Tunable Electrically Small Antennas

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Motivation and outline

• Mobile Ionospheric Heating
  ▪ Mobile version of HAARP
  ▪ Requires efficient, compact antenna

• Inductively coupled electrically small antenna (ESA) design
  ▪ Optimized in CST MWS 2014
  ▪ Capacitive tuning

• Antenna designed at 10x frequency for development
  ▪ 45 – 100 MHz

• Gain slightly larger than dipole

• Maximum power capabilities estimated

• Array Size and ERP Estimation
HAARP

- High Frequency Active Auroral Research Program
  - Studies the effects of high power HF on the ionosphere
  - Operating frequency: 2.8-10 MHz
  - 21 m wide, 16 m tall
  - Occupies 33 acres
Electrically Small Antenna

- An electrically small, inductively coupled antenna design
  - $k \cdot a < 0.5$
- Highly resonant structure
  - Provides natural match to 50 Ohm source
- Up to 98% efficient
- Small Loop Antenna (SLA) inductively couples to Capacitively Loaded Loop (CLL)

Circuit Model

- Small Loop Antenna
  - \( L_1 = 77 \, \text{nH} \)
  - \( R_1 = 3 \, \text{m}\Omega \)
- Magnetic Coupling
  - \( k = 0.1 \)
- Capacitively Loaded Loop
  - \( L_2 = 184 \, \text{nH} \)
  - \( C_1 = 12.4 \, \text{pF} \)
  - \( R_2 = 160 \, \text{m}\Omega \)
- Resonant frequency dominated by \( L_2 \) and \( C_1 \)
Tuning with Dielectric Insertion

- Resonant frequency adjusted by changing capacitance of CLL
  - e.g. inserting a dielectric
- Eccostock HiK
  - \( \varepsilon_r = 15, \tan\delta = 2 \cdot 10^{-3} \)
  - 45 - 100 MHz
- Teflon
  - \( \varepsilon_r = 2.1, \tan\delta = 2 \cdot 10^{-4} \)
  - 83 – 100 MHz
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  - $\varepsilon_r = 2.1$, $\tan \delta = 2 \cdot 10^{-4}$
  - 83–100 MHz
- HiK corrected $\varepsilon_r = 6.6$
- 5–10 times smaller than dipole
Radiation Efficiency

- Radiation efficiency decreases as dielectric is inserted
  - 98 – 20%
  - Mostly due to losses in dielectric
- ESA is most efficient when \( k \cdot a \) close to original
  - i.e. close to natural resonance of structure

Note: Radiation Efficiency = \( \frac{P_R}{P_A} \)
Experimental Setup

- Adjustable D-Dot height (0.6 - 10 m)
- Prodyn AD-55: $A_{eq} = 3 \cdot 10^{-3} \text{ m}^2$
  - Differential regime

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width</td>
<td>25 cm</td>
</tr>
<tr>
<td>Length</td>
<td>30 cm</td>
</tr>
<tr>
<td>Height</td>
<td>15 cm</td>
</tr>
<tr>
<td>Stub Length</td>
<td>2.65 cm</td>
</tr>
<tr>
<td>Stub Space</td>
<td>0.38 cm</td>
</tr>
<tr>
<td>SLA Radius</td>
<td>4.5 cm</td>
</tr>
<tr>
<td>Wire Diameter</td>
<td>0.2 cm</td>
</tr>
</tbody>
</table>
Gain

- Simulated E-Plane Gain Pattern
  - $f = 101.8$ MHz (No dielectric inserted)
  - Peak Gain $= 2.2$ dBi
  - 3 dB Beamwidth $= 144^\circ$
Gain

- Simulated E-Plane Gain Pattern
  - $f = 101.8$ MHz (No dielectric inserted)
  - Peak Gain = 2.2 dBi
  - 3 dB Beamwidth = 144°
Theoretical Maximum Power

- Maximum power limited by breakdown strength
- Duty cycle/pulse width limited by:
  - Efficiency
  - Specific heat capacity of dielectric
  - Ability to remove heat
Theoretical Maximum Power - Feed

$P_{\text{max}} = P_{\text{sim}} \left( \frac{E_{\text{max}}}{E_{\text{sim}}} \right)^2$

- Feed port (30 kV/cm): 180 kW in air.
- Will easily surpass strength of gap with coaxial insulation.

