Current Research and Development Activities of Wireless Power Transfer in Japan

Nov. 11, 2015

COST-WIPE

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Contents

Introduction of Kyoto University

Kyoto and Kyoto University

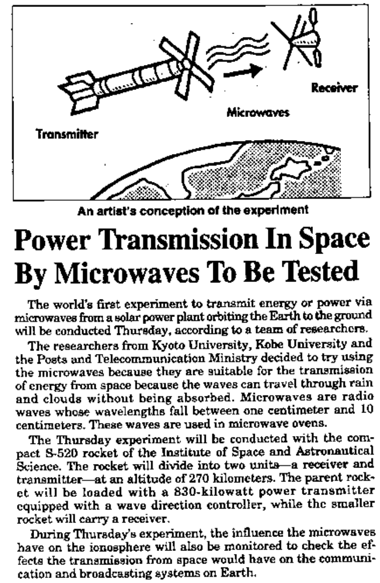
- Kyoto Univ. Data (2015) -
Professors : 1,032 (5,445 Employees)
Students : 13,569 (Under Graduate)
4,773 (Master), 3,671 (Ph.D)
Novel Prizes (Prof. Yamanaka, Prof. Yukawa,
Prof. Tomonaga, Prof. Tonegawa, Prof. Fukui..)

APMC2018 will be held at Kyoto.

Microwave Power Transfer Experiments at Kyoto Univ.

1983
First MPT Rocket Experiment
In the World - MINIX-

1992
MPT Experiment to
Fuel-free Airplane
- MILAX -



Power Transmission In Space By Microwaves To Be Tested

The world's first experiment to transmit energy or power via microwaves from a solar power plant orbiting the Earth to the ground will be conducted Thursday, according to a team of researchers.

The researchers from Kyoto University, Kobe University and the Posts and Telecommunication Ministry decided to try using the microwaves because they are suitable for the transmission of energy from space because the waves can travel through rain and clouds without being absorbed. Microwaves are radio waves whose wavelengths fall between one centimeter and 10 centimeters. These waves are used in microwave ovens.

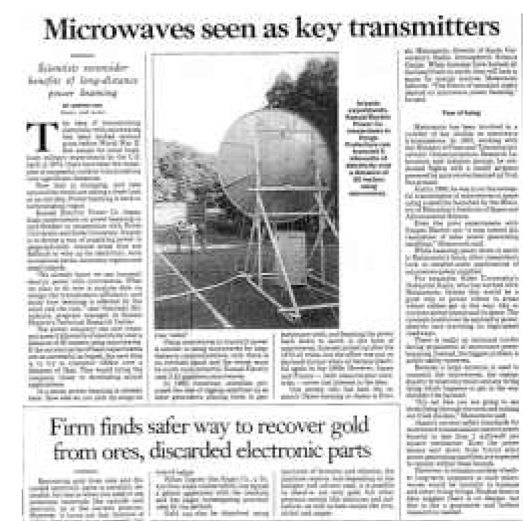
The Thursday experiment will be conducted with the compact S-520 rocket of the Institute of Space and Astronautical Science. The rocket will divide into two units—a receiver and transmitter—at an altitude of 270 kilometers. The parent rocket will be loaded with a 830-kilowatt power transmitter equipped with a wave direction controller, while the smaller rocket will carry a receiver.

During Thursday's experiment, the influence the microwaves have on the ionosphere will also be monitored to check the effects the transmission from space would have on the communication and broadcasting systems on Earth.

1993
Second MPT Rocket
Experiment
- ISY-METS -

1996
Retrodirective
MPT System
Open Experiment

2001
Solar Power
Radio Integrated
Transmitter
- SPRITZ -



1994-95
Ground-to-Ground
MPT Experiment

2009
Airship-to-Ground
MPT Experiment

Advanced Microwave Energy Transmission Laboratory A-METLAB (Inter-university Collaborative Facility)

Collaborative Research Facility
METLAB&SPSLAB

+

Anechoic Chamber
18m(L) x 17m(W) x 7.3m(H)
1) Plane-Polar Near Field Scanner for 10mϕ, 10t, 10kW Phased Array
2) High Power Absorber (>1W/cm^2)
3) Clean Room (Class 100,000)

Measurement Room

Preparation Room

New Collaborative Research Facility

A-METLAB

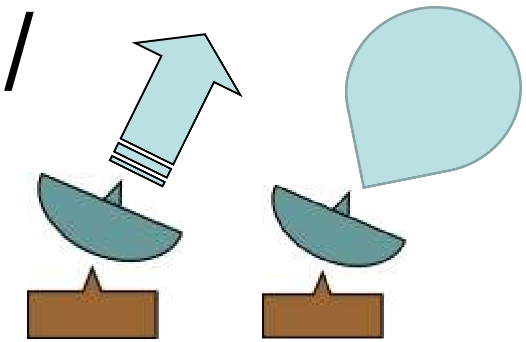
Building 34.0m(L)x21.0m(W)x9.97m(H)
Area 714.00㎡
Total Floor Area 824.72㎡

Research Facility for Satellite Phased Array

Wireless Power Transfer Consortium for Practical Application (WiPoT)

http://www.wipot.jp/

info@wipot.jp



General Chair :

Naoki Shinohara (Kyoto University)

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- **Company members : 30 (Corporation in Japan)**
  University members : 38
  Institute members : 3
- **Established on April 1, 2013**
- **Member fee : 250,000 yen / year (company), free (university)**

WiPoT

WiPoT Activities

- 5 Working Groups
  - WG1 : **Wide Beam and Low power**,
    WG2 : **Narrow Beam and High Power**,
    WG3 : **WPT in Pipe**, WG4 : **Market Research**,
    WG5 : **Standardization**
- Symposiums
  - 2013 Invited Speaker : **Prof. Zoya Popovic**, Univ. of Colorado
  - 2014 Invited Speaker : **Dr.Charlie Greene**, PowerCAST Corp.
  - 2015 Invited Speaker : **Dr. Hatem Zeine**, CEO of Ossia Corp.


Overview of Wireless Power Transfer

Utilization of Radio Waves

- Information, Broadcast :

  Information added (modulated) on carrier (radio waves) (Information from transmitter)

- Radar (Remote Sensing) :

  Information (amplitude, phase, etc.) reflected from target on carrier (Information from target)

- Heating :

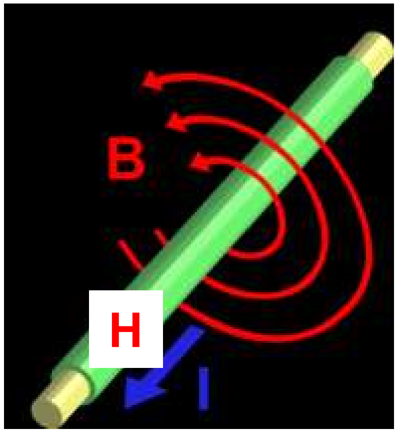
  Energy conversion from radio waves to heat

- Power Transfer :

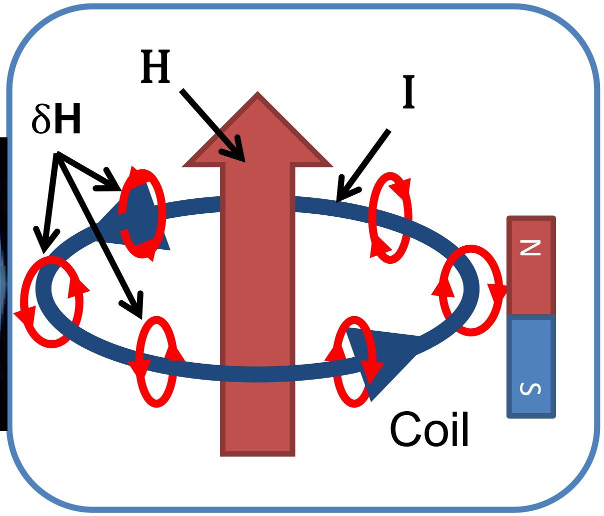
  Energy conversion from radio waves to electricity

WPT Theory

Ampere's law :

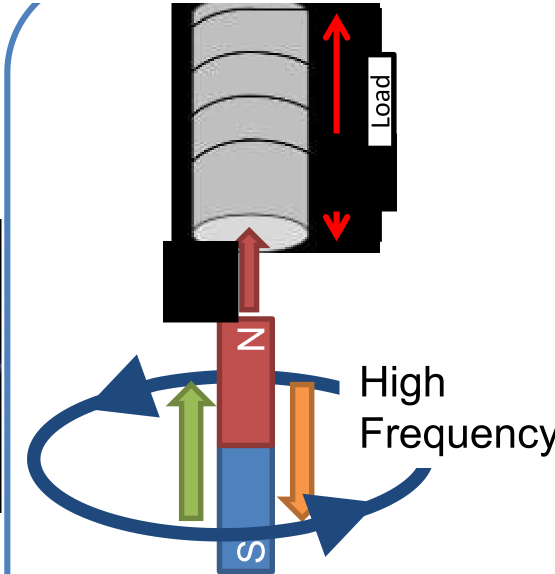


[redacted]



Electromagnet

Inductive Coupling WPT



Faraday's law :

[redacted]

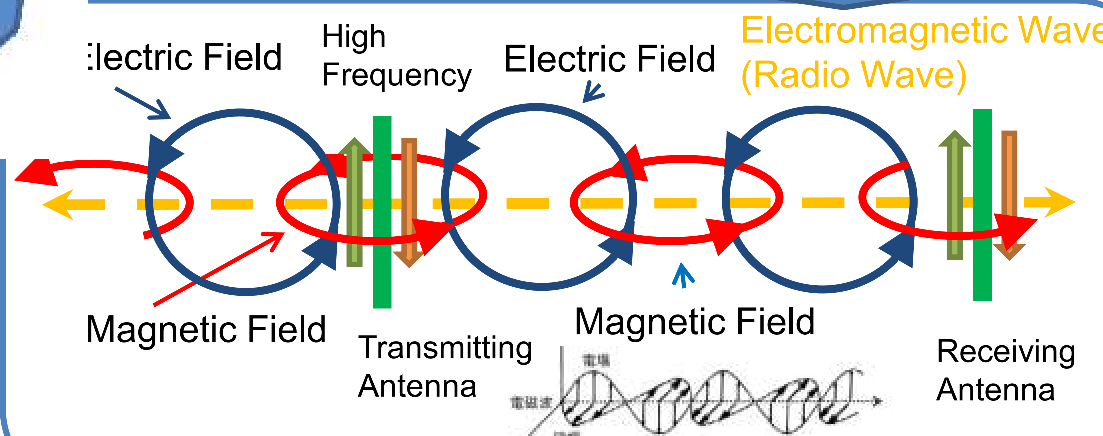
WPT via Radio Waves

$$\vec{S} = \vec{E} \times \vec{H}$$
$$(W / m^2)$$

Radio Wave Itself Is Energy.

What we need Is frequency conversion only.

$$rot\vec{H} = \vec{J} + \frac{\partial \vec{D}}{\partial t}$$
$$rot\vec{E} = -\frac{\partial \vec{B}}{\partial t}$$
$$div\vec{D} = \rho$$
$$div\vec{B} = 0$$

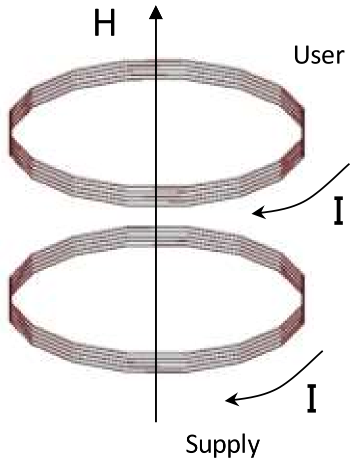


Maxwell's Equations

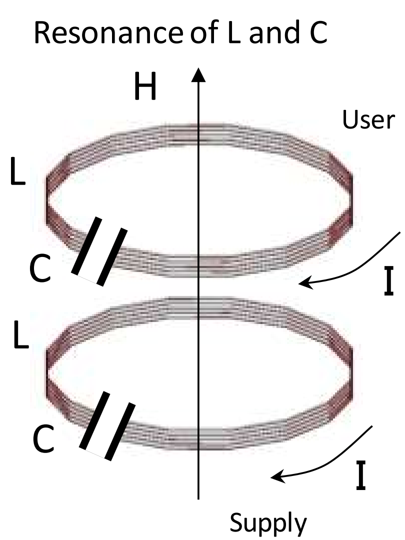
Raidowave Power (Electric Power)

Various Wireless Power Transfer

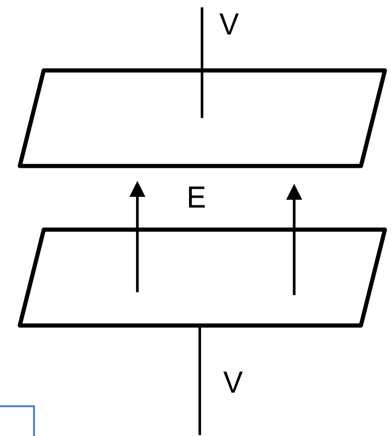
Inductive Coupling



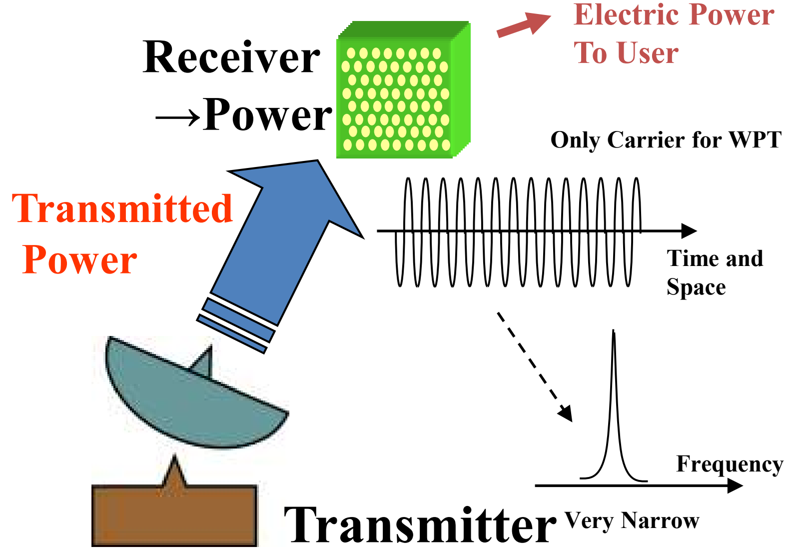
(Magnetic) Resonance Coupling



Conductive Coupling



Radio Waves (Microwaves)

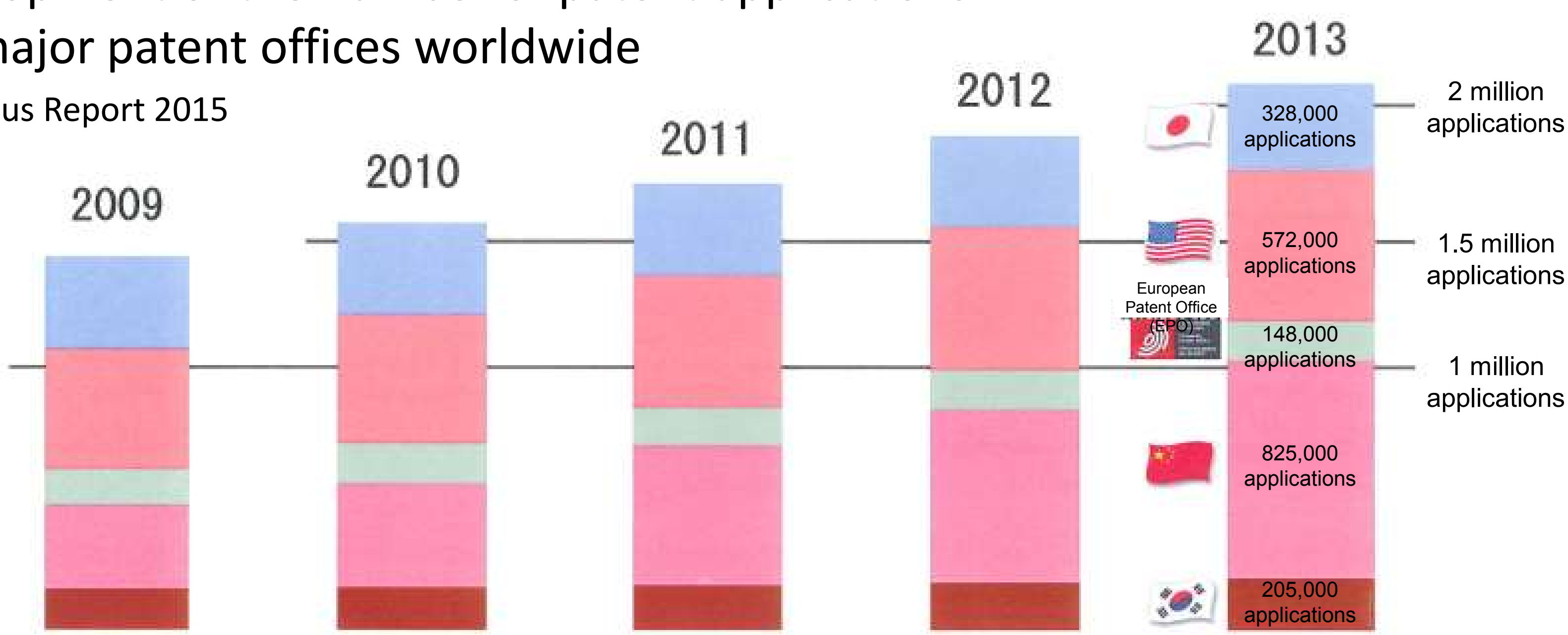


On Patent Application Technical Trends Surveys in 2014: How patent information can be effectively utilized

- More than two million patent applications were filed worldwide in 2013.
- Patent information is a value source publicly released from R&D activities.
- R&D trends and directions in different countries and regions can be surmised from the information.

Development of the number of patent applications in five major patent offices worldwide

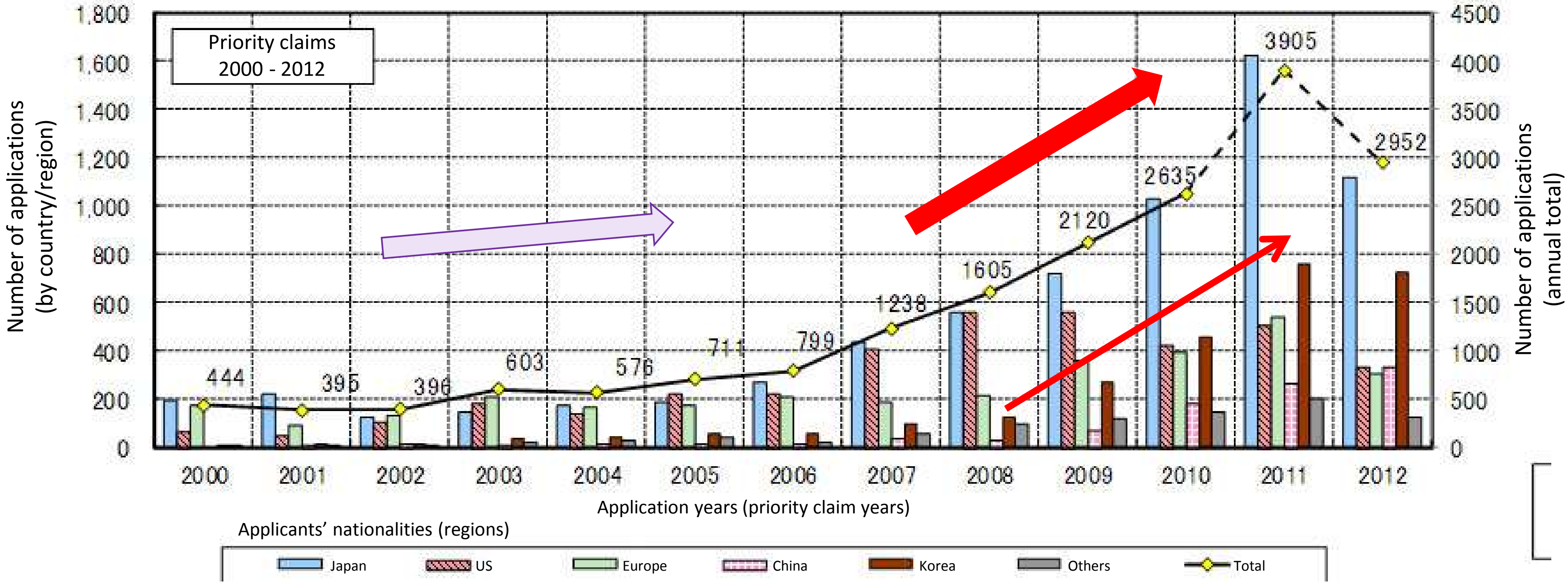
JPO Status Report 2015



Technical Trends in Wireless Power Transfer Systems: An overview of patent applications

Nationalities of applicants

Fig. 4-2-5: Development of applications by applicants of different nationalities, and application ratios



Note: In 2011 or any subsequent years, the figures may not reflect all data due to database collection delays and certain delayed cases based on PCT, etc.; the same shall apply to the graphs below.

Patent Application Trends in Companies

Number of applications by specific applicants

- Panasonic (943, 1st), Samsung Electronics (807, 2nd), Qualcomm (715, 3rd), Toyota Motor Corp. (611, 4th)
- As WiTricity made 254 applications (11th) and KAIST made 239 applications (12th), overseas ventures and research institutes are quite active in this field.

Table 4-4-1: Top-ranking applicants in terms of number of applications

Application years (priority claim years): 1995 - 2012

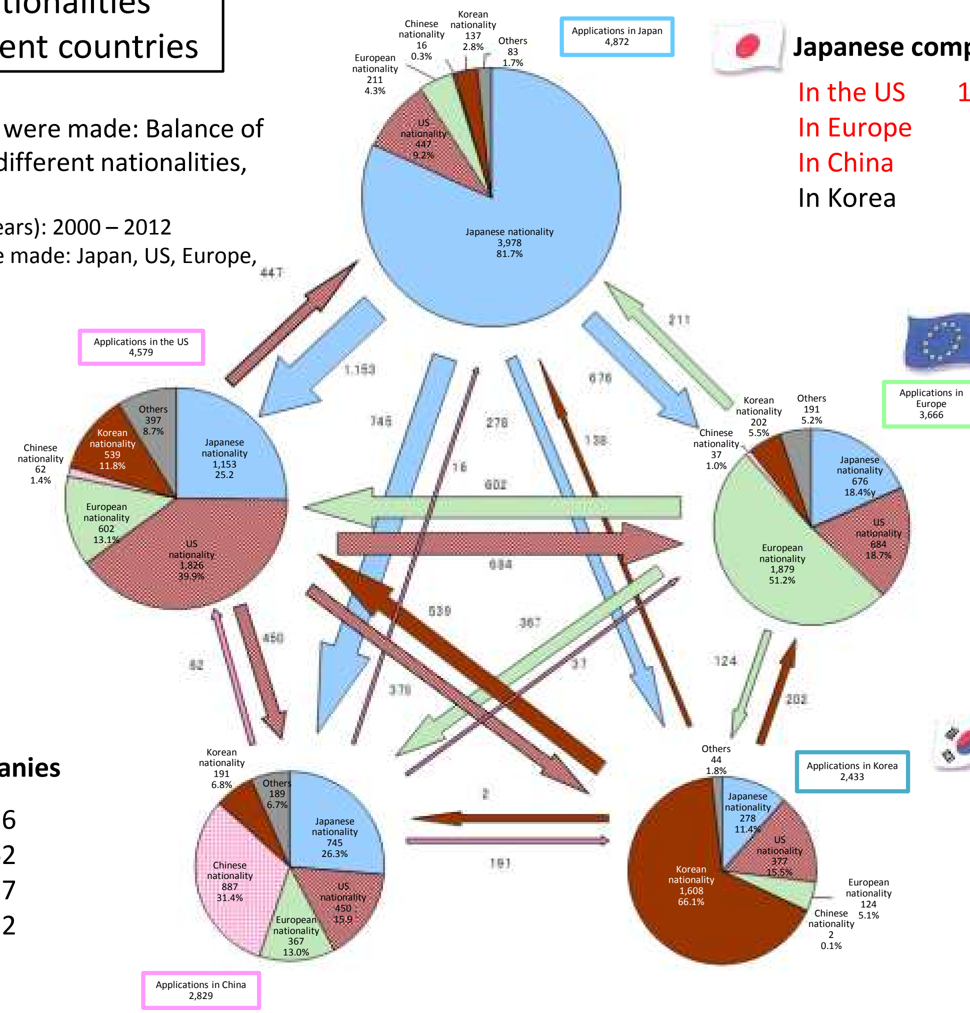
Countries where applications were made: Japan, US, Europe, China, Korea

Rank	Applicant	No. of applications
1	Panasonic Corp.	943
2	Samsung Electronics (Korea)	807
3	Qualcomm (US)	715
4	Toyota Motor Corp.	611
5	Access Business Group (US)	503
6	Sony Corp.	437
7	Toyota Industries Corp.	360
8	Seiko Epson Corp.	345
9	Philips (the Netherlands)	337
10	SEW-Eurodrive (Germany)	266
11	WiTricity Corp. (US)	254
12	Korea ADV INST SCI & Technology (Korea)	239
13	LG Innotek Co., Ltd. (Korea)	234
14	Siemens (Germany)	229
15	Toshiba Corp.	216
16	Robert Bosch GmbH (Germany)	210
17	Semiconductor Energy Laboratory Co., Ltd.	191
18	BAARMAN D W (US)	181
19	SANYO Electric Co., Ltd.	179
20	Philips Intellectual Property GMBH (Germany)	178

Technical Trends in Wireless Power Transfer Systems: An overview of patent applications

Applicants of different nationalities making applications in different countries

Fig. 4-2-9: Countries where applications were made: Balance of applications by applicants of different nationalities, made in different countries
Application years (priority claim years): 2000 – 2012
Countries where applications were made: Japan, US, Europe, China, Korea



Japanese companies

In the US	1,153
In Europe	676
In China	745
In Korea	278

European companies

In Japan	211
In the US	602
In China	367
In Korea	124

US companies

In Japan	447
In Europe	684
In China	450
In Korea	378

Chinese companies

In Japan	16
In the US	62
In Europe	37
In Korea	2

Korean companies

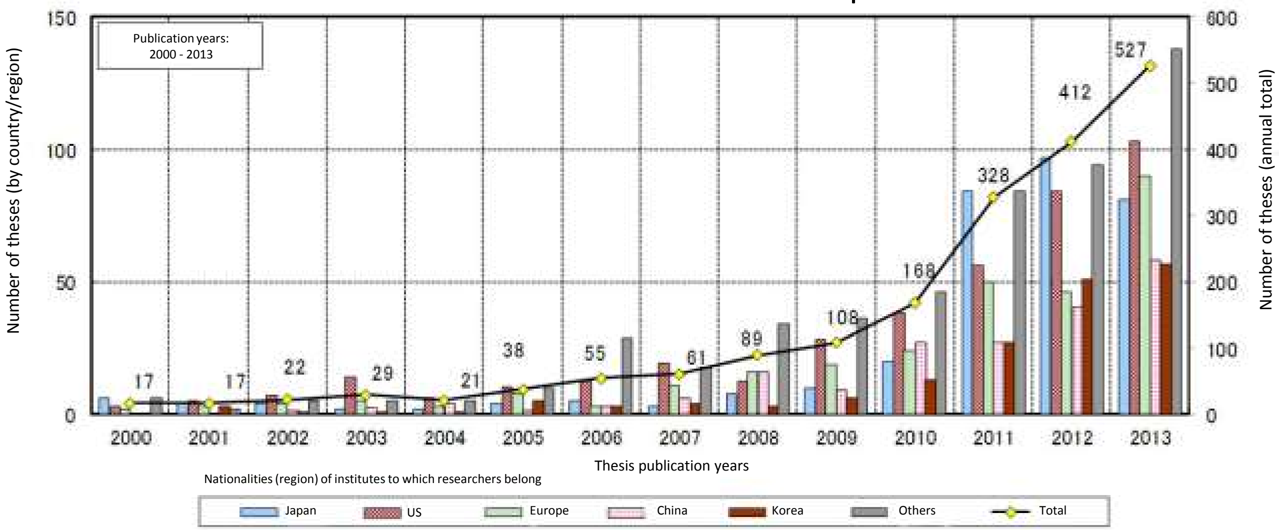
In Japan	138
In the US	539
In Europe	202
In China	191

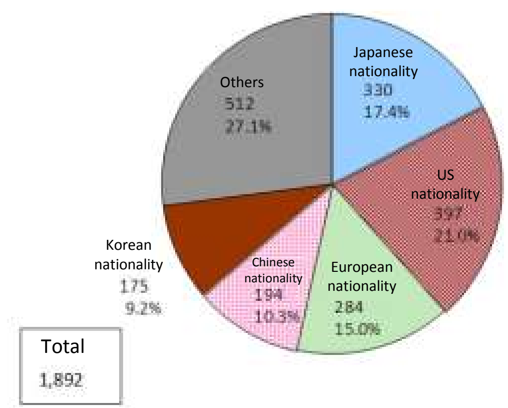
Technical Trends in Wireless Power Transfer Systems (Papers)

Number of published theses

- The number of published theses on wireless power transfer systems started to be on the rise in 2006, and has jumped since 2010.
- Theses issued by Japanese universities and research institutes, etc. amounted to 330 (17%), US theses were 397 (21%), European theses were 274 (15%), Chinese accounted for 10%, and Koreans accounted for 9%.
- The greatest thesis publication category was "others," that is, universities and research institutes other than those in Japan, US, Europe, China, and Korea (512, 27%).

Fig. 5-2-1: Development of theses released from researches of institutes in different nationalities and thesis publication ratios





Technical Trends in Wireless Power Transfer Systems (Papers)

Number of theses published by individual researchers

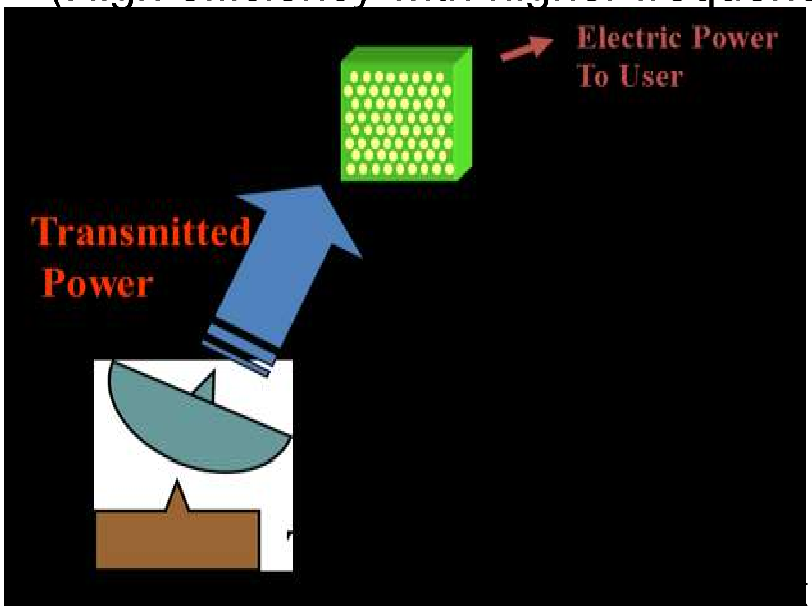
- A total of 230 theses were issued by five researchers including Covic, Hu, and Boys of the University of Auckland (New Zealand).
- Many theses have been issued by Japanese researchers, including Shinohara, Awai, Hori, and Imura, etc. Research activities in Japan are also quite active.

