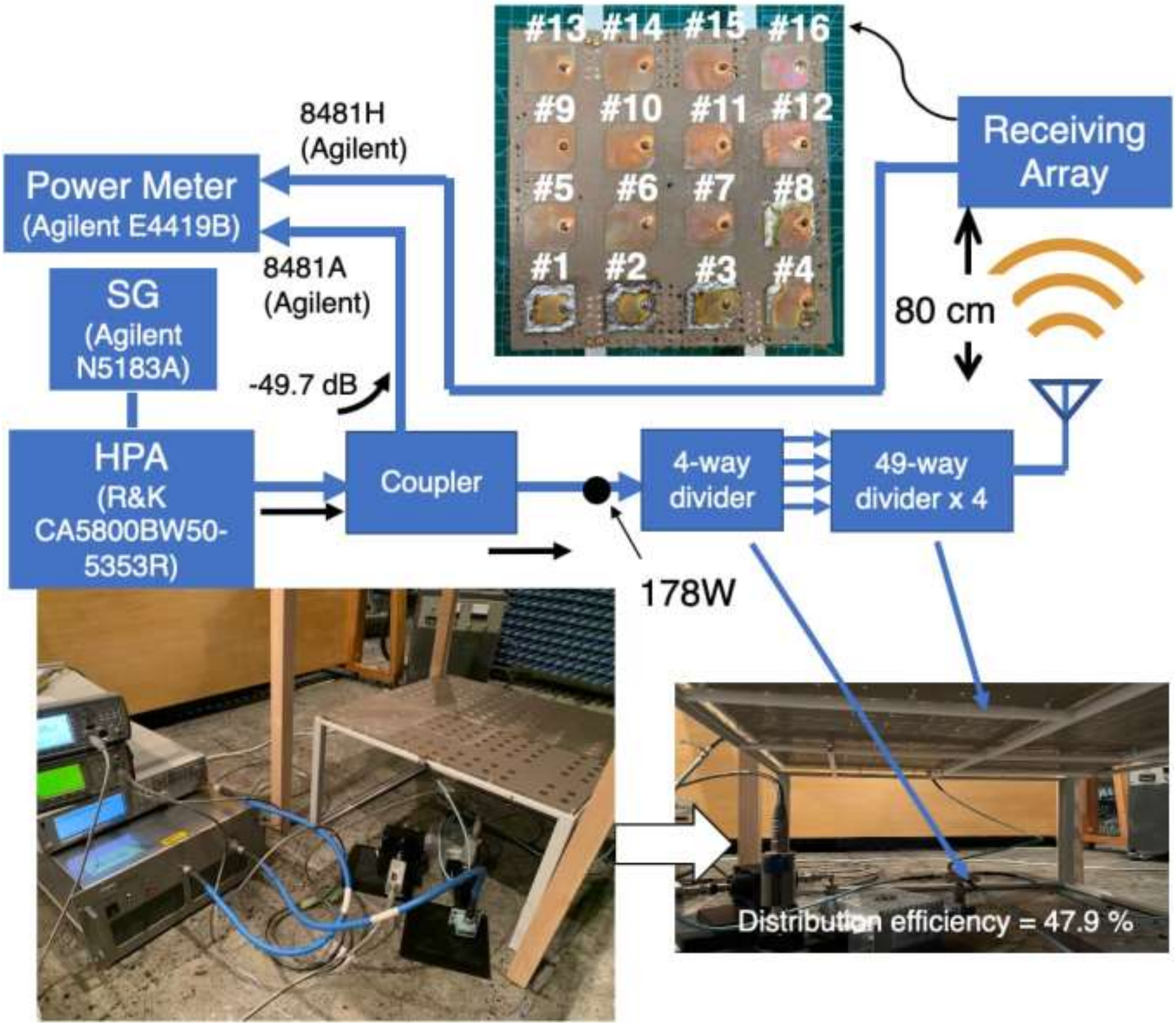
Power Density

Axial Ratio



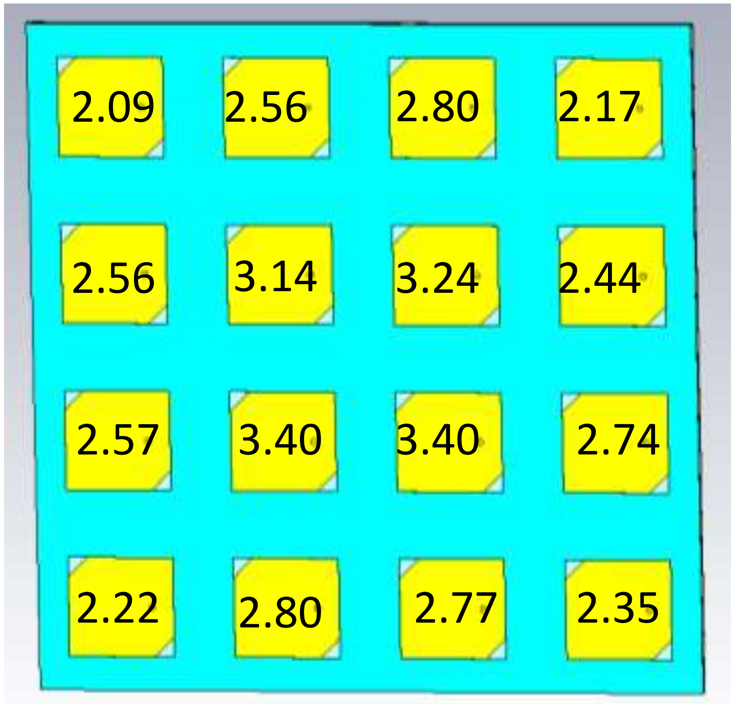


Measurement Setup of Receiving Power



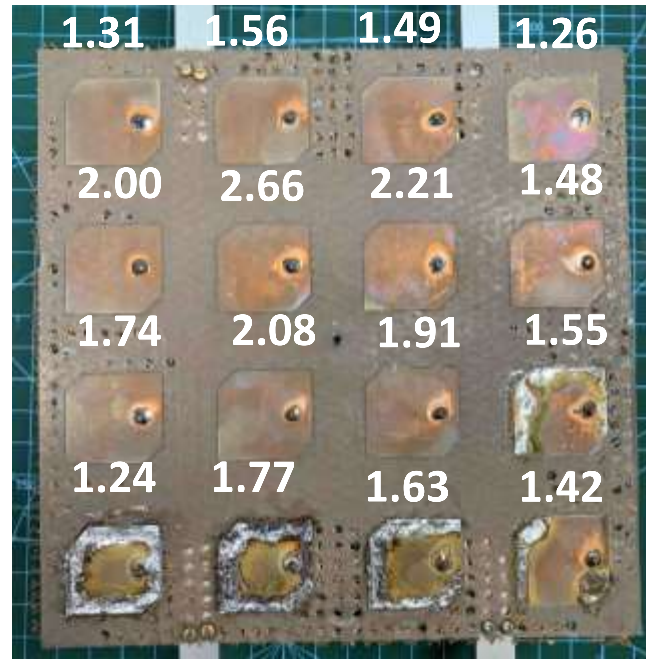
Measured Receiving Power

< Simulation >



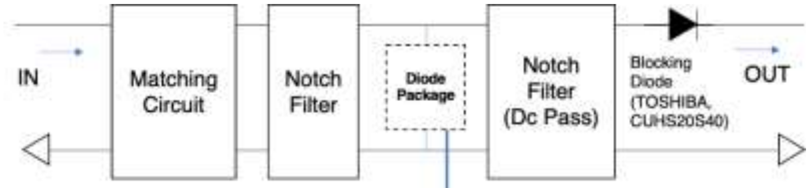
Tx Power(W)	85.3
Rx Power (W)	43.2
Port-to-Port Efficiency (%)	50.6
CV	0.15

