Antennas & RF Sensors: Changing the Way We Live
(from mobile telephony to electronic textiles and RFIDs)

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Why so much interest in Antennas and RF Devices?

- Miniaturization need for sensors and mobile systems
- More than 50% of a system-on-a-chip consists of passive RF devices
- Conformal antennas for commercial and military applications
- Compact communication systems with higher data rates
- Multifunctionality to decrease complexity & cost

- RF & Microwave Magazine 2006
- IEEE Spectrum
(CNN) -- It's not Silicon Valley, but Chaska, Minnesota, may be moving to the leading edge of Wi-Fi technology as it begins offering the service for all city residents.

One of only a handful of cities in the nation to try it, Chaska -- just southwest of Minneapolis -- plans to have most of the city's 15 square miles Wi-Fi operational by the end of October.

The city of Chaska, Minnesota, aims to provide Wi-Fi access all over town.
Wireless Implanted Devices

Implantable

Wearable

- Cochlear implant
- Eye implant
- Shoulder implant
- Heart implant
- External force actuators
- External trigger mechanisms
- Pump for bioother liquids in the body
- Artificial lung/air pump
- Artificial bladder
- System to close/open bladder
- External control system nerve motion detector
- Nerve simulator
- Dropped foot implant
Enabling RF Technology for Daily Life Convenience
60 trillion wireless sensor till 2010-12, viz. 10,000 for every person in the world

Wearable Antennas and Sensors are being developed with conductive textiles to:
- Monitor Health (blood pressure, fluid levels etc.)
- Position Detection
- Decrease Weight and Complexity of Existing Wireless Devices

System design to communicate various RF components to each other

Engineered Substrates for:
Miniaturization,
Multifunctionality & Greater Bandwidth

Challenges:
- Convenient way of Substrate Patterning & Printing (Metamaterials) is not yet realizable
- Integration of RF circuits is not realistic in existing technology (only in low constant materials)

Health Monitoring Challenges:
- Tissue Characterization
- Understand effect of RF signals on human body
- EM Compatibility with biological structure

Incorporate various RF technology (Bluetooth, GPS, Health Monitoring) into existing devices
- Small RF devices
- High gain antennas for far distance communication (GPS)

From syringe
Coated matrix template
Repeat printing process on top of solid sheets
Sensor Systems/System on a Chip Overview

**Purpose:** Detect chemical agents and vapor mixed in the air at low levels.

**Deployment:** Sensor can be placed in the air-ducts of air conditioning systems.

**Size:** 2-3cm per side. Fairly flat

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Sources: Prismark
RFID Everywhere

Aviation
- Electronic Toll Collection
- Access Control
- Animal Tracking
- Inventory Control
- Tracking Runners in Races!
- Anti-Theft

Automobile industry

Pharmaceuticals

ID Cards

2000 RFID points
Ohio State’s RFID Bug Tracking Radar Goes Up to 190ft (63m)

1. 5.9 GHz CW signal transmitted
2. Signal intercepted by tag (up to 200’ away), harmonic re-radiated
3. 11.8 GHz signal received, down-converted
4. IF Signal: Indicates presence of tag

Transmit/Mixing Circuits

Proposed Array:
- Xmit ~ 14” x 7”
- Rec ~ 7” x 3.5”
- Gain ~ 20 dBi

Meandered Loop Tag
- Tag measures 9.5 mm x 9.5 mm.
- 9.5 mm ~ 0.19λ at 5.91 GHz (Xmit freq.)

RF Front End

• Xmit: 5.9 GHz
• Rec: 11.8 GHz

- Gain ~ 20 dBi

- Meandered Loop Tag
Polyphase Multi-band Predistortion Linearization to Suppress Intermodulation Interference

Before

After
RFID Reader System Remains a Challenge

- RFID readers and tagging promise to revolutionize retail, supermarket and warehouse shelving systems, including purchasing process and habits.

Fading is a major issue. Spatial and polarization diversity of the distributed antennas overcome fading in both static and dynamic environments.
For a typical container 10’x10’x40’ with tightly stacked cartons, we need to use 8 distributed antennas to illuminate entire container. Folded tags are also needed to get good performance.