Table 5-4-5: Top-ranking researchers in terms of numbers of theses issued Thesis publication years: 2000 - 2013

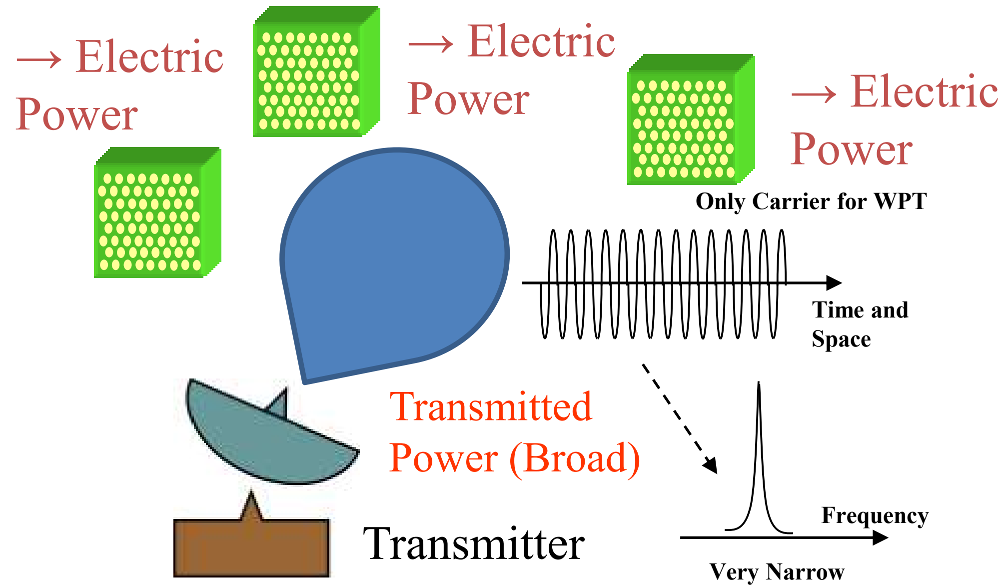
Rank	Researcher	Affiliation	No. of theses
1	Covic, G.A	University of Auckland (New Zealand)	65
2	Hu, A.P	University of Auckland (New Zealand)	47
3	Boys, J.T	University of Auckland (New Zealand)	46
4	Madawala, U	University of Auckland (New Zealand)	38
5	Thrimawithana, D	University of Auckland (New Zealand)	34
6	Naoki Shinohara	Kyoto University	32
7	Fu, W.N	Hong Kong Polytech Univ (Hong Kong)	24
8	Ghovanloo, M	Georgia Institute of Technology (US)	22
8	Ho, S.L	Hong Kong Polytech Univ (Hong Kong)	22
10	Ikuo Awai	Ryutech	19
11	Yoichi Hori	University of Tokyo	18
11	Takehiro Imura	University of Tokyo	18
11	Georgakopoulos, S.V	Florida Institute of Technology (US)	18
14	Mingui Sun	Hong Kong Polytech Univ (Hong Kong)	17
15	Joungho Kim	KAIST (Korea)	16
16	Hidetoshi Matsuki	Tohoku University	15
16	Fumihiro Sato	Tohoku University	15
16	Georgiadis, A	Ctr Tecnol Telecomunicac Catalunya (China)	15
16	Jonah, O	Florida Institute of Technology (US)	15
16	Mongiardo, M	Perugia Univ (Italy)	15
21	Collado, A	CTTC (Spain)	14
21	Dionigi, M	Perugia Univ (Italy)	14
21	Ishizaki, T	Georgia Institute of Technology (US)	14
24	Nobuyoshi Kikuma	Nagoya Institute of Technology	13
24	Hiroshi Hirayama	Nagoya Institute of Technology	13

Various Wireless Power Transfer via Radio Waves

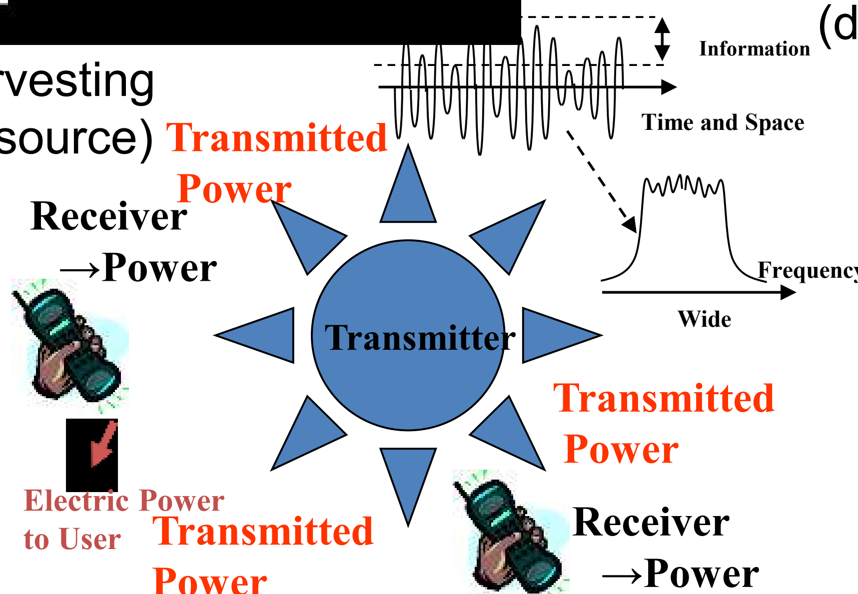
(a) Beam-type
(High efficiency with higher frequency)



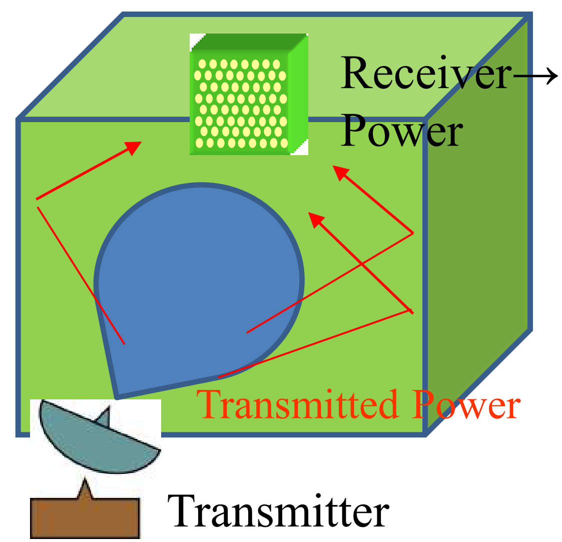
(b)Ubiquitous-type (Low efficiency, like RF-ID)



(c) Energy Harvesting
(No power source)



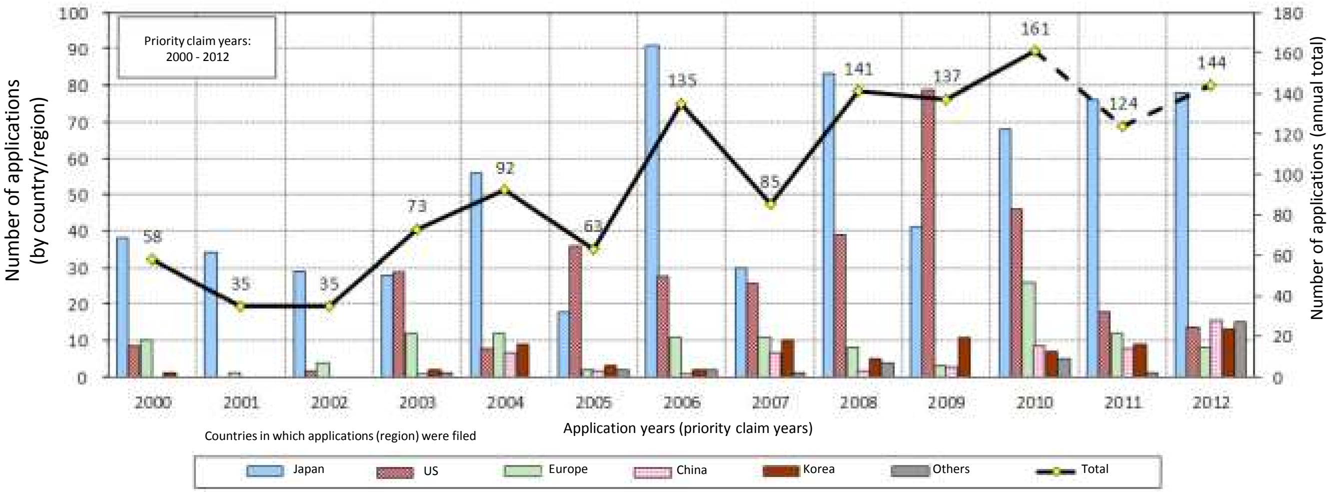
(d) In Closed Area (like Waveguide)

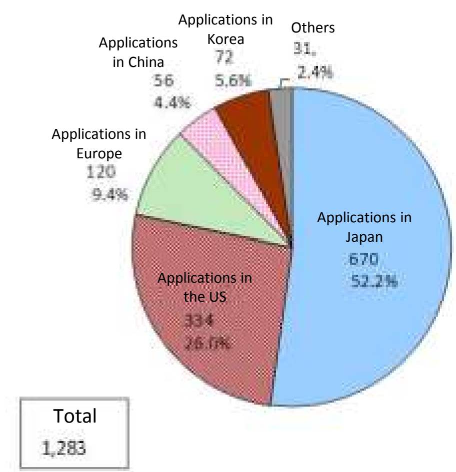


Technical Trends in Wireless Power Transfer Systems

Microwave system

Fig. 4-3-34: Microwave system - development of number of applications and application ratios





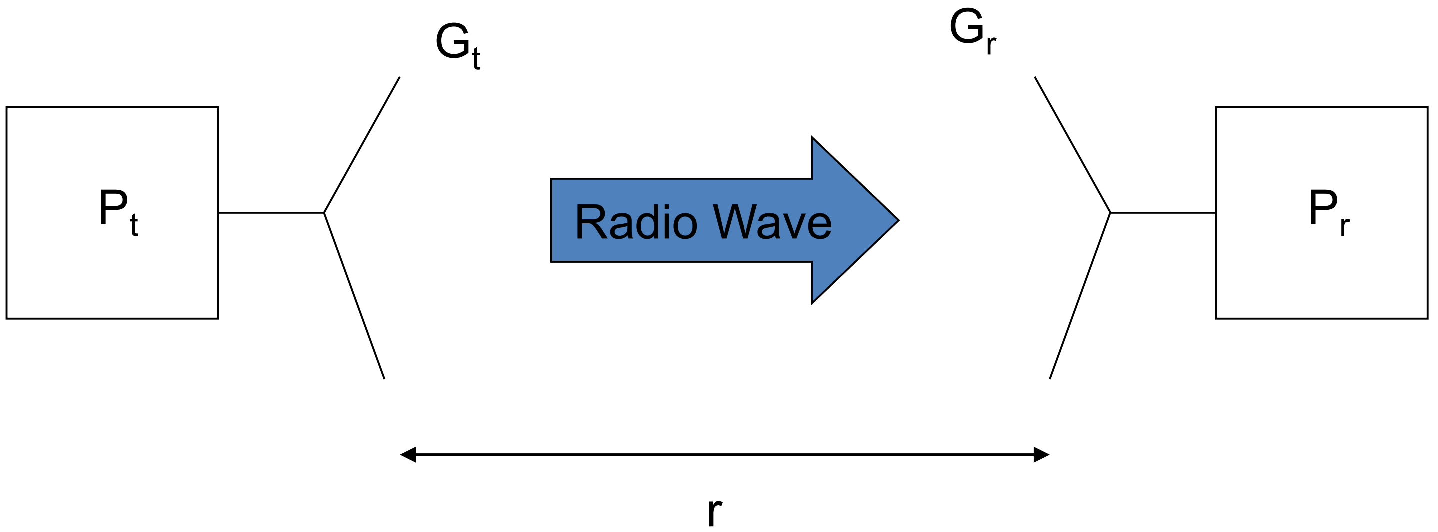
Technologies of Wireless Power Transfer via Radio Waves

Power Propagation Theory of Radiowave
- Friis' Transmission Formula -

Friis' Transmission Formula

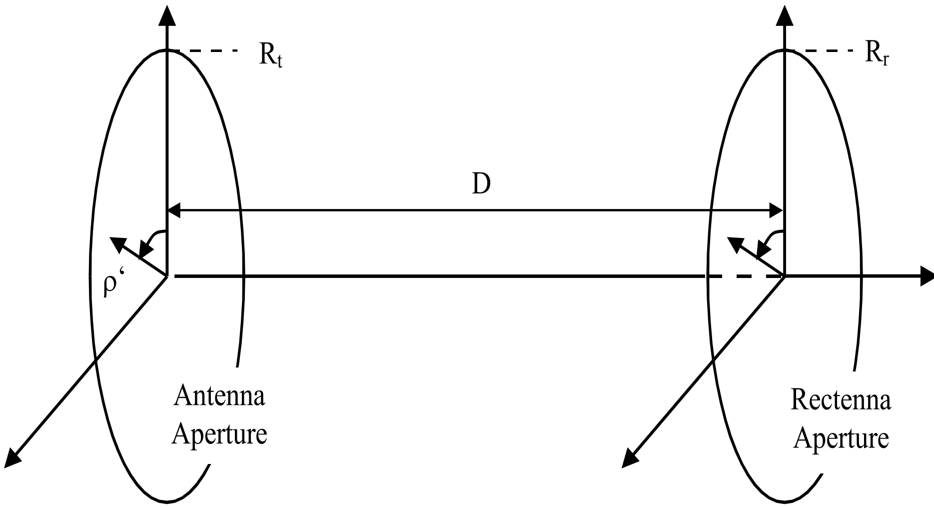
$$P_r = G_t G_r P_t (\lambda / 4\pi r)^2$$

P_t : Tranmitted Power, P_r : Received Power
G_t : Transmitting Antenna Gain, G_r : Receiving Antenna Gain
λ: Wave Length, r : distance



Formula of Efficiency of Wireless Power Transfer via Radiowaves

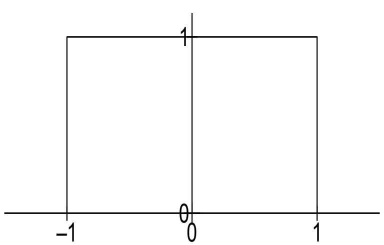
τ parameter



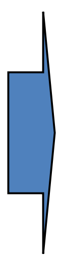
Fraunhofer's Diffraction ($|\boldsymbol{r_0}|, |\boldsymbol{r}| << D$)

$$g(\boldsymbol{r}) = \frac{\exp(jkD)}{D} \exp\left(\frac{jk}{2D}\right) \iint f(\boldsymbol{r_0}) \exp\left\{-\frac{jk}{D}(ux+vy)\right\} d\boldsymbol{r_0}$$

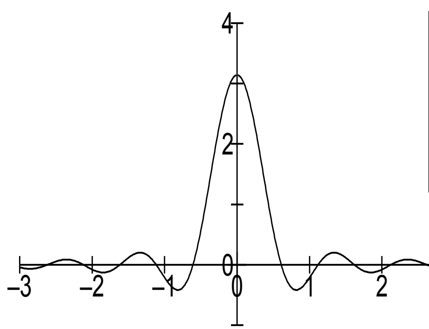
Electric Field on Antenna



Radius

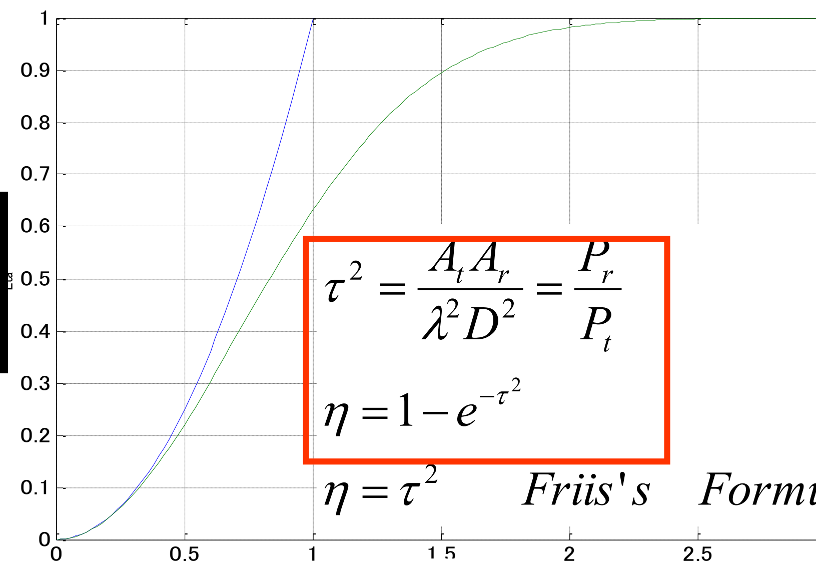


Electric Field in Field



Radius

τ parameter and beam collection efficiency



$$\tau^2 = \frac{A_t A_r}{\lambda^2 D^2} = \frac{P_r}{P_t}$$

$$\eta = 1 - e^{-\tau^2}$$

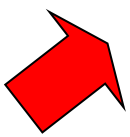
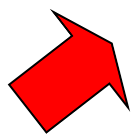
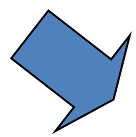
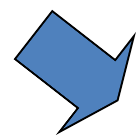
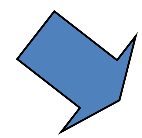
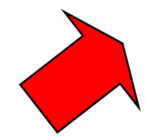
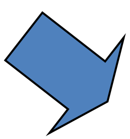
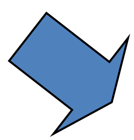
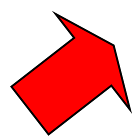
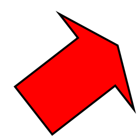
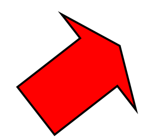
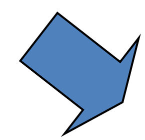
$$\eta = \tau^2 \quad Friis's \quad Formula$$

τ

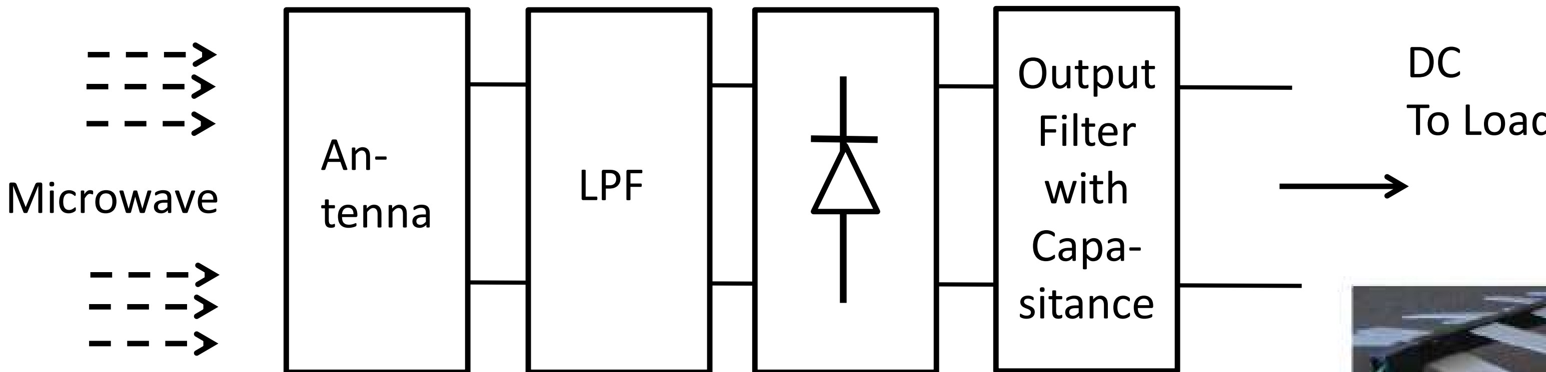
D:distance, $A_{t,r}$: effective area of Tx, Rx antenna

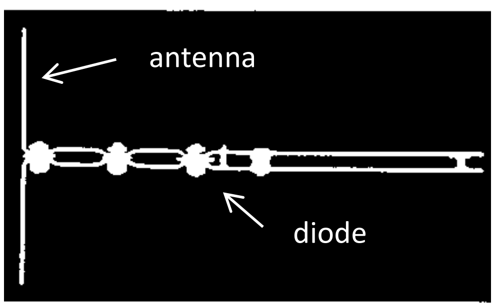
•W. C. Brown, The history of power transmission by radio waves, IEEE Trans. Microwave Theory and Techniques, MTT-32, pp.1230-1242, 1984.

Higher Frequency or Lower Frequency?

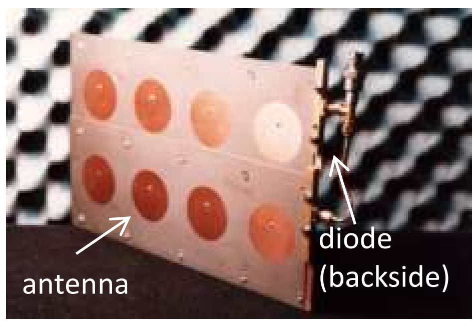
Frequency for WPT via Radio Wave	Beam Efficiency (if same antenna)	Antenna Size (if same efficiency)	Circuit Efficiency	Power	Loss in Atmosphere
					
					
Which is better?	Higher Frequency	Higher Frequency	Lower Frequency	Lower Freque ncy	Lower Frequency

Rectenna – Rectifying Antenna – Radio wave -> DC Power Converter

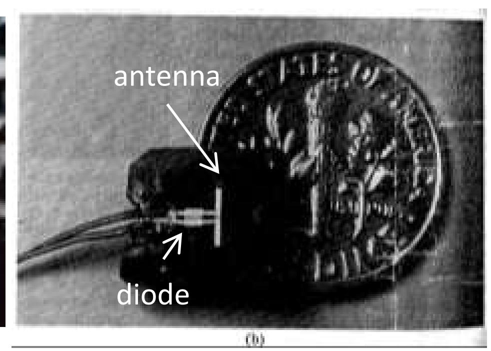




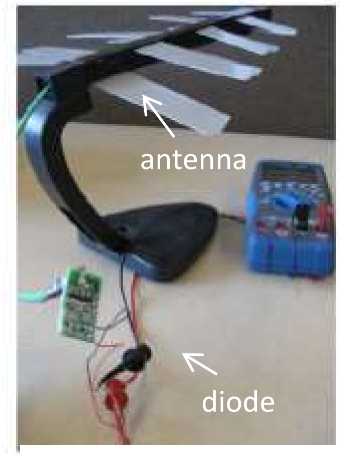
Brown&JPL Rectenna
(2.45GHz) 1970-75



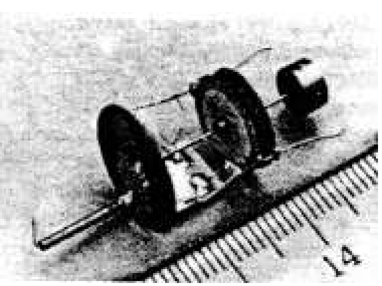
Rectenna by Hokkaido Univ.
(2.45GHz) 1984



Rectenna byTexas A&M Univ.
(35GHz) 1992

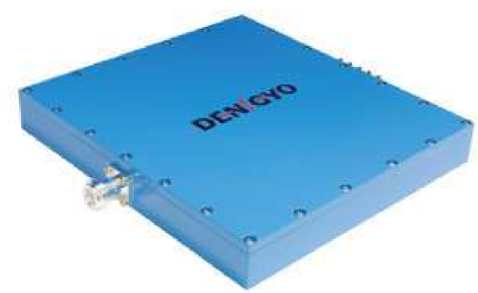


Rectenna by Intel co.
(674 - 680 MHz) 2009



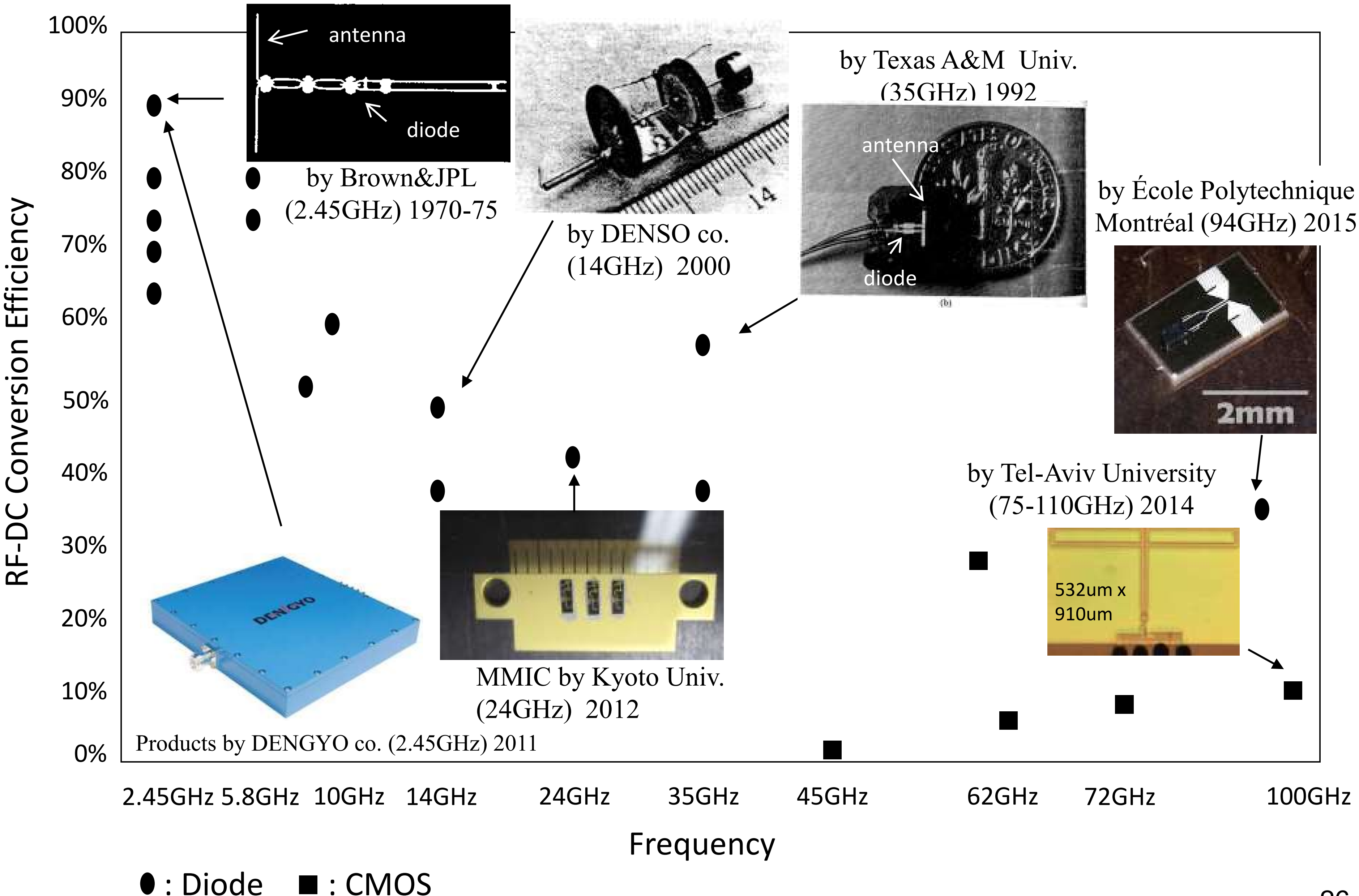
Rectenna
by Kyoto Univ.
(5.8GHz) 2001

Rectenna
byDENSO co.
(21GHz) 1997

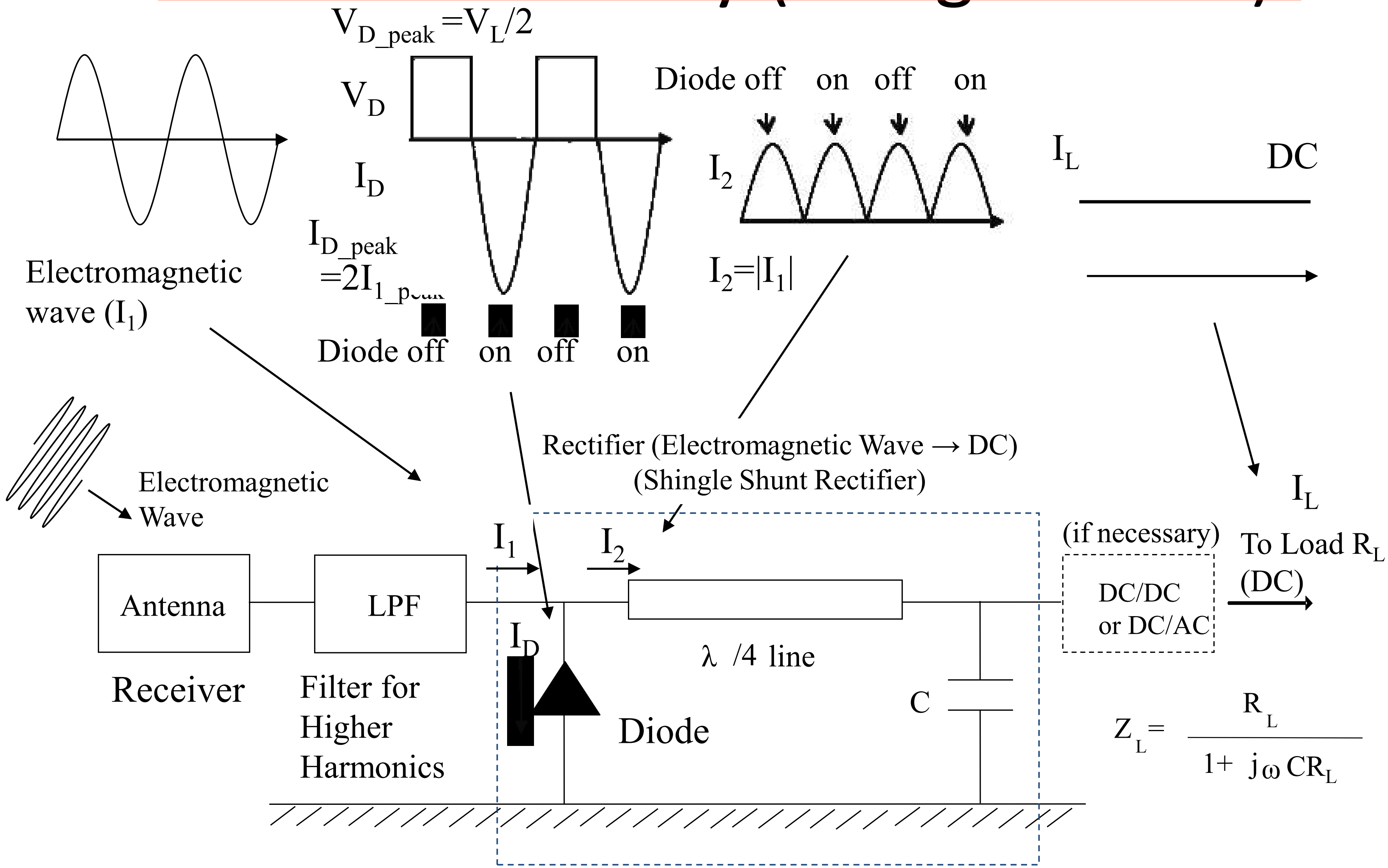


Commercial Rectenna by DENGYO co. (2.45GHz) 2011

Frequency Characteristics of Efficiency of Rectenna

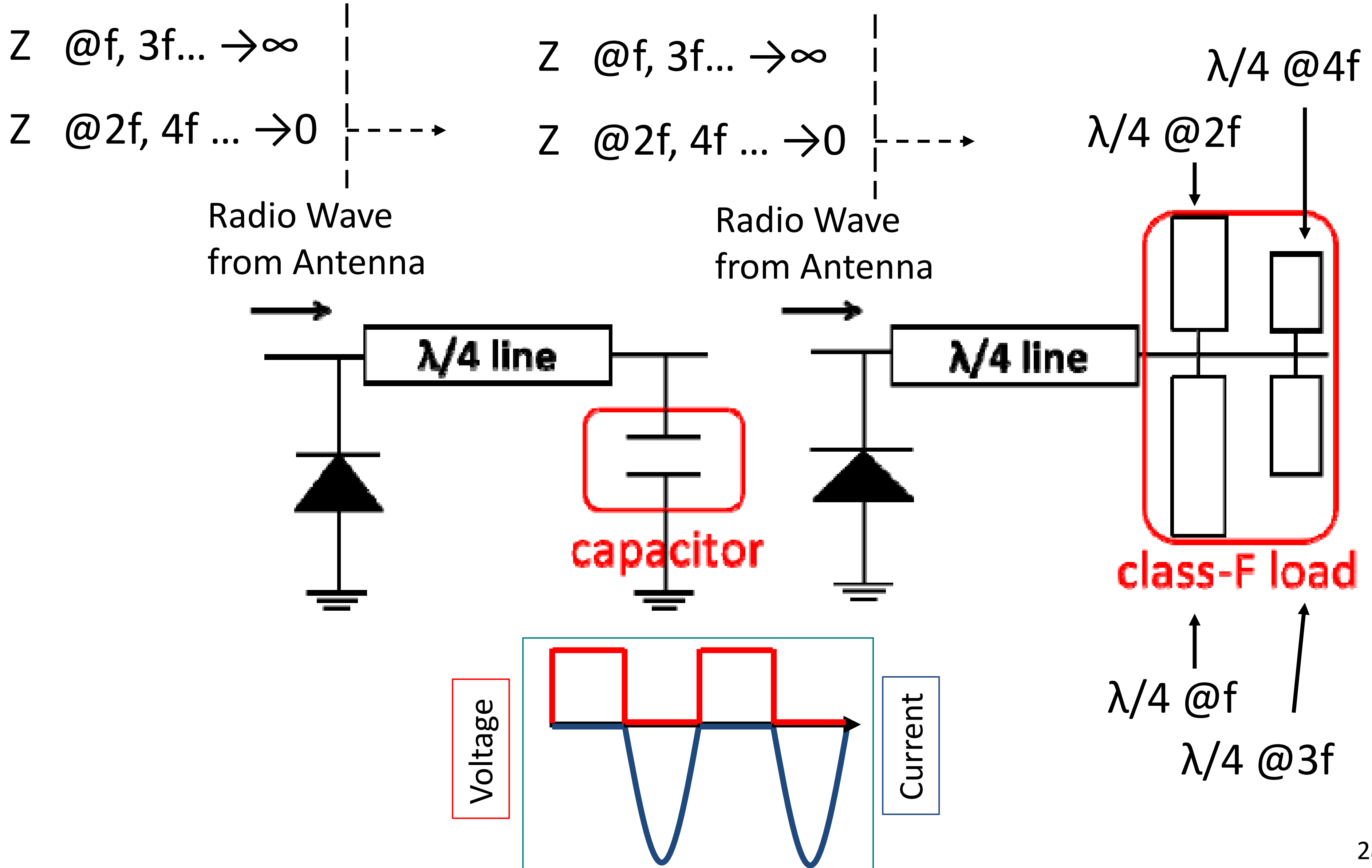


Rectenna Theory (Shingle Shunt)



$$Z = \frac{Z_L + jZ_0\tan(\beta\ \lambda\ /4)}{Z_0 + jZ_L\tan(\beta\ \lambda\ /4)} \quad Z_0 = \begin{cases} \dfrac{Z_0^2}{Z_L} \xrightarrow{C_L\to\infty} \infty & \text{Open for odd harmonics} \\ Z_L \xrightarrow{C_L\to\infty} 0 & \text{Short for even harmonics} \end{cases}$$

Class-F Load Rectifier (Kyoto University)



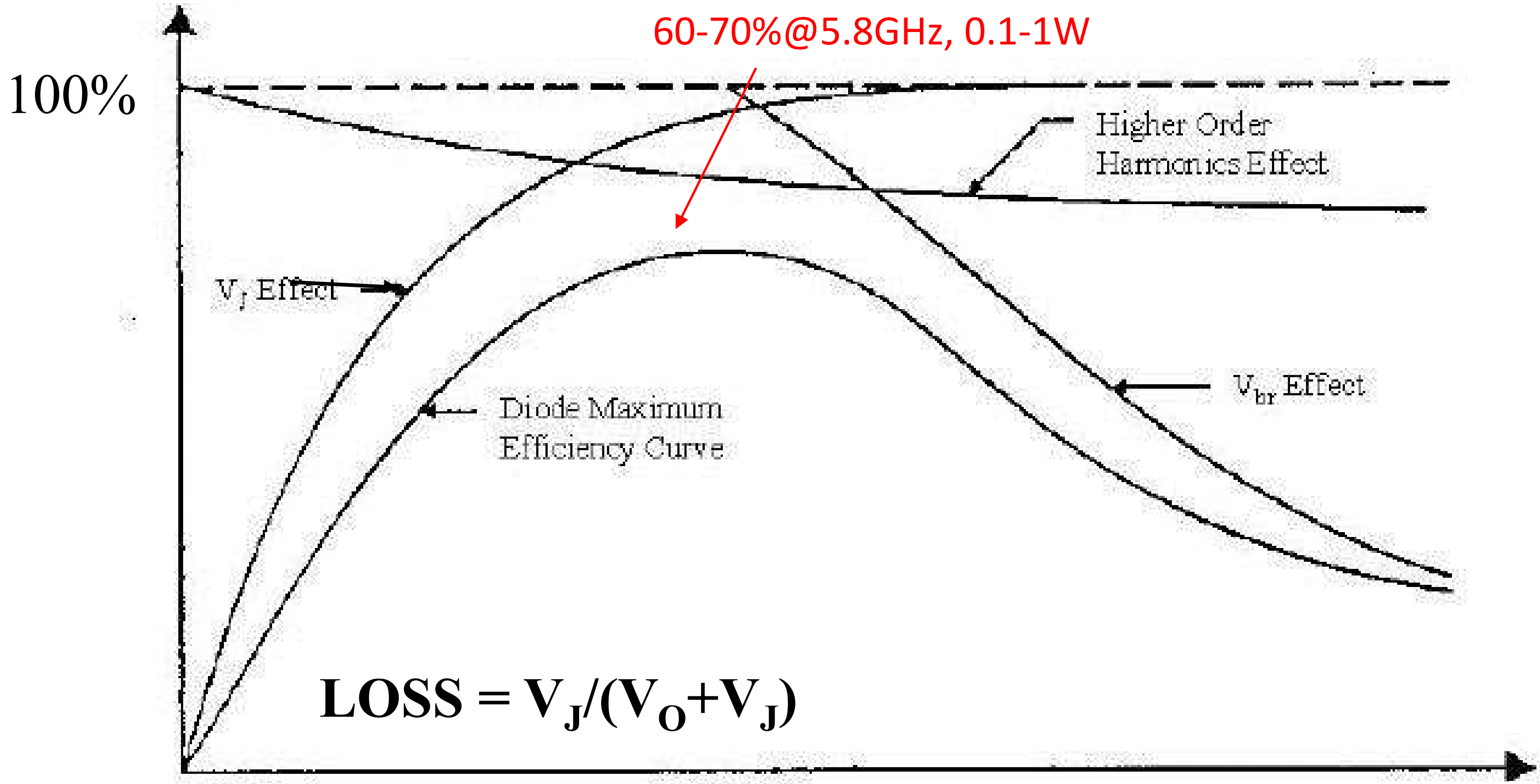
Characteristics of Rectenna

RF-DC conversion efficiency

World Record : 90%@2.45GHz, 4 W (1975, USA and 2011, Japan)

