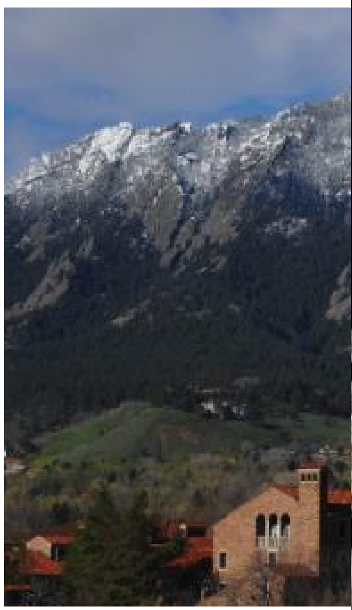
WPT on the Dark Side of the Moon

and other aerospace applications

Zoya Popovic
Department of Electrical, Computer and Energy Engineering
University of Colorado, Boulder, U.S.A.



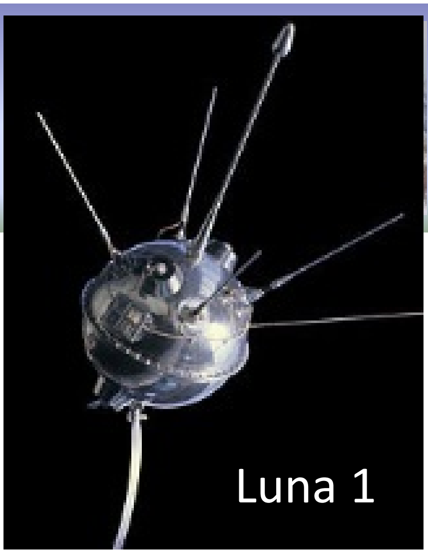
- >$454 million in
- largest NASA-func
  the past 20 years

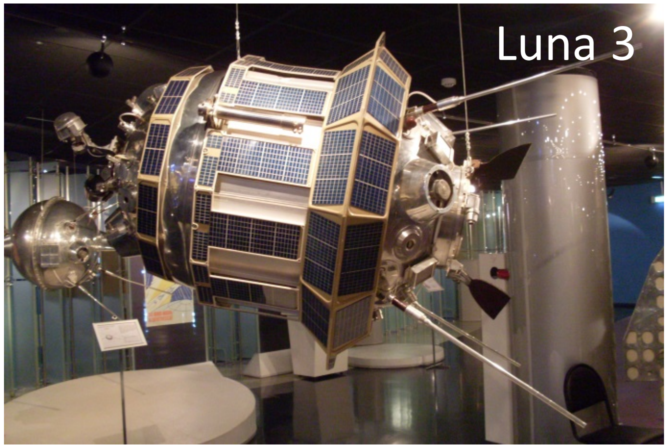
ed; 42 professors; 2

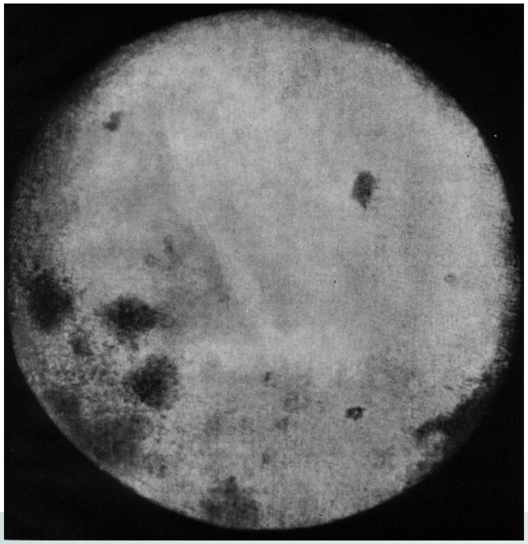
- 200 PhD students, 400 undergraduates

Lunar Exploration

- First unmanned spacecraft: Soviet Union's Luna in 1959; first photos of dark side by Luna 3
- U.S. NASA Apollo 8 (man orbiting mission) and Appolo 11-17 manned landing missions
- After 1972, the Moon has been visited by only unmanned spacecraft
- Rovers: Soviet 1973 Lunkhod, China 2013 Yutu
- Orbital missions since 2004: Japan, China, India, the United States, and ESA
- Discovery of lunar water ice in permanently shadowed craters at the poles and bound into the lunar regolith
- Future manned missions to the Moon have been planned, including government as well as privately funded efforts.
- The Moon remains, under the Outer Space Treaty free to all nations to explore for peaceful purposes.





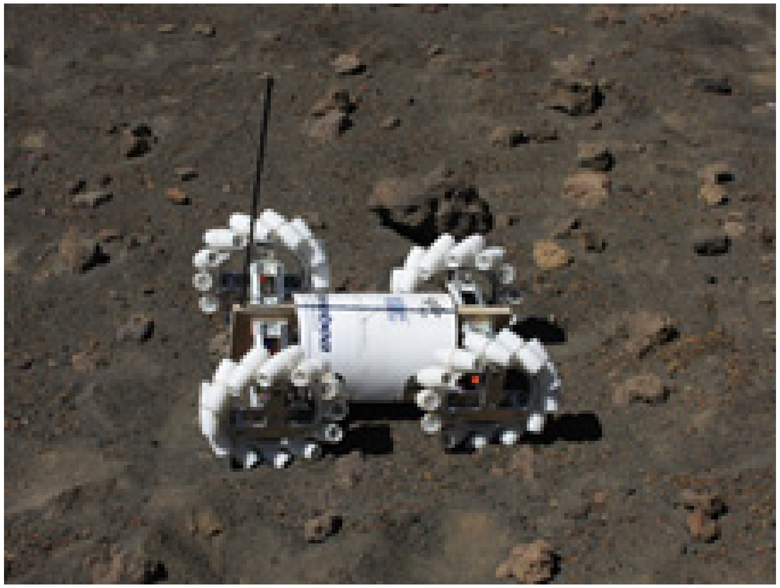


NASA Lunar Exploration

Global Exploration Strategy (December 2006)

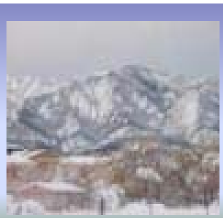
- Robotic precursor missions used to characterize critical environmental parameters and lunar resources
- Human return to the moon no later than 2020
- Develop a solar-powered lunar base at the ***South Pole***

- In-Situ Resource Utilization: use lunar materials to produce oxygen and extract water from ice reservoirs with a robotic mission.
- Tested rovers on Mauna Kea, Hawaii, in 2010

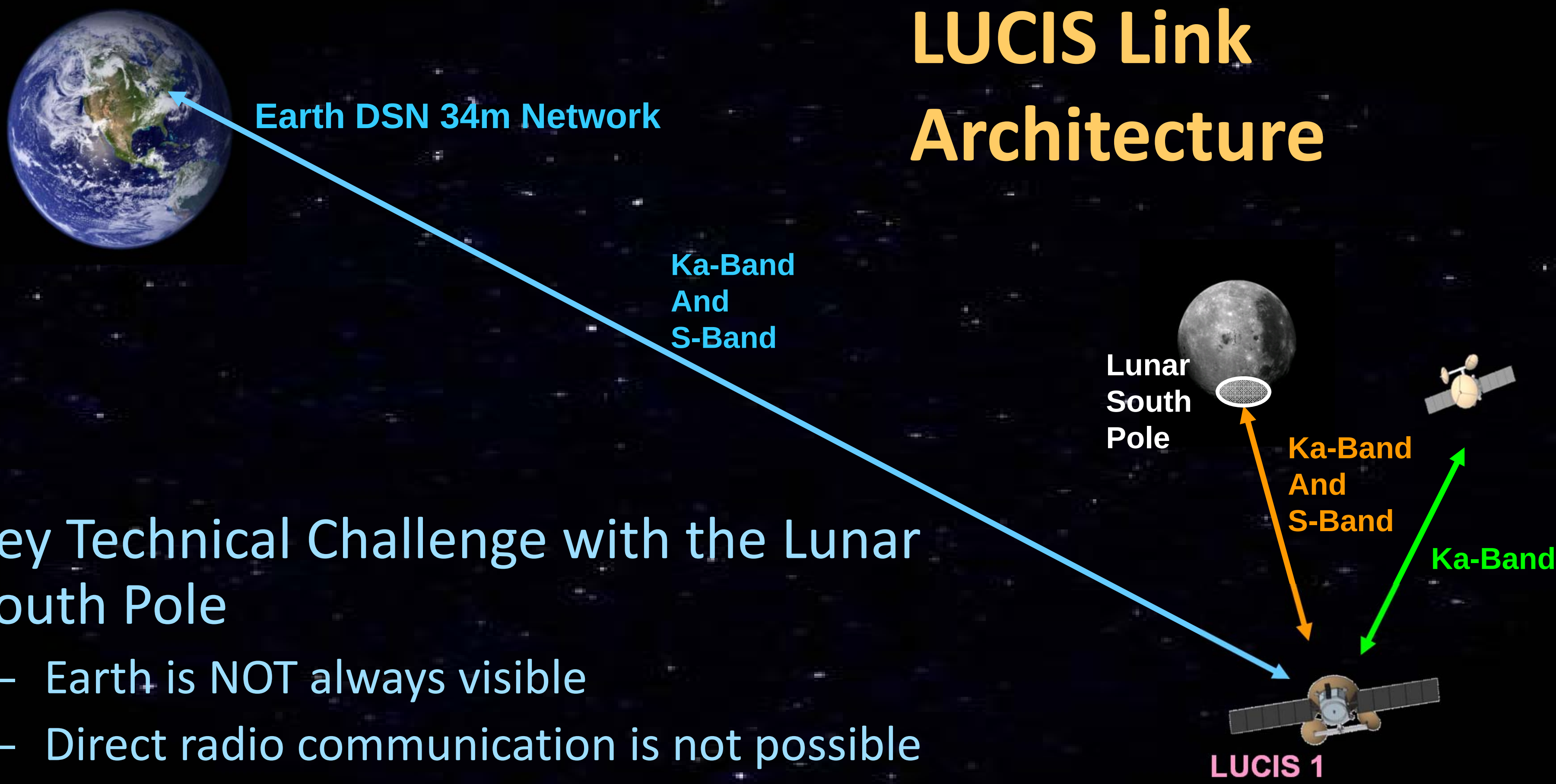


Water on the Moon?

Communications on the Moon

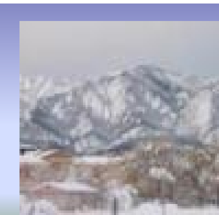


LUCIS Link Architecture



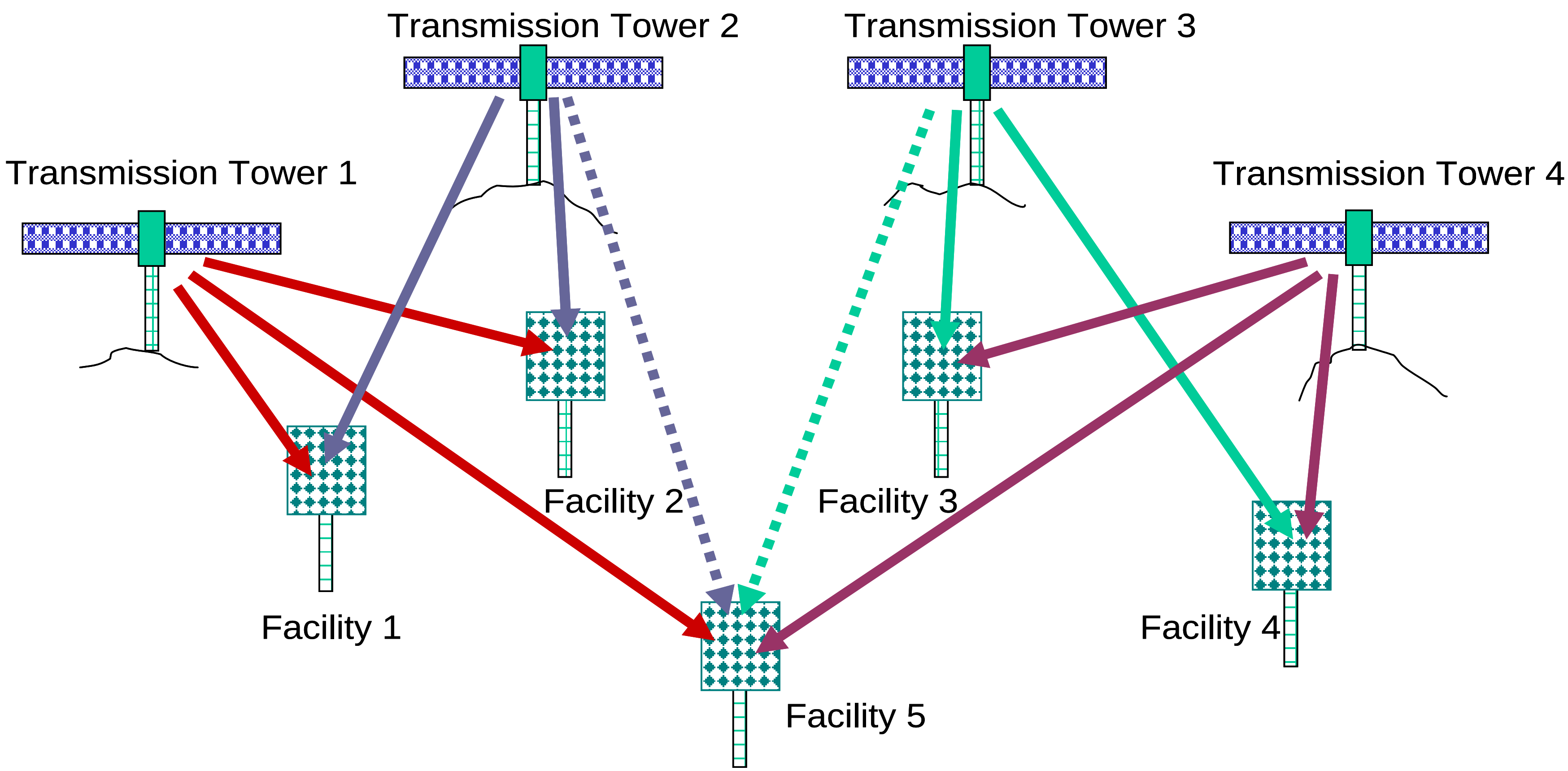
- Key Technical Challenge with the Lunar South Pole
  - Earth is NOT always visible
  - Direct radio communication is not possible
  - Lunar relay architecture expandable to provide global coverage of the lunar surface for human exploration phases

Lunar research station power problem



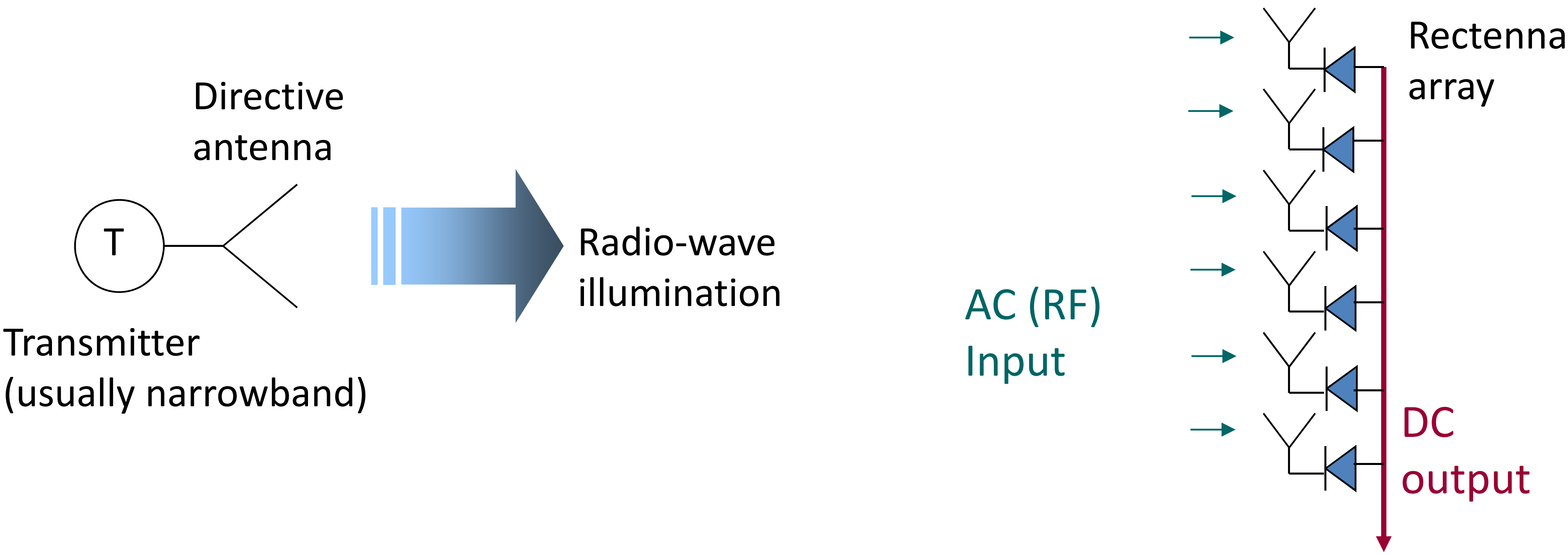
- How to deliver power to facilities on the lunar surface in places where there is little or no sunlight?
- Load stations are planned to be 0.5 to 2km away from mountain-tops where photovoltaic generation stations can be placed
- Each site expected to require 10kW of power
- Cables estimated to have a mass of ~7,500kg for five load stations
  - large distances, large mass
  - sensitive to temperature
  - expensive to transport from Earth to the Moon
  - may be a safety hazard for lunar operations
  - susceptible to solar flare induced transient effects
  - large diameter due to high voltages and power levels
  - difficult to manage due to residual cable stresses.
  - difficult to move in the event that a different facility needs to be powered

Possible solution:WPT



	Transmitter 1	Transmitter 2	Transmitter 3	Transmitter 4	Total power
Facility 1	5kW	5kW			10kW
Facility 2	5kW	5kW			10kW
Facility 3			5kW	5kW	10kW
Facility 4			5kW	5kW	10kW
Facility 5	2.5kW (5kW)	2.5kW (0)	2.5kW (0)	2.5kW (5kW)	10kW

Wireless power beaming

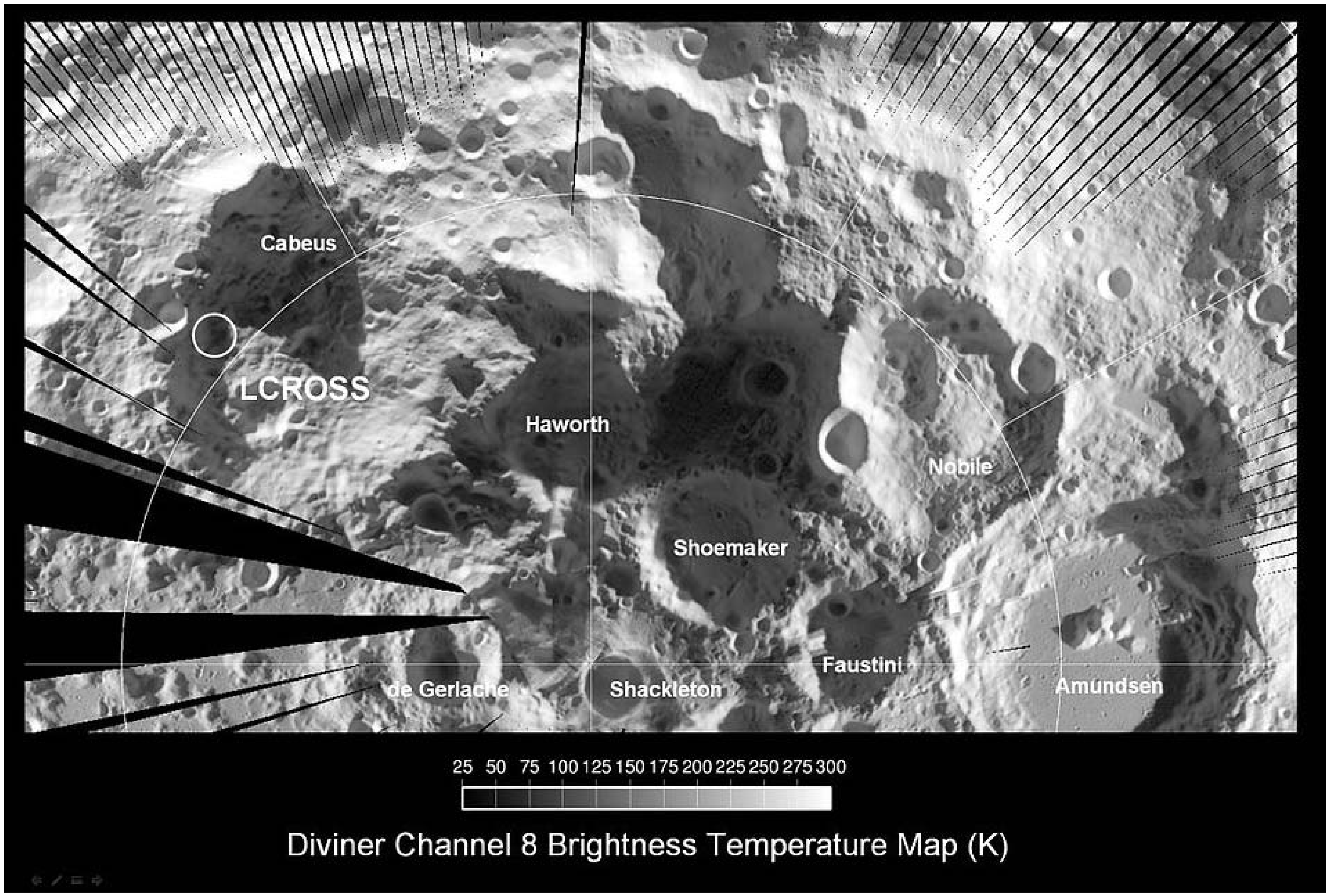


Demonstrated applications, relatively high power **directive** beaming:

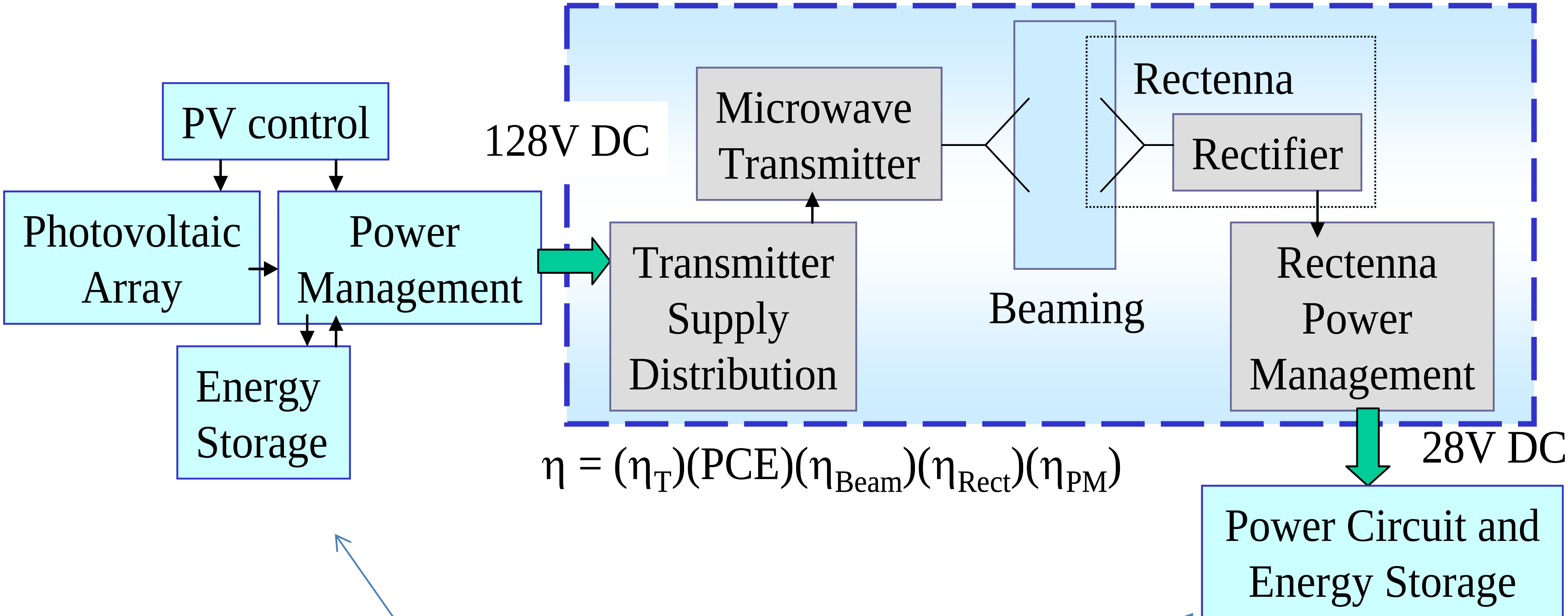
- proposed for helicopter powering (Brown, 1984)
- solar-powered satellite-to-ground power transmission (NASA McSpadden et al.,1996; Japan, Shinohara et al., 1998)
- inter-satellite power transmission, utility power satellites (Chang et al., 1992)
- mechanical actuators for space-based telescopes (Epp et al., 2000)
- small dc motor driving (Fujino et al., 1994)
- short range wireless power transfer, e.g. between two parts of a satellite

Lunar base powering stations

- Environment: no light at bottom of craters on the South Pole, but continuous light at crater edges
- No wind, low gravity, short line-of-sight (small radius)



Block diagram of WPT system



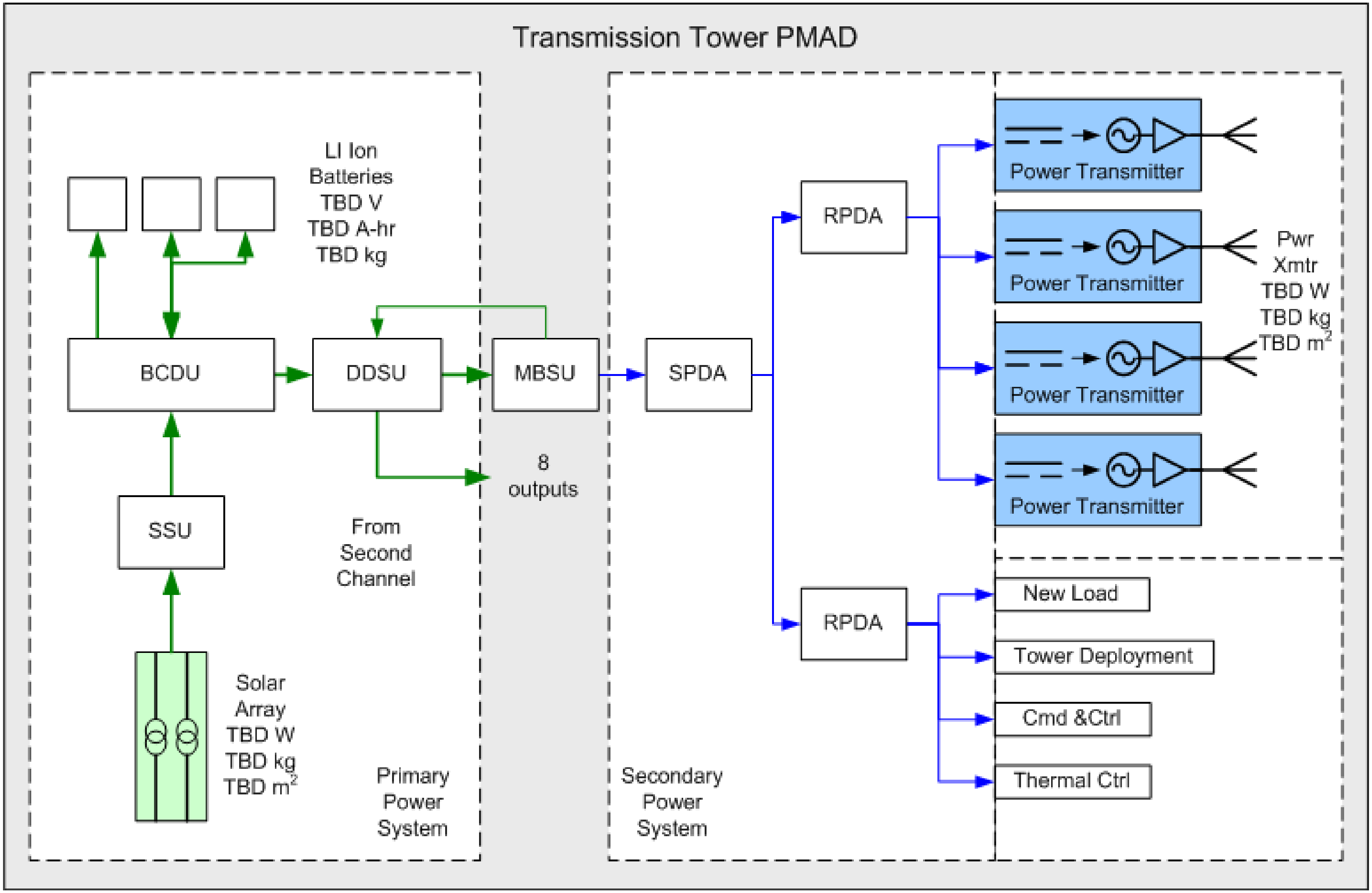
$$\eta = (\eta_T)(PCE)(\eta_{Beam})(\eta_{Rect})(\eta_{PM})$$

Some parts are independent of the power transmission system

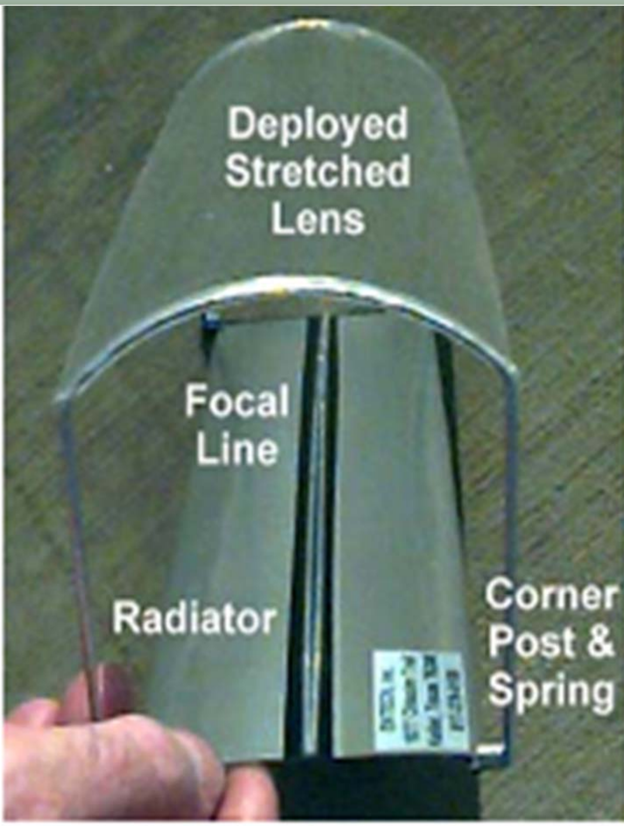
Efficiency breakdown

Efficiency	Description	Max Demonstrated
$\eta_T = \frac{P_{RF,antenna}}{P_{DC,in}}$	Total microwave transmitter DC-RF conversion efficiency, where $P_{RF,Out}$ is the RF power delivered to the transmitting antenna.	70-80% power and frequency dependent [3,4]
PCE	Power-combining efficiency of the transmitter (no single RF source provides the required multiple kW)	80-90%, combiner-type dependent [5]
$\eta_{Beam} = \frac{P_{RF,Trans}}{P_{RF,\mathrm{Rec}}}$	Beaming efficiency between the transmit and receive apertures, including the free-space propagation loss	About 80% for far-field (see next section)
$\eta_{\mathrm{Rect}} = \frac{P_{DC,\mathrm{Rectified}}}{P_{RF,\mathrm{Rec}}}$	Rectification efficiency of the rectenna, where the input is the received RF power at the aperture, and the output the non-regulated DC power	80% [6]
$\eta_{PM} = \frac{P_{DC,out}}{P_{DC,\mathrm{Rectified}}}$	Rectenna power management efficiency required to produce given fixed output voltage	85-90% dependent on rectenna number and power [7]

Transmitter



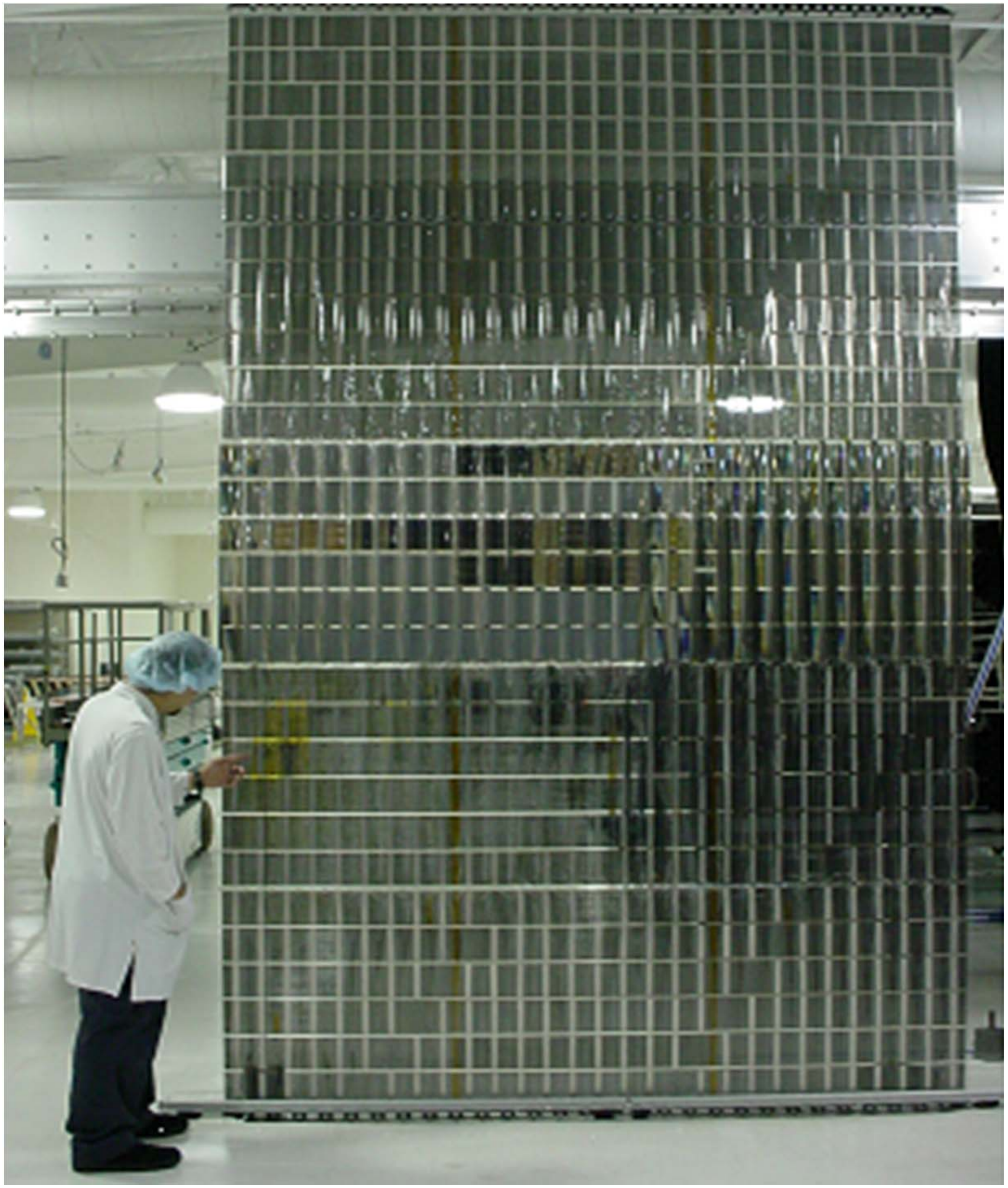
PV Technology



- Stretched Lens Arrays (SLA)
- Fresnel lens and high efficiency multi-junction cells provide improved PV performance
- The Fresnel lens concentrates the Sun power density by 8:1
  - light weight,
  - scalable with a capacity of 100’s of kW’s
  - provides good radiation resistance
  - has a built in passive thermal management (radiator)
  - has a high specific power (~300 W/kg)
  - can operate at high voltages (300 – 600V)

O’Neill, Mark J. Int. Conf. Solar Concentrators for the Generation of Electricity or Hydrogen, 2005, “ENTECH's Stretched Lens Array (SLA) for NASA's Moon/Mars Exploration Missions, Including Near-Term Terrestrial Spin-Offs”

PV Technology



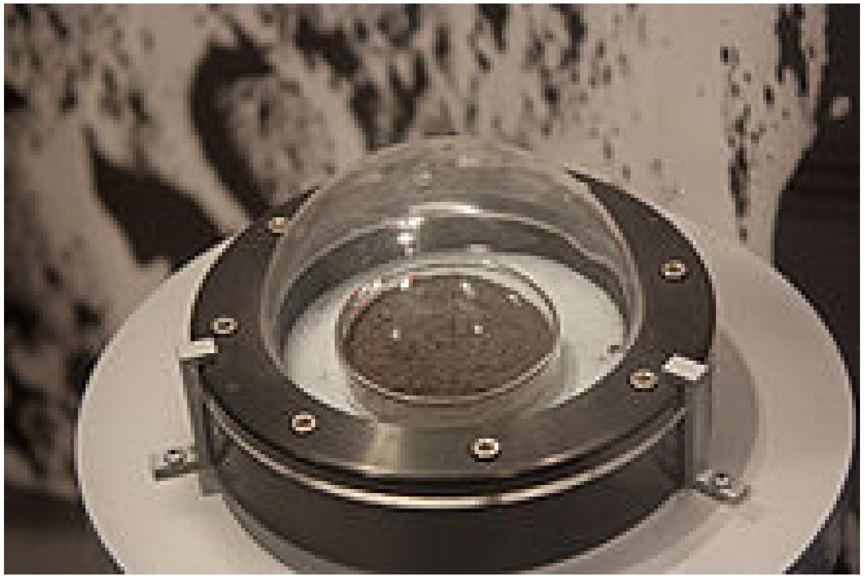
- For a lunar power generation station, Entech, ATK and NASA (Glenn Research Center) developed a 2.5m by 5m   4-kW SLA square rigger (SLASR) array
- This modular SLASR is expected to be easily mass produced.
- Expected to have specific power levels in excess of 1000 W/kg

O'Neill, Mark J., 4th World Conference on Photovoltaic Energy Conversion, Waikoloa, Hawaii, May 7-12, 2006, "Stretched Lens Array (SLA) for Collection and Conversion of Infrared Laser Light: 45% Efficiency Demonstrated for Near-Term 800 W/kg Space Power System"

Grounding system

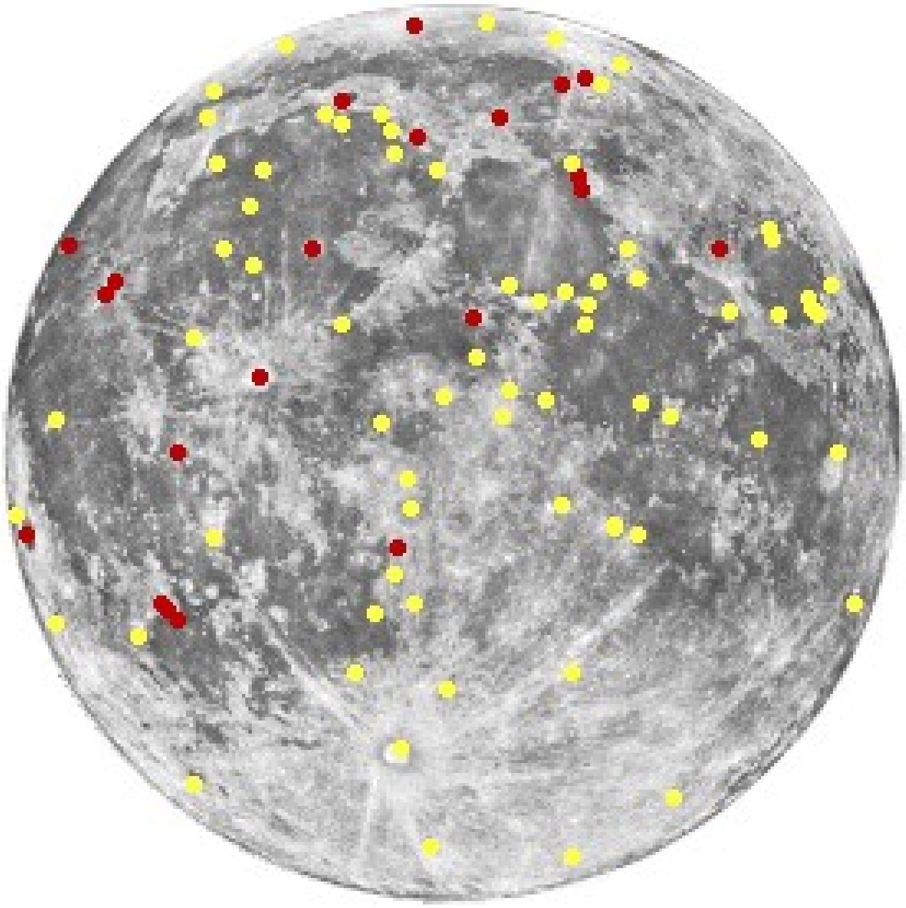
- **Lunar regolith is an insulator**

Compound		Composition (wt %)	
		Maria	Highlands
Silica	SiO_2	45.4%	45.5%
Alumina	Al_2O_3	14.9%	24.0%
Lime	CaO	11.8%	15.9%
Iron Oxide	FeO	14.1%	5.9%
Magnesia	MgO	9.2%	7.5%
Titanium dioxide	TiO_2	3.9%	0.6%
Sodium Oxide	Na_2O	0.6%	0.6%
Total		99.9%	100.0%



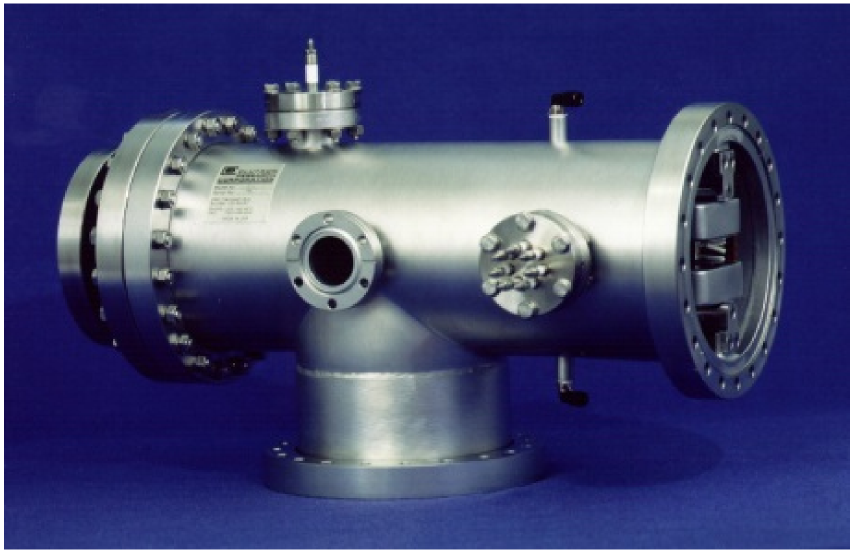
Grounding system

- **Surface of the moon highly charged** due to interaction with the local plasma environment and solar radiation-induced photoemission of electrons
  - Surface static charging is periodic over both short and long timescales.
  - During the lunar day, surface charges positively, at night negatively.
  - Due to orbital variations, the moon has periods of time where interaction with the geomagnetic plasma sheet of the earth creates enhanced charging. Cycles peak approximately every 18 years
  - Static potential of the lunar surface varies daily between +10 and -600V and possibly to several kV