We place 2 antennas to cover a 10’x10’x10’ volume of the container. For the entire container, we need 8 distributed antennas.
Real Time THz Imaging of Excised Tissue

TARGET APPLICATION: Breast Cancer Detection

- 1 in 8 women will have breast cancer in their lifetime
- 96% curable if caught early

American Cancer Society, Inc, Surveillance Research

Current Breast Cancer Detection Issues:
- X-rays not of sufficient resolution/information; also not desirable due to inherent ionization.
- 80% of biopsies unnecessary
- Excised tissue imaging is desirable during operation but very slow

THz Imaging System Overview

Working Principles

Direct detection of THz radiation using diodes having superior noise performance

- Build compact detector layouts suitable for 2D arrays
- Explore/optimize array topologies for maximum number of detectors (equivalently pixels), power transfer and detection performance
- Investigate suitable imaging algorithms to be incorporated into the imager signal back-end
- Frequencies: 100GHz, 500GHz, 800GHz
Body Worn Antenna Coverage with Diversity Module

20dB – 30dB fluctuation reduces to 3dB – 4dB

Normalized received power [dBm]

Azimuth angle [deg]
**Miniature Antennas and Arrays for THz Imaging**

**Multiband Antennas:**
- Detection at multiple frequencies
- Smaller size antennas to avoid aberrations

**Antennas with controlled radiation patterns**
- More antenna elements (pixels)

**Photonic Crystals & Metamaterials**
- High gain apertures and miniature arrays
- Negative refraction for sub-wavelength focusing

Dual band folded slot antenna for 500 & 800GHz breast cancer detection

Imaging arrays with multiple detector (antenna array) layouts for pattern diversity

Metamaterial miniature antennas for small pixel size

Much smaller metamaterial-based multiple antennas for pattern control
Continually Evolving
802.15.3a
UWB
802.11n
802.16 WiMax
Canopy
802.15.3
802.11a/g
802.11b WiFi
802.15.1 Bluetooth
GPRS/EDGE
ZigBee
802.15.4 GSM/EDGE
Blackberry

Range (meters)
10000
1000
100
10
1
1000
5000
10000
500
100
10
1

Transmission rate (Mbps)
500
50
10
5
1
0.5
0.1

Data Rate (bits/sec)
Fixed
Mobile/Nomadic

Multi-mode Multi-band Radios
RF Freq./BW

Wireless Landscape
Applications

- Multifunctional Radios
- Software Radios/Radars
- Short Range Giga-bit Comm. & Data transfer
- UWB imaging from MHz to THz.
- Sensing and monitoring
- Identification
- Body worn systems
- THz imaging

Solution Trends

- Materials
  - Magnetics films/Multiferroics
- Composites (polymers, mixed material systems, multi-layered, emulated anisotropy)
- High speed interconnects
- Structurally reinforced smart skins (carbon nanotubes, ceramics)
Military Challenges

- OSD report (Appendix C, p.9): Over the long term 2012-2030, JTRS, including wideband networking waveforms (WNM), will provide a fully integrated information system network to include active and passive information operation management across the joint and combined environment. The system will also include a self-establishing and self-healing smart network, which will automatically manage the RF domain.

- WNM will operate from 225-400MHz, and is intended to enhance or replace current systems such as the Single Channel Ground and Airborne Radio System (SINGARS, 30-88MHz), EPLRS (450-470 MHz), and Link 16.

- Given that typical wavelength size antennas are $\lambda/2$ long/wide (5m or ~15ft at 30MHz), they must not only be structurally embedded, but also much smaller (miniature) than currently available to accommodate future real estate.
Future Smaller Aircraft Needs

**Challenges**

- Small size UAVs and RF congestion (communications, imaging and information gathering on small platforms)
  - **high speed communications:** from 15kb/sec to 5Mbits/sec, 3000 times higher speeds
  - 30-5000MHz ultrawide band antennas (with wavelength 5m or 15ft) must be reduced in size by a factor of ~5-10 and integrated on small platforms with gains for high data rates
  - High gain/narrow-band antennas for radar, imaging, guidance, satellite communication, and other specific applications
    - ---current Global Hawk SatCom antenna is still a (rotating) reflectors,
    - ---future apertures must be conformal and suitable even for small UAVs
- Entire UAV surface may serve as a RF (smart) skin, implying structural integrity of the RF functional layers
- **Volumetric exploitation** to address low frequency performance is a major design and computational challenge.
- Multiphysics tools must address concurrent structural/fatigue and RF performance requirement; need for multiphysics design optimization tools
- UAV sections may be removable and re-bonded for multiple missions
Traditional antennas will be a thing of the past!!