Usual Rectenna: 70-80%@2.45GHz, 0.1-1W

60-70%@5.8GHz, 0.1-1W



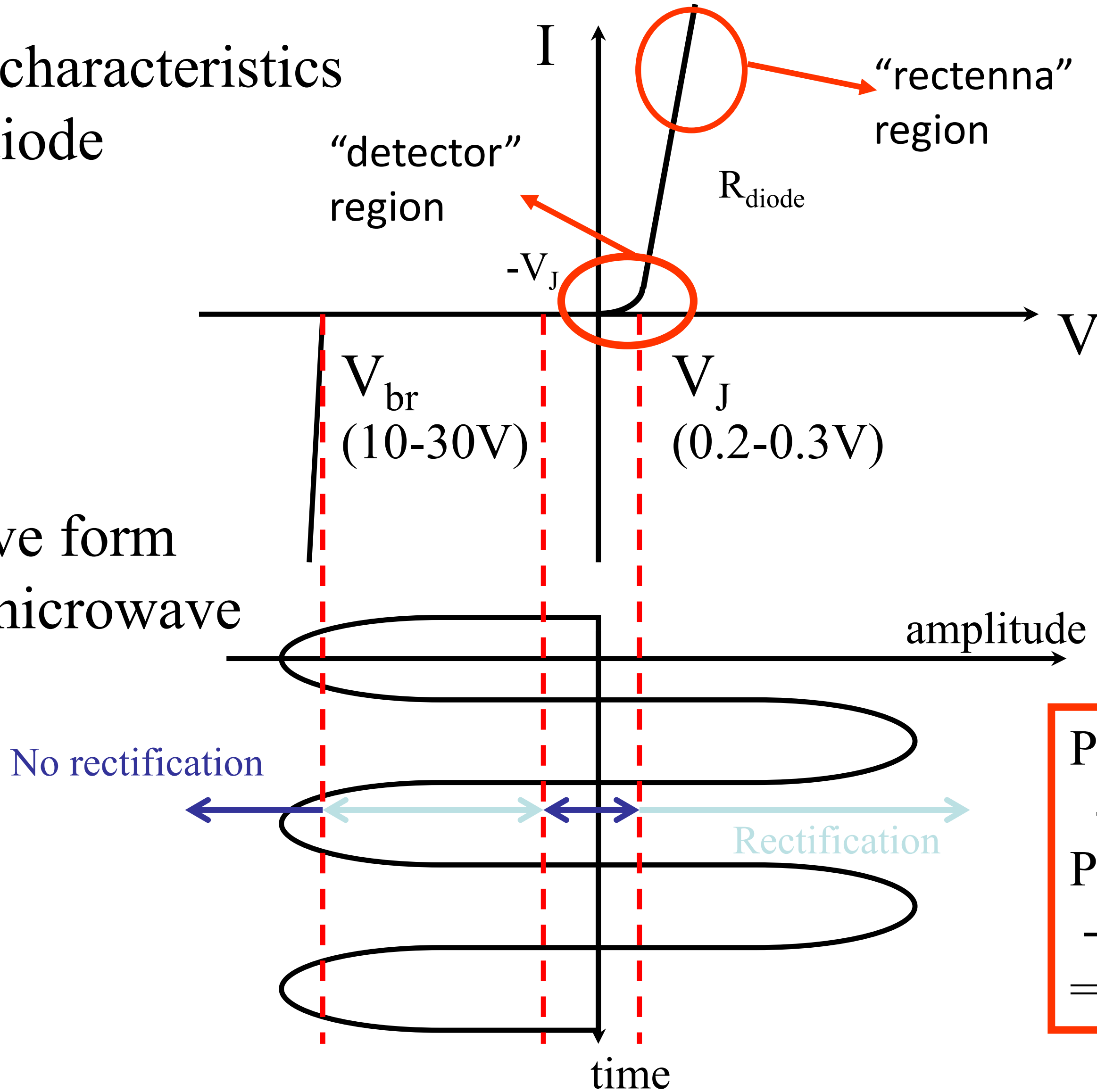
$$LOSS = V_J/(V_O+V_J)$$

Input Power or Connected Load

Diode Characteristics and RF-DC Conversion Efficiency

V-I characteristics of diode

Wave form of microwave



$$I = I_s \left(e^{\frac{eV}{kT}} - 1 \right)$$

e: electrical charge,
k: Boltzmann's constant ,
T: the absolute temperature

Schottky-barrier diode
(Low V_J)

Power weak or load small
-> almost < V_J region
Power large or load large
-> almost >V_{br} region
=> Efficiency decreases.

Theory by T.Yoo-K.Chang

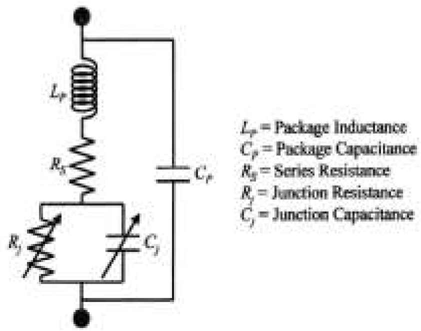
RF/DC conversion efficiency

$$\eta_d = \frac{P_{dc}}{P_{dc} + P_{loss}} = \frac{1}{1 + A + B + C}$$

Power loss on diode

$$P_{loss} = LOSS_{on,R_s} + LOSS_{off,R_s} + LOSS_{on,diode}$$

(a) Schottky diode equivalent circuit:



Power loss on Rs at diode ON

$$LOSS_{on,R_s} = \frac{1}{2\pi}\int_{-\theta_{on}}^{\theta_{on}} \frac{(V - V_{bi})^2}{R_s} d\theta$$

$$A = \left(\frac{LOSS_{on,R_s}}{P_{dc}}\right) = \frac{R_L}{\pi R_s}\left(1 + \frac{V_{bi}}{V_o}\right)^2 \left[\theta_{on}\left(1 + \frac{1}{2\cos^2\theta_{on}}\right) - \frac{3}{2}\tan\theta_{on}\right]$$

Power loss on Rs at diode OFF

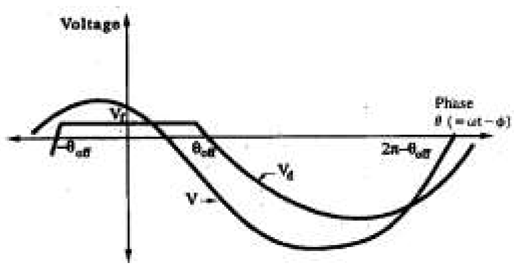
$$LOSS_{off,Rs} = \frac{1}{2\pi}\int_{\theta_{on}}^{2\pi-\theta_{on}} \frac{(V - V_d)^2}{R_S} d\theta$$

$$B = \left(\frac{LOSS_{off,R_s}}{P_{dc}}\right) = \frac{R_s R_L C_j^2 \omega^2}{2\pi}\left(1 + \frac{V_{bi}}{V_o}\right)\left(\frac{\pi - \theta_{on}}{\cos^2\theta_{on}} + \tan\theta_{on}\right)$$

Power loss on Rj at diode ON

$$LOSS_{on,diode} = \frac{1}{2\pi}\int_{-\theta_{on}}^{\theta_{on}} \frac{(V - V_{bi})V_{bi}}{R_s} d\theta$$

$$C = \left(\frac{LOSS_{on,diode}}{P_{dc}}\right) = \frac{R_L}{\pi R_s}\left(1 + \frac{V_{bi}}{V_o}\right)\frac{V_{bi}}{V_o}(\tan\theta_{on} - \theta_{on})$$



T.- W. Yoo and K. Chang, "Theoretical and Experimental Development of 10 and 35 GHz Rectennas", *IEEE Trans. MTT*, Vol.40, No.6, 1992, pp.1259- 1266

Rs, Cjo and Efficiency by T.Yoo-K.Chang

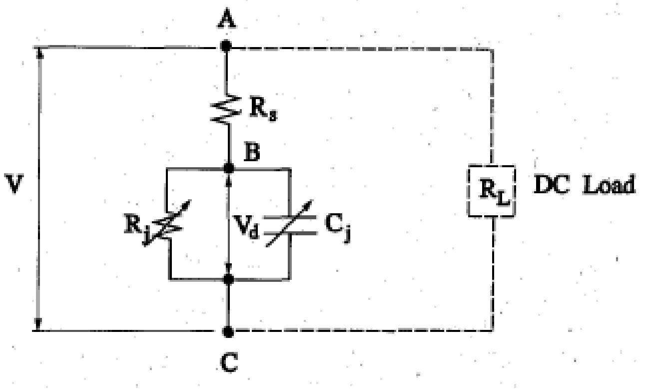


Fig. 3. Equivalent circuit of a *Ka*-band beamlead Schottky diode used for the derivation of a closed-form equation. R_j and C_j model the intrinsic junction for the diode, R_S is the parasitic series resistance of the diode and R_L is the dc load.

Point A : Rs = 0.5Ω, C_{jO}= 3 pf
for a 2.45 GHz, R_L=100Ω
Point B : Rs = 4.85Ω, C_{jO}= 0.13 pf
for 35 GHz, R_L=100Ω

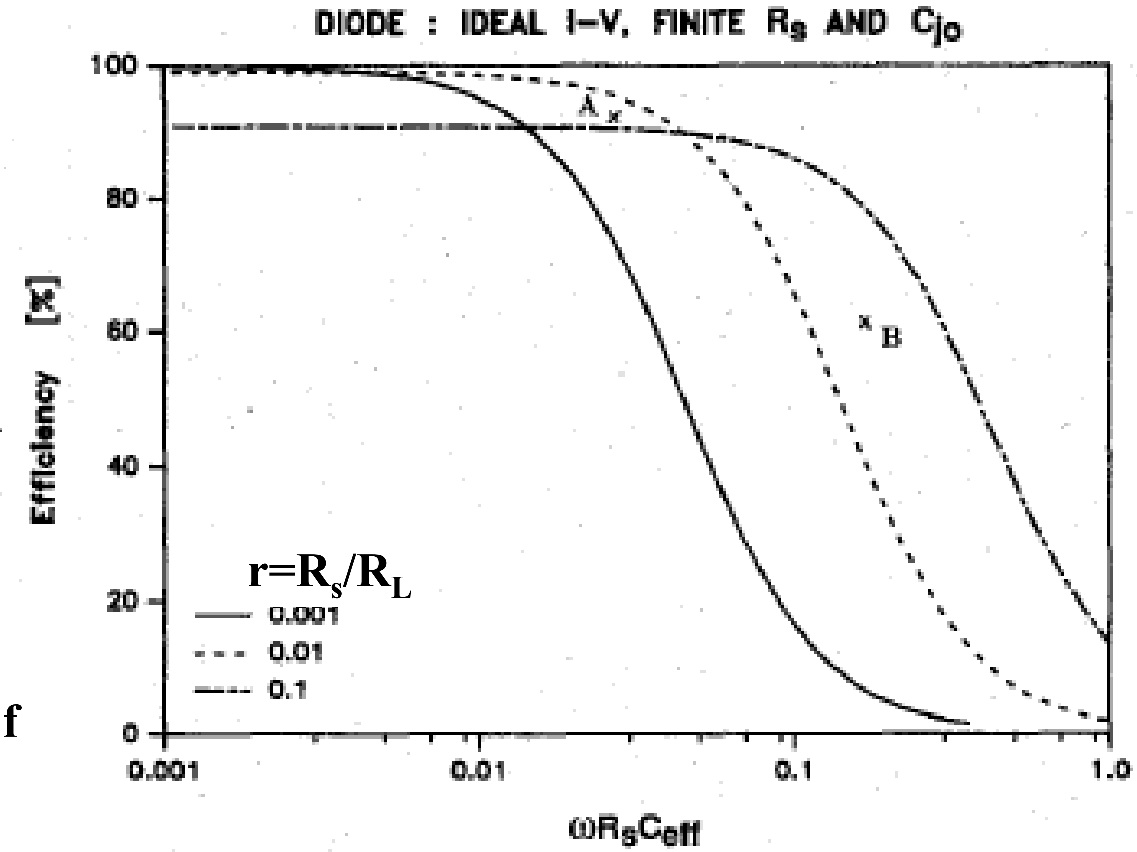
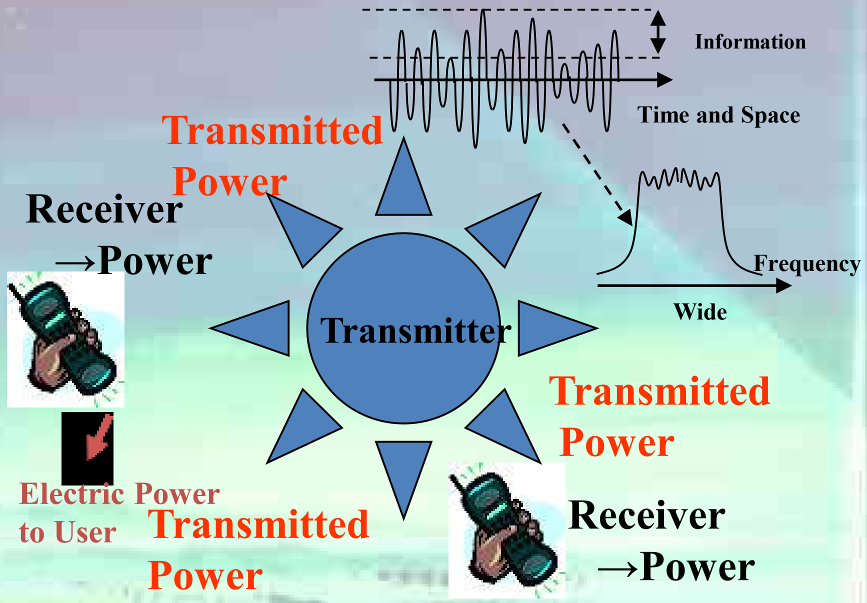


Fig. 6. Microwave-to-dc power conversion efficiency of an ideal diode with finite R_S and C_j.

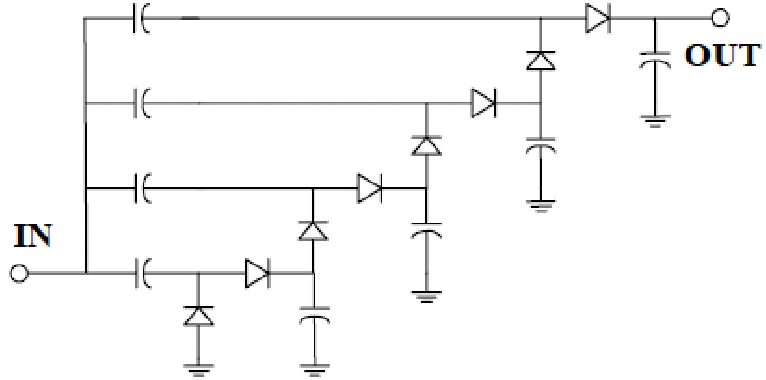
T.- W. Yoo and K. Chang, “Theoretical and Experimental Development of 10 and 35 GHz Rectennas”, *IEEE Trans. MTT*, Vol.40, No.6, 1992, pp.1259- 1266

Energy Harvesting in Japan

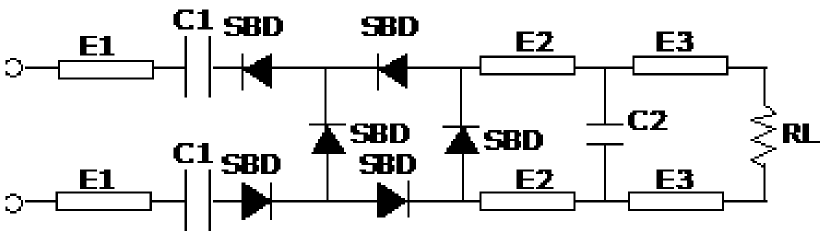


Suitable Rectenna for Energy Harvesting (1/2)

- Charge Pump -> High Voltage but Low Efficiency

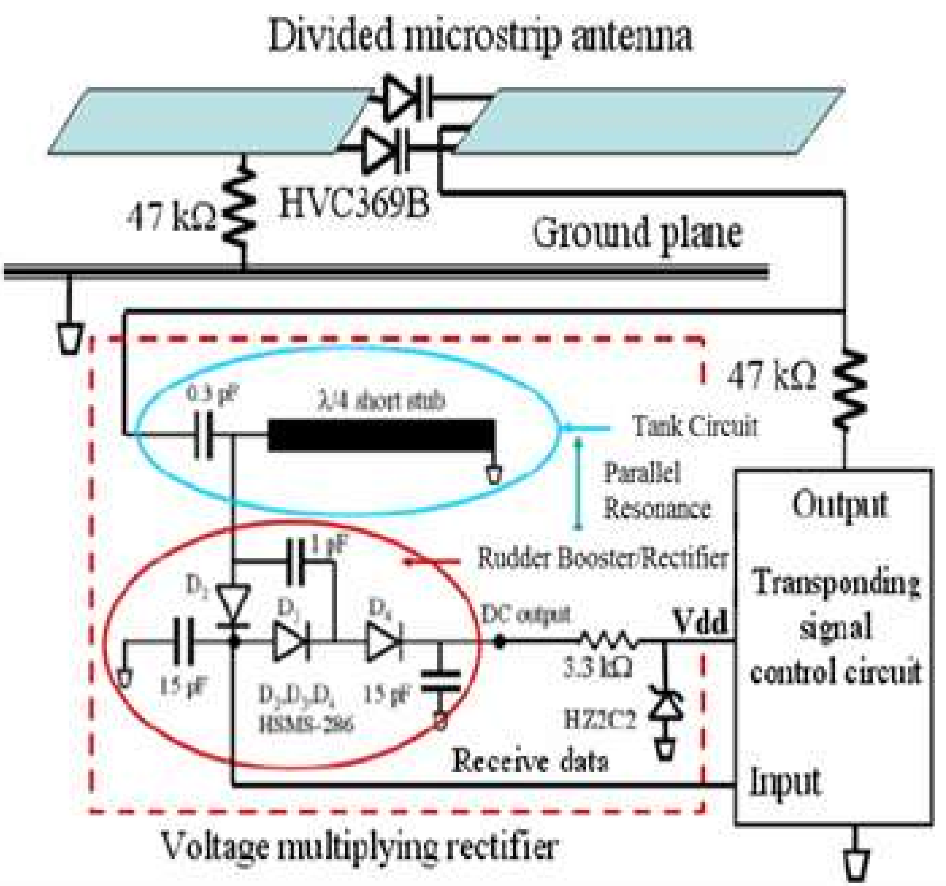


- Zero Bias Diode -> Low Efficiency
- Suitable Impedance Matching

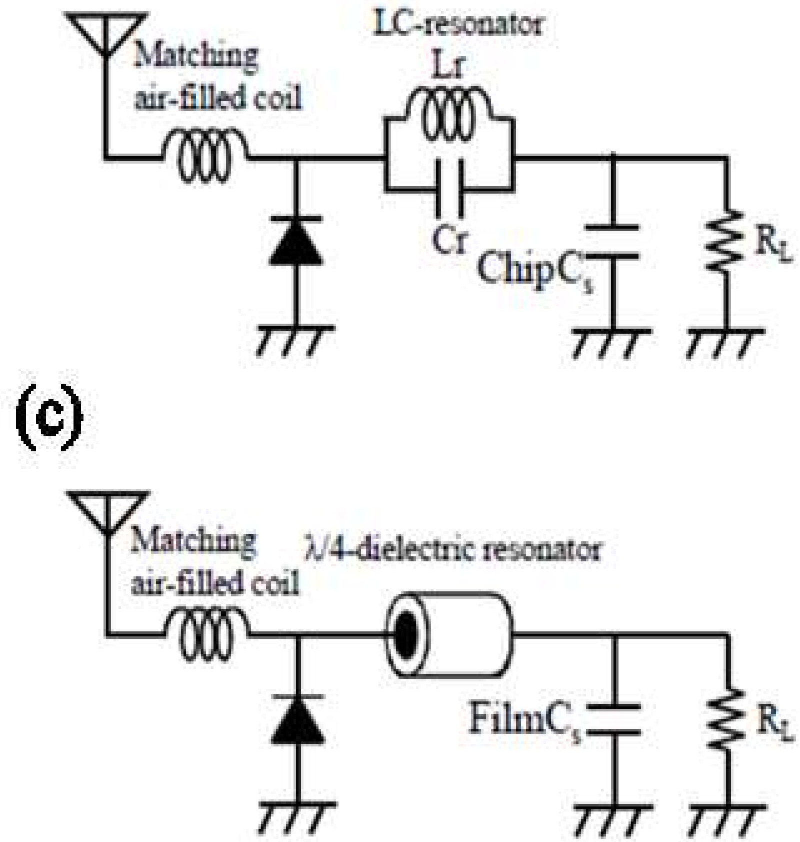


Suitable Rectenna for Energy Harvesting (2/2)

- Rectifying Circuit with Resonator

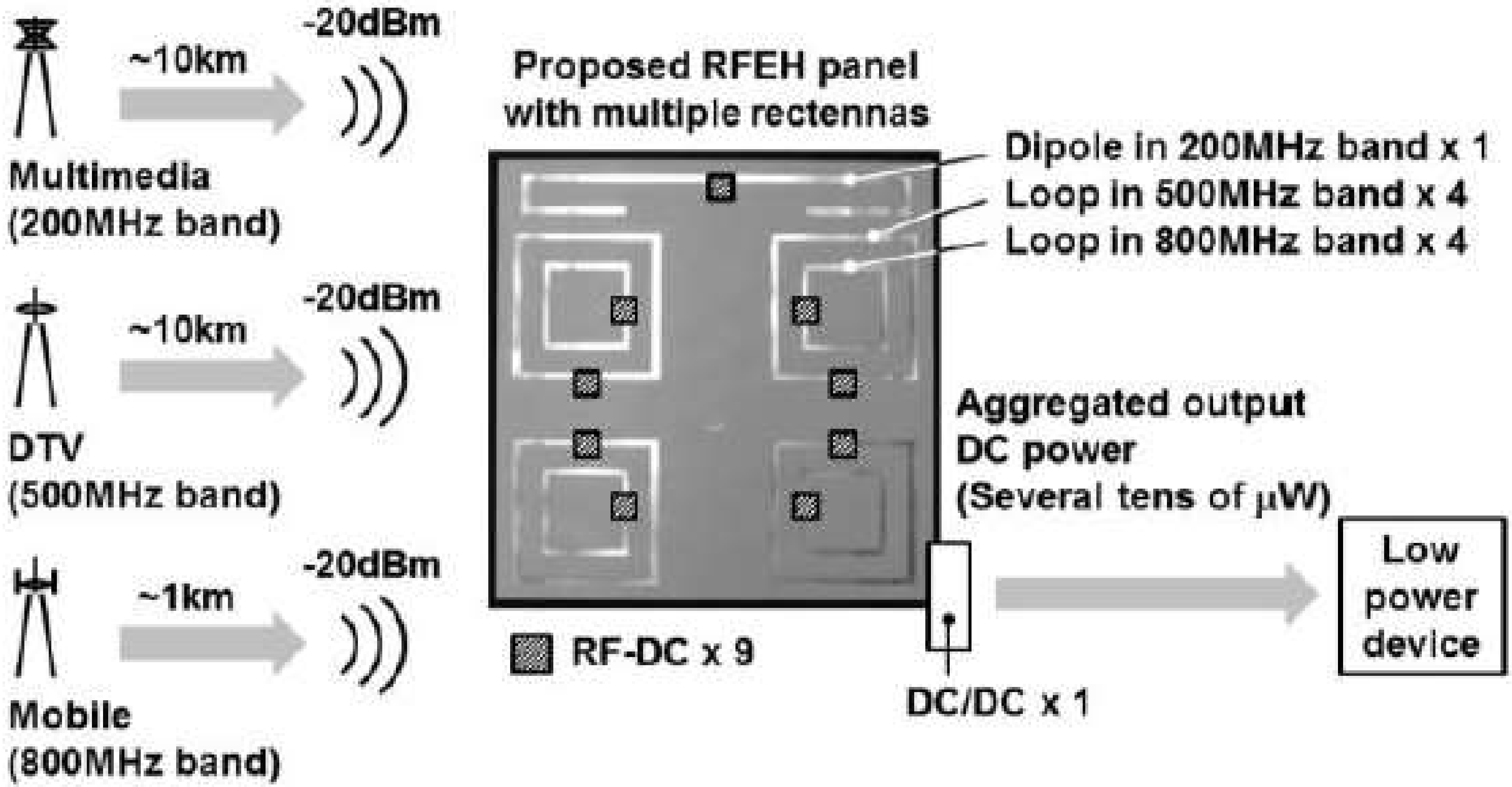


Tohoku Univ, Jpapan



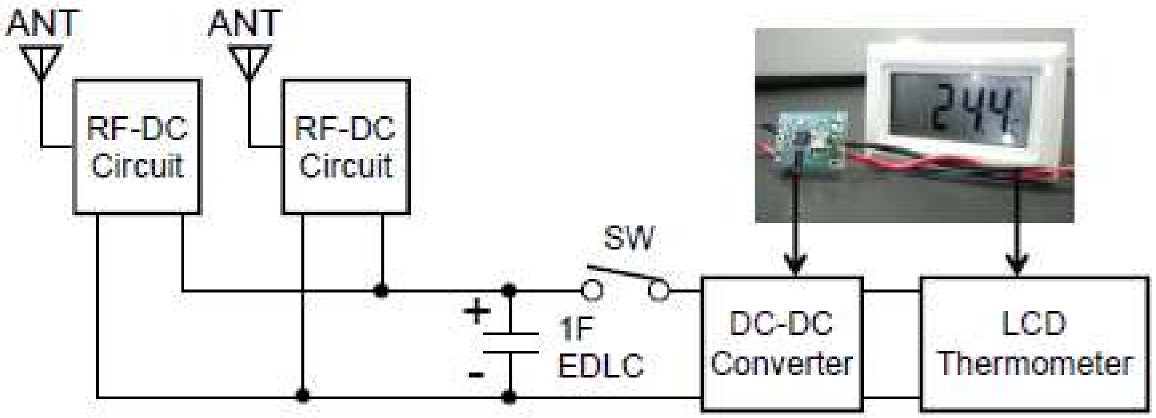
Toyama Univ, Jpapan

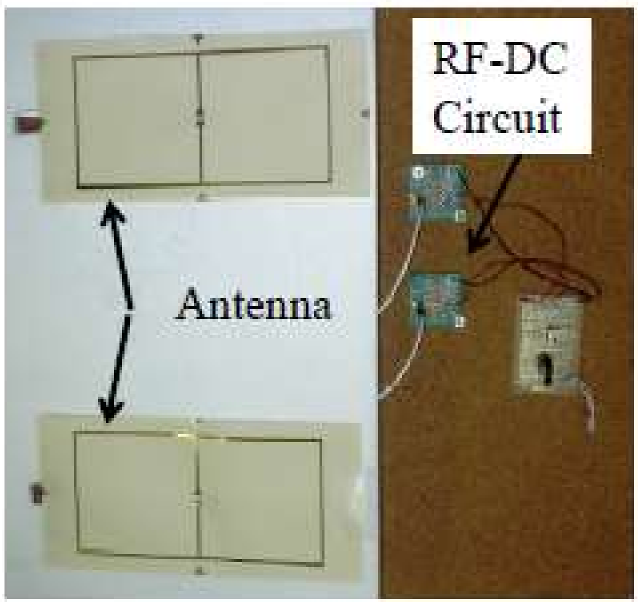
Energy Harvesting from TV/Mobile Phone by ATR/Renesas

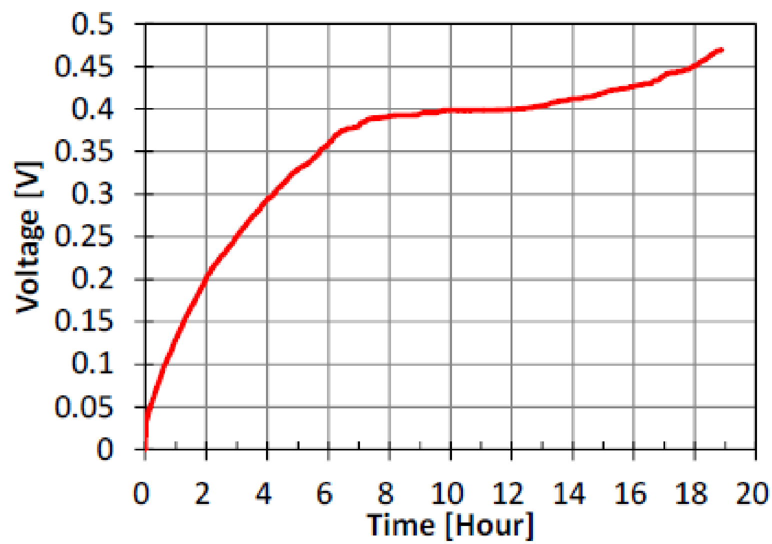


Yoshida, Y., et al., "Development of Energy Harvesting Circuit from Broadcasting Waves (in Japanese)", Proc. of IEICE2015

Energy Harvesting from TV/Mobile Phone by ATR/Renesas

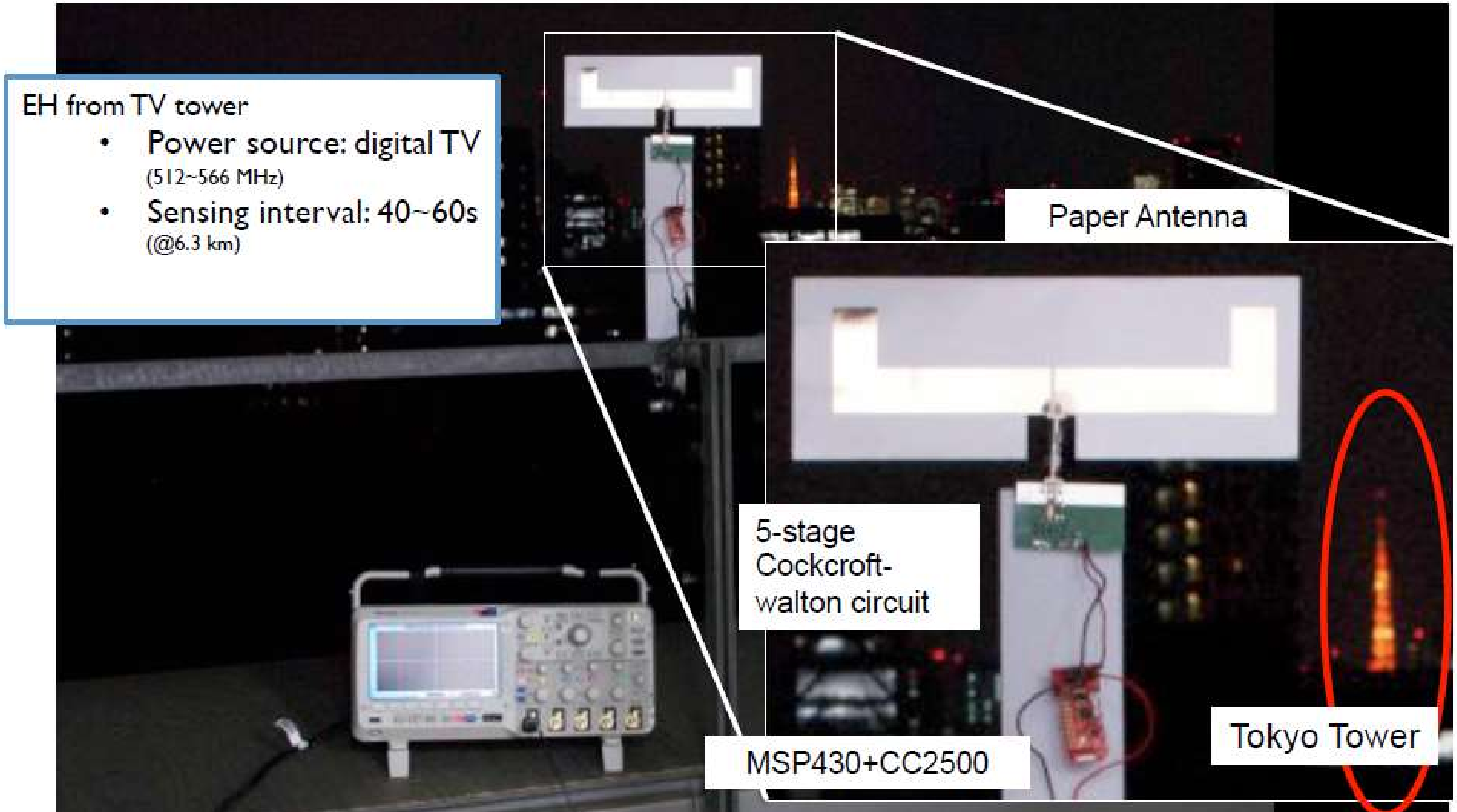






Kitazawa, S., et al., "Field Test Results of RF Energy Harvesting from Cellular Base Station", Proc. of GSMM2013

Energy Harvesting from TV Tower Signal by Univ. of Tokyo and Georgia Inst. of Tech.