Grounding

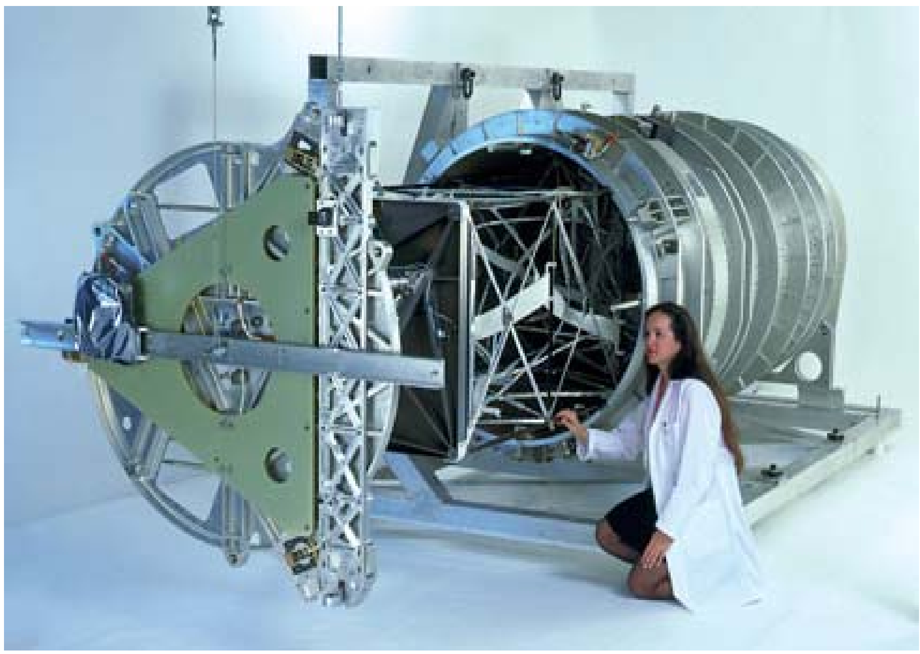
- Grounding : electrical connection of the primary reference of the electrical device to a large enough conductive mass such that charges transferred to the mass do not result in a significant increase in the overall charge of the mass.
- **Power beaming has significant grounding advantages when compared to transmission via cables.**
- Various approaches to lunar grounding (charge management) proposed:



  - Use of grounding rods with the injection of conductive materials into the lunar regolith
  - Use of ion/electron guns to expel positively or negatively charged ions
  - Ion Proportional Surface Emission Cathode (MIT)
  - Field Effect Emitters (Space Systems/Loral)

WPT Channel

- On lunar surface, 2km range requires towers for the transmit antennas (1737.10 km (0.273 Earth's))
- Towers for the rectenna receivers in order to provide safety of personnel at the load stations.
- Example: ATK's Folding Articulated Square Truss (FAST) Mast technology
  - installed on the International Space Station in 2006, <8ft to 115ft



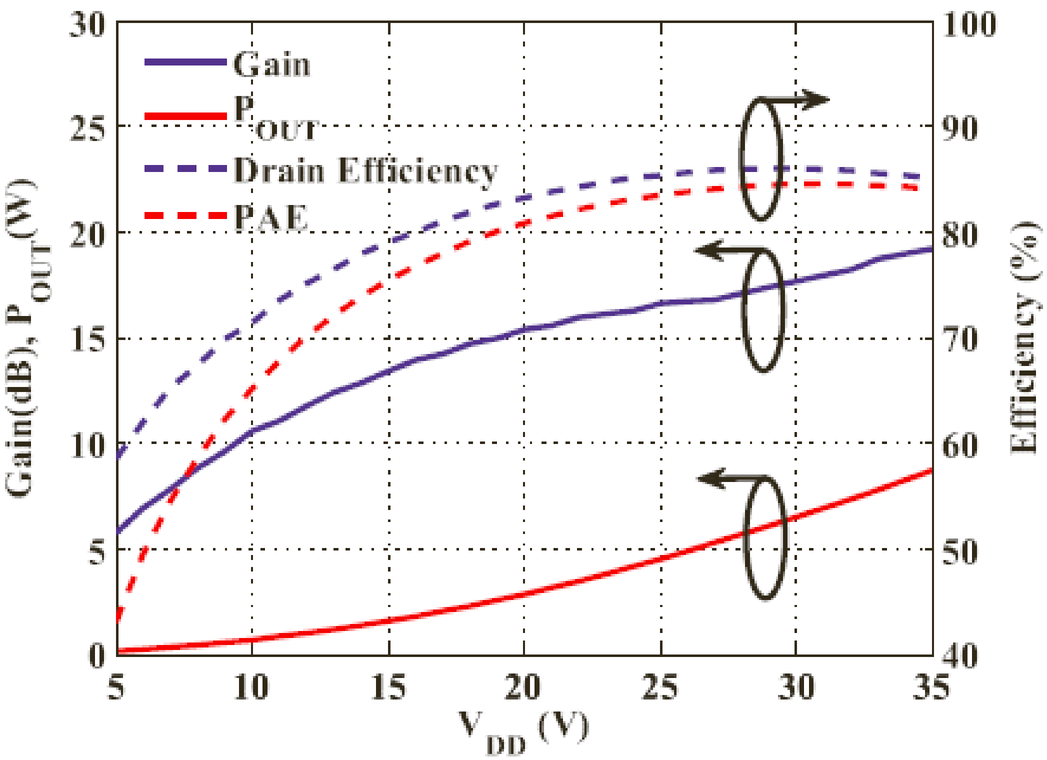
  - A motor driven, internally-threaded canister shell to extrude the boom
  - Stowed and transitioning portions of boom are fully contained within canister
  - Near full stiffness and strength throughout deployment
  - Large deployment push force capability
  - Remotely retractable and deployable
  - No rotation during deployment

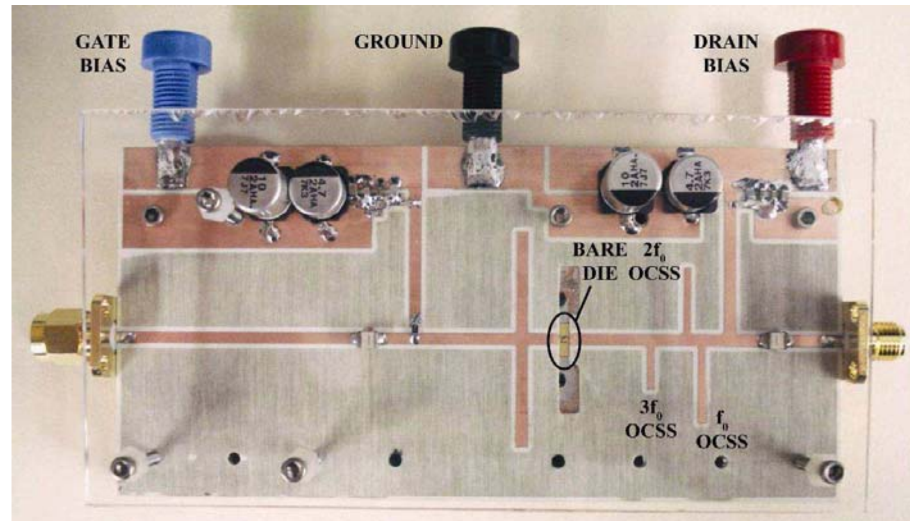
- Frequency choice: tradeoff between antenna size, transmitter amplifier PAE and rectifier efficiency
- DC input is 128V, some DC-DC conversion needed to supply the required voltage needed for microwave devices (typically 8 to 48V range). Can be very efficient (98% is relatively easy to demonstrate).
- Power combining needed at transmit

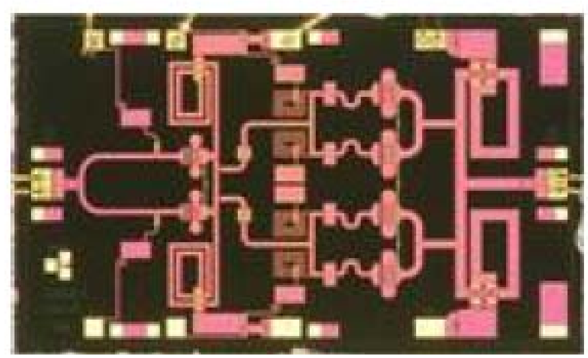
Number Of Subarrays	Number Of Elements Per Subarray	Power Transmitted Per Subarray
350	64	22 W (28 W)
175	128	45 W (56 W)
130	170	60 W (75 W)

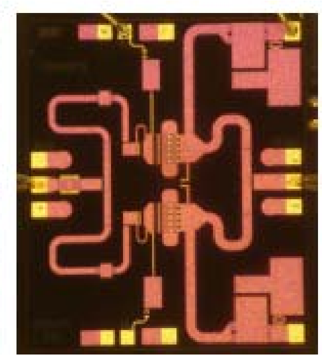
Transmitter RF Power Amplifiers

- Below 1GHz, efficient LDMOS for higher power PAs
- Above 1GHz, GaN PAs have PAE>80% for 5-10W output power, 60% at X-band

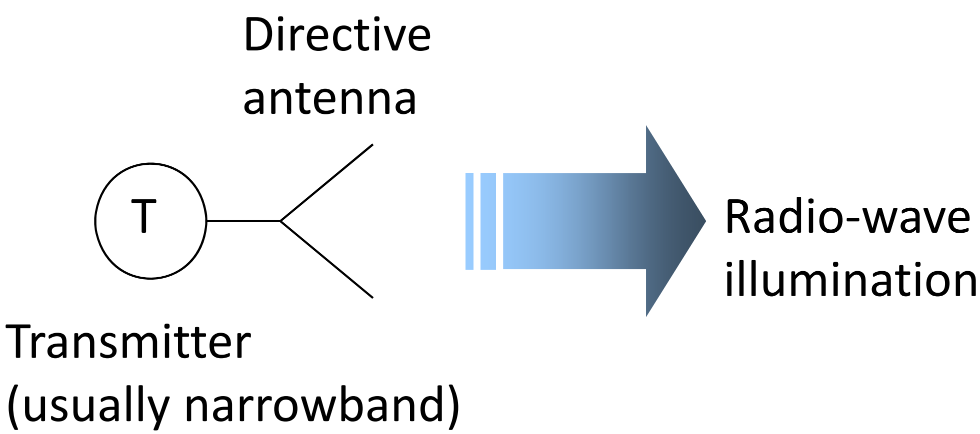


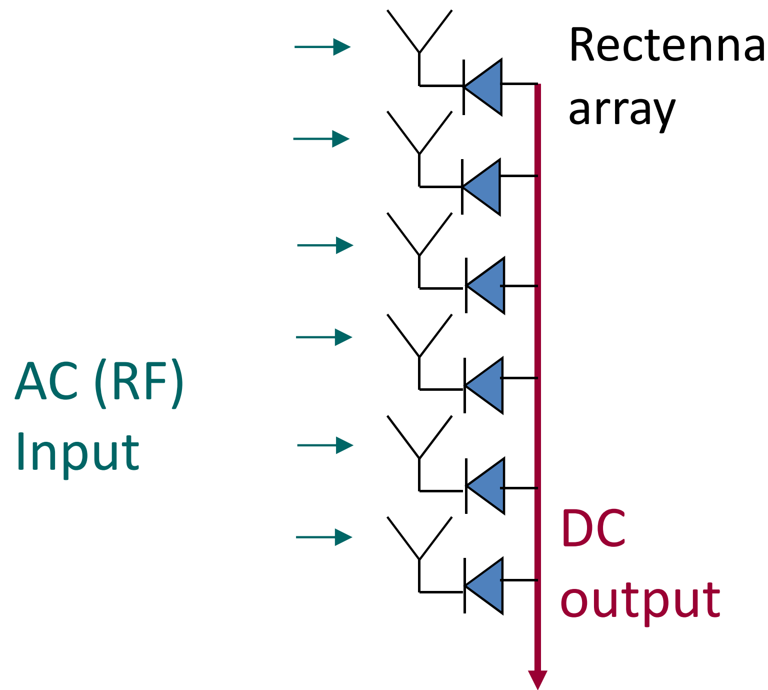






WPT Receiver





Power-combining array of active transmit antennas

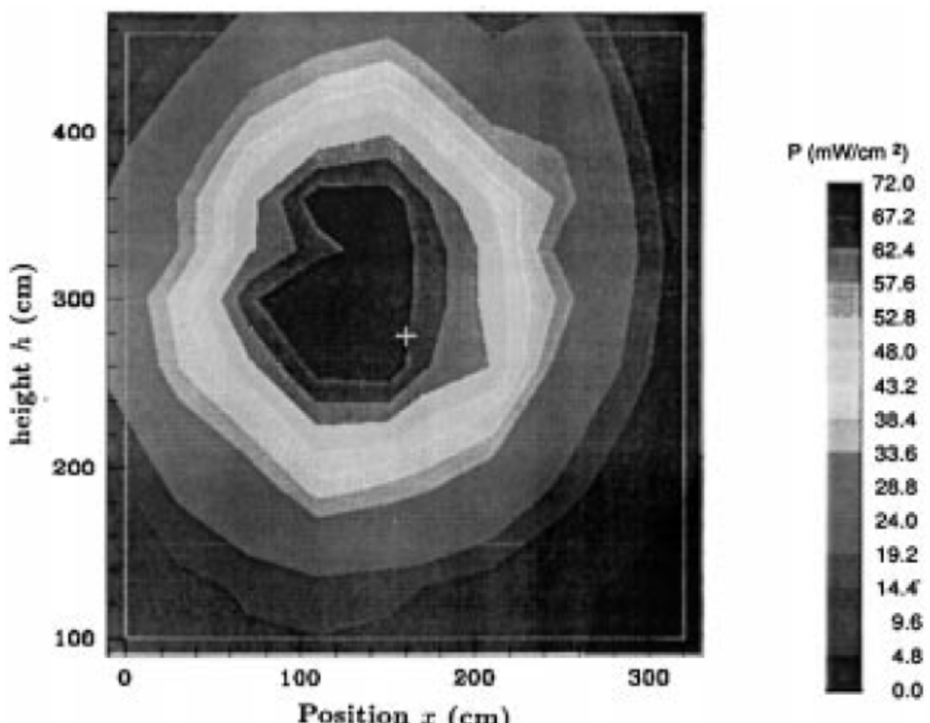
Array of antennas integrated with rectifiers

Rectenna array illumination

$$A / D = \lambda^2 / 4\pi \qquad \tan\theta_{-3dB} = d / R \Rightarrow 2d = aperture.$$

$$\eta_{Beam} = \frac{P_{RF,Trans}}{P_{RF,\mathrm{Re}\,c}} = \frac{A_{Trans} A_{\mathrm{Re}\,c}}{\lambda^2 R^2}$$

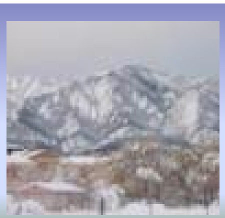
Beaming efficiency



- Measured power flux from parabolic transmitter at receiving rectenna. The power exhibits radial symmetry, with peak power flux occurring in the center (details can be found in reference

N. Shinohara and H. Matsumoto, “Experimental study of large rectenna array for microwave energy transmission,” *IEEE Transaction MTT*, vol. 46, no. 3, pp. 261–267, Mar. 1998.

Beaming efficiency for multiple transmitters



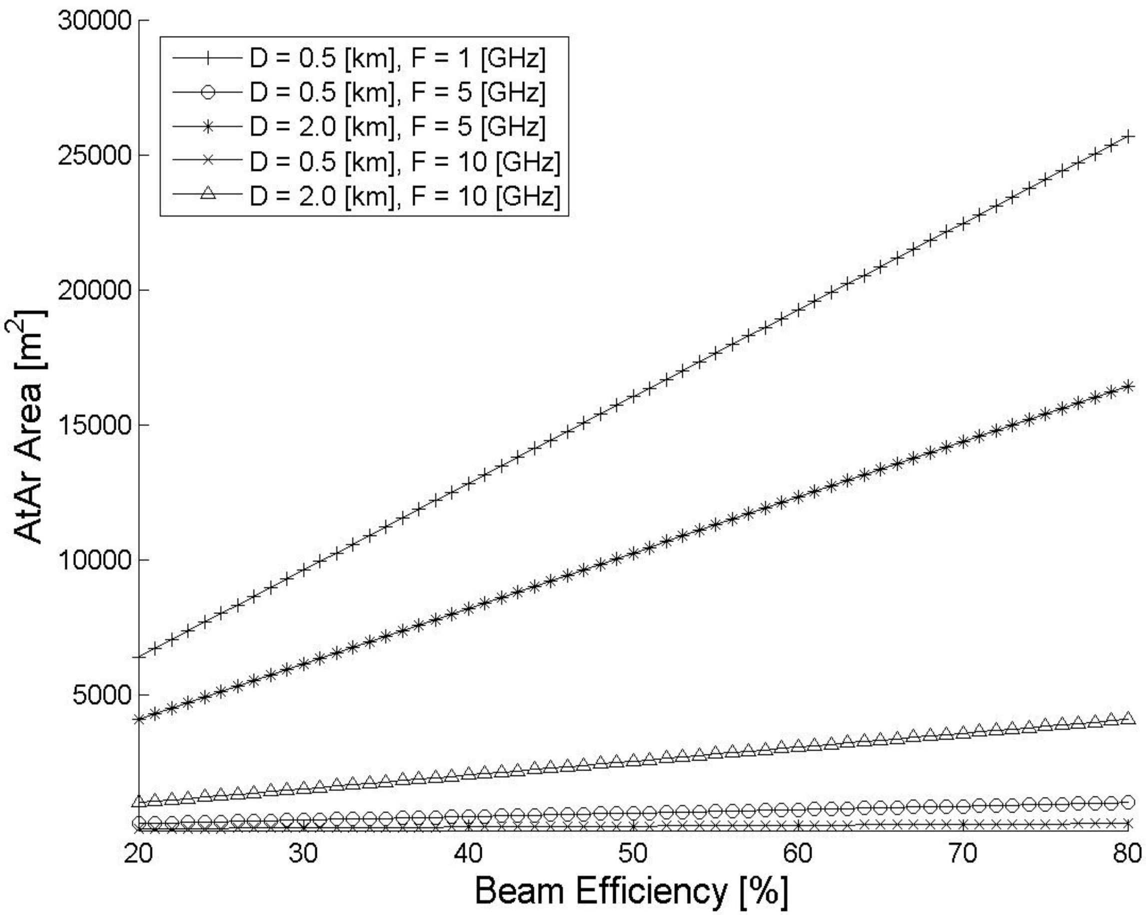
$$\tan\theta_{-3dB} = di / R_{ij} \Rightarrow 2di = aperture.$$

$$A_i / D_i = \lambda^2 / 4\pi$$

$$\eta_{ij} = \frac{P_{Rj}}{P_i} = \frac{A_i A_j}{\lambda^2 R_{ij}^2} \qquad R_{ij} = \kappa\lambda \qquad \kappa > 1000$$

$$P_{Rj} = \sum_{i=1}^{4} P_{Ti} \frac{A_j A_i}{\lambda^2 R_{ij}^2} = \frac{A_j A_i}{\lambda^4} \sum_{i=1}^{4} \frac{P_{Ti}}{\kappa_{ij}^2}$$

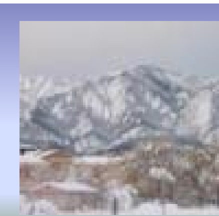
$$\eta_{ij} = \frac{P_{Rj}}{\sum_{i=1}^{4} P_{Ti} / \kappa_{ij}^2} = \frac{A_i A_j}{\lambda^4}$$



Example plot of product of transmit and receive apertures, in square meters, for 3 frequencies and 2 ranges (R=D=0.5 and 2km). The graph shows how the size varies as a function of beaming efficiency.