Artificial or Real Materials?
Antenna Miniaturization Approaches

Increase Antenna Electrical Size

Slow down currents flowing on antenna, using inductive and capacitive loading:

\[ u_g = \frac{1}{\sqrt{L_{\text{eff}}C_{\text{eff}}}} \]

\[ Z = \frac{\sqrt{L_{\text{eff}}}}{\sqrt{C_{\text{eff}}}} \]

Load antenna near fields with material \( \varepsilon_r, \mu_r \):

\[ \nabla^2 \vec{E} + \omega^2 \mu_{\text{eff}} \varepsilon_{\text{eff}} \vec{E} = 0 \]

\[ Z = \frac{\mu_{\text{eff}}}{\sqrt{\varepsilon_{\text{eff}}}} \]

Increase Radiation, Bandwidth and Efficiency Compared to un-miniaturized Antennas

Artificial Transmission Line (ATL)

Material Loading
Matching Networks Significantly Improves Low Frequency Performance

Possible matching Circuit from Optimization

Single-Stage Complex Matching

Infinite-Stage Complex Matching

Final Operating Frequency can go down to 175MHz
Interdigital capacitive loads; As the frequency increases, capacitance increases to cancel inductive load caused by the ground plane. This results in nearly purely resistive impedance, giving rise to the large bandwidth.
2-18GHz Performance

- **Frequency Band**: 2-18 GHz
- **Polarization**: Dual Linear
- **Overall Size**: 22”x22”
- **Total Elements**: 2664 Dual Pol
- **Active Elements**: 64 Dual Pol
- **Aperture Thickness**: 0.8”

- **8x8 Active Array Broadside Gain**

Gain (dBi)

- CSA11 Measured
- Theoretical 8X8 Unit Cell Gain

0.4 W/element
Enabling Miniaturization of Broadband Apertures

Munk’s/Harris Corp. Current Sheet Aperture (CSA)...

Just another way of capacitive coupling
Matching with Negative Elements

- Antenna final size: $\lambda/12 \times \lambda/18$
- 3.5:1 bandwidth
- No use of any material loading

Realized Gain before…

**240 to 1050 MHz (4.5:1)**

Keep (almost) the same bandwidth

Decrease the antenna size by 3

**82 to 275 MHz (3.5:1)**

After…

**Values from optimization**

**Reactance**

- Input

- Antenna

- $-1.45\text{pF}$
- $-256\text{nH}$
- $0\text{pF}$
- $-77\text{pH}$
- $-128\text{pF}$
- $-18.5\mu\text{H}$

- 25
...... benefits for magnetic materials are there

![Graph showing realized total gain (dB) vs. frequency (MHz) for different configurations of M3 ferrite cylindrical cavity. The graph compares free standing, over infinite ground plane, and infinite ground plane with varying dimensions (w1, w2, h1)].

- Free standing
- Over infinite ground plane, h1 = 3''
- Infinite ground plane, w1=3'', w2=4'', h1 = 3''
- Infinite ground plane, w1=1'', w2=1'', h1 = 3''
- Infinite ground plane, w1=1'', w2=1'', h1 = 4''
- Infinite ground plane, w1=1'', w2=1'', h1 = 5''
Limitation of current magnetic materials & losses

• Existing materials turn out to be "very" lossy at UHF frequencies, for antenna applications.

• Losses cancel out the miniaturization obtained by the ferrites.

• Material losses need to be lower than 0.005 in order for the ferrite loading to be beneficial.