R. Shigeta, et al., "Ambient RF Energy Harvesting Sensor Device With Capacitor-Leakage-Aware Duty Cycle Control," IEEE Sensors Journal, Vol. 13, No. 8, pp.2973-2983, July 2013.
R. Vyas, et al."E-WEHP: An Embedded Wireless Energy Harvesting Platform for Powering on Sensors using existing, ambient digital TV Signals present in the Air," IEEE Transactions on Microwave Theory & Techniques, Vol. 61, No. 6, pp. 2491-2505, June 2013.

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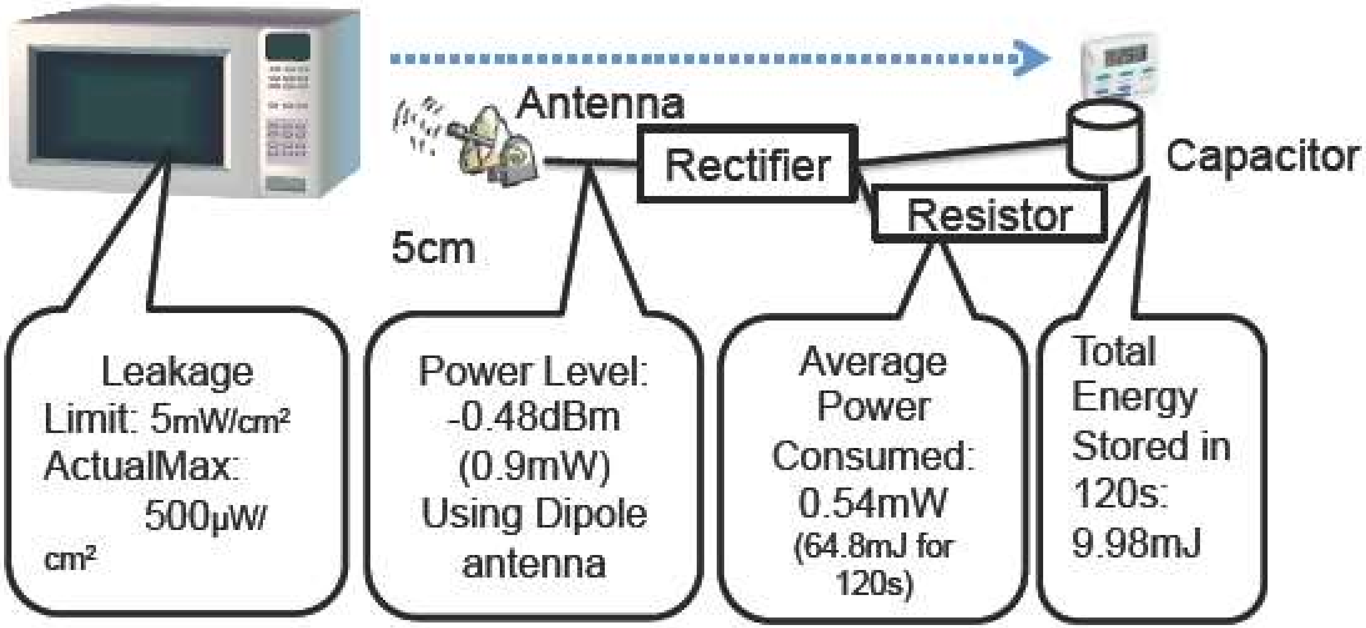
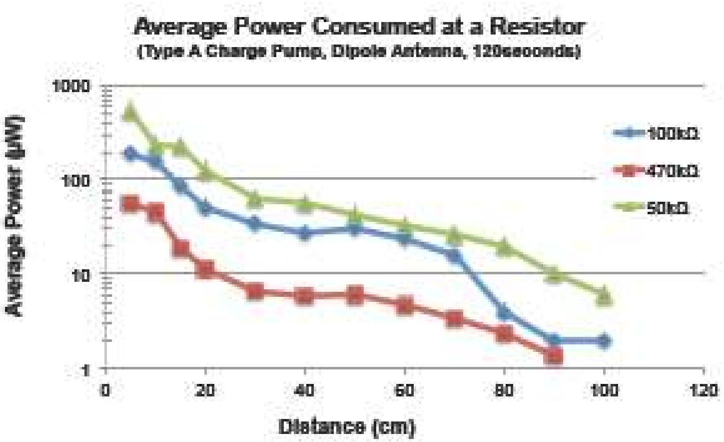
http://www.wired.co.uk/magazine/archive/2013/09/start/print-your-sensors-then-plant-your-crops

Prof. Kawahara's Lab. at Univ. of Tokyo



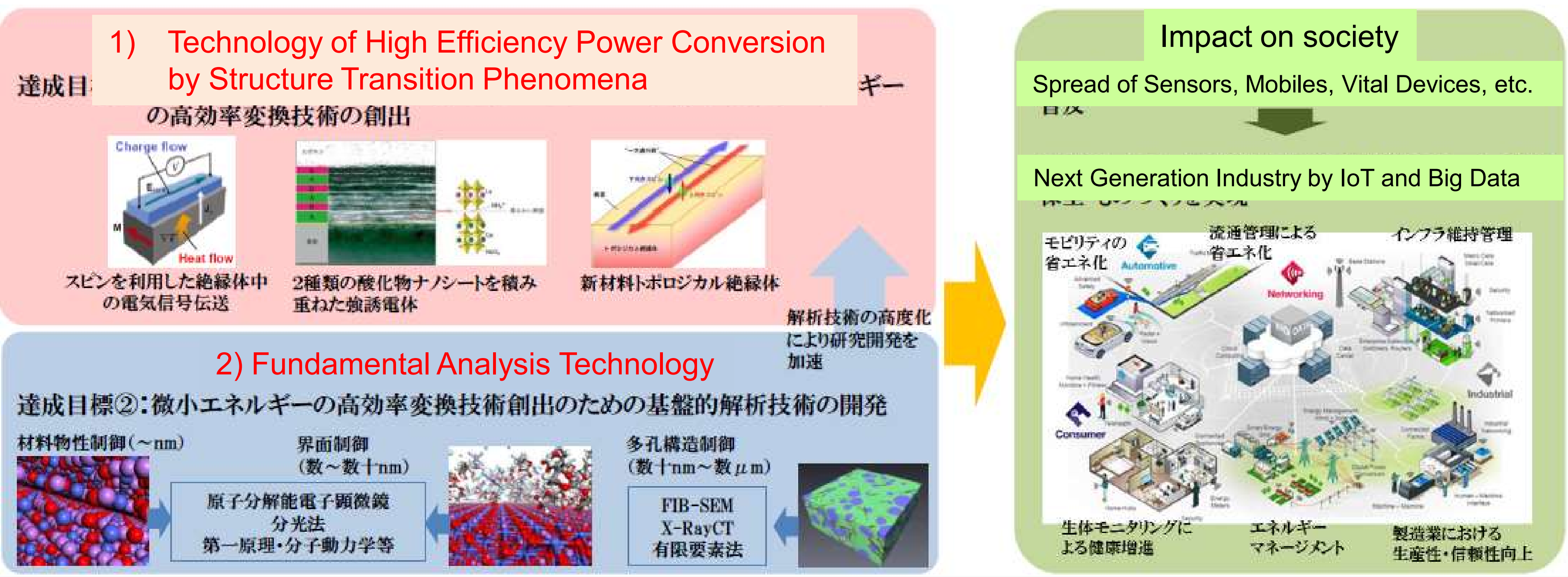


Y. Kawahara et al., "Power Harvesting from Microwave Oven Electromagnetic Leakage," UbiComp 2013 , pp. 373-382, Zurich, CH, Sept. 2013.

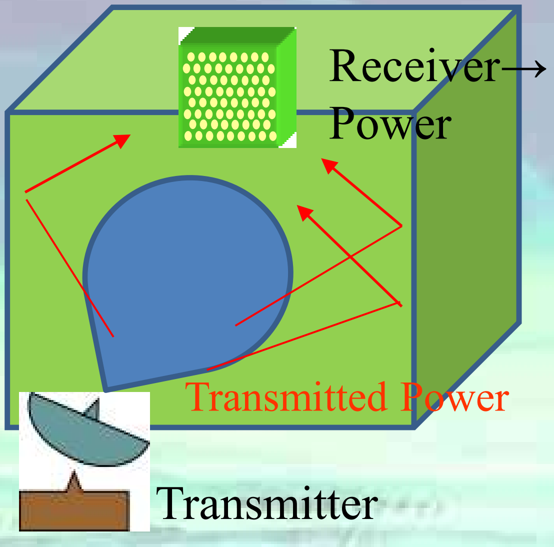
National R&D Project of Energy Harvesting by MEXT and JST (2015-2018 + 4 years)

Scientific Innovation for Energy Harvesting Technology

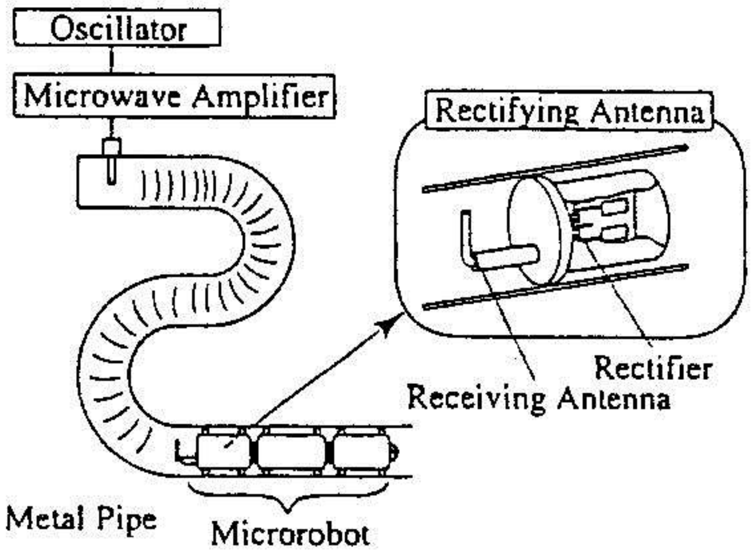
Under Selection Now!

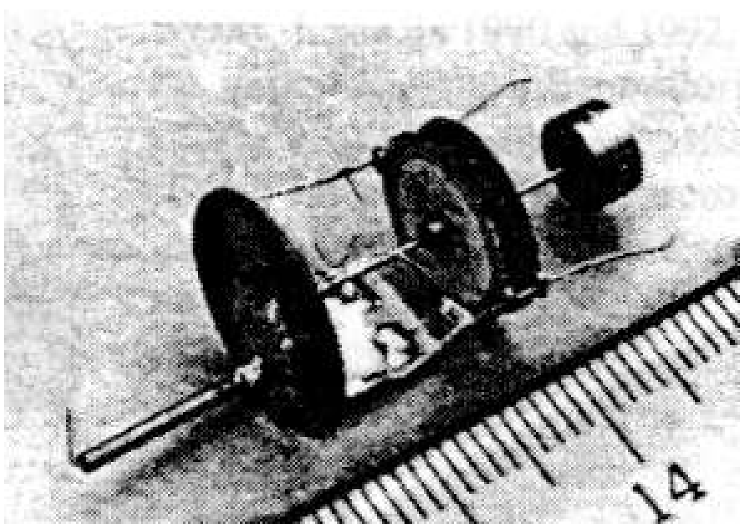


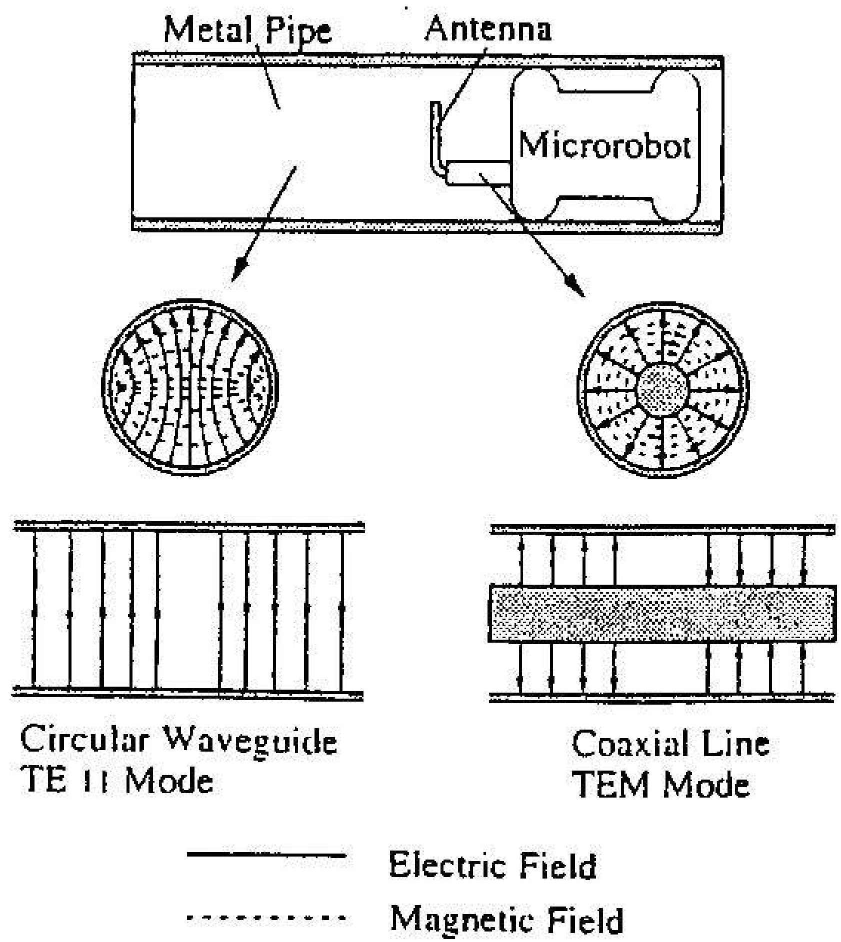
WPT in Closed Area at Kyoto Univ. and in Japan



Small Robot in Pipe by DENSO corp.

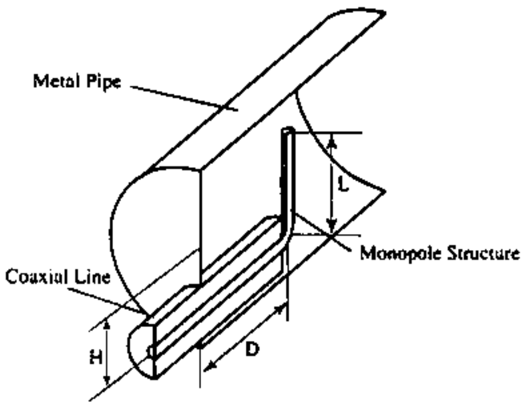






- T. Shibata, Y. Aoki, M. Otsuka, T. Idogaki, and T. Hattori, Microwave Energy Transmission System for Microrobot, IEICE-Trans. Electr., Vol. 80-C, No.2, pp.303-308, 1997

Small Robot in Pipe by DENSO corp.



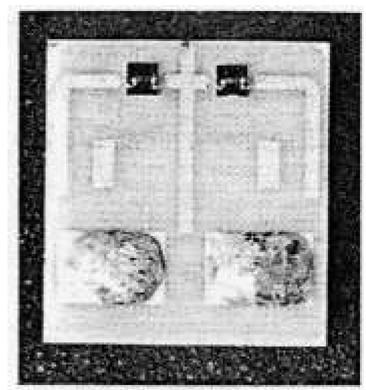
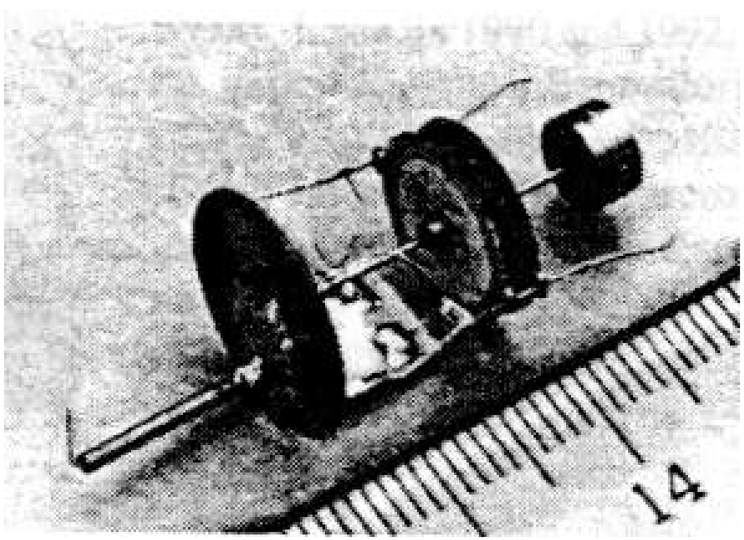
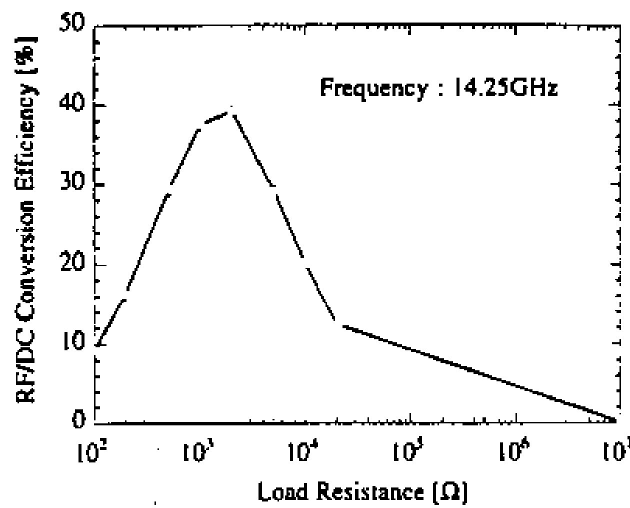


Fig. 6 Voltage doubler.

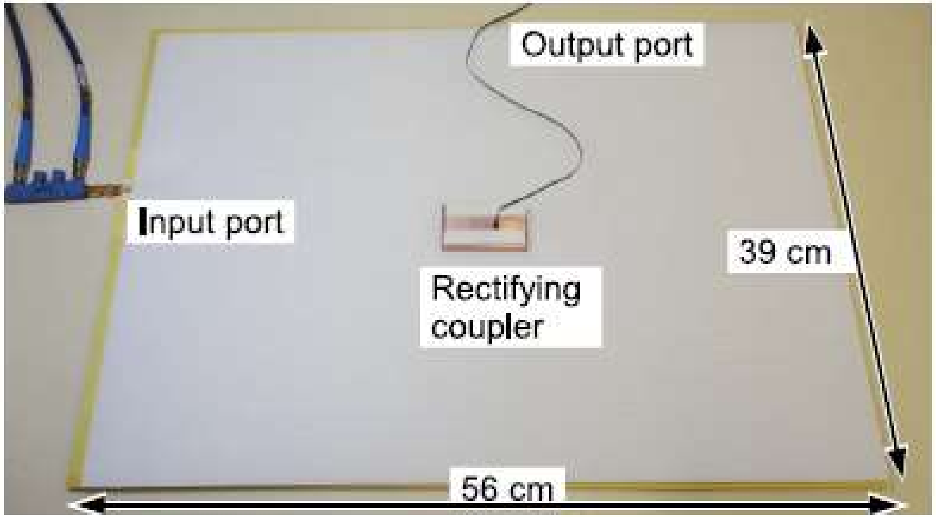
Antenna - Monopole
LPF - ?
Rectifier – Single Shunt
Diode - ?
Frequency - 14-14.5 GHz
RF-DC Conversion Efficiency
- 39% @ 100mW, 2kΩ





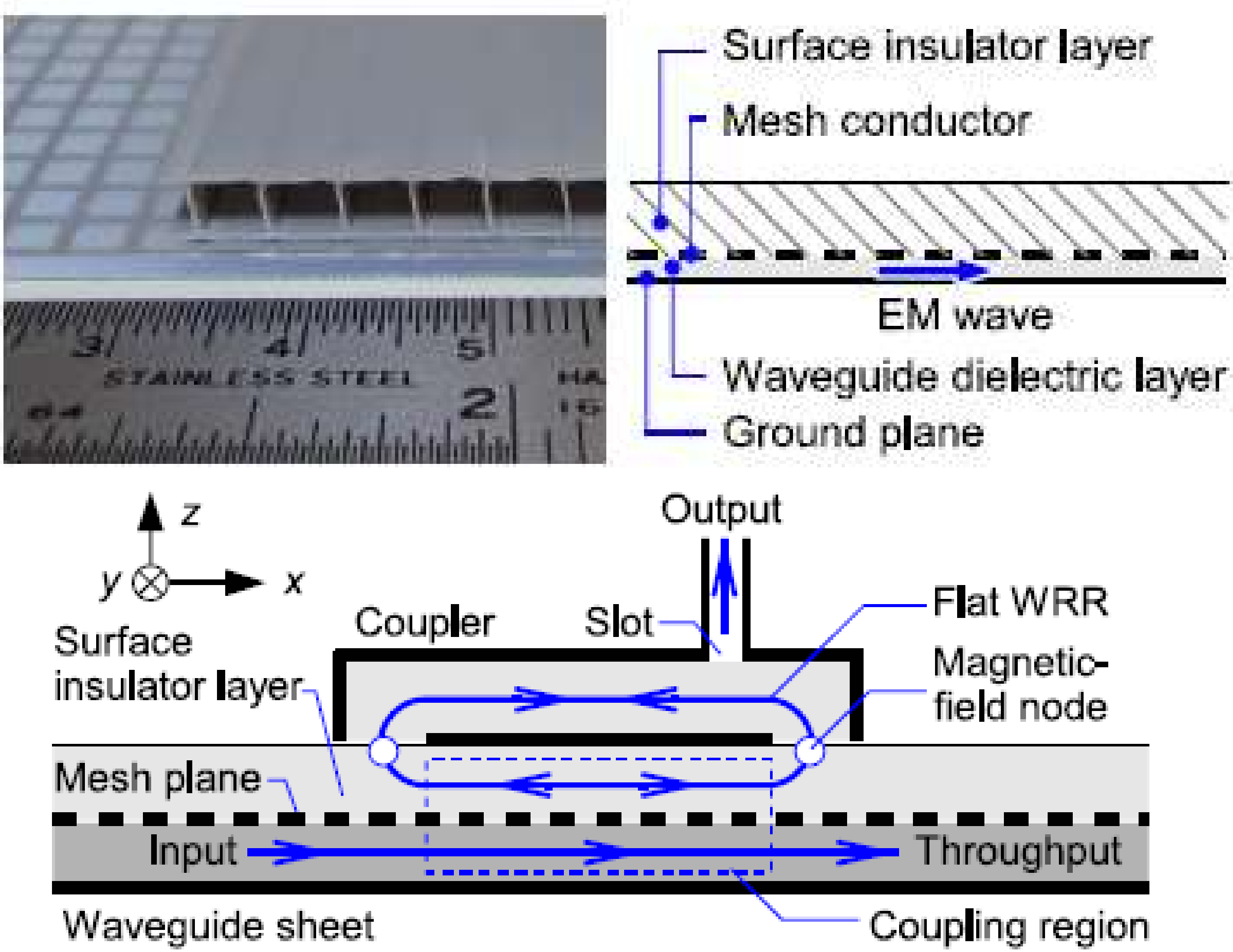
- T. Shibata, Y. Aoki, M. Otsuka, T. Idogaki, and T. Hattori, Microwave Energy Transmission System for Microrobot, IEICE-Trans. Electr., Vol. 80-C, No.2, pp.303-308, 1997

Surface WPT (2D WPT) by NICT



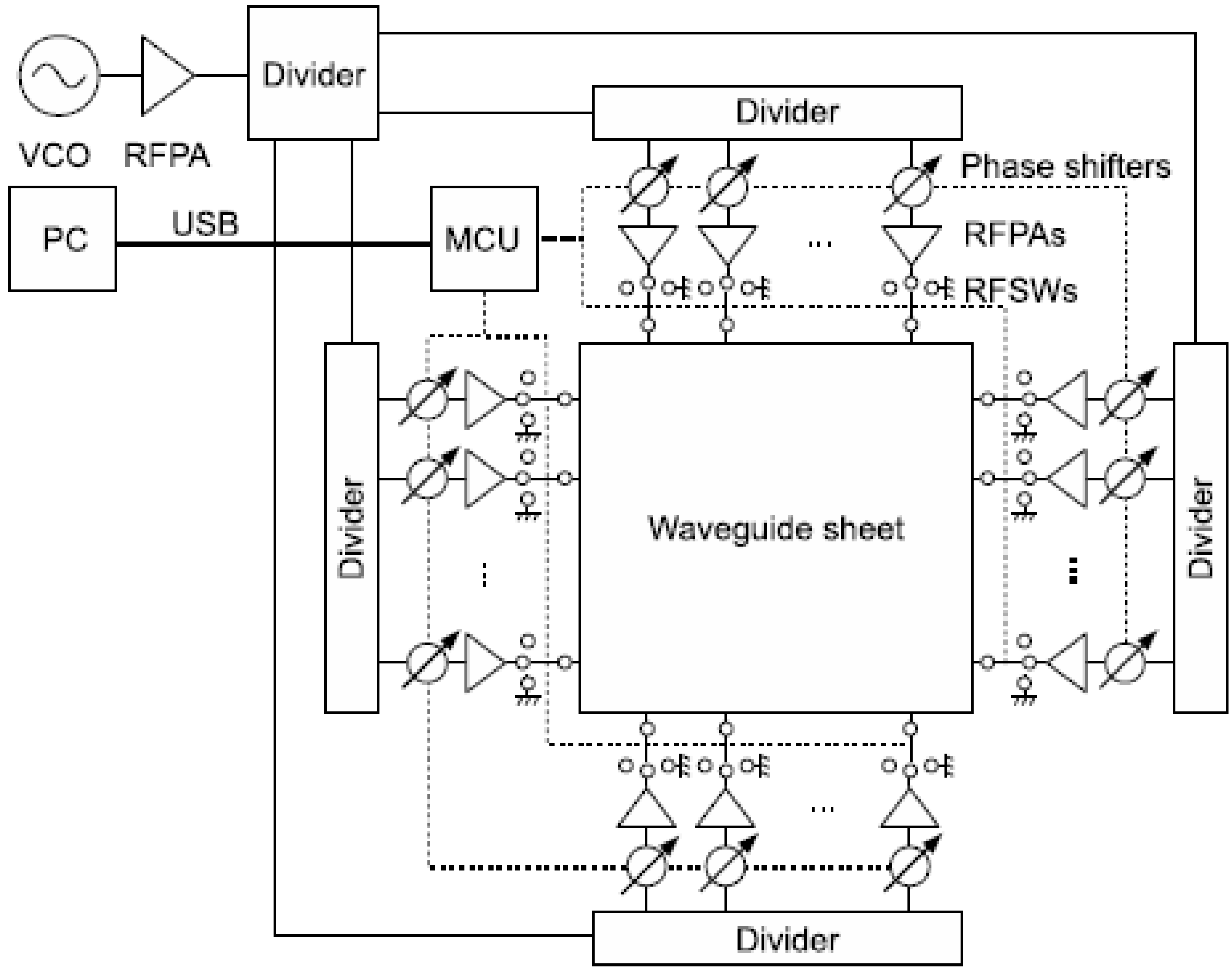
Noda, A., and H. Shinoda, "Selective wireless power transmission through high-Q flat waveguide-ring resonator on 2-D waveguide sheet," *IEEE Trans. MTT,* Vol. 59, No. 8, pp. 2158–2167, 2011.

Surface WPT (2D WPT) by NICT



Noda, A., and H. Shinoda, "Selective wireless power transmission through high-Q flat waveguide-ring resonator on 2-D waveguide sheet," *IEEE Trans. MTT,* Vol. 59, No. 8, pp. 2158–2167, 2011.

Surface WPT (2D WPT) with Phased Array by NICT

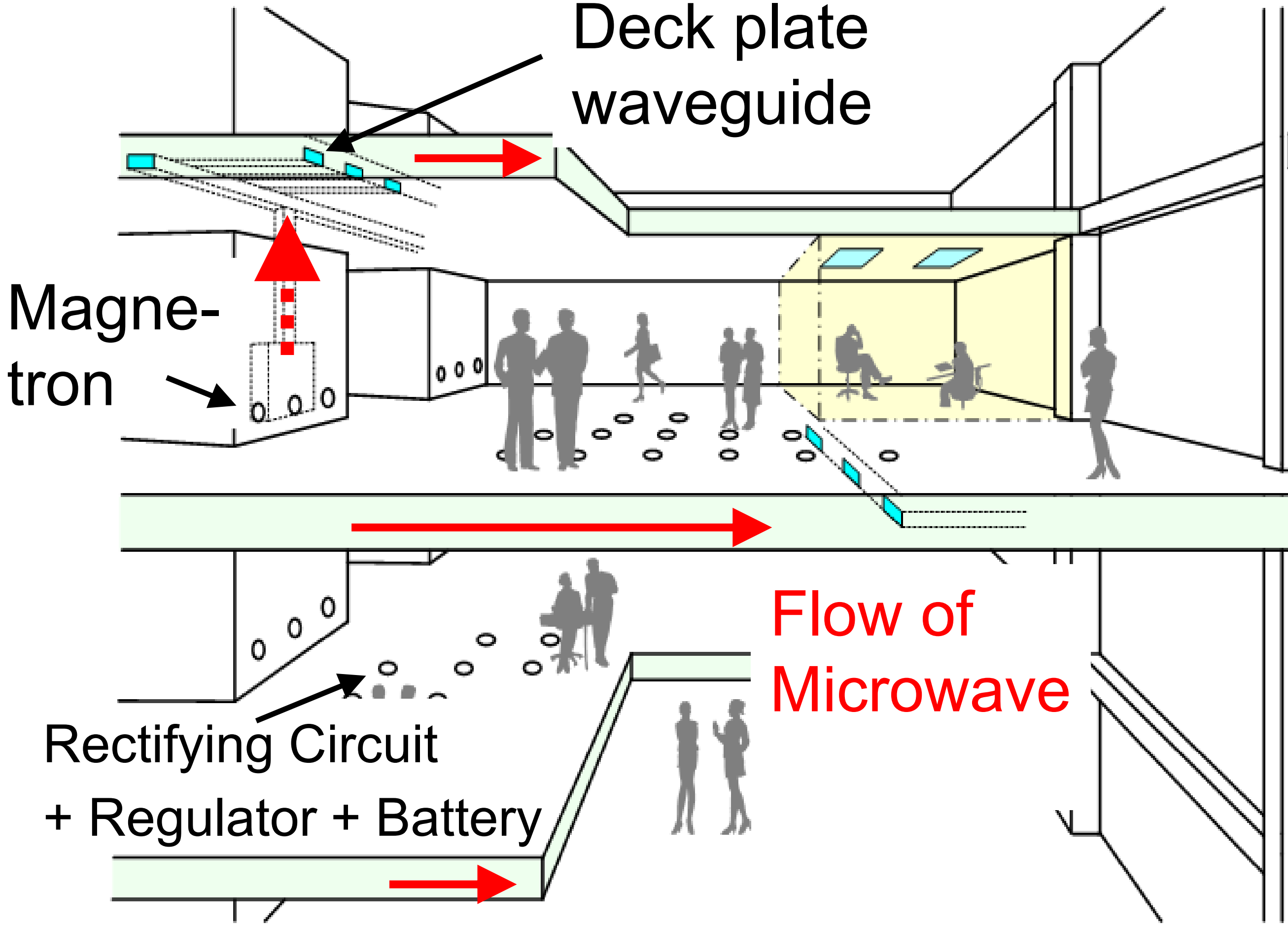


Noda, A., and H. Shinoda, "A Phased Array Feeding System for 2-D Waveguide Power Transmission (*in Japanese*)", *Proc. of IEICE,* BSC-1-8, March 2013

Wireless Power Distribution System for Buildings

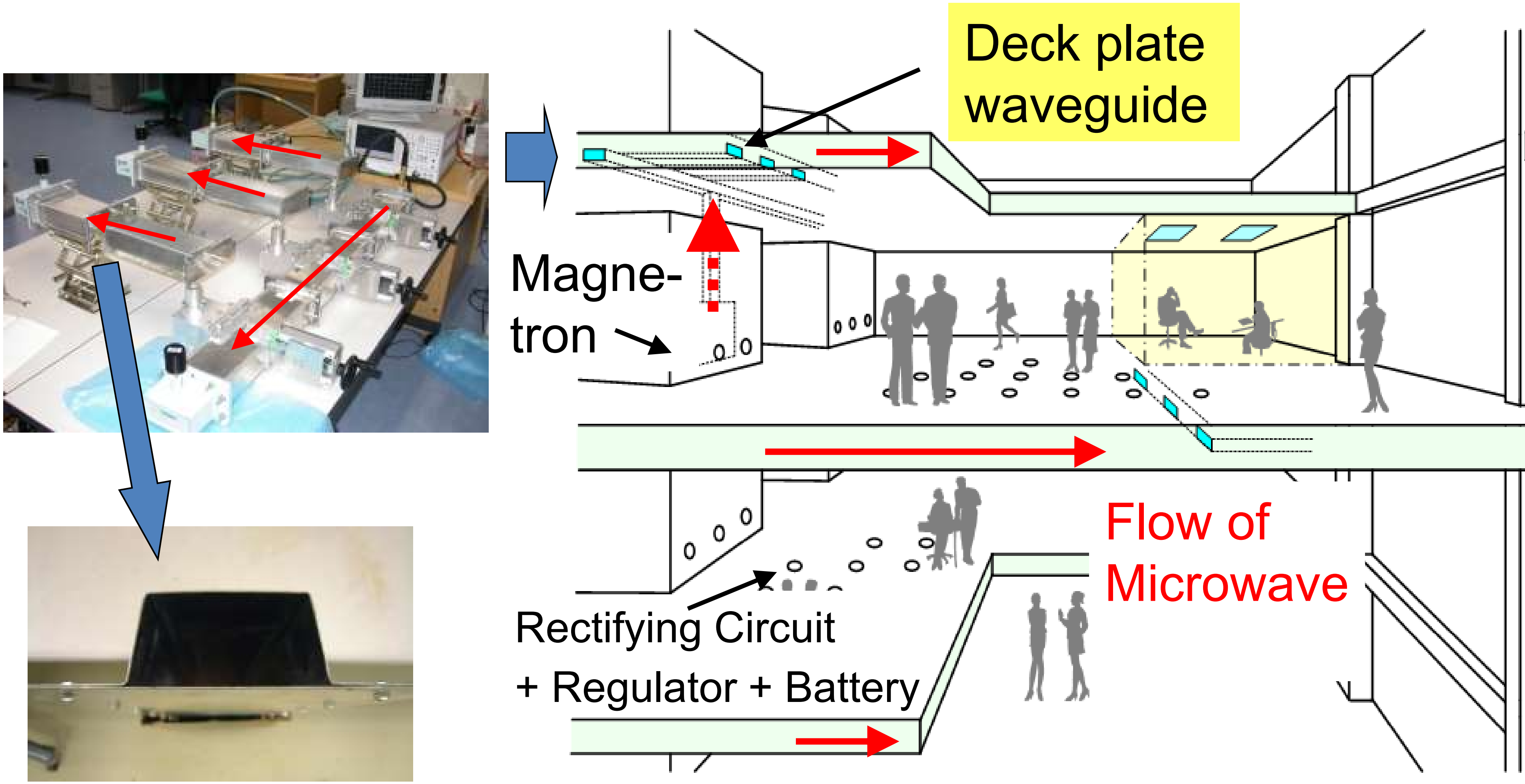
- <u>Design Policy</u>
  - Using building components without change
  - ISM band CW (2.45 GHz)
  - Low Cost
- <u>Merit</u>
  - Low initial introduction cost
  - Flexibility to system change
  - Ubiquitous power supply