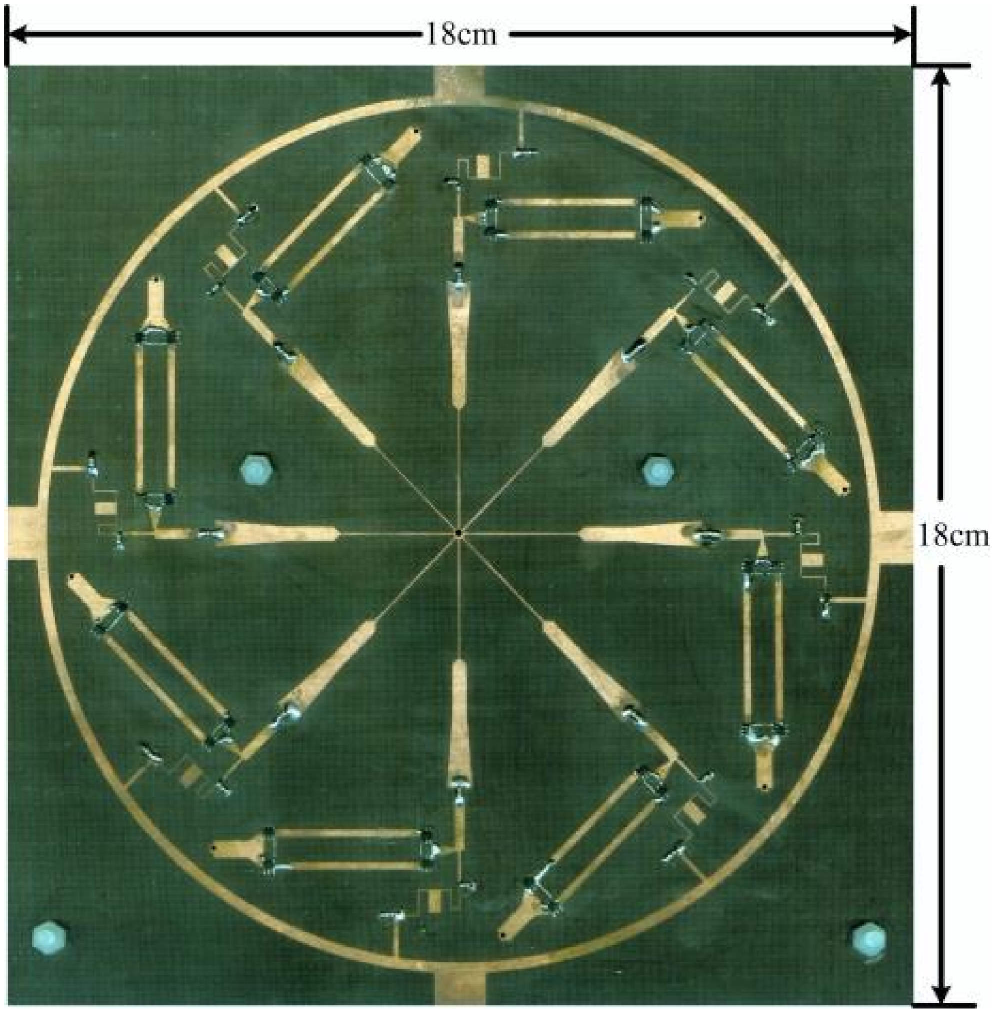
$$A_T A_R = 0.8\lambda^2 \cdot (2km)^2$$

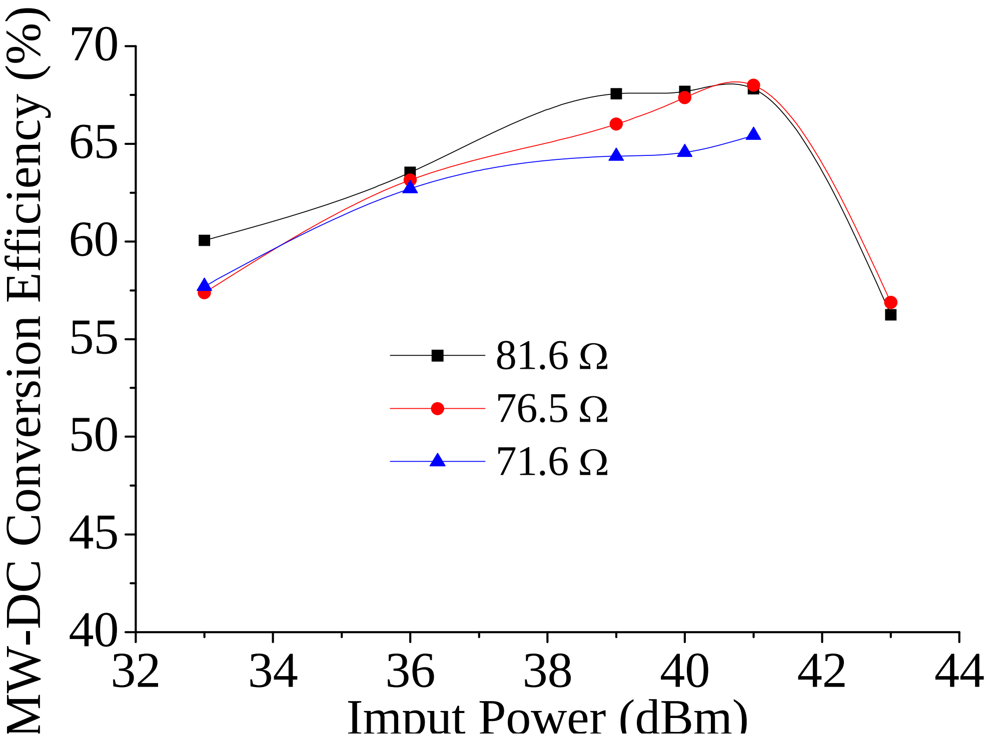
Beaming efficiency = 80%



Frequency/ Wavelength	AT AR	Transmit aperture No. of el. N Directivity D	HPBW and Far Field	Receive aperture No. elements N	Spot size
2GHz / 15cm	72,000 m^4 Not in far field at all	16m x 16m N=106 x 106 D=51dB	0.48° FF~14km!	16m x 16m N=106 x 106	**d=17m**
	Borderline far field	10m x 10m , N=133 x 133 D=47dB	0.77° FF~2.7km	27m x 27m N=360 x 360	**d=27m**
		5m x 5m, N= 67 x 67 D=41dB	1.59° FF~670m	54m x 54m N=720 x 720	**d=55m**
5GHz / 6 cm	11,520m^4 Not in far field	10m x 10m, N=333 x 333 D=55dB	0.32° FF~3.5km	10m x 10m N=333 x 333	**d=11m**
	Borderline far field	5m x 5m, N= 150 x 150 D=49dB	0.63° FF~1.7km	21m x 21m N=700 x 700	**d=22m**
		3m x 3m, N=100 x 100 D=44.8dB	1° FF~600m	36m x 36m N=1200 x 1200	**d=36m**
10GHz / 3cm	2,880 m^4 Not in far field at all	7.3m x 7.3m, N=485 x 485 D=58dB	0.23° FF~7.1km	7.3m x 7.3m N=485 x 485	**d=8m**
		3m x 3m, N=200 x 200 D=50dB	**0.51° FF~1.2km**	**18m x 18m N=1200 x 1200**	**d=18m**

Diode high-power rectifier





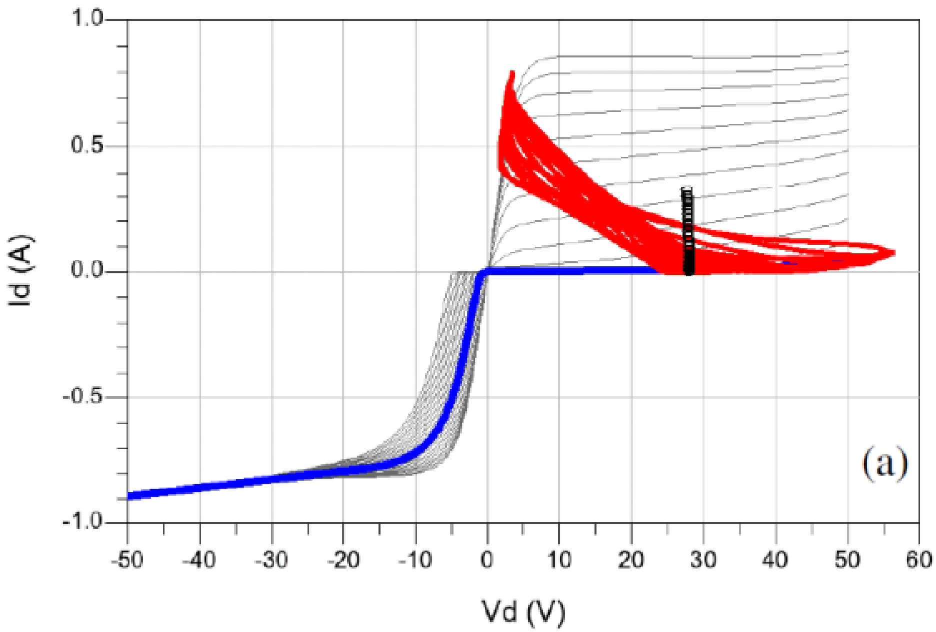
Power Capacity: 43dBm;

Maximum Conversion Efficiency: 68.3%.

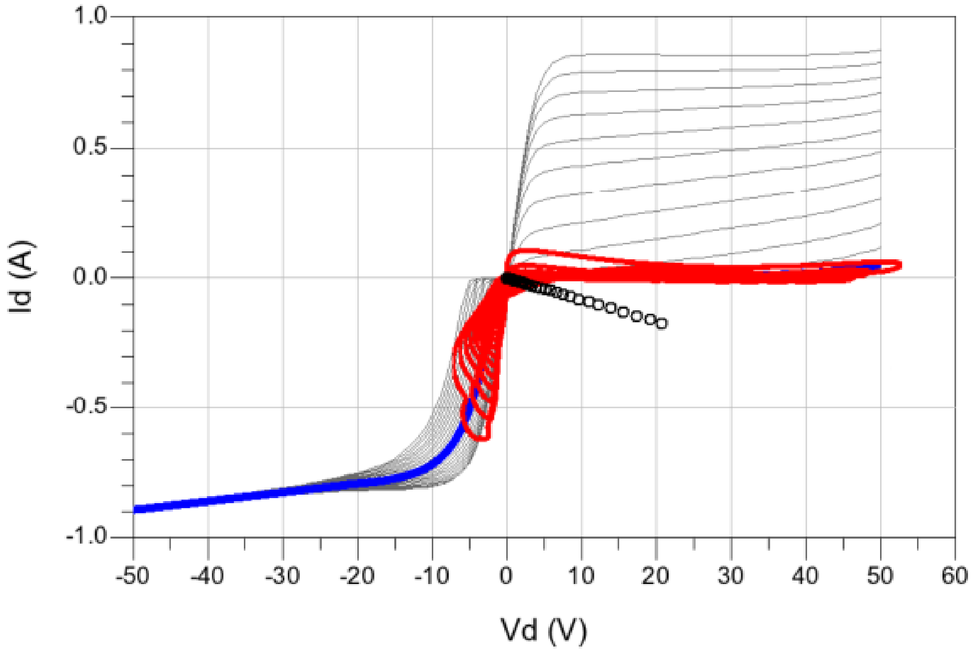
Wan Jiang, Biao Zhang, Liping Yan, Changjun Liu， "A 2.45 GHz Rectenna in a Near-Field Wireless Power Transmission System on Hundred-Watt Level" IMS 2014

Transistor PA-Rectifier Duality

Power Amplifier



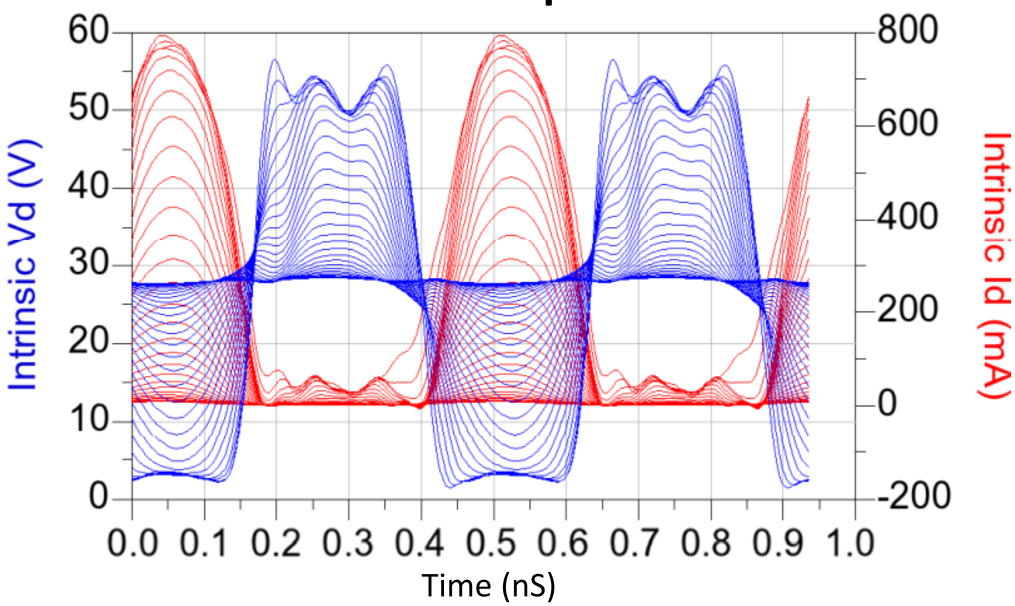
Rectifier



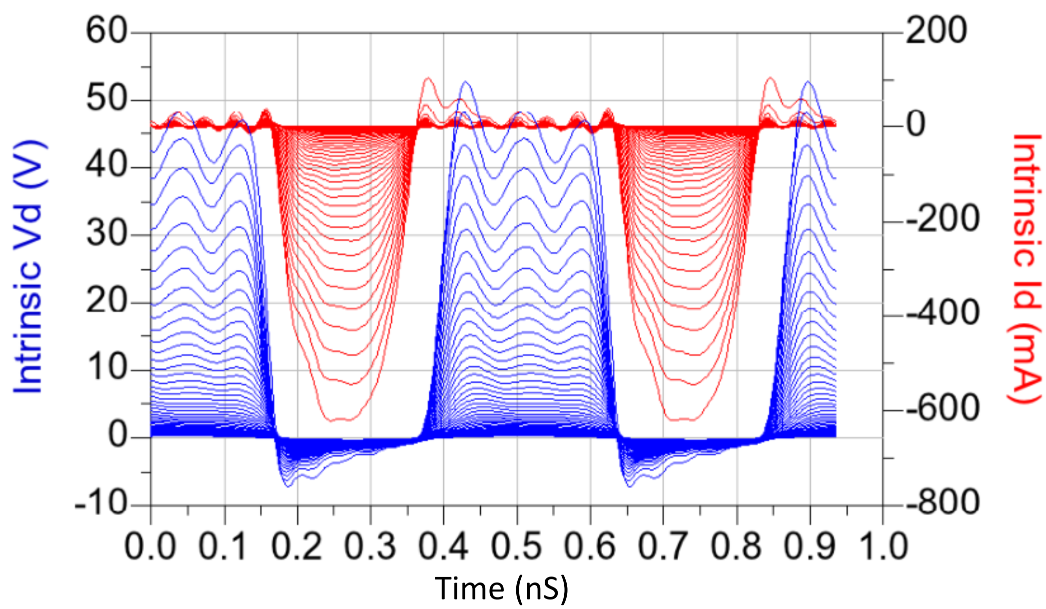
- Both simulations performed with 8x75 um GaN HEMT nonlinear model at 2.14 GHz in a Class-F circuit with 5 terminated harmonics
- Simulated GaN transistor I-V curves (gray), dynamic load lines (red), drain DC bias point (black circle), and transistor characteristic (blue) at Vgs = -4.9 V
- Power swept from 0 to 40 dBm (Vdd = 28 V for PA operation)

Transistor PA-Rectifier Duality

Power Amplifier

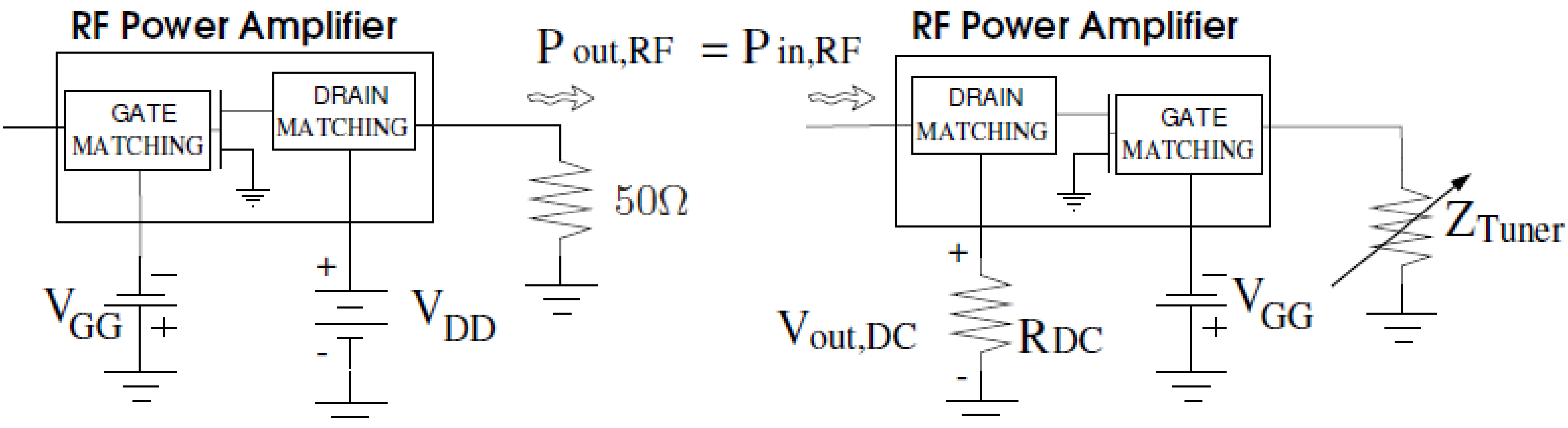


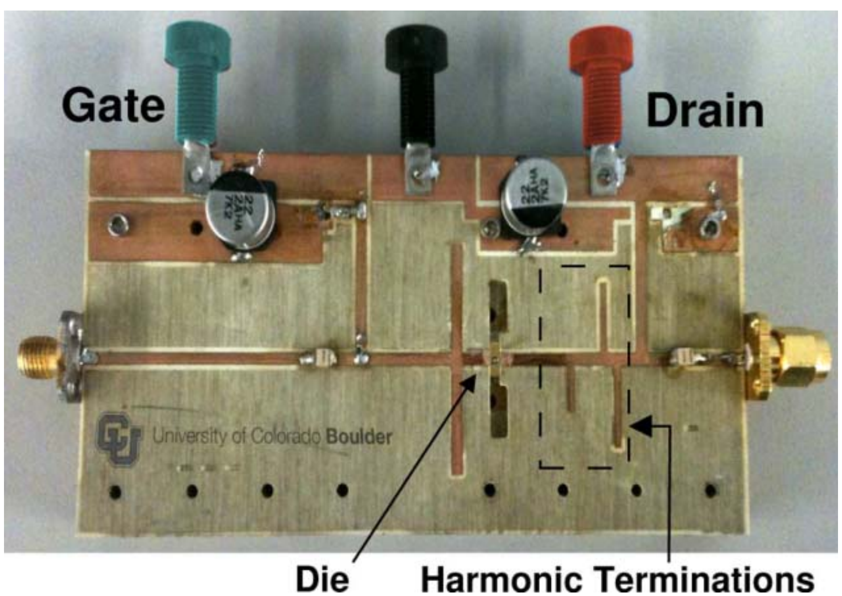
Rectifier

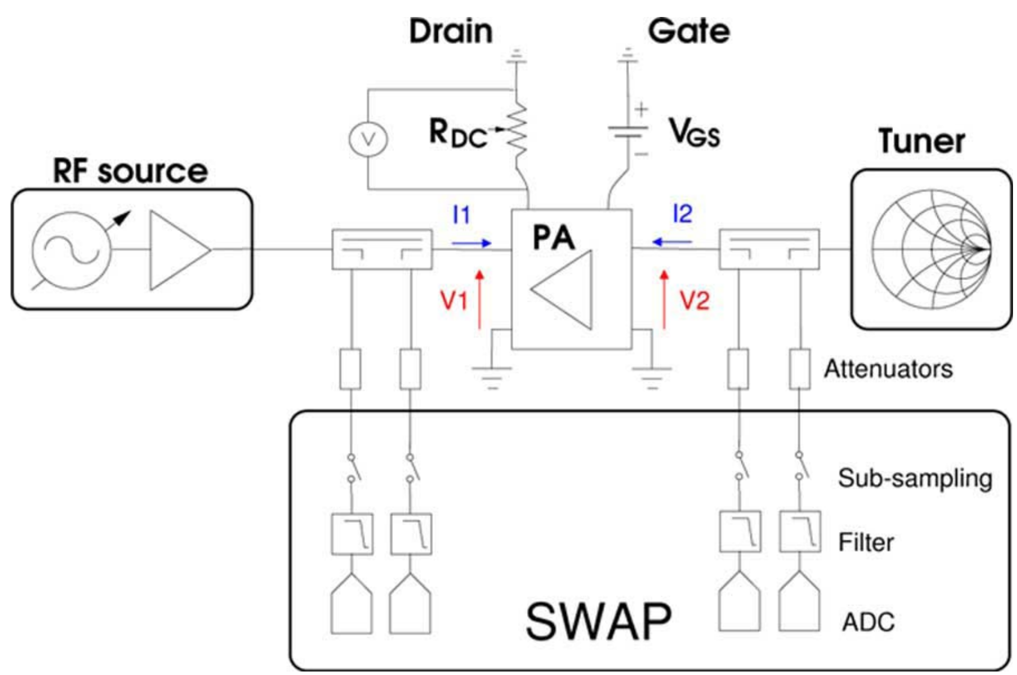


- Simulated GaN transistor time-domain intrinsic drain voltage (blue) and current (red) as the power is swept from 0 to 40 dBm (Vdd = 28 V for PA operation)
- High efficiency PA and rectifier operation achieved with time-reversal duality of transistor’s main current source