Material specifications (<500 MHz)
- losses < 0.005
- \( \varepsilon_r = \mu_r \) (impedance matching)
- \( \varepsilon_r, \mu_r \) values: 8 - 14

Material losses cause gain reduction

Gain reduction appears as shifting up in frequency

\( \tan\delta \) must be < 0.005

\( f_o : -15 \text{dB frequency, lossless} \)

\( f : -15 \text{dB frequency, losses} \)
Antenna Miniaturization Techniques

1. Slow down current flow by material loading
   - Homogeneous material (broadband)
   - Inhomogeneous, anisotropic material (narrowband)
   - Magnetic Material (narrowband, bias required)

2. Control current phase velocity by controlling L and C of equivalent transmission line model

\[ k = \frac{v_g}{c} = \frac{\partial k}{\partial \beta} \]

\[ v_p = \frac{k}{\beta} \]

\[ Z_c = \sqrt{\frac{L_{eff}}{C_{eff}}} \quad v_p = \frac{1}{\sqrt{L_{eff} C_{eff}}} \]

Eploiting 3D Anisotropy...

• 3D anisotropy modifies the k-ω diagram of the material medium

• Concurrent slow wave velocity & impedance matching lead to small RF devices with high sensitivity and high gain vs bandwidth.

\[
\frac{v_s}{c} = \frac{\partial k}{\partial \beta} \\
\frac{v_p}{c} = \frac{k}{\beta}
\]

Material DNA

Flat sections, imply slow velocity

• math concepts to RF designs and actual antenna realizations

- RBE mode
- Frozen Modes
- DBE mode
- MPC mode

12dB vs. 1.7dB

1.7dB vs. 1.7dB

100% aperture efficiency
Realization and Demonstration of Degenerate BandEdge (DBE) Mode in a Periodic Assembly

Field profile for reception

New FEM Domain Decomposition Tools required (for 16M DOFs):
---1.4GB vs 30GB
---CPU: 2.5 hrs

Feeding Schemes: Slot on ground plane, dipole in $B_1$ layers
Easier to implement, external feed/matching

Directivity: 10.15dB, over 100% aperture efficiency
Performance of the Degenerate BandEdge -DRA Antenna

![Graph showing Gain x Bandwidth vs. ka for DRA Region and Leaky Wave Region](image)

- **DRA Region**: Optimal Curve
- **Leaky Wave Region**: Points representing different configurations

**Key Points**:
- Hybrid DBE Mode DRA Antenna
- DBE Antenna Prototype

Parameters:
- $\lambda_o/8.12$
- $\lambda_o/18$
- $45^\circ$
Emulation of Anisotropy using Standard Printed Lines

DBE Structure – 1D volumetric crystals

Emulating Anisotropy with Coupled Lines

\[
\begin{pmatrix}
45 & 0 & 0 \\
0 & 17.78 & 0 \\
0 & 0 & 45
\end{pmatrix}
\]

DBE Modes can be achieved by tuning strip lengths/widths

→ Printed Lines (Std. Fabrication Technology)
  • Small antennas employing DBE resonance for impedance matching
  • Miniature Printed Arrays
  • Small Couplers, Delay lines and Phase Shifters

Possible Applications:

Coupled lines (even mode odd mode impedances) emulate rotation of anisotropic ε tensor (phase shift difference between two lines)
Printed Lines with Lumped Elements allow for much Greater Control of the Dispersion Diagram and Propagation Properties

- Flatter $\rightarrow$ higher Q/gain (slow velocity)
- Inflection point $\rightarrow$ high Q, greater bandwidth (slow velocity, excellent matching at dielectric interface – zero acceleration)
- $kd = 0 \rightarrow$ lower frequency resonance (small size)
- $kd = \pi \rightarrow$ standard DBE/resonance

**Realization:**

4-port circuit model

**Engineered Crystals to Control $k-\omega$ diagram**
Equivalent Circuit Realization of the DBE Antenna
(TL pair with Controlled Coupling, Patent Disclosure)

Capacitively Loaded TLs: Coupling Capacitor tunes DBE

L1 = L2 = L3 = 1nH,
C1 = 10pF, C2 = C3 = 1pF

K – Bloch Wave Number

Frequency (GHz)

0 0.5 1 1.5 2 2.5 3 3.5 4 4.5 5 5.5 6 6.5 7 7.5 8
π/4 π/2 3π/4 π 5π/4 3π/2 7π/4 2π