<u>Conceptual diagram of WPDS</u>



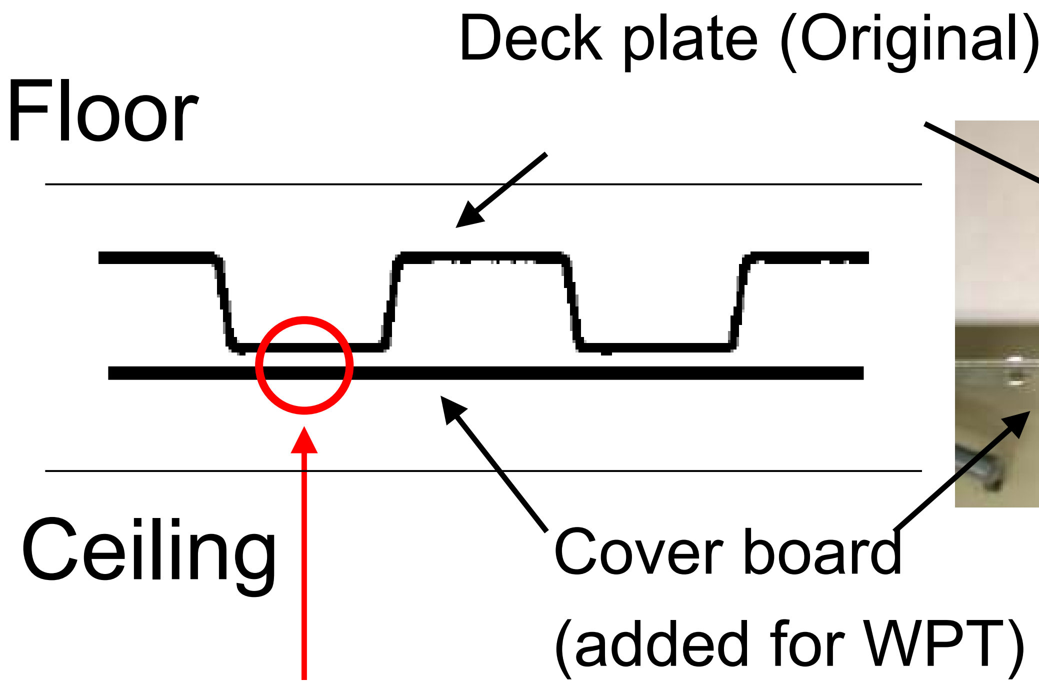
Shinohara, N., et al., "Microwave Building as an Application of Wireless Power Transfer", Wireless Power Transfer, pp.1-9, 2014.4

Wireless Power Distribution System for Buildings

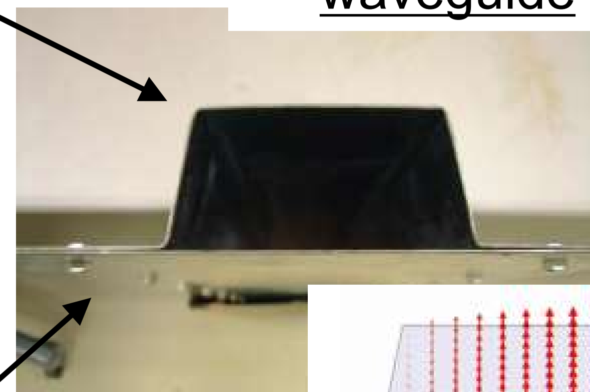


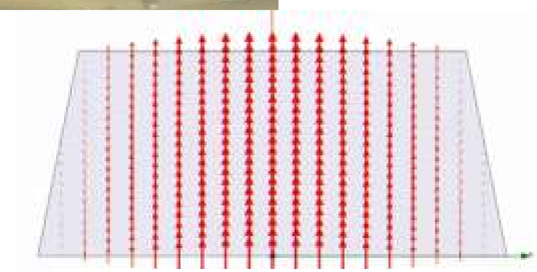
Shinohara, N., et al., "Microwave Building as an Application of Wireless Power Transfer", Wireless Power Transfer, pp.1-9, 2014.4

Deck Plate in Floor



Prototype of deck plate waveguide





TE_{10} Mode for 2.45GHz

Cut-off Frequency : 1.43GHz

Cut-off Frequency for higher mode : 2.86GHz

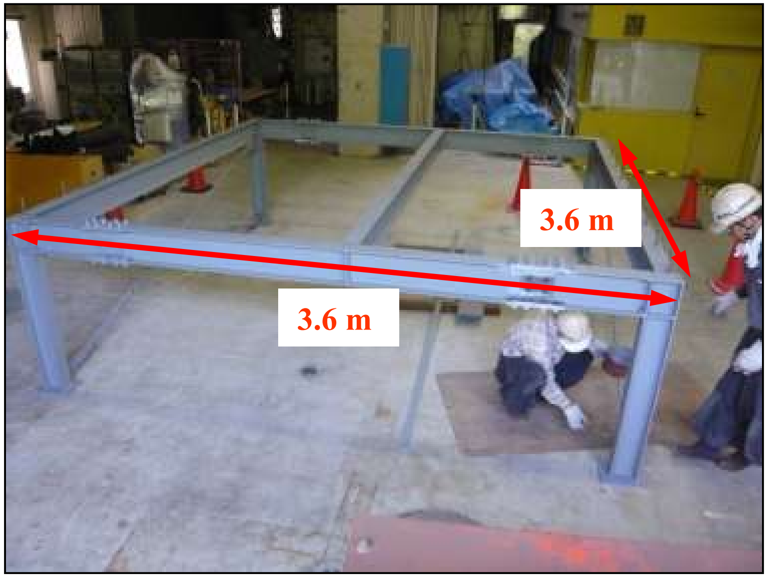
Connection method

Experimental Results	Attenuation constant [dB/m]
1. Spot welding	0.69
2. Bolted connection	0.37
3. Solder joint	**0.02**

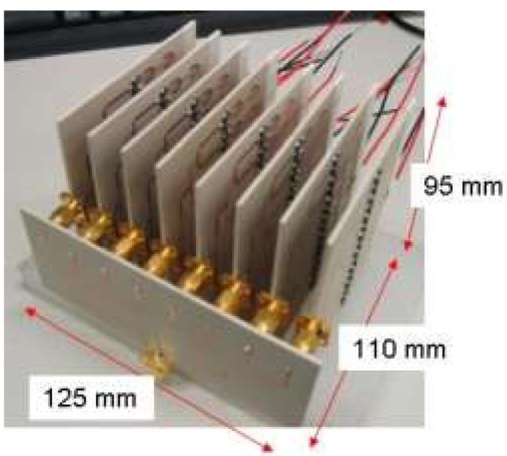
Theory 0.018 dB/m

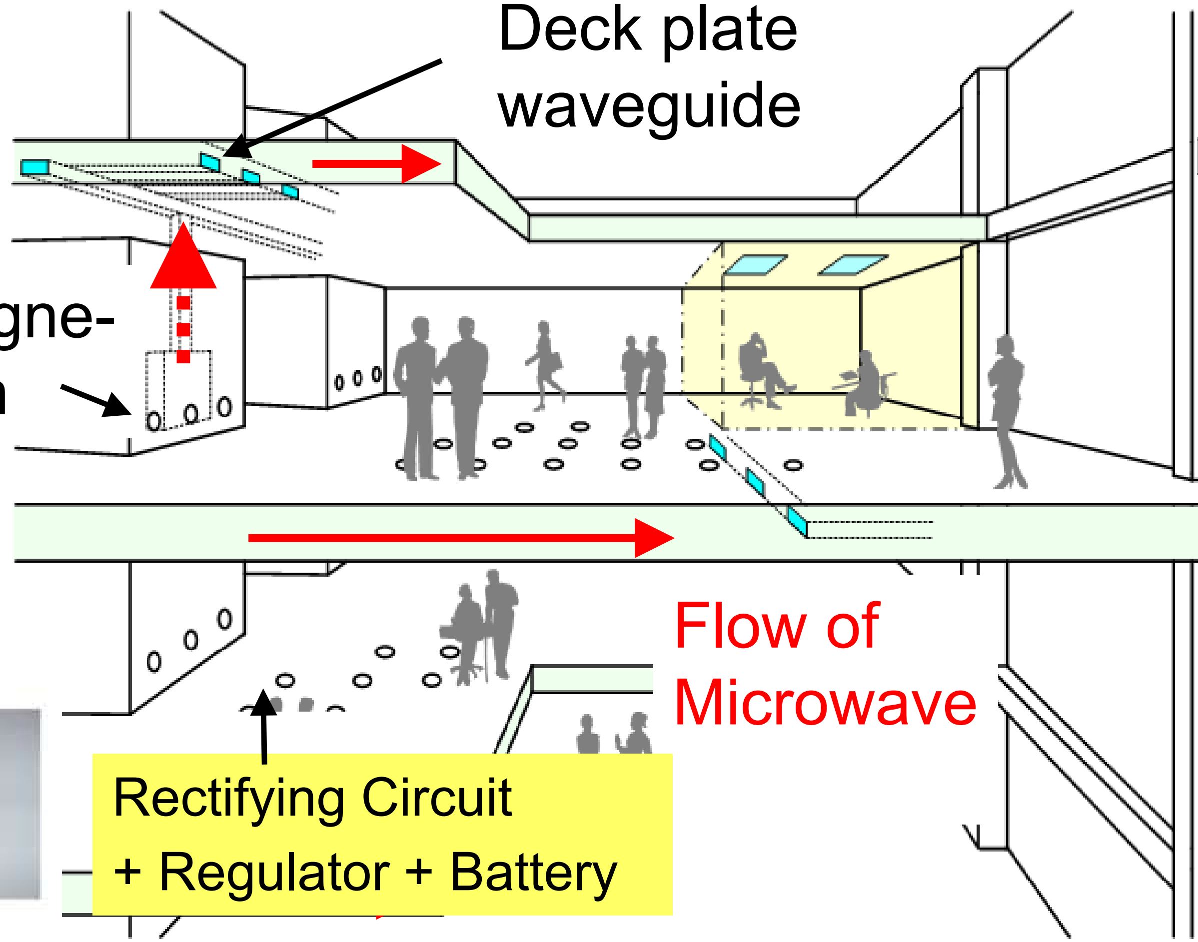
Shinohara, N., et al., “Microwave Building as an Application of Wireless Power Transfer”, Wireless Power Transfer, pp.1-9, 2014.4

Experiment with Building Company (2008)



Wireless Power Distribution System for Buildings

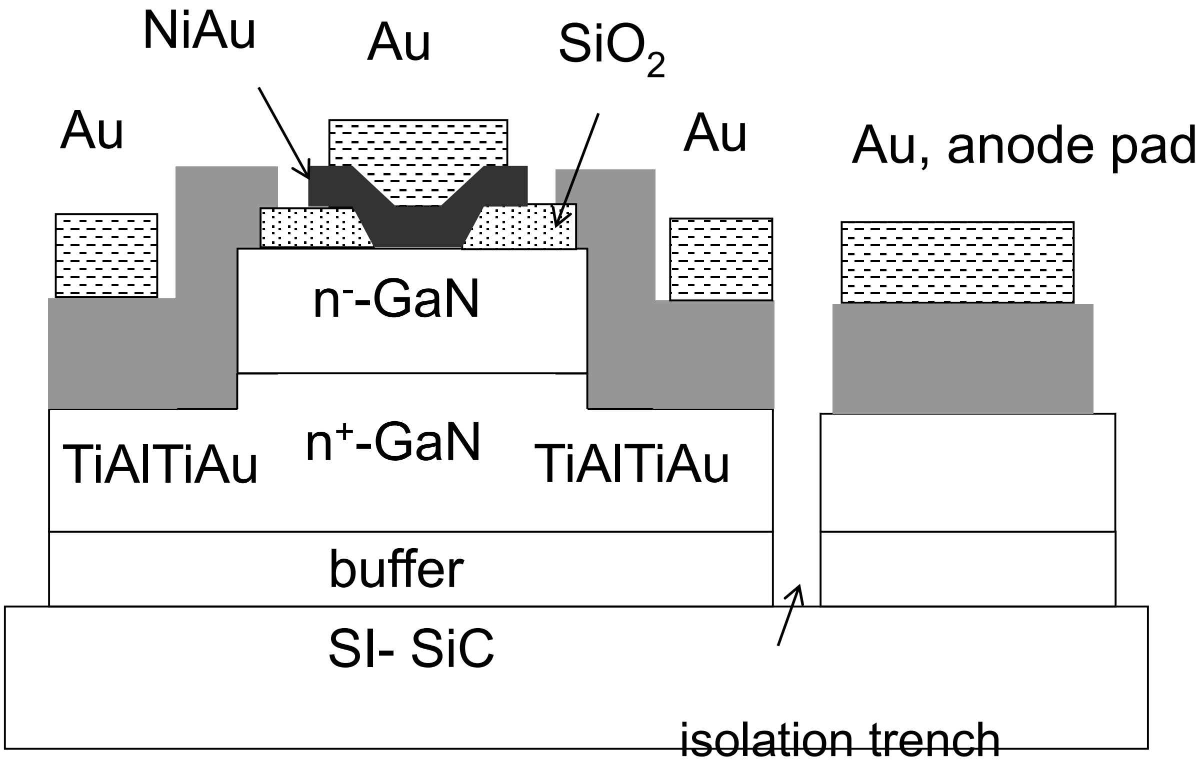


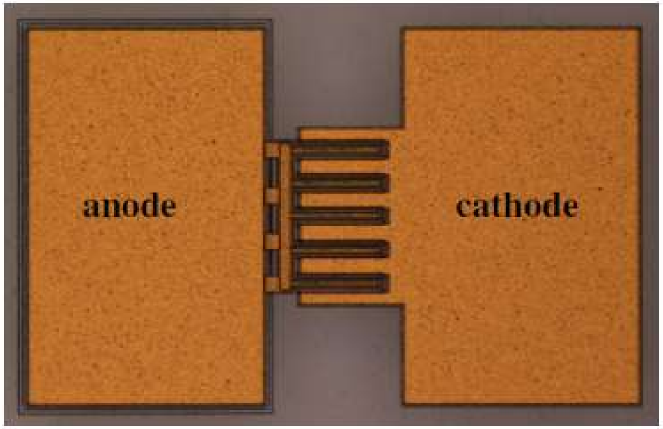


Shinohara, N., et al., "Microwave Building as an Application of Wireless Power Transfer", Wireless Power Transfer, pp.1-9, 2014.4

Developed GaN Schottky Diode

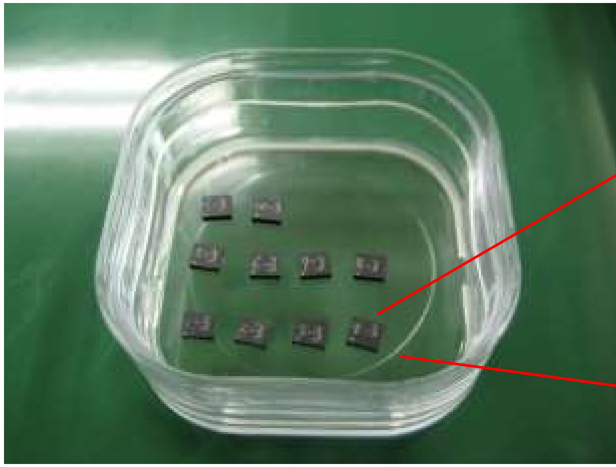
Developed in Tokushima University

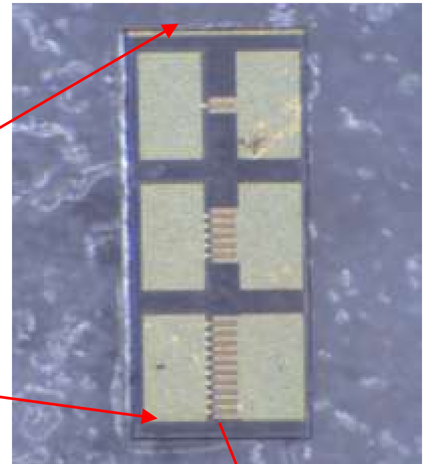




K. Takahashi et al., “GaN Schottky Diodes for Microwave Power Rectification”, Japanese Journal of Applied Physics (JJAP), Vol.48, No.4, 2009, pp.04C095-1 - 04C095-4

GaN Rectenna by Kyoto University and Tokushima University

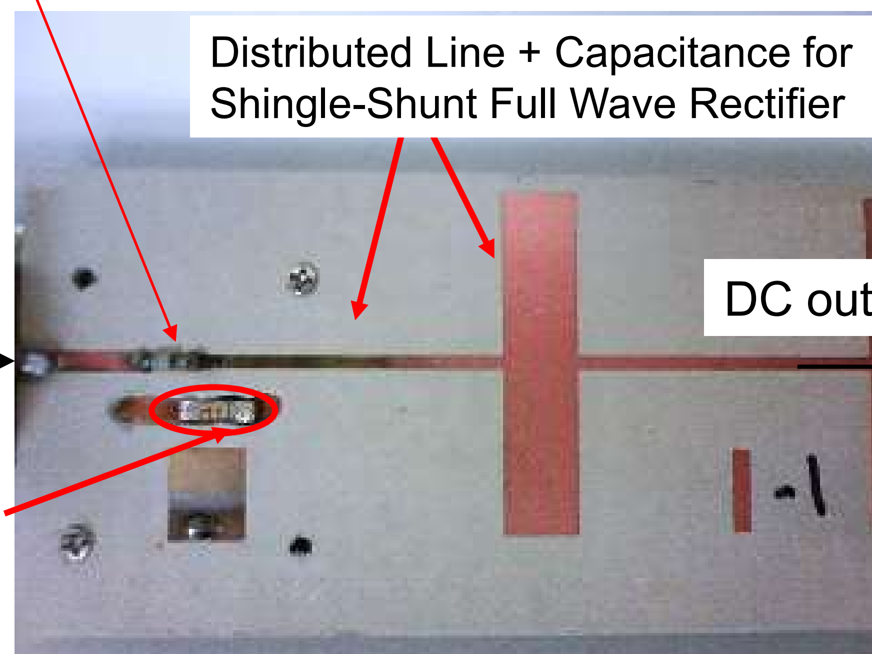




Rectenna by Kyoto Univ.

GaN Diode for MPT
by Tokushima Univ.

Rs : 4.04ΩVf
: 0.750V



Distributed Line + Capacitance for
Shingle-Shunt Full Wave Rectifier

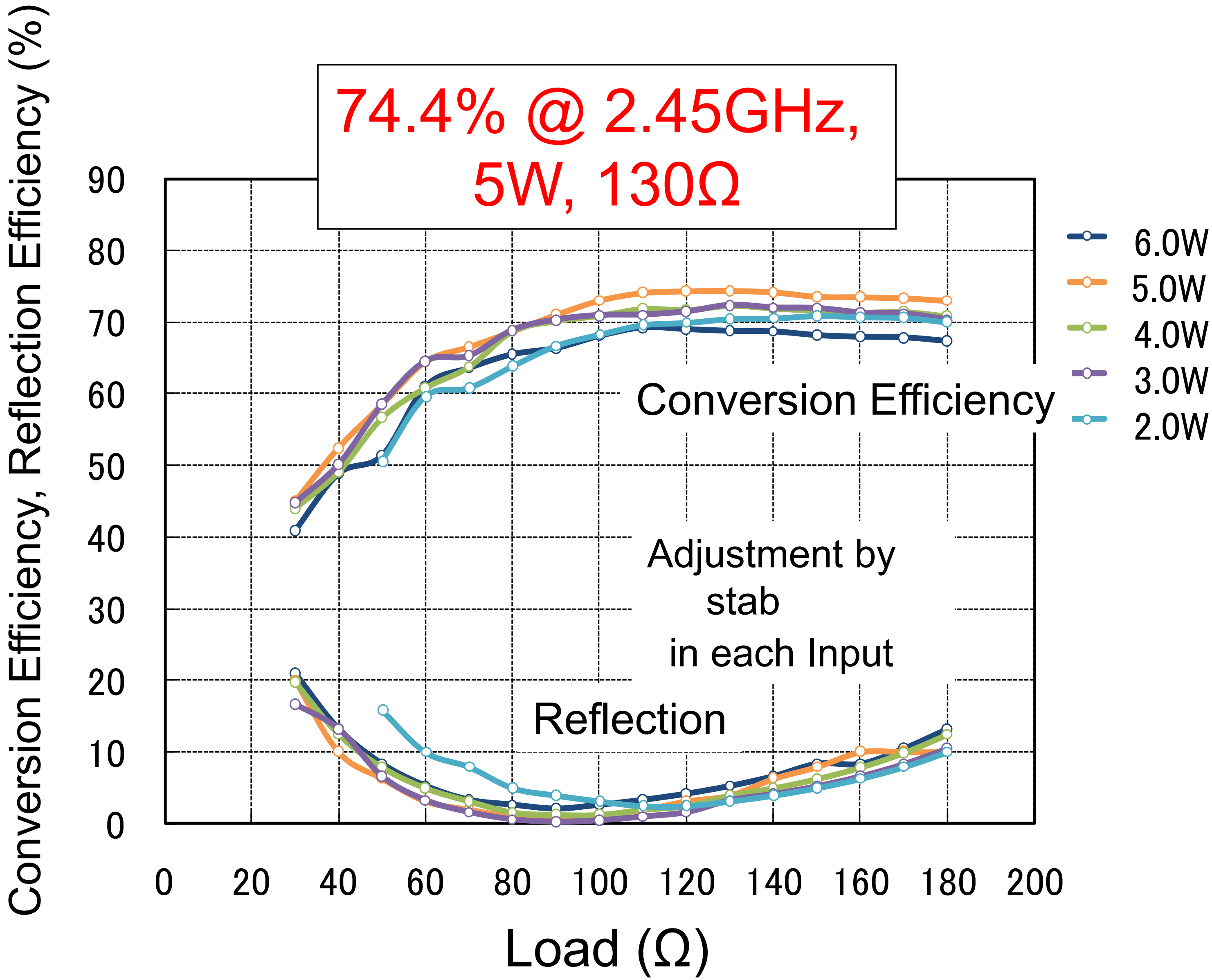
Microwave input

DC output

GaN Schottky Diode

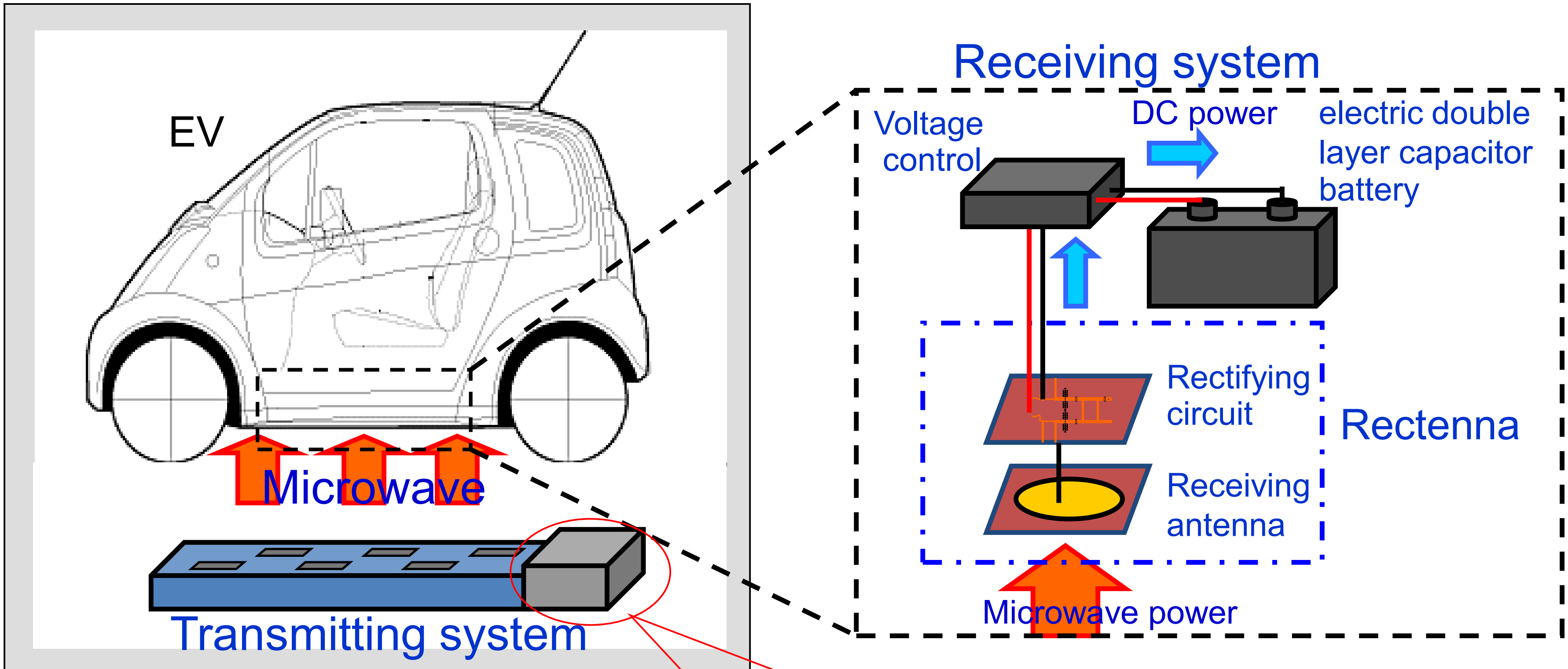
Shinohara, N., et al., “Microwave Building as an Application of Wireless Power Transfer”, Wireless Power Transfer, pp.1-9, 2014.4

GaN Rectenna by Kyoto University and Tokushima University



Shinohara, N., et al., "Microwave Building as an Application of Wireless Power Transfer", Wireless Power Transfer, pp.1-9, 2014.4

MPT in Very Short Distance (EV Microwave Charger)



Wave source: Magnetron
Frequency: 2.45GHz
High efficiency, low cost

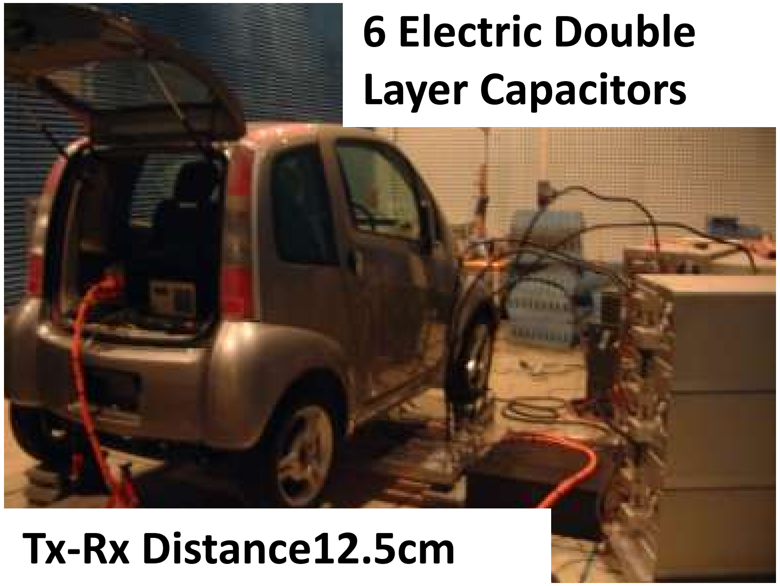
・Transmit by microwave

(If we control the radiating pattern, we can transmit power for long distance.)

・receive and rectify the power by the Rectenna

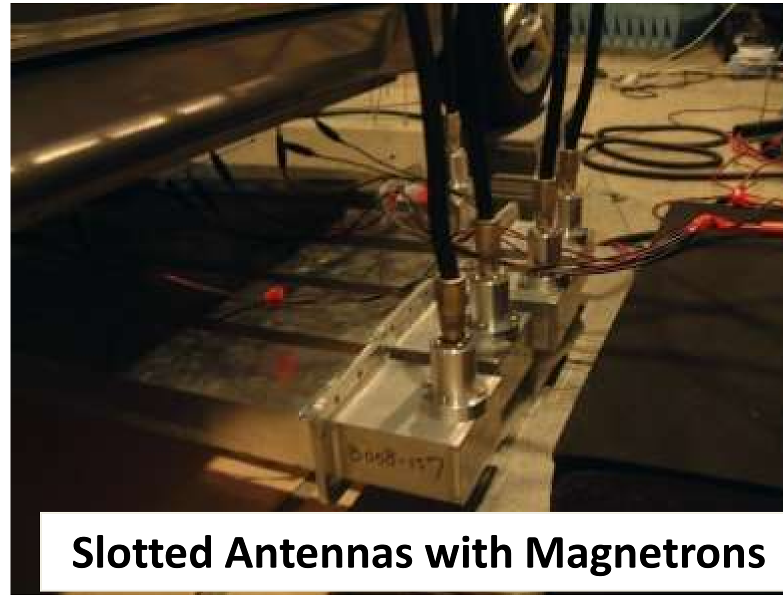
They are thin and lightweight.

First Experiment of Wireless Charging of EV with Microwave by Kyoto Univ. with Nissan Motor co.(2004)



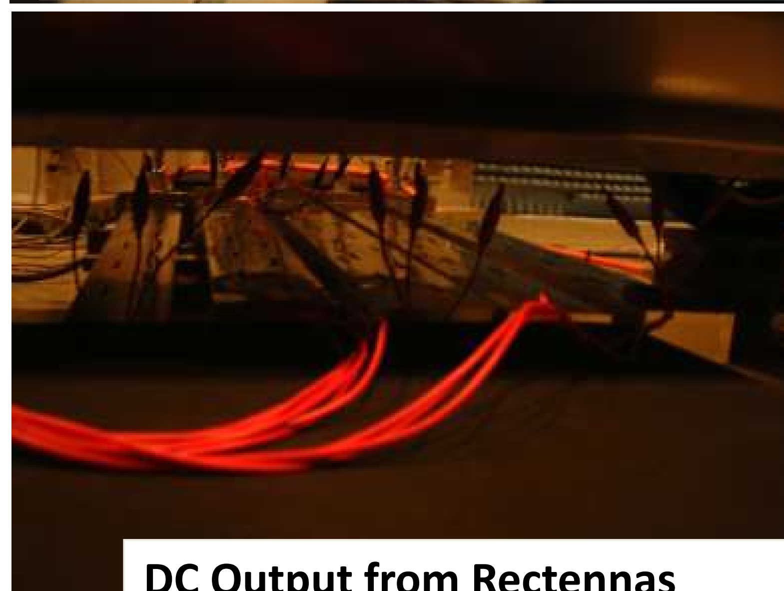
6 Electric Double Layer Capacitors

Tx-Rx Distance12.5cm



Slotted Antennas with Magnetrons

81 Rectennas in Bottom of EV



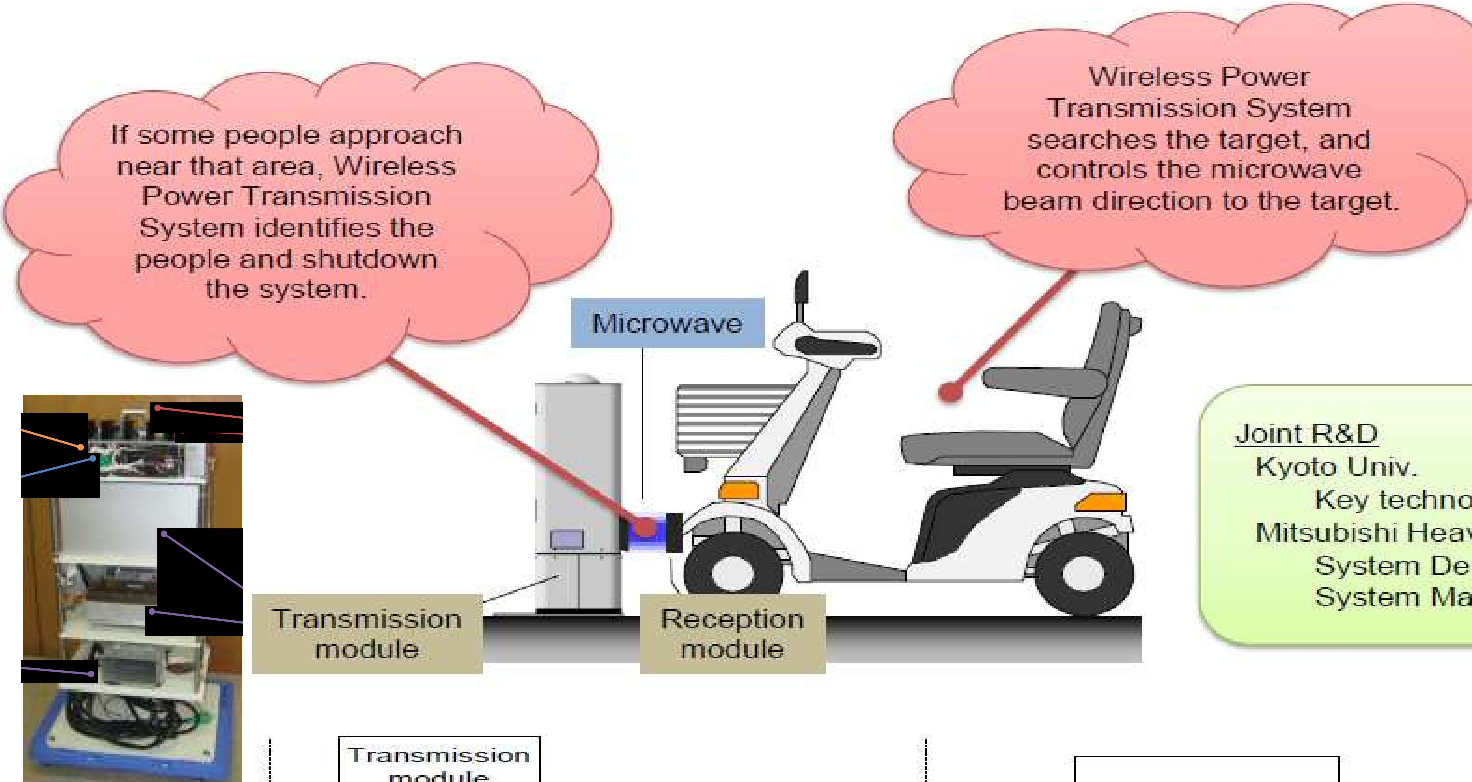
DC Output from Rectennas

Microwave Charging System by MHI co. with Mitsubishi Motors Co., Fuji Heavy Industries, Ltd, Daihatsu Motor Co., Ltd., and Kyoto University (2006-2008)

Magnetron
(2.45GHz)
Directly Drive
by 6.6kV

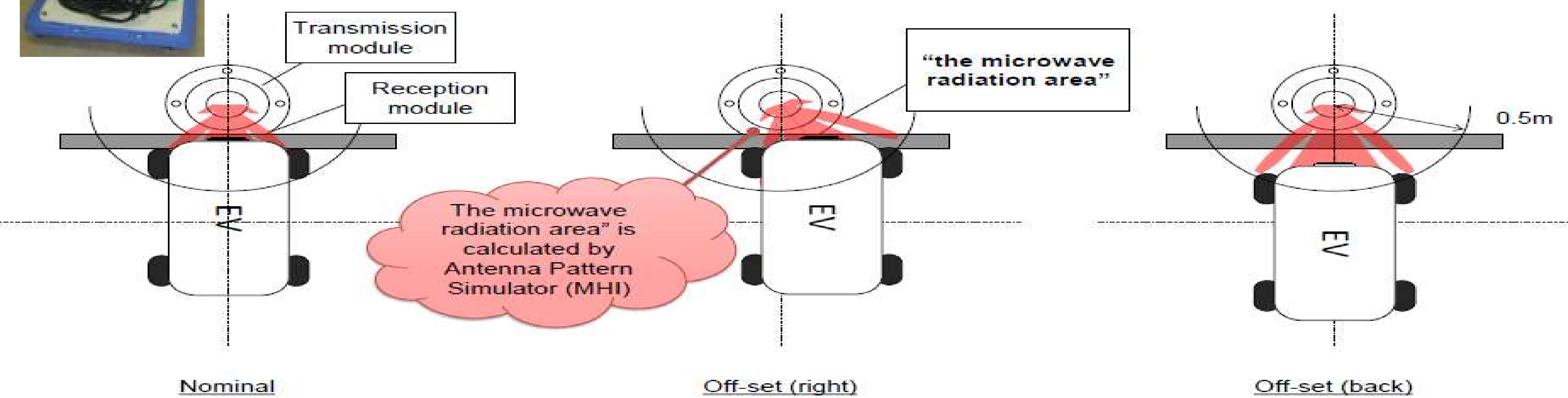
The total efficiency, including the heat recycling, was approximately 38% with an output power of 1 kW at a distance of 12.5 cm.

