Energy Harvesting

IEEE RFID 2026 Tutorial presented by **Greg Durgin**

Contact Info: durgin@gatech.edu

- If you would like an official-looking certificate for attendance, email me:
  - A list of each session attended
    - Session I: RF in RFID
    - Session II: Energy-Harvesting/Circuits
    - Session III: Circuits and Cryptography/Middleware
    - Session IV: Tires/PLCs, Neuromorphic RFID
  - Three things that you learned in that session

Introductions

RFID4n: The Finest Granfalloon in All of RFID!

Brian Degnan is a semiconductor design and process engineer with extensive experience in low power circuit design and cryptography for RFID, as well as characterizing advanced nodes at 3 nm and beyond.

Daniel Dobkin is the author of The RF in RFID, and has been involved in semiconductor characterization and reliability since the days when a micron was small.

Jeffrey Dungen combines expertise in radio communications with knowledge of the software needed to exploit the capabilities of Bluetooth Low Energy and other active RF technologies.

Gregory Durgin is a professor at the Georgia Institute of Technology, with broad experience in radio propagation, low-power circuitry, and the use of nonlinear devices in radio communications.

Kevin Berisso is the Director of the AutoID Lab at the University of Memphis, focused on the practical integration of RFID and visual code identification with automated materials handling and inventory management.

Goals of this Talk

- Provide a Basic Understanding of How RF Energy-Harvesting works
- Provide some history into the development of RFID RF harvesting technology
- Learn circuits the FUN way! (graphically)
- Develop a feel for the performance, limitations, and future of passive RFID technologies
  a.k.a. Why does RFID work the way it works?

Outline of this Tutorial

- Introduction
- Basics of Wireless Power Transfer
- What Comes Out of an Antenna?
- Converting RF to DC
- Conversion Efficiency
- Now Let's do it in CMOS
- The Future

Basics of Wireless Power Transfer

Taxonomy of Wireless Power Transfer

High Power

Near Field / High Power:
- autonomous charge station
- electric vehicle charging
- in-room device charging
- induction kitchen rangetop

Far Field / High Power:
- space solar power
- point-to-point wireless power
- in-flight drone charging
- microwave oven

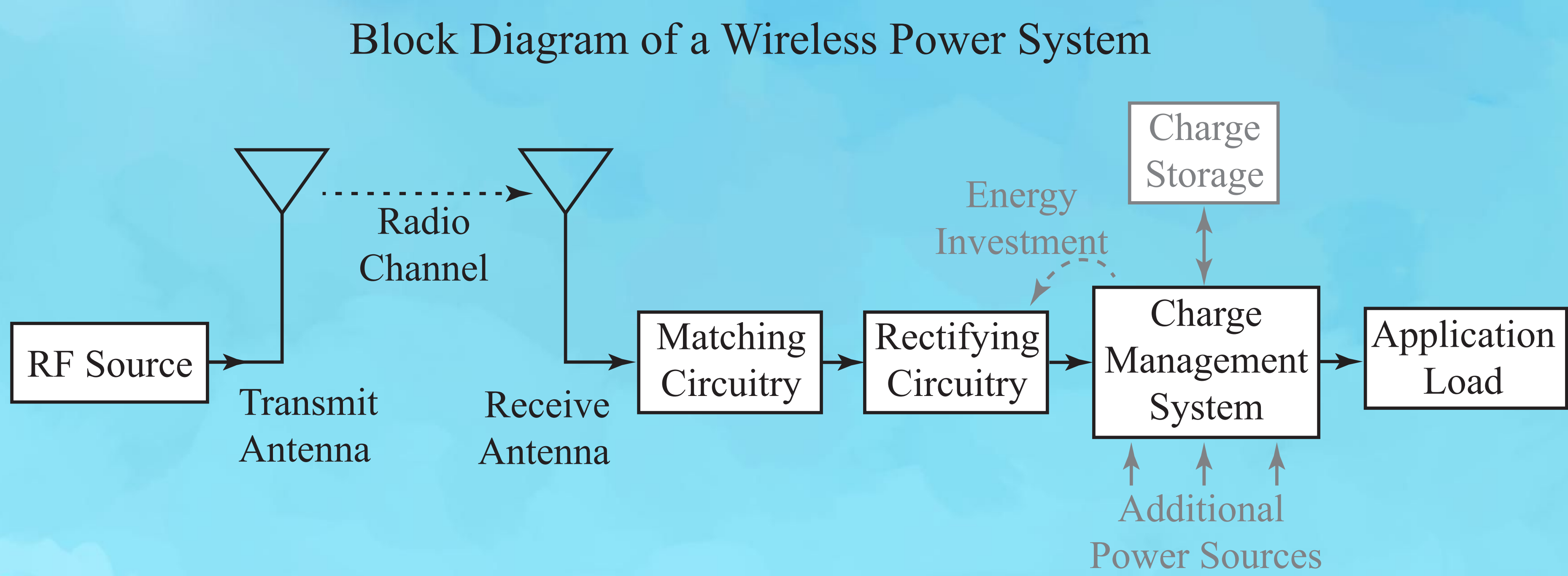
Near Field ⟷ **Far Field**

Near Field / Low Power:
- smart farecards, keycards
- portable electronic charge mat
- inductive RFID
- NFC payments

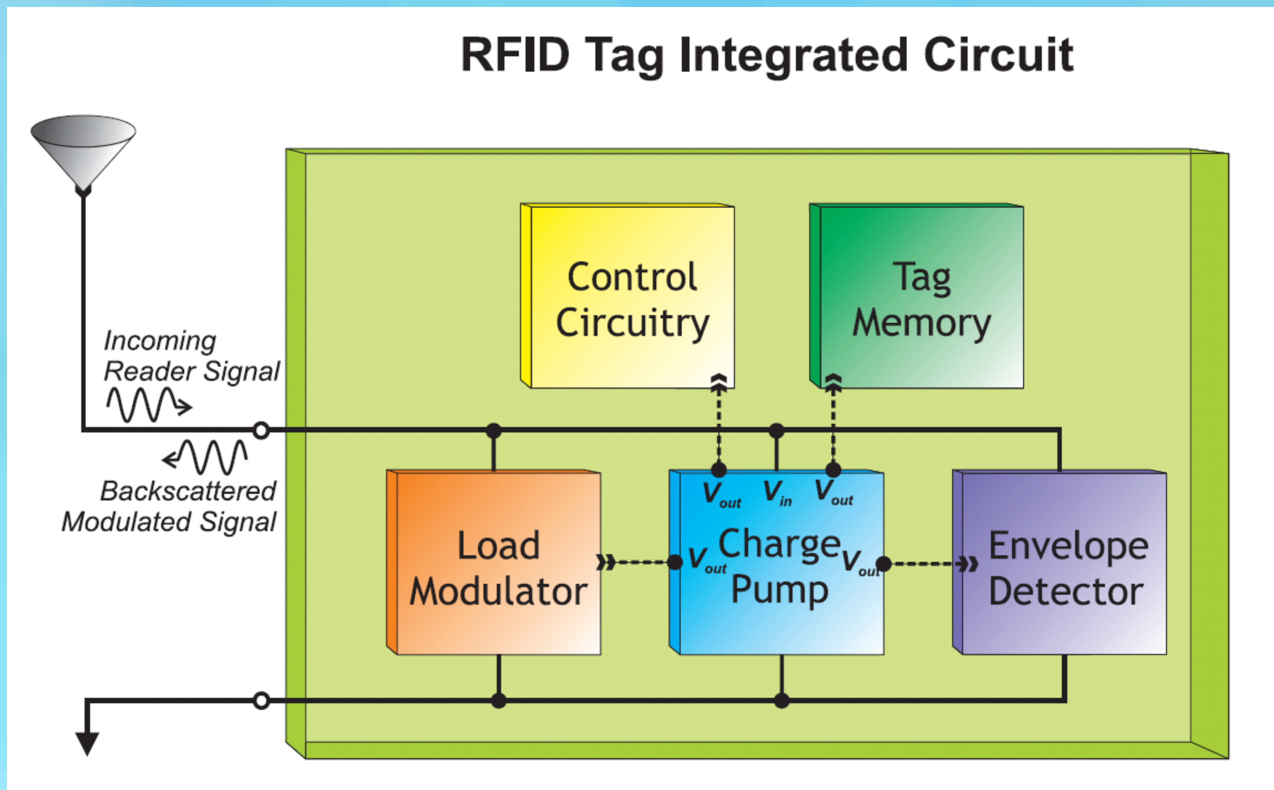
Far Field / Low Power:
- wireless sensors
- UHF RFID
- highway toll tags

Low Power

Basic Parts of All Wireless Power Systems



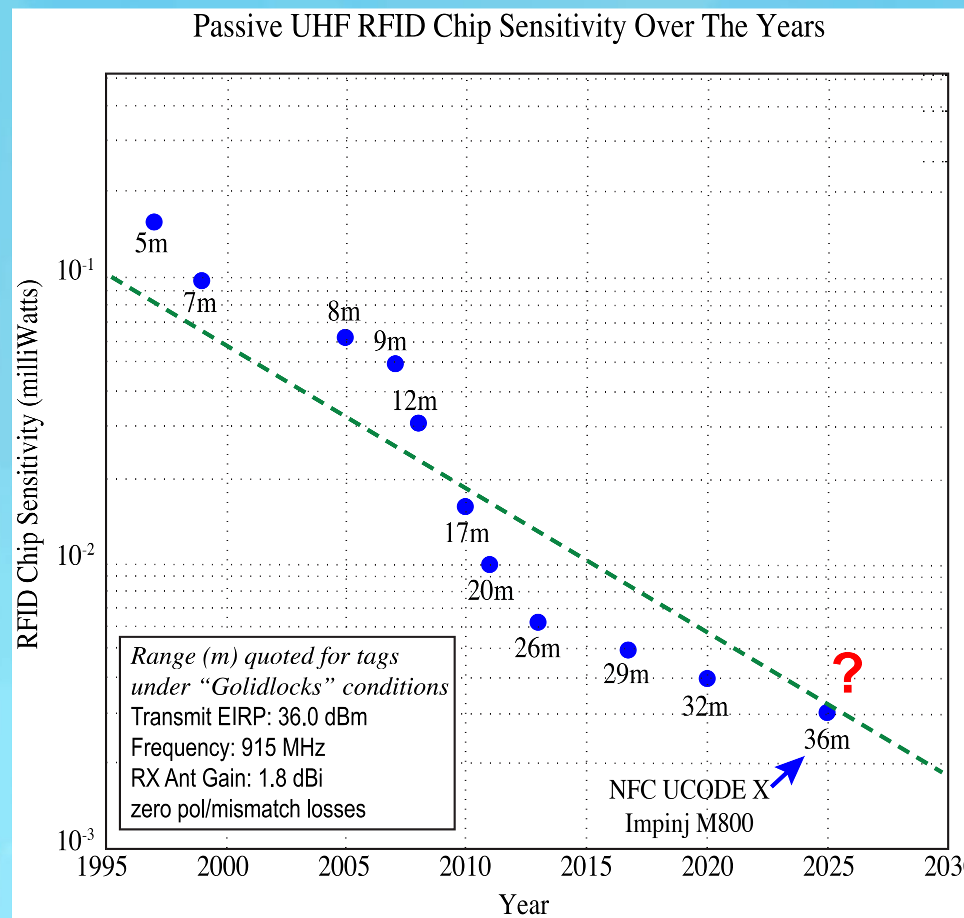
Basic Components of an RFID Tag



M.S. Trotter, J.D. Griffin, and G.D. Durgin. "Power-Optimized Waveforms for Improving the Range and Reliability of RFID Systems." *IEEE RFID 09 Conference*, Orlando, FL. April 2009. 8 pages.

Historical Power-Up for UHF RFID

- Uses "Goldilocks" link assumptions
  - Maximum unlicensed EIRP
  - No blockages, fading
  - Dipole tag antenna, floating in space
  - No polarization mismatch
- Innovation lowers "turn-on" power
  - Smaller integration size
  - Power-stingy circuitry
  - Antenna design and matching
  - Charge management systems
- Fundamental limit imposed by conventional CMOS processes that convert CW RF … *and we're there!*



G. D. Durgin, "RF thermoelectric generation for passive RFID," *2016 IEEE International Conference on RFID (RFID)*, Orlando, FL, USA, 2016, pp. 1-8

What Comes Out of an Antenna?