CM = 0.5pF
CM = 1.5pF
CM = 2.5pF
CM = 2.5pF (DBE)

DBE design Guidelines:
- Unit cells with capacitively loaded TLs (C > L) are tuned to DBE via coupling capacitor (CM).
- Inductively loaded (thin) TLs (L < C) are tuned to DBE through inductive coupling (LM).
- Pros & Cons of CM tuning: CM can be easily realized with chip capacitors. However (C > L) TLs are very thick on low contrast substrates.
- Pros & Cons of LM tuning: Thin TLs have L > C. But, realizing LM on printed circuits is challenging (needs transformers)
- Combination of thick and thin TLs for miniaturization & CM tuning.
Choose Circuit Layout Suitable for Circular Cascading

Microstrip and Lumped Element Realization via Full Wave Simulators

Substrate: Duroid, \( \varepsilon = 2.2 \tan \delta = 0.0009 \)
2 inch x 2inch x 0.125inch (5.08 cm x 5.08 x 0.3175cm) Same with Ground Plane

Frequency (GHz) vs. K – Bloch Wave Number
Optimal Antenna Size Using DBE Mode
Printed on High $\varepsilon_r$ Substrate

The antenna has dimensions of $\lambda_0/9.6 \times \lambda_0/9.3 \times \lambda_0/16$ at 1.445 GHz.

This design seems to be the smallest antenna anywhere for the given gain and bandwidth.

Realization of these elements on devices with self-scanning capabilities should provide for satellite to handheld communication.
DBE Antenna with Lumped Capacitor Loading

**Antenna Layout**

Capacitively coupled coax

**Electric field at DBE Resonance**

**Measured Gain**

0.4%BW
2dB Realized Gain

Explore 20% shift in resonance frequency for reconfiguration (time varying DBE antenna)

**Radiation efficiency is 35% due to the lossy lumped elements**

6.9dB Broadside Directivity
Thicker substrate increases the bandwidth:
125mil = 0.25% BW vs. 275mil 1.5%BW
Varactor Loaded Tunable Antennas

Antenna Design

Varactors (cm)

RF input
Control ground (18nH)

Antenna Footprint (on $\varepsilon_r=2.2$ substrate):
2" × 2" × 0.25"

$\lambda_o/4.0 \times \lambda_o/4.0 \times \lambda_o/31$ @ 1.490GHz (cm = 0.0pF)
$\lambda_o/4.3 \times \lambda_o/4.3 \times \lambda_o/35$ @ 1.366GHz (cm = 0.5pF)
$\lambda_o/4.8 \times \lambda_o/4.8 \times \lambda_o/39$ @ 1.218GHz (cm = 1.0pF)
$\lambda_o/5.4 \times \lambda_o/5.4 \times \lambda_o/43$ @ 1.087GHz (cm = 1.5pF)

Experimental verification
Skyworks smv-1405 varactors:
2.67pF (0V bias) - 0.63pF (30V bias)

Tunable from 1.12GHz to 1.31GHz

Improving antenna performance:
1) Varactors tunable from 0pF to 2pF (1GHz – 1.5GHz)
2) Low loss varactors
3) Smaller capacitances for higher frequencies
Higher order K-ω Diagram Using Multiple Transmission Lines

Effect of Tree-way Coupling (CM3 nonzero)
- Lower order K-ω branch can display a 6th order behavior.
- Symmetric stationary inflection points (similar to SIP in MPCs)

• Symmetric Stationary Inflection Points in the Propagation Spectrum
• Achieved without resorting to lossy ferromagnetic layers!
Magnetic Substrates and Realization of Magnetic Photonic Crystal Modes

DBE vs. MPC Antenna Performance

Observed Field along the DBE Microstrip Coupled Lines Indicating Field Amplification

2 Unit cell Circular DBE Antenna Prototype
Tuning Non-Reciprocal $K-\omega$ Diagrams.

- Ferrite substrate **only** under the coupled sections.

