Transparent Antennas—Our Experiences of Starting Research Projects

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Getting Started

A speech

http://www.oscars.org/awards/academyawards/legacy/ceremony/80th.html
Overall Philosophy

Q: What do you plan to do?
   A: Solve an interesting engineering problem that has high scientific merits and broad impact on our daily life

Q: What if there is no such problem?
   A: Will research, discuss, communicate, and find one

Q: What if you have no resources?
   A: Will learn from successful people, will make or invent some
1. An interesting problem
2. Basic science due to complex structure and material assembly
3. Impact on space exploration
4. Impact on homeland security
5. Impact on communication, vehicular safety, and many more…
Learn

Literature search

1. Antennas made from transparent conductors
2. Antennas fabricated from meshes
Two Types of Transparent Antennas

1. Antennas made from transparent conductors
   a. Advantage: can be invisible
   b. Disadvantage: generally low transparency if reasonable antenna performance is required

2. Antennas fabricated from meshes
   a. Advantage: can be highly transparent yet effective
   b. Disadvantage: visible to eyes in most cases
Our Approach

What is the most important application for us?
• Cube Satellite (CubeSat)
• Reduced payload
• Reliable antennas

Meshed Antenna

High Transparency, Low Cost
Learn about Meshed Antennas

- Coaxial probe feed and insert feed
- Transparency is defined as $P_{\text{tran}} = \frac{A_{\text{antenna}} - A_{\text{metal}}}{A_{\text{antenna}}} = \frac{A_{\text{transparent}}}{A_{\text{antenna}}}$
- MATLAB to write and run HFSS for creating geometry and simulations.
Learn about Meshed Antennas

- Coaxial probe feed and insert feed
- Transparency is defined as \( P_{\text{tran}} = \frac{A_{\text{antenna}} - A_{\text{metal}}}{A_{\text{antenna}}} = \frac{A_{\text{transparent}}}{A_{\text{antenna}}} \)
- MATLAB to write and run HFSS for creating geometry and simulations.
What’s Known Already
What We Found New

![Graphs showing the relationship between peak gain and line width, and probe insert and line width.](image)

Utah State University
More Findings

- Most of the current flows horizontally.
- Are all the vertical lines necessary?
- If not, then they can be removed to improve transparency.
Experiments with Vertical Lines

- Impedance Bandwidth (%)
  - Transparency (%)
  - Values range from 1.25 to 1.5

- Radiation Efficiency
  - Transparency (%)
  - Values range from 0.75 to 0.9

- Peak Gain (dB)
  - Transparency (%)
  - Values range from 4 to 6
1. By carefully designing the mesh geometry, it is possible to achieve an effective highly transparent antenna

2. How do we prototype it?

3. How do we characterize it?
Fabrication With Circuit Board
Milling Machine
Challenges for Milling Machine

Time, Accuracy (bits size), Cost (maintenance, broken bits, …)
Printing Antennas

Can we do it?
Screen Printing

We are engineers
Six antennas were screen printed on clear plastic sheets. Two types of antennas are integrated with solar cells for testing.
Antenna Pattern Measurement
Measured Results

Fig. 8 The radiation pattern in the H-plane for a meshed patch antenna with an optical transparency of 61%.

The radiation pattern in the H-plane for a meshed patch antenna with an optical transparency of 61% and a solid patch antenna.
Screen Printing—Accuracy!
Inkjet Printing

Are we ready now?
Thesis: CONDUCTIVE INKJET PRINTED ANTENNAS ON FLEXIBLE LOW-COST PAPER-BASED SUBSTRATES FOR RFID AND WSN APPLICATIONS
Amin H. Rida
Georgia Institute of Technology, May 2009
A More Cost Friendly Option

Epson C88+, <= $100.00

Conductive ink from Novacentrix
An Improved Measurement Method
Flow Chart

Design → Print → Cure → Test
Inkjet Printing Essentials

- Printer — Epson C88+ (< $100.00)
- Conductive Ink — JS-15 silver ink (NOVACENTRIX)
- Cartridges (prefilled, refillable)
- Substrates: Paper, Photo paper (at least 4 stars), Transparencies, Kapton, PET (Polyethylene Terephthalate) with extra ink absorbing layer (NOVACENTRIX)
- Curing — Oven or PulseForge 3100 (NOVACENTRIX)
Verification of Printing Quality

- Quick test on conductivity

<table>
<thead>
<tr>
<th>Conductors</th>
<th>Test Print</th>
<th>Novacentrix</th>
<th>Copper</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative Resistance(Ω)</td>
<td>open</td>
<td>0.5</td>
<td>&lt; 0.1</td>
</tr>
</tbody>
</table>

- Comparison on antenna performance
More Printed Examples
Integration with Solar Cells
Findings on Solar Cell Integration

- Two Orientations have comparable effect on the antenna performance, one may be less lossy but not as practical for actual integration.
- The reduction in the antenna gain due to the solar cells is more than 3 dB, but this number may be reduced with a more accurate assembly.
- The effect of 95% transparent antenna on solar cell performance is less than 3%.
Are We Done?

