ANALYSIS OF A TUNABLE ELECTRICALLY SMALL ANTENNA

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Abstract

A tunable, metamaterial-inspired, electrically small antenna topology is evaluated for a possible future use as the principle radiating element in a mobile Ionospheric Heating (MIH) system. The RF source signal is fed via a 50 Ω coaxial cable into a small semi-loop antenna (SLA). This inductively couples to a capacitively loaded loop (CLL) providing a natural 50 Ω match to the source. The resonant frequency of the antenna can be adjusted by varying the capacitance of the CLL via inserting a large permittivity dielectric. A simplified circuit model is used to show that the resonant frequency can be tuned between 40 – 100 MHz. Also, the maximum power handling capabilities achievable with this antenna topology at frequencies relevant to ionospheric heating (~ 10 MHz and below) are estimated.

I. INTRODUCTION

The High Frequency Active Auroral Research Program (HAARP) studies the effects of high power EM radiation on the ionosphere and consists of a 180 element array sitting on approximately 1.2·10⁵ m² of land in Alaska. Each element consists of two sets of crossed dipoles designed to transmit at 2.8 and 10 MHz at various polarizations. The larger crossed dipole sits 16 m above the ground with a length and width of 21 m taking up 441 m² each [1]. A proposed mobile version of these antennas are described in this manuscript using electrically small antennas (ESAs) capable of radiating high power while also adding the ability to tune the resonant frequency ± 50% of the band center with an instantaneous bandwidth on the order of 1 %. The proposed design is 5 to 10 times smaller than a comparable dipole at the same frequency.

II. ELECTRICALLY SMALL ANTENNA

The design shown in Figure 1, first introduced by a group at the University of Arizona [2], consists of a Small Loop Antenna (SLA) as the driving element (not shown in the figure), and a Capacitively Loaded Loop (CLL) as the radiating element. The SLA inductively couples to the CLL which creates a highly resonant system (defined by the dimensions of the CLL) and naturally matches to a 50 Ω RF source without the need for any balun transformers or matching networks.

This type of antenna is defined as electrically small since its $k·a$ product is less than 0.5, where $k$ is the wave number $2\pi/\lambda$ and $a$ is the radius of the smallest sphere enclosing the entire antenna (Wheeler sphere) [3].

Furthermore, for ease of measurement and fabrication, an antenna at ten times the frequency of HAARP was designed. The dimensions are presented in Table 1. Data produced in this manuscript was determined using the 100 MHz model.

Figure 1. The experimental ESA indicating the length, width, and height of the CLL on top of a square aluminum ground plane.

Table 1. Antenna dimensions for 100 MHz ESA.

<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>Gap Space</td>
<td>0.38 cm</td>
</tr>
<tr>
<td>SLA Radius</td>
<td>6.5 cm</td>
</tr>
<tr>
<td>Wire Diameter</td>
<td>0.2 cm</td>
</tr>
<tr>
<td>Ground Plane Length</td>
<td>61 cm</td>
</tr>
</tbody>
</table>

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A. Circuit Model

This antenna can be modeled using circuit theory which simulates the electrical characteristics including resonant frequency, input impedance and reflection coefficient. Additionally, resistances can be used to model radiation efficiency and losses. The circuit model allows for relatively quick analysis of parameter changes made to the resonant structure without allotting large amounts of computing power to simulating the EM structure. The SPICE model of this antenna is presented in Figure 2.

The circuit parameters, defined by the electrical characteristics of the antennas are: \( R_1 \) and \( L_1 \) - the resistive copper loss and inductance of the SLA, respectively, \( k \) - the coupling coefficient between the SLA and CLL, \( R_2 \) - a combination of resistive copper losses of the CLL, dielectric losses and radiation resistance, \( L_2 \) and \( C_1 \) - the inductance and capacitance of the CLL and are mainly responsible for determining the resonant frequency of the antenna, defined as

\[
f_{res} = \frac{1}{\sqrt{L_2 \cdot C_1}}. \tag{1}
\]

The resonant frequency of the antenna can be tuned by either adjusting either of the terms under the radical in Equation (1). Since the inductance of the CLL is determined by the dimensions of the copper and is difficult to change once built, it is elected to tune using the capacitance \( C_1 \). One method of achieving this adjustment is by inserting a high permittivity dielectric into the gap built into the CLL to increase the capacitance. By increasing the capacitance of the CLL (\( C_1 \) in the circuit model) from 12.4 pF to 80 pF the model is tuned from 100 to 40 MHz. The effect of this change in is presented in Figure 3.