Antenna Matching

$$P_T = \frac{4R_S R_A}{\underbrace{\left|\tilde{Z}_S + \tilde{Z}_A\right|^2}_{\text{mismatch losses}}} P_S$$

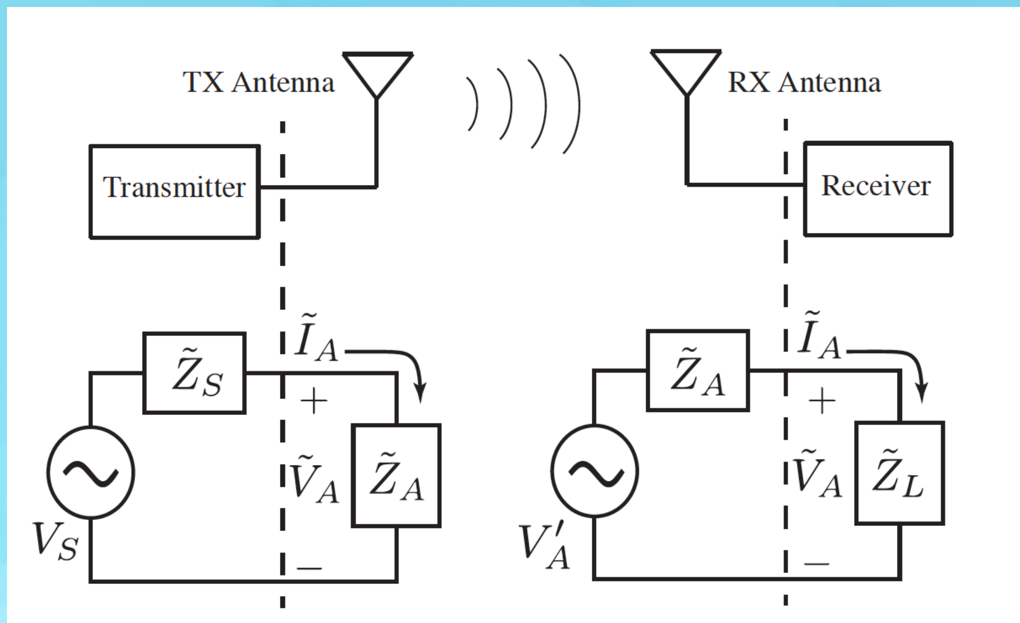
Not all of the source power transmits

$$P_R = \frac{V_A'^2}{8R_A}$$

This is the received power at RX antenna

$$V_A = \left|\tilde{V}_A\right| = \frac{2\left|\tilde{Z}_L\right|\sqrt{2R_A P_R}}{\left|\tilde{Z}_A + \tilde{Z}_L\right|}$$

For energy-harvesting, you also need to check the voltage amplitude



$$P_L = \frac{4R_L R_A}{\underbrace{\left|\tilde{Z}_A + \tilde{Z}_L\right|^2}_{\text{mismatch losses}}} P_R$$

Not all of the received power makes it into the load

Example UHF RFID Tag

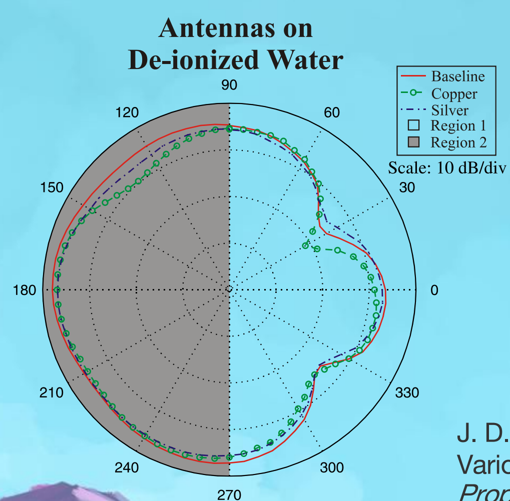
- Electrically shortened half-wave dipole
- Radiation path is meandered to lower terminal capacitance at the IC
- Electrical “ballast” at the ends to add electrical length and bandwidth
- Inductive coupling loop added to boost real impedance and reactive component
- Radiation pattern is the same as nearly all other short UHF tags

Alien UHF RFID Squiggle Tag

Enemy of UHF Power Transfer: Everything

Detrimental Effects When Tags Placed on Objects

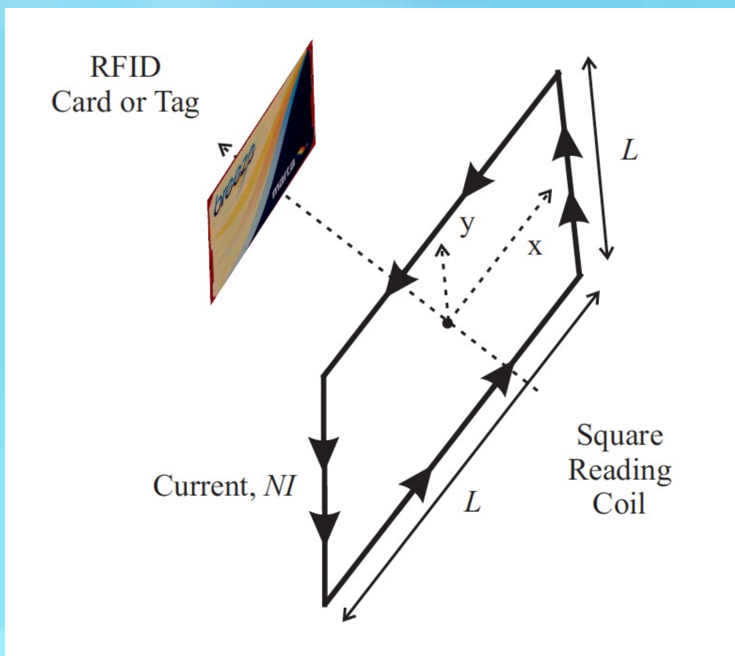
- Gain Penalty to the Radiation
- “Pattern Sucking”
- Highly Mismatched Circuit

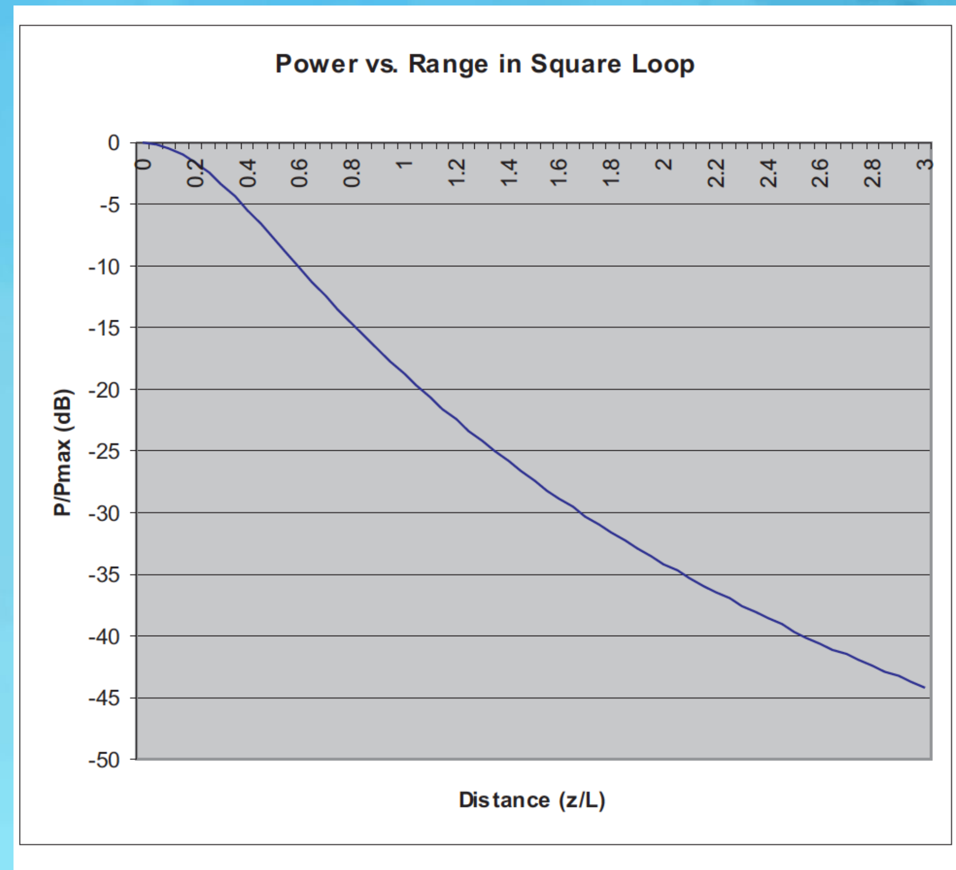


	AGP (dB)	ϵ_r	$\tan\delta$
Cardboard Sheet	0.9	≈ 1	≈ 0
Acrylic Slab	1.1	2.6	0.0061
Pine Plywood	4.7	1.7	0.036
De-ionized Water	5.7	77.3	0.048
Ethylene Glycol**	7.4	33	0.4
Ground Beef ***	7.4	50	0.7
Aluminum Slab	9.4	-	-

J. D. Griffin, G. D. Durgin, A. Haldi and B. Kippelen, "RF Tag Antenna Performance on Various Materials Using Radio Link Budgets," in *IEEE Antennas and Wireless Propagation Letters*, vol. 5, pp. 247-250, 2006

