Finite-Difference Time-Domain Simulations of Dependence of Maximum Gain on Material Conductivity and Geometry for Antenna Applications

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Abstract

Much research has been done on antennas made of high conductance material, including measurements of the radiation pattern and gain of antennas. This project investigates antennas made of low conductance or "lossy" materials, and concentrates on the effects that different antenna conductances, dimensions, and geometries have on the gain of the antenna. Numerical simulation methods, particularly finite-difference time-domain (FDTD) calculations, were used to solve approximately for the propagation of electromagnetic waves around and inside such antennas. We show that the gain of a lossy antenna is relatively insensitive to the conductance over a wide range of conductances and geometries and explore the limits for reasonable gain therein. We also show that a significant change in behavior occurs when the conductivity corresponds to a skin depth that is approximately equal to the thickness of a plane antenna made of lossy material.

Introduction

Much work has been done on the behavior of antennas, such as modeling electromagnetic behavior and antenna characteristics including the gain, radiation pattern, and bandwidth. Most of the research has been conducted on antennas made of material with high conductivity, as high conductivity leads to better transfer of electrons and electromagnetic radiation through the antenna. However, this leaves the question of how great an effect the conductivity of the antenna actually has on its performance. Work has been done investigating the effect of placing an antenna in a lossy medium, but not much research has been done on the properties of antennas made of materials with low conductivity, or lossy materials. There has been work done investigating the effect geometry has on antenna performance, but there is little research in the literature concerning the effect antenna conductivity has on its performance when coupled with the physical geometry of the antenna. A deeper understanding in this area is crucially important for expanding upon the knowledge in both electrical engineering and physics and allowing for future improvements in antenna design and other applications of electromagnetic theory. This project will use finite-difference time-domain electromagnetic simulation software to model the behavior of antennas under varying specifications of conductivity and geometry and investigate the effects these parameters have on antenna performance.

Simulations

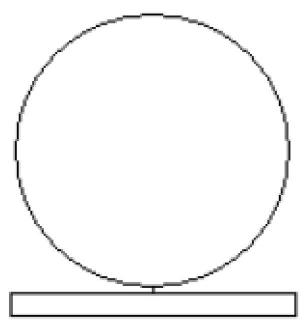

Figure 1: Circular Monopole Antenna

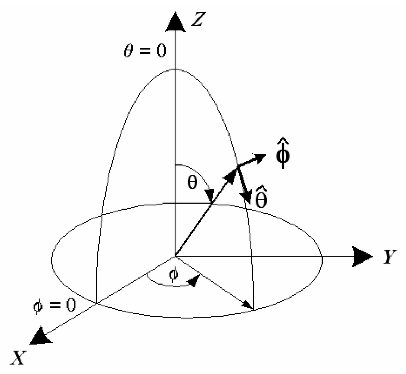

Figure 2: Spherical Coordinate System (courtesy of Remcom, Inc. (2))

Geometry: Circular Monopole
Maximizes surface area of lossy material in 2-dimensions

Rectangular Plane | Circular Disk

Length = 11.582cm | Width = 0.475cm | Radius = 5.052cm

Range of Conductivities: PEC to 10 S/m
Operating Frequency = 1.32 GHz
Orientation: XZ plane