So far we have been practicing at S band (around 2.5 GHz), what if we want to go higher on the frequency?
- Antenna will be smaller
- Mesh lines has to be finer accordingly to keep the transparency
- Harder to fabricate

What if the application requires “invisible” antenna? Mesh can still be seen
Antennas from Transparent Conductors

- Transparent Conducting Oxides
  - Indium Tin Oxide (ITO)
  - Fluorine-doped Tin Oxide (FTO)
  - Aluminum-doped Zinc Oxide (ZnO:Al)
  - Indium-doped Zinc Oxide (ZnO:In)

- Trade-off between Transparency and Conductivity
  Limits due to intrinsic physics of the material;
  Improvement requiring further development of technology.
Plasma Frequency

A frequency that separates transparency frequency (visible) and reflective bands (microwave frequency).

Limitation on Charge Carrier Density

Maximum Value for Electron Density \((N_e)\)

Electron density cannot exceed a certain value to keep the film non-reflective to the visible light.

\[
N_e < \frac{4\pi^2 \varepsilon_\infty m^*}{\mu_0 q^2 \lambda^2_{visible}}
\]

The typical value for maximum \(N_e\): \(1.5 \times 10^{21}\) cm\(^{-3}\)

Skin Depth, Transparency and Surface Resistance

- **Skin Depth**
  
  For light (higher than plasma freq): \[ \delta \approx \frac{2m^*}{Z_\infty q^2} \frac{\omega^2 \tau}{N_e} \]

  For microwave (lower than plasma freq): \[ \delta \approx \left( \frac{2}{\omega \mu \sigma} \right)^{\frac{1}{2}} \]

- **Film Transparency**
  
  Approximation: \[ T(t) \approx e\left(\frac{-2t}{\delta}\right) \]

- **Surface Resistance**
  
  Microwave conductivity can be found from surface resistance and film thickness. \[ Rs = 1/(N_e q \mu_e t) \]
Material Properties

- **High Transparency**
  
  Low $N_e$, or high $\mu_e$, or high $m^*$ $\Rightarrow$ high $\delta$ $\Rightarrow$ high transmission of light

- **High Conductivity for Better Radiation Efficiency**
  
  High $N_e$, or high $\mu_e$ $\Rightarrow$ high $\sigma$ $\Rightarrow$ low $\delta$ $\Rightarrow$ low loss

- **Trade-off**
  
  $N_e$ fixed at its maximum acceptable value ($1.5 \times 10^{21}$ cm$^{-3}$);
  $\mu_e$ made as high as possible (50~70 cm$^2$V$^{-1}$s$^{-1}$).
Effect of Electron Mobility

- Mobility Effect on Thickness and Surface Resistance

**Thicknss vs Electron Mobility**

<table>
<thead>
<tr>
<th>$\mu_e$ (cm²V⁻¹s⁻¹)</th>
<th>0</th>
<th>20</th>
<th>40</th>
<th>60</th>
<th>80</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t$ (µm)</td>
<td>0.2</td>
<td>0.4</td>
<td>0.6</td>
<td>0.8</td>
<td>1.0</td>
<td>1.2</td>
</tr>
</tbody>
</table>

- T=70%
- T=80%
- T=90%

**Surface Resistance vs Electron Mobility**

<table>
<thead>
<tr>
<th>$\mu_e$ (cm²V⁻¹s⁻¹)</th>
<th>0</th>
<th>20</th>
<th>40</th>
<th>60</th>
<th>80</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_s$ (Ω/sq)</td>
<td>0</td>
<td>20</td>
<td>40</td>
<td>60</td>
<td>80</td>
<td>120</td>
</tr>
</tbody>
</table>

- T=70%
- T=80%
- T=90%
Effect of Electron Mobility
(*TCO Patch Antennas*)

Mobility Effect on Radiation Efficiency

40% efficiency can be achieved at high transparency (90%) with future technology ($\mu_e = 90~100 \text{ cm}^2\text{V}^{-1}\text{s}^{-1}$).
A language that we all can understand

1. Effectiveness of the transparent antenna from ITO is bounded by material technology

2. Under the current material technology, we can do the following to achieve realistic efficiency
   a. Increase the operational frequency
   b. Use a substrate with low permittivity

3. A good alternative to meshed antenna at higher frequency such as Ka band or higher (space, car radar, etc.)
What Else Can be Done?

1. ITO is expansive, so a cheaper alternative is always a good thing
2. CNT conductor
   a. Cheaper
   b. Higher transparency
   c. Low conductivity, not yet applicable to antenna design

Invent some