Microwave Related Research and Applications

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June 27th, 2012

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Outline

- General Overview
- Introduction of Microwave History and Research
- Some Examples of Recent Development
- Summary
Sunny days per year: 360
Originally settled: 10,000 BC
Population: 750,000
Altitude: 2400’ - 9600’
Number of Golf Courses: 56
University Facts

Year founded: 1885 (Statehood: 1912)

Undergraduates: 28,442
Graduates students: 7,105
Engineering u-grads: 2,494

NSF Research Rank:
14th (among public)
21st overall

NSF identified less than ten universities providing quality electromagnetics instruction and research, in which the University of Arizona was one of them.

Engineering: $22,282,196
ECE: $ 8,188,862

First University-Led Mission to Mars

http://phoenix.lpl.arizona.edu/

OSIRIS-REx
ASTEROID SAMPLE RETURN MISSION
Microwave Applications
(300 MHz - 300 GHz)

Communications
Remote Sensing

5000-element phased array for Patriot Missile

Space based Radar

Auto Radar

Detect and track moving target globally
New Applications

- **Imaging**
  - See-thru clothes/wall medical
  - 3-D T-Ray Image of a Tooth

- **Microwave / millimeter wave imaging**
  - Through fog, smoke, and sand
  - Concealed weapon detection
  - Chemical / biological agent detection

- **Medical applications**
  - Detection
  - Treatment

- **Wireless power transmission**
  - Space applications
  - Alternative solar power?
Early History - Ancient Times

Thales of Miletus
- 600 BC, amber rubbing cloth

Aristotle
- 400 BC, force could not be communicated other than by some tangible means as pressure or impact

Lucretius of Magnesia
- 200 BC – 100 AD

Compass
- 200 BC – 100 AD
History - 16 to Early 19 Century

William Gilbert
De Magnete
Understanding of electricity

René Descartes
Vortex Magnetism
Understanding of magnetism

Carl Friedrich Gauss
Gauss Law / Magnetometer
First fundamental law - electric field
Propagation at finite velocity
19th Century

Michael Faraday  
Magnetic Induction

James Clerk Maxwell  
Maxwell Equations

Heinrich Hertz  
Electromagnetic Radiation

\[ \nabla \cdot E = \frac{\rho}{\varepsilon_0} \]
\[ \nabla \cdot B = 0 \]
\[ \nabla \times E = -\frac{\partial B}{\partial t} \]
\[ \nabla \times B = \mu_0 J + \mu_0 \varepsilon_0 \frac{\partial E}{\partial t} \]
Late 19th Century

Late 19th Century – 1901

Karl Ferdinand Braun

Guglielmo Marconi

Jagadish Chandra Bose

Contribution to wireless telegraphy

Reduced to 5mm; semiconductor junction for detection; ignited gun powder/rang a bell

Point-contact Semiconductor

Transatlantic Radio Transmission

Millimeter-wave Transceiver

Cathode Ray Tube
Early 20th Century

First—radio transmissions of voice and music

Lee De Forest
Reginald Fessenden
Edwin H. Armstrong

Audion
Heterodyne Receiver
FM Radio

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Some materials from IEEE IMS 60's anniversary celebration
Pre-WWII

Pre-World-War-II Period

Albert H. Taylor & Leo C. Young
Radar Effect (1922)

George C. Southworth
Waveguide Experiments (~1930)

Russel Varian, Sigurd Varian & William W. Hansen
Klystron (1937)

Harry Boot and John Randall
Magnetron (1940)
WWII - Radar

World War II – Radar
MIT Radiation Laboratory (1940-1945)

MIT Radiation Laboratory

Lab Buildings

N. Marcuvitz

J. Schwinger

R. H. Dicke

A. H. Compton

V. Rush

K. Compton

A. L. Compton

F. O. Lawrence

J. R. Conant

Rad Lab Series (28 volumes)
Transistor

1947: Invention of the Transistor

First (point contact) transistor

John Bardeen
Walter Brattain
William Shockley

10mm

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Some materials from IEEE IMS 60's anniversary celebration
1952: Breakthrough in Radio Astronomy

First detection of emissions from neutral galactic hydrogen (the famous 21 cm line due to hyperfine splitting)
In 1943, the Hungarian engineer Zoltán Bay sent ultra-short radio waves to the moon, which, reflected from there, worked as a radar, and could be used to measure distance, as well as to study the moon.