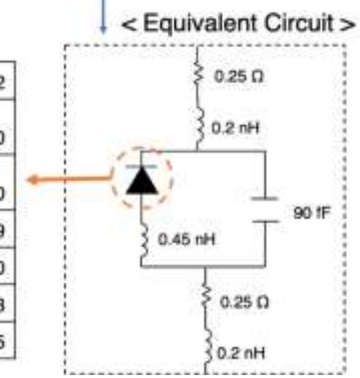
< Measurement >



Tx Power(W)	85.3
Rx Power(W)	27.3
Port-to-Port Efficiency (%)	32.0
CV	0.22

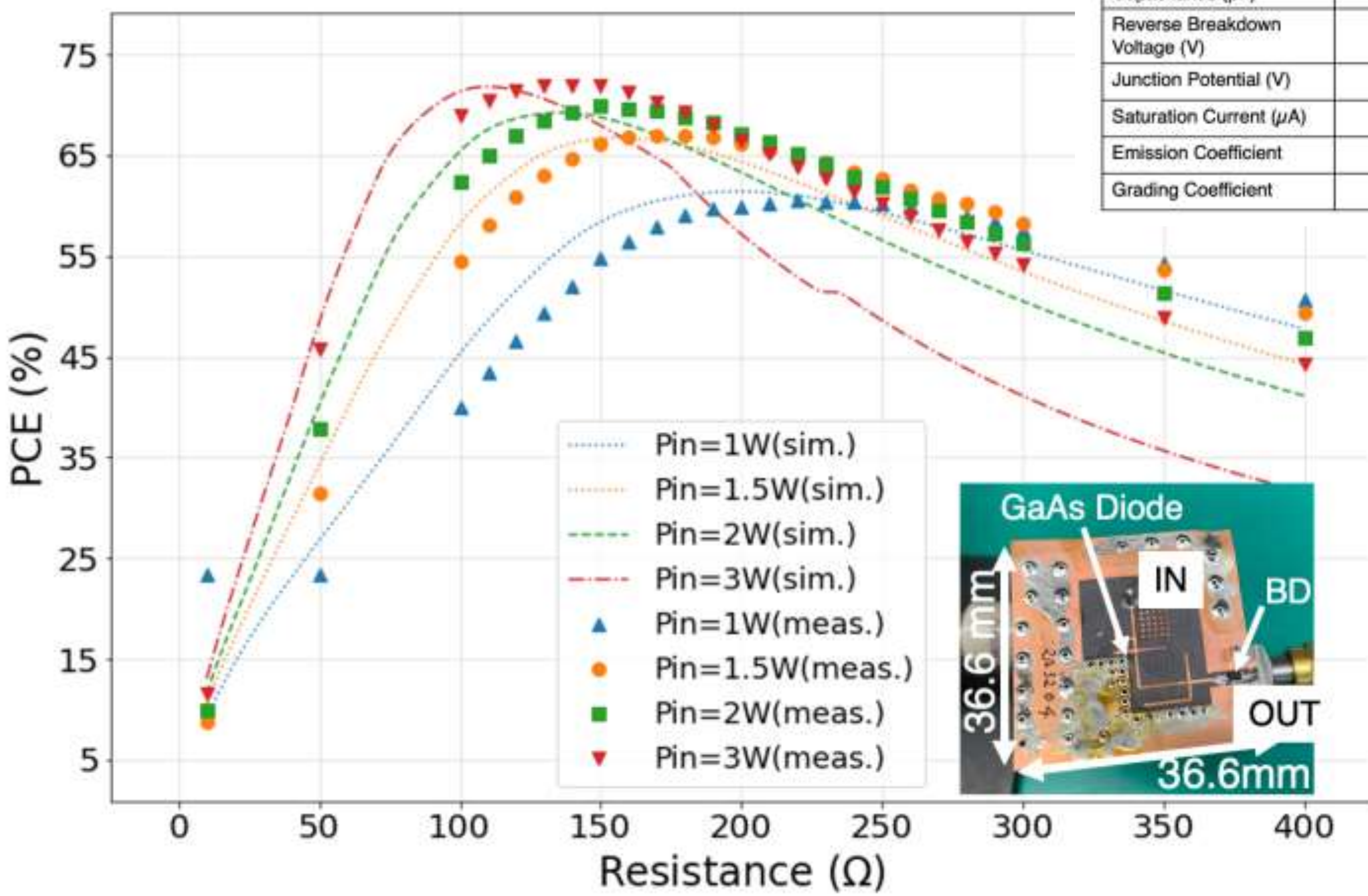
Developed Rectenna



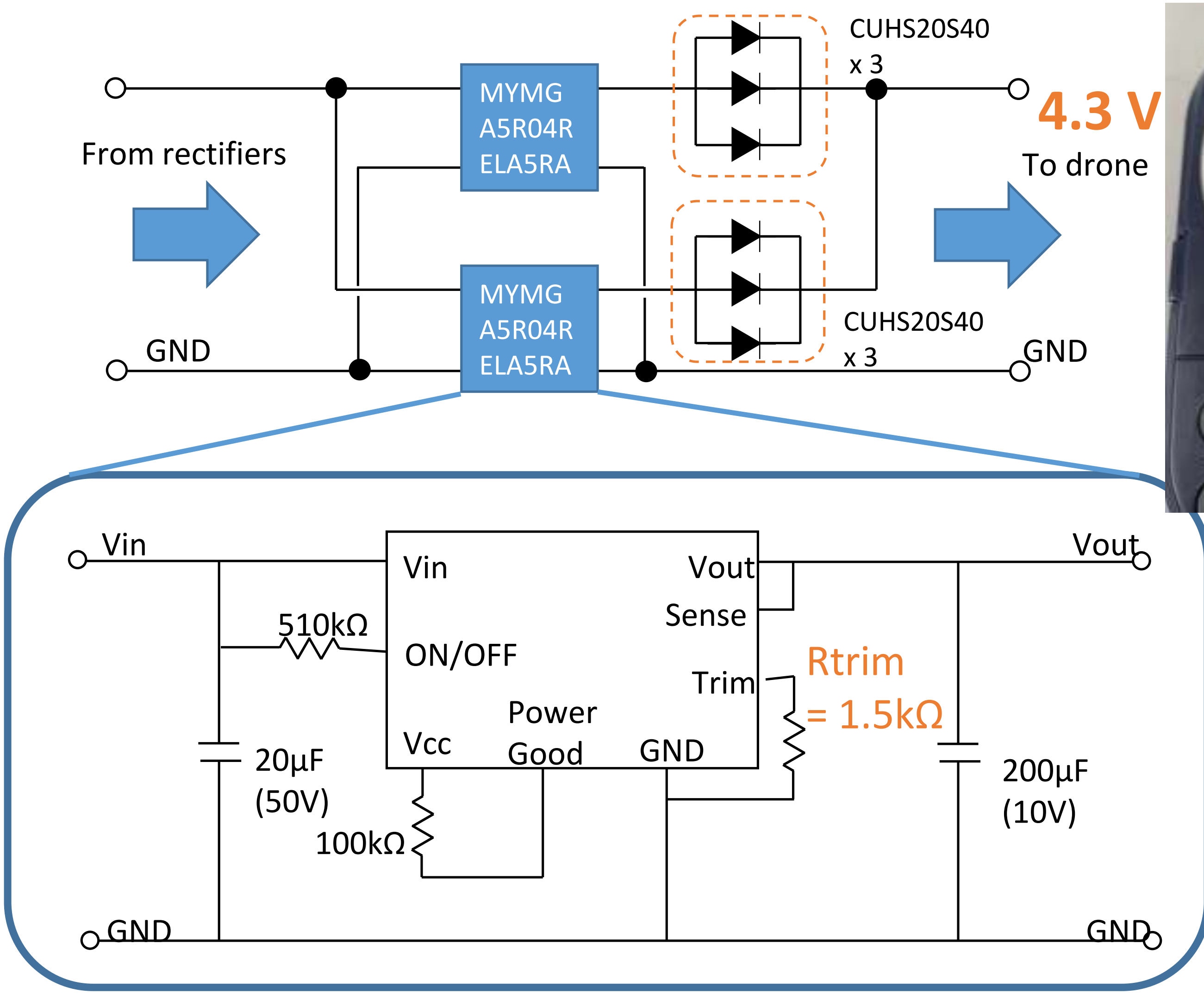


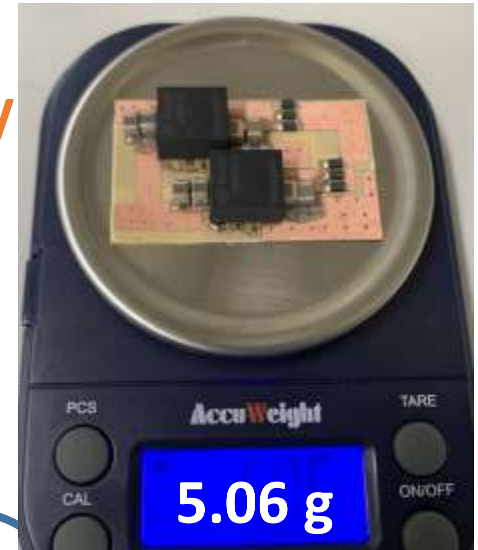
SPICE for GaAs SBD

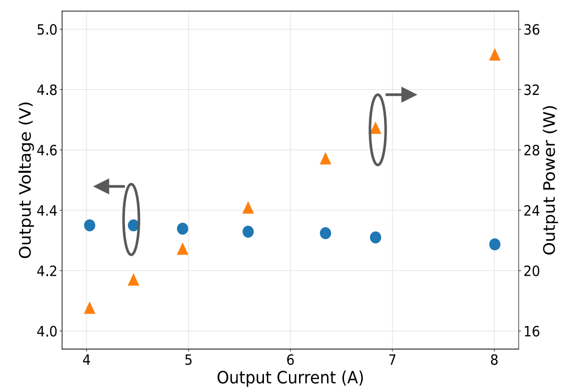
Ohmic Resistance (Ω)	0.82
Zero-bias Junction Capacitance (pF)	3.0
Reverse Breakdown Voltage (V)	60
Junction Potential (V)	0.9
Saturation Current (μA)	6.0
Emission Coefficient	1.63
Grading Coefficient	0.5