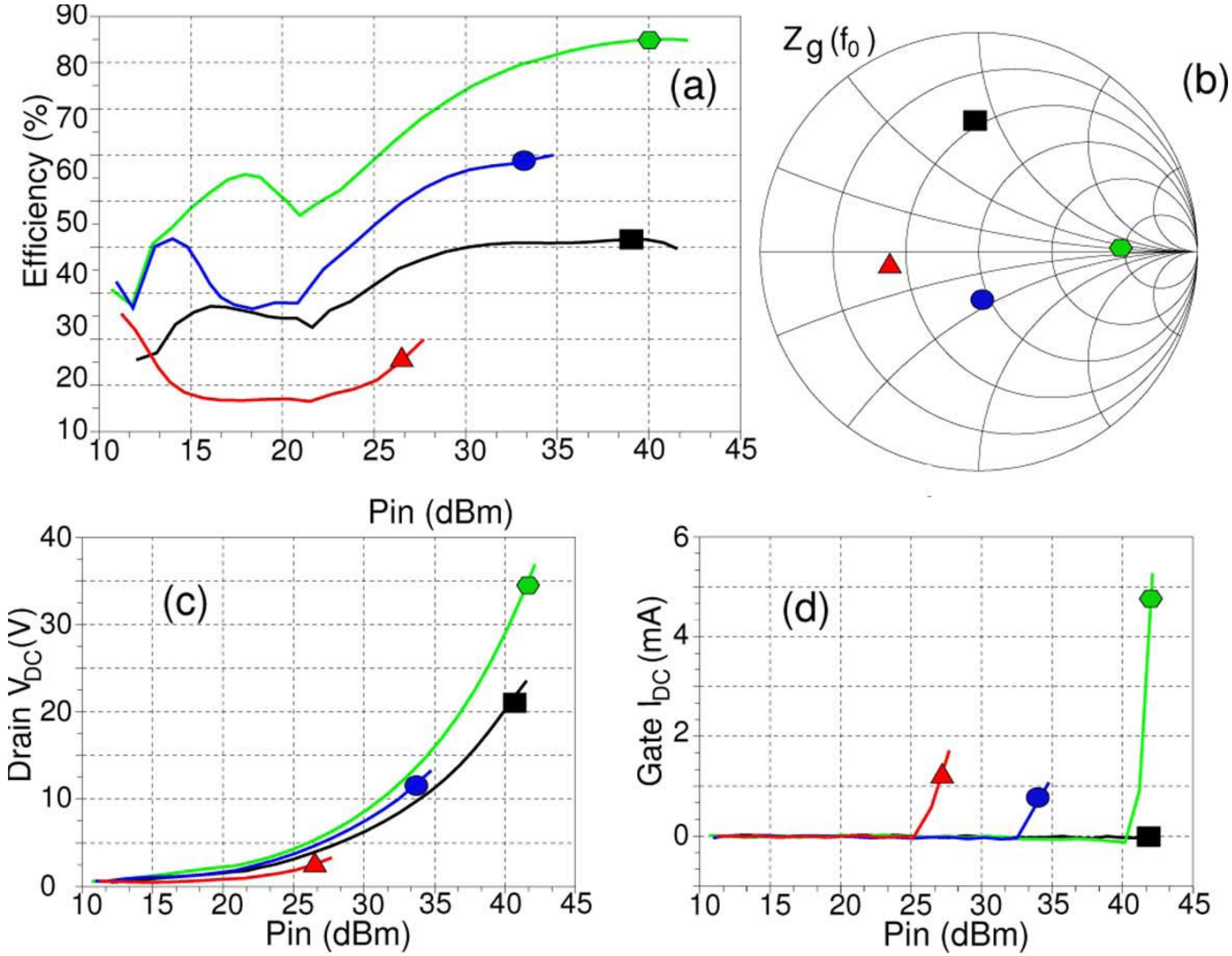
S-band self-synchronous rectifier



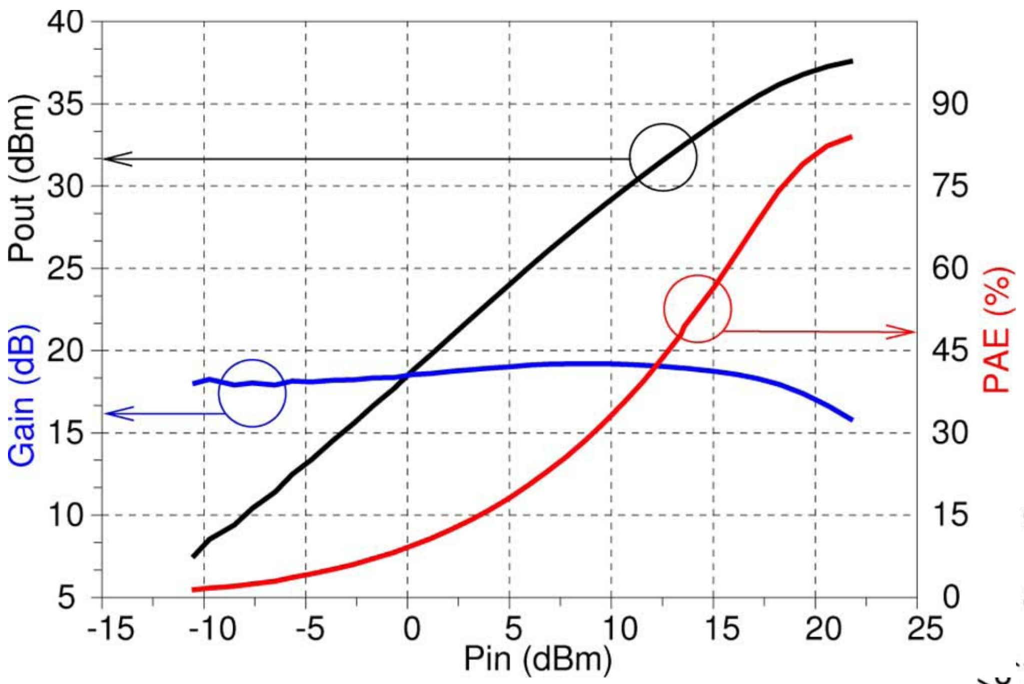




Performance of 2.11GHz rectifier

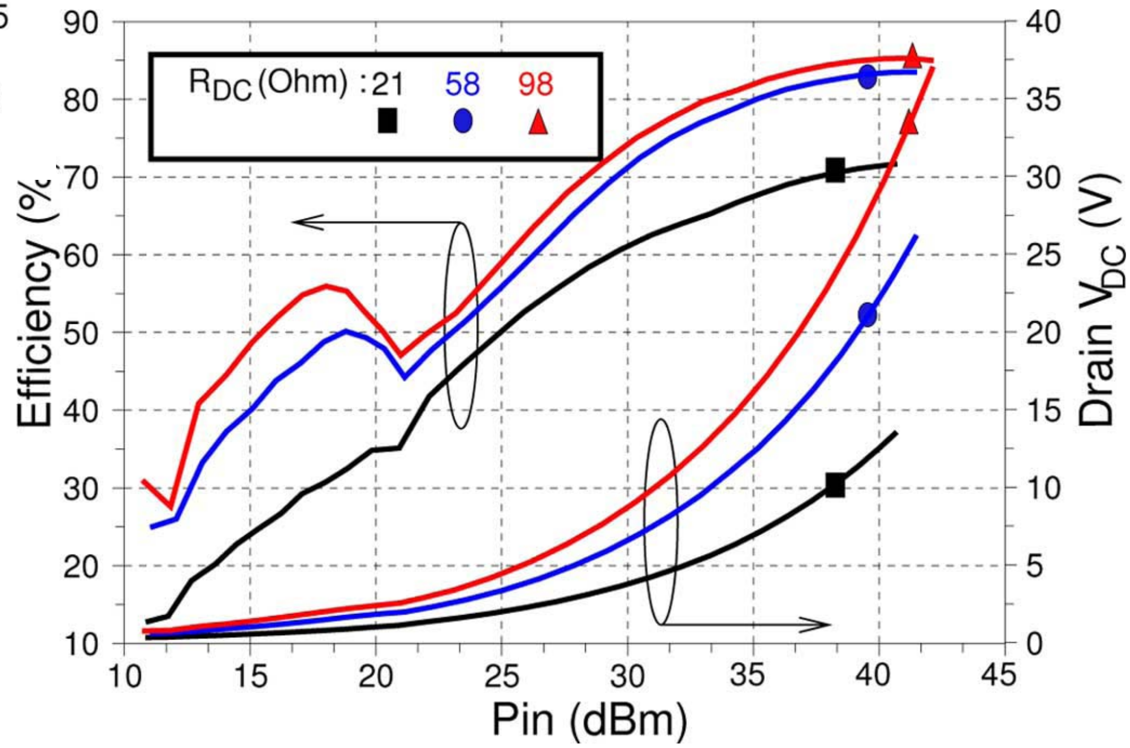


Measured performance



Rectifier, self-synchronized
2.11GHz, Class F-1
85% conversion efficiency
Vout = 35V, Pin=10W
Vout = 26V, Pin=8W

Amplifier, 2.11GHz, Class F-1
PAE=83%
Pout=8W at Vdd=28V

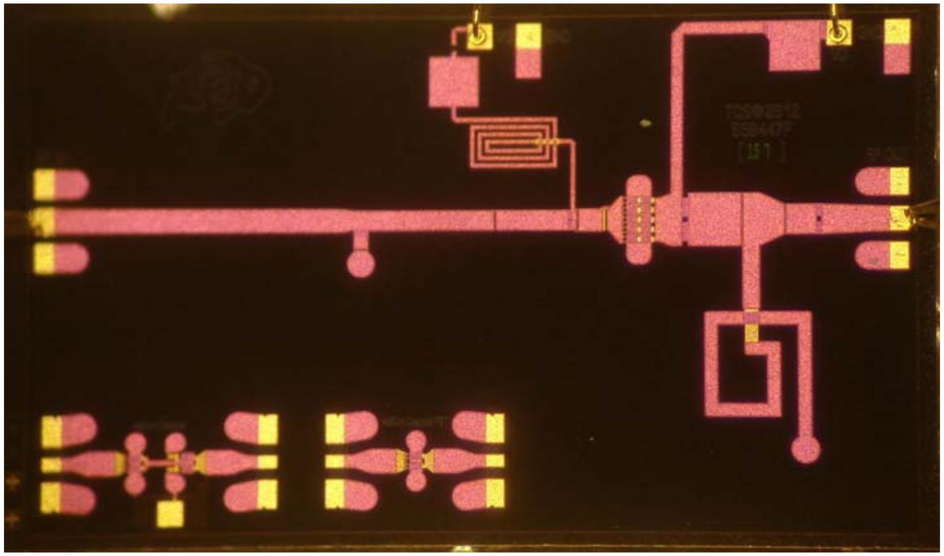


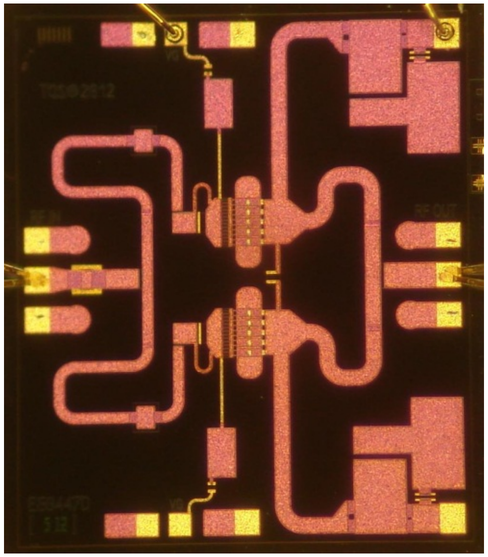
"High-Efficiency Harmonically Terminated Diode and Transistor Rectifiers," M. Roberg, T. Reveyrand, I. Ramos, E.A. Falkenstein, Z. Popović, *IEEE Trans. Microwave Theory Tecnh., Vol. 60,* No.12, pp.4043-4052, Dec. 2012

0.15 µm TriQuint GaN MMICs

Circuit A

Circuit B





2.3 mm

3.8 mm

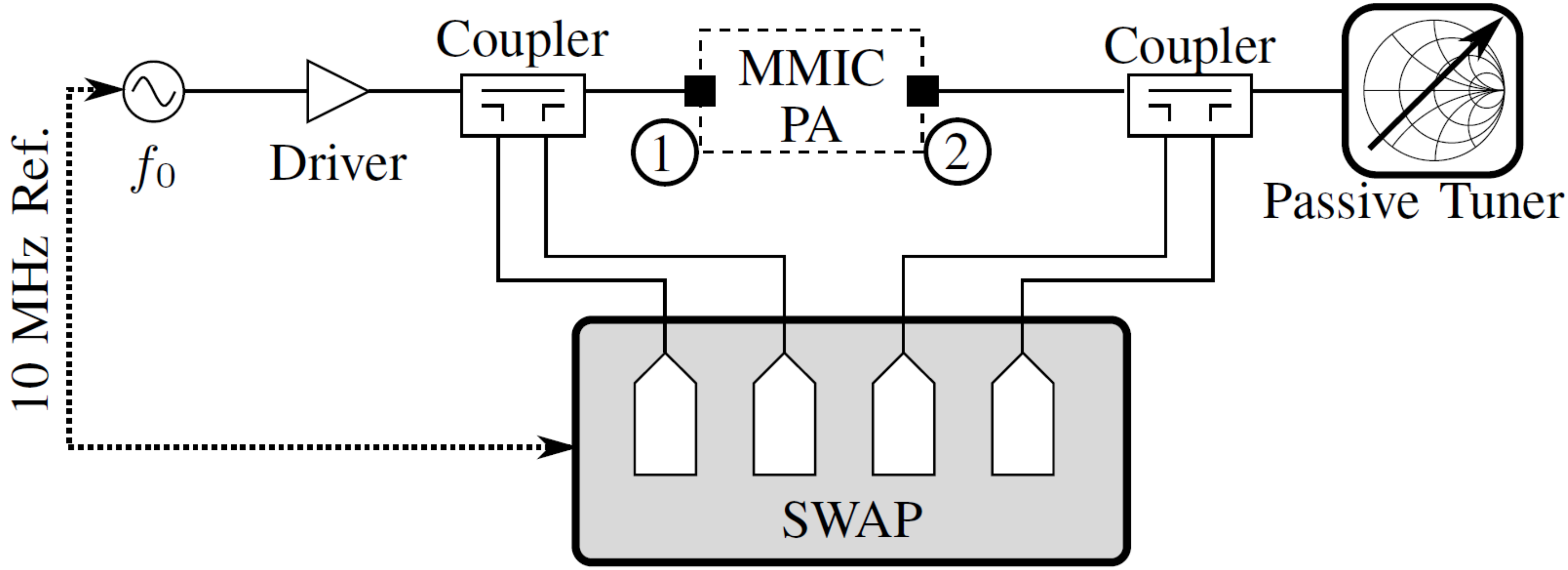
2.0 mm

- Single-stage
- 10 x 100 µm FET
- Class-B bias in pinch-off
- Optimized for PAE

- Single-stage, power combined with non-isolated reactive combiner
- Two 10 x 100 µm FETs
- Biased in deep Class-AB

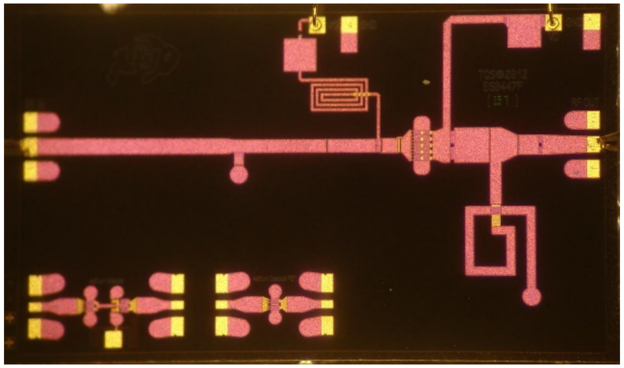
PA Measurement Setup

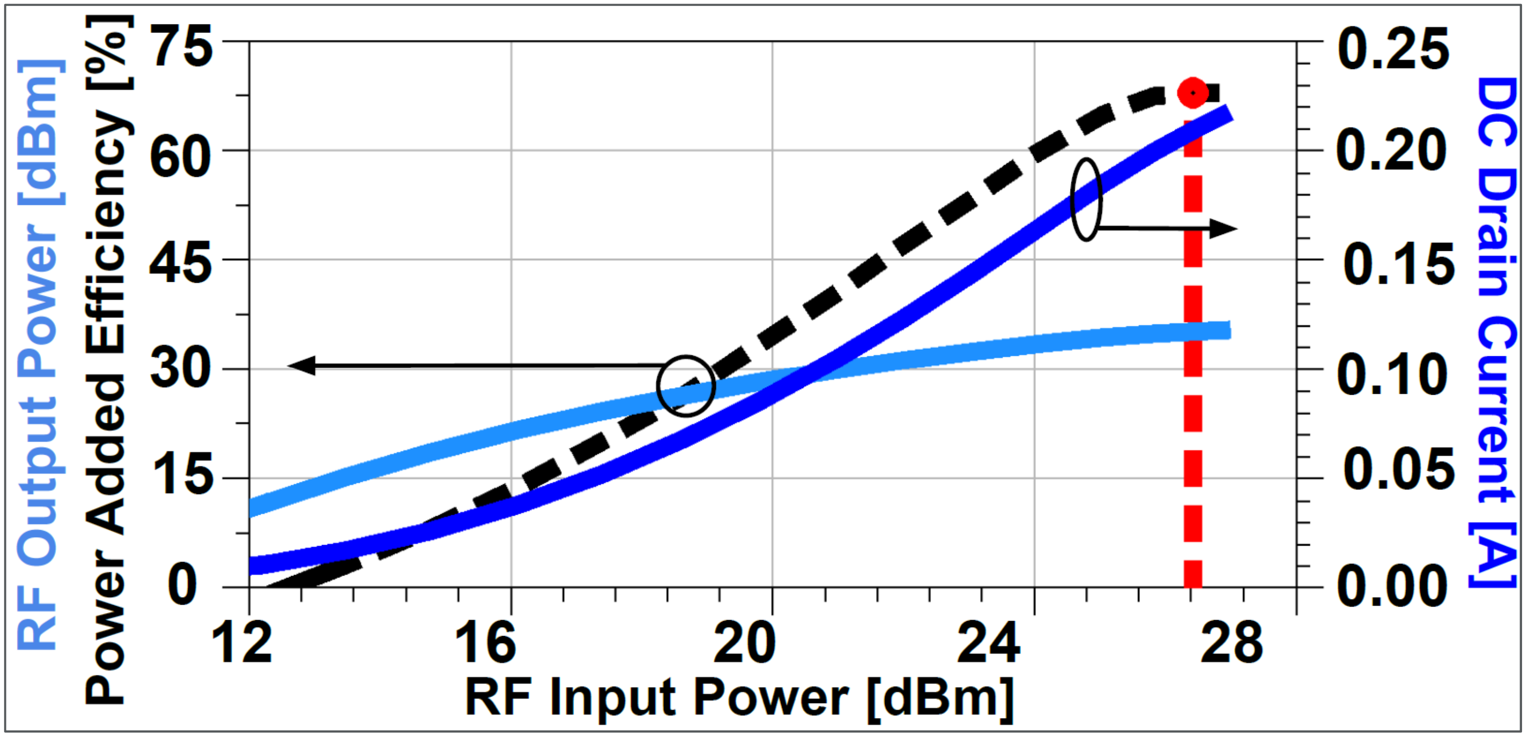
- 4 Channel time-domain receiver operating as LSNA
- Couplers acquire absolute incident and reflected waves
- SOLT calibration at fundamental and 2nd harmonic



Circuit A PA Performance

- Peak PAE = 67.87%
- peak η_{DE} = 78.36%
- P_{in} = 26.42 dBm
- P_{out} = 35.16 dBm
- V_G = -4.0 V
- V_{DD} = 20 V
- f_0 = 10.1 GHz

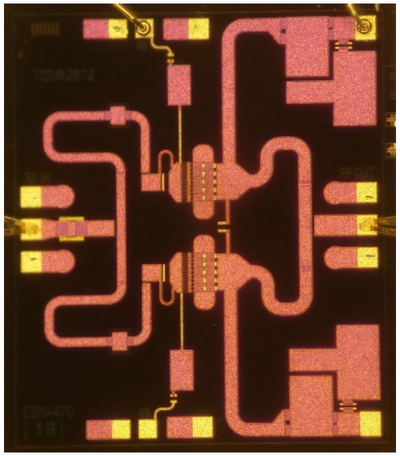


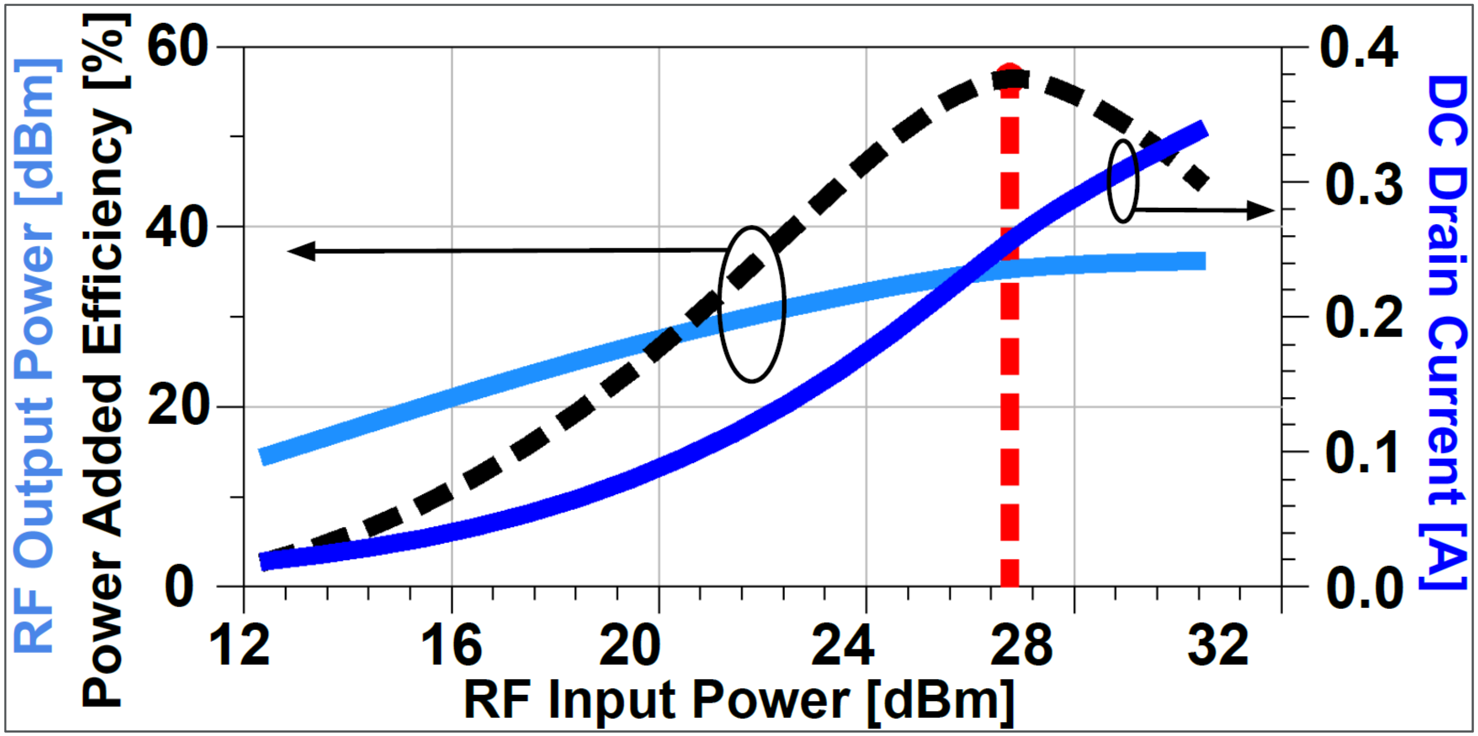


Circuit B PA Performance

- Peak PAE = 54.47%
- peak η_{DE} = 65.75%
- P_{in} = 26 dBm
- P_{out} = 35 dBm

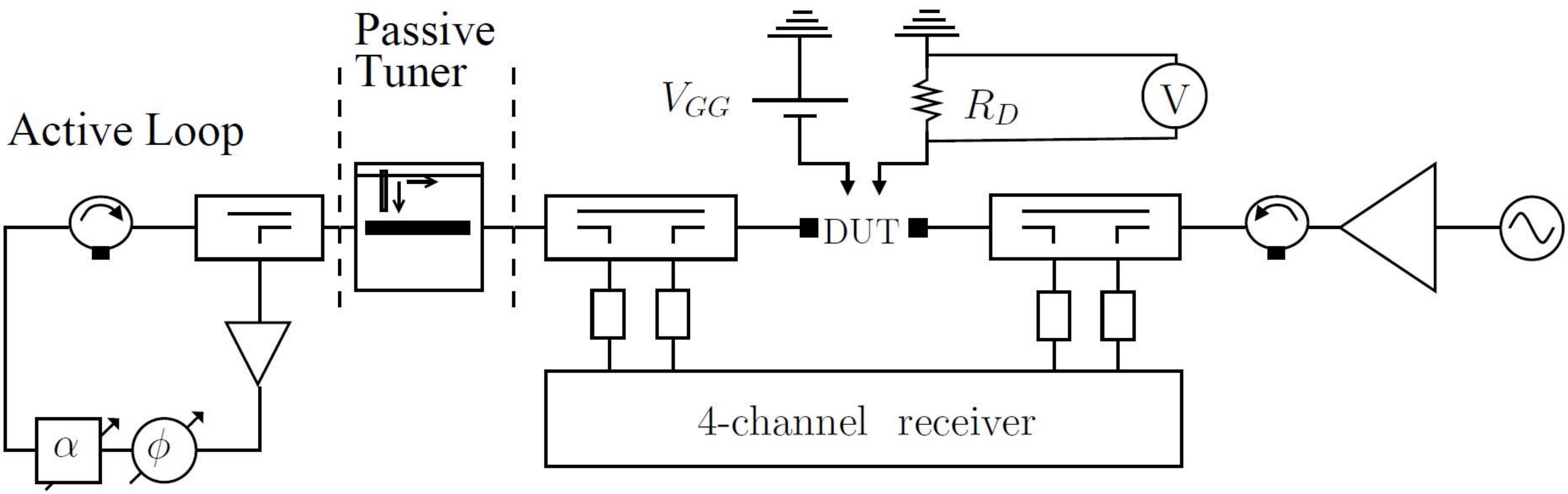
- V_G = -3.4 V
- V_{DD} = 20 V
- f_0 = 10.1 GHz