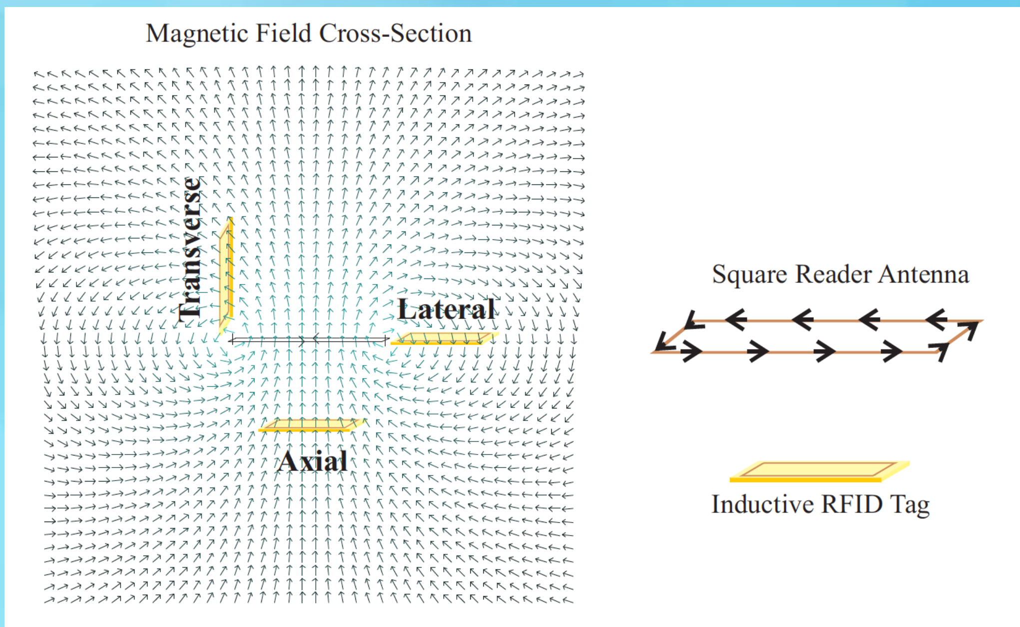
Near-Field Excitation





Separation distance: $r << \lambda$

Magnetic Field Modeling of a Pick-up Coil

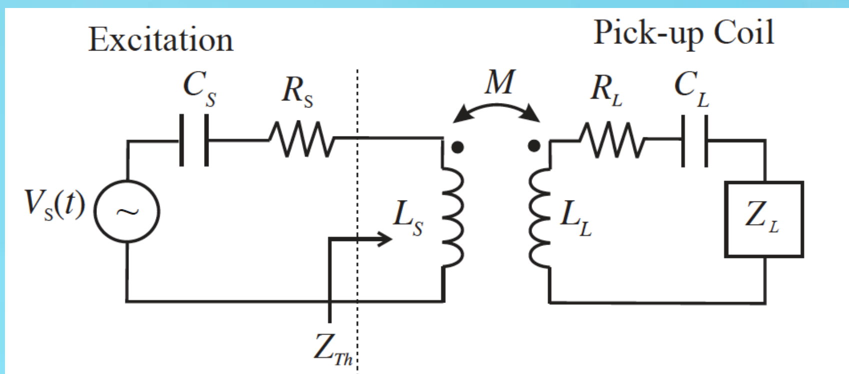


Three Modes of Inductive Wireless Power Transfer

- Axial
- Lateral
- Transverse

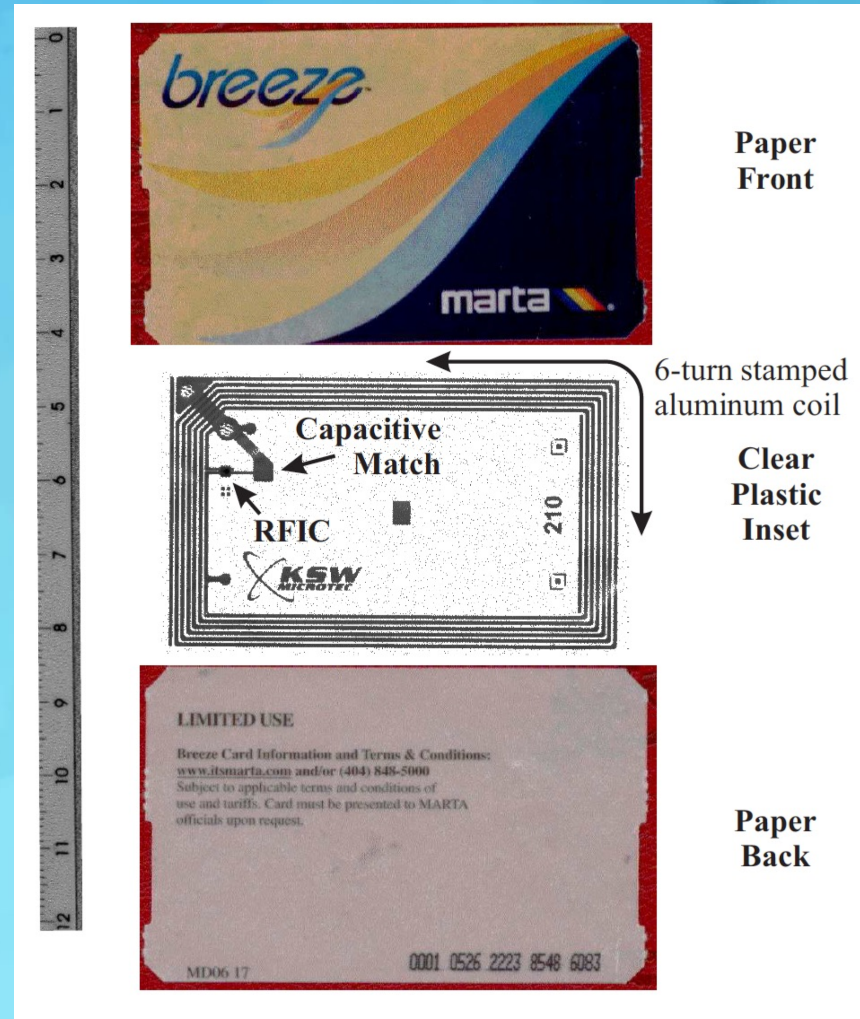
Anatomy of HF RFID

How to make an HF energy-harvesting circuit



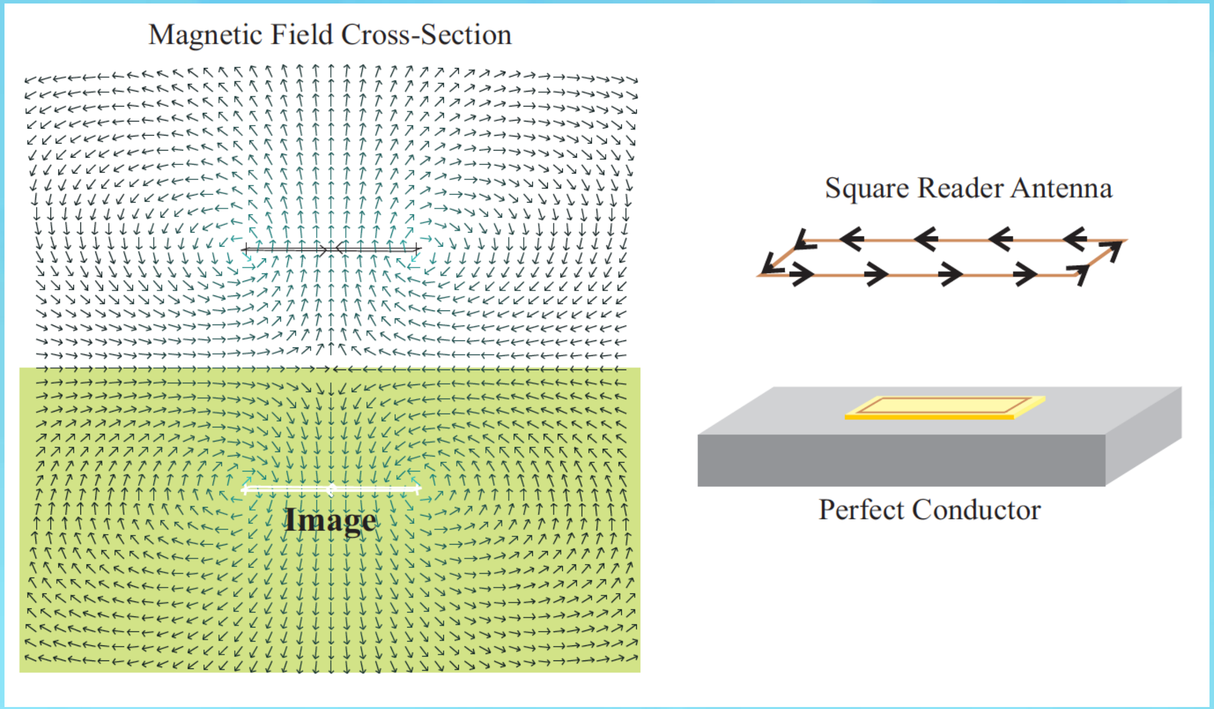
Inductive Load Thevenin Equivalent

$$\tilde{Z}_{th} = j2\pi f L_S + \frac{4\pi^2 f^2 M^2}{R_L + j2\pi f L_L - \frac{j}{2\pi f C_L} + \tilde{Z}_L}$$



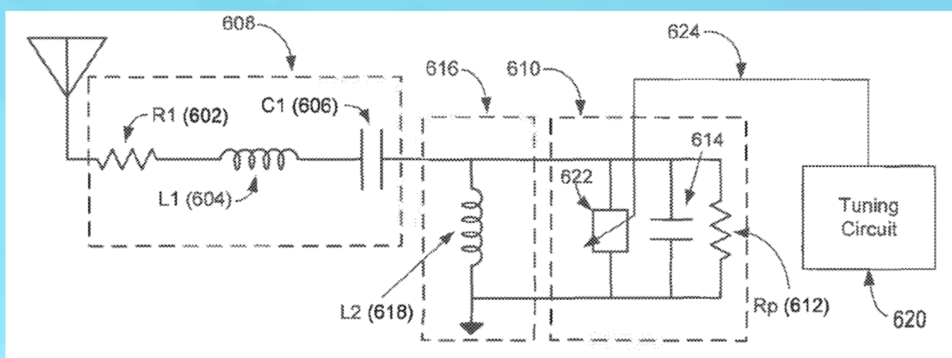
Enemy of Inductive Power Transfer: Metal

- Eddy/Image currents do not allow perpendicular fields near metal
- Leads to bad impedance mismatch *and* drop in mutual coupling between tag and reader



AutoTune in RFID Tags and Power Transfer

- Auto-tune circuit powers on before the rest of RFID tag's state machines
- Used in HF and UHF tags
- Circuit switches in different RF capacitors until maximum power achieved



US009471816B1

(12) **United States Patent**
Hyde et al.

(10) **Patent No.: US 9,471,816 B1**
(45) **Date of Patent: Oct. 18, 2016**

(54) **INCREASING DYNAMIC RANGE OF RFID TAG SELF-TUNING**

(71) Applicant: **Impinj, Inc.**, Seattle, WA (US)

(72) Inventors: **John Hyde**, Corvallis, OR (US); **Theron Stanford**, Seattle, WA (US); **Harley Heinrich**, Snohomish, WA (US); **Omer Onen**, Redmond, WA (US); **Charles Peach**, Kirkland, WA (US)

(73) Assignee: **IMPINJ, INC.**, Seattle, WA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **14/711,717**

(22) Filed: **May 13, 2015**

G06K 19/073; G06K 19/07756; G06K 19/07745; G06K 19/0775; G06K 7/10297; G06K 7/10158; G06K 19/0723
USPC 340/10.5, 10.34, 10.1, 10.6, 334, 572; 235/492, 488; 438/26
See application file for complete search history.

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2015/0227832	A1 *	8/2015	Diorio	....	G06K 19/07745 235/492

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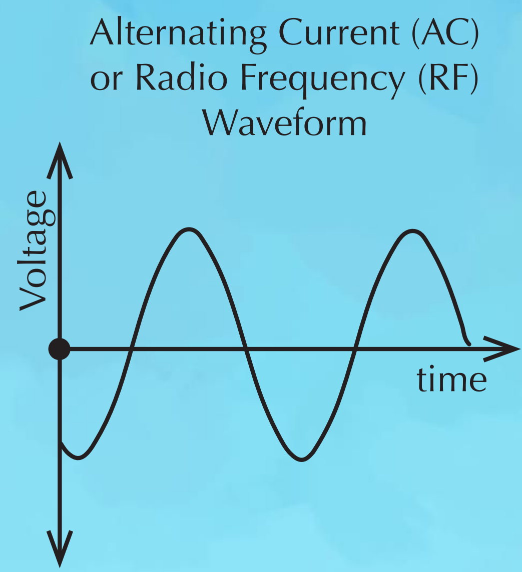
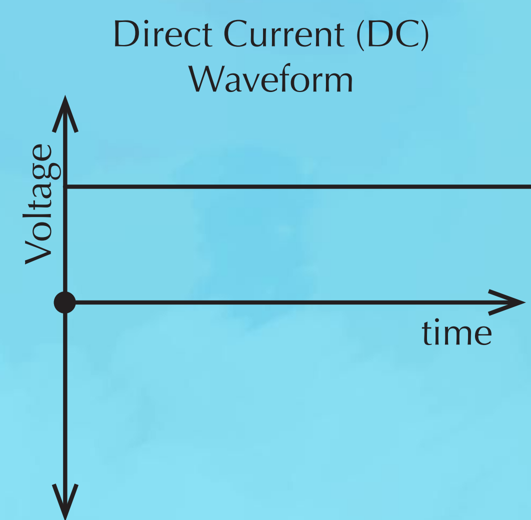
Converting RF to DC

How to Rectify RF

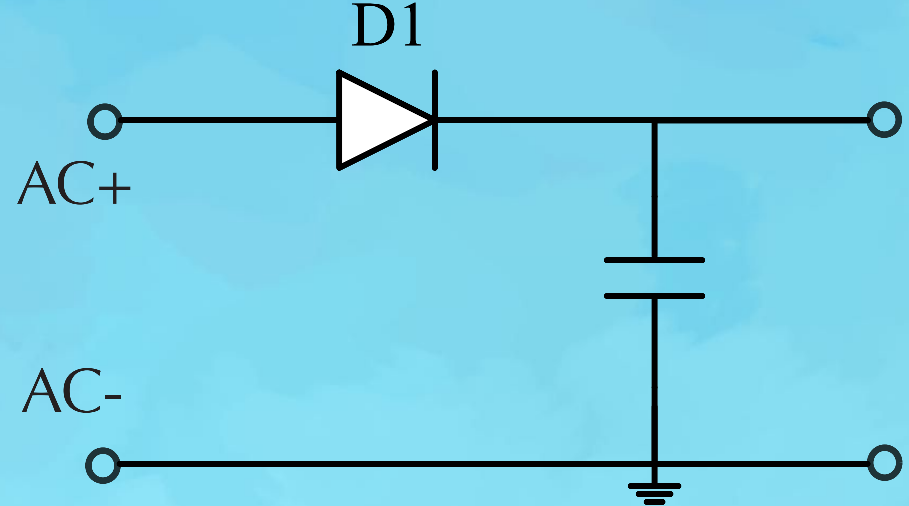
- RF is just a high-frequency form of alternating current
- But we need DC voltage to drive memory, logic, sensing, etc.
- Need a nonlinear circuit to passively "change" frequencies (by definition)



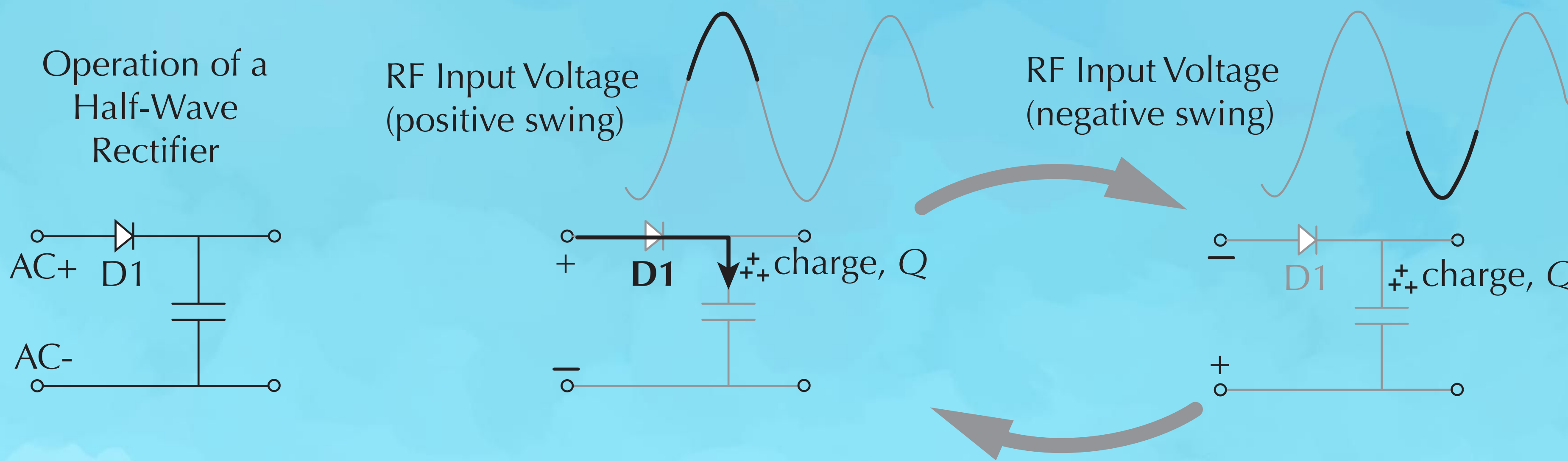


Half-Wave Rectifier

- Half-wave rectifier for RF-to-DC conversion
- Similar circuit is also used as a detector
- Extremely simple design
- Only converts on one cycle of the RF waveform

