

# Dielectric Materials and Attenuation

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## Overview

This is the procedure for lab 1b. This is a one-week lab. The prelab should be done BEFORE going to the lab session. In this lab the dielectric properties of materials and how these properties affect electric fields will be analyzed. Reference materials for this and other labs are on the lab website. **For help**, contact TAs or instructor.

## Lab 1b Objectives

- Determine the effects of dielectric properties on signal propagation
- Explore signal attenuation due to the lossy-ness of a material.
- Develop understanding of Decibel calculations.

*Please Note: The material covered in this lab is NOT a replica or validation of what is taught in class. The lab is an opportunity to learn different material, in a different setting.*

## Equipment

The TA will have all the equipment ready for you. You do not need to purchase parts or materials for any of the ECE3300 labs. The list of equipment needed for this lab is the following: measuring cup, tablespoon, salt, sugar, distilled and tap water, cup, plexiglass tank, paper towels, dielectric probe kit, water-proof dipole antenna and reference dipoles tuned to 433 MHz, Network Analyzer (NA), dielectric probe and HP85070, cables, Matlab®.

## Prelab material

### I. Attenuation

Electrically lossy materials such as salt water and some human tissues cause attenuation of the electric field as it passes through them. This attenuation is calculated as

$$|E(z)| = E_o e^{-\alpha z} \quad (1)$$

where  $z$  is the distance (meters) from a reference point at which  $E_o$  (V/m) is measured. The attenuation constant,  $\alpha$ , is given in Nepers/meter or Np/m. A “neper” is not really a unit, but is just a placeholder. The effective units of  $\alpha$  are then 1/m, so that  $\alpha z$  is unitless.

Power is proportional to the **SQUARE** of the electric field, so the power as a function of distance from the reference point,  $P_o$ , is computed as:

$$|P(z)| = P_o e^{-2\alpha z} \quad (2)$$

The devices (network analyzer and spectrum analyzer) available in the lab measure **POWER** because measuring voltage and current is impractical at high frequencies.

Attenuation is a function of the permittivity ( $\epsilon$ ), conductivity ( $\sigma$ ), and frequency ( $f$ ). Increasing conductivity or frequency increases the attenuation.

The attenuation constant  $\alpha$  is calculated as:

$$\alpha = \omega \left\{ \frac{\mu \epsilon'}{2} \left[ \sqrt{1 + \left( \frac{\epsilon''}{\epsilon'} \right)^2} - 1 \right] \right\}^{1/2} \quad (\text{Np/m}) \quad (3)$$

$$\epsilon' = \epsilon_r \epsilon_o, \quad \epsilon'' = \sigma / \omega, \quad \mu = \mu_r \mu_o, \quad \omega = 2\pi f$$

The phase constant  $\beta$  is another parameter useful for calculating velocity of propagation  $u_p$  and wavelength  $\lambda$ :

$$\beta = \omega \left\{ \frac{\mu \epsilon'}{2} \left[ \sqrt{1 + \left( \frac{\epsilon''}{\epsilon'} \right)^2} + 1 \right] \right\}^{1/2} \quad (\text{rad/m}) \quad (4)$$

$$u_p = \omega / \beta \quad (\text{meters/second}), \quad \lambda = 2\pi / \beta \quad (\text{meters})$$

**Prelab Problems:**

- a) Write a Matlab® function that calculates  $\alpha$ ,  $\beta$ ,  $\lambda$ , and  $u_p$  (eqns 3 and 4). Check it by calculating the velocity of propagation in air, which should be roughly  $2.99 \times 10^8$  m/s = speed of light.
- b) Using a Matlab script and your functions, create data to show how the frequency and material affect the propagation parameters by filling in Table 1.

*Table 1 - Wavelength, attenuation constant, and velocity of propagation as a function of material and frequency*

Material	Freq. (MHz)	$\lambda$ (m)	$\alpha$ (Np/m)	$\beta$ (rad/m)	$u_p$ (m/s) $\times 10^8$
Air	100	2.9979	0	2.096	2.9979
Air	400				
Air	900				

Muscle <sup>1</sup>	100				
Muscle	400				
Muscle	900				
Fat	100				
Fat	400				
Fat	900				
Brain	100				
Brain	400				
Brain	900				
Skin-dry	100				
Skin-dry	400				
Skin-dry	900				

- c) Write a Matlab<sup>®</sup> function to calculate the absolute power as a function of distance (z) for a propagating wave in a lossy dielectric material (eqn 2) with attenuation parameters  $\alpha$ . Use  $P_o = 1$  W for your calculation.
- d) Create a Matlab script to plot the power vs. distance for 100 MHz, 400 MHz, and 900 MHz for each of the materials in the table. Plot all three frequencies on the same graph of a given material. The distance should be large enough to allow the power to decrease to 90% of its max value.
- e) Use a Matlab<sup>®</sup> script to show how power for 2/3 muscle<sup>2</sup> varies as a function of distance and frequency using a SINGLE plot with at least three lines on it. (Assuming  $P_o = 1$  W, this may also be a good plot to use 3D plotting in Matlab such as surface or mesh)

## II. Decibels

Decibels (dB) are calculated by the equation:

$$P_{dB} = 10 \log_{10}(P)$$

or, since power is proportional to the square of the voltage, by:

$$P_{dB} = 20 \log_{10}(V)$$

Decibels can be either with or without units in practice. Without units, they represent a ratio of two numbers. For instance, if  $P_1 = 1$ W, and  $P_2 = 2$ W, then their ratio is :

<sup>1</sup> For all biological materials  $\mu_r = 1$ .