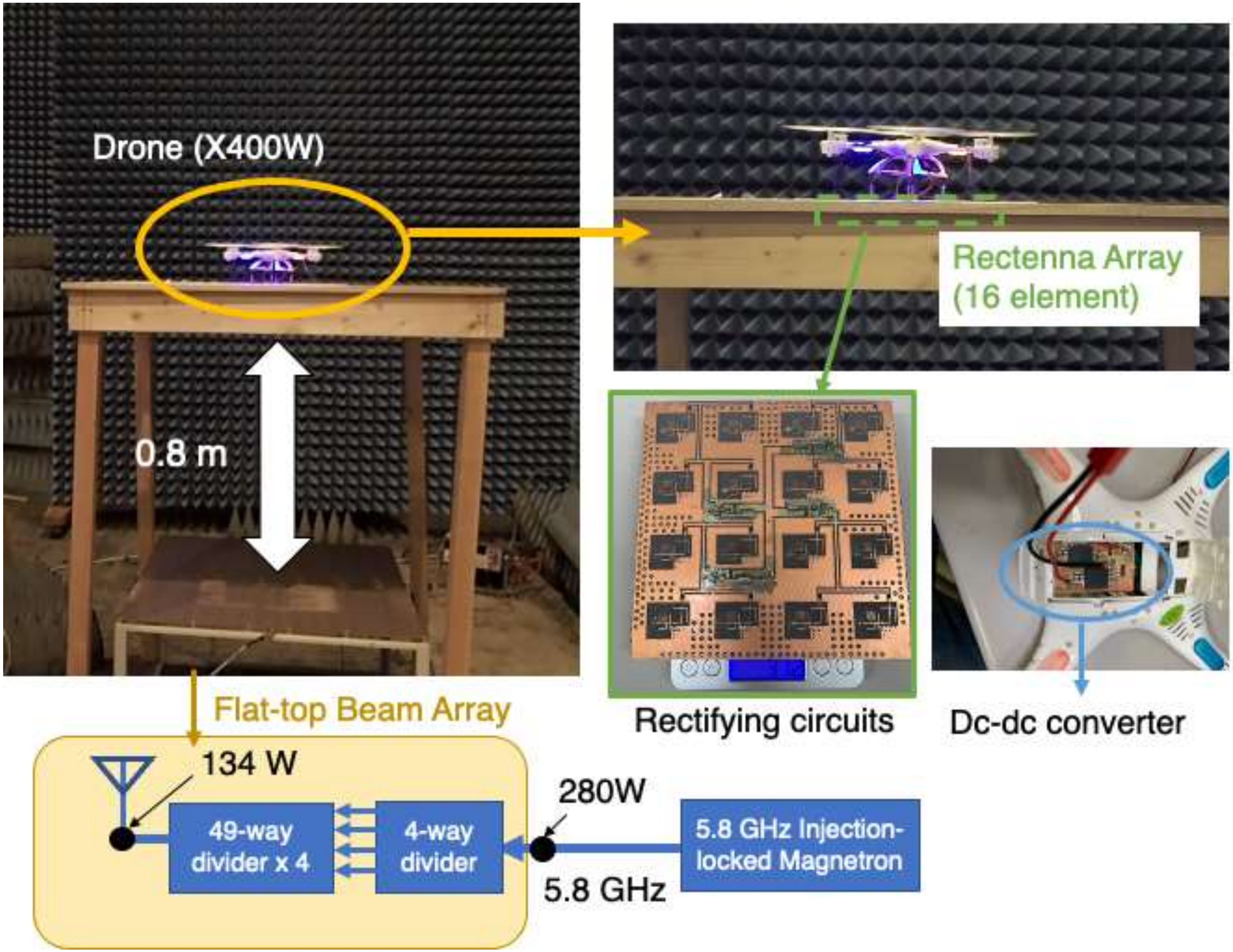
Developed DC/DC Converter



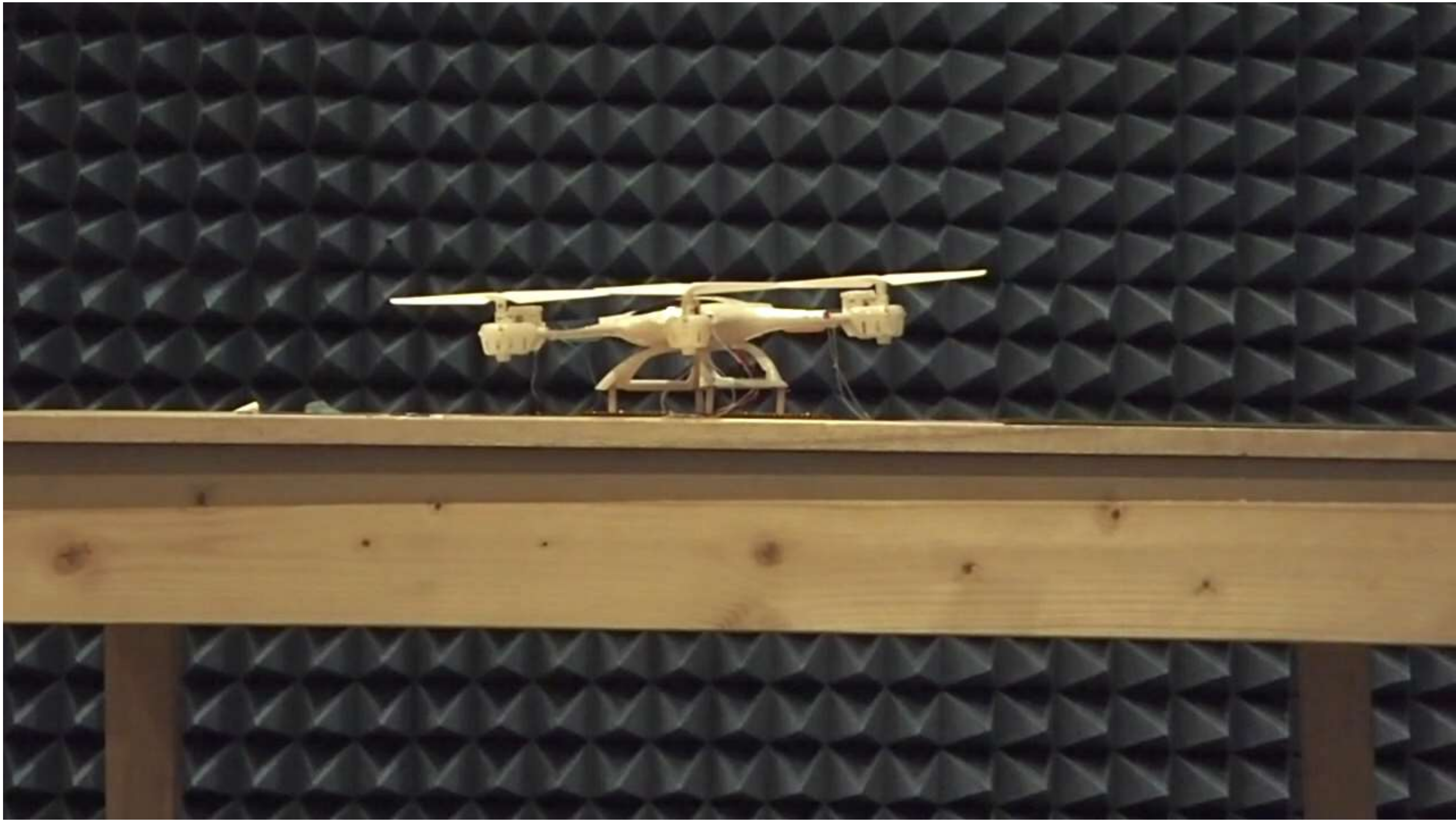




Flight Test (without Battery)



Flight Test (without Battery)



Minimum 7 min. flight by WPT is succeeded!!

Conclusions

Extension for Longer Distance WPT System

Frequency : 5.8GHz, Tx Power : 280W, Rectenna Size : Same

This Work (Tx = 70cm Square)

Antenna Elements	16 x 16
Beam Form	Flat Top
Gain (dBi)	24.9
HPBW in Far Field (deg)	11.0