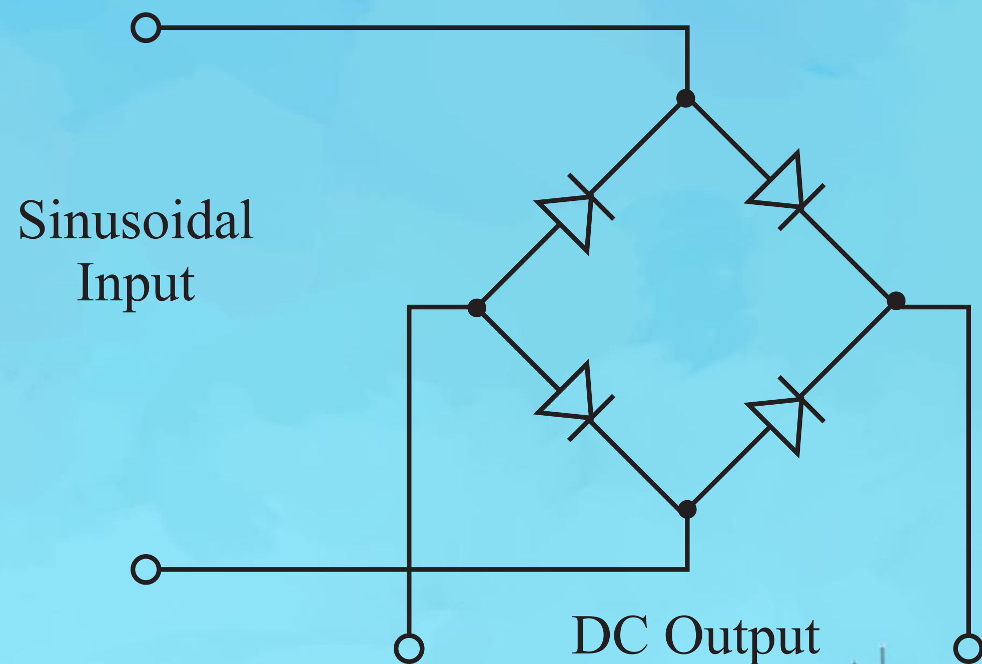


Half-Wave Rectifier Operation

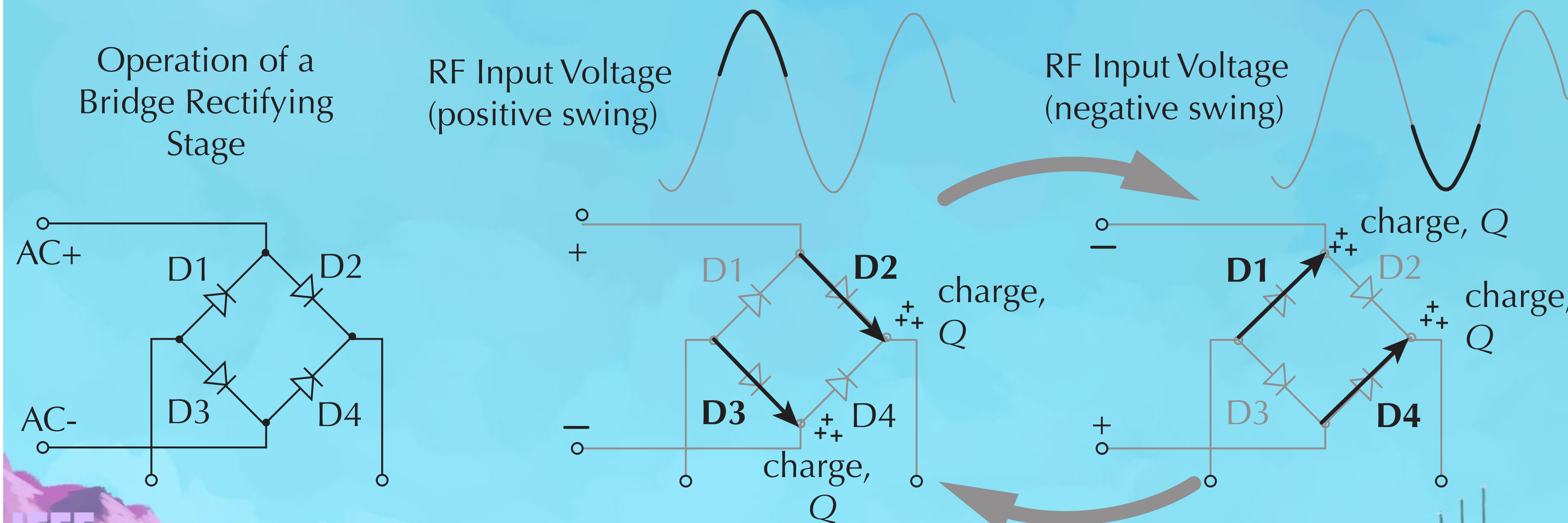


Bridge Rectifier

- Used in AC-to-DC power conversion
- Useful because there are no capacitors (except at the output to smooth ripple on the DC supply)
- Full-wave rectification
- Less useful for RF because it requires turning on two diodes per cycle (loss of conversion efficiency at low levels)

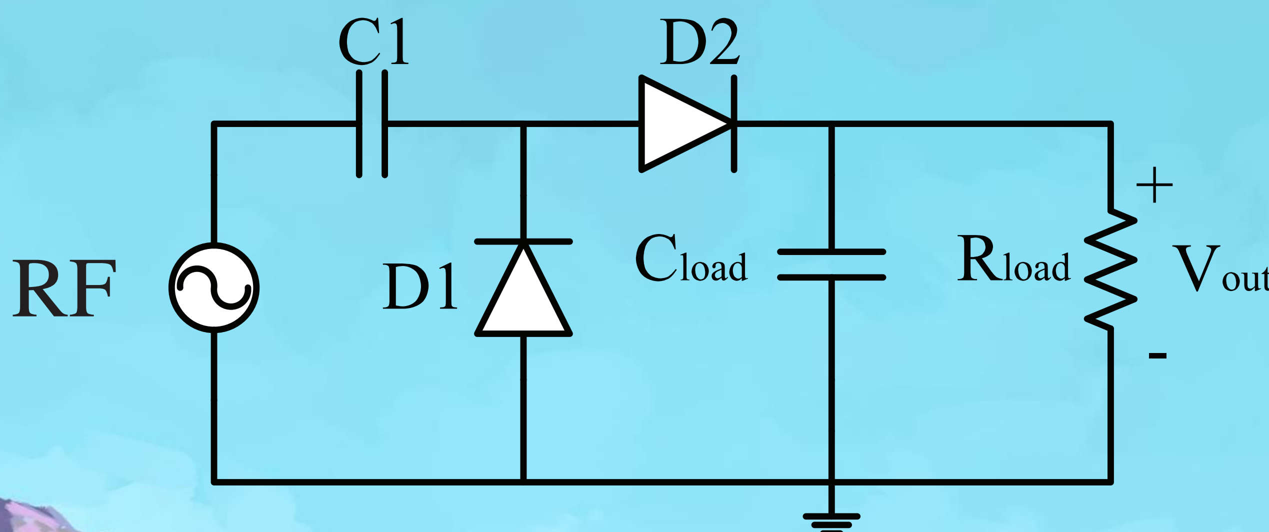


Bridge Rectifier Operation

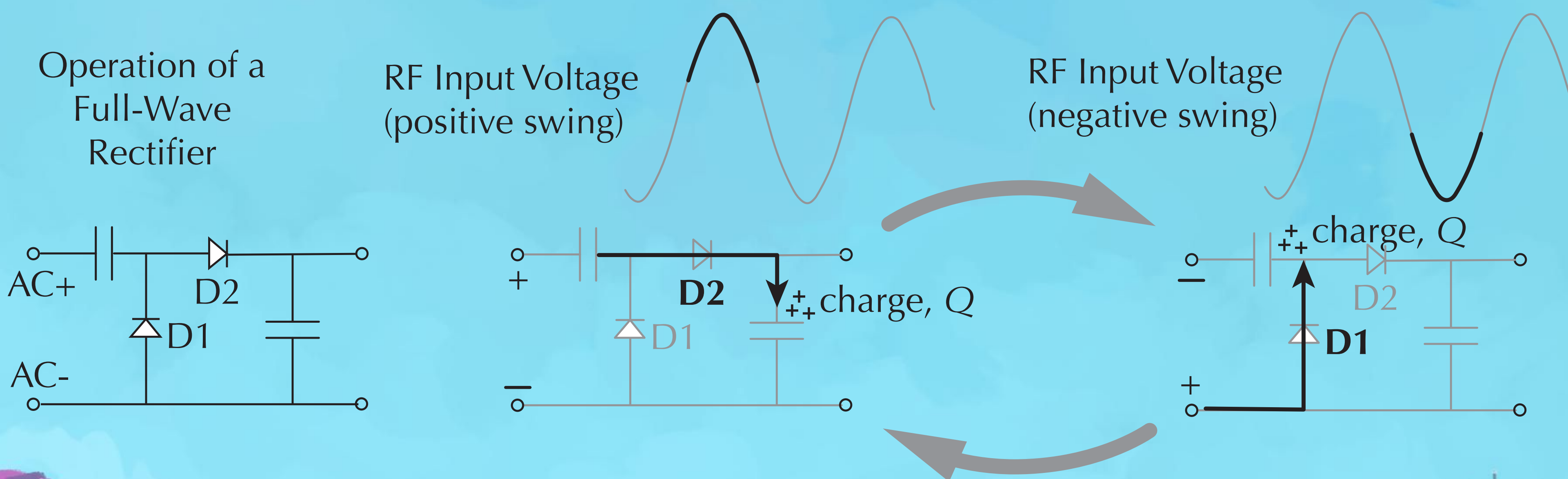


Full-Wave Rectifier/Doubler

- Two capacitors and diodes
- Arranged to *double* DC voltage at the output (often called a voltage doubler)
- Only one diode needs to turn on at a time



Full Wave Rectifier/Doubler Operation



It's Actually Easy to Build a Diode Rectifier

- Thomas and Degnan showed that you can even do it by accident!
- Right is diagram of a microcontroller pin with electrostatic discharge (ESD) diodes and capacitors that behave like RF rectifiers

S. J. Thomas, B. P. Degnan, C. Callupe Chavez and B. Culver, "Backscatter Ex-Nihilo: Single-component, Fully-passive Backscattering for Microcontrollers," *2020 IEEE International Conference on RFID (RFID)*, Orlando, FL, USA, 2020

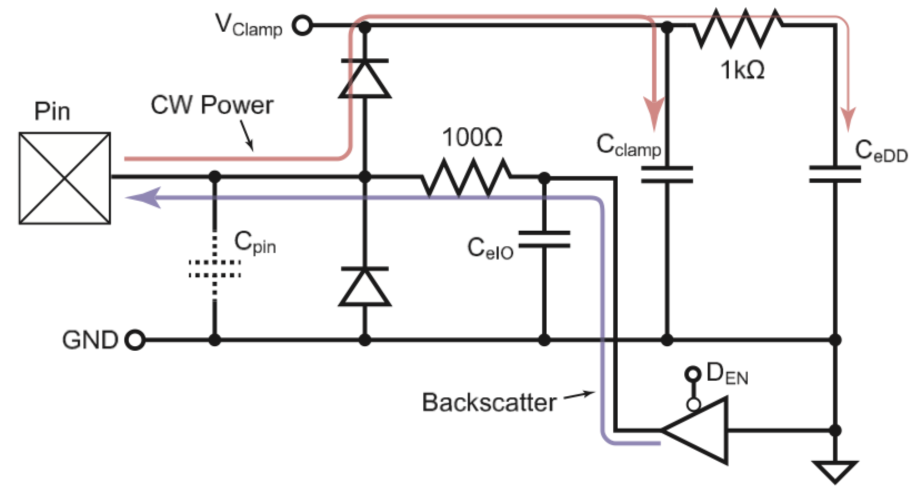
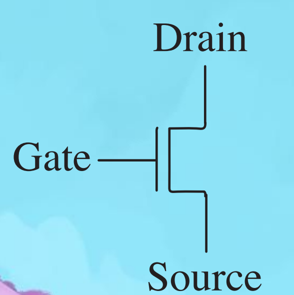


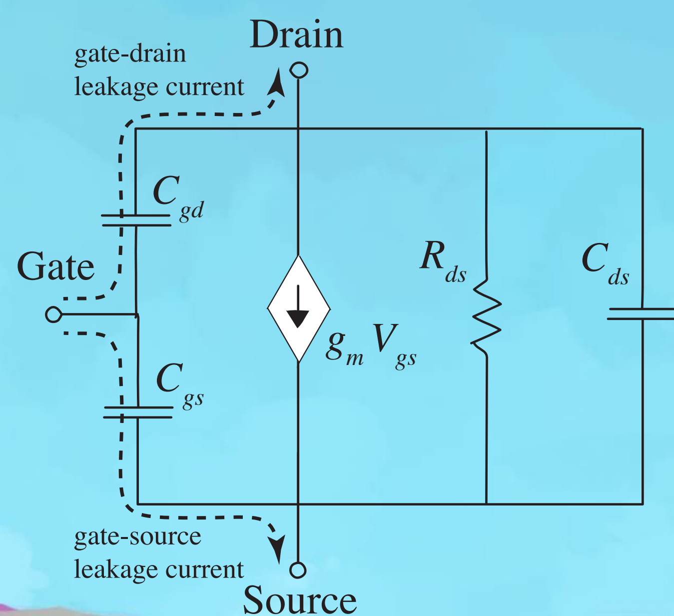
Fig. 4. The illustration depicts a simplified ESD structure where an ESD diode is used to place charge on capacitor. The GPIO driver enable line is then used as a backscatter load.

