Millimeter wave
Wireless Energy Transmission

Prof. Yosef Pinhasi

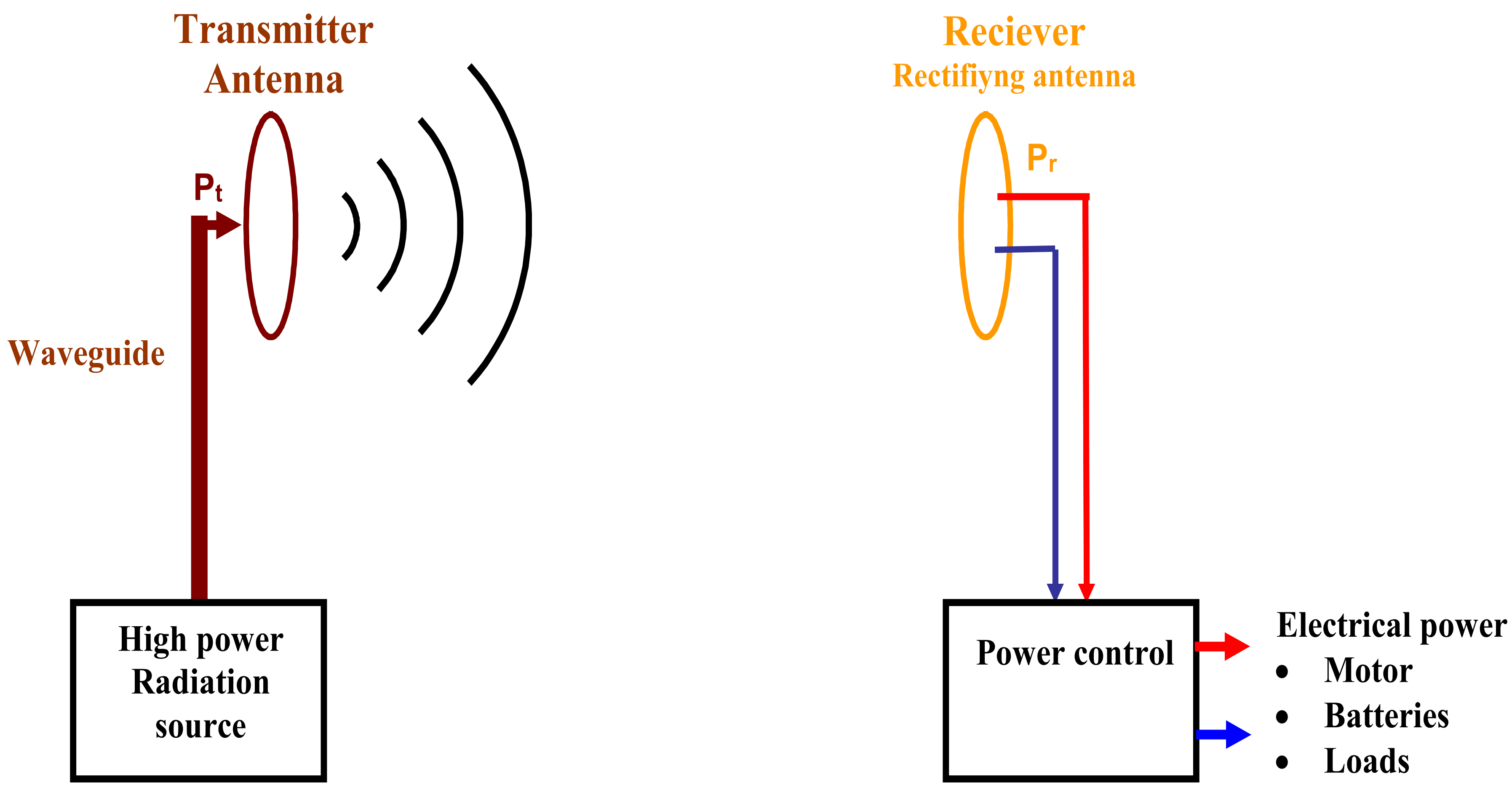
- Dr. Ariel Etinger
- Oz Livne
- Boris Litvak
- Lidor Dahan

Wireless transfer of electrical energy

- Wireless power transfer - WPT
- Wireless energy transmission
- Energy harvesting
- Radiative power beaming

Technology	Range	Directivity	Frequency	Antenna devices	Current and or possible future applications
Inductive coupling	Short	Low	Hz – MHz	Wire coils	Electric tooth brush and razor battery charging, induction stovetops and industrial heaters.
Resonant inductive coupling	Mid	Low	kHz – GHz	Tuned wire coils, lumped element resonators	Charging portable devices (Qi), biomedical implants, electric vehicles, powering busses, trains, MAGLEV, RFID, smartcards.
Capacitive coupling	Short	Low	kHz – MHz	Electrodes	Charging portable devices, power routing in large scale integrated circuits, Smartcards.
Magneto-dynamic coupling	Short	N.A.	Hz	Rotating magnets	Charging electric vehicles.
Microwaves	Long	High	GHz	Parabolic dishes, phased arrays, rectennas	Solar power satellite, powering drone aircraft.
Light waves	Long	High	≥THz	Lasers, photocells, lenses	Powering drone aircraft, powering space elevator climbers.

Radiative power beaming scheme



System components

- High power radiation source
- Transmission system
- Directive focusing antenna
- Rectifying antenna – RECTENNA
- Power control

Applications

- RFID
- Satellites
- Low altitude UAVs
- Aircrafts / Drones
- Remote sensors

Frequency spectrum for wireless communications

BAND		IEEE	FREQUENCY	WAVELENGTH
Extremely Low Frequency	ELF		3 – 30Hz	
Super Low Frequency	SLF		30 – 300Hz	
Ultra Low Frequency	ULF		300 - 3,000 Hz	1,000 - 100 Km
Very Low Frequency	VLF		3 - 30 KHz	100 – 10 Km
Low Frequency	LF		30 - 300 KHz	10 - 1 Km
Medium Frequency	MF		300 - 3,000 KHz	1 - 0.1 Km
High Frequency	HF		3 - 30 MHz	100 - 10 m
Very High Frequency	VHF		30 - 300 MHz	10 – 1 m
Ultra High Frequency	UHF		300 - 3,000 MHz	1 - 0.1 m
		L	1 - 2 GHz	
		S	2 - 4 GHz	
Super High Frequency	SHF		3 - 30 GHz	10 - 1 cm
		C	4 - 8 GHz	
		X	8 - 12 GHz	
		Ku	12 - 18 GHz	
		K	18 - 26.5 GHz	
		Ka	26.5 - 40 GHz	
Extremely High Frequency	EHF		30 - 300 GHz	1 - 0.1 cm
		V	40 - 75 GHz	
		W	75 - 110 GHz	
Sub-millimeter (TeraHertz)	FIR		300 - 3,000 GHz	1 – 0.1 mm
Mid infra-red	MIR		3 – 30 THz	100 – 10 μm
Near infra-red	NIR		30 – 300 THz	10 – 1 μm

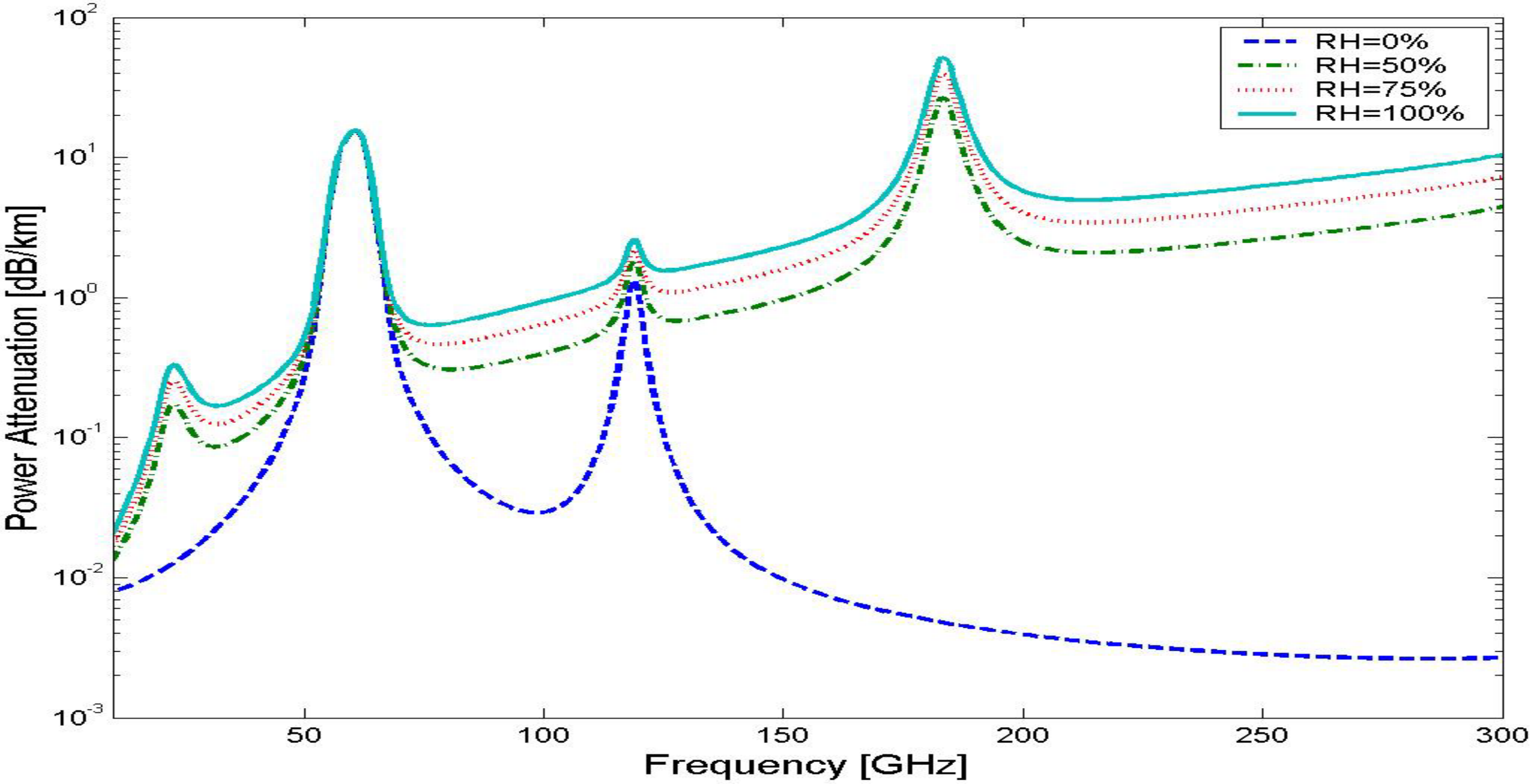
Radiative Energy Transmission

- Wireless energy transmission using millimeter wave radiation.
- Frequency: 94GHz (W-band atmospheric window).
- Directive dish antenna focuses radiation onto a rectifying antenna (Rectenna).
- The rectenna converts radiative millimeter waves to DC voltage.
- Charging elements energize batteries ans super-capacitors.

Extremely High Frequencies

- Free of users.
- Wide band
- High directivity and spatial resolution.
  (when utilizing high gain antennas)
- Small antenna and equipment size.
- Atmospheric windows – low attenuation
- 35GHz , 94GHz

Atmospheric transmission



Transmitting dish antenna

IET Microwaves, Antennas & Propagation

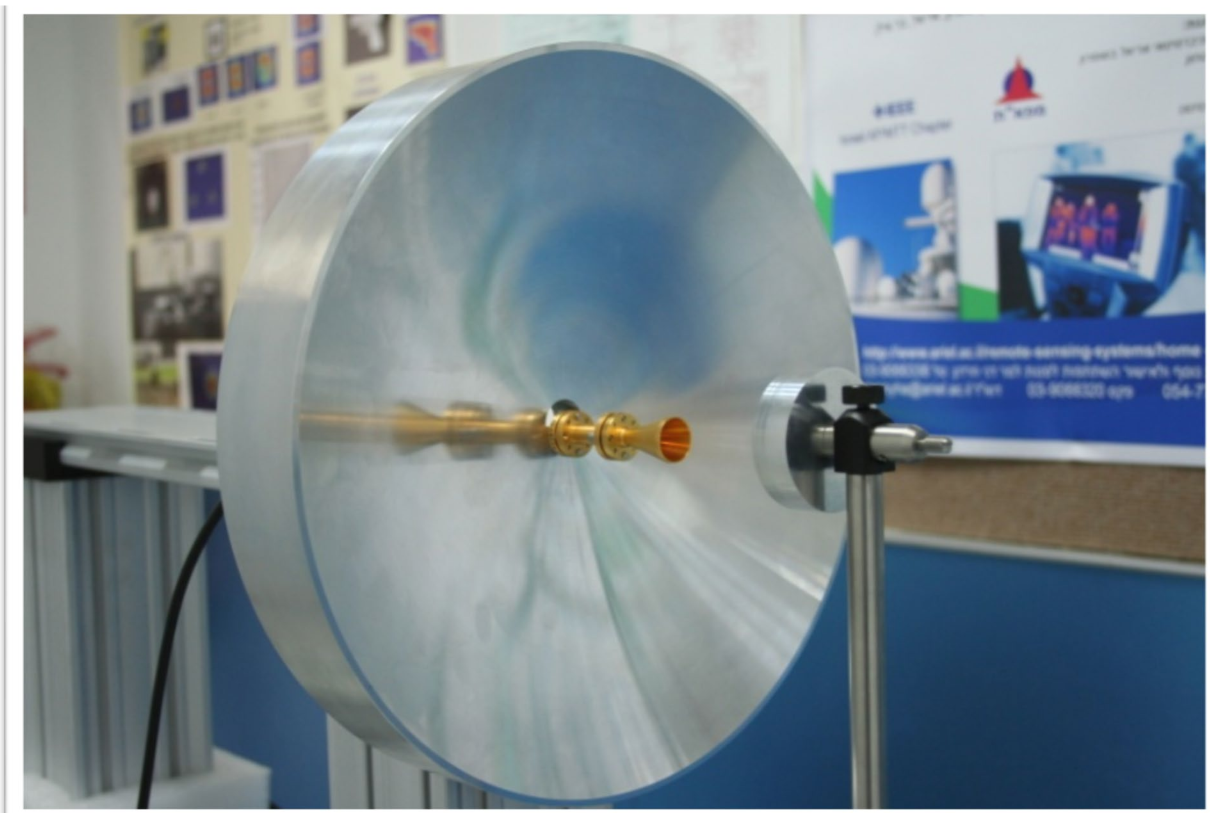
Research Article

Millimetre wavelength variable focusing antenna for power beaming and active denial systems