Available Distance (m)	**0.76**

Antenna Elements	16 x 16
Beam Form	Normal (Uniform)
Gain (dBi)	33.1
HPBW in Far Field (deg)	3.8
Available Distance (m)	**2.21**

Extended System (Tx = 140cm Square)

Antenna Elements	32 x 32
Beam Form	Flat Top
Gain (dBi)	32.0
HPBW in Far Field (deg)	5.8
Available Distance (m)	**1.44**

Antenna Elements	32 x 32
Beam Form	Normal (Uniform)
Gain (dBi)	39.6
HPBW in Far Field (deg)	2.0
Available Distance (m)	**4.19**

HPBW : Half Power Beam Width

Perspective of Wireless Power Transfer in Next Decade

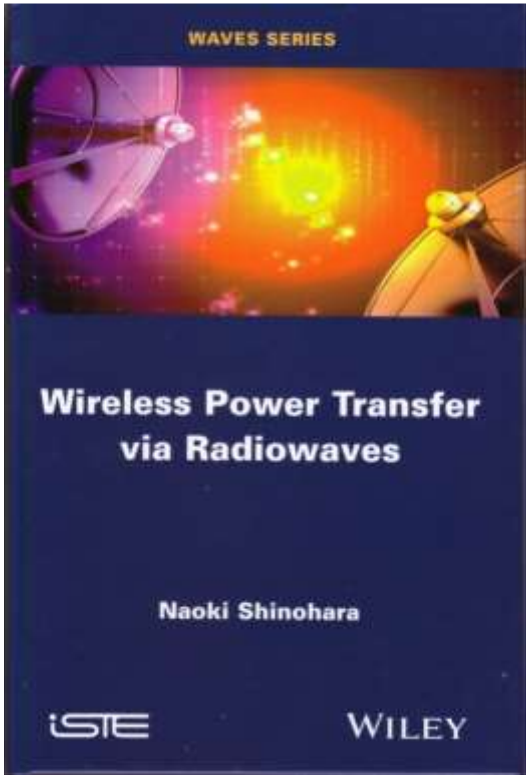
- - 2010 R&D period of WPT
- 2010 – 2020 Commercialization of Inductive WPT
- 2020 – Commercialization of Wide-Beam WPT via Microwaves (On-going)
- 2030 - Commercialization of Narrow-Beam WPT via Microwaves (Hopefully)
- 2040 – IoT and IoE Society (Our Dream1)
- 2050 - Power from Space (SPS) (Our Dream2)