The Problem With Diodes

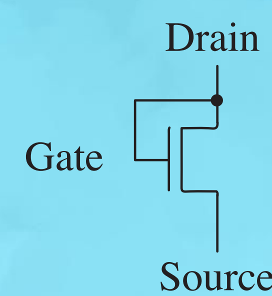
- RF transmissions nearly always produce low voltages at the output of the antenna
- Thus, lower RF levels convert at lower efficiencies
- This is a fundamental limit of *any* conversion circuitry (PN diodes, Schottky diodes, CMOS diodes, etc.)

MOSFET Circuit Element



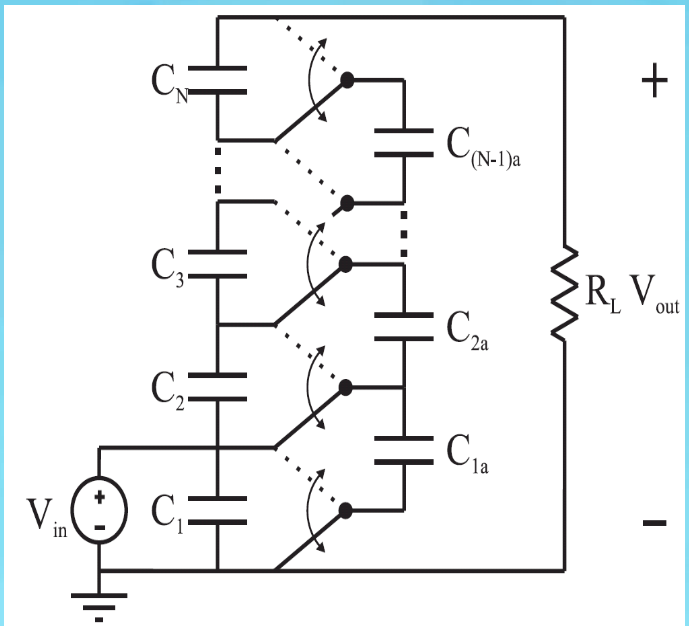


Diode-Connected MOSFET



Charge Pumps

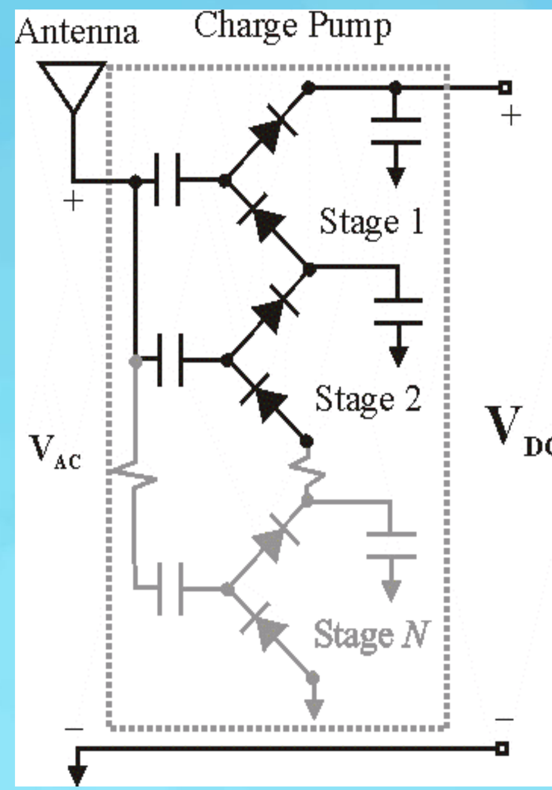
- Cockcroft-Walton multiplier (1932)
  - Only uses capacitors
  - Also requires mechanical switching
- Part of Nobel Prize-winning work on splitting atom
- Required large voltages for their particle accelerator
- Still used today



Multi-Stage Rectifier Circuit

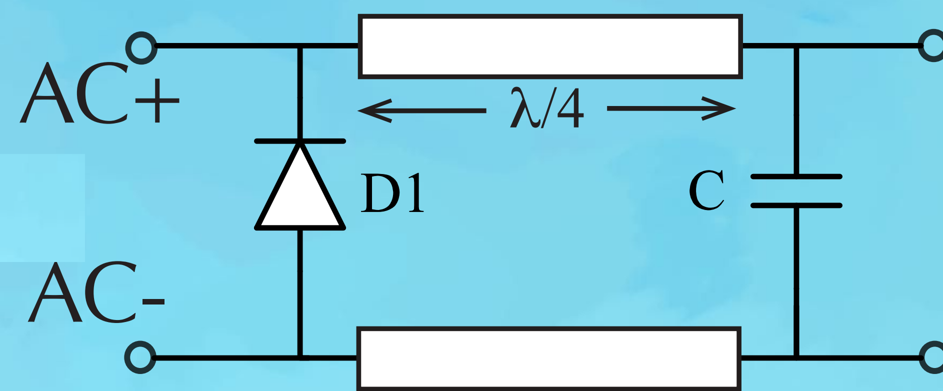
- Charge pump rectifier
  - Diodes and capacitors
  - AC voltage converted to DC
  - Voltage stepped up (current stepped down)
- Ideal Voltage Conversion:

  $V_{DC} = N(V_{AC})_{pp} - 2NV_{TO}$
- Drawbacks
  - Higher complexity
  - Diminishing returns for added stages
  - Longer charging transient

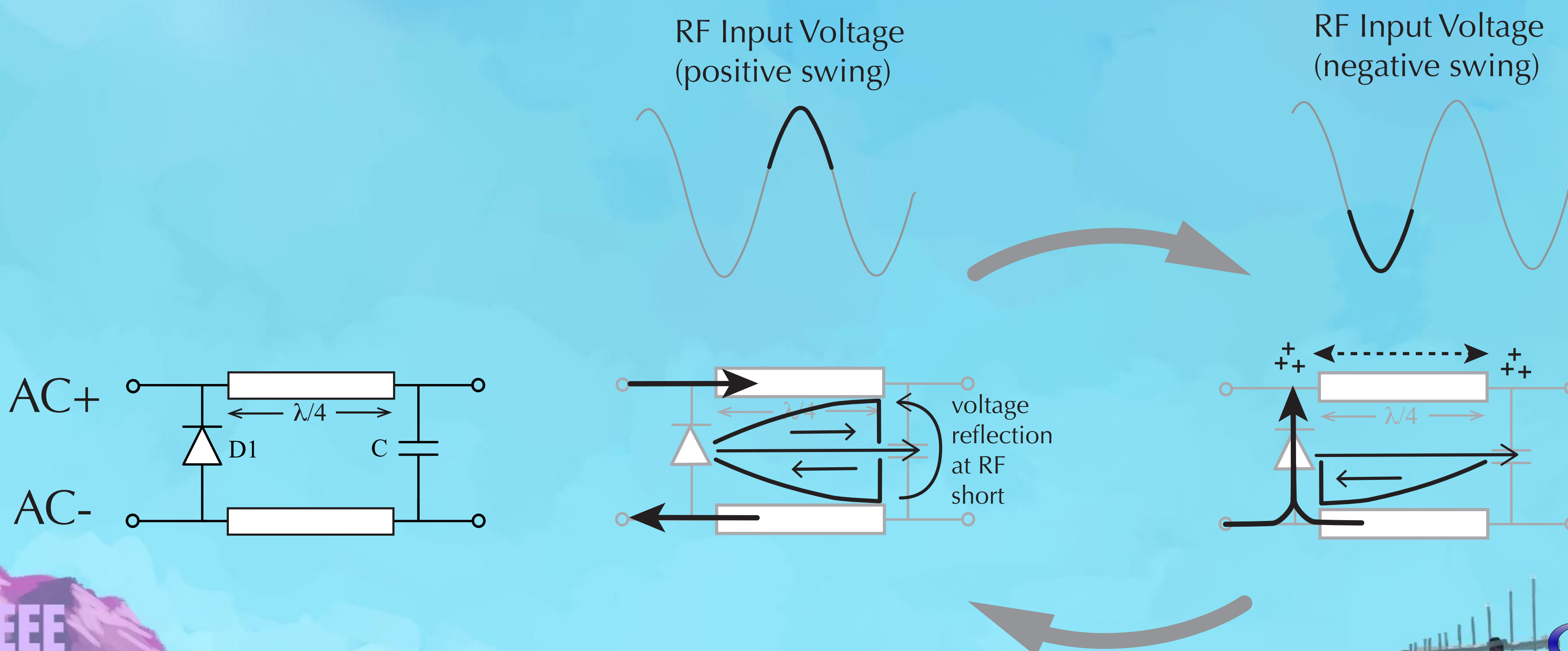


Single Shunt Rectifier

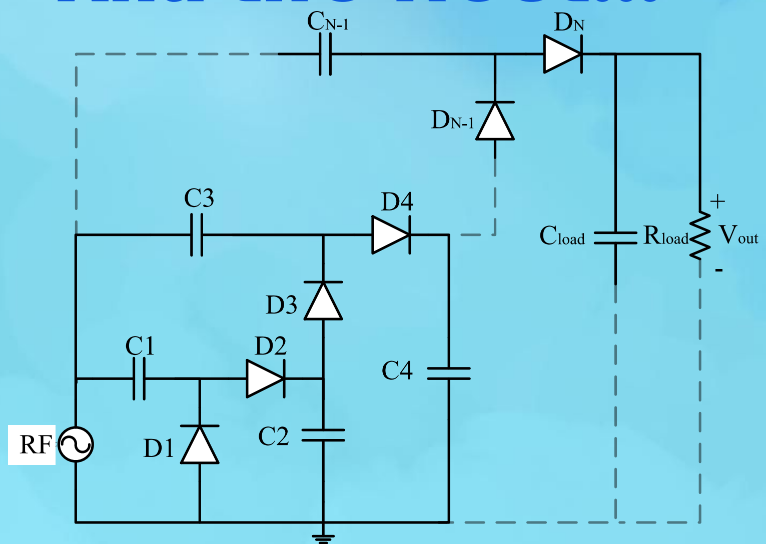
- Single diode+cap and quarter-wave transformer line
- Only one turn-on voltage, but full-wave rectification
- Useful for IoT devices on circuit boards



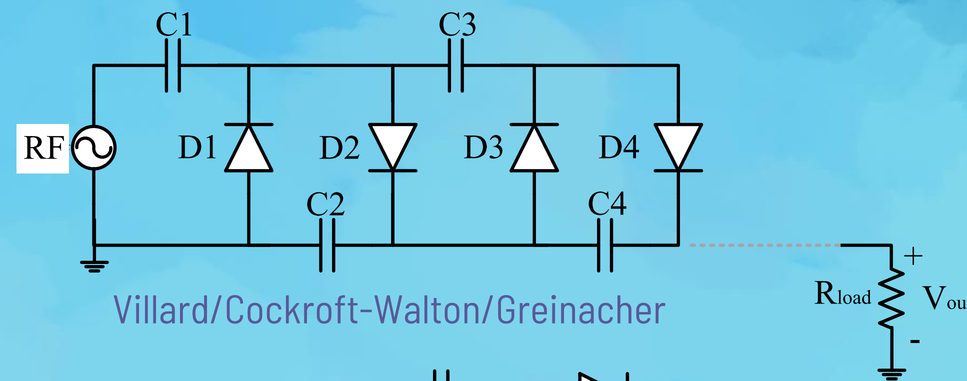
Single-Shunt Rectifier Operation



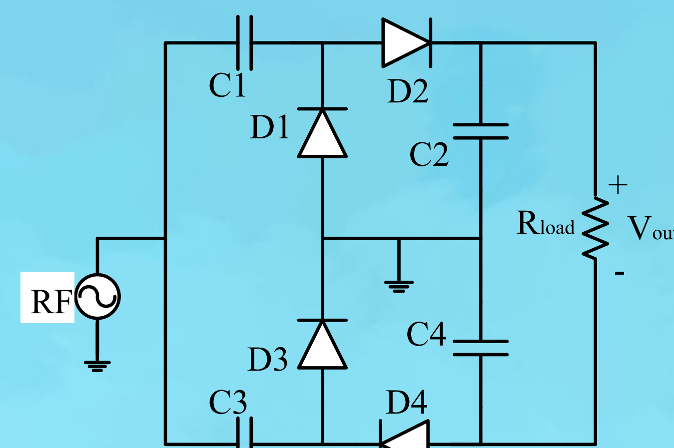
And the Rest...