ISSN 1751-8725
Received on 10th April 2014
Accepted on 12th March 2015
doi: 10.1049/iet-map.2015.0054
www.ietdl.org

Erez Danieli, Amir Abramovich, Yosef Pinhasi ✉

Department of Electrical and Electronic Engineering, Ariel University, Ariel, Israel
✉ *E-mail: yosip@ariel.ac.il*

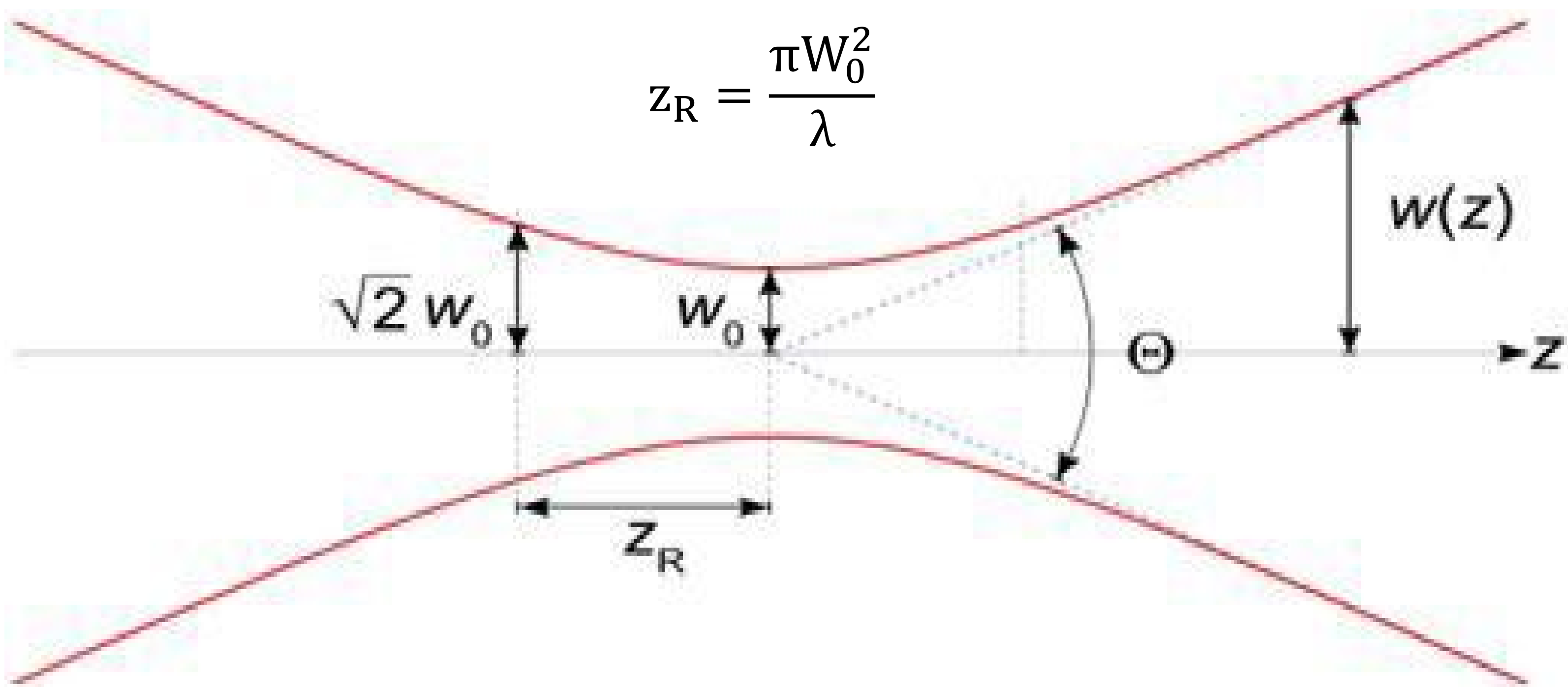


Gaussian beam

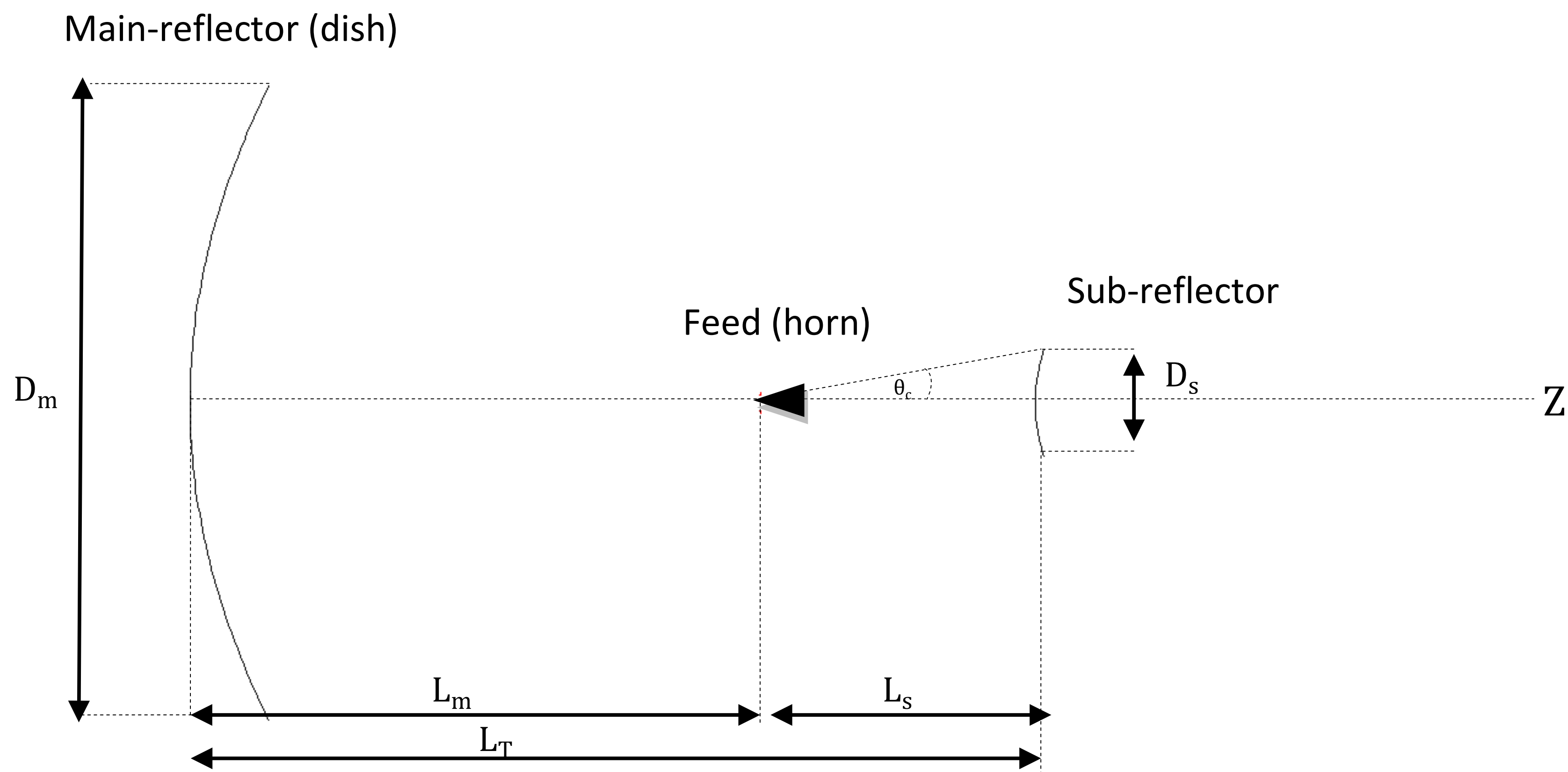
$$E_{0,0}(r,z) = E_{0,0}\left[{}^{W_0}/_{W(z)}\right]\exp\left[{}^{-r^2}/_{W(z)^2}\right]\exp\left\{-jkz - ik\frac{r^2}{2R(z)} + i\zeta(z)\right\}$$

$$R(z) = z\left[1 + \left(\frac{z_R}{z}\right)^2\right] \qquad W(z) = W_0\sqrt{1 + \left(\frac{z}{z_R}\right)^2}$$

$$z_R = \frac{\pi W_0^2}{\lambda}$$



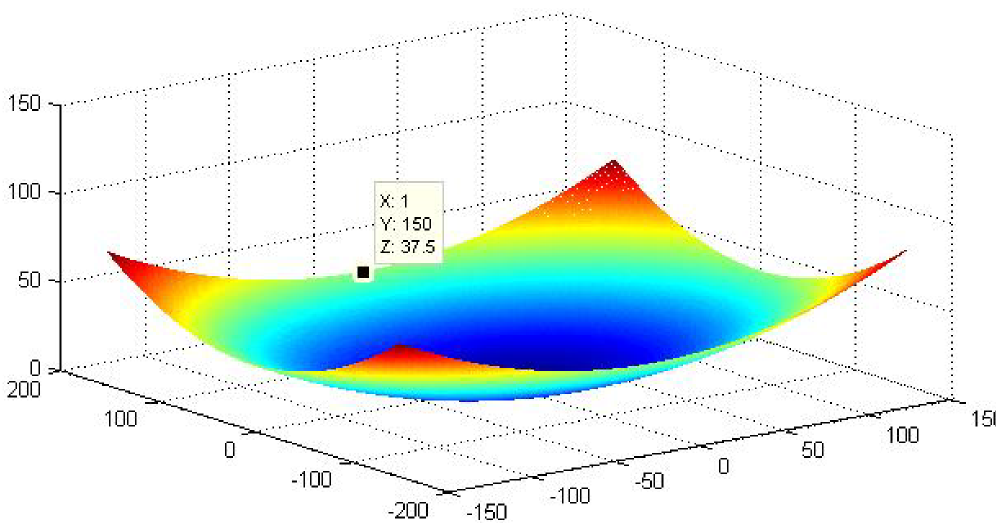
Cassegrain configuration

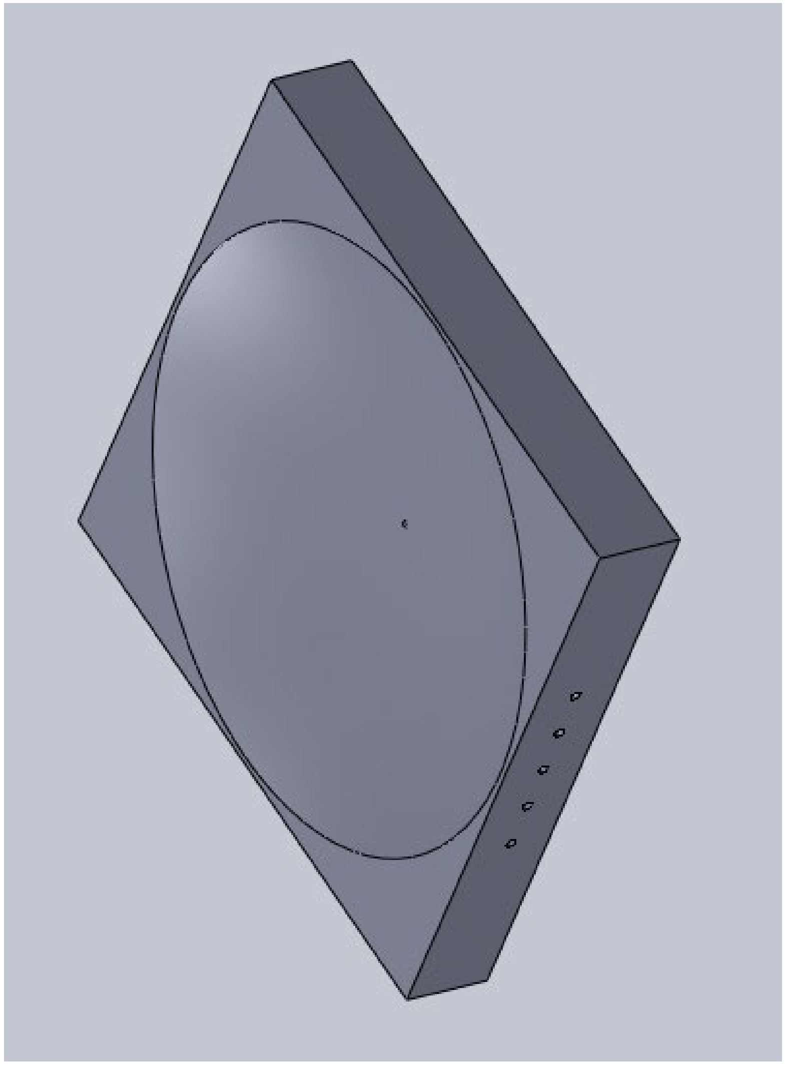


$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} 1 & z \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ \frac{-2}{R_2} & 1 \end{bmatrix} \begin{bmatrix} 1 & L_t \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ \frac{2}{R_1} & 1 \end{bmatrix} \begin{bmatrix} 1 & L_s \\ 0 & 1 \end{bmatrix}$$