**Provides Several Advantages:**
- Ferrite losses kept to a minimum (only small ferrite substrate sections)
- High epsilon ($\varepsilon_r \approx 15$) ferrite ($\mu_r > 1$) adds to miniaturization
- Radiation mechanism similar to patch antennas (fringing fields on dielectric substrate)
- Ferrite inclusion allows for design flexibility for matching and tunability

- Standard bandwidth increase techniques can be incorporated
Specific Design with Magnetic Inserts

- Substrate: Rogers Duroid $\varepsilon_r = 2.2$, $\tan\delta = 0.0009$
- Ferrite inclusions: Calcium Vanadium-doped Garnet (CVG) ($4\pi M_s = 1000G$, $\Delta H = 6Oe$).

- Novel MPC concept improves beneficial properties of DBE antennas:
  - Close to optimal gain and bandwidth
  - Broadside radiation pattern (suitable for phased arrays)
  - Smaller footprints (suitable for tightly packed arrays)

- 21% footprint reduction with MPC Design (over DBE antenna)
- 12%-14% Bandwidth Improvement
  - For the thin substrate (d=100mil), 12% improvement
  - For the thick substrate (d=400mil), 14% improvement
Substrate Thickness Effect

MPC, $d = 100\text{mil}$
- FBW = 0.7635\%
- Gain = 6.2845dB

MPC, $d = 200\text{mil}$
- FBW = 2.2302\%
- Gain = 6.5290dB

MPC, $d = 300\text{mil}$
- FBW = 3.8922\%
- Gain = 6.4109dB

MPC, $d = 400\text{mil}$
- FBW = 5.7554\%
- Gain = 6.3185dB

DBE-2, $d = 400\text{mil}$
- FBW = 5.0314\%
- Gain = 6.7626dB
MPC Antenna with Unbiased Ferrite Blocks

Reflection

Realized Gain

\[ \sim 330 \text{ MHz shift} \]

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>Reflected Power (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.467</td>
<td>-5.19</td>
</tr>
<tr>
<td>2.799</td>
<td>-6.23</td>
</tr>
<tr>
<td>3.465</td>
<td>6.23</td>
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<tr>
<td>3.794</td>
<td>5.19</td>
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\[ \text{Unbiased Ferrites (H\&S Simulation)} \]

\[ \text{Unbiased Ferrites (Measurement)} \]
Realized Gain with Biasing

- 5.76 dB
- 1.55 dB
- -0.03 dB

MPC resonance at 2.35 GHz

Linearly polarized Broadside radiation
Performance Comparisons

MPC

DBE

Patch

All antennas are on 2”x2” finite ground planes.
G/Q Footprint Comparison

- DBE 4” x 4”
- PATCH 1.8” x 1.8”
- ε_r = 2.2
- DBE 2” x 2”
- MPC 2” x 2”
- ε_r = 9.6
- DBE 2” x 2”
- OSU-ESL double loop
  Max. radius 6cm
- Iizuka-Hall Printed Antenna
  10cm x 1cm (no GP)
- Iizuka-Hall Wire Antenna
  10cm x 1cm (no GP)
Future Radios will Likely be on Hybrid Substrates

Radio Receiver

Amps, phase shifters in CMOS

Feed network on polymer

Antenna on polymer

Interconnects between Silicon and Polymer

Protective polymer layer

<1 mm
High speed data lanes overlaid on top of standard FR4 board targeting.

A SERDES I/O signaling over a backplane utilizing OTT interconnects

**Issue:** Limiting Speed due to Interconnects

**chip-to-chip link**

**multi-chip bus connection.**
Printing on Polymers is Challenging

- Printing on smooth PDMS surface (no surface modifications)
- Printing on microtextured PDMS (only evaporation)
- Printing on microtextured PDMS (evaporation and electroplating)
- Printing on microtextured and surface modified composite surface

Cracks formed on metal surface
Peeling from PDMS surface
Transfer Molding/Lift-off and Electroplating

**Transfer Molding**

- Plastic negative mask on PDMS mold
- Thin copper seed layer (~1 um)

**Lift-off negative mask in acetone**

**Electroplating**

- Negative pattern mask
- Copper electrode (Anode)
- Thin copper seed layer (cathode)
- Polymer composite substrate