Let's Join Our Dream!! : IoE and IoT Society

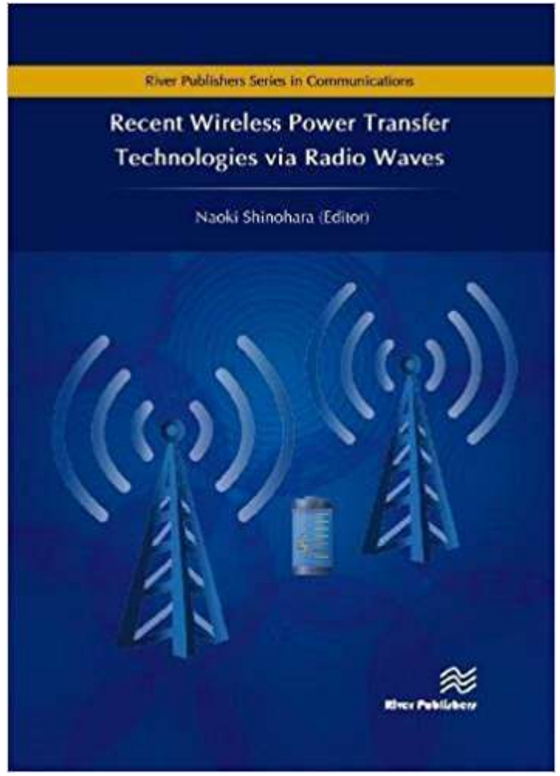
IoT : Internet-Of-Things, IoE : Internet-Of-Energy

"The best way to predict the future is to invent it."
(by Alan Kay)

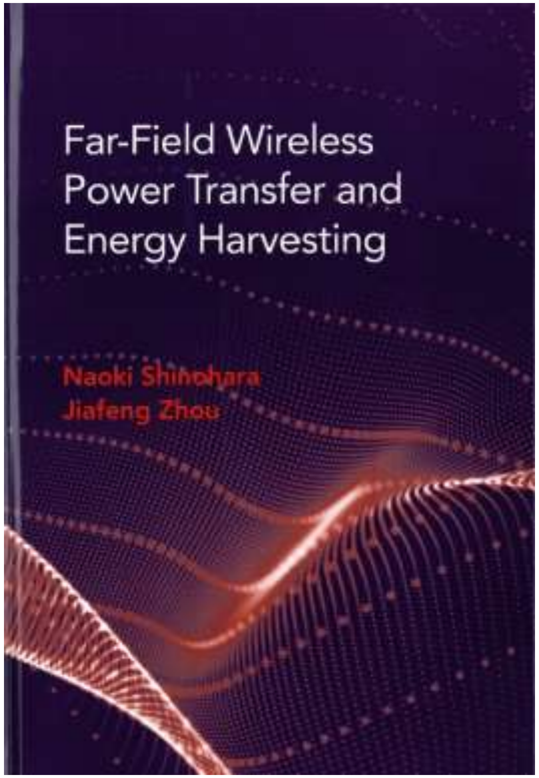
WPT Text Books



Wireless Power Transfer via Radiowaves (Wave Series)
Naoki Shinohara
ISTE Publishing &
John Wiley & Sons, Inc.,
UK & USA, 2014.1
ISBN 978-1-84821-605-1



Recent Wireless Power Transfer Technologies via Radio Waves
ed. Naoki Shinohara
River Publishers, EU, 2018.5
ISBN 978-879360-924-2



Far-Field Wireless Power Transfer and Energy Harvesting
ed. Naoki Shinohara
and Jiafeng Zhou,
Artech House, UK, 2022.8
ISBN 978-1630819125