# Design of a 3D Microwave Imaging System

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Department of Engineering

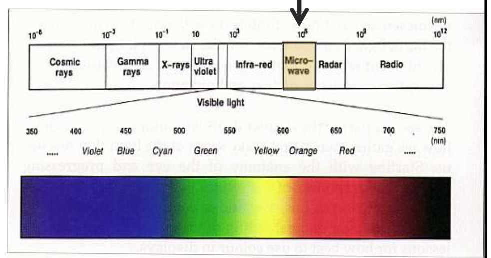
Advisor: *Dr. Yong Zhou*

Spring 2012 – Senior Design II

Good morning, my name is Drew Jaworski and today I will be presenting my project for Senior Design II, the Design of a 3D microwave imaging system. My advisor is Dr. Yong Zhou.

# Why Microwave Imaging?

- **Electromagnetic Imaging Systems**
  - Vision
    - Nature doesn't always know best!
  - X-Ray
    - Ionizing Radiation
  - Infrared ("thermal")
    - Limited to Surfaces
  - MRI (quantum mechanics)
    - Expensive and Invasive
  - **Microwave**
    - **Non-Ionizing**, **Surface-Penetrating**, **Less Expensive**!
- **Applications**
  - Medical imaging (cancerous tumors)
  - Industrial scanning (forging defects)




Pictures: http://www.nist.gov/oles/dietimage.cfm

I'd like to start by explaining why I am researching microwave imaging. There is a broad spectrum of electromagnetic radiation which interacts with the matter around us. Human vision uses only a small part of that spectrum, so attempting to take advantage of the rest of what exists can benefit our ability to visualize the world around us. Microwave radiation has the advantage of being non-ionizing, so it is safe to use for extended periods of time, surface penetrating, so it can help us see things that are otherwise hidden, and significantly less expensive than other options. It has applications in medical imaging and industrial scanning.

## **Project Goals** (overview)

1. Determine System Criteria
   - Frequency range
   - Necessary hardware
2. Ultra-wideband antenna design (*HFSS*)
3. High frequency circuit layout (*HFSS*)
4. Prototype hardware construction
5. Vector network analyzer signal analysis
6. Automated data acquirement (*NI Labview*)
7. Data Processing (*Matlab*)

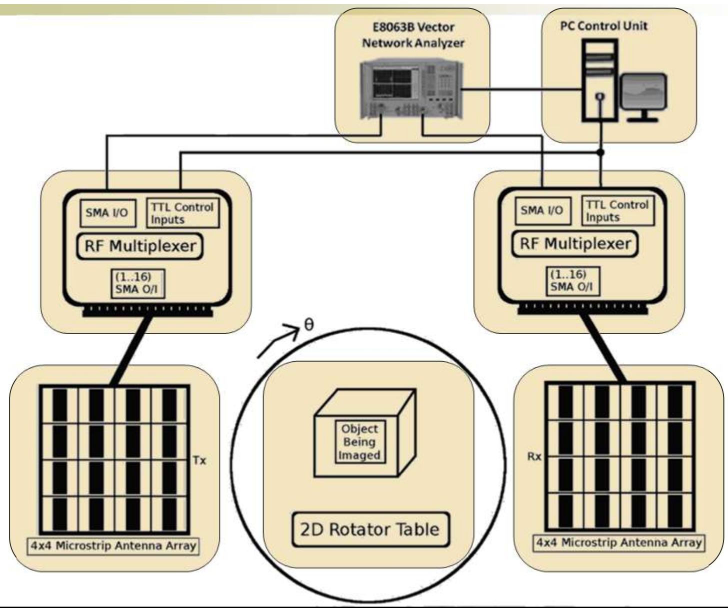
My project consists of a number of goals, beginning with determining the criteria of my system in order to determine what limits I have on my design, such as the operating frequency range and the necessary hardware. I also need to design an ultra-wideband antenna, that is, an antenna which can radiate at a broad range of frequencies, as well as work with high frequency circuit layout using Ansoft HFSS, which is a powerful electromagnetic structure simulation software. I then need to construct prototype hardware which will be connected to a network analyzer, which is a piece of testing equipment for determining the electrical characteristics of very high frequency systems. Finally, I must automate data collection from my system using National Instruments' Labview hardware and software and Matlab for processing the acquired data into images and 3-dimensional models.

## Project Constraints

- <u>Size</u>
  - Entire system less than (1[m] x 1[m] x 1[m])
- <u>Budget</u>
  - $300 from Engineering department
  - Personal funds
- <u>FCC Regulations</u>
  - Medical device band: 3.1[GHz]–10.6 [GHz]
- Many others related to trying to manage the above constraints

For reasons of space-optimization, my system needs to be limited to a size of roughly 1 cubic meter. For budgetary reasons, my project was provided up to $300 from the Engineering department as well as my own funds should I exceed that. The Federal Communications Commission has strict guidelines for my research, which limit me to the medical device band of 3.1 to 10.6 gigahertz. I also have many other limiting factors which arise when trying to meet the listed constraints.