Wireless Power Transfer to Electric Vehicle in Hospital (Project of 'Center of Innovation' supported by JST)



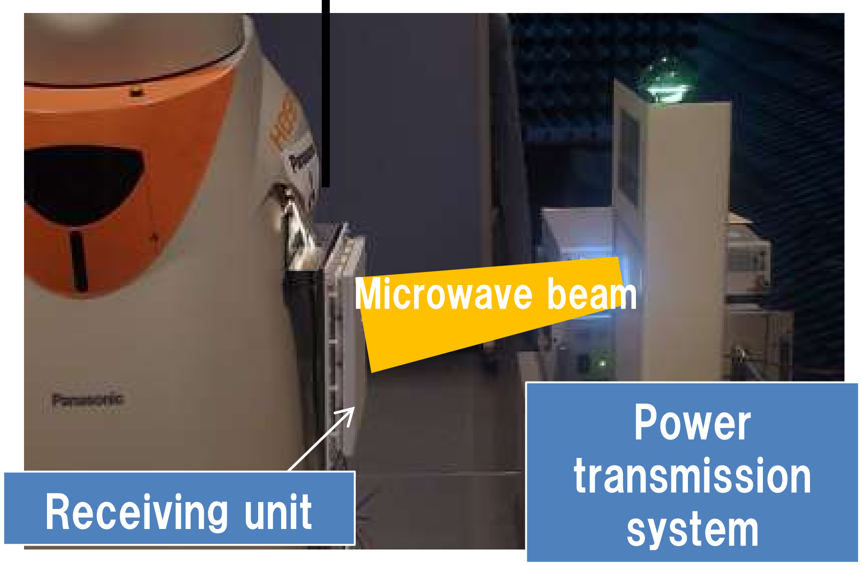
by Kyoto University
with MHI co.
From 2013

Joint R&D
Kyoto Univ.
Key technology
Mitsubishi Heavy Industries
System Design
System Manufacturing

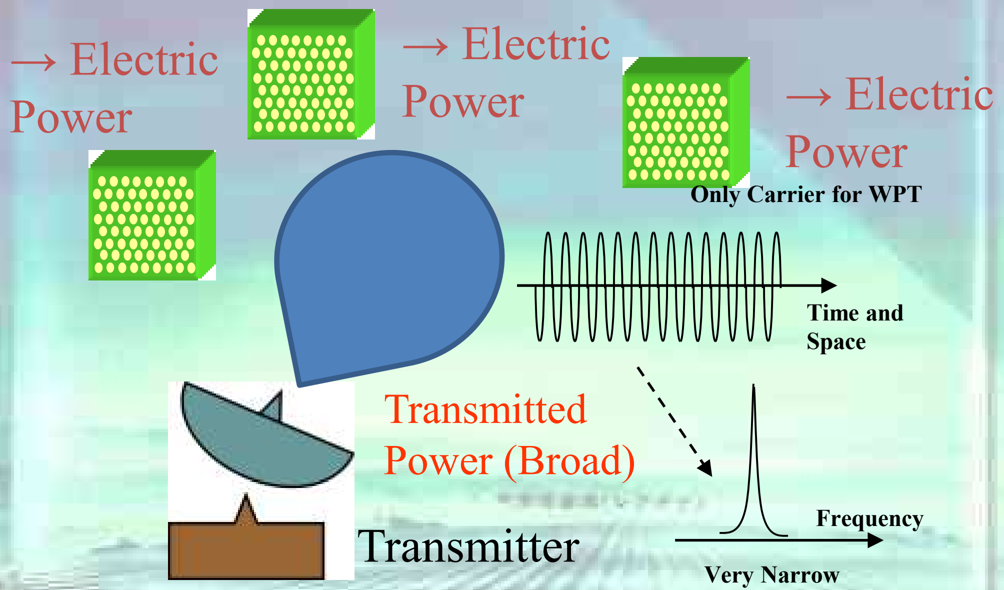


Microwave power supply system for moving object (Project of 'Center of Innovation' supported by JST)

by Kyoto University
with Panasonic co.
From 2013



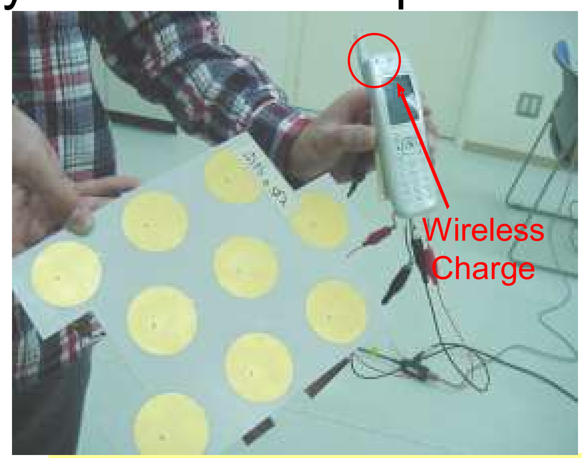
Ubiquitous-type WPT (Wide Beam, Low efficiency) at Kyoto Univ. and in Japan

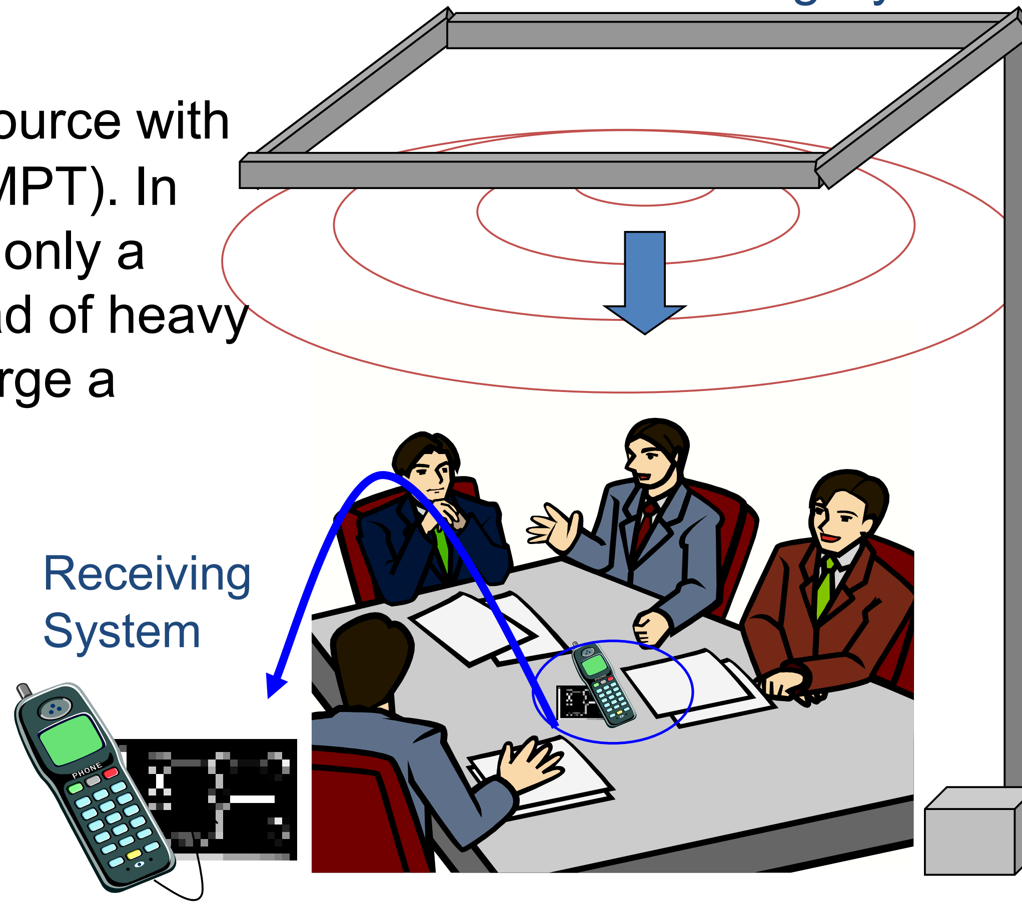


Ubiquitous Power Source (UPS)

Weak point of ubiquitous network society is a power source.

We propose a wireless power source with microwave power transmission (MPT). In most advanced system, we bring only a receiving system, rectenna instead of heavy battery. At first step, we try to charge a battery via microwave power.





Wireless Power source
in every time
and in everywhere

→ **"Ubiquitous Power Source"**

Shinohara, N., et al., "Study on Ubiquitous Power Source with Microwave Power Transmission", Proc. of International Union of Radio Science (URSI) General Assembly 2005, C07.5(01145).pdf, 2005

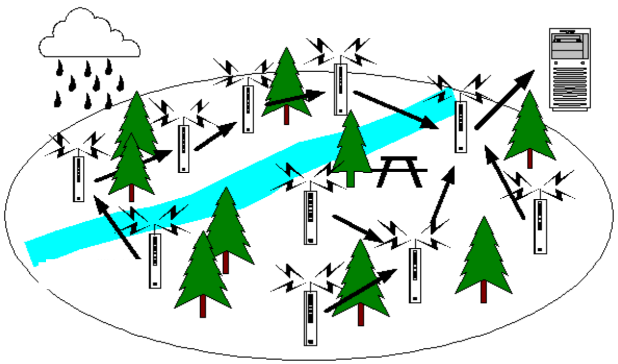
ZigBee Sensor Network

Sensor network is adaptable to widely applications

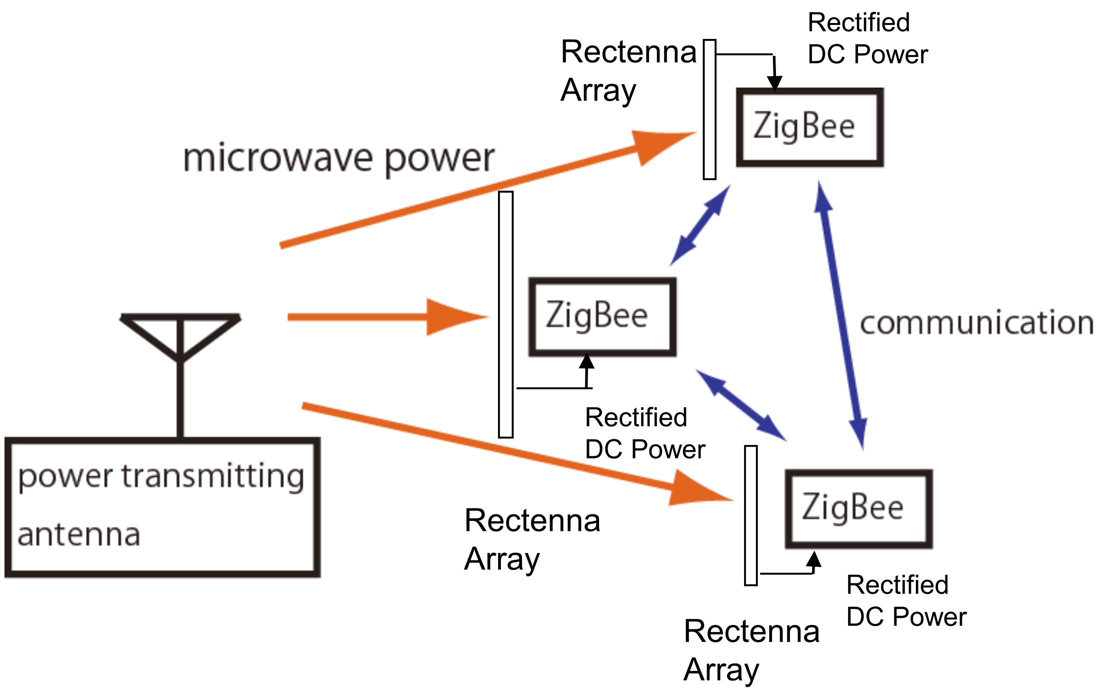
- ･Building automation
- ･Agricultural production management

Power cable
⇒ Wiring cost

Batteries
⇒ Changing batteries



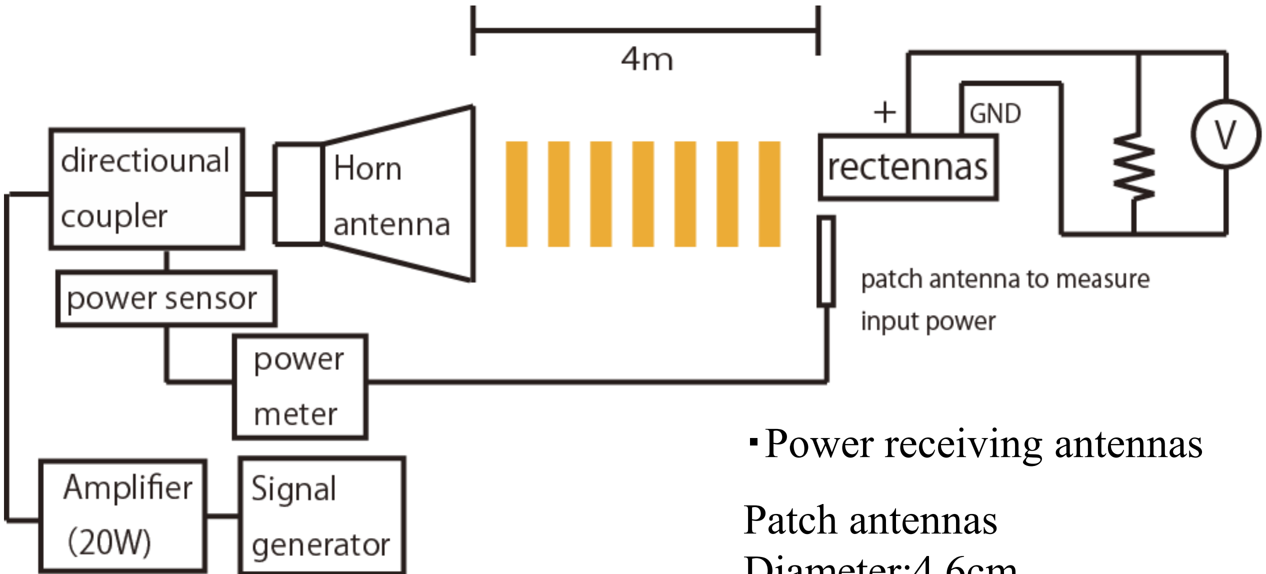
Japan Association for the 2005 World Exposition

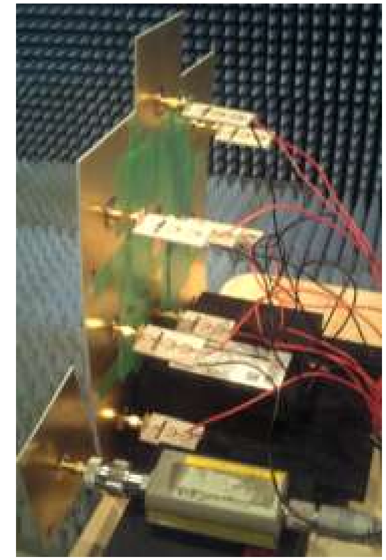


- MPT
  ⇒ 2.45GHz band (ISM band)
- Wireless communication device
  ⇒ ZigBee (2.45GHz band)
  : low power consumption

Shinohara, "Development of Rectenna with Wireless Communication System", Proc. of EuCAP2011, 2011.4.10-15, pp.4139-4142

Wireless power transmission experiments





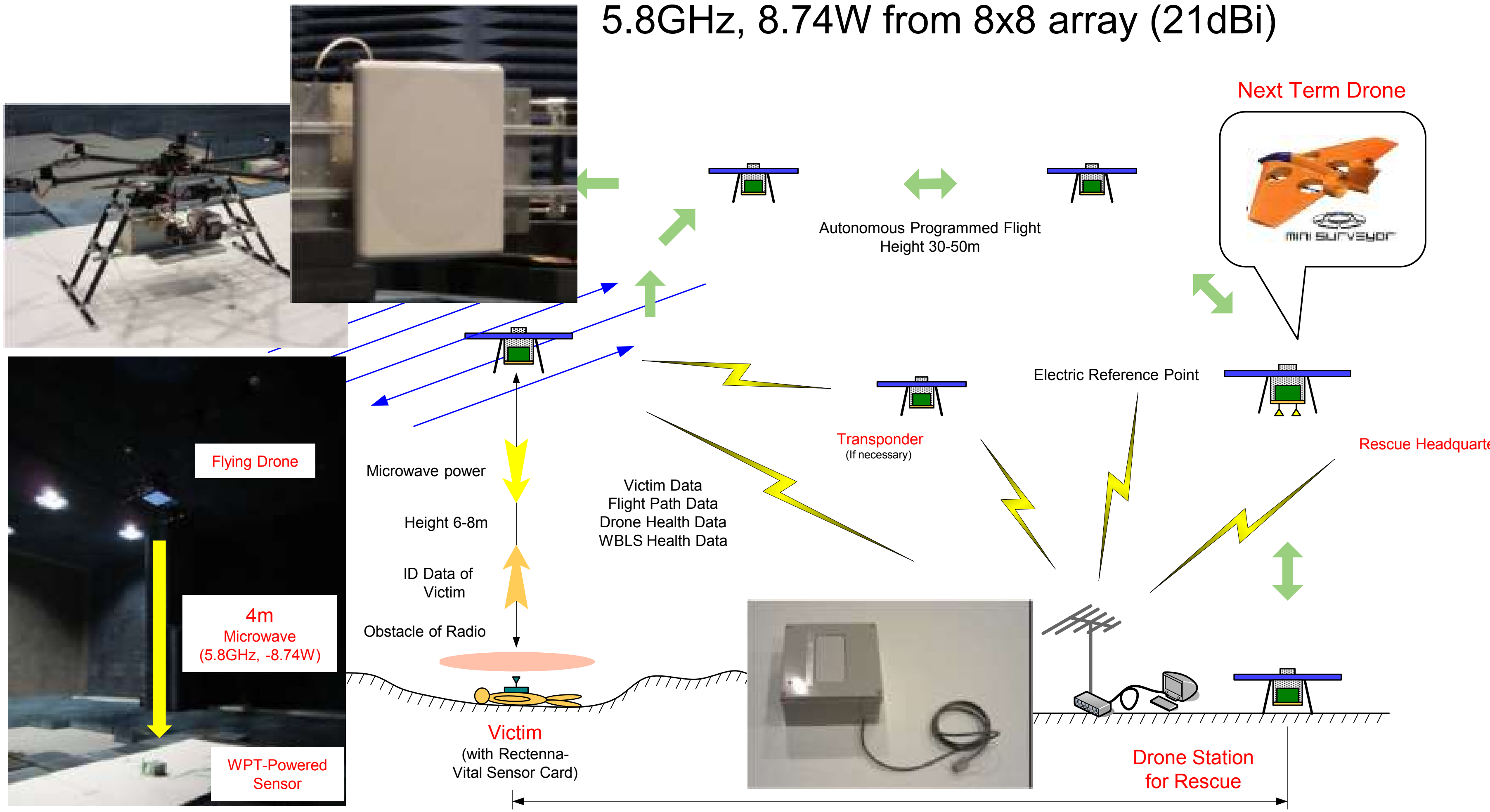
・Power receiving antennas

Patch antennas
Diameter:4.6cm
Gain:6~8dBi

- Rectification circuit was connected patch antenna.⇒<u>rectenna</u>
- We measured conversion efficiency by wireless microwave.
- 9 rectennas with circuits were connected to 140Ω output load in parallel.

Shinohara, "Development of Rectenna with Wireless Communication System", Proc. of EuCAP2011, 2011.4.10-15, pp.4139-4142

Demonstration of WPT-powered Sensors with Drone



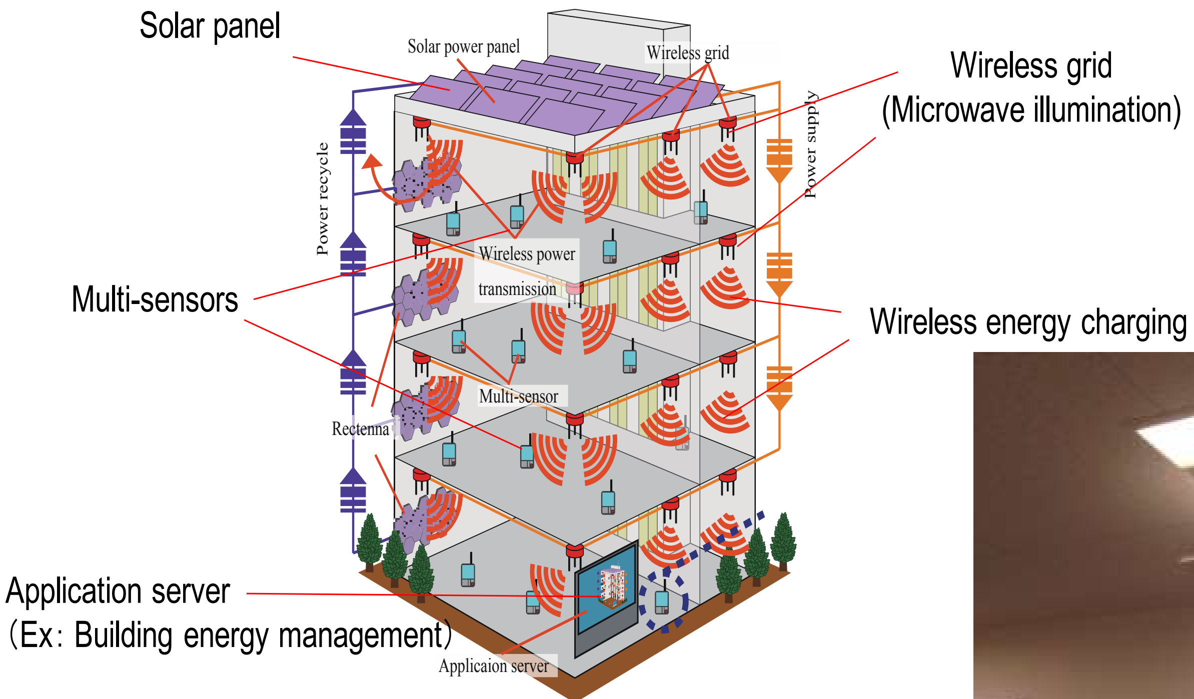
Demo (Jul. 16, 2015)

6.1mW Received at 2 rectennas (10.2dBi)

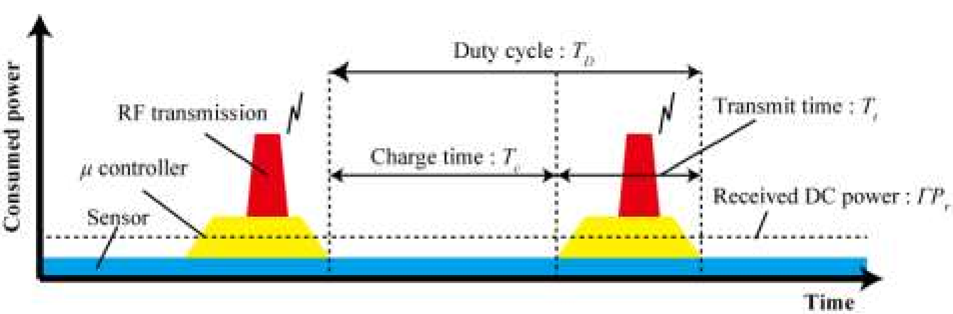
Applications : Rescue of victims, WPT-powered sensors at volcano, Inspection of infrastructures (Bridges, Tunnels..)

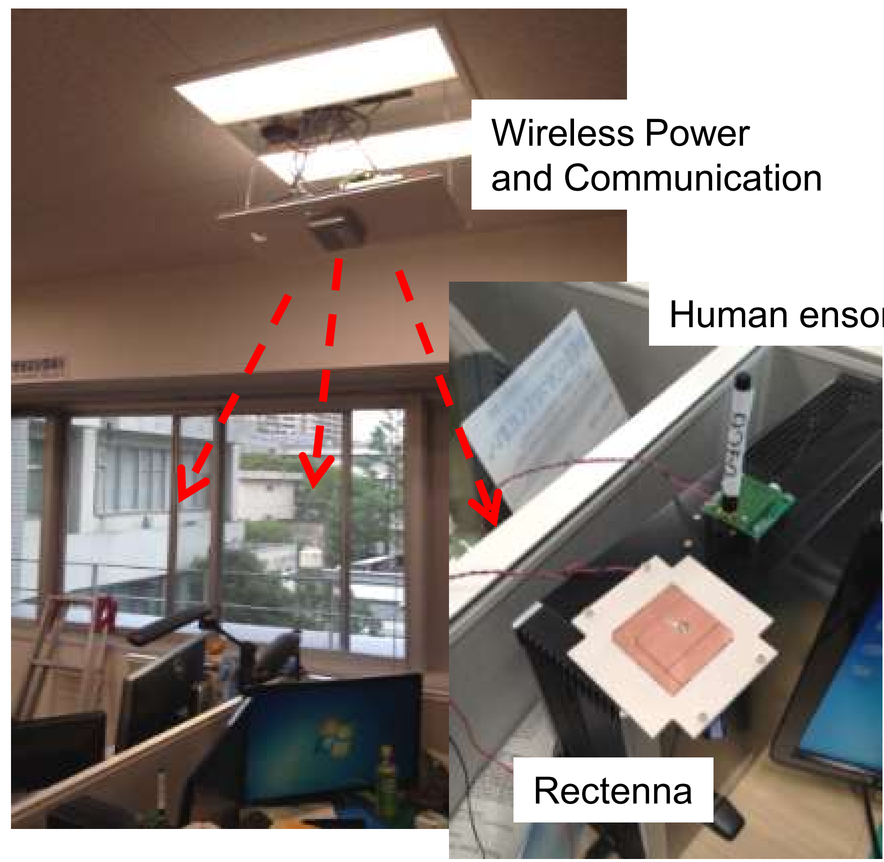
by WiPoT, Kyoto Univ., Mini-Surveyor Consortium, Autonomous Control Systems Laboratory Ltd.

Prof. Sakaguchi's Lab. in Osaka Univ.



920MHz,
1W system

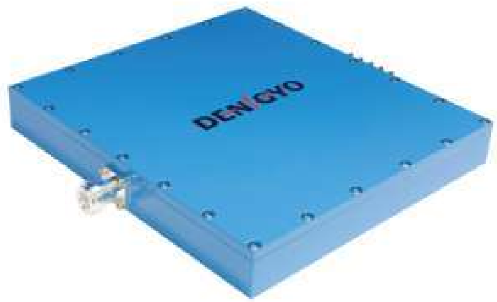




Commercial Product of Rectenna for Energy Harvesting in Japan

- 90% RF-DC Conversion Efficiency at 2GHz-Band

(by Nihon Dengyo Kosaku, co.)

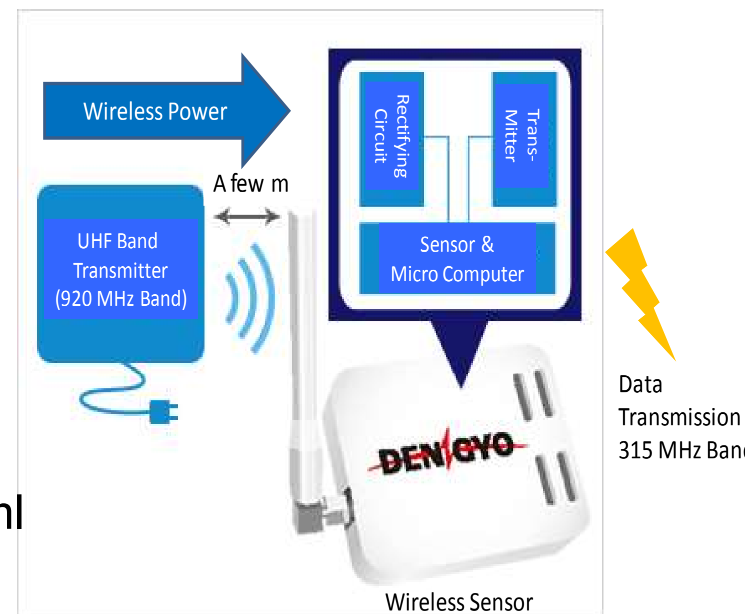


http://www.den-gyo.com/technology/index.html

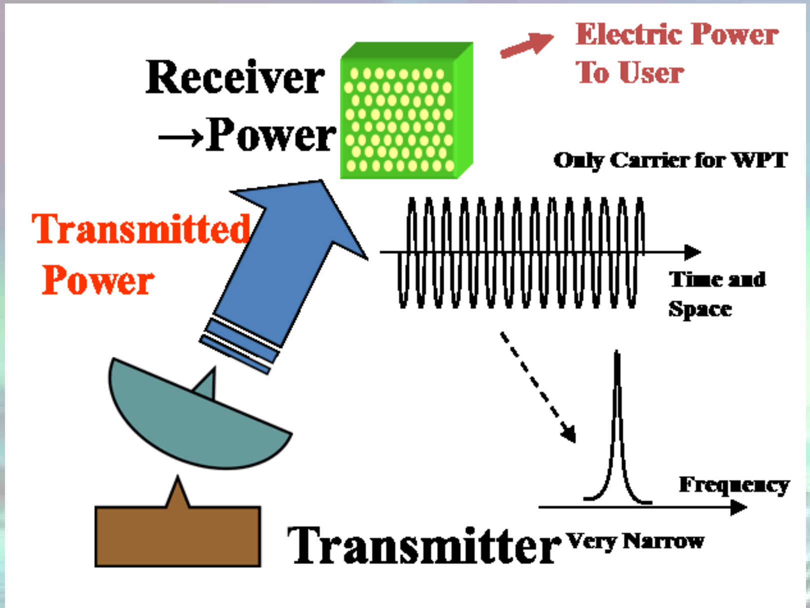
- Battery-less Sensor

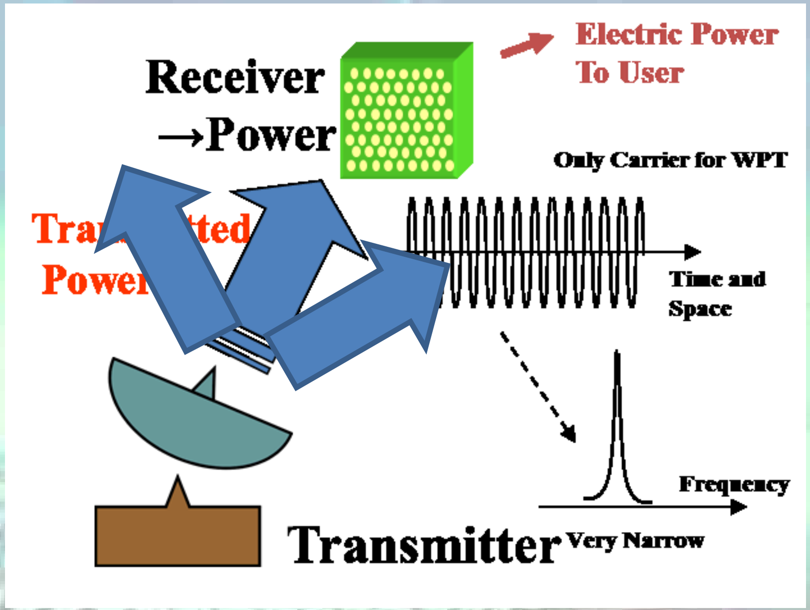
(by Nihon Dengyo Kosaku, co.)