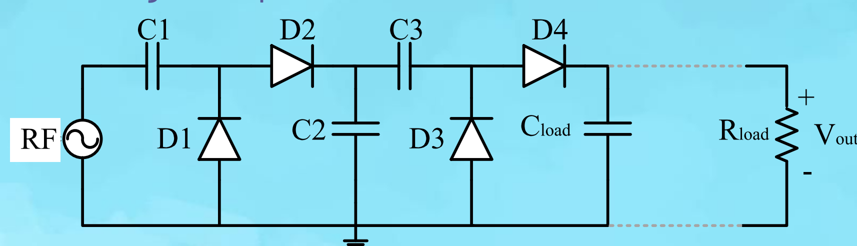
Dickson Charge Pump



Villard/Cockroft-Walton/Greinacher



Modified Cockroft-Walton/Greinacher

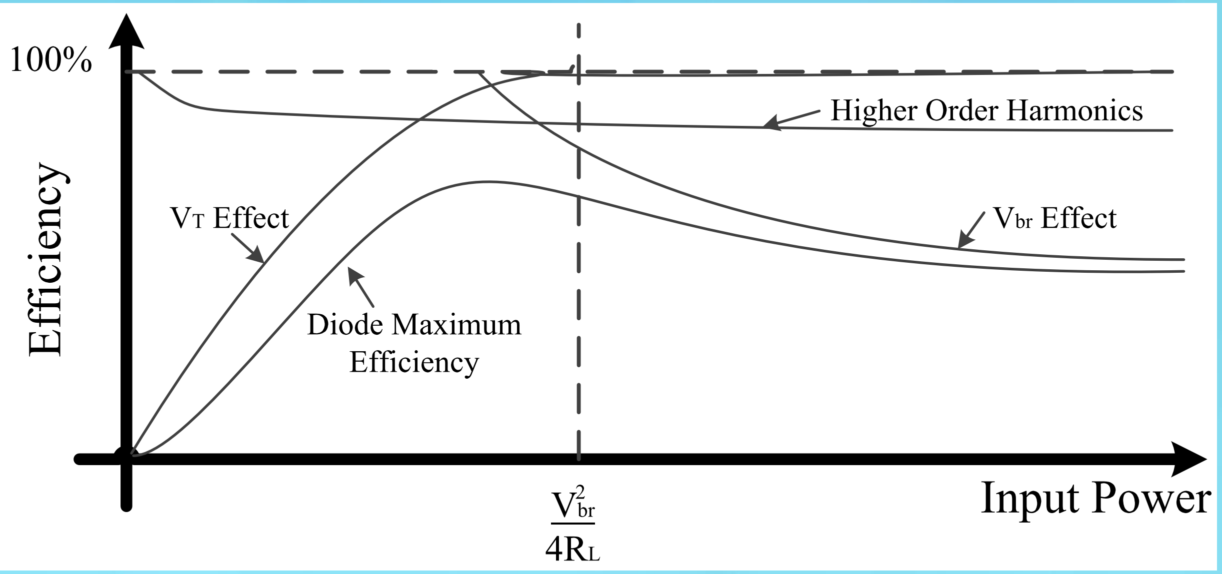


N-Voltage Multipler

Conversion Efficiency

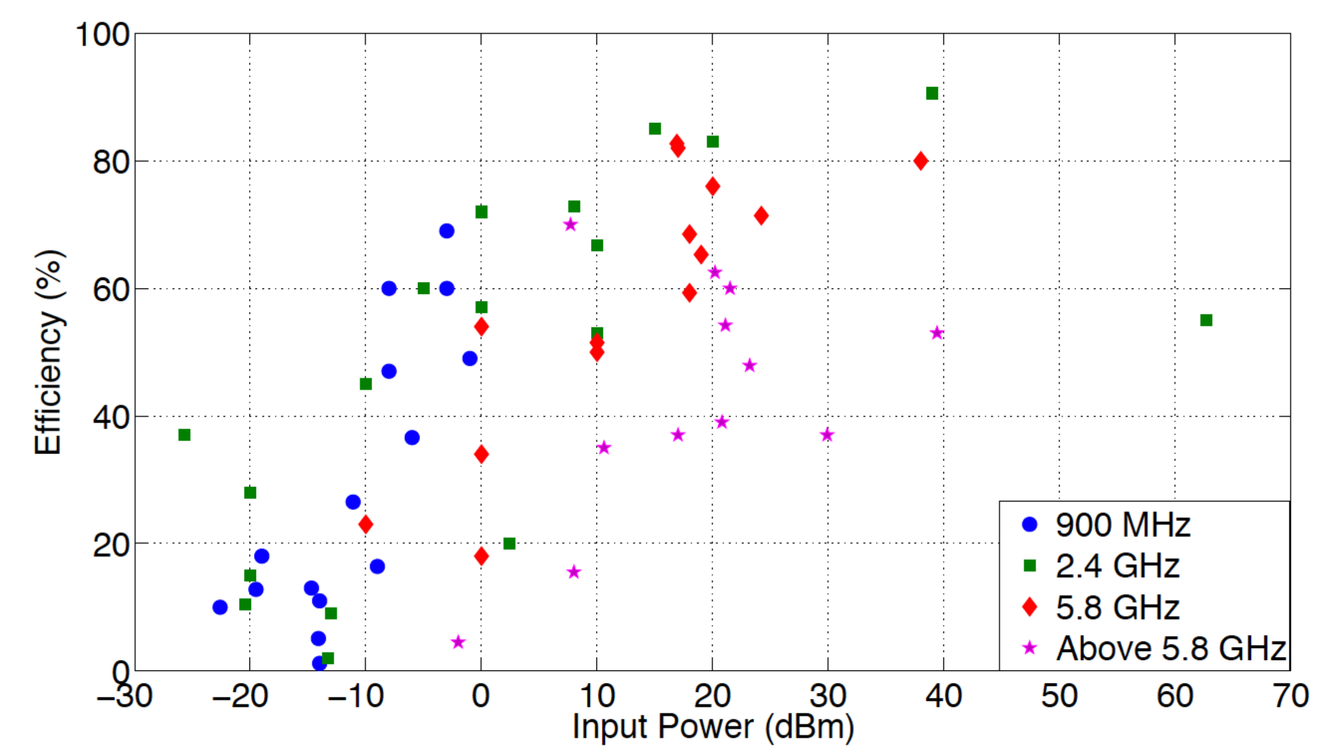
Diode Efficiency

- Harmonics and other inefficiencies (all powers)
- Losses due to the diode/transistor turn-on effect (low-power)
- Reverse breakdown of diodes (high-power)



C. R. Valenta and G. D. Durgin, "Harvesting Wireless Power: Survey of Energy-Harvester Conversion Efficiency in Far-Field, Wireless Power Transfer Systems," in *IEEE Microwave Magazine*, vol. 15, no. 4, pp. 108-120, June 2014

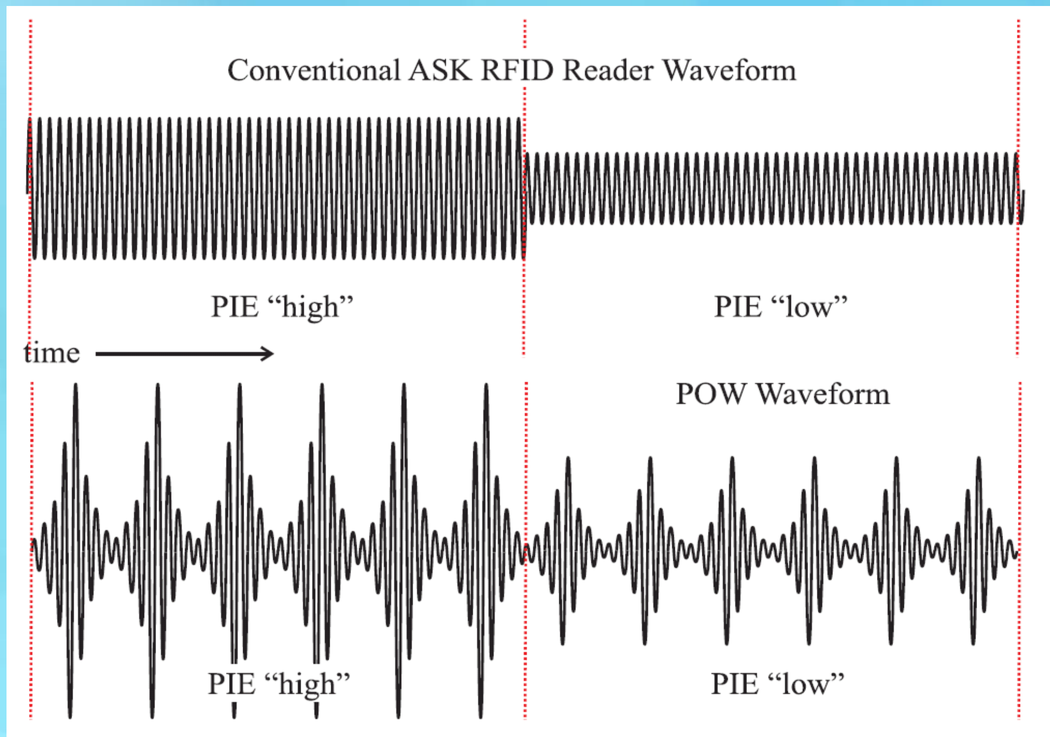
The Valenta Diagram



Christopher Valenta
GTRI

C. R. Valenta and G. D. Durgin, "Harvesting Wireless Power: Survey of Energy-Harvester Conversion Efficiency in Far-Field, Wireless Power Transfer Systems," in *IEEE Microwave Magazine*, vol. 15, no. 4, pp. 108-120, June 2014

Power Optimized Waveforms



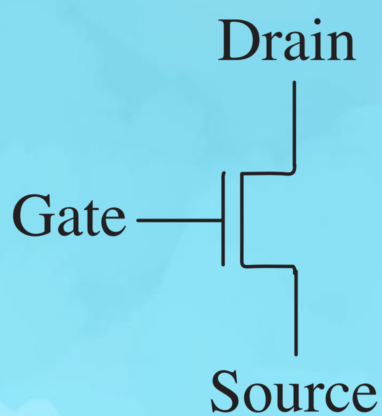
Matthew Trotter
Georgia Tech

M. S. Trotter, J. D. Griffin and G. D. Durgin, "Power-optimized waveforms for improving the range and reliability of RFID systems," *2009 IEEE International Conference on RFID*, Orlando, FL, USA, 2009, pp. 80-87

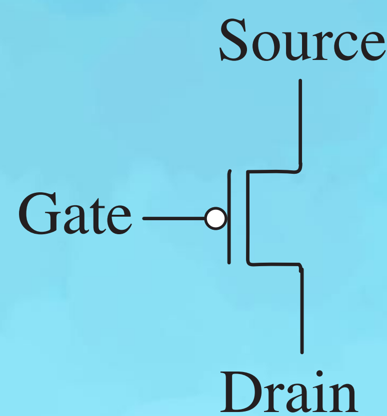
Now Let's Do It In CMOS!

Complimentary Metal Oxide Semiconductor Si Transistors

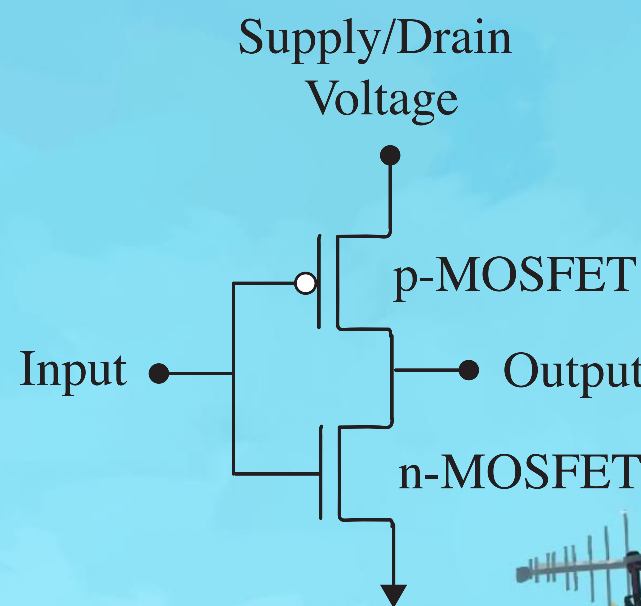
n-MOSFET
Circuit Element



p-MOSFET
Circuit Element



CMOS
Inverter



Mandal Charge Pump

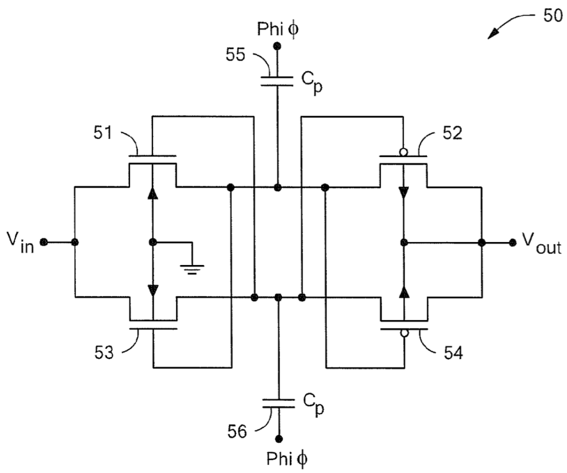


FIG. 8

US008045947B2

(12) **United States Patent**
Mandal et al.