Perhaps the first use of the word microwave in an astronomical context occurred in 1946 in an article "Microwave Radiation from the Sun and Moon" by Robert Dicke and Robert Beringer. This same article also made a showing in the New York Times issued in 1951.
1959: Invention of the Integrated Circuit

Jack Kilby

Robert Noyce

7:41
Monolithic Microwave Integrated Circuits (MMICs)

Emergence of Monolithic Microwave Integrated Circuits (MMICs)

1968, first GaAs MMIC, Texas Instruments
94 GHz receiver

IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES
VOL. MTT-16, pp. 451-454, JULY 1968
GaAs Integrated Microwave Circuits
E.W. Mehal and R. W. Wacker

1977, Plessey
1-stage MMIC amplifier Using 0.8 μm gate FET

1979, TI
X-band GaAs MMIC push-pull amplifier

1979, Raytheon
1st MMIC power combiner & 1st MMIC with via holes

1979, NEC Corp.
1st MMIC LNA (20 GHz)
Advanced materials have created new possibilities

- **Semiconductor technologies**
  - GaAs, InP, GaN HEMTs

- **High-**$T_c$** superconductors**

- **Meta-material**
  - Electromagnetic bandgap structures
  - Negative index of refraction ($\varepsilon$, $\mu$) materials
  - New microwave components / design methodologies

- **Nanotechnology**
  - Material preparation & fabrication process enable much smaller devices than previously possible
  - New microwave applications ???
A Few of the Latest Developments

- Wireless communications
- GaN
- MEMS, RFIDs
- Millimeter-wave and THz technology
- Metamaterials
- RF nano science/technology
Group Information

- Rockwell Science Center (2000-2003): Antenna / MMIC design; Phased Arrays; Reconfigurable Circuits / Antennas; Electromagnetic Crystal Components; Human Motion Power Harvesting
- Raytheon (2003-2005): Phased Arrays; Power Amplifiers; DEW Systems; Nano-Devices / Materials
- University of Arizona (2005-present): 4 Post-Docs, 3-PhD, 2-MS; 8 PhD, 4-MS, undergrads
Our research focus on microwave / mmW / THz antennas, circuits and applications. Capabilities including: Complete Design / Simulation / Fabrication / Characterization.

Research Areas:

- Meta-material for Microwave Applications
- Novel THz Components
- Nano Devices and Antennas
- Power Harvesting Applications
- Biological Inspired Direction Finding
- Microwave Thermal Acoustic Imaging
- Microwave / THz & Micro-fluid (Lab-on-a-Chip)
- 3-D Integrated mmW Circuits and Antennas / MMIC
- Multi-Functional Microwave Components

http://ece.arizona.edu/~mwca/
What is Meta-Materials

Artificial composite materials that have special properties (electromagnetic here) that may or may not exist for natural materials

Electromagnetic / Photonic Crystal Band Gap Structure

Double Negative Materials
Left-Handed Materials
Negative Refractive Index*

Often due to inhomogenities embedded in host media
Periodic media or effective media description
Not limited to EM properties

Brief History

• Concept existed long time ago – resurrected recently *
  - In 1898, J. C. Bose: rotation of polarization plane by man made twisted structures
  - In 1914, K. F. Lindman: small wire helix
  - In 50 – 60’s, artificial dielectrics
  - Many periodic structures have been studied

• Left-handed media / Negative index of refraction
  - In 1968, Veselago considered $\varepsilon < 0, \mu < 0$ media
  - Poynting vector opposite of phase velocity, $n < 0$
  - In 2000, Smith et al demonstrated first example

• Electromagnetic crystal / band gap structures
  - In 1887, multi-layer film studied by Lord. Rayleigh
  - In 1987, Yablonovich & Johns independently suggested 2-D & 3-D band gaps

Permittivity and Permeability Space

Left-handed media:
a whole new class of metamaterials!!!
- “negative Doppler shift,
- “backwards” Cherenkov radiation
- novel optical properties
Many Applications with Designed $\varepsilon$, $\mu$

1. Perfect Lens

\[ n = -1 \]