http://www.den-gyo.com/solution/solution10_b.html



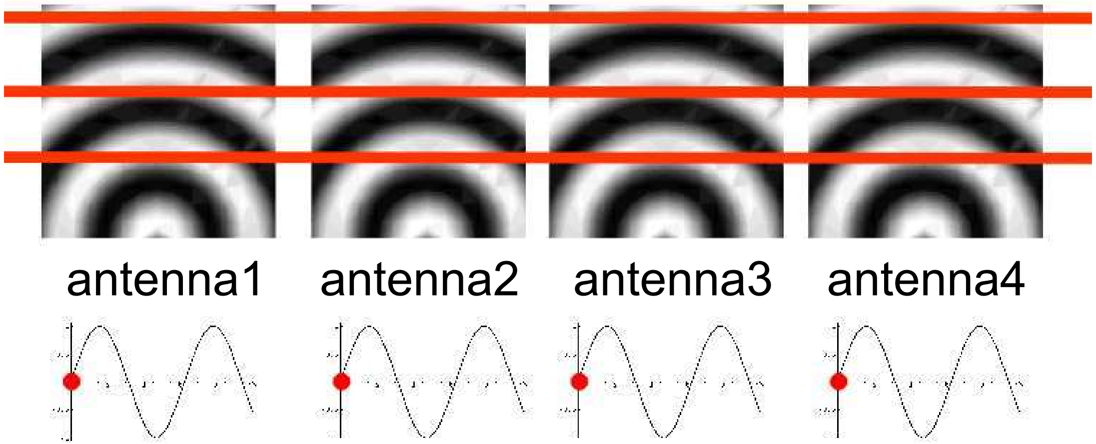
Beam-type WPT (Narrow Beam, High efficiency) at Kyoto Univ. and in Japan





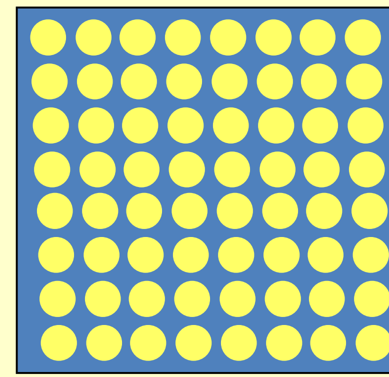
Phase Array for Beamforming

(a) Same phases of radio waves from different antennas



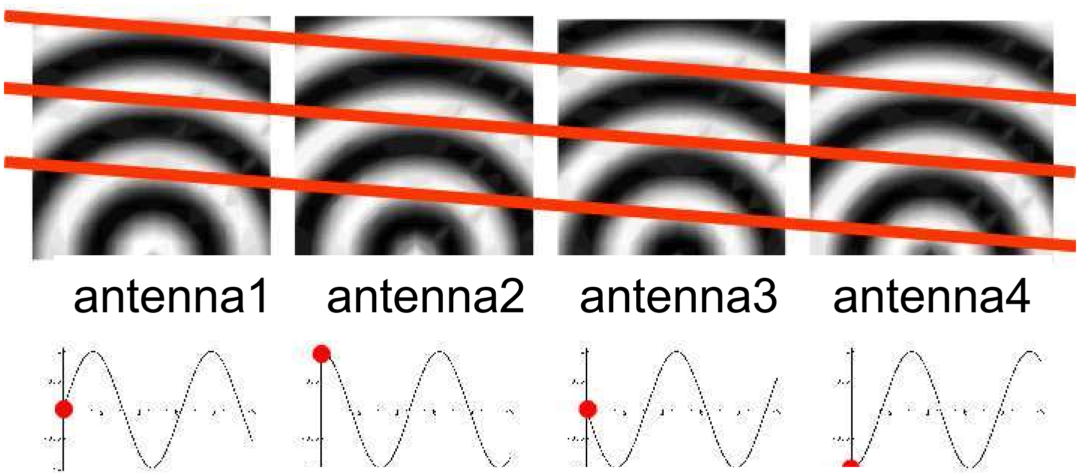
●: antenna, X-axis: distance from antenna

→ Equivalent phase plane is front
=Beam direction is to front



2D Phased Array
with Circular Antennas

(b) Different phases of radio waves from different antennas



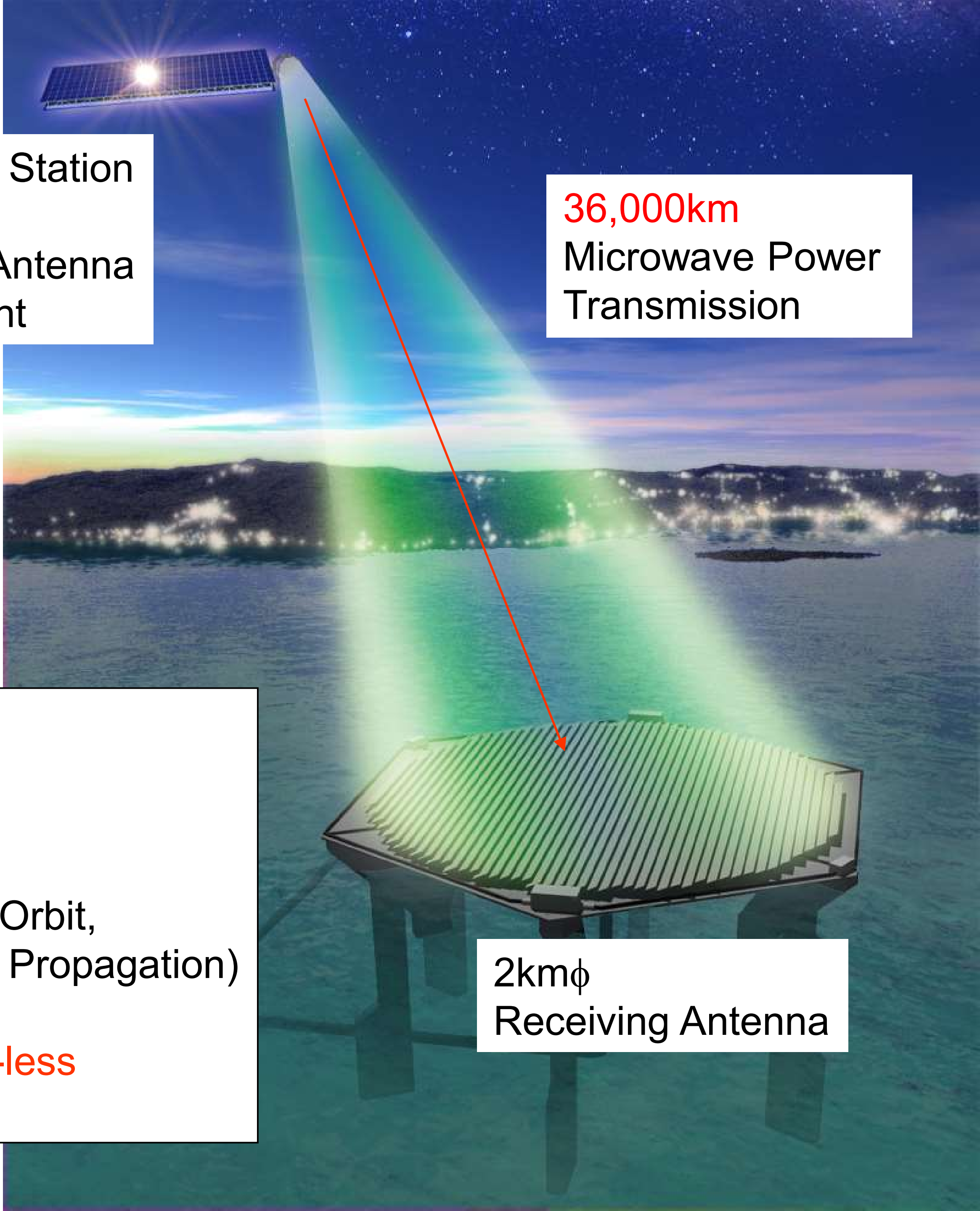
●: antenna, X-axis: distance from antenna

→ Equivalent phase plane is oblique

=Beam direction is to oblique

Future Dream of MPT:

Solar Power Satellite (SPS)



Energy Availability Factor

Ground PV

: < 15% (Night, Rain…)

Space PV (SPS)

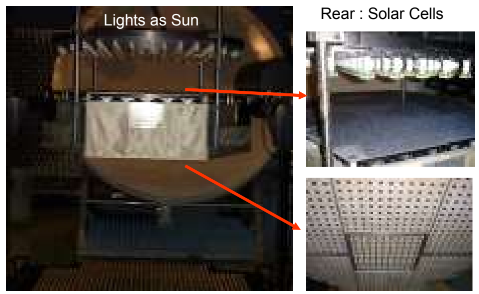
: >90% (No Night in 36,000km Orbit,
No Rain by Microwave Propagation)

-> SPS is huge, stable, and CO_2-less Power Station

Phased Array Developed in Japan

Semi-Conductors

1992 (for Airplane Experiment)
2.45GHz, Total Power >1.2kW
96 array module, 3in1 sub-array
HPA PAE >40% (GaAs)
By Kyoto Univ. and Kobe Univ.

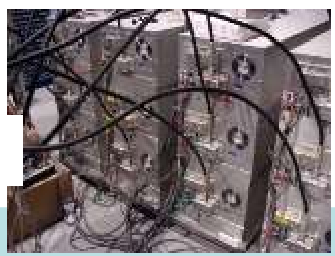


2000 SPTITZ (for SPS)
5.8GHz, Total Power >25W
100 array module with Solar Cell,
System Eff. >15% (GaAs)
by JAXA and Kyoto Univ.

2010 5.8GHz,
Total Power >1.9kW
256 array module
HPA PAE >70% (GaN)
thickness <30cm
at Kyoto Univ.

2015 5.8GHz,
Total Power >1.6kW
304 array module
4in1 sub-array
HPA PAE >70% (GaN)
thickness <2.5cm
by METI & JSS

Magnetrons



2000 SPORTS2.45
2.45GHz,
Total Power >4kW
12 magnetron array
Eff. >70%
at Kyoto Univ.

2001 SPORTS5.8
5.8GHz,
Total Power >2.7kW
9 magnetron array
Eff. >65%
at Kyoto Univ.

2009 for Airship Exp.
2.45GHz,
Total Power >440W
2 magnetron array
(light weight)
by Kyoto Univ.

2015 2.45GHz
Total Power >10kW
500m Field Exp.
by METI & JSS

1990 2000 2010

MILAX Airplane Experiment (1992.8)

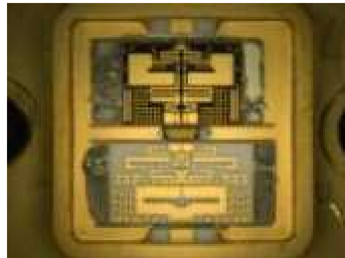
Kyoto Univ., Kobe Univ., CRL, Nissan motor co., Fuji heavy industry co., ISAS in Japan

1992 (for Airplane Experiment)
2.45GHz, Total Power >1.2kW
96 array module, 3in1 sub-array
HPA PAE >40% (GaAs)

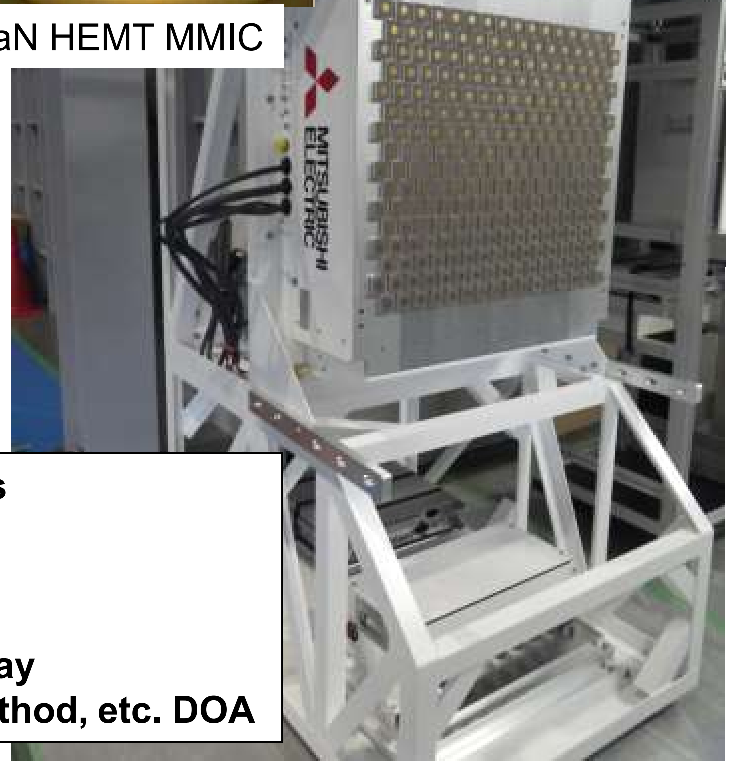
Developed by IHI Aerospace (former Nissan Motor Co.)

Phased Array Antenna at Kyoto University (2010)

Research Facility for
- Beam Forming Experiments
- Target Detecting Algorism Experiments
- Development of Antennas (with Microwave Circuits)
- Development of Microwave Circuits (with Antennas)
- Rectenna Experiments
- Wireless Power Transmission Experiments



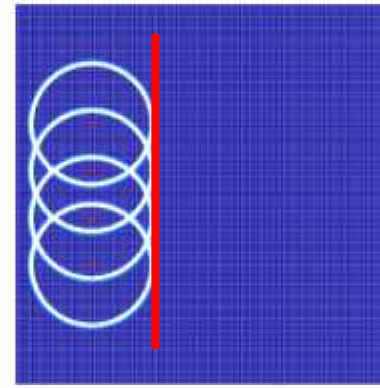
GaN HEMT MMIC



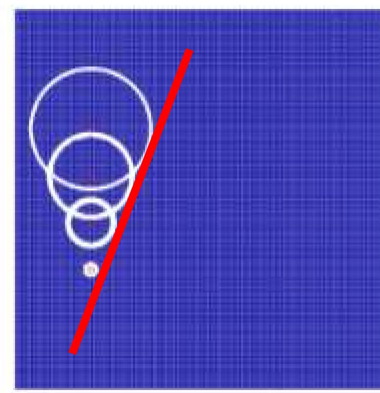
- **256 Antenna Elements**
- **1.5kW**
- **GaN FET F-Class HPA (7W, >70%)**
- **MMIC 5bit Phased Array**
- **REV, PAC, Parallel Method, etc. DOA**

Advanced Phased Array at Kyoto University

Front (Equal Phases)



Dawn (Controlled Phases)

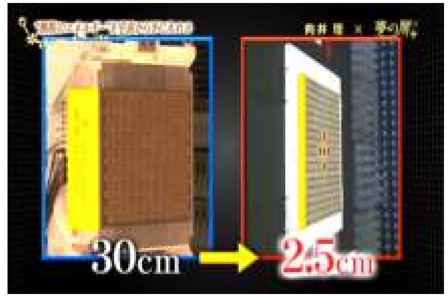


MPT Experiment on Feb. 2015 (1)
Thin-High Efficiency Phased Array with GaN MMIC

2.5cm thickness phased array
GaN MMIC Amplifiers
5.8GHz, 1.8kW

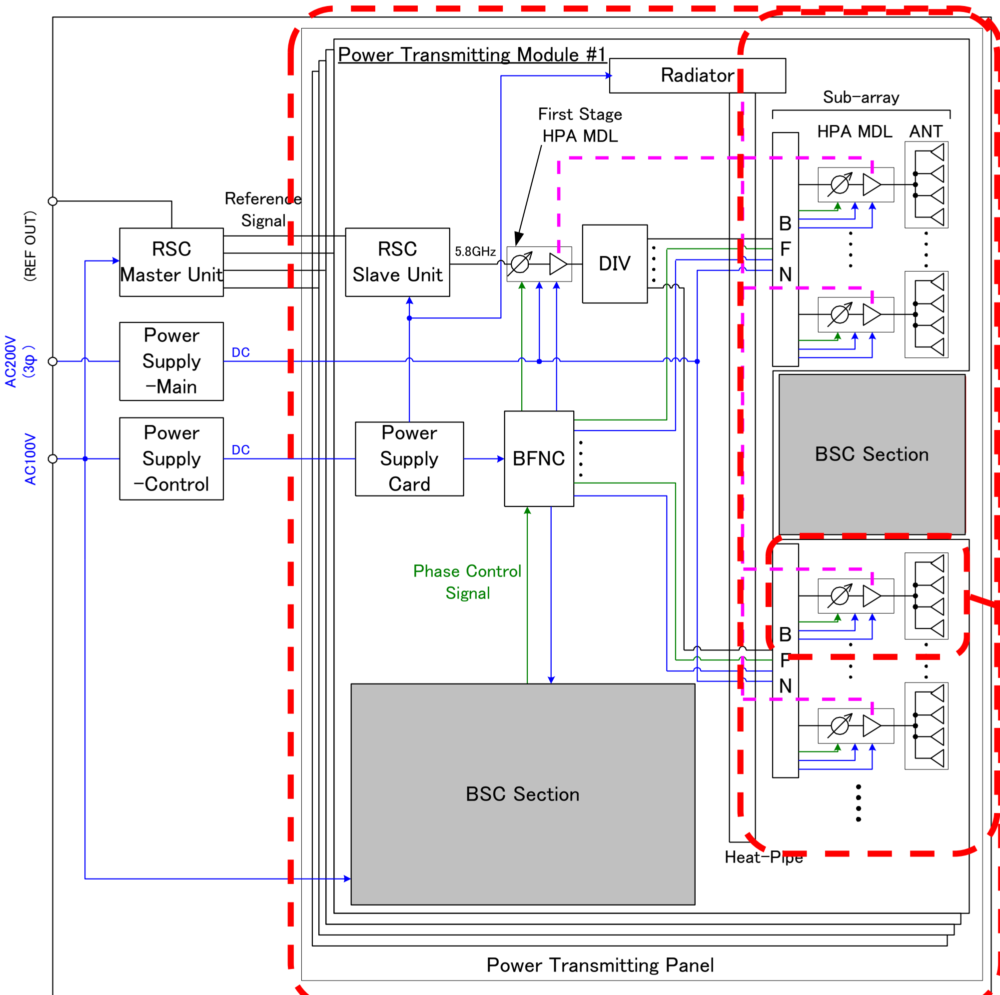
Developed by Mistubishi Electric Corp. (Phased Array), IHI Aerospace (Rectenna Array), Supported by METI

Developed Thin Phased Array Antenna (FY2009-2014) by Japanese SPS Committee

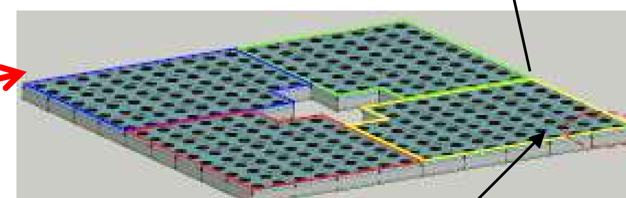


(120cm x 120cm) , 5.8GHz, 1.8kWCW

Thin Phased Array



Power Transmitting Module Image

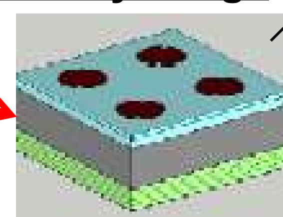


60cm x 60cm, ≧ 450W , ≦1.9kg

Transmitting ANT

(76 Sub-array ANT)

Sub-array Image



Sub-array ANT (4 elements)

HPA MDL (PAE >70%) (High Power amplifier Module)

BFN(Beam Forming Network)

(66mm x 66mm x 25mm(Thickness))

: RF/IF Signal
: Power Line
: Control Signal
: Thermal Path

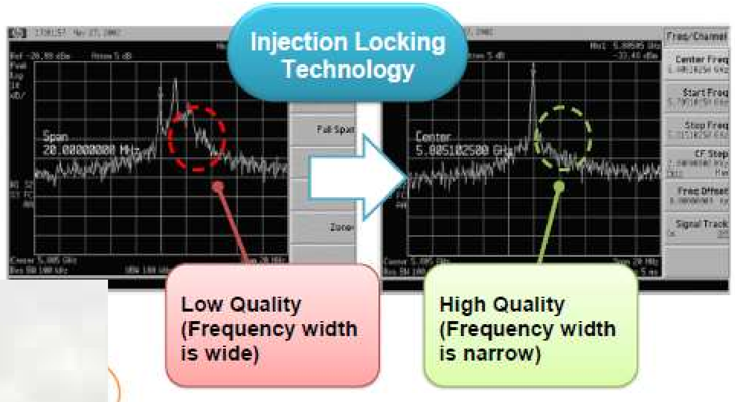
RSC: Reference Signal Control
BSC: Beam Steering Control
BFN: Beam Forming Network
BFNC: BFN for Control Signal

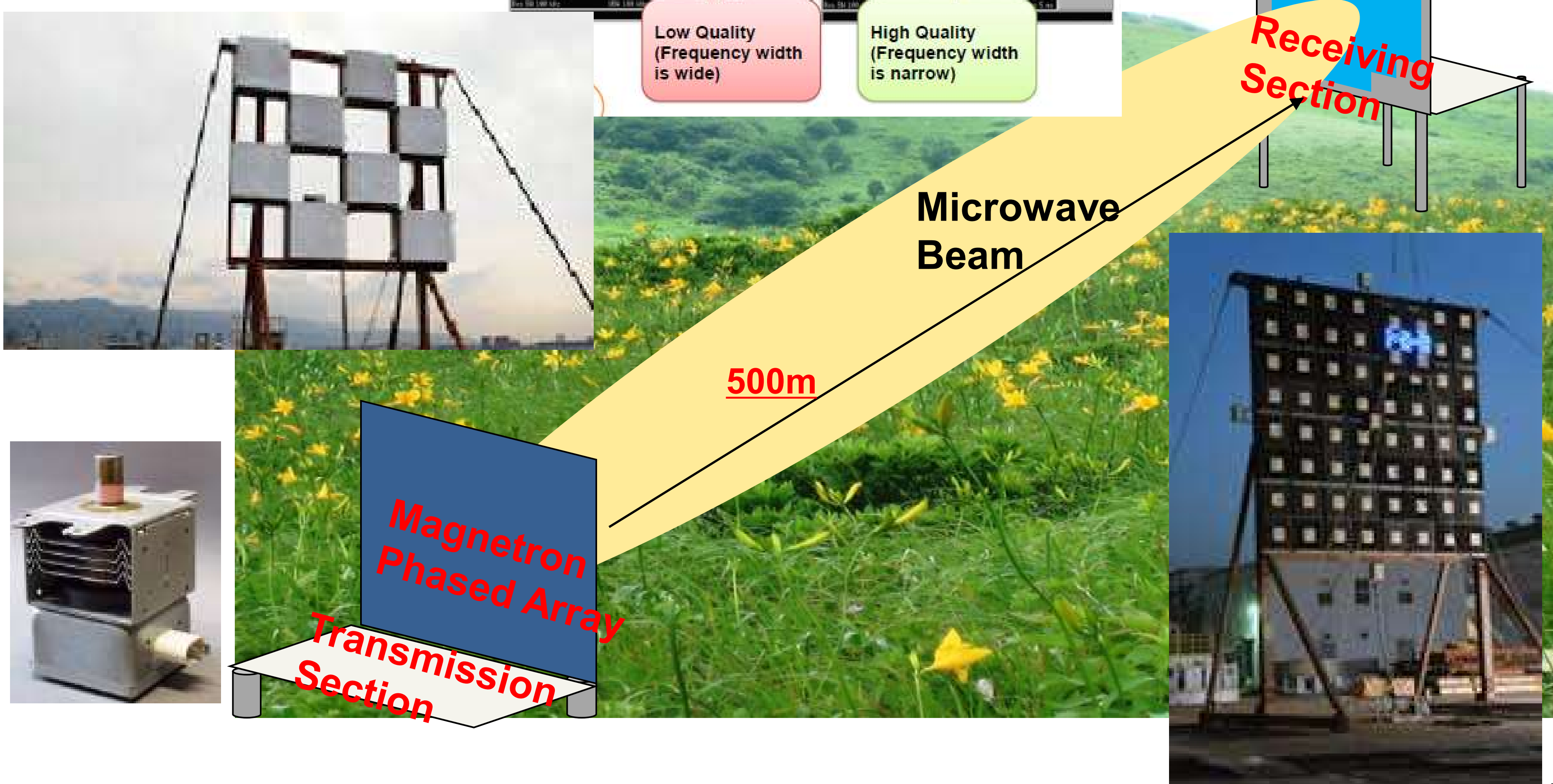
DIV: Divdier
HPA MDL: High Power Amplifier Module
ANT: Antenna

Developed by Mistubishi Electric Corp., Supported by METI

MPT Experiment on Feb. 2015 (2)
High Power-Low Cost Phased Array with Magnetrons

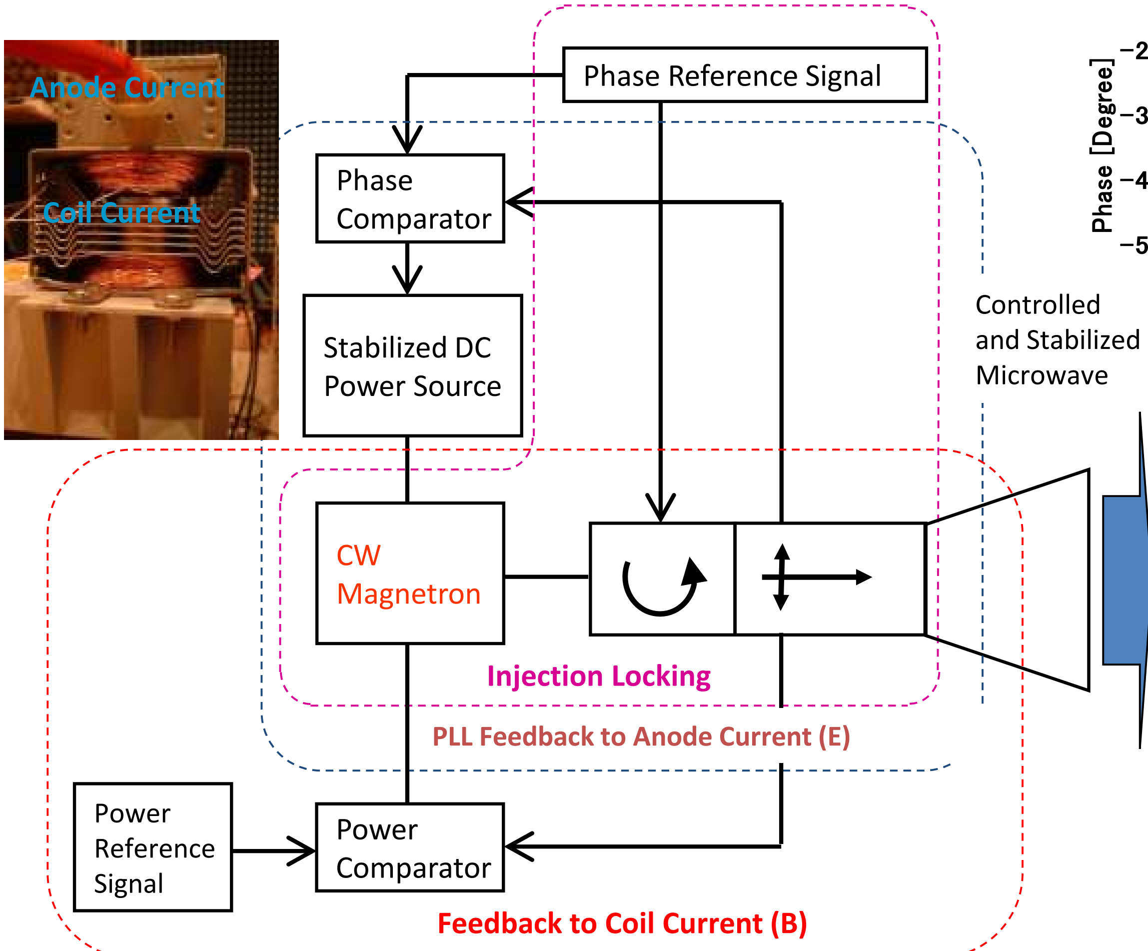
Magnetron phased array
2.45GHz, 10kW
Height 13m





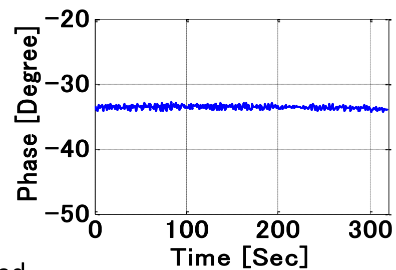
Developed by Mistubishi Heavy Industries, Supported by METI

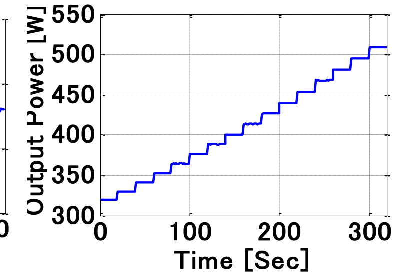
Phase and Amplitude Controlled Magnetron at Kyoto Univ.



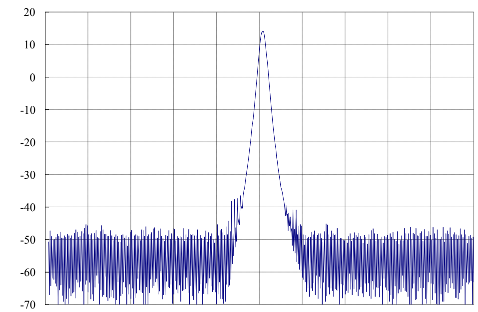
PACM for phased array system

Stable Phase in Changed Power



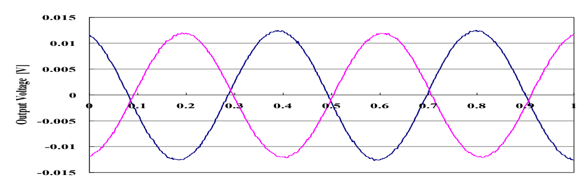


Wave Spectrum of PACM



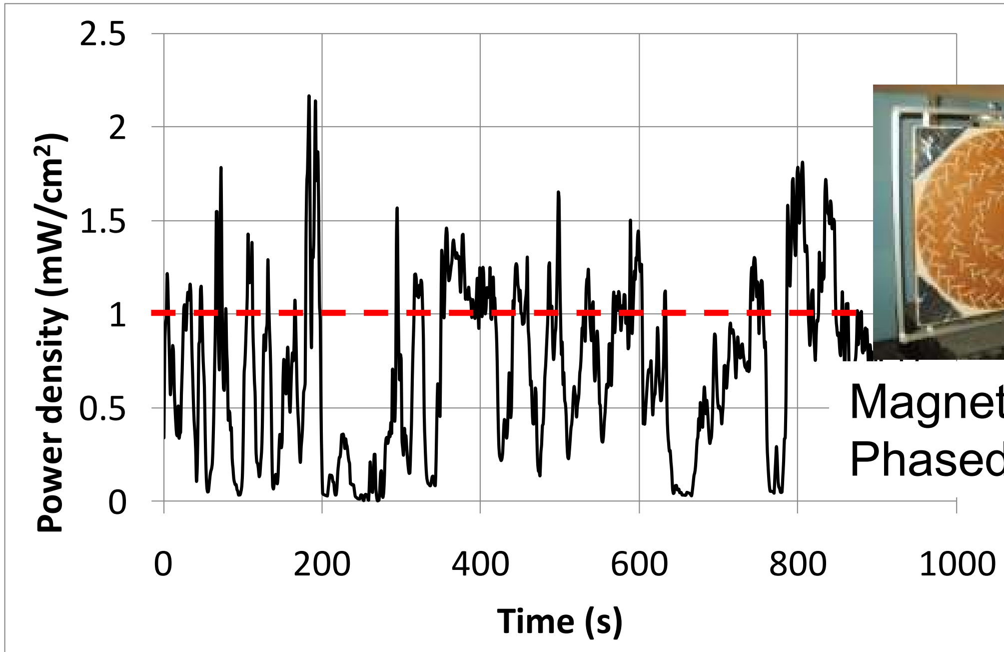
center:2.45GHz , span:10.0MHz , RBW:100kHz, Pi/PO: -33dB

Wave Forms of Two PACMs

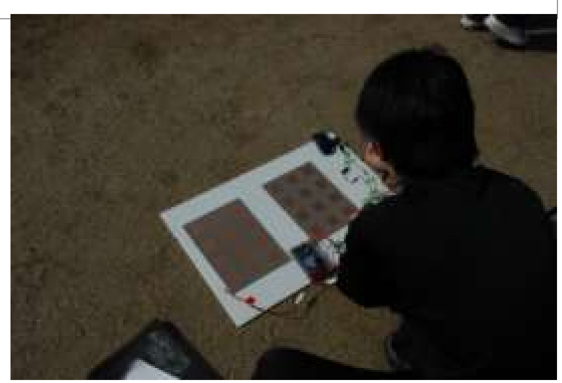


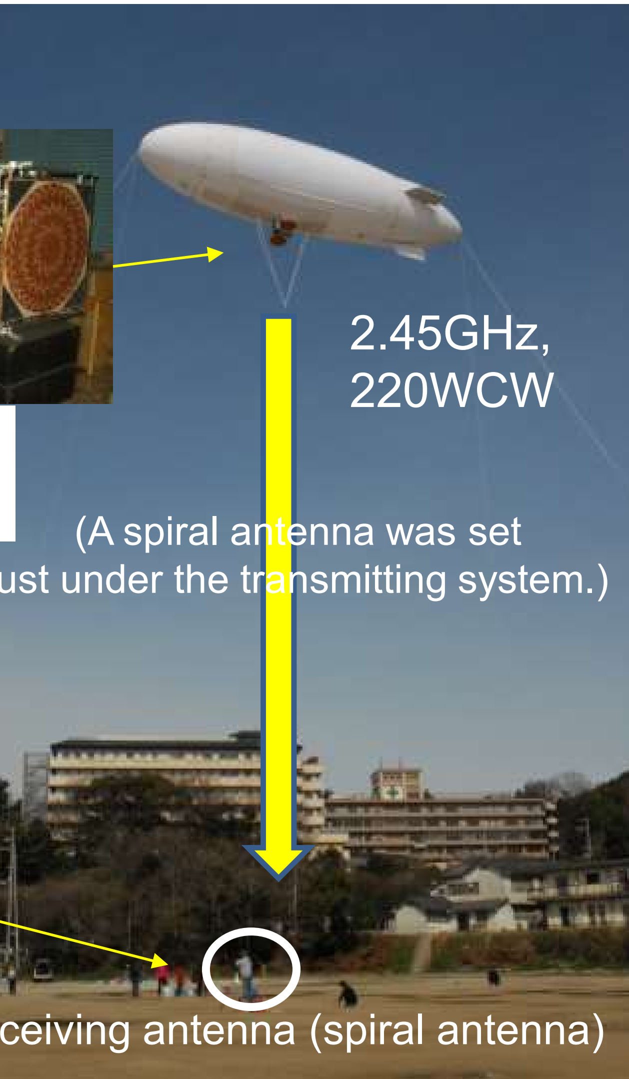
WPT in Emergency – Power from Space – 2009, by Kyoto University