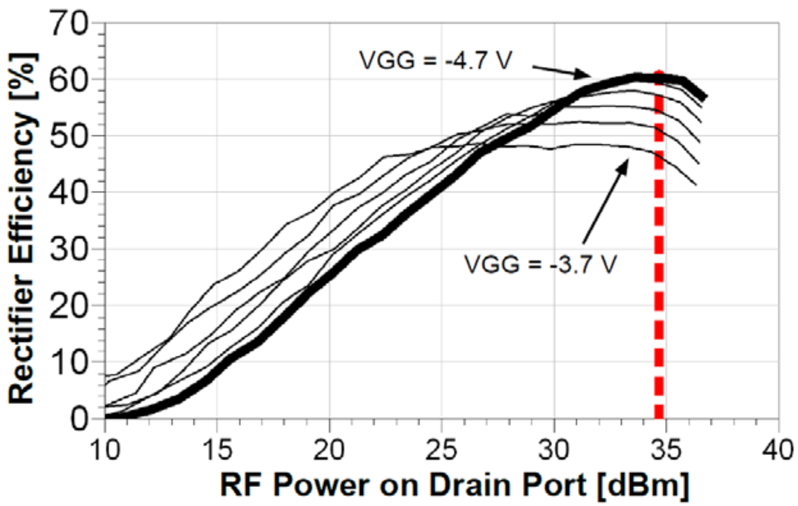
Rectifier Measurement Setup

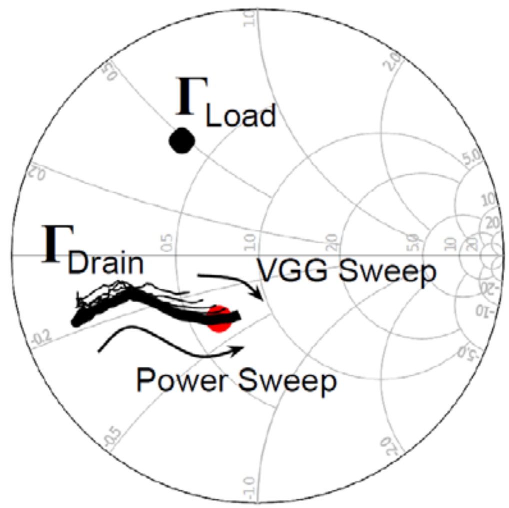
- 4 Channel time-domain receiver operating as LSNA
- Input is RF drain of DUT, output is DC drain of DUT
- Gate is DC biased and RF terminated (self-sync)
- DC drain load, RF gate termination, V_G are swept



Important Rectifier Parameters

$$\eta_R = \frac{P_{DC}}{P_{RF,injected}} = \frac{2|V_{DC}|^2}{R_D \cdot Re\{V_D(f_0) \cdot I_D^*(f_0)\}}$$



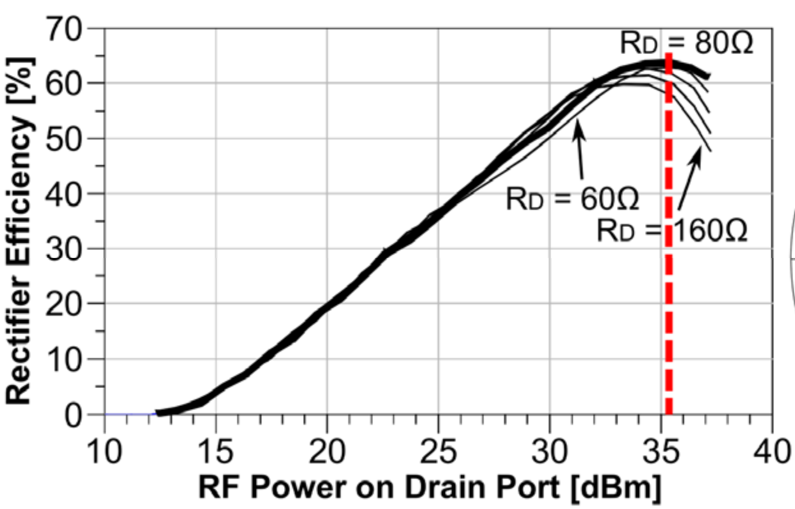


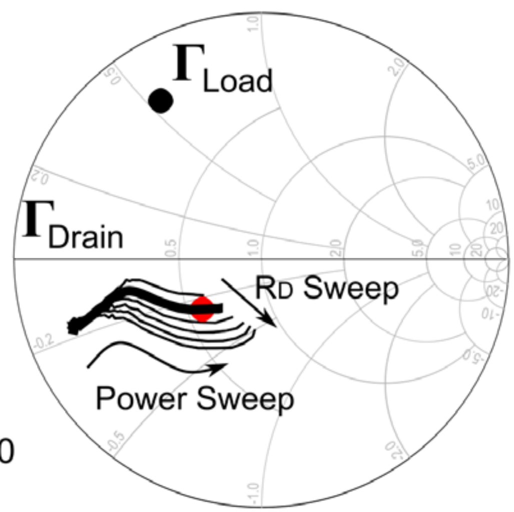
Z_{load} – Large Effect

- Active loop used to obtain optimal RF gate load

V_G – Moderate Effect

- Class-B or class-C to ensure rectifier mode



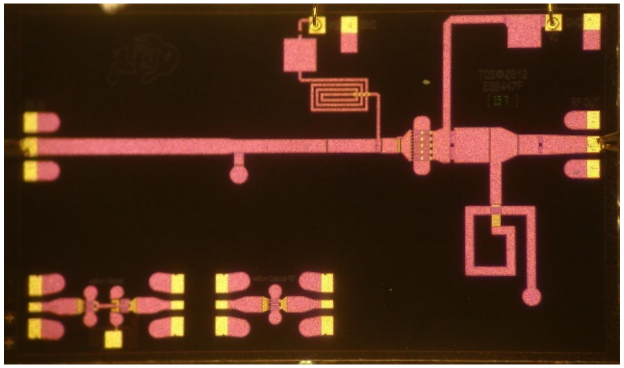


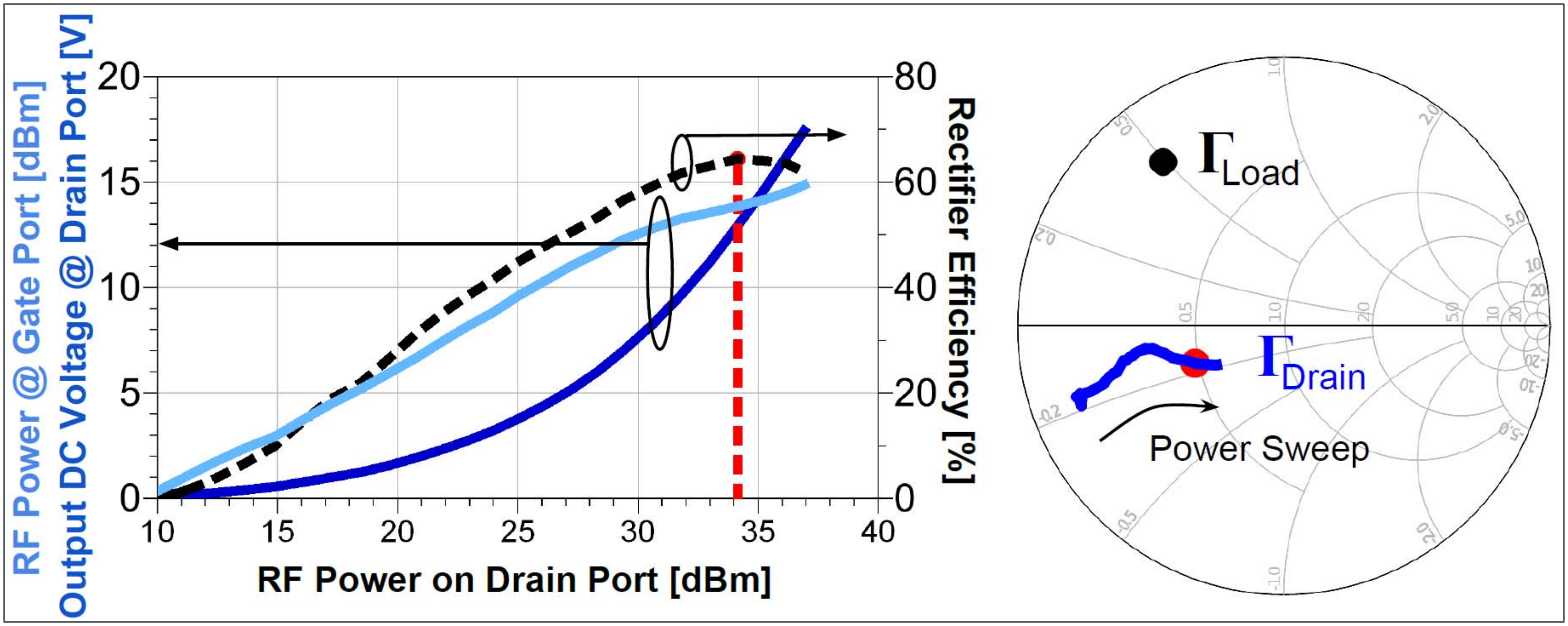
R_D – Moderate Effect

- Set by theory of class of operation of PA dual
- Small effect on η_R
- Impacts RF input impedance

Circuit A Rectifier Performance

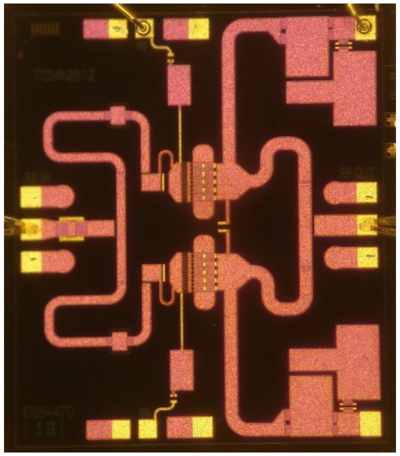
- Peak η_R = 64.40%
- V_G = -4.7 V
- R_D = 100 Ω
- Z_{load} = 8.45 + j24.5 Ω

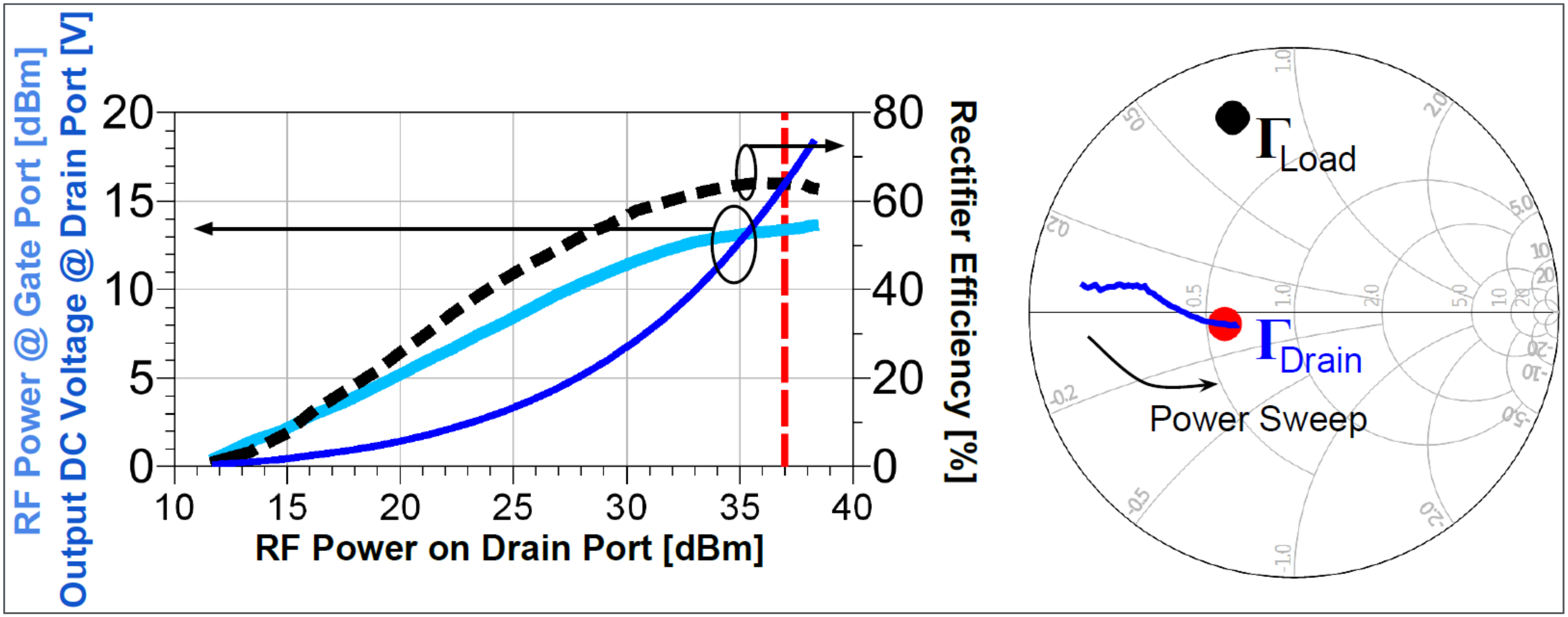




Circuit B Rectifier Performance

- Peak η_R = 63.94%
- V_G = -4.7 V
- R_D = 80 Ω
- Z_{load} = 9.8 + j35.75 Ω



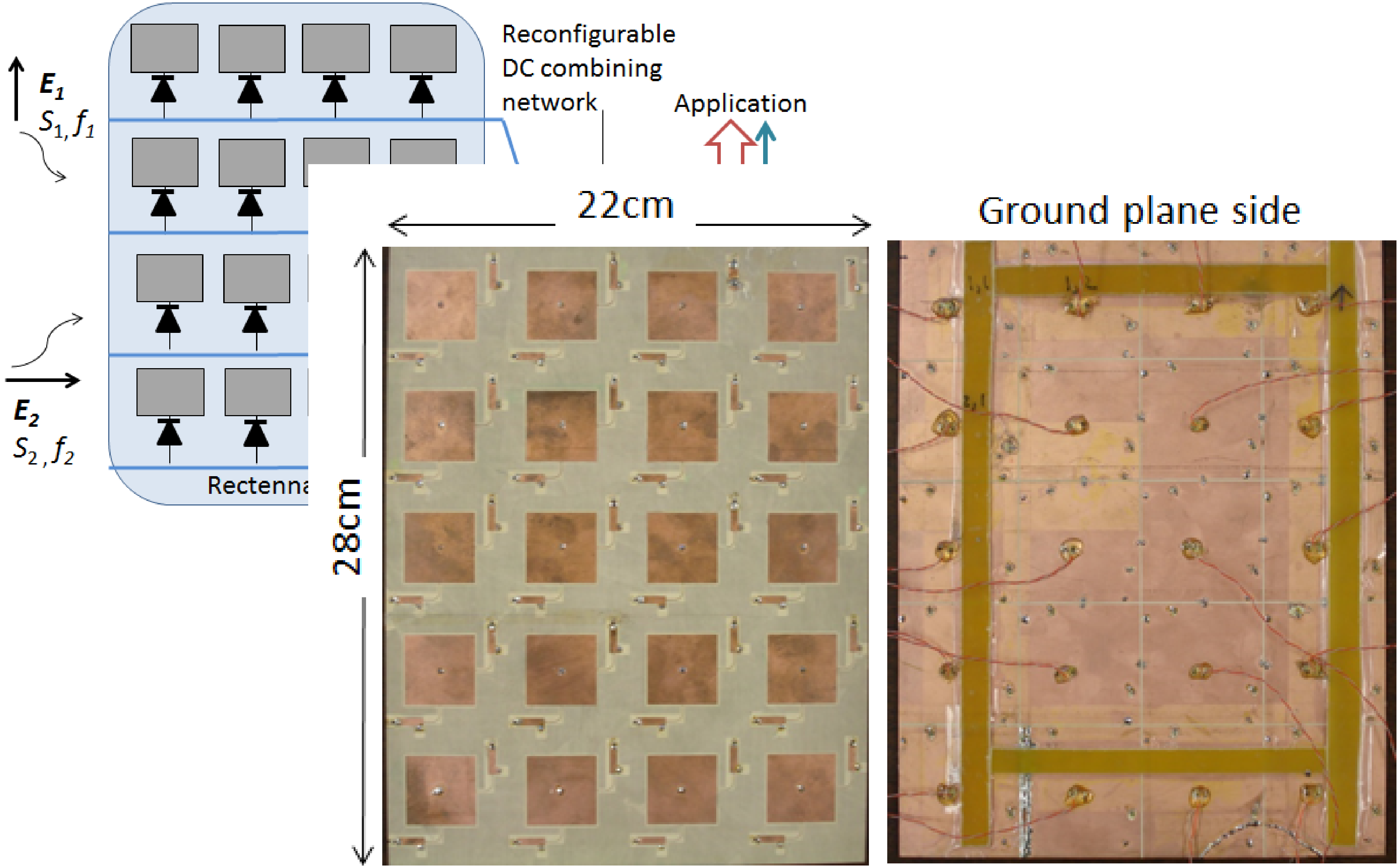


PA / Rectifier Comparison

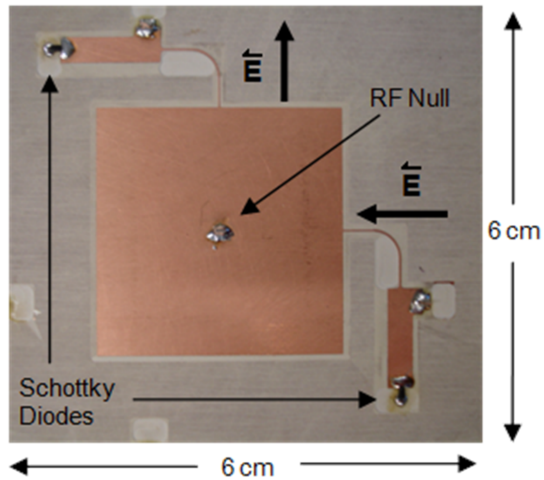
	Power Amplifier		Rectifier	
Circuit	A	B	A	B
Peak Efficiency (%)	67.8	56.4	64.4	63.9
DC Power (W)	4.2	5.1	1.7	3.2
RF Power (W)	3.3	3.4	2.6	5.0

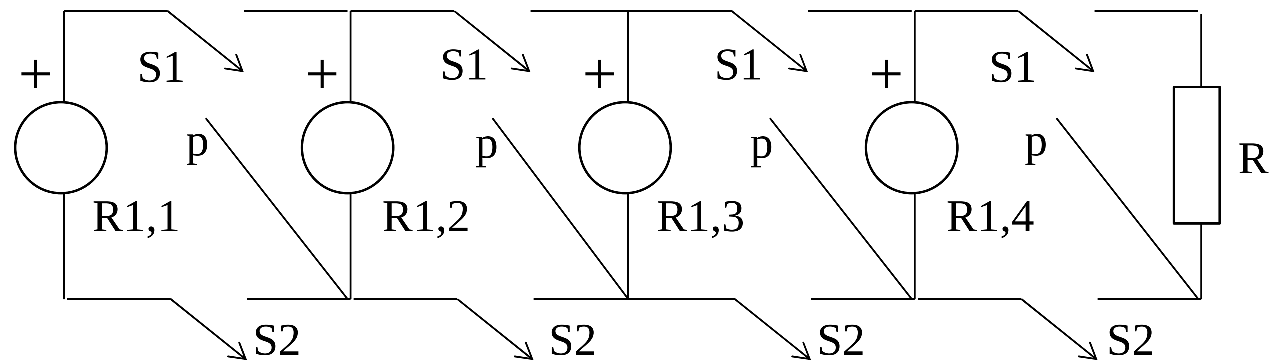
- GaN HEMTS are good candidates for both PA and rectifier operation
- High-efficiency, self-synchronous, transistor rectifiers can be designed as PAs and then operated as rectifiers
- A need exists for non-linear transistor models extracted from first and third quadrants of I-V curves
- Due to high power levels in wireless power beaming, GaN HEMT rectifiers are suitable