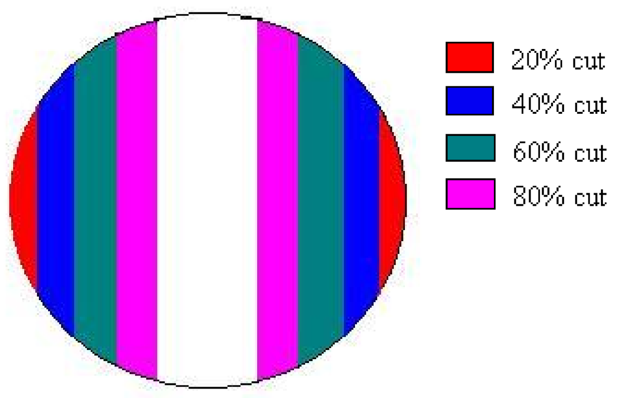

Figure 3: Radial cuts of geometry

1) Maximum gain measured at each conductivity value

2) Surface area decreased

3) Maximum gain measured for full range of conductivity values

4) Repeat 2 and 3 above for radial cuts of 20%, 40%, 60%, 80%, …, 98%

Results

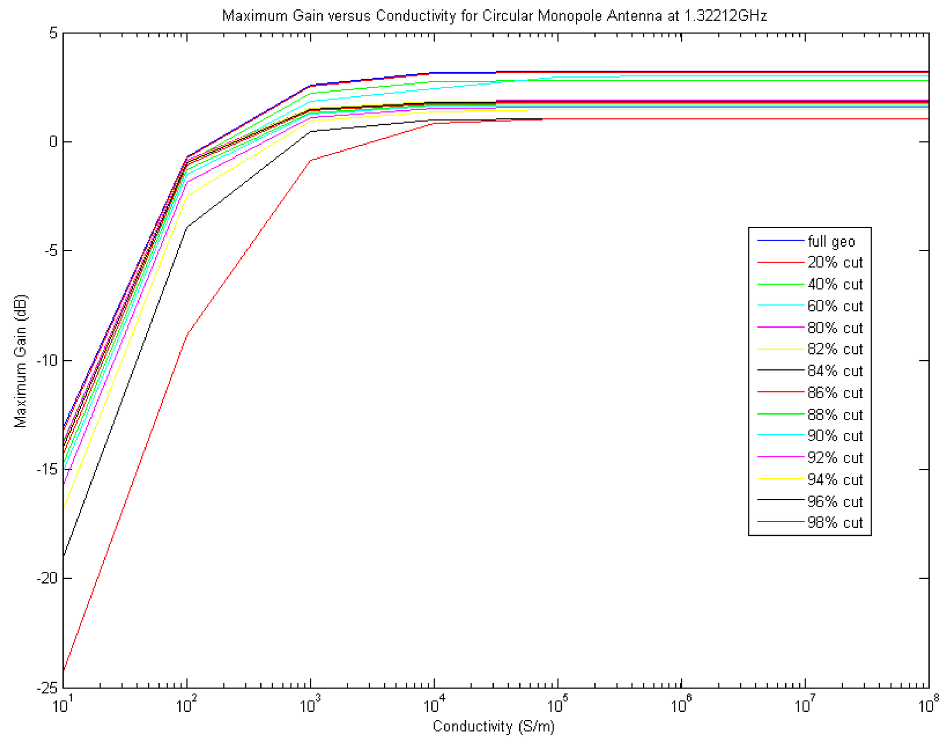

Figure 4: Maximum Gain versus Conductivity Plot

Knee in data occurs at point where antenna behavior changes significantly →
Skin depth δ ≈ 1.2 mm ≈ thickness of antenna

δ << d

$$r = \frac{1}{2 r_c \sigma \delta}$$

δ >> d

$$r = \frac{1}{r_c d \sigma}$$

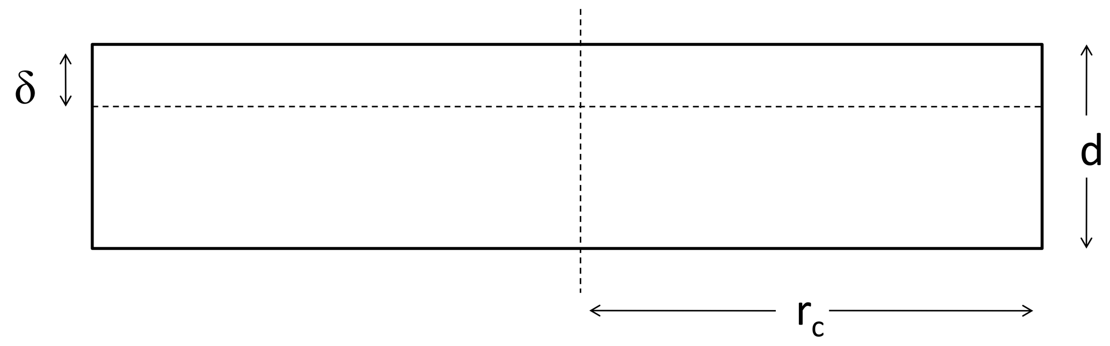

Figure 5: Cross-Sectional Area of Antenna

r = per-unit-length resistance
δ = skin depth
r_c = radius of circular disk
d = thickness
σ = conductivity

Analysis/Conclusions

Data from the plot of maximum gain versus conductivity shows a change in behavior from areas of high conductivity (10^4 S/m and above) to areas of low conductivity (100 S/m and below). To find the conductivity at which this change occurs, we used a method previously used by Paul (1) to find the position of the knee in the data. To do this, one uses the straight line that the antenna behavior exhibits at high conductivities and finds where the extrapolation of this line intersects with the extrapolation of the line describing antenna behavior at low conductivities. Based on the percentage of geometry cut, we found that the knee occurs between 118.9 – 157.7 S/m corresponding to skin depths of 1.27-1.10mm. This is approximately equal to one cell size, or the thickness of the simulated antenna.

This shows that a significant change in the behavior of the antenna occurs when the skin depth is approximately equal to the thickness of the antenna. This result agrees with results found by Paul (1), that show a significant change in behavior occurs for a wire when the skin depth is of the order of magnitude of the radius of the wire. Our result shows that this behavior also exists for plane antennas made of lossy material. Future work could investigate inductance effects in the behavior of lossy antennas, or consider different geometries than those considered in this project.

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References

(1) Paul, Clayton. Introduction to Electromagnetic Compatibility. New York: John Wiley & Sons, Inc., 1992. See pp. 142-144.
(2) XFDTD Reference Manual, Version 6.5. Remcom, Inc., 2007. See p. 3-5.