![Figure 2. Circuit model for ESA showing principle of operation. Approximate values for a 100 MHz antenna are \( R_1 = 3 \text{ m}\Omega, L_1 = 77 \text{ nH}, k = 0.05, L_2 = 184 \text{ nH}, C_1 = 12.4 \text{ pF}, R_2 = 161 \text{ m}\Omega. \)](image)

The coupling coefficient is quite low due to the large amount of leakage fields. This value is proportional to the square of the ratio of the SLA to CLL area when viewed side on. If the coupling were brought closer to unity, the radiation resistance would approach the 50 \( \Omega \) source impedance. At this point, the losses present in the CLL would become negligible (on the order of 10’s of m\( \Omega \)). However, because the coupling is so low, the radiation resistance appears on the order of 100s of m\( \Omega \), making the losses on the same order. This leads to large amount of power deposited into the dielectric where long term operation may not become feasible.

III. THEORETICAL MAXIMUM POWER

As previously described, due to the low coupling between the driving and radiating elements, the antenna, under specific conditions, may be quite lossy. In order to estimate the maximum power capability, CST Microwave Studio® was used to determine the electric field strength given a 0.5 W input power. Using the dielectric strength, the peak power can be estimated. Furthermore, the relative deposited power into the dielectric was used to estimate the maximum pulse width before the dielectric begins to melt.

A. Breakdown

When analyzing the electric field distribution within the antenna, there are two regions for which breakdown is most probable; the feed through point for the SLA, and the gap in the CLL. To extrapolate a maximum power before breakdown Equation (2) is used in conjunction with the simulation.

\[
P_{\max} = P_{\text{sim}} \left( \frac{E_{\max}}{E_{\text{sim}}} \right)^2 \tag{2}
\]
Figure 4. Electric field intensities in the SLA Feed (left) and the CLL gap (right) for 100 MHz antenna with 0.5 W excitation.

In the 50 Ω air-filled feed port, a peak power of 280 kW is estimated using $E_{\text{max}} = 3 \text{ MV/m}$, $E_{\text{sim}} = 4 \text{ kV/m}$, and $P_{\text{sim}} = 0.5 \text{ W}$.

Because of the highly resonant nature of this system, the gap in the CLL has much higher field magnitudes. This limits the power before breakdown to 20 – 40 kW depending on if calculated with field enhancement values near the corners (14 kV/m), or bulk field values (10 kV/m) with air. This value can increase drastically if a dielectric is inserted between the gap, i.e. Teflon with a dielectric strength 15 times that of air. With Teflon, the power is estimated to increase to 1 – 2 MW.

B. Pulse Width

A simple Joule heating calculation is used to determine the maximum duty cycle of the antenna. Given the specific heat of the dielectric and a certain efficiency loss into the dielectric, a maximum pulse width before melting of the dielectric can be estimated. Operating at 1 MW excitation with 20 % loss into the dielectric, Teflon (melting point 330 °C) would melt or alter its properties at 252 ms. If a hot spot 10% of the volume of Teflon is assumed, it will melt a factor of ten times quicker. A ceramic dielectric can be used in place of a polymer for enhanced thermal and/or electrical properties.

C. 10 MHz power capabilities

To estimate the full size power capabilities the original dimensions were simply increased by a factor of ten on all axes.

At ten times the size, it is estimated that the antenna can handle up to ten times the power due to there being a larger size gap in the CLL and feed, thus making breakdown less possible. In simulation it was found that the fields within the gap and feed do not scale precisely linearly. The fields in the gap reduce to 1.4 kV/m in the bulk, and 2 kV/m at the corners in the field enhancement region, increasing the maximum power to 1.6 MW for air using the bulk field, and 3.7 – 23.8 MW using Teflon for both field enhancement and bulk field strengths, respectively. Additionally, the maximum pulse width is extended by a factor of 1000 due to there being 1000 times the mass of Teflon within the gap of the CLL since its dimensions were also increased on all axes. This increase in size allows the dielectric to absorb a proportional amount of additional energy.

IV. CONCLUSION

An electrically small antenna at 100 MHz has been presented utilizing a highly resonant capacitive loaded design. A circuit model showing tunability from 40 to 100 MHz via adjusting the capacitance was introduced. Maximum power capabilities of this ESA were estimated on the order of 1 - 2 MW. At frequencies relevant to ionospheric heating, the power capability was estimated at up to 23.8 MW.

V. REFERENCES