2. Electrically Small Antennas

3. Cloaking

References:

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Zero Index Metamaterial

Snell’s Law: \( n_1 \sin \theta_1 = \sin \theta_1 = n_2 \sin \theta_2 \),
if \( n_2 = 0, \theta_1 = 0 \)

High gain monopole antenna demonstrated – a new design methodology developed

Metamaterial Research - Active Metamaterials

Metamaterial Issues:
1. High Loss
2. Narrow Bandwidth/High dispersion

• To compensate loss or even to provide gain
• Possibility to trade gain for bandwidth
• New physical phenomena and potential applications

First Demonstration of negative index of refraction with gain


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Microwave for Energy Applications

• Wireless power transmission
  – Solar power satellites
  – Space power generation / distribution
  – Aircraft / airborne station powering
  – Energy scavenging from environment
  – “Immortal” wireless sensors

• Fusion: Intense source of coherent, mm-wave (> 1MW cw) radiation to heat a fusion plasma and control its instabilities

Early History - Wireless Power Transmission

- **Heinrich Hertz**
  - Parabolic dishes for both transmitting and receiving (focused beam): more closer to modern practices

- **Nicola Tesla**
  - 1899, Colorado Springs;
  - Tesla coil for power transmission; no focusing
  - 300 KW input power; 150 KHz; $10^8$ V RF voltage

- **Westinghouse Experiment**
  - 1930’s,
  - 100 MHz dipoles; 25 ft apart; 100’s Watts

Point-to-point narrow beam necessary: large antenna at higher frequency; Lack of microwave sources

Modern History – Powering Aircrafts

- Microwave Powered Helicopters (Raytheon Company, 1960’s)
  - Enabled by availability of high power microwave tubes
  - 400 W, 3 GHz magnetron; 100W DC driving a fan (thermionic diode rectifier)
  - 270W DC power for helicopter demonstration (4480 semiconductor diodes)

- Airplane demonstration (Canada, 1987)
  - 2.45 GHz, 4.5m dish, 10KW transmitter;
  - 150W DC power, 70% efficiency, 150m altitude

- Airplane demonstration (Japan, 1992)
  - 2.41 GHz, 1.2m phased array, 1KW transmitter
  - 52% efficiency, 15m altitude

First proposed in 1968

**Concept**

- **Large solar panel in space**
  - Geostationary orbit: constant high illumination
- **Power transmission to earth via microwave high power transmitter**
  - Power conversion efficiency
  - Transmission loss
  - Size, weight, cost
- **Receiving stations on earth to convert to DC power**
  - RF-DC conversion efficiency

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Geostationary SPS Example

Sun Intensity: 0.14 W/cm²
Solar panel size: 9 mi²
Overall efficiency: 80%
System Weight: 100’s tons

2 x 10⁷ KW
U.S. 2004 level: 3.35 x 10⁹ KW
Full power of 3-Gorges Dam

Safety issue: Power density on earth in the order of 10’s – 100’s mW/cm²

- Most technologies are mature enough or close to be
- Several commercial and government initiatives

Power Harvesting - Wireless Transmission

Distributed wireless sensors are highly desirable for many applications. Power issue is key: Nobody is going to change batteries for them!

Rectenna on sensor nodes allow wireless charging

**Issues:**
- Compactness
- Efficiency (at low power: i.e., 1 mW)
- Energy storage

**Solutions:**
- Metamaterial inspired antenna ($\leq 0.1\lambda$)
- Antenna doubles as matching circuit
- Low turn-on voltage diode
- Direct charging of super-capacitor

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THz Background

Unallocated communication band

Higher bandwidth / data capacity / spatial resolution than microwave

Less scattering loss, non-ionizing radiation than optical / X-ray
THz Applications

- Coverage in IR and optical blind conditions
- Concealed object screening
- Biomedical imaging and semiconductor quality control
- Chemical and bio-agent sensing and detection

* D. Arnone et. al., *Physics World*, 0953-8585, April 2000
* Optics.org, analysis article, Oct. 28, 2002
Motivations

We need THz components
Source, detector, filter, waveguides, antenna, quasi-optics, materials…

We need integration of components
Solid-state devices, packaging, systematic fabrication…