(10) **Patent No.: US 8,045,947 B2**
(45) **Date of Patent: *Oct. 25, 2011**

(54) **RF POWER EXTRACTING CIRCUIT AND RELATED TECHNIQUES**

(75) Inventors: **Soumyajit Mandal**, Cambridge, MA (US); **Rahul Sarpeshkar**, Arlington, MA (US)

(73) Assignee: **Massachusetts Institute of Technology**, Cambridge, MA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 909 days.

This patent is subject to a ter
claimer.

(21) Appl. No.: **11/609,060**

(22) Filed: **Dec. 11, 2006**

(65) **Prior Publication Data**

US 2007/0087719 A1 Apr. 19, 2007

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T DOCUMENTS
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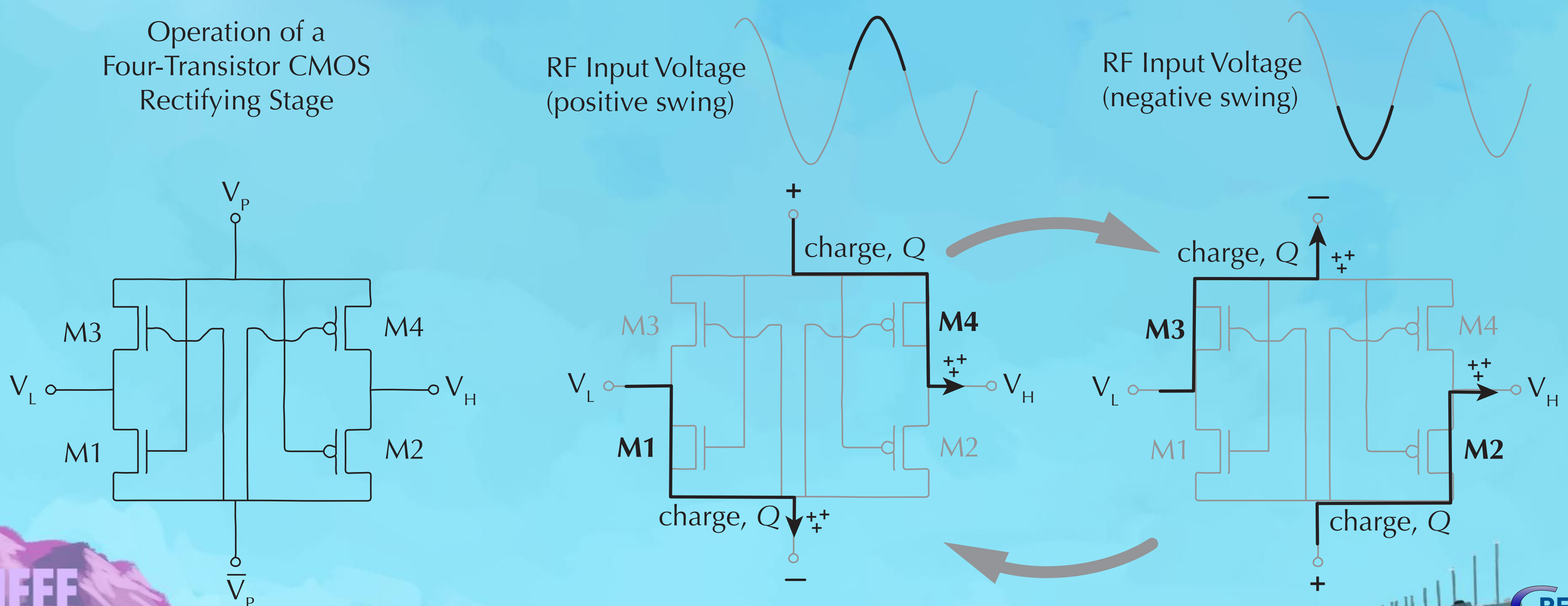
un Liao
— Daly, Crowley, Mofford &

- 4-transistor, Repeatable Unit
- Self-biasing unit (DC on gates to optimize)
- Simple, Elegant

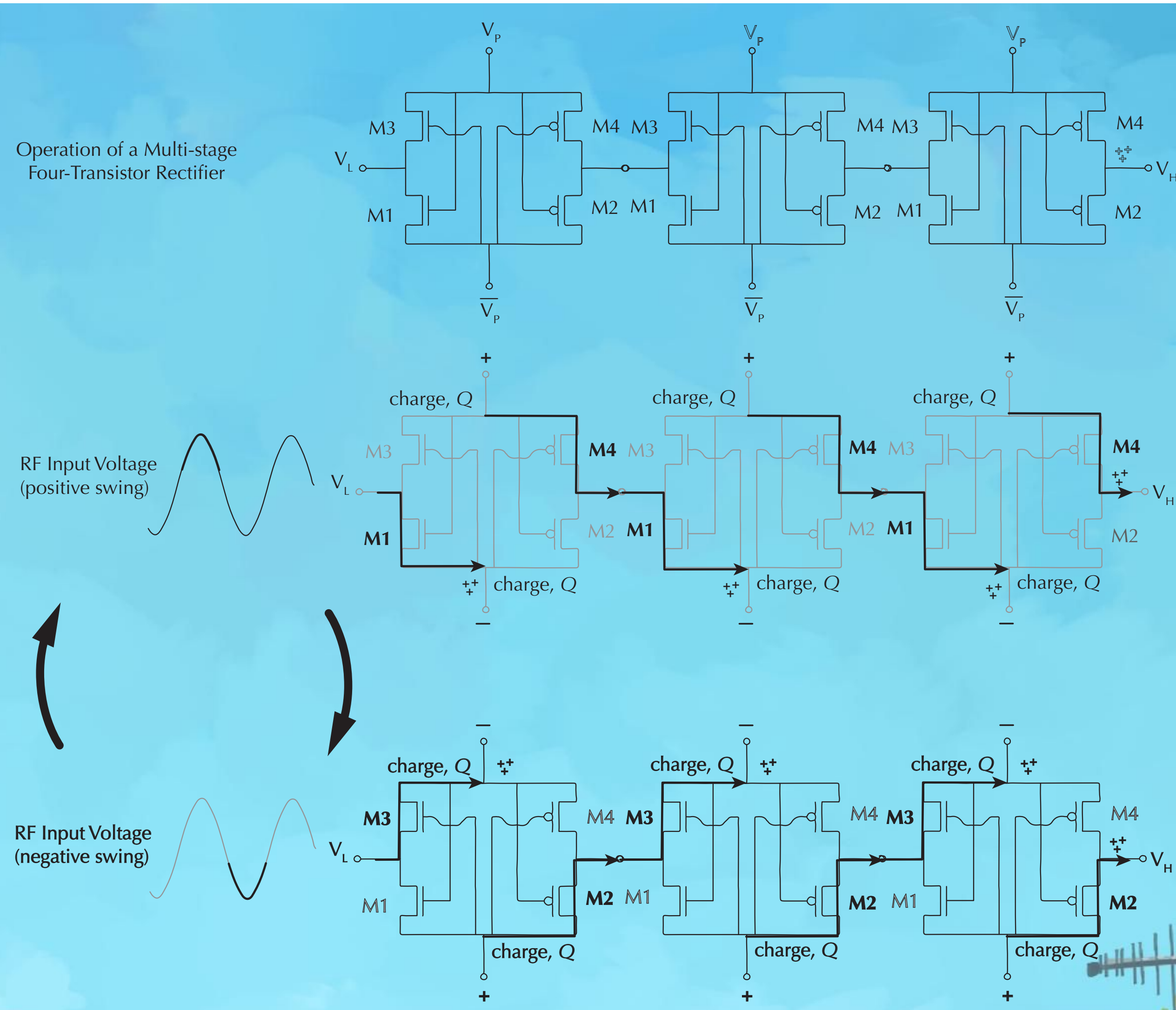
Soumyajit Mandal
MIT/Brookhaven National Labs

Mandal Charge Pump Operation

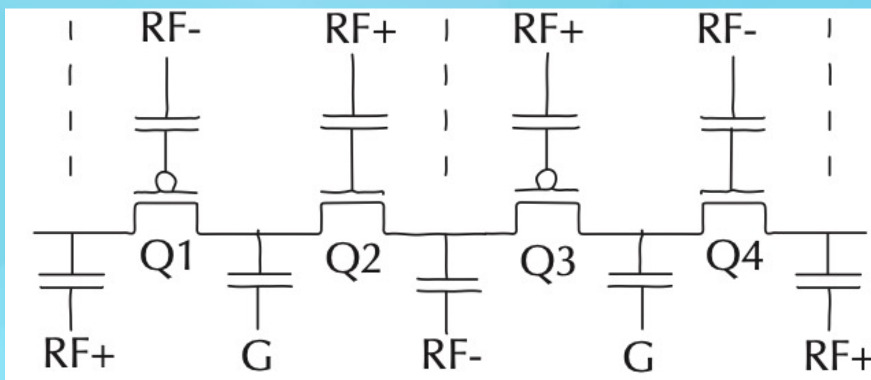


Multiple Stages

Mandal Charge Pumps can be connected in series to boost DC voltage



Oliver Charge Pump



US008115597B1

(12) **United States Patent**
Oliver et al.

(10) **Patent No.:** **US 8,115,597 B1**
(45) **Date of Patent:** **Feb. 14, 2012**

(54) **RFID TAGS WITH SYNCHRONOUS POWER RECTIFIER**

(75) Inventors: **Ronald A. Oliver**, Seattle, WA (US); **John D. Hyde**, Corvallis, OR (US); **Charles J. T. Peach**, Seattle, WA (US)

(73) Assignee: **Impinj, Inc.**, Seattle, WA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 1012 days.

(21) Appl. No.: **12/042,117**

(22) Filed: **Mar. 4, 2008**

Related U.S. Application Dat

(60) Provisional application No. 60/905,41
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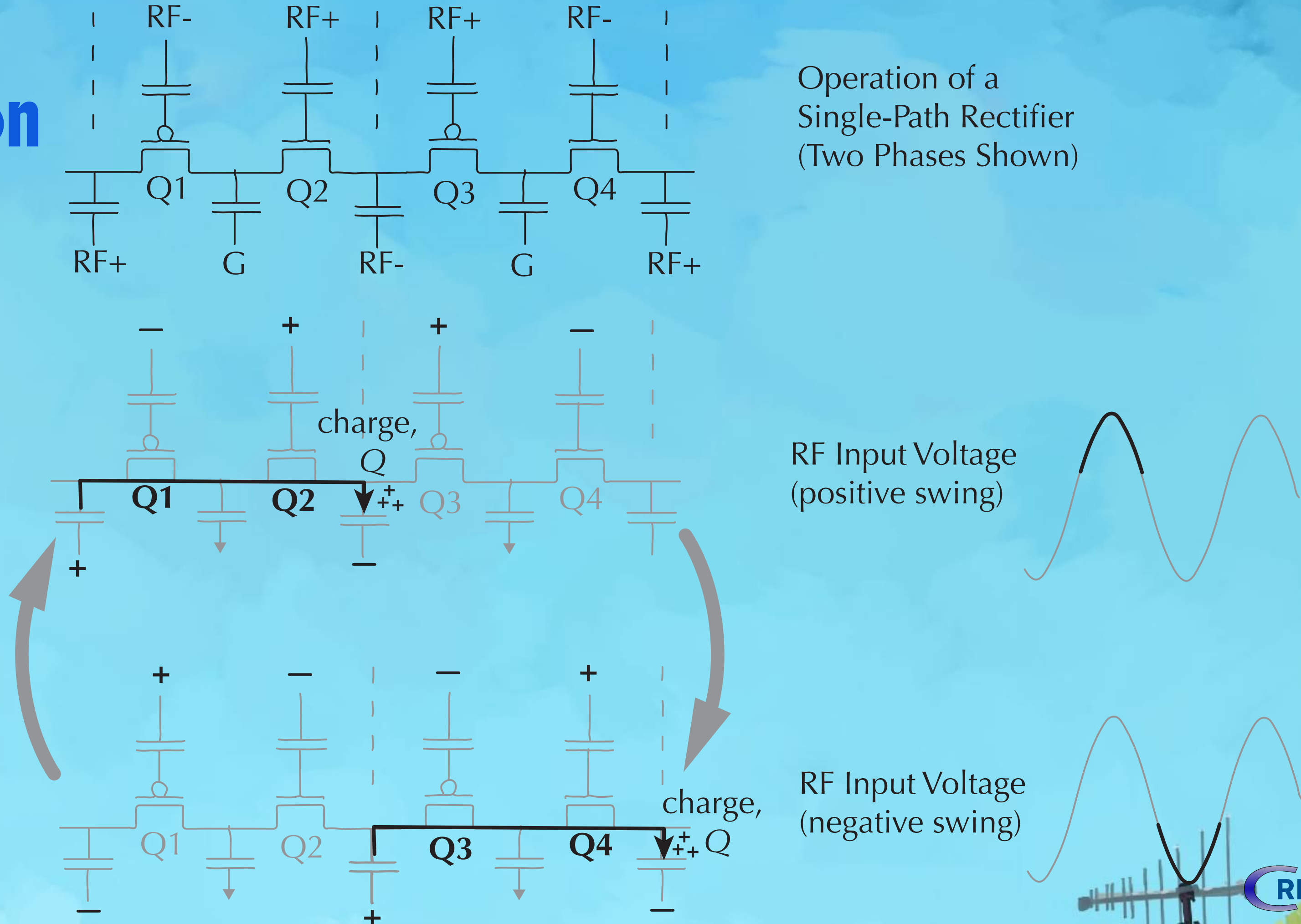
LICATIONS