$P_{\text{sim}} = 0.5 \text{ W}$

100 MHz
Theoretical Maximum Power - CLL

\[ P_{\text{max}} = P_{\text{sim}} \left( \frac{E_{\text{max}}}{E_{\text{sim}}} \right)^2 \]

- Feed port (30 kV/cm): 180 kW
- Air (30 kV/cm): 20 - 40 kW
- Teflon (200 kV/cm): 1 - 2 MW
Theoretical Maximum Power at 10 MHz

- Operating at 1 MW and 20% loss into dielectric:
  - 148 seconds before entirety of volume begins to melt
  - 10% of volume:
    - 15 seconds
Antenna Parameters

• Directivity (dB), $D$
  • A function of angle describing the radiation pattern of an antenna
  • Does not include antenna losses or matching with driver

• Gain (dBi), $G$
  • Measure of how much power is radiated in a direction versus an isotropic radiator (can also be a function of angle)
    • $G = \varepsilon_R \cdot D$
    • Lossless, isotropic radiator: Radiates in all directions equally, i.e. $G = 0$ dBi in all directions

• ERP (Effective Radiated Power, dBW)
  • A gauge of how much power is effectively radiated in one direction
  • Gain plus power delivered (dBi+dBW)
Antenna Parameters

HAARP Element
- Gain: ~3 – 8 dBi [1]
- Size: 21 x 21 x 16 m
  - Area: 441 m² (0.1 acre)
  - Volume: 7056 m³
- Excitation: 10 kW
- ERP of array: 3.6 GW

TTU ESA
- Gain: 2.2 – 3 dBi
- Directivity: 3 – 4 dB
- Size: 3 x 2.5 x 1.5 m
  - Area: 7.5 m²
  - Volume: 11.25 m³

doi: 10.1109/EMCECO.2005.1513076
Array Size

**HAARP**
- 180 element array (15 x 12)
- Size: 31.6 acres
- Gain: 20 – 30 dBi
- Power Input: 3.6 MW
- ERP: 85 – 95.5 dBW
  (0.3 – 3.5 GW)
- \( G_{array} \approx \sqrt{N_{elements} \cdot G_{antenna}} \)

**TTU ESA**
- 180 element size:
  - \( \frac{1}{2} \lambda \) spacing: 201 x 247.5 m (12.3 acre)
  - \( \frac{1}{10} \lambda \) spacing: 69 x 79.5 m (1.4 acre)
  - Gain: \( \sim 25 \) dBi
- 30 x 30 m array:
  - \( \frac{1}{2} \lambda \) spacing:
    - 9 Elements
    - Gain: \( \sim 12 \) dBi
  - \( \frac{1}{10} \lambda \) spacing:
    - 25 elements
    - Gain: 2.2 dBi + 14 dB = 16.2 dBi
Effective Radiated Power

- Exciting ESA with available HAARP power (3.6 MW):
  - 25 element array: 81.8 dBW (151.4 MW)

- Matching HAARP’s ERP (3.6 GW)
  - 3.4 MW per element in 25 element array
    - Excitation needed = 85 MW
  - 66.7 kW per element in 180 element array
    - 12 MW Excitation
Size Comparison (all same ERP)

- **Blue**: HAARP – 180 elements (3.6 MW)
  - ¾ λ spacing between centers
  - 320 x 400 m
- **Green**: TTU – 180 elements (12 MW)
  - λ/2 spacing between element sides
  - 201 x 248 m (12.3 acre)
- **Orange**: TTU – 180 elements (12 MW)
  - λ/4 spacing
  - 4.2 acre (119 x 143 m)
- **Red**: TTU – 180 elements (12 MW)
  - λ/10 spacing
  - 1.4 acre (69 x 80 m)
- **Yellow**: TTU – 25 elements (85 MW)
  - 30 x 30 m array (0.2 acre)
  - λ/10 spacing
Controllable polarization will be possible by orienting ESA’s as shown.

May also reduce coupling between elements, and could make closer spacing possible.

Ongoing research.
Accomplishments

• ESA successfully designed and tested at 100 MHz (over previously GHz frequencies)
• Antenna pattern determined
  – Experiment and simulation are consistent
• Antenna tunable over 50% frequency range
• Size of ESA roughly 5 to 10 times smaller compared to dipole at same frequency
Future Work

• Confirm directivity as function of tuned frequency
• Antenna Array Simulation
  – Cross coupling effects (could be beneficial at lower frequencies)
• Breakdown strength in MHz regime
  – Air and select dielectrics
• Refine design focused on low loss tangent material (realistic material)
• Develop direct drive antenna concepts