<sup>2</sup> The body is often modeled as being composed of 2/3 muscle. To obtain the properties of 2/3 muscle, multiply the  $\epsilon_r$  and  $\sigma$  of muscle by 2/3

$$\frac{P_2}{P_1} = \frac{2 \text{ W}}{1 \text{ W}} = 2 \text{ (no units)} \xrightarrow[\text{linear}]{\text{dB}} 10 \log_{10} \left( \frac{P_2}{P_1} \right) = 3 \text{ dB}$$

So we can say  $P_2 = 2P_1$  or that  $P_2$  is 3 dB higher than  $P_1$ .<sup>3</sup>

Decibels can also be used to describe the magnitude (as opposed to the ratio) of power. In that case, it has a unit. The unit depends on the units on the power being measured:

$$P = 2 \text{ W} \leftrightarrow 10 \log_{10}(2) = 3\text{dBW} \text{ (dB}\times\text{Watts)}$$

$$P = 2 \text{ mW} \leftrightarrow 10 \log_{10}(2) = 3\text{dBm} \text{ (dB}\times\text{milliWatts)}$$

$$P = 2 \mu\text{W} \leftrightarrow 10 \log_{10}(2) = 3\text{dB}\mu \text{ (dB}\times\text{microWatts)}$$

For example if:

$$P(z) = P_o e^{-2\alpha z} \left( \frac{\lambda}{4\pi d} \right)^2 = 2\text{W} \cdot 0.2 \cdot 0.6 \text{ (yes, I just made these numbers up)}$$

Multiplication of values can be done using 2 different methods:

Method 1

Multiply the values and then convert the result to dB:

$$P_{dB}(z) = 10 \cdot \log_{10}(2\text{W} \cdot 0.2 \cdot 0.6) = -6.1979 \text{ dBW}$$

Convert each part of the equations to dB first, and then add them:

$$\begin{aligned} P_{dB}(z) &= 10 \cdot \log_{10}(2) \text{dBW} + 10 \cdot \log_{10}(0.2) \text{dB} + 10 \cdot \log_{10}(0.6) \text{dB} \\ &= 3.0103 \text{ dBW} - 6.9897 \text{ dB} - 2.2185 \text{ dB} \\ &= -6.1979 \text{ dBW} \end{aligned}$$

The “units” on the dB are chosen based on the ONLY element with units in the equation (dBW in this case).

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<sup>3</sup> The value of 10 is multiplied by the log instead of 20, because we are measuring POWER. If we were measuring electric field and converting to power, we would have used 20, because the power is proportional to the electric field squared.

**Prelab problem:**

- f) Verify that the two methods described above give the same results. Fill in the missing parts of tables 2 and 3.

*Table 2 - Decibel Conversions*

Voltage		Power	
Linear	dB	Linear	dB
10		10	
1		1	
0.01		0.01	
	60		60
	-3		-3
0.1	-20	0.316	-5

*Table 3 – Math in dB*

3 dBm - 6 dB =	
8 dBW - 4 dB =	
9 dBμ + 3 dB =	

- g) Read article [2] in References section, available on the lab website.

**Lab Procedure**

**Measure the attenuation as a function of distance.**

The propagation in a lossy medium can be described by either of the equations:

$$|E(z)| = E_o e^{-\alpha z} \quad (\text{for electric field})$$

$$|P(z)| = P_o e^{-2\alpha z} \quad (\text{for power})$$

where z is the distance traveled in the medium and α is the attenuation constant.

For this part of the lab the attenuation constant α will be calculated, measure and compared. It will be found using measurements of the change in power due to different distances between an antenna

placed in the tank and an antenna close to one side. It will also be calculated using the measured dielectric constant of the water in the tank.

**Procedure:**

- a) Using the dielectric probe and HP85070 software to measure the dielectric properties of the solution in the plexi-glass tank. Stir the water before testing. Compute the values of  $\epsilon'$  and  $\epsilon''$  from the measured values.