Microwave power density at the center of the receiving site



Magnetron Phased Array

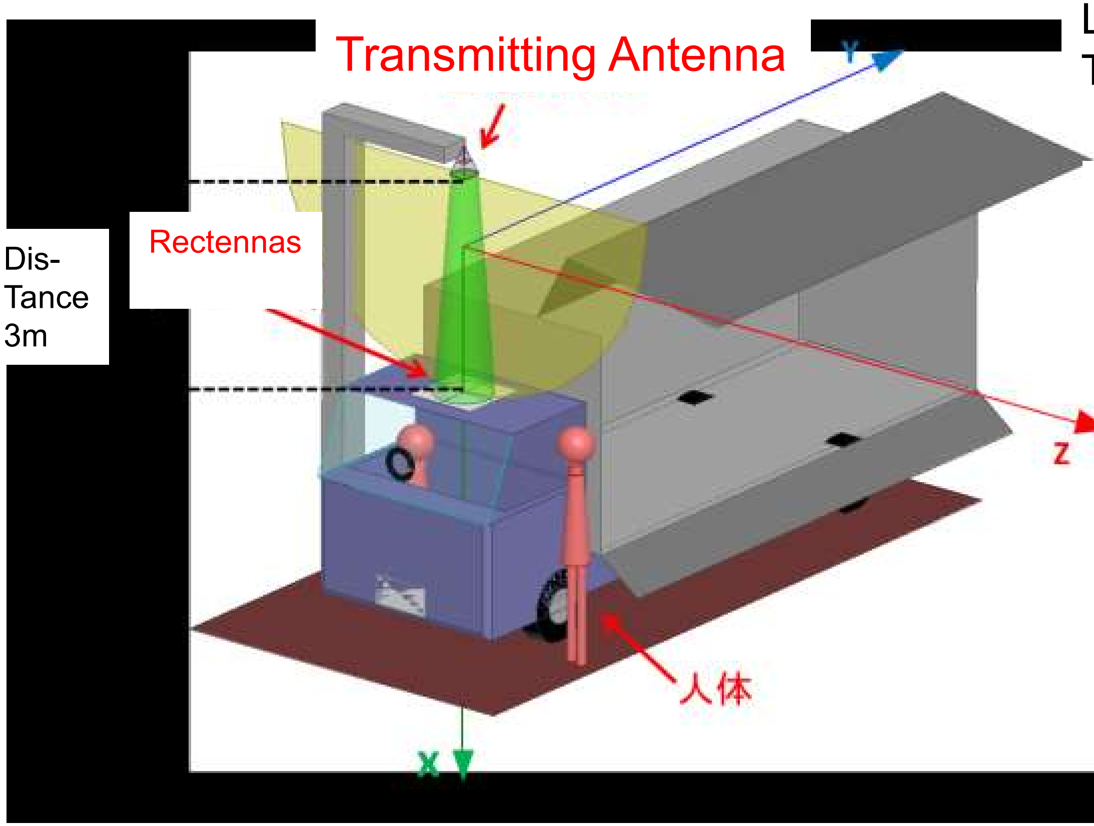




Mitani, T., et al., "Demonstration Experiment of Microwave Power and Information Transmission from an Airship", Proc. of 2nd International Symposium on Radio System and Space Plasma 2010, pp.157-160, 2010

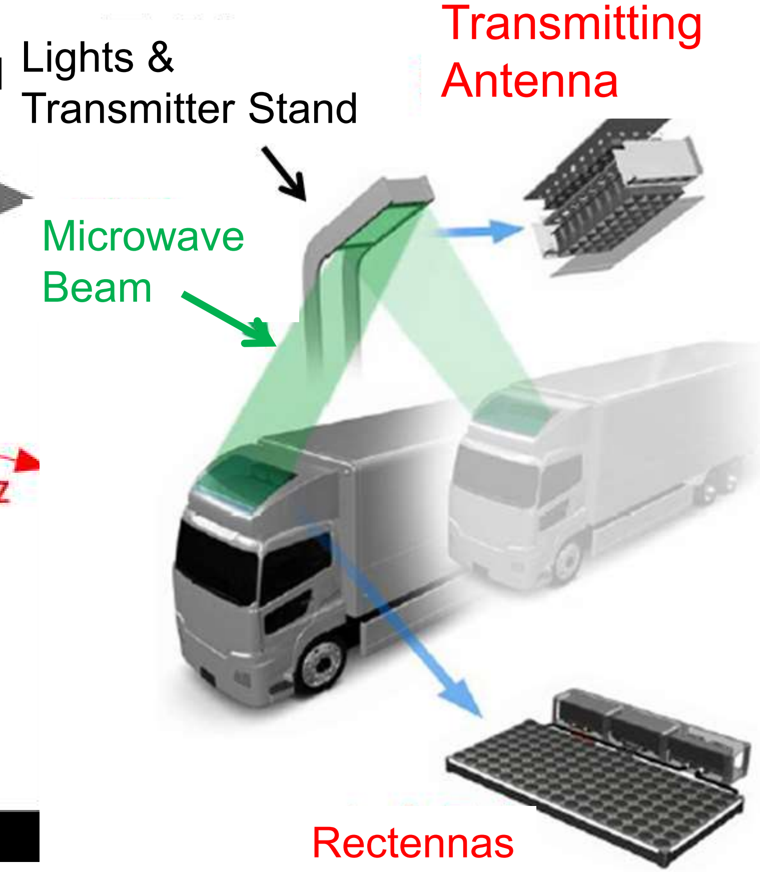
A new microwave power supply system

- In Parking



Transmission Distance1-4m

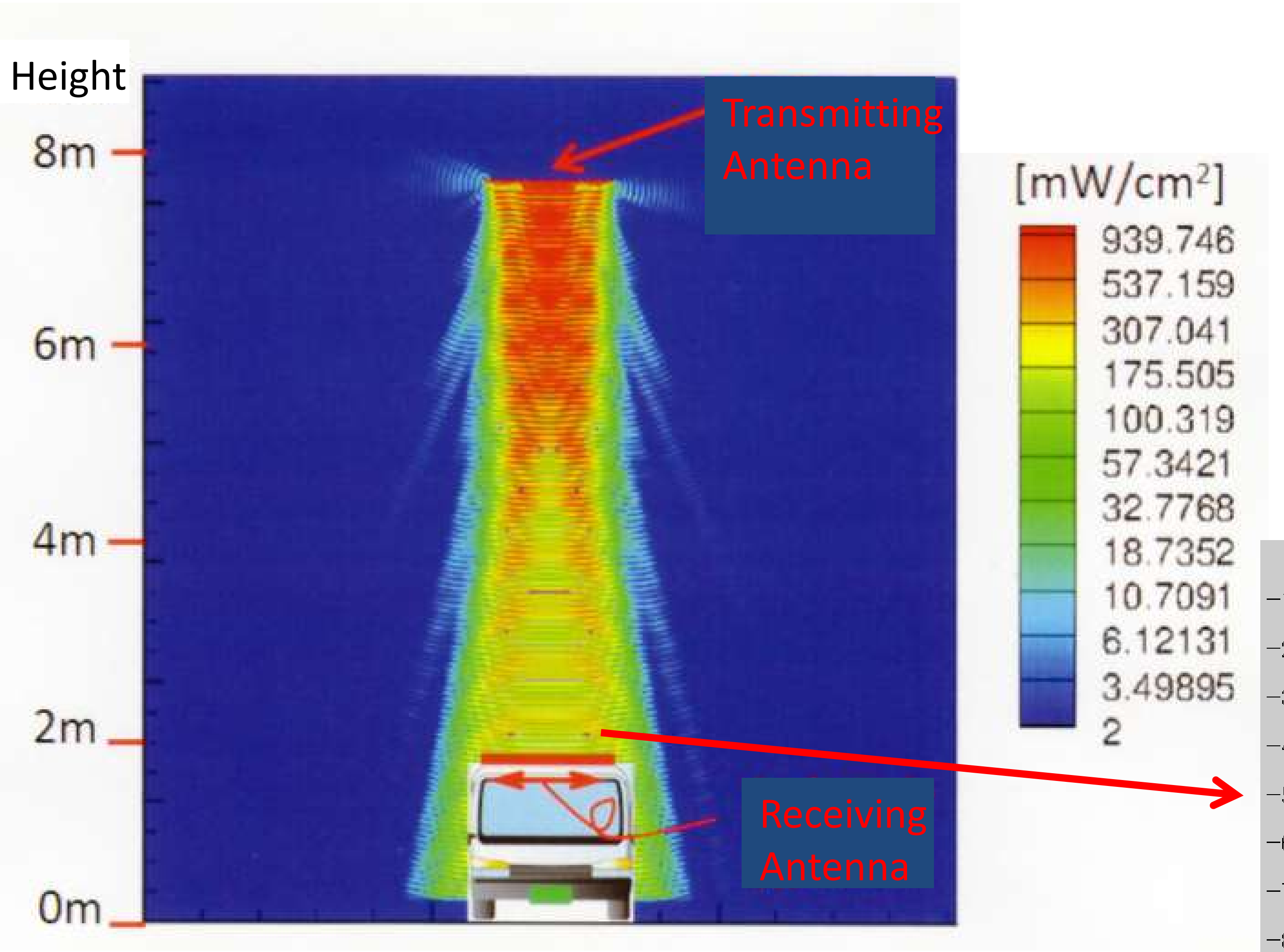
- In Driving



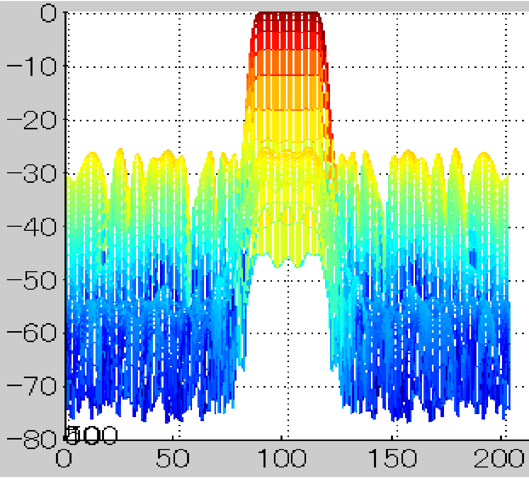
Transmission Distance 4-10m

Collaborative Research with Volvo

FDTD Simulation of Mid-Distance MPT



Flat Beam
by Genetic Algorithm



トラックやバスに非接触充電 Volvoなどがレクテナを開発

豊橋技術科学大学は走行中のEVへの給電で進展

ボルボテクノロジー・ジャパンと日本電業工作の研究グループ（上）と、豊橋技術科学大学の研究グループ（下）

電気自動車（EV）向けワイヤレス給電技術に関する研究開発が活発になっている。スウェーデンVolvo社が同グループのアジアにおける研究開発拠点として2012年に東京に設立したボルボテクノロジー・ジャパンと、豊橋技術科学大学はそれぞれ、最新の研究成果を発表した。

現在、EVの普及を妨げている主要因の一つが、大容量のLiイオン2次電池を搭載していること。Liイオン2次電池のコストはEVの車両価格の1/3程度を占めると言われている。搭載する容量を抑えれば、走行距離は短くなってしまう。こうした課題を解決する方法の一つとして、ワイヤレス給電の適用が検討されているのだ。充電の手間が少ないワイヤレス給電を用いて充電回数を増やし、その分2次電池の搭載容量を抑える狙いである。

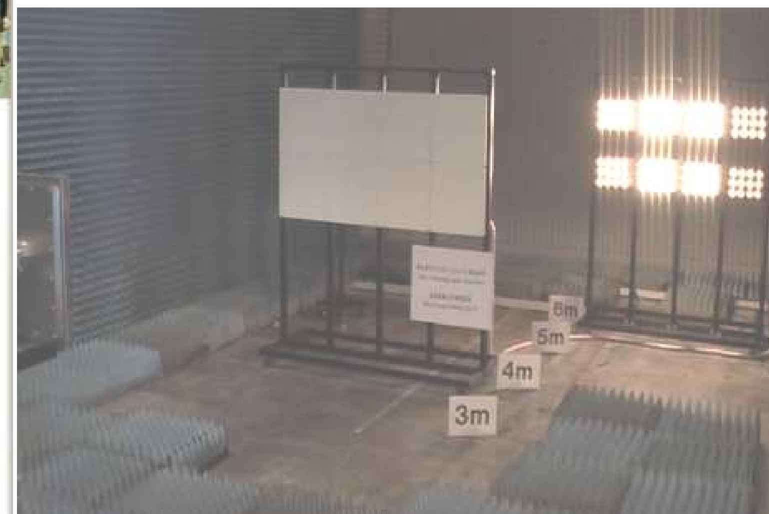
レクテナの効率は約84%

ボルボテクノロジー・ジャパンは日本電業工作と共同で、4m離れた場所へ10kW級の電力を無線伝送する技術を開発した（図1）。マイクロ波を用いたワイヤレス給電方式を採用する。同方式はこれまで、電磁誘導方式や磁界共鳴方式などに比べて電力伝送効率が低いのが大きな課題とされてきた。それを今回、高効率な「レクテナ」を開発することで差を縮めた。

レクテナは、アンテナ（antenna）と整流回路（rectifier）が一体となった、電磁波を直流の電力に変換するデバイスである。日本電業工作はレクテナ開発で高い技術力を持つ企業。今回、10kWの大出力ながら約84%と高い変換効率を達成するレクテナを開発した。この数字には、レクテナ分

図1 10kW級の高効率レクテナを開発
京都大学生存圏研究所の電波暗室で、電力伝送実験に成功した(a)。開発したレクテナの出力は1個当たり約1.3kWで、16個の素子を組み合わせている(b)。

High Power Rectenna Array



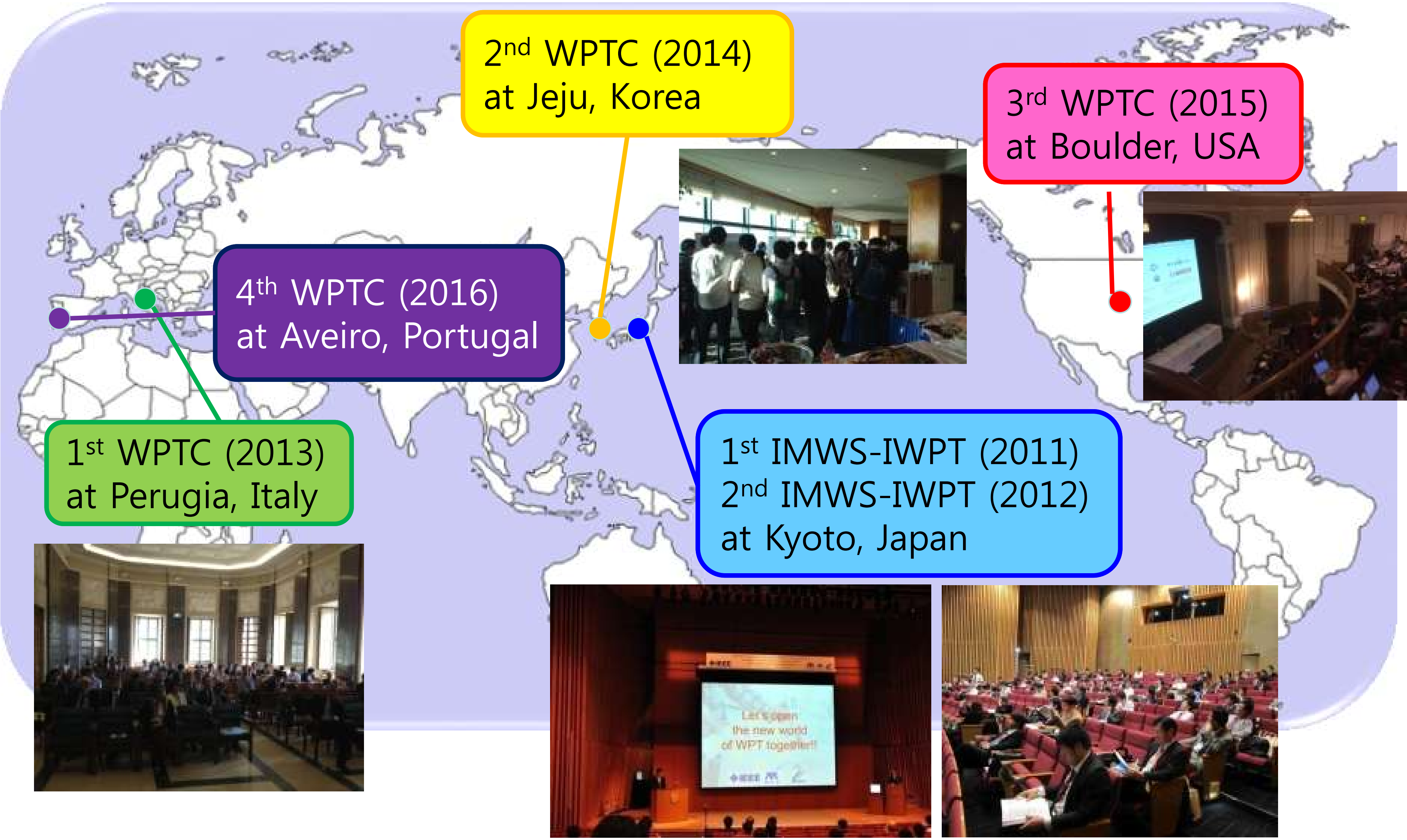
2.45GHz, 10kW, >80%

Nikkei Electronics Magagine
’12.7.9

with Volvo
and Nihon Dengyo Kosaku

Activities of Scientific Society and Industrial Standardization of WPT in Japan and in the World

IEEE Wireless Power Transfer Conference (WPTc)



IEEE Wireless Power Transfer Conference WPTc2015 (Former IMWS-IWPT)

Univ. of Colodado, US, May 13-15, 2015

Conference Hall (Old Main)

Poster Session

History of WPTc (IMWS-IWPT)

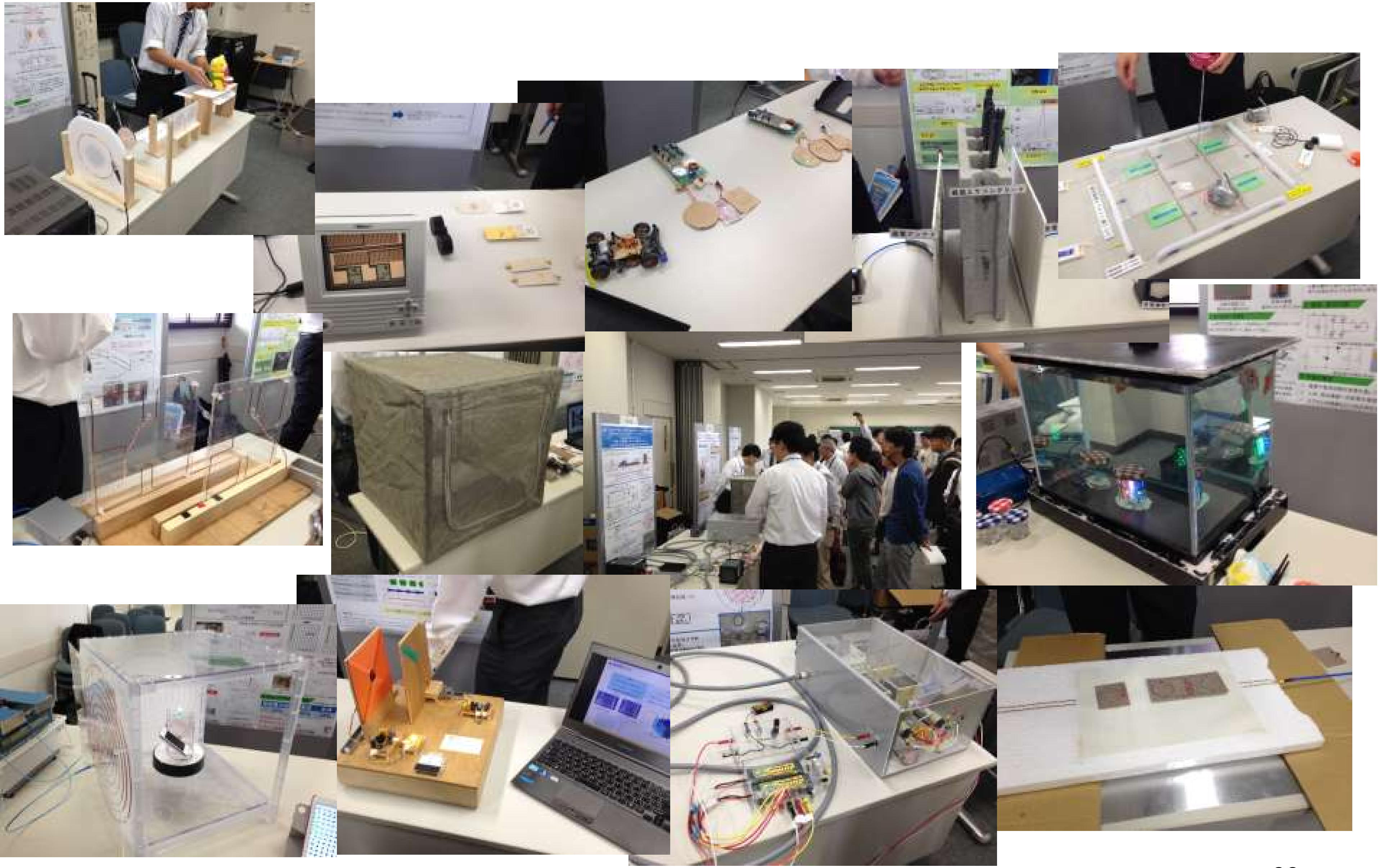
- 2011 paper 59/ 69 (88%) from 8 countries,
  142 attendees (pre), 176 (total)
- 2012 paper 60/ 68 (88%) from 7 countries,
  117 attendees (pre), 146 (total)
- 2013 paper 62/ 77 (80%)
  90 attendees (pre)
- 2014 paper 73/103 (71%) from 19 countries,
  187 attendees (pre), 203 (total)
- 2015 paper 93/166 (53%) from 29 countries
  164 attendees (pre), 199 (total)

IEICE Technical Committee on Wireless Power Transfer (Domestic)

http://www.ieice.org/cs/wpt

- FY2010
  - 30 papers in 5 meetings, participants 246
- FY2011
  - 38 papers in 4 meetings, participants 241
- FY2012
  - 58 papers in 6 meetings, participants 471
- FY2013
  - 43 papers in 6 meetings, participants 421
- FY2014 (reorganized)
  - 106 papers in 8 meetings, participants 760
- FY2015 (Until August)
  - 38 papers in 3 meetings (+5 meetings will be held.)

IEICE Student WPT Competition (Sep., 2014)



2015 Asian Wireless Power Transfer Workshop (AWPT 2015)

Greeting

The first Asia international workshop on Wireless Power Transfer technology(AWPT) will be held at Tamkang University, Taiwan, from **Dec.10 to 11, 2015**. This workshop is sponsored and organized by the Technical Committee on Wireless Power Transfer of the Institute of Electronics, Information and Communication Engineers, and Department of Electrical Engineering of Tamkang University. Wireless power transfer technology is bringing our life more comfortable and convenient and is one of the most important and innovative technologies in nowadays. The workshop aims on providing an international forum to exchange on the future trends or the latest advances of research and development in wireless power transfer technology. The workshop is also intended to enhance the friendship between the researchers in Asia.

Venue

Tamsui Campus, TamKang University

No.151, Yingzhuan Rd. Tamsui Dist., New Taipei City 25137, Taiwan

http://english.tku.edu.tw/map/TamsuiFreeway.pdf

ITU Activities

ITU : International Telecommunication Union (Founded in 1865)

which cites the following purposes for the union:

- to maintain and extend international cooperation between all members of the union for the improvement and rational use of telecommunications of all kinds;
- to promote and to offer technical assistance to developing countries in the field of telecommunications;
- to promote the development of technical facilities and their efficient operation;
- to promote the extension of the benefits of the new telecommunication technologies to all the world's inhabitants;
- to harmonize the actions of members in the attainment of these ends;
- to promote, at the international level, the adoption of a broader approach to telecommunications issues, an approach that includes other world and regional organizations and nongovernmental organizations concerned with telecommunications.

Discussion Result is published as

Question → Report → Recommendation → Regulation

Discussion for Q. ITU-R 210/1 (WPT) in Study Group 1 (SG1) - Working Party 1A (WP1A)

- 2001 : Information which was attached on SG1 Chairman's Report
  Results of contributions form US in 1997-2000
- May 2009 : SG1 Chairman's Report Annex 14 to 1A/135-E Working document toward a preliminary draft new report regarding Question ITU-R 210-2/1 Power transmission via radio frequency beam (wireless power transmission)
  Results of contributions form JAXA(Japan) on Feb.-May 2009
- Sep. 2009 : SG1 (Spectrum Management) Chairman's Report
  Merge of JAXA and US contributions
- 2013 : Separated reports of '**Beam**' and '**Non-Beam**' as a result of contribution from Japan
- 2014 : Approval of Non-Beam WPT Report
  - **New Report ITU-R SM.2303** - Wireless power transmission using technologies other than radio frequency beam
- 2015 : Contribution of Beam WPT
  - [Beam] **SG1 Chairman's report**
  - [Beam] Deadline of Question of BEAM WPT is expended to 2017
  - [Non-Beam] **Revised Report (ITU-R SM.2303-1)**
  - [Non-Beam] **Preliminary Draft of New Recommendation**
  - Liaison to IEC, ISO, IEEE, URSI, WIPE, WiPoT…..

Question ITU-R 210-3/1

Wireless power transmission (June, 2015)

decides that the following information be gathered

1 What applications have been developed for use of WPT technologies?

2 What are the technical characteristics of the emission employed in or incidental to applications using WPT technologies?

3 What is the WPT's standardization situation in the world?

decides that the following Questions should be studied

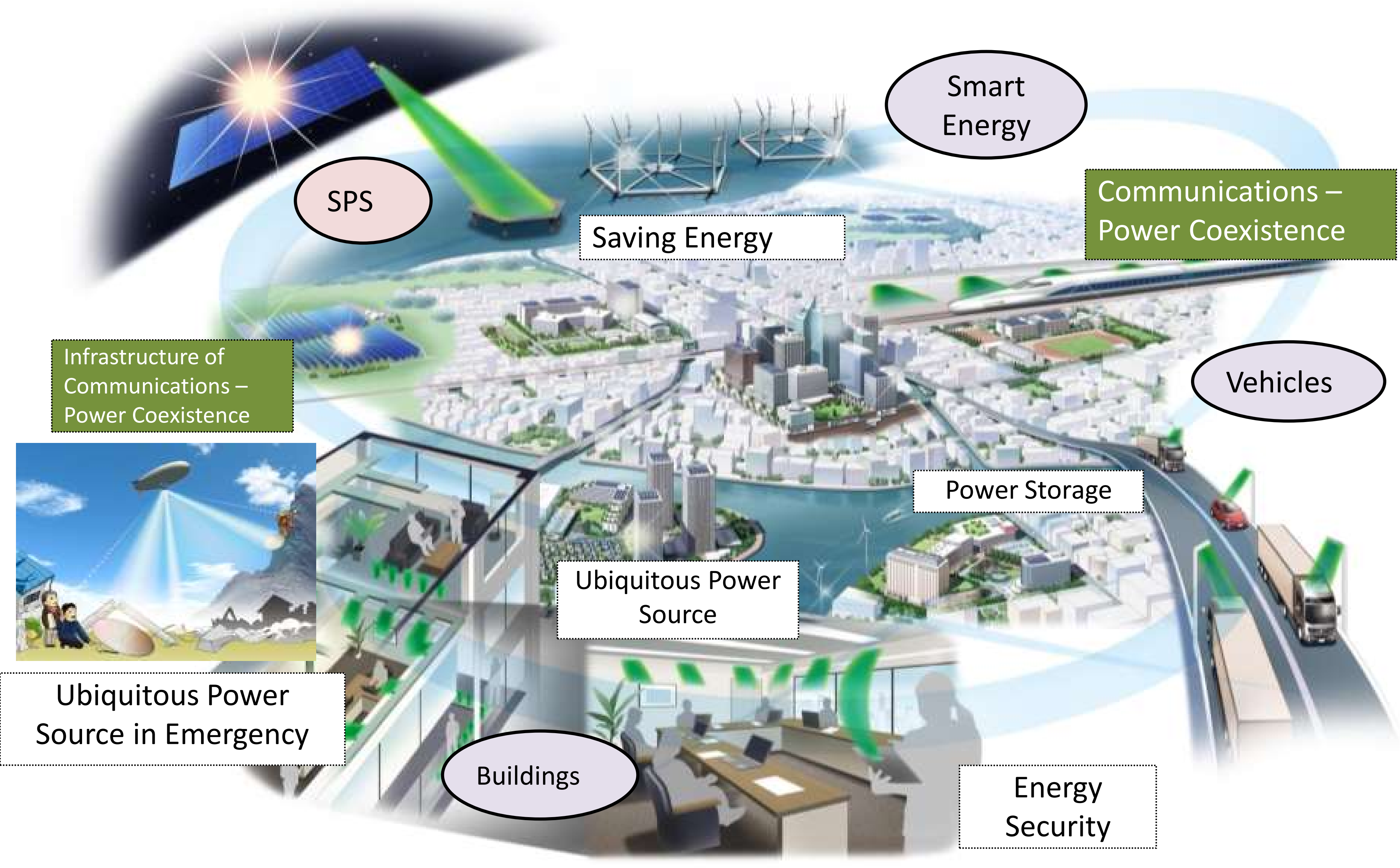
1 Under what category of spectrum use should administrations consider WPT: ISM, or other?

2 What radio frequency bands are most suitable for WPT?

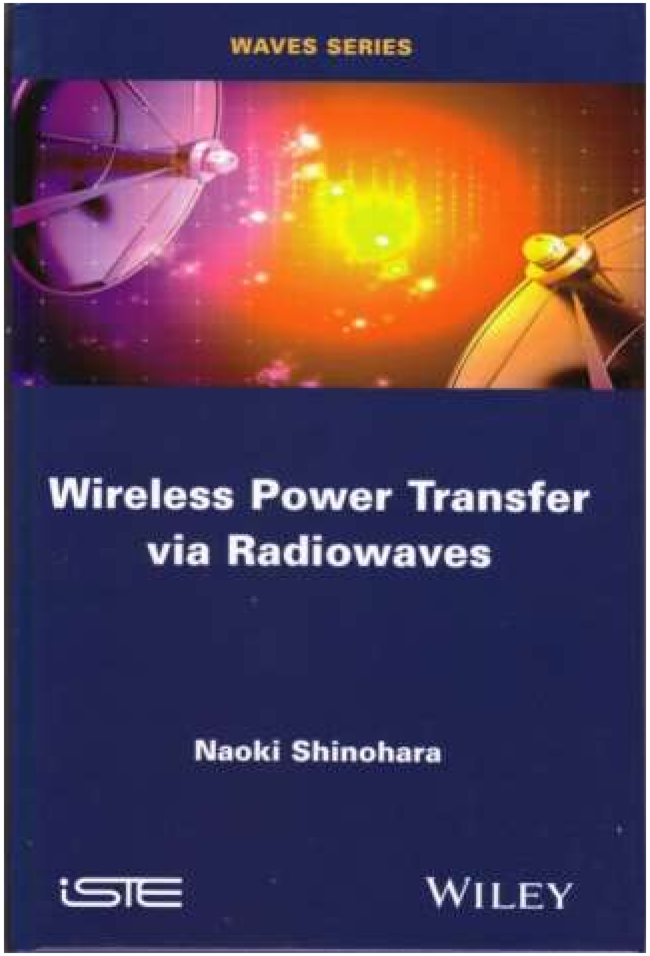
3 What steps are required to ensure that radiocommunication services, including the radio astronomy service, are protected from WPT operations?

Conclusion

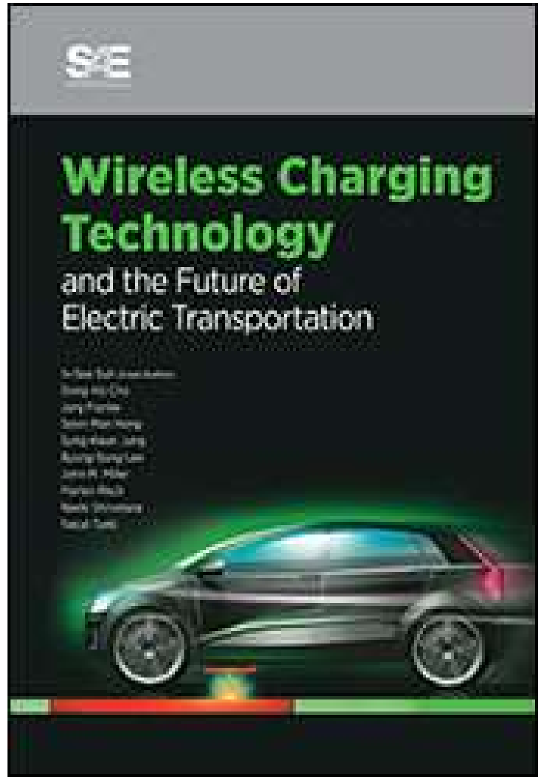
Our Dream : Wireless Power Society



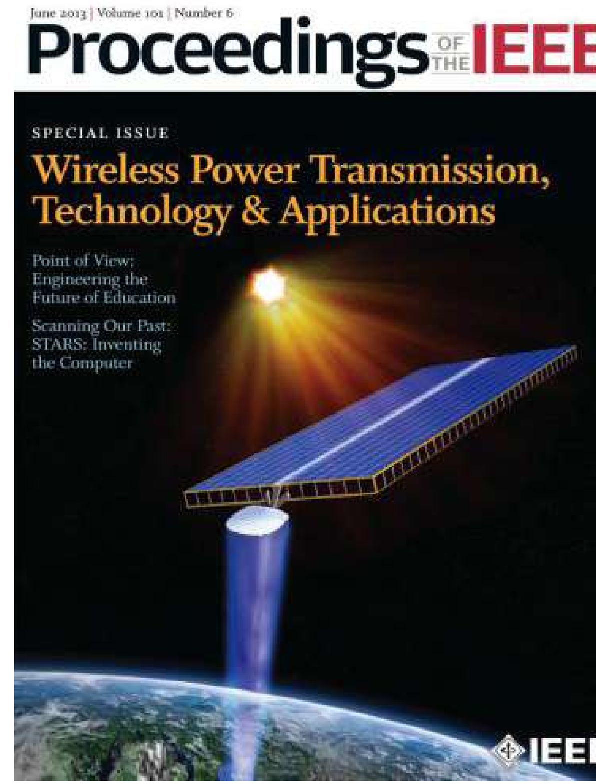
WPT Books and Journals



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
(Paper Book and Kindle)



Wireless Charging
Technology and the Future of
Electric Transportation
SAE Book
Ed. In-Soo Suh,
Chap.9 by Shinohara
2015.6
ISBN 978-0-7680-8153-4



Proceedings of IEEE
2013.6
18 WPT Papers
[Guest Editors]
K. Wu
D. Choudhury
H. Matsumoto