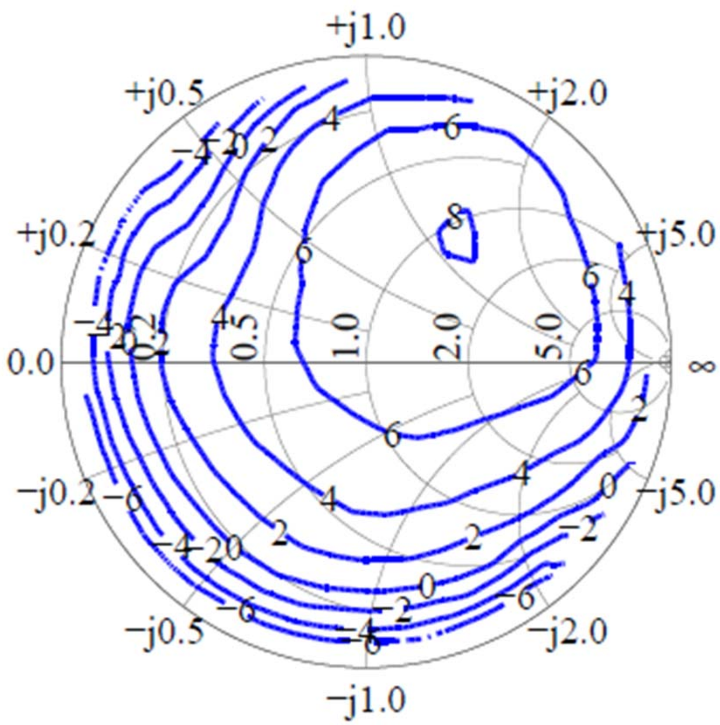
Rectenna Arrays

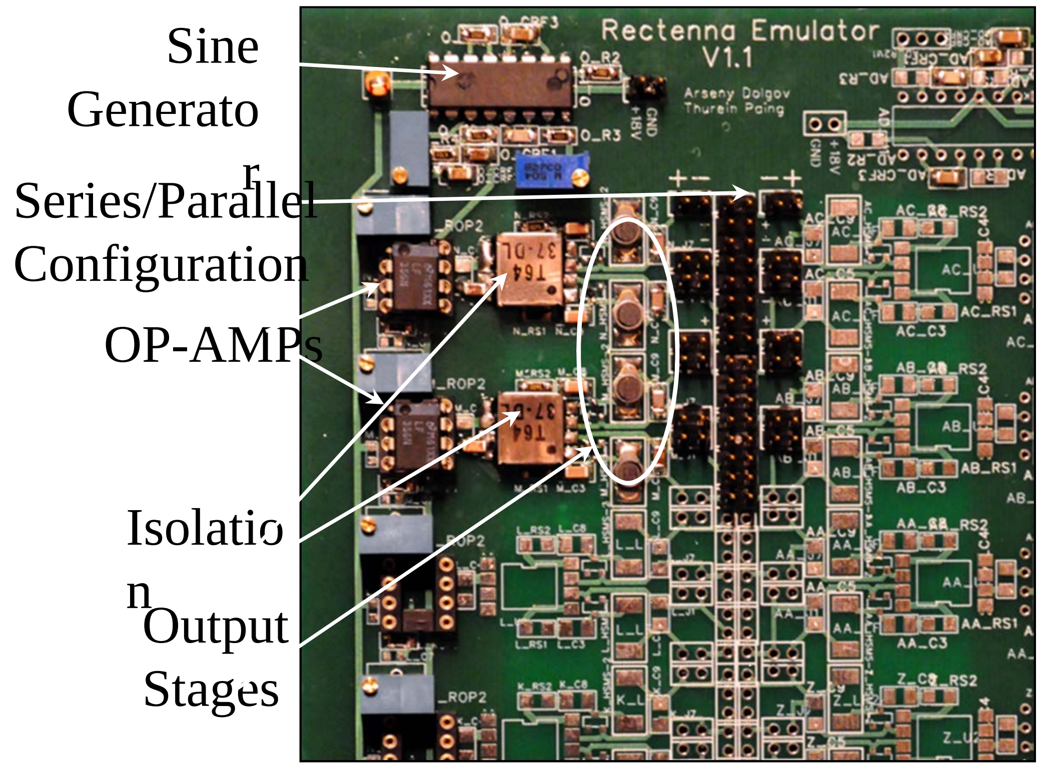


Elements of rectenna array



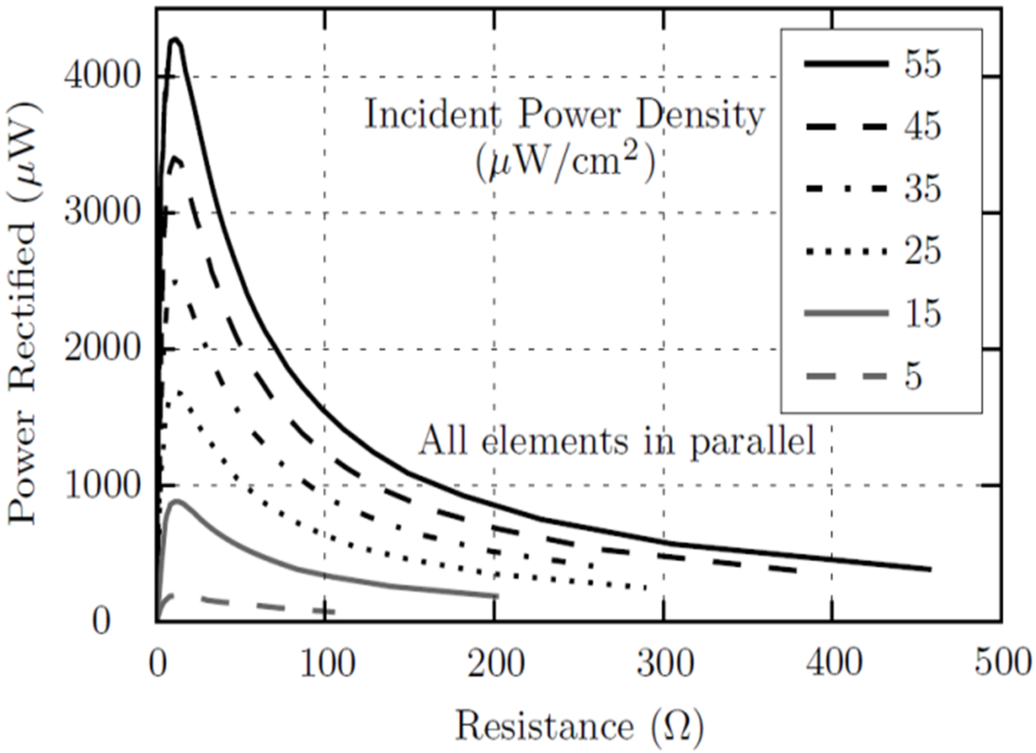


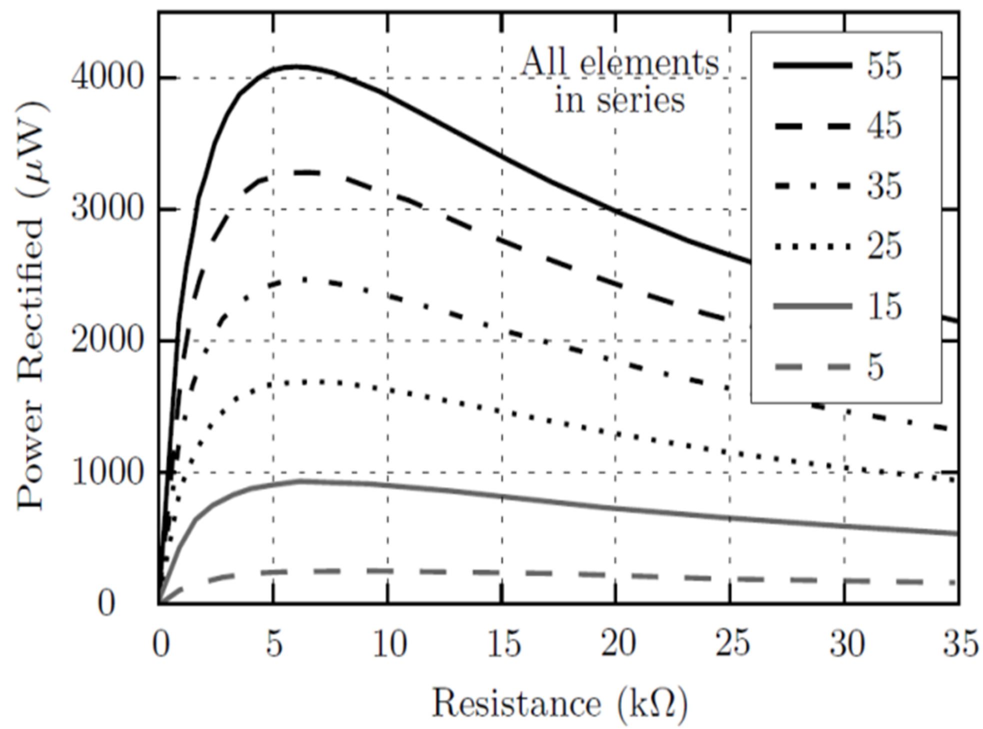




Reconfigurable DC

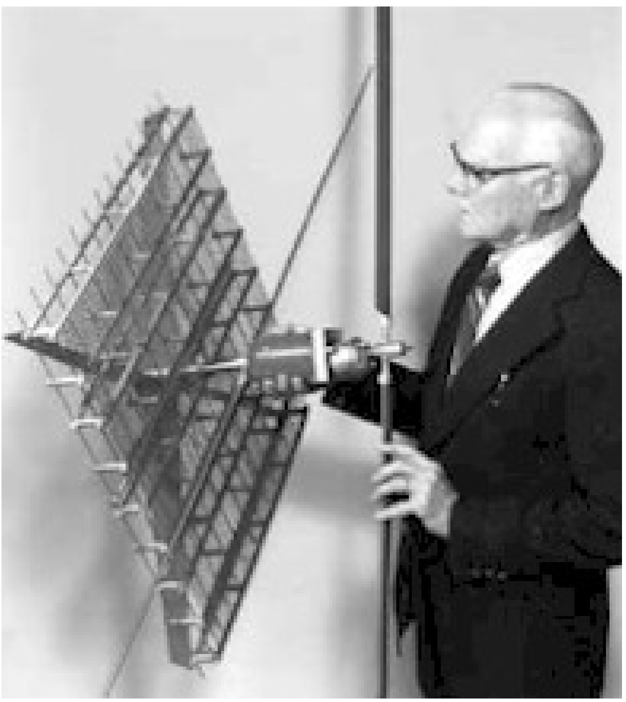
Array conf.	N=20 parallel	10P × (2S)	5P × (4S)	4P × (5S)	2P × (10S)	N=20 series
$R_{opt}(\Omega)$	10	300	100	500	1.8k	5k
P_{max}(mW)	4.3	3.9	3.2	4.7	4.4	4.1



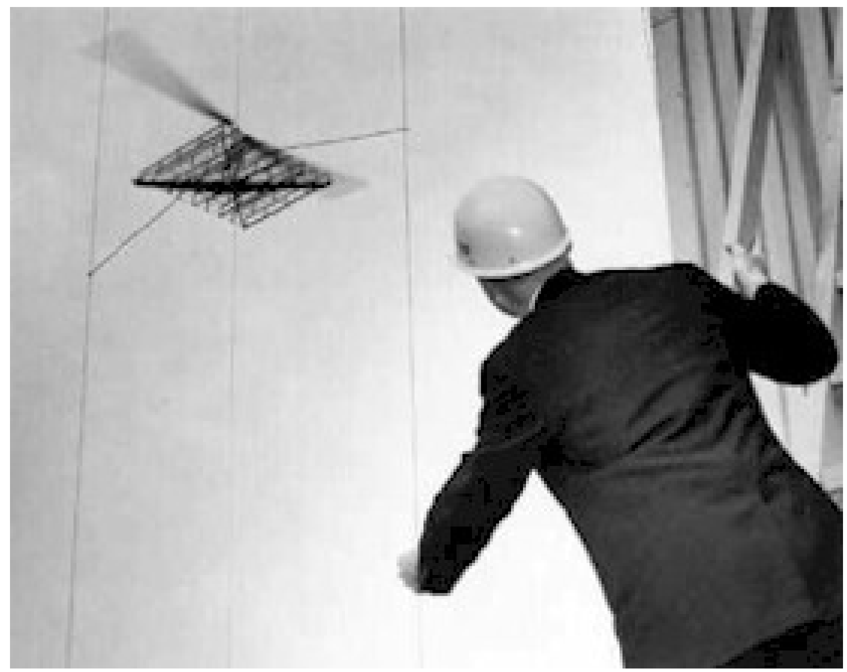


Other aerospace WPT applications

- Micro and nano-drone powering
- Harvesting satellite antenna sidelobes for low-power sensor powering
- Structural health monitoring of aircraft

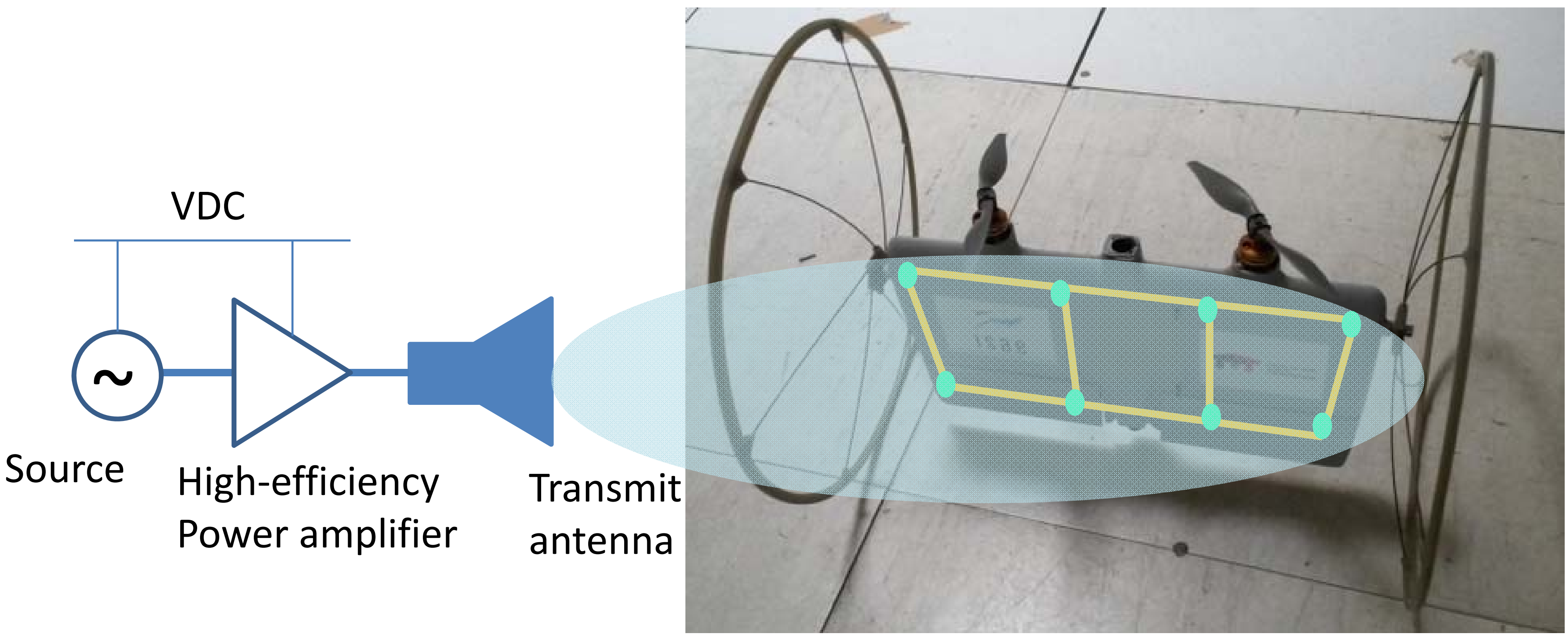


- In 1964, with an Air Force contract, Willian Brown demonstrated a wirelessly-powered helicopter (drone!)
- Power at 2.45GHz was beamed onto the array and the helicopter flew for over 10 hours



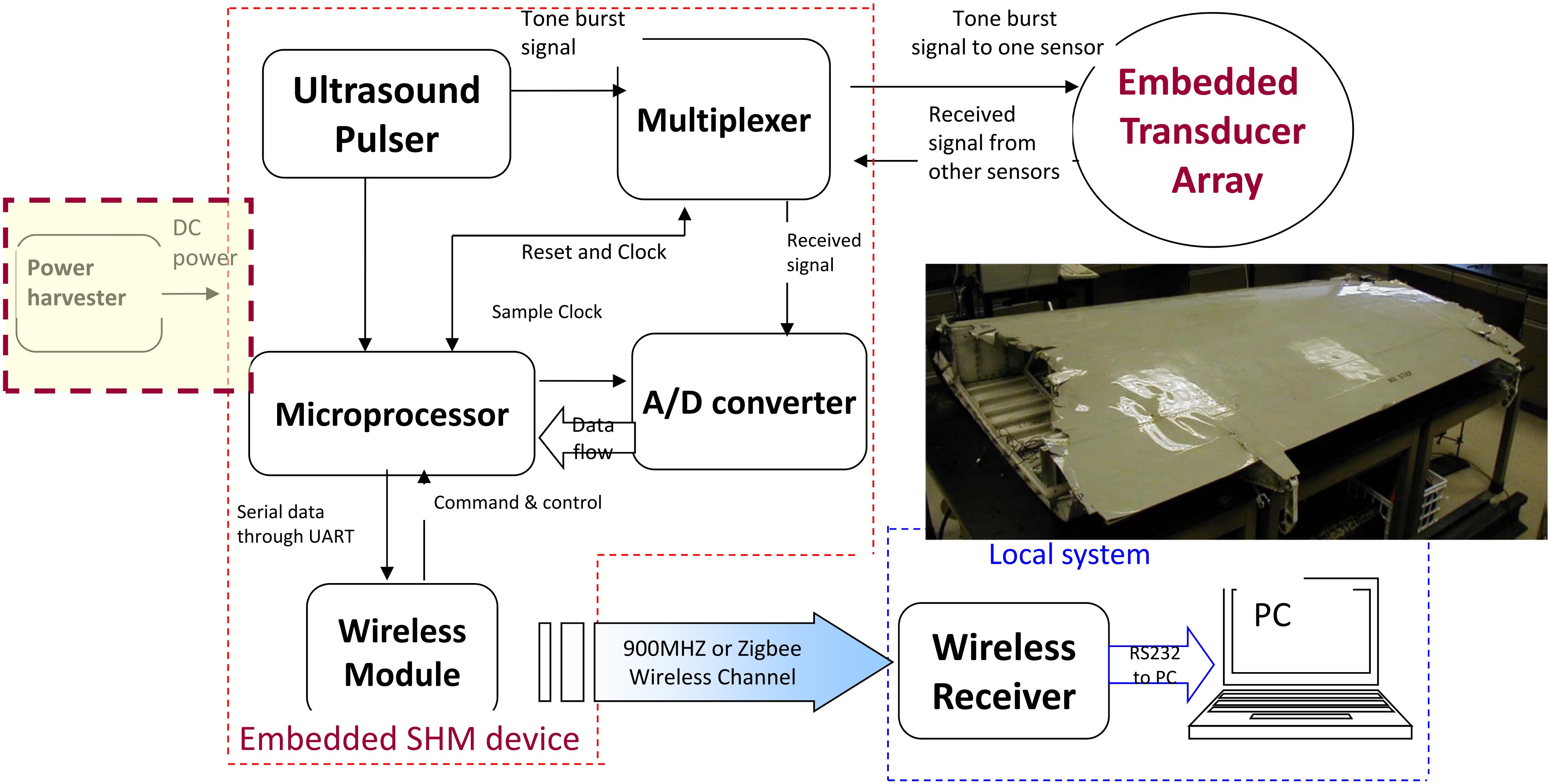
Powering a micro-drone

1. Recharging battery wirelessly on ground
2. Recharging periodically in flight
3. Recharging in confined environments
4. Recharging multiple micro-drones