We need universality and customizability
Plug-and-play, easy customization…

EMXT passives fabricated via rapid prototyping

Source \[\rightarrow\] EMXT Based THz Passives \[\leftrightarrow\] Detector \[\rightarrow\] Apps!
Microwave Thermal Acoustic Imaging and Spectroscopy (TAIS)

- **Microwave Contrast**
  - Benign vs. malignant tissues
- **Ultrasound Resolution**
  - < 1mm vs. cm
- **Promising application:** Breast cancer detection, etc.
- **Full EM + Acoustic model developed**
- **Experimental verification**
Encouraging initial experimental results (spectroscopy, much shorter pulse)
Full model for new spectroscopy information
Complete Antenna + Matching + Waveform + Power Design
Electromagnetic Crystal

- Periodic dielectric structures: often called photonic crystal (PXT)
- Forbid EM wave propagation – band gap
  - Periodicity $\sim \lambda_{\text{gap}}/2$
- Many components realized: waveguides, resonators, filters, multiplexers

Analogous to semiconductor band gap
Triangular-lattice array of air cylinders in a dielectric background
- Center core defect to form the wave tunnel
- Defect modes within the band gap of the complete EMXT
- 90% energy concentration in the core $\rightarrow$ low radiation and material losses
3-D Rapid Prototyping

- Objet (TM) polymer jetting prototyping
- Layer-by-layer printing of structures
- Printing resolution 42um (x) by 42um (y) by 16um (z)
- UV curable model material
  Support material removable by water flushing
- Possibility of mixing various printing materials to achieve arbitrary spatial material properties
- Rapid prototyping of arbitrary shapes
- Alignment and assembly not necessary
- Mass production achievable with very low cost
Prototype THz EMXT Structures

- Pre-measured model material properties
- Large enough refractive index contrast
- THz-TDS transmission characterization
- Excellent agreements with simulations

* Z. Wu et al., Opt. Express 21, 16442, 2008
Simulation: Gaussian / Waveport

- Identical coupling to free space at input and output interfaces
- Transmitted power exponentially decays as waveguide length increases (Neglect multiple-reflections)
- Calculated loss matches well with wave-port simulation
THz Characterization: THz-TDS

THz Time Domain Spectrometer

- Control Unit
- Dispersion Compensation
- Ultra-fast Laser
- THz Transmitter
- Collimating Optics
- THz Detector

- Photoconductive antenna THz-TDS
- Ultra-fast gating / Coherent Measurement
- Transmission / Reflection setup available
  Material with magnetic behavior → both setups needed

Experimental Testing Setup

- Fabricated THz waveguide samples (Glossy modes)
- Quasi-optics to focus the beam waist to 2.7mm
Power Loss Extraction

0.03 dB / mm Loss Factor Measured
Measurement / Simulation Agree Well (~ 7 GHz shift)
EMXT Horn Antenna

Circular waveguide TE11 feeding
Polymer loss: constant conductivity 0.459

4.2mm flared to 8mm aperture radii (12.4 degree)
35mm optimized horn length along axis
Simulated Antenna Radiation Patterns

Far-Field Radiation Pattern of Phi= 0° Cut (x-z plane)

- Directional beam at two working frequencies
- Comparison with copper horn
Far-Field Antenna Measurement

THz RAM

Far-Field Distance

TDS Transmitter

EMXT Horn

Automated Rotation Stage

TDS Receiver

THz RAM
Measured Radiation Patterns

103 GHz

125 GHz

150 GHz

170 GHz

Good Radiation Patterns Demonstrated
Good Agreement Between Measurement and Simulation
Conclusion

Microwave to THz Spectrum

• Very Exciting Research Fields
  - New Materials – Nano-scale; EMXT; Metamaterials
  - New Spectrum
  - Better Components – Antennas, waveguides, Better systems

• Extensive Applications in Microwave to THz

  Communication / Sensing
  Bio-medical / High-speed Electronics
  Power / Energy
  Astronomy
  MORE ???

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Biological Inspired RF Direction Finding

- Human ears are great at DF
  - Great accuracy using two ears
  - Even with just a single ear
  - "Cocktail Party" effect
  - Environment learning, etc.

Can we learn from human ears?

Head-Like Scatter with 2-monopole antennas

UWB Antennas - Single Ear