Measured Tank water @ 440 MHz,  $\epsilon'' =$  \_\_\_\_\_ and  $\epsilon''' =$  \_\_\_\_\_

Computed Tank water @ 440 MHz,  $\epsilon' =$  \_\_\_\_\_ and  $\epsilon'' =$  \_\_\_\_\_

- b) Clean and put away the dielectric probe kits and close the 85070 software.
- c) Configure the Network Analyzer (NA) to display  $S_{12}$  (= the transmission coefficient T) over the frequencies of 200 to 600 MHz. (Ask to TA for help)
- d) Attach the water-proof dipole antenna to port 1. This antenna will act as the transmitting antenna inside a lossy medium.
- e) Attach the reference dipole antenna to port 2 and place it next to the tank to act as a receiver for the setup.
- f) Using the scale on the bottom of the tank take several measurement of the power ( $S_{21}$  on the analyzer) to fill in table 4 for the frequency of 433 Mhz. Keep the measurements in the range of 15 cm to 45 cm between antennas. If the antenna in the tank is too close to the sides or bottom, too much power is reflected and this may affect the readings. So, keep the antenna centered vertically in the tank.

*Table 4 - Power vs. Distance at 433 Mhz*

Power					
$ P_{dB}(z)  = S_{21}$					
Distance (z)					

**\*\*NOTE - stir the water in the tank between measurements to keep the salt and sugar well mixed**

- g) Now using the equation (3) compute  $\alpha$  for the system using the dielectric properties tested in section a) of the lab (the tank water). Remember the conversion of measured values  $e'$  and  $e''$  to  $\epsilon'$  and  $\epsilon''$  respectively.

$\alpha =$  \_\_\_\_\_ (nepers/m)

- h) Compare this to the value calculated if the tank water is considered low-loss using the following equations from Table 7-1 (Ulaby):

$$\alpha = \frac{\sigma}{2} \sqrt{\frac{\mu}{\epsilon'}} \quad \text{where } \sigma = \epsilon'' \omega$$

$\alpha =$  \_\_\_\_\_ (nepers/m)

- i) Using the values in Table 4 determine the measured values of  $\alpha$  using the following equation:

$$\alpha = -\frac{P_{dB}(z_2) - P_{dB}(z_1)}{8.6859 \cdot (z_2 - z_1)} \quad \text{(derived at the end of hand-out)}$$

There will be four values for  $\alpha$  computed from the data, eliminate any bad points and average the rest to get an approximate value for the attenuation constant.

$\alpha \approx$  \_\_\_\_\_ (nepers/m)

Are the calculated values close to the measured  $\alpha$ ? \_\_\_\_\_

**Discussion: (Do this during lab with your other students and your TA)**

- Describe the effect of material, frequency, and distance on power attenuation. Compare your predicted and measured attenuation
- Explain possible reasons for the differences in the calculated and measured attenuation constant.
- Describe the dielectric regions in a cardiac pacemaker communication system (inside the body, outside of the body) where the attenuation model of this lab is most applicable.
- Apply what you have learned and make a judgment. For a 433 MHz cardiac pacemaker communication system, the 1mW transmitter will be implanted 10cm below the surface of the chest. The receiver has a sensitivity of -75 dBW.<sup>4</sup> Considering ONLY loss in the body is there enough power to meet the receiver requirement if the receiver is held next to the body?
- What other sources of loss can you see in the system that should be accounted for?

*Hint: Calculate the power transmitted in dBW. Calculate the attenuation in the body (I'd use 2/3 muscle for average or brain for worst case), and convert it to dB.*

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<sup>4</sup> This means that the receiver must receive -75dB of power in order to work properly.

Turn in a copy of your lab notebook (including the discussion items above) to your TAs homework locker. Turn in your written end of lab report (See Lab 0 – Writing Lab) to the HOMEWORK locker. Both are due by beginning of the next lab.

***Derivation of calculating the attenuation constant from measurements of power and distance:***

Defining  $|P(z)| = P_o e^{-2\alpha z}$  for two different distances  $z_1$  and  $z_2$  gives:

$$|P(z_1)| = P_o e^{-2\alpha z_1} \quad \text{and} \quad |P(z_2)| = P_o e^{-2\alpha z_2}$$

then by dividing to eliminate  $P_o$  creates an equation that a function of the change in  $z$ .

$$\frac{|P(z_2)|}{|P(z_1)|} = \frac{e^{-2\alpha z_2}}{e^{-2\alpha z_1}} = e^{-2\alpha(z_2 - z_1)}$$

converting to dB on both sides result in

$$P_{dB}(z_2) - P_{dB}(z_1) = -20 \log_{10}(e) \cdot \alpha \cdot (z_2 - z_1) \approx -8.6879 \cdot (z_2 - z_1)$$

and finally

$$\alpha = -\frac{P_{dB}(z_2) - P_{dB}(z_1)}{8.6879 \cdot (z_2 - z_1)}$$

**References**

[1] F. Ulaby, *Fundamentals of Applied Electromagnetics*, 6th ed., 2007, ch. 7, sec. 6, pp. 343-344.  
 [2] S. Gabriel, R. Lau, C. Gabriel, "The Dielectric Properties of Biological Tissues II: Measurements in the Frequency Range 10 Hz – 20 GHz" in *Phys. Med. Biol.*, Vol. 41, 1996, pp. 2251-2269.

Optional Reading Materials with more interesting and exciting information are available on the website.