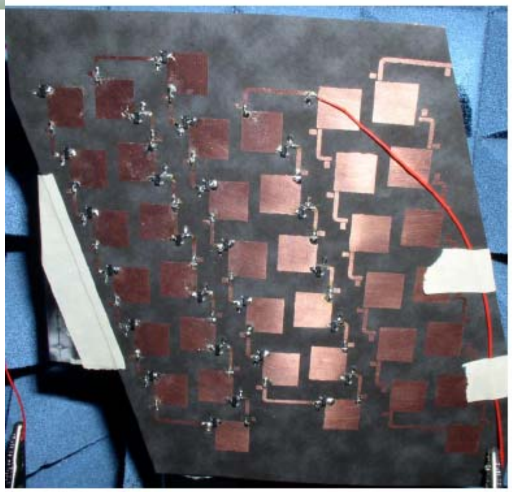


Recharging on ground

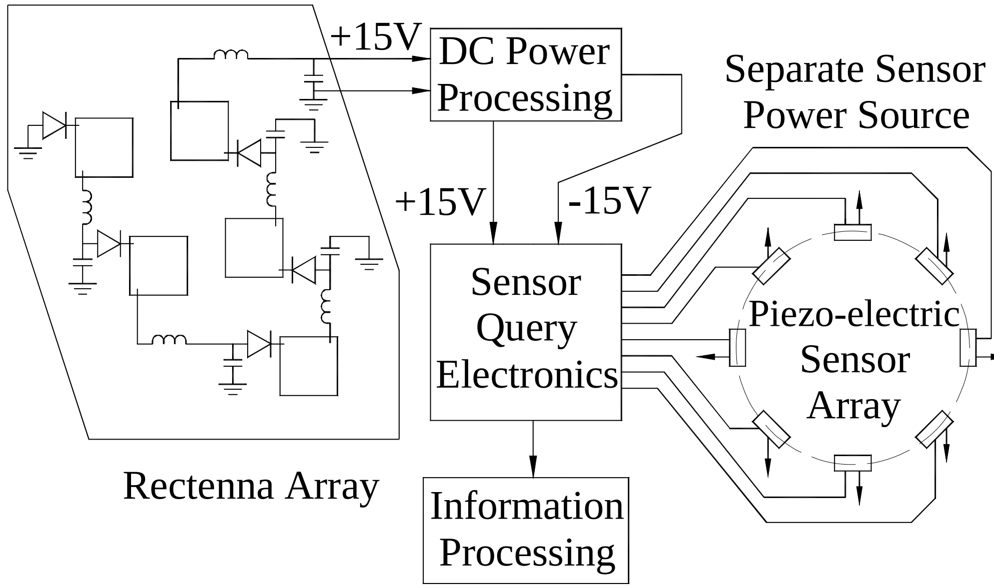
Background: acoustic health monitoring of aircraft wings

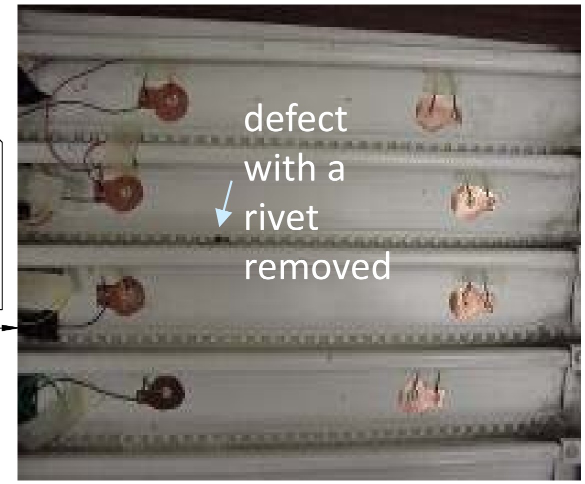


Defect detection when wirelessly powered

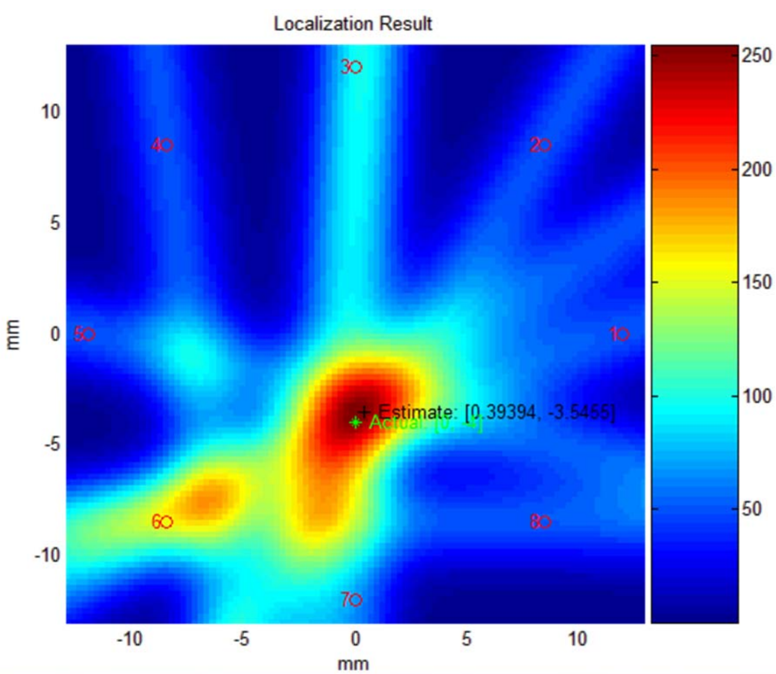


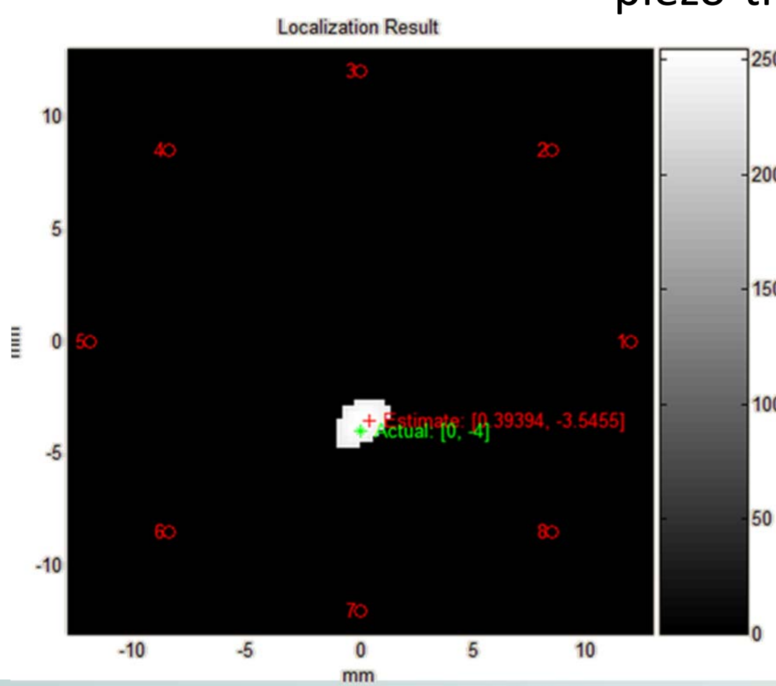
Rectenna array single frequency, 10GHz, LP





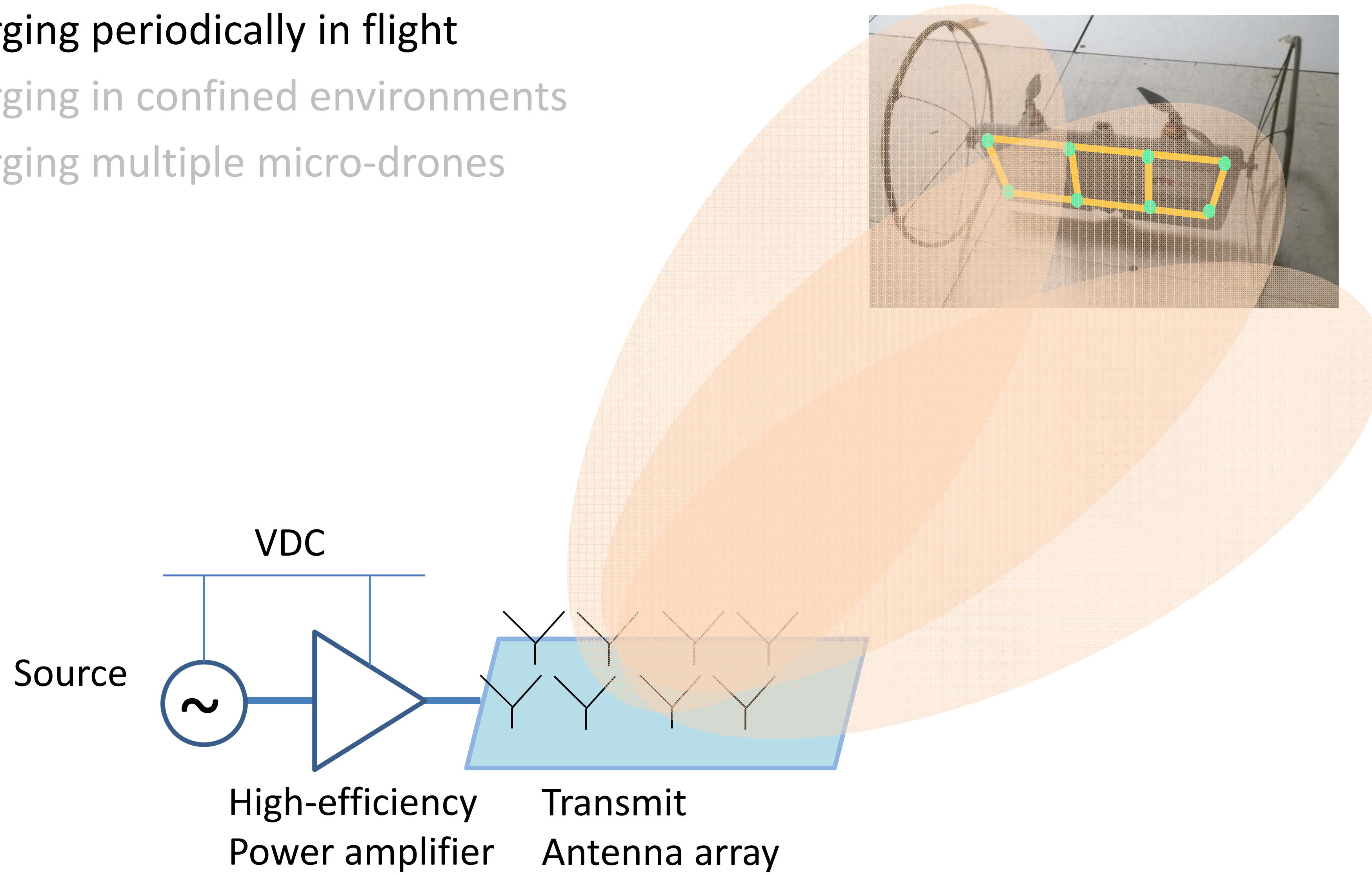
Back of wing with piezo-transducers



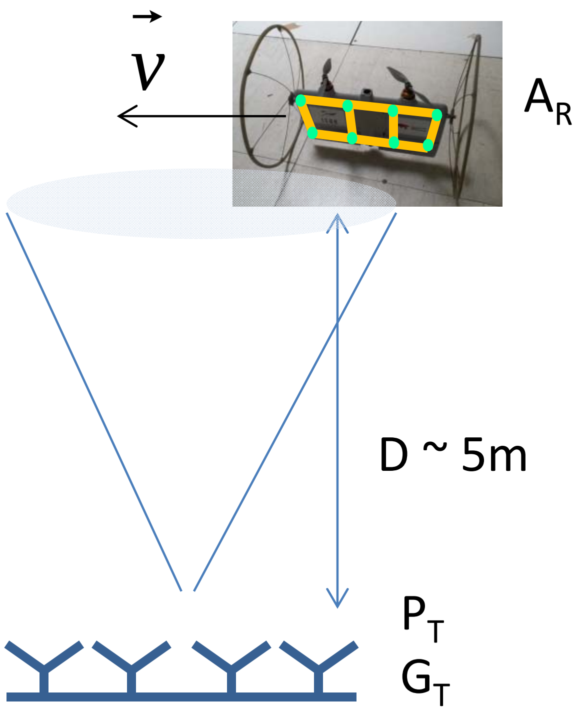


2. Powering in flight

1. Recharging battery wirelessly on ground
2. Recharging periodically in flight
3. Recharging in confined environments
4. Recharging multiple micro-drones



Powering a micro-drone in flight



Line-of sight link: $P_{R,DC} = \eta_C P_T G_T A_R \dfrac{1}{4\pi D^2} \cdot \alpha$

Conversion efficiency (η_C)

Polarization mismatch (α)

Antenna gain and electrical size: $\dfrac{A}{\lambda^2} = \dfrac{G}{4\pi}$

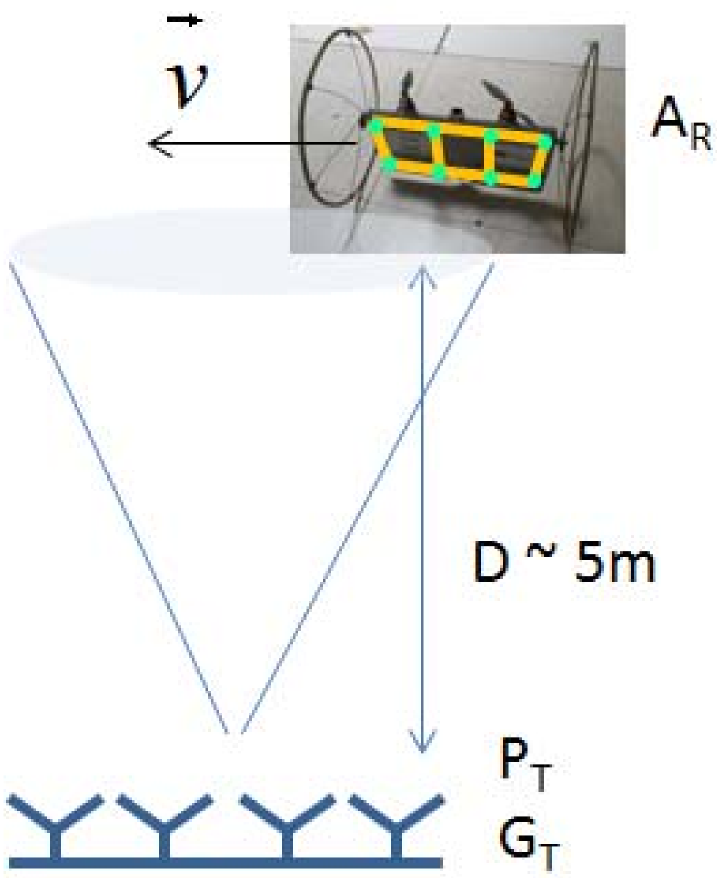
Half-power beamwidth: $\theta^\circ_{3dB} \approx \sqrt{\dfrac{32000}{G}}$

Time it takes for drone to fly through single beam: $t = K \cdot \dfrac{D}{v} \dfrac{1}{\sqrt{A_T / \lambda^2}}$

$$(\mathrm{E}_{WPT})_{\max} = K \cdot \eta_C P_T \frac{1}{Dv} A_R \sqrt{\frac{A_T}{\lambda^2}}$$

Maximum possible energy available for storage
-for a given D and v, determines size of transmit antenna array (K~0.9)

Powering a micro-drone in flight: an example, no tracking



variable	value
P transmitted	100W
η RF-DC	50%
Area of rectenna	0.1m^2
Powering distance	5m
Transmit array size	10 λ x 10 λ
Transmit gain	1200
3-dB beamwidth	10 deg
Micro-drone speed	5m/s
Time through beam	15s
Received energy	1 kJ

Powering a micro-drone

1. Recharging battery wirelessly on ground
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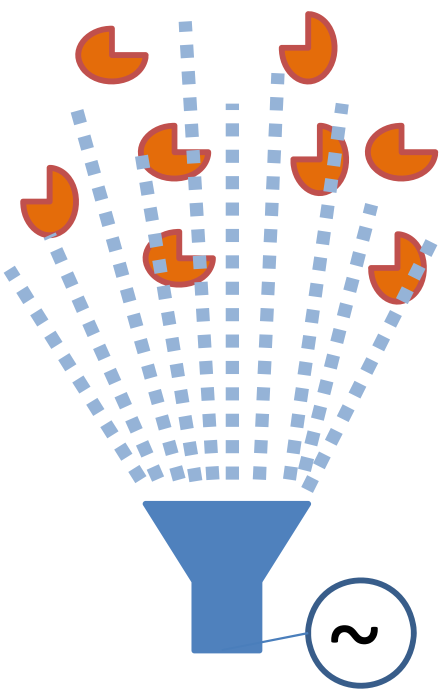
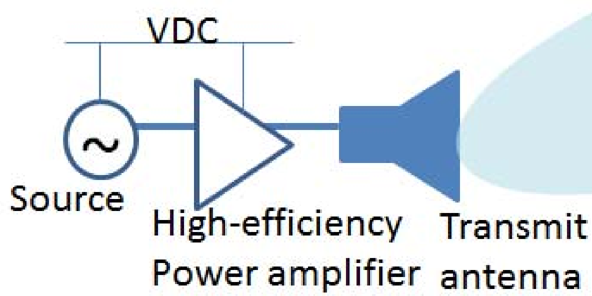
4. Recharging multiple micro-drones

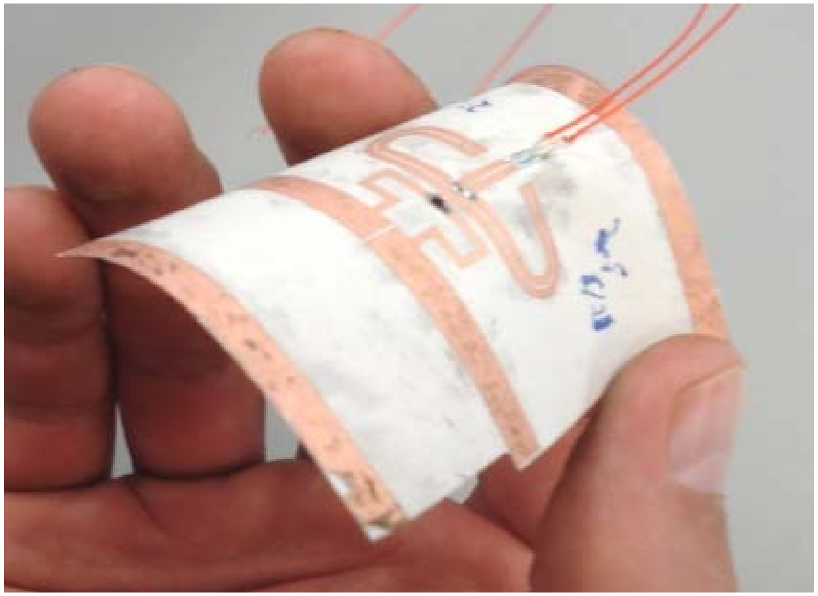


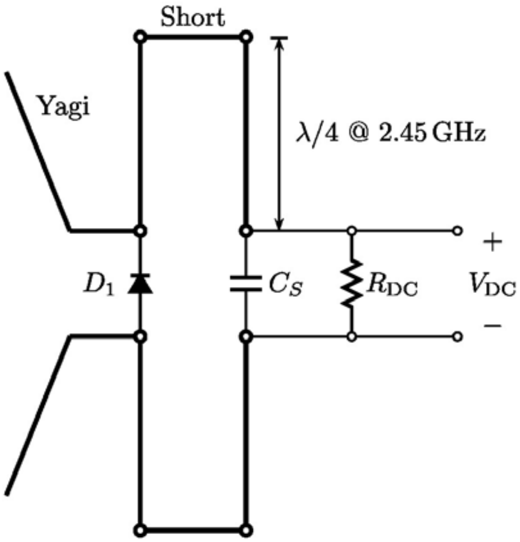
Source



Some relevant details

- Antenna possibilities on micro-drones
- Transmitter antenna arrays, receiver arrays
- Propagation environment (caves, etc.) and allowed power densities
- Polarization, varying power density, varying frequency

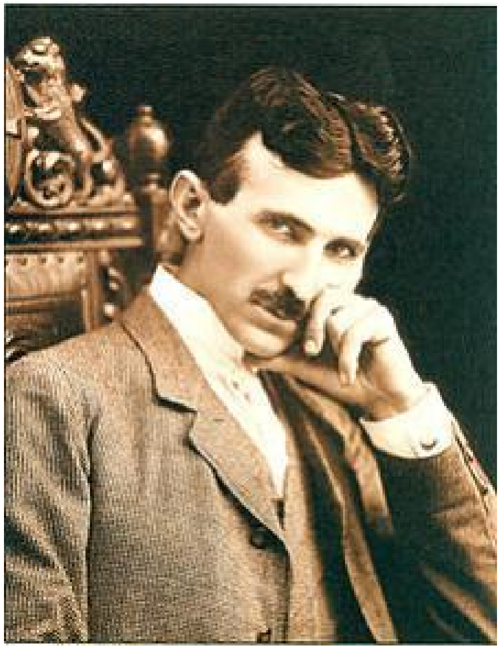


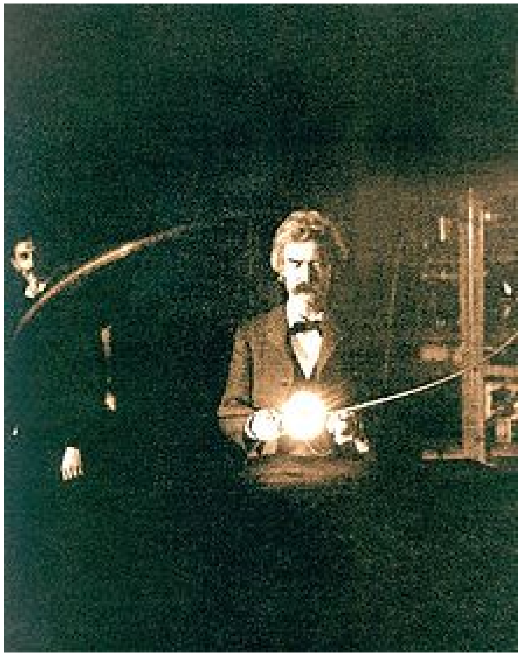


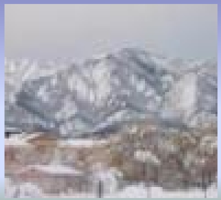
IMS competition:
- Dual frequency
- 2.4GHz and 915MHz
- 1uW/cm^2
- printed Yagi
- capacitor and diode
- 0.5gr mass

Nikola Tesla’s United States Patent No. 685,954, Nov. 5, 1901
Method for utilizing effects transmitted through natural media

Claim 11:
“…utilizing effects or disturbances transmitted through the natural media from a distant source, which consists in storing in a condenser … electrical energy derived from an independent source, and using, for periods of time predetermined as to succession and duration, the accumulated energy so obtained to operate a receiving device.”







Thank you !

Questions?