**Reference electrode**

- Flexible, thick conduction lines on composite

**Reactive Ion Etching**

**Stamp Mold**

- PDMS-Ceramic Composite

**Evaporated thin seed layer (cathode)**

**Cu^2+ sulfate-sulfuric acid solution**

**M+**

**M+**

**M+**

**Evaporated thin seed layer (cathode)**

**Polymer composite substrate**

**Evaporated thin seed layer (cathode)**

**Polymer composite substrate**
Flexible Microstrip Line Via Electrodeposition

Conducting loss: \( \frac{0.1 \text{dB}}{74 \text{mm}} \cdot 1000 \text{mm} = 1.35 \text{dB/m} \) @ 1 GHz

High flexibility and high conductivity
Carbon Nanotube Printing on Polymer-Ceramic Composites

Carbon Nanotube/Silver coated textiles for integration into polymer-ceramic composites.

Key features:
• Mechanically very flexible & strong
• Strong adhesion with polymer-ceramic composites
• Scalable production process
• Comparable performance compared to traditional antennas

• Developed E-textile patch gain was within 90% of the ideal PEC patch gain)--- Measured gain was 6dB at 2GHz (viz.
Direct CNT Printing on Polymer

Step 1: Grow Aligned CNTs on a Glass Substrate

Key Critical Parameters:
- CNT Length
- CNT Density
- CNT Vertical Uniformity

Step 2: Spin Coating with Polymer Solution

Key Critical Parameters:
- Spin Coating Rate
- Polymer type (higher shrinkage rate when cured)

Step 3: Transfer to Larger Polymer Substrate
Step 1: Growing Aligned CNTs

This process involves using a quartz tube.

1. Prepare the platform for the CNT (Si, SiO2 or Quartz)
   Si, SiO2, Quartz etc.

2. Deposit Catalyst (Fe)-Optional

3. Grow Nanotubes inside Quartz Tube
   Quartz Tube Furnace 79400 (1000 °F)

Key Observations:

- Length of CNTs are very critical to achieving high conductivity.
  We have found out that CNTs with about 100um length has the best conductivity characteristics.

- Density of CNTs are very critical to higher conductivity
  We found that the grow-process is very vital to achieving denser aligned nanotubes. We developed our own process to achieve the best performance.

- Uniformity of CNTs in vertical direction
  We found out that CNTs tend to pull each other at the tips. Therefore, they have higher contact area. This leads to higher conductivity. In other words, we are using aligned CNT process to achieve non-aligned tips for higher contact area.
Step 2: Spin Coating With Polymer

Take off the silicon wafer by Hydrofluoric (HF) acid
Or peel it off

(Before Curing: Resistance is R0)

(After Curing: Resistance is R0/2)

Key Observations:

- Curing leads to shrinkage in polymer, which in turn improves conductivity.

- Higher shrinkage ratio is critical to achieving higher conductivity. For PDMS, it has about 2% shrinkage. For instance rubber has 4% which leads to 100% improvement in conductivity.
Step 3: Transfer to Larger Polymer Substrate
Carbon Nanotube Printing on Polymers for Layered Packaged Electronics?

- Over 6 dB Gain

![Graph showing frequency vs. gain with overlaid text: Within 1dB of the Perfectly Conducting Patch.](image)

![Diagram of layered packaging with labels: antenna layer, feeding layer, circuits layer, microstrip patches, dipoles, bowties, feeding networks, impedance tuning stubs, filters, mixers, LNAs, etc.](image)
Packaging Trends – A Bigger Challenge?

• Low Cost IC’s Still Need Viable Packaging
• Likely bigger challenge than the chipset for MMW/THz
• Commercial Packaging extends to MMW frequencies
  – DC to 50+ GHz
  – Progress continues up in frequency
• Plastic Packages in use to ~30 GHz
Multi-physics, multi-domain co-simulation of system-in-package (SiP)

Working with Prof. Jin-Fa Lee

Co-Simulation Multi-Domain
- **Spice-like CKT Domain**

  - Full Wave Analyses
    - Linear: Freq. Domain
    - Coupled thru EM Trans. Cond.
    - Nonlinear: Time Domain

  $S$ matrices or generalized transfer functions
  Possibly take into account nonlinear effects of conductivity

- **Thermal Analysis**

Layout to EM simulation
Full wave frequency domain analysis
EM-Spice co-simulation results
Many Thanks to my Students & Collaborators at ElectroScience

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