RFID Air Interface-EPC Radio-

- Series Pair of 2-transistor, Repeatable Unit
- Draws Less Current from Antenna
- Does not self-bias

Ron Oliver
Impinj Fellow

Oliver Charge Pump Operation



Operation of a Single-Path Rectifier (Two Phases Shown)

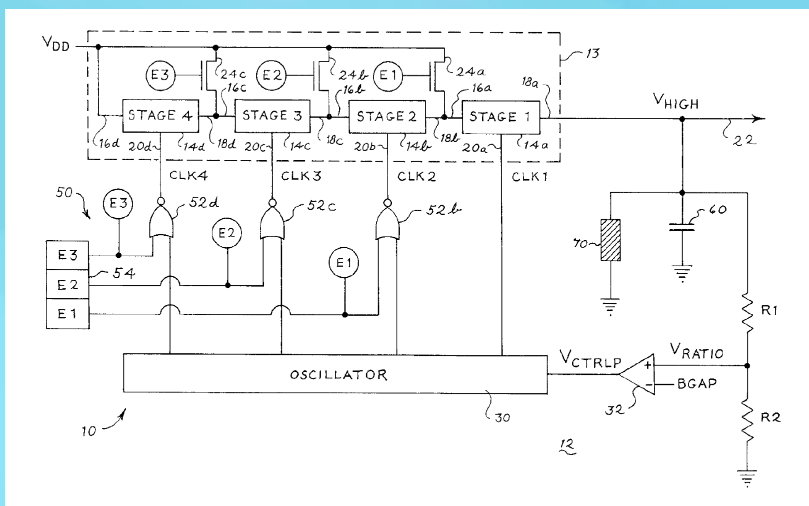
RF Input Voltage (positive swing)

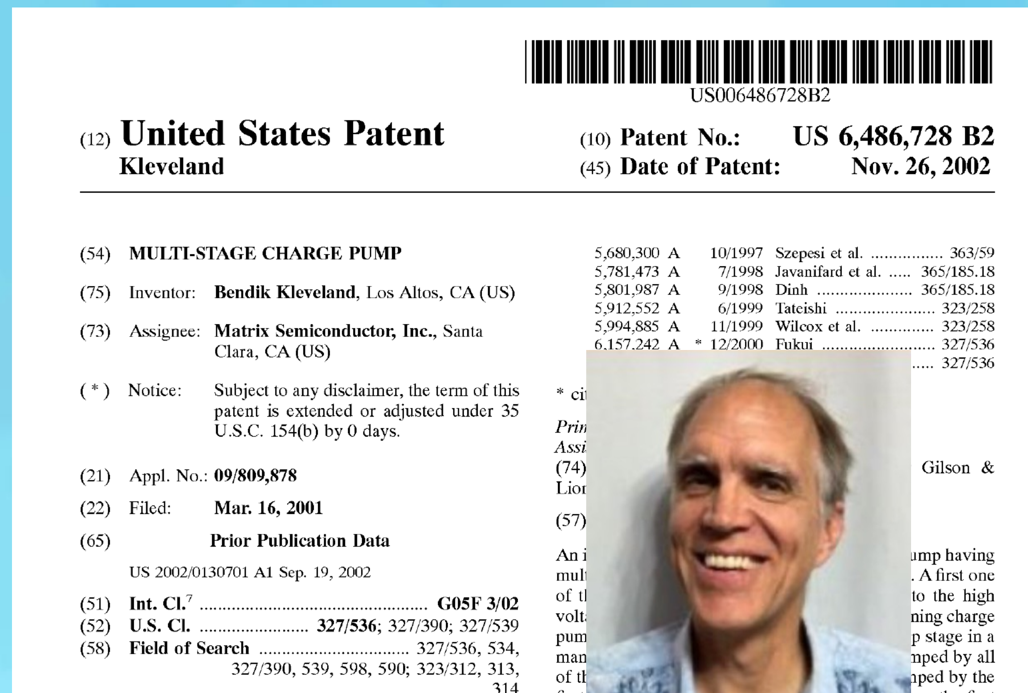
RF Input Voltage (negative swing)

Notes on CMOS Charge Pumps

- Mandal charge pump is simpler to design because it self-biases
- Oliver charge pump is less efficient per stage than Mandal – unless the gates are biased (then it becomes more efficient than Mandal)
- Historical bifurcation in the usage among different RFID types due to these CMOS pumps
  - Inductive RFID – Mandal charge pumps and variations since voltage level is rarely an issue
  - UHF RFID – Oliver charge pumps and variations due to range and voltage requirements

Boosting the Voltage





US006486728B2

(12) **United States Patent**
Kleveland

(10) **Patent No.:** **US 6,486,728 B2**
(45) **Date of Patent:** **Nov. 26, 2002**

(54) **MULTI-STAGE CHARGE PUMP**

(75) Inventor: **Bendik Kleveland**, Los Altos, CA (US)

(73) Assignee: **Matrix Semiconductor, Inc.**, Santa Clara, CA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **09/809,878**

(22) Filed: **Mar. 16, 2001**

(65) **Prior Publication Data**

US 2002/0130701 A1 Sep. 19, 2002

(51) **Int. Cl.**[7] **G05F 3/02**
(52) **U.S. Cl.** **327/536**; 327/390; 327/539
(58) **Field of Search** 327/536, 534, 327/390, 539, 598, 590; 323/312, 313, 314

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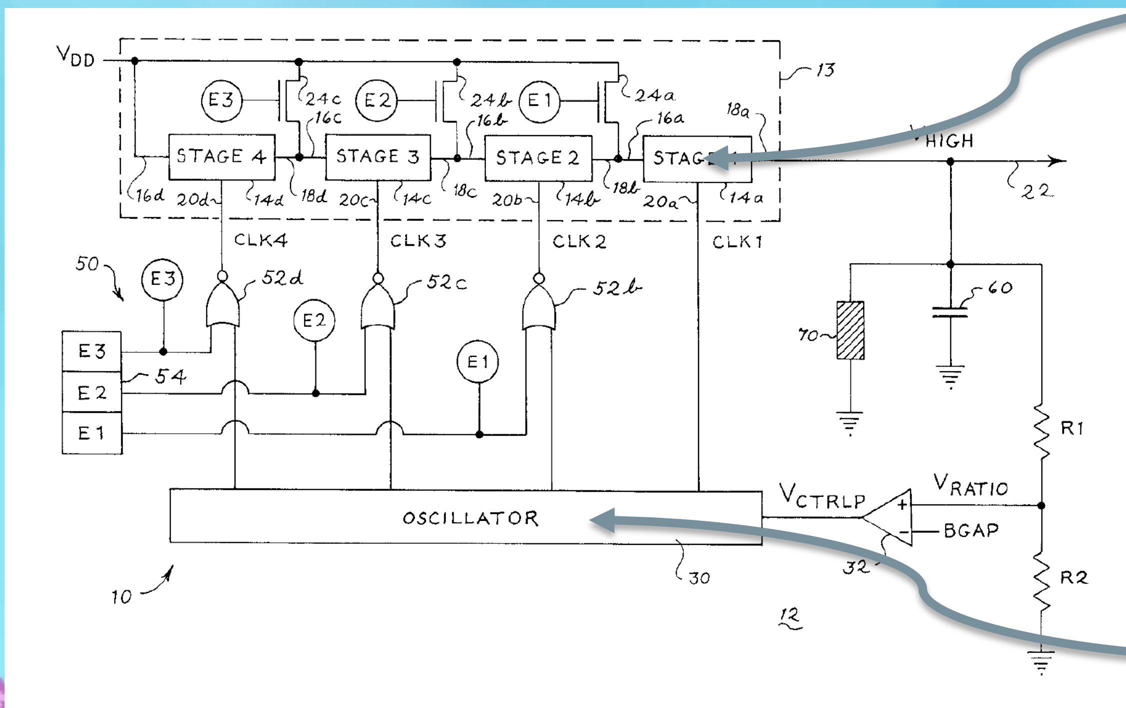
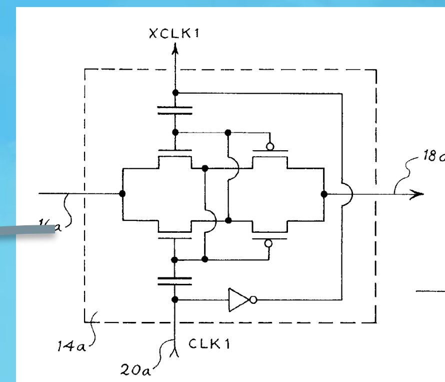
Bendik Kleveland
Matrix/Entrepreneur

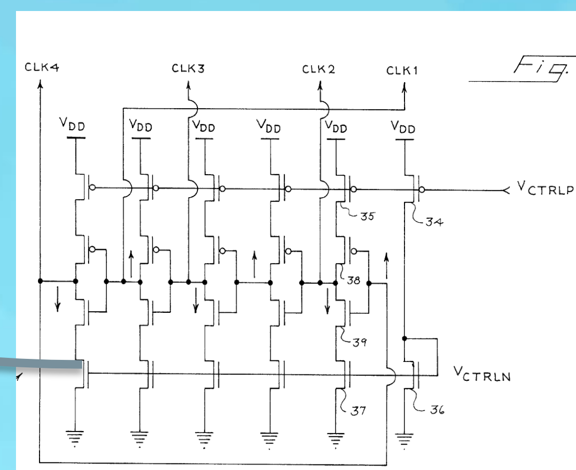
DC-to-DC Conversion



"Throttleable" Charge Pump



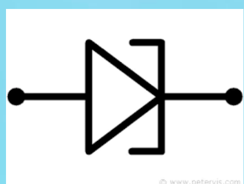
Mandal-like rectifier driven by digital clock instead of RF



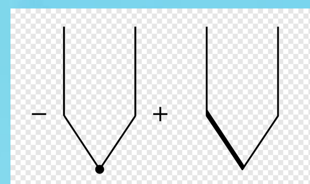
Ring Oscillator with control line

The Future

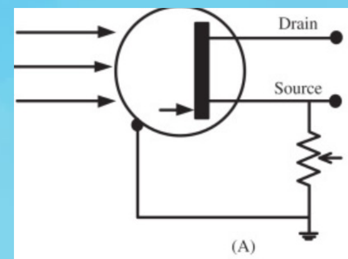
Exotic Devices



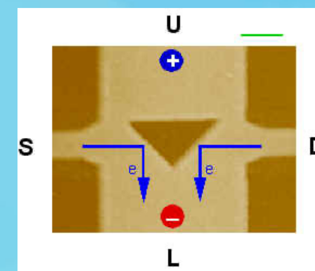
Tunnel diodes



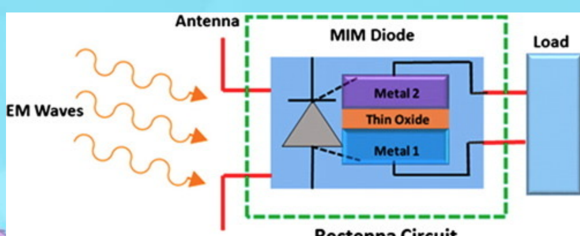
Thermoelectric conversion



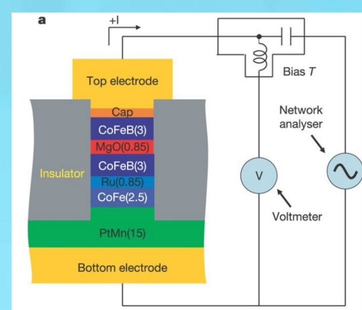
Pyroelectric conversion



Ballistic Diodes



MIM Diodes



Spin Diodes

A Bright Idea?

The Ending