Main (dish) reflector

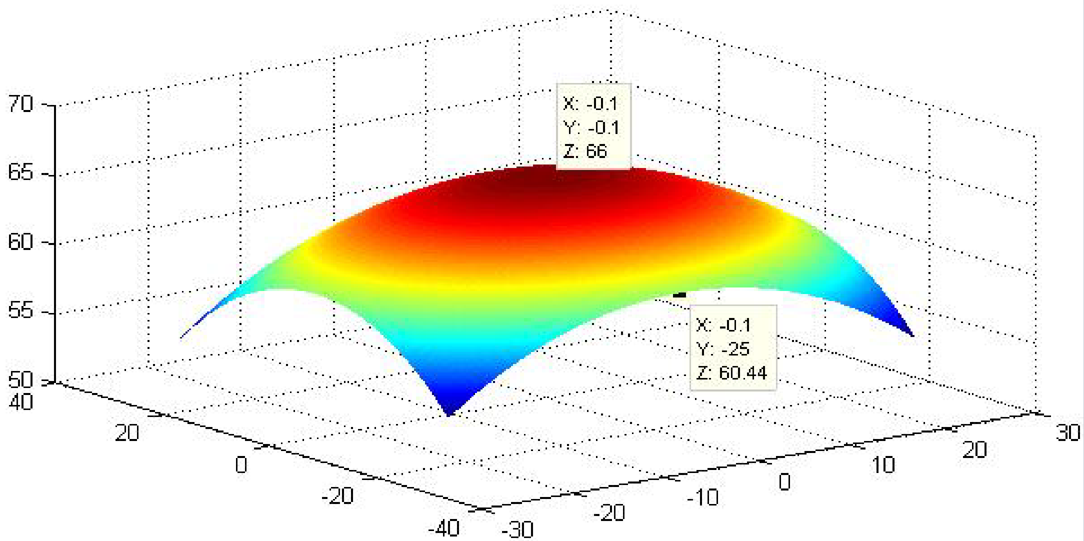
$$z(x, y) = \frac{x^2 + y^2}{4F} - F$$

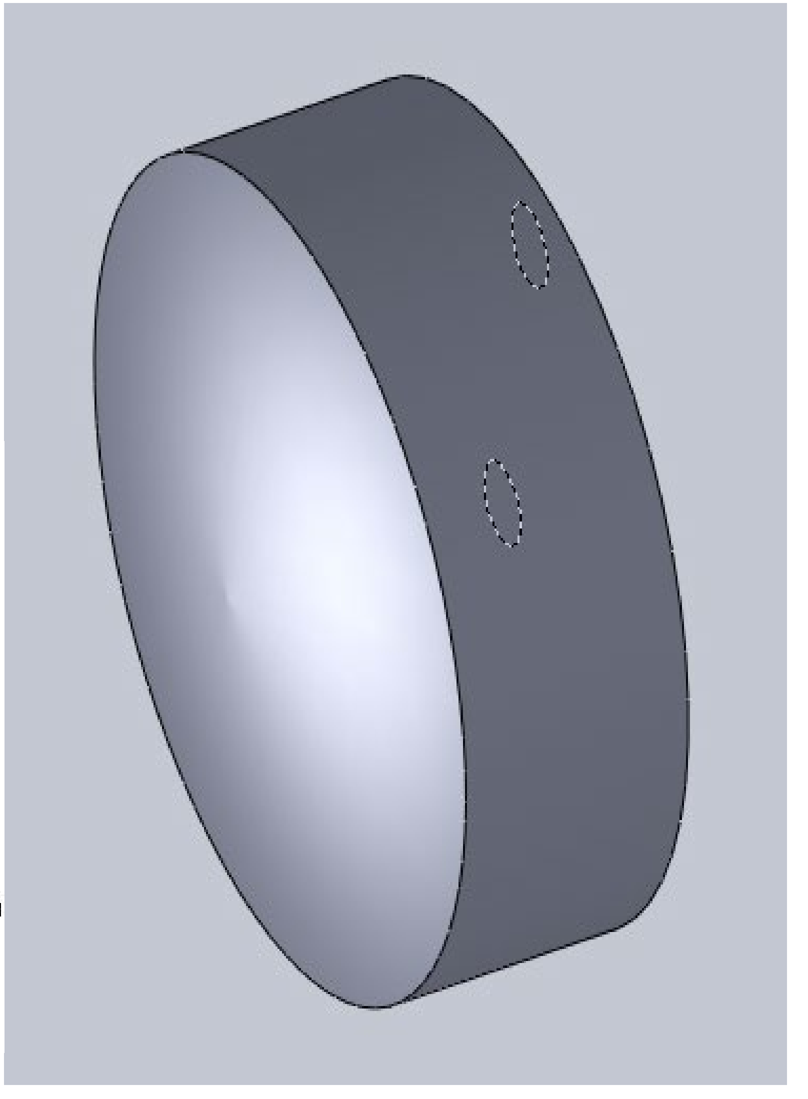




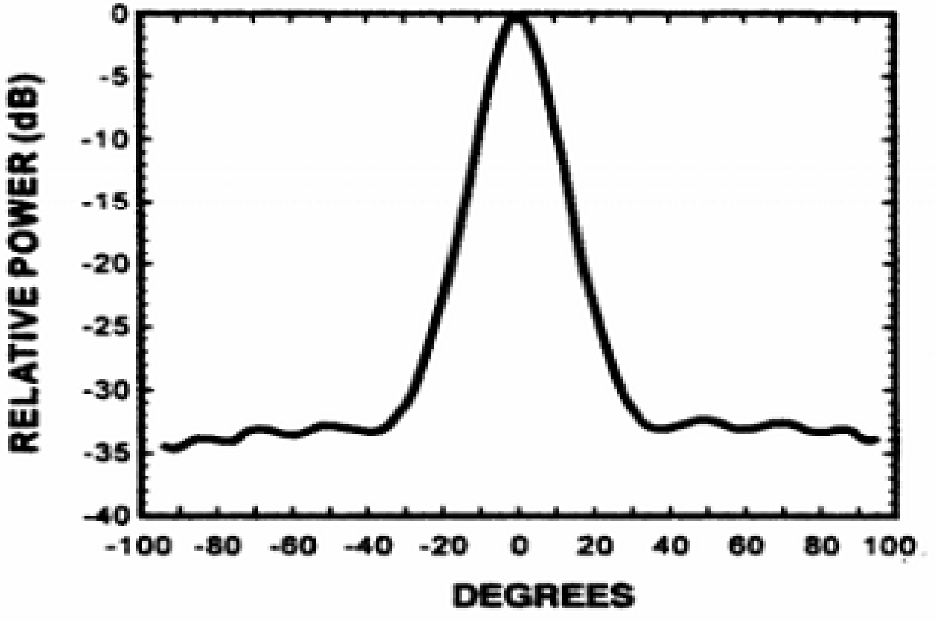
Sub reflector

$$z(x,y) = a\sqrt{1 + \frac{x^2 + y^2}{c^2 - a^2}}$$





The feed



RELATIVE POWER (dB)
0
-5
-10
-15
-20
-25
-30
-35
-40
-100
-80
-60
-40
-20
0
20
40
60
80
100
DEGREES

Antenna parameters

- W_{00}=3.14mm
- R_1=295mm
- R_2=75mm
- L_s=67.8mm
- L_T=125mm
- z=10m
- D_s=50mm
- $D_m = 300$mm

Focusing region

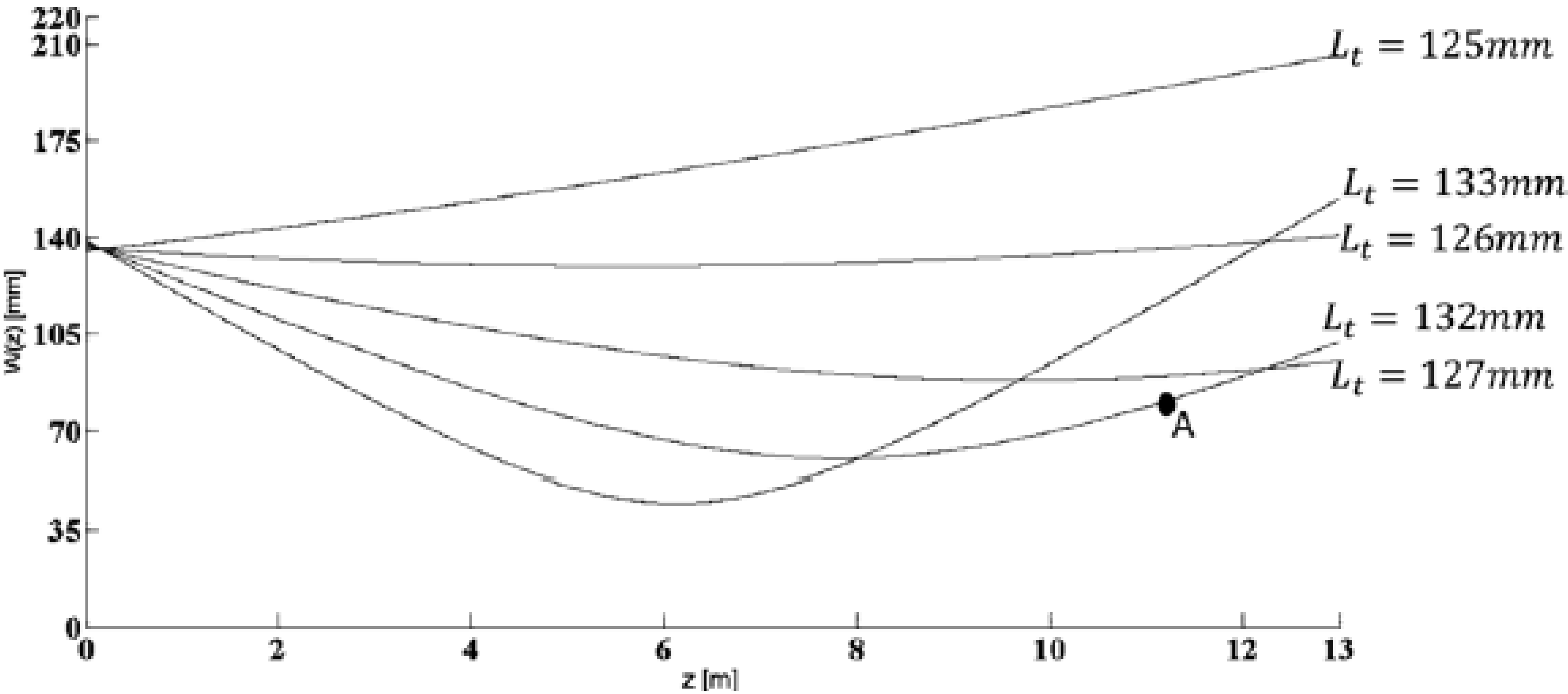
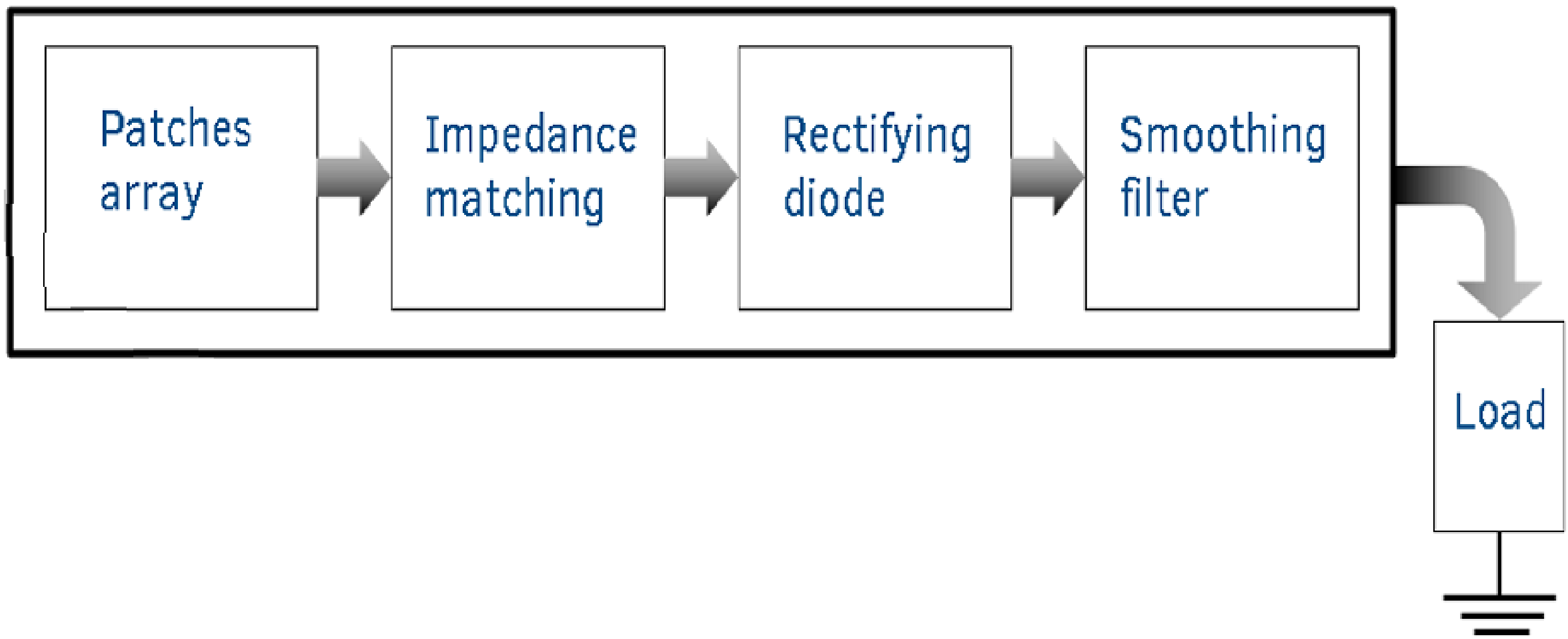


Fig. 3 *Beam radius W(z) as a function of the distance z for various values of* L_t

MMW
Half-wave
Rectifying Antenna

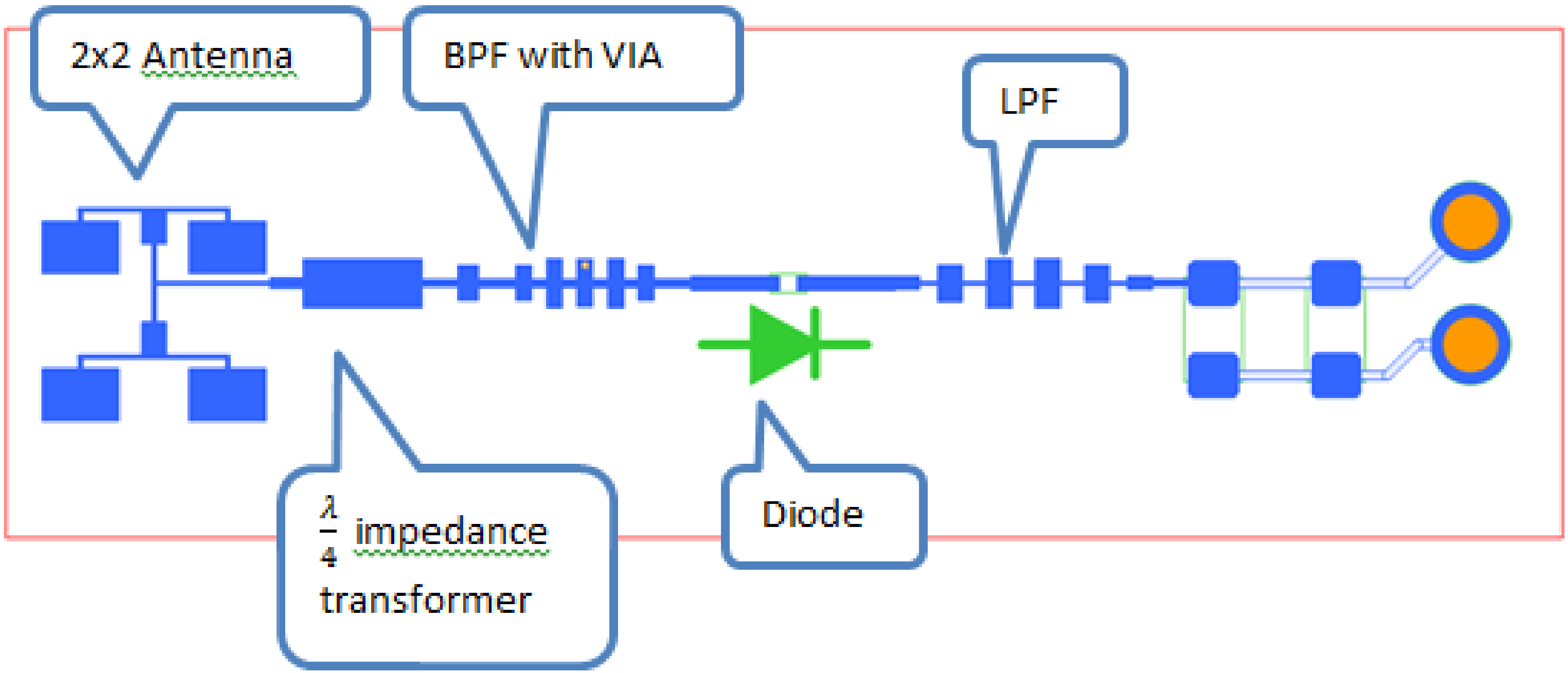
RECTENNA

RECTENNA

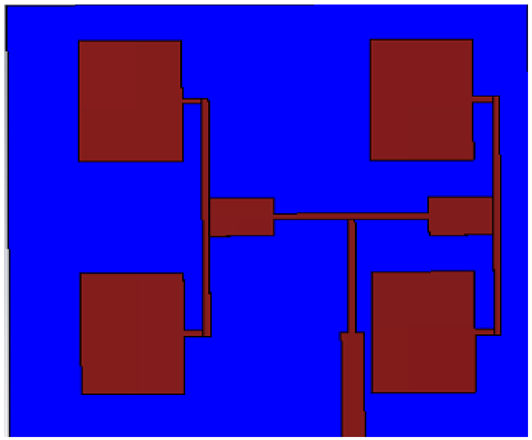


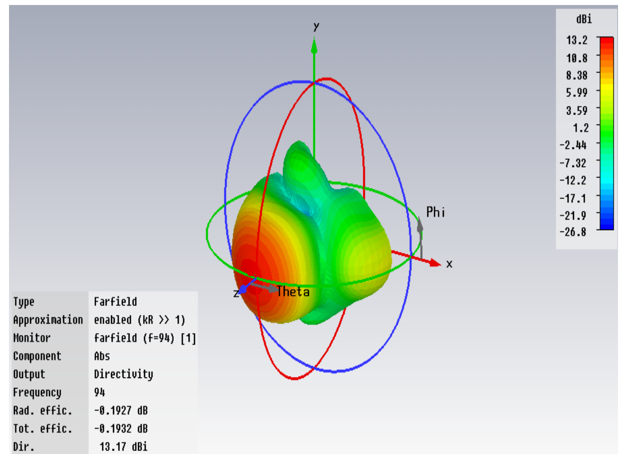
Patches array
Impedance matching
Rectifying diode
Smoothing filter
Load

Hybrid Rectenna 2x2 array

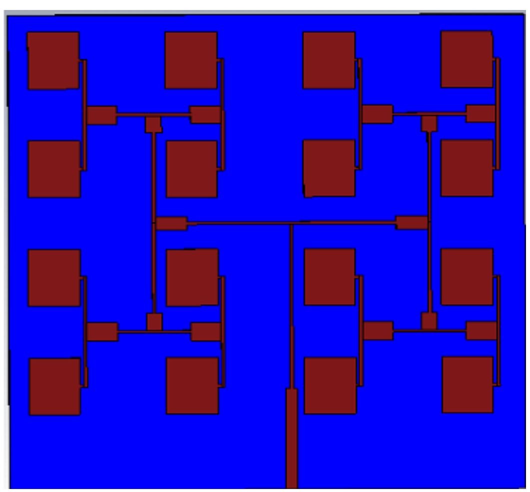


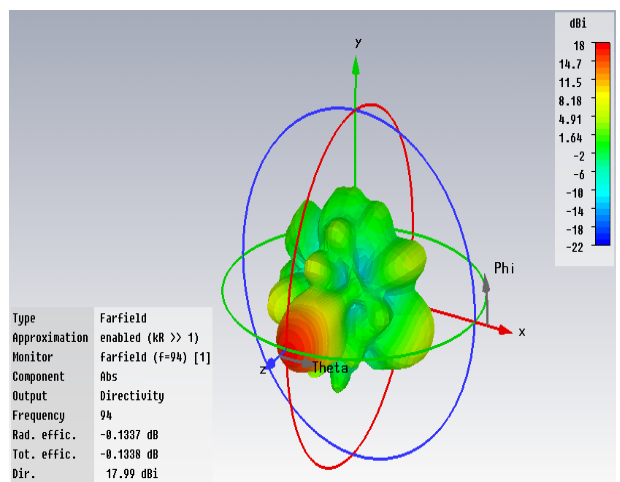
Results of CST simulation 2x2 rectenna array





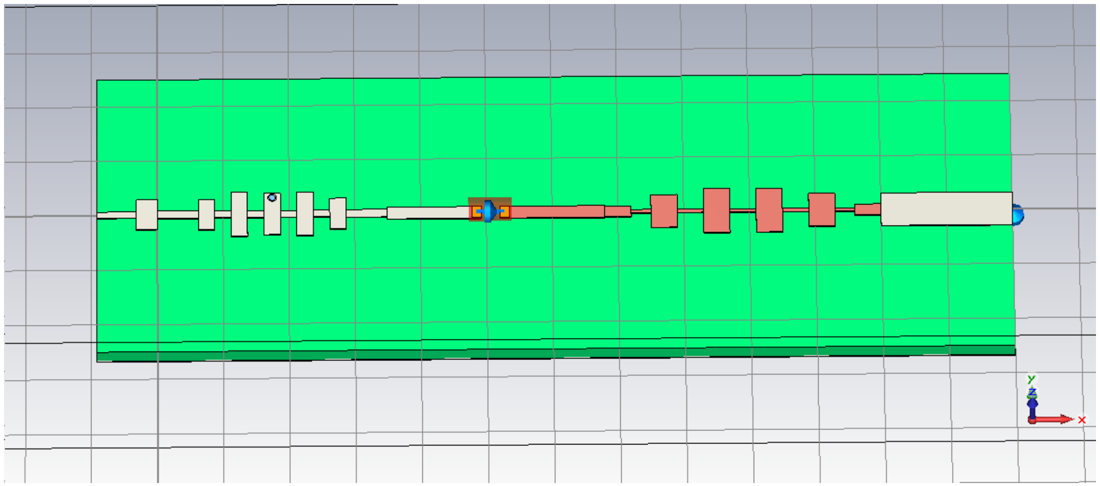
2x2 rectenna array

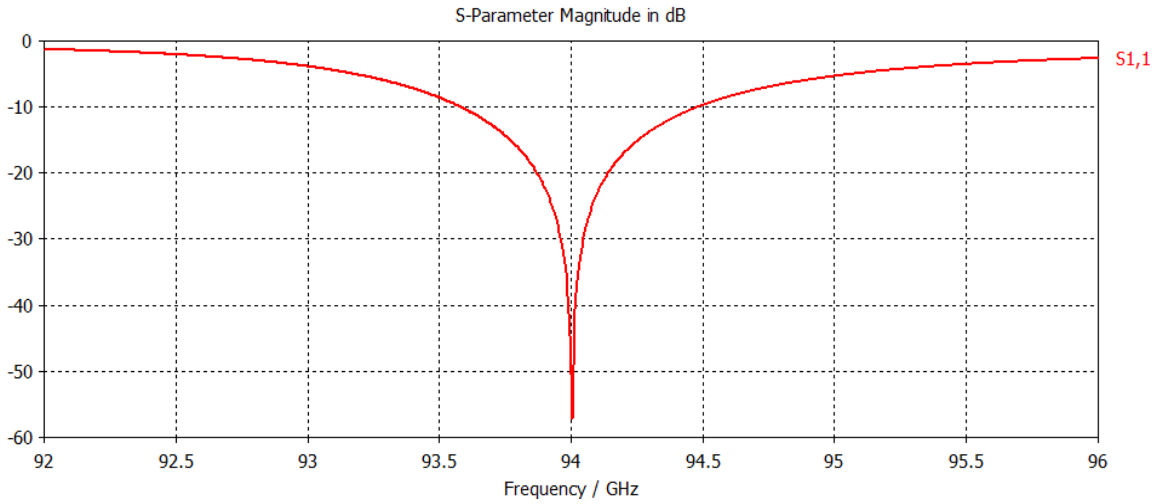


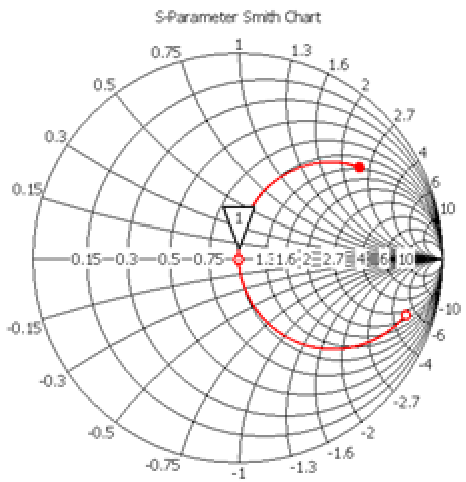


4x4 rectenna array

Impedance matching network and filter

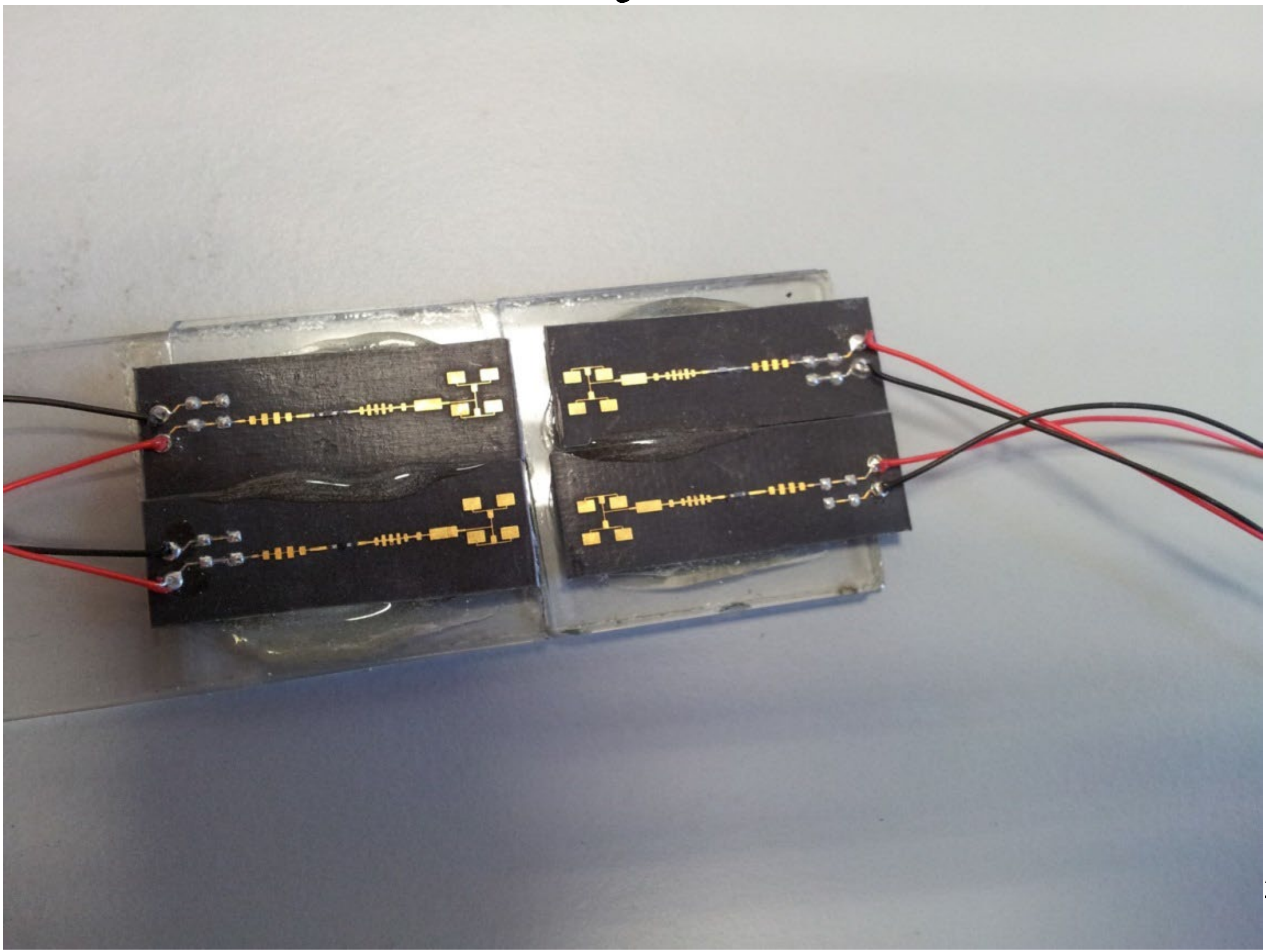




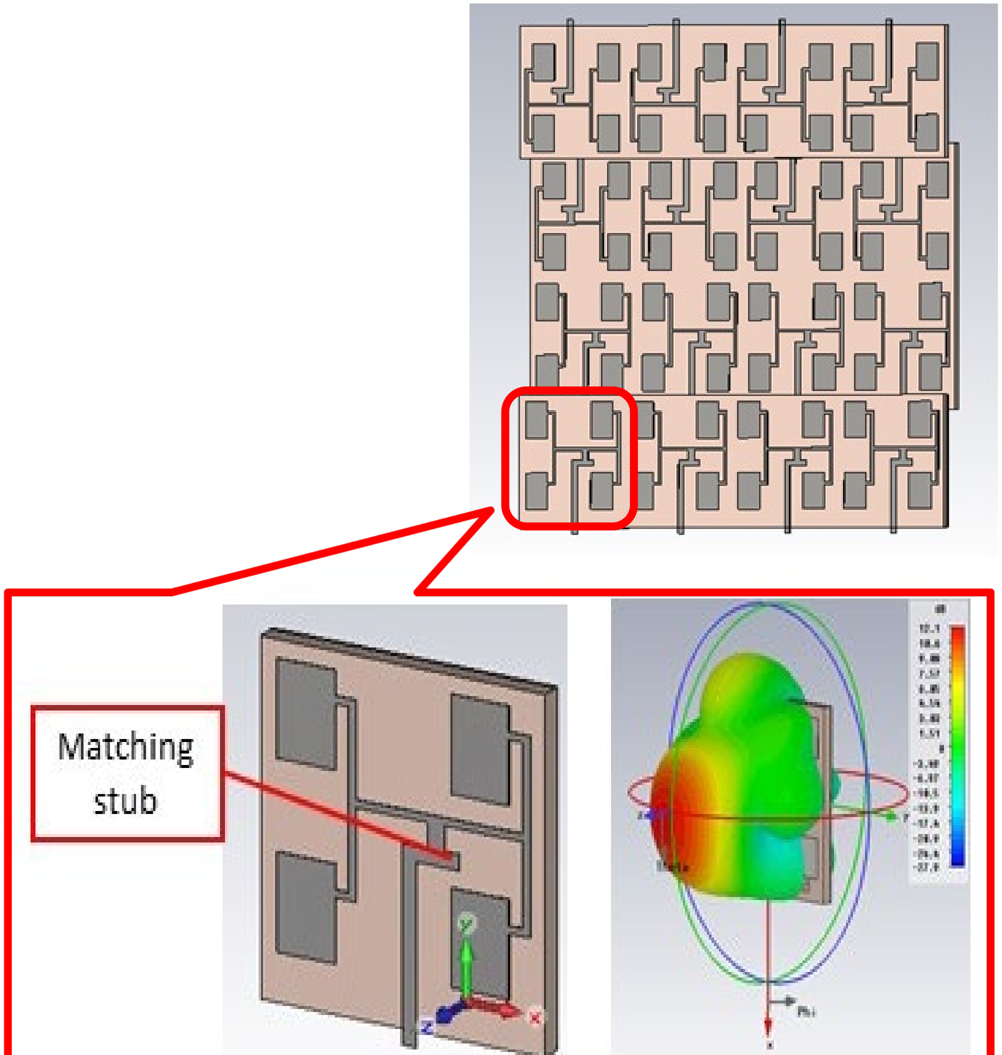


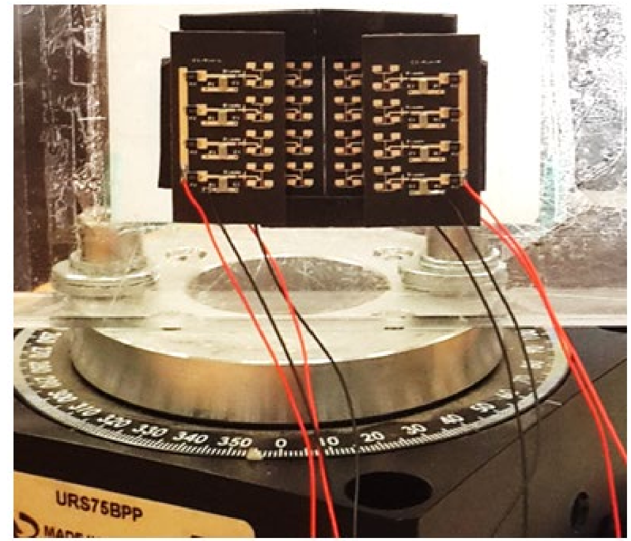
Four patches rectenna

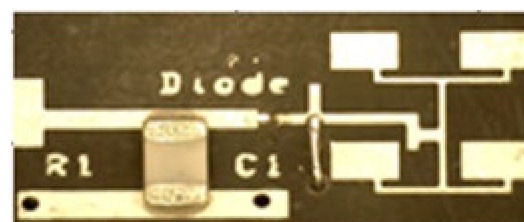
Rectenna array 4x4 elements



64 elements rectenna

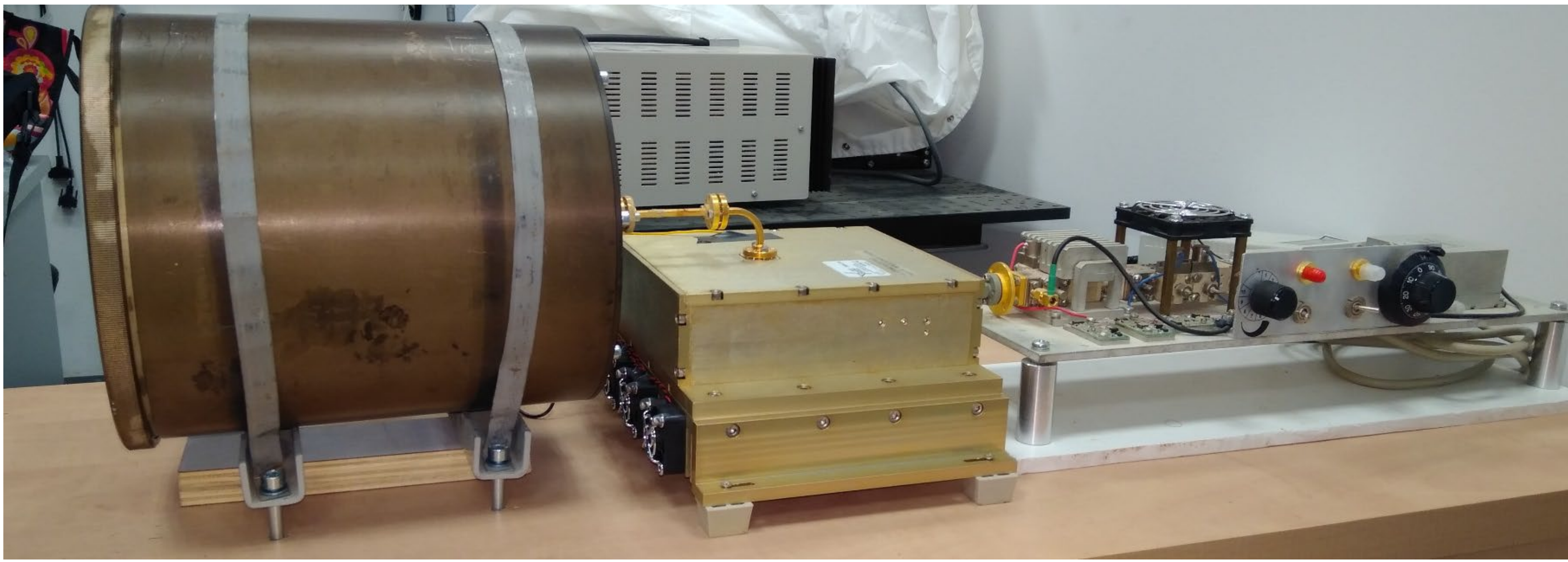




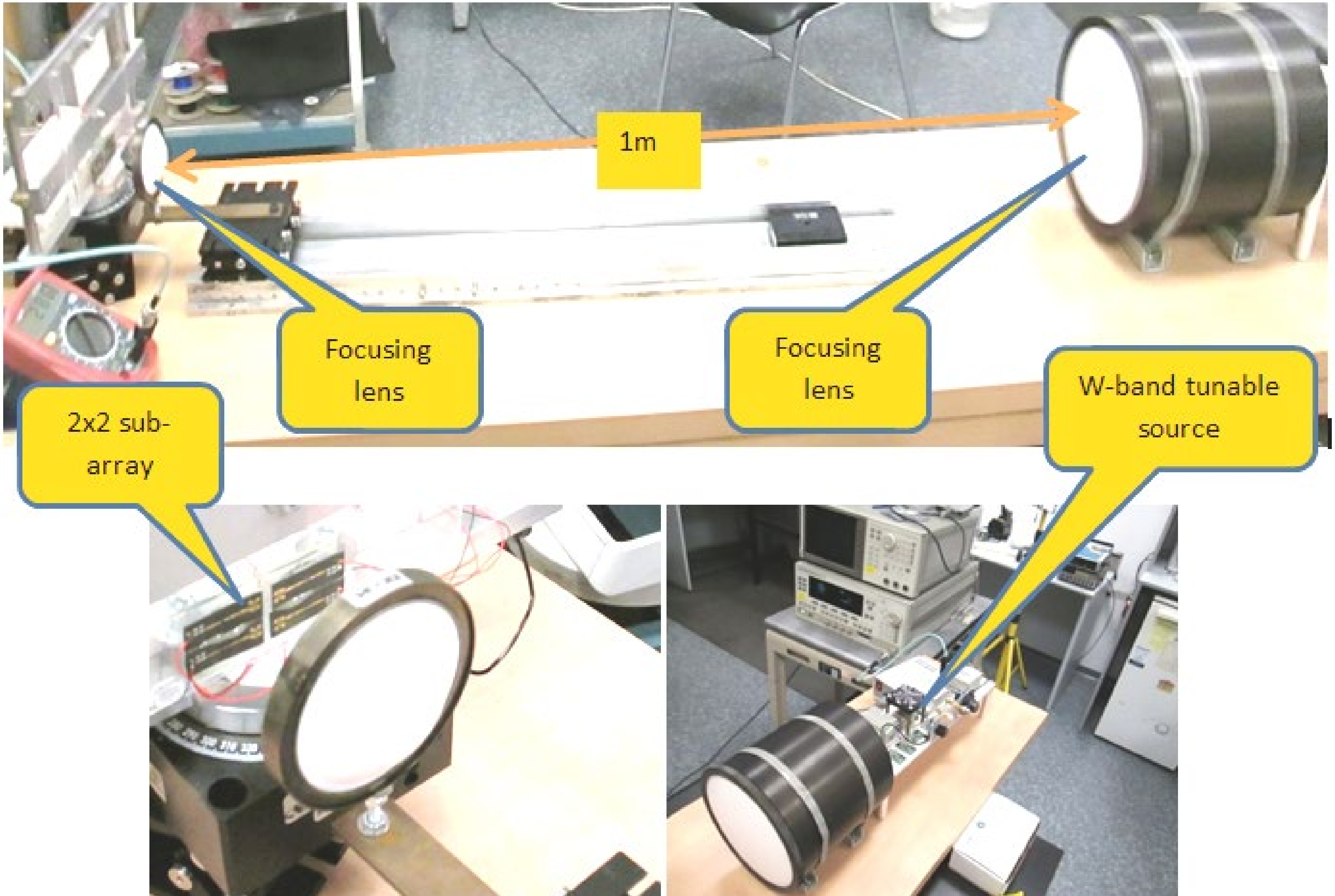


Use of MOT diode

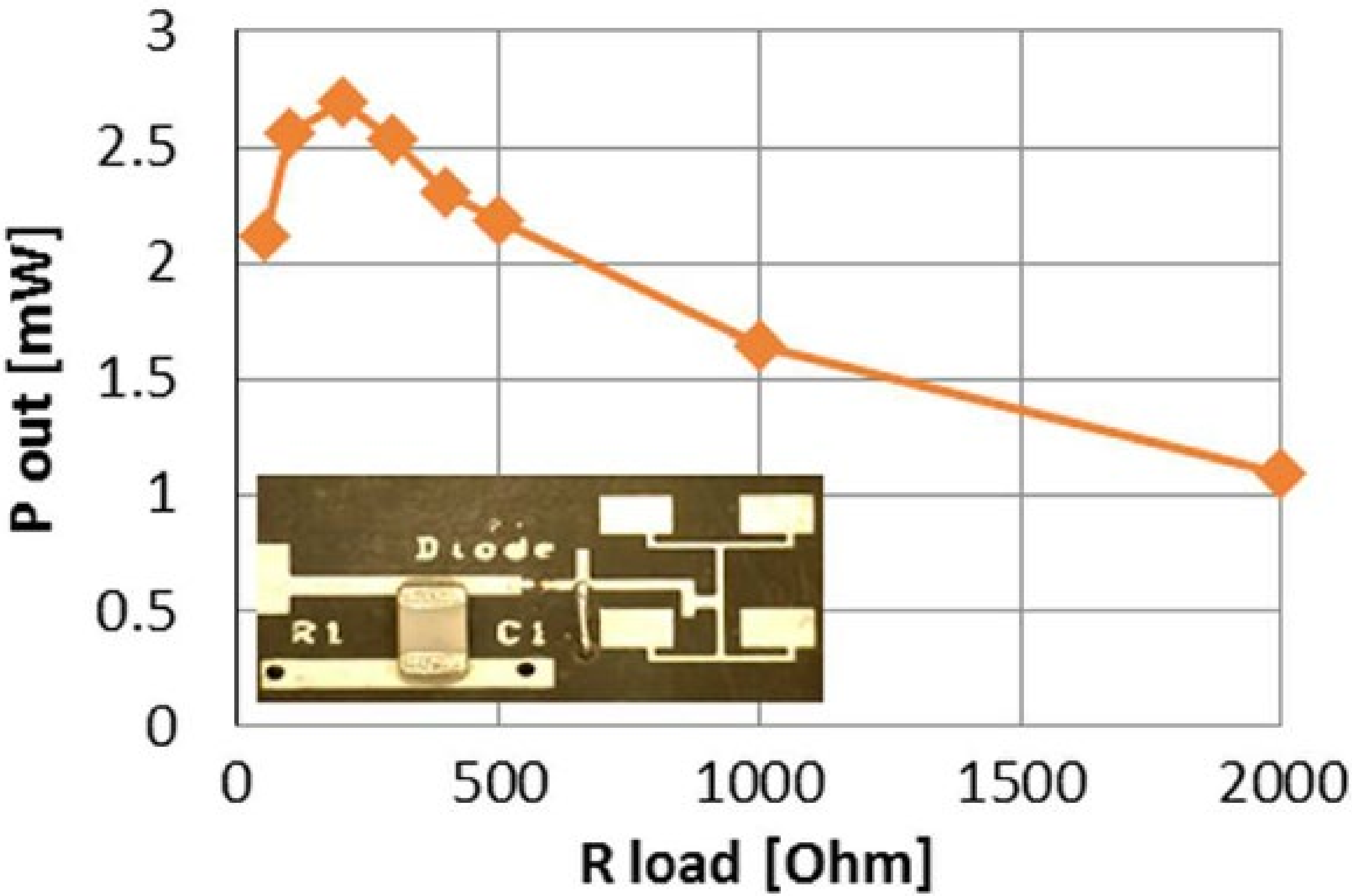
2W Solid-state amplifier – 94GHz



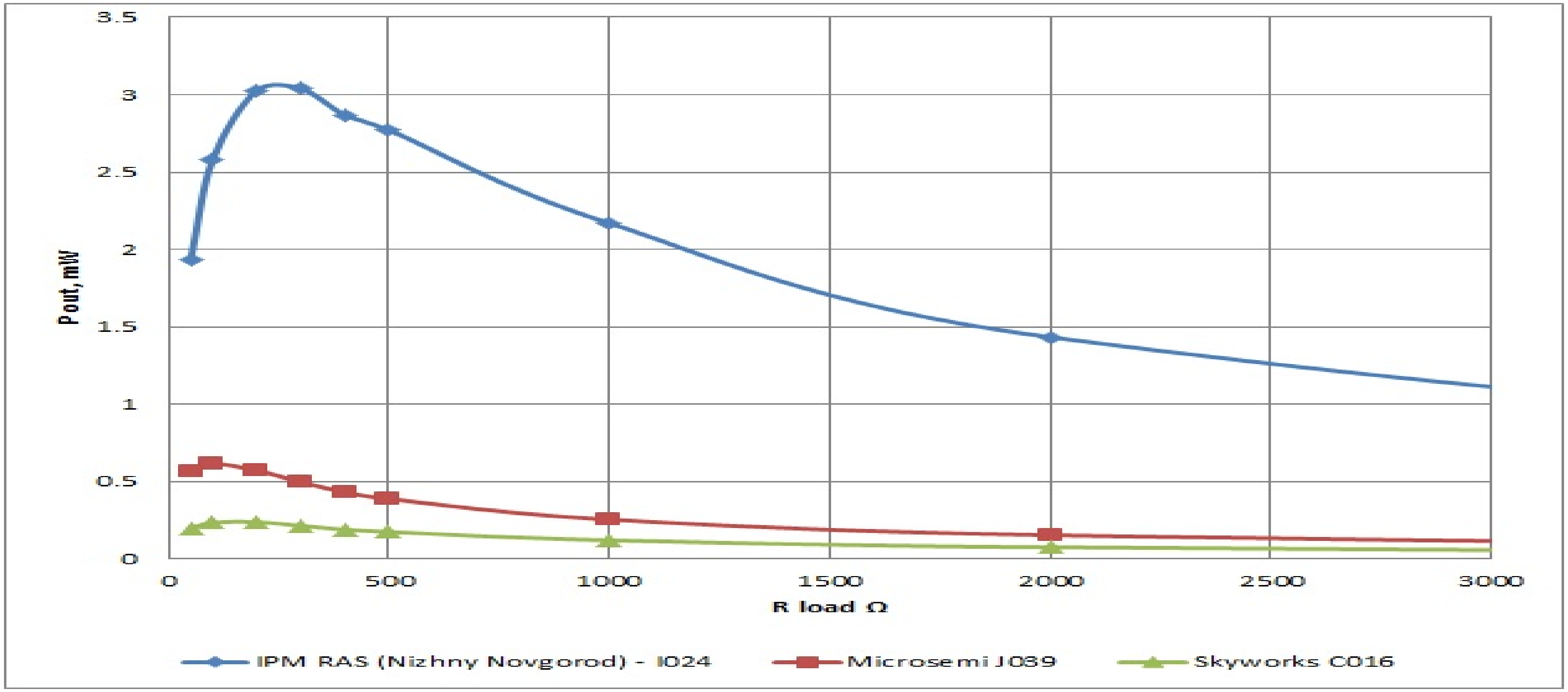
Power transfer with 0.4W source



DC power vs. Load



DC power vs. Load

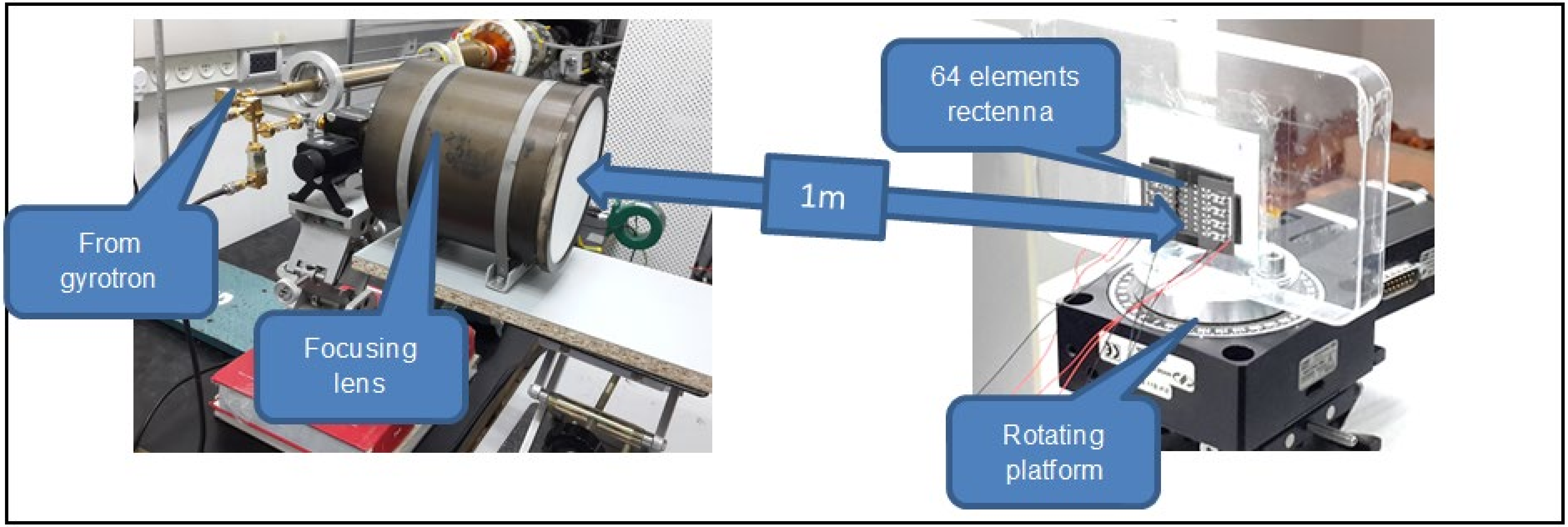


$$E_{conv}^{Microsemi} = \frac{P_{DC}}{P_{rf}} = \frac{0.62mW}{17.6mW} = 0.035 = 3.5\%$$

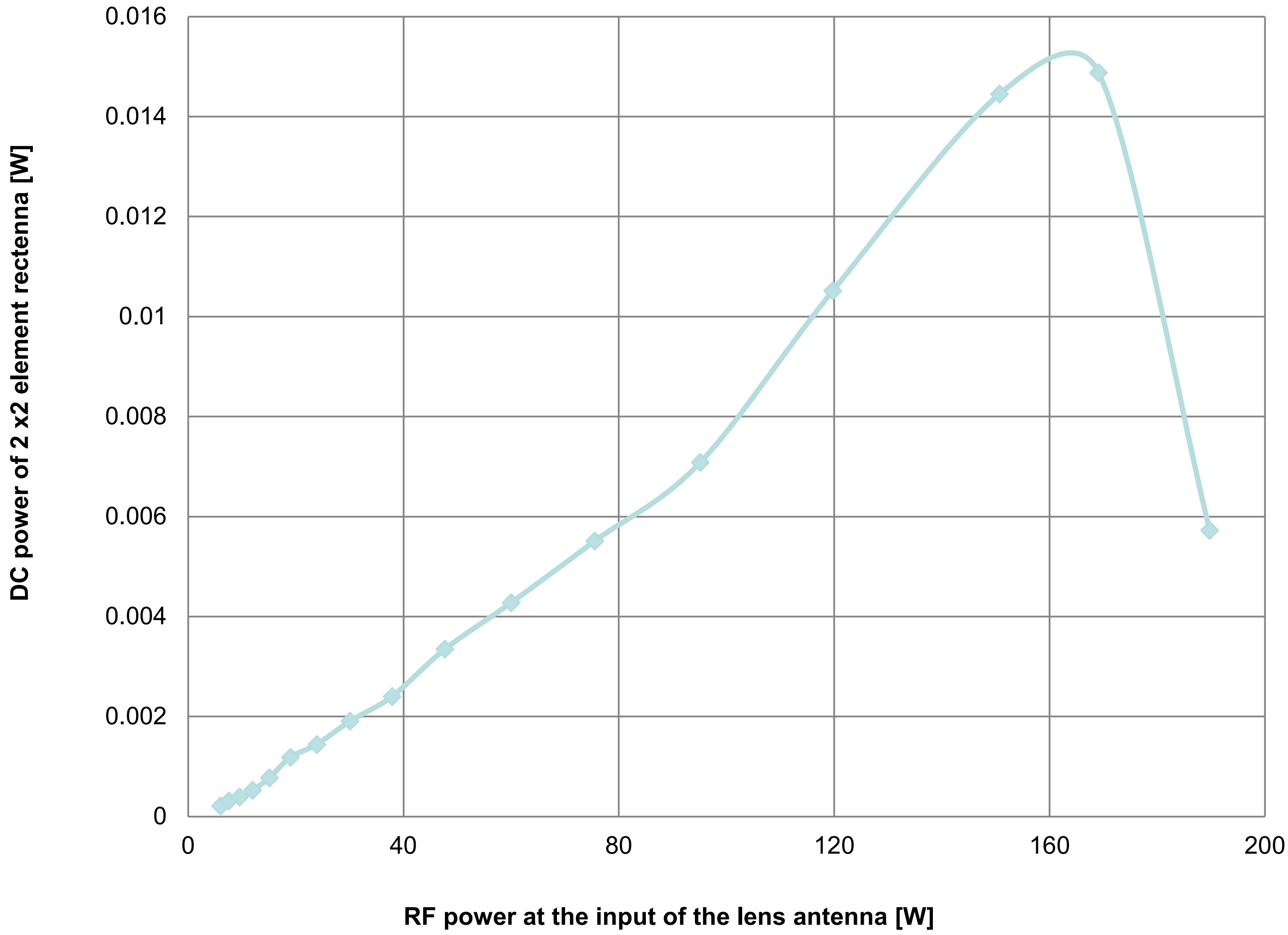
$$E_{conv}^{Skyworks} = \frac{P_{DC}}{P_{rf}} = \frac{0.24mW}{17.6mW} = 0.014 = 1.4\%$$

$$E_{conv}^{Mott} = \frac{P_{DC}}{P_{rf}} = \frac{3.3mW}{17.6mW} = 0.186 = 18.6\%$$

The W-band experimental setup with the Gyrotron source



DC power vs. RF power



$E_{RF\text{-}DC}$ = 15mW / 73mW = 20.5%

Vol. **131** (2017) *ACTA PHYSICA POLONICA A* No. 5

12th Symposium of Magnetic Measurements and Modeling SMMM'2016, Częstochowa–Siewierz, Poland, October 17–19, 2016

Characterization of a Schottky Diode Rectenna for Millimeter Wave Power Beaming Using High Power Radiation Sources

A. Etinger, M. Pilossof, B. Litvak, D. Hardon, M. Einat, B. Kapilevich and Y. Pinhasi*

Ariel University, Ariel 40700, Israel

Two principal elements play a role in a wireless power beaming system: a high power radiation source as the transmitter and a rectifying antenna (rectenna) as an RF to DC converter at the receiving site. A millimeter wave power transmission is analyzed using transmission system and a W-band rectenna based on a low-barrier Schottky diode. A quasi-optical approach is presented here, using free-space Gaussian propagation and optical ABCD matrices for lenses. Experiments are made to estimate the optimal load resistance and power handling capability of a single rectifier. A low power W-band tunable solid-state source delivering 0.4 W CW power equipped by the focusing lenses is used to characterize the responsivity of the rectenna. A pulsed power gyrotron is used to identify the diode breakdown point. It was found that the RF-to-DC conversion efficiency corresponding to the optimal load of 200 Ω is about 20.5% while the maximum DC power converted by the diode with optimal load is about 15 mW before breakdown.

DOI: 10.12693/APhysPolA.131.1280

PACS/topics: 84.40.–x, 88.80.hp, 88.80.ht, 42.25.Bs applied sciences

MDPI

Review

Wireless Power Transfer via Subterahertz-Wave

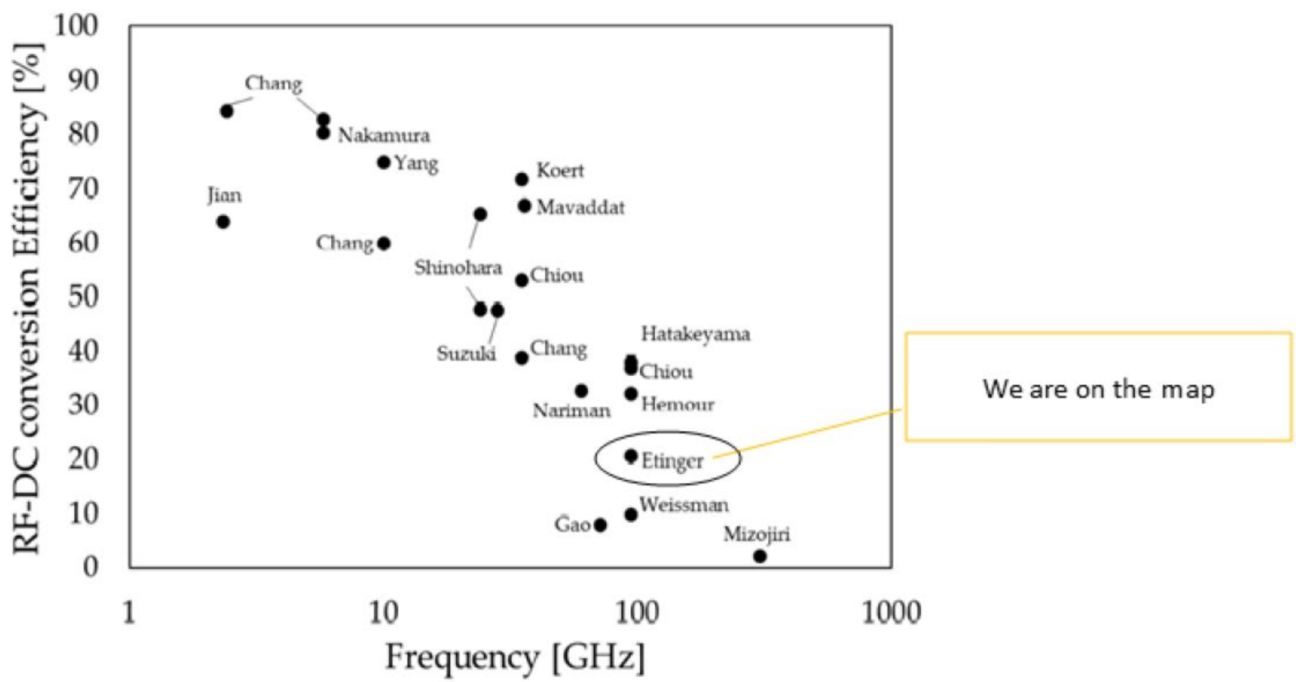
Sei Mizojiri * and Kohei Shimamura

Department of Engineering Mechanics and Energy, University of Tsukuba, Tsukuba 305-8577, Japan; shimamura@kz.tsukuba.ac.jp

* Correspondence: mizojiri@spl.kz.tsukuba.ac.jp

Received: 25 September 2018; Accepted: 13 December 2018; Published: 17 December 2018

check for updates

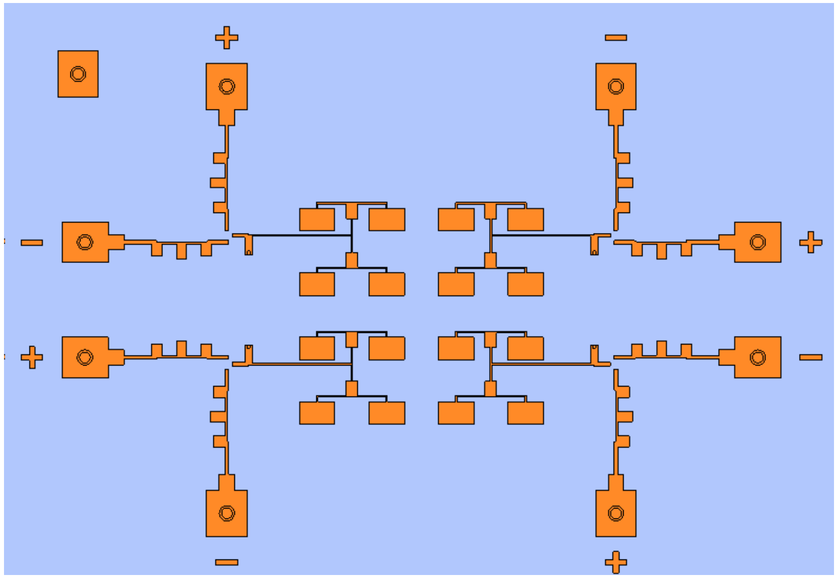


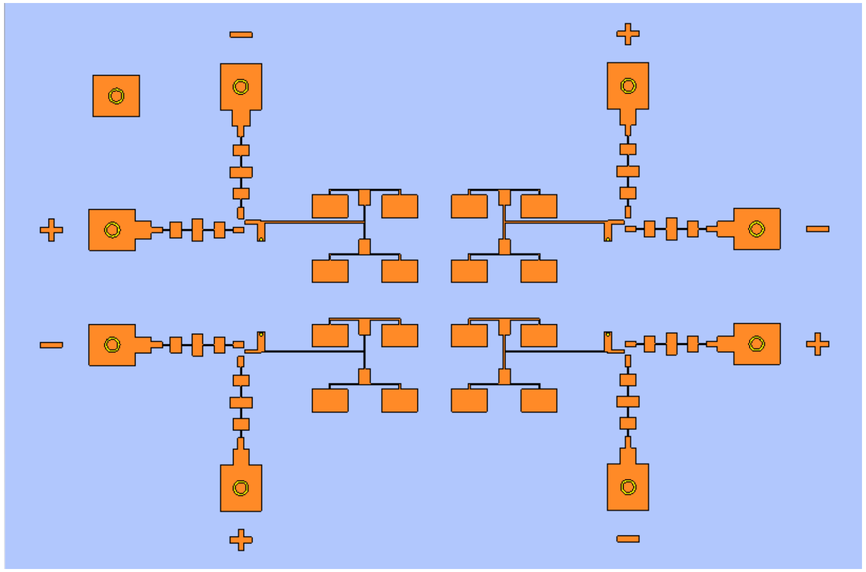
MMW
Full-wave
Rectifying Antenna

RECTENNA

Full Wave Rectenna Circuits

- MS8350 (Microsemi)
- MA4E1319 (Macom)
- MA4E2040 (Macom)

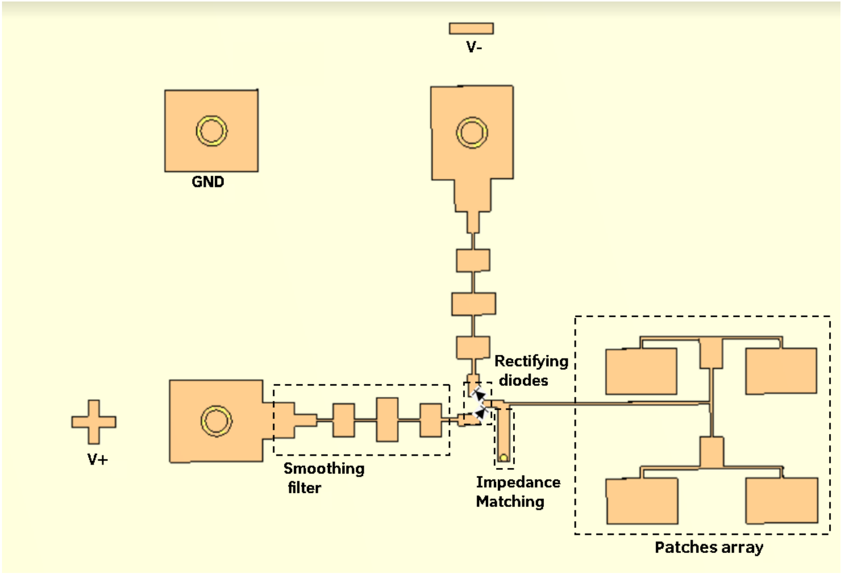


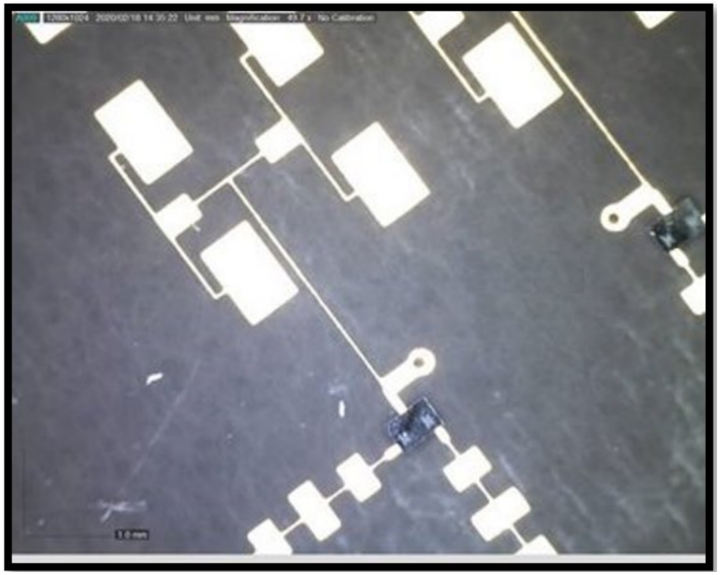


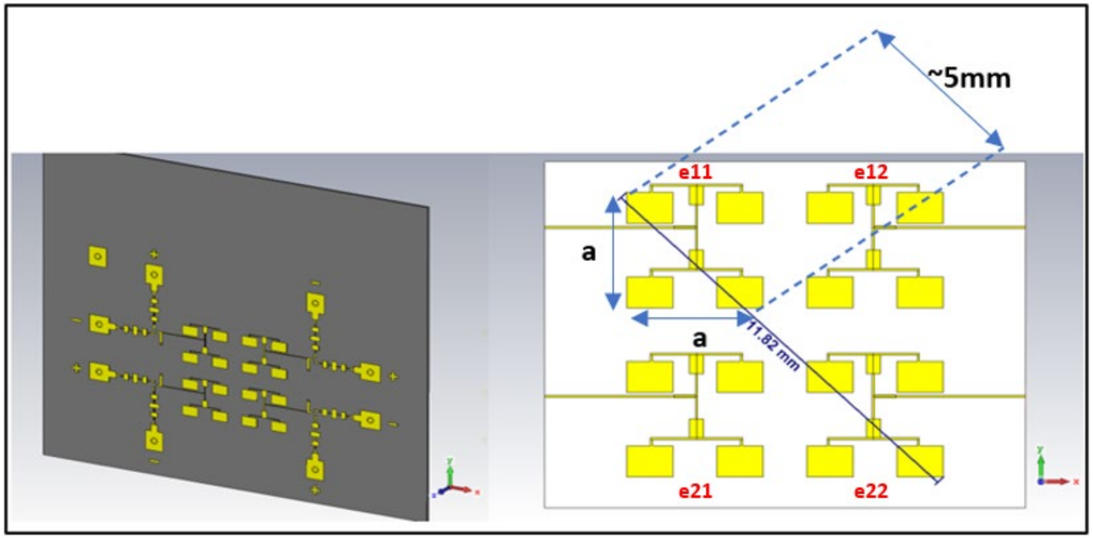
MMW diode rectifiers

Configuration	1	2	3
Rectifing diode	MA4E2040	MA4E1317	MA4E1319
	Full/Half wave	Half wave	Full wave
Impedance matching	SWP4-156	NA	SWP2-296
Load resistor[Ω]	100	100	500
DC power[mW]	46	13	21
Efficiency[%]	33~	9~	16~

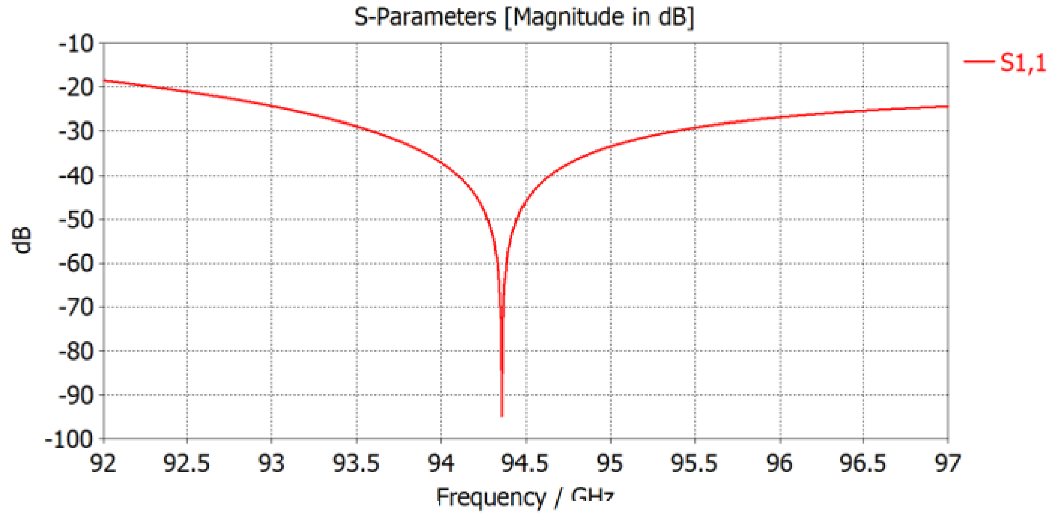
The Rectenna layout

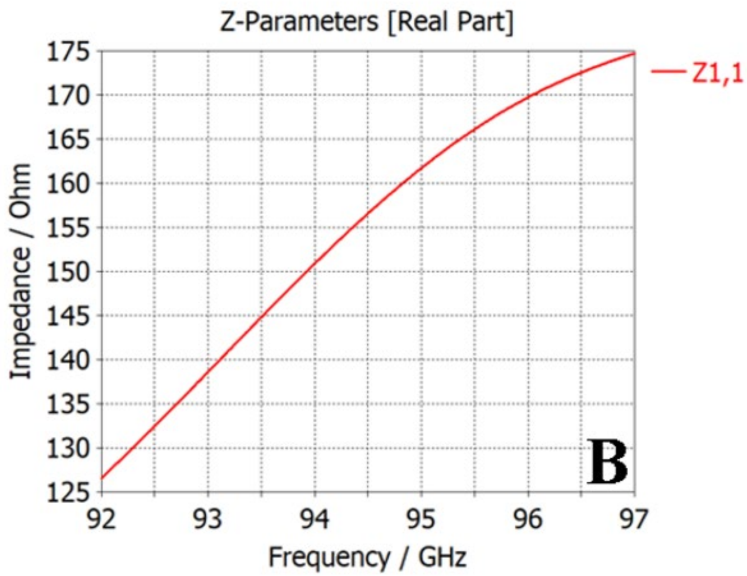


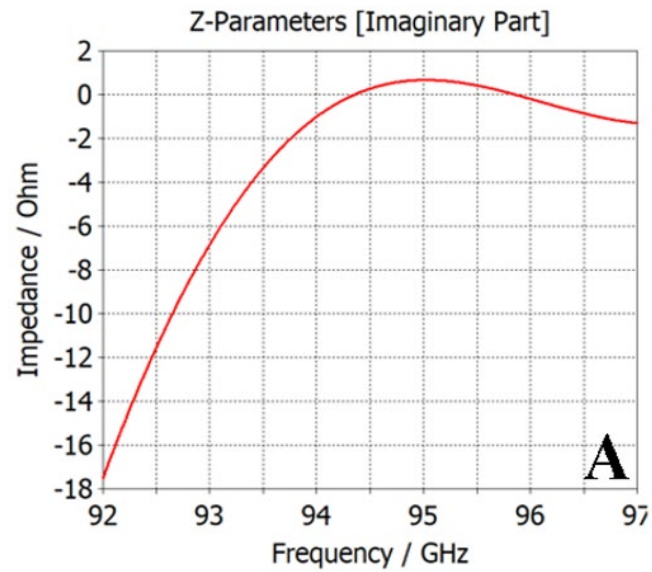




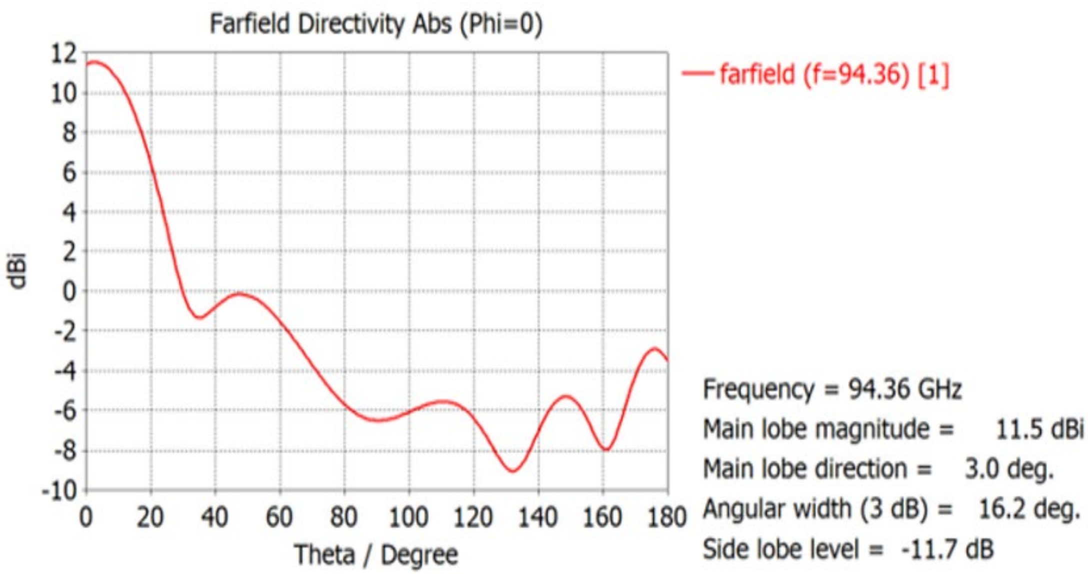
S11 and impedance

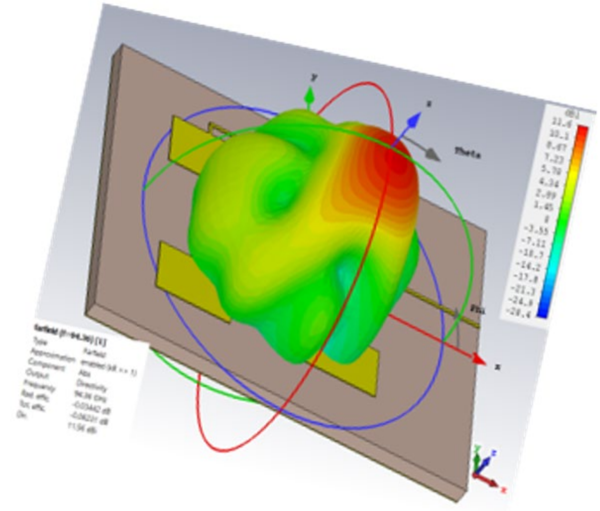


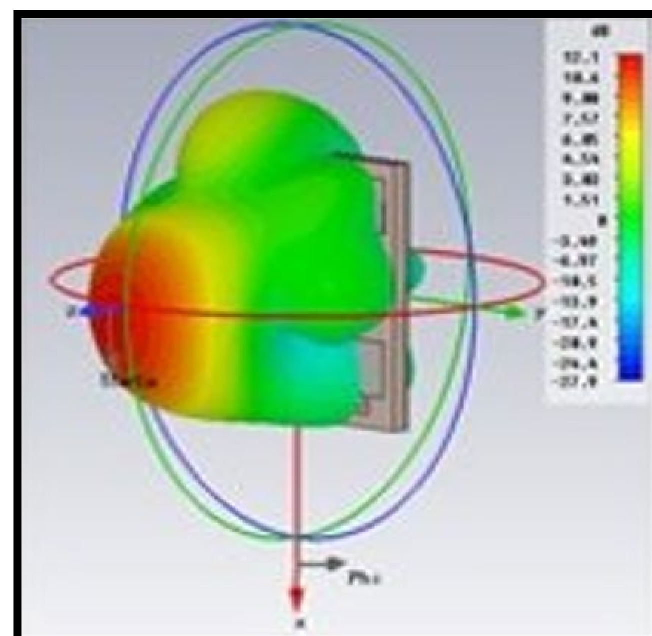




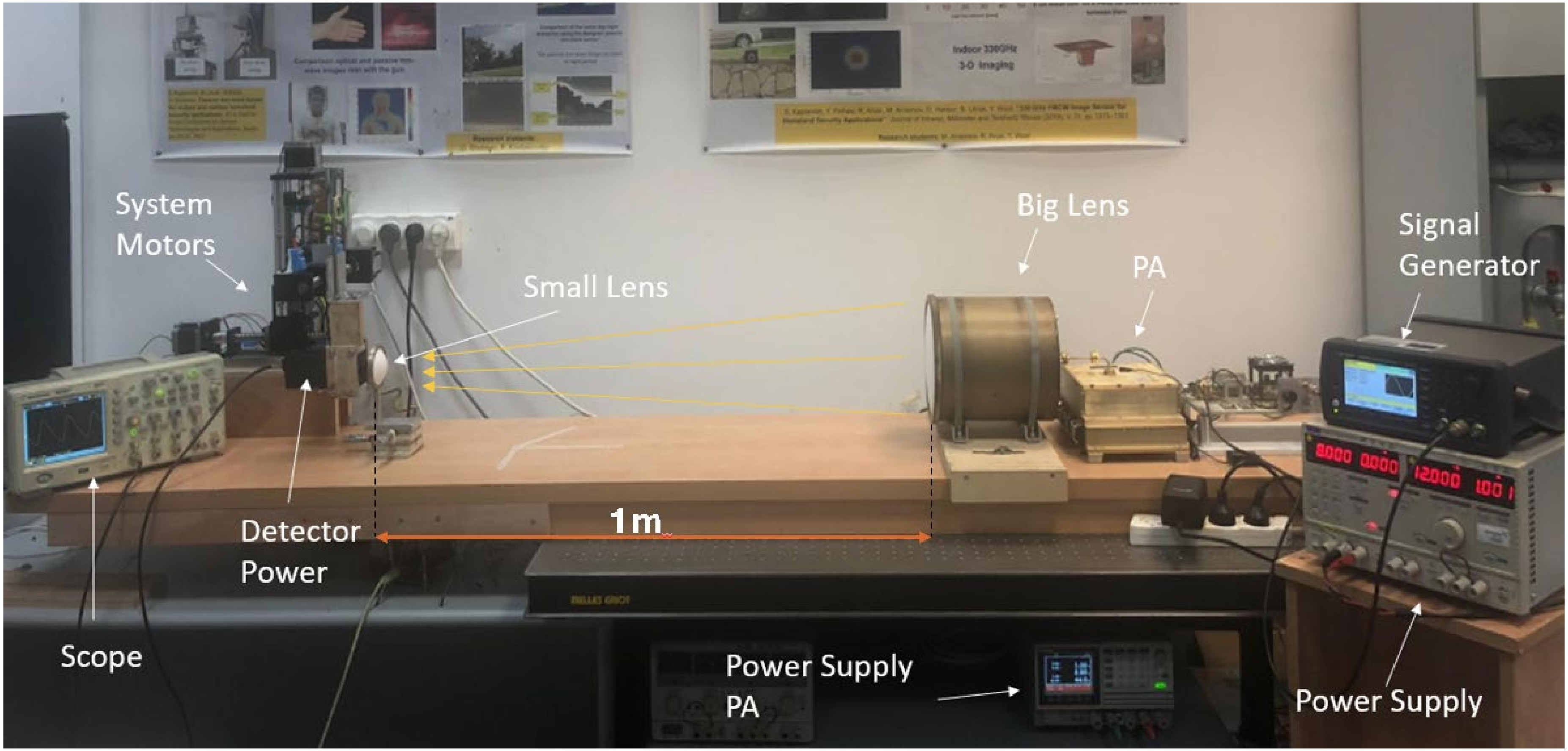
Pattern


Farfield Directivity Abs (Phi=0)
12
10
8
6
4
2
0
-2
-4
-6
-8
-10
dBi
0
20
40
60
80
100
120
140
160
180
Theta / Degree
farfield (f=94.36) [1]
Frequency = 94.36 GHz
Main lobe magnitude = 11.5 dBi
Main lobe direction = 3.0 deg.
Angular width (3 dB) = 16.2 deg.
Side lobe level = -11.7 dB

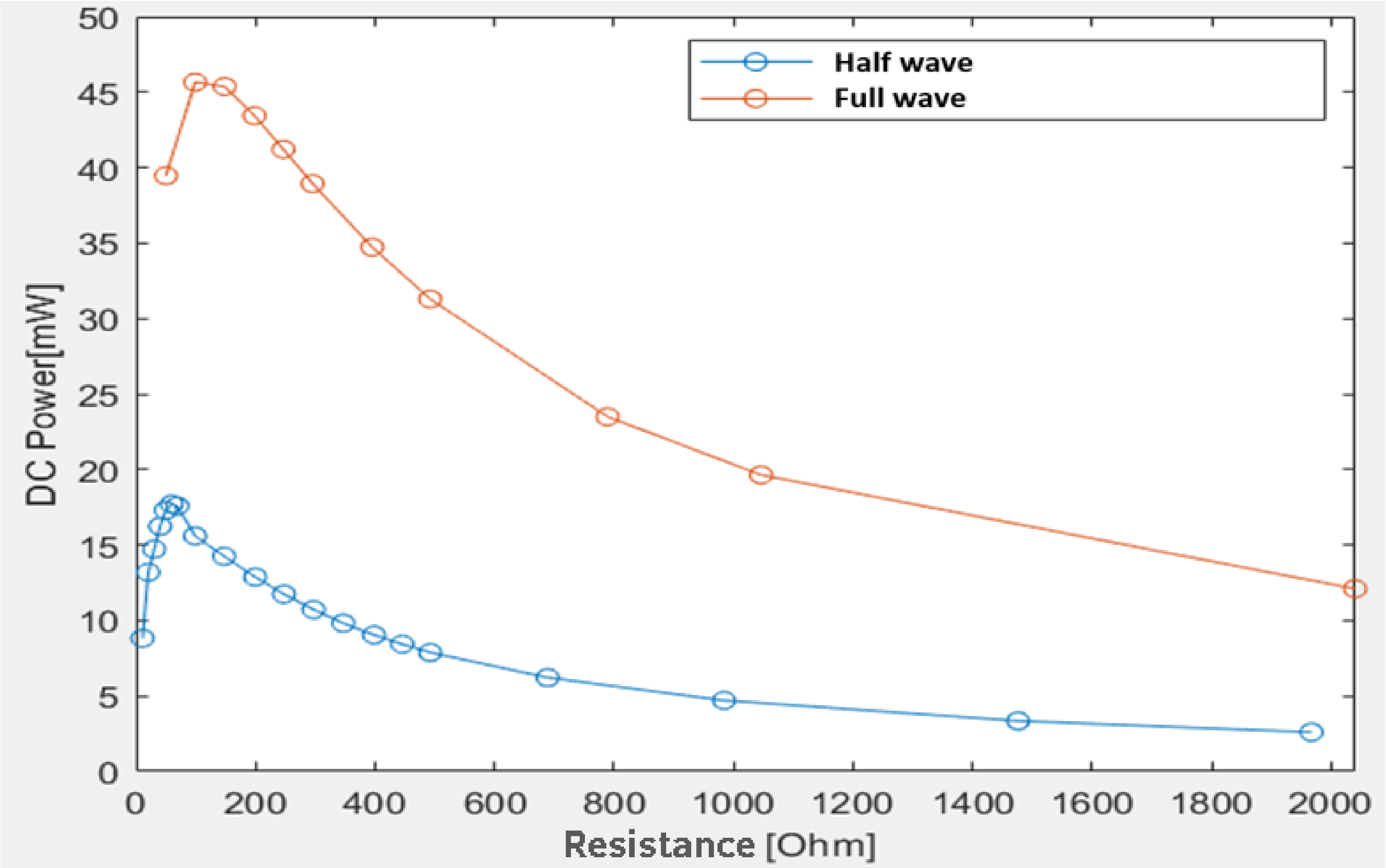




Experimental setup



DC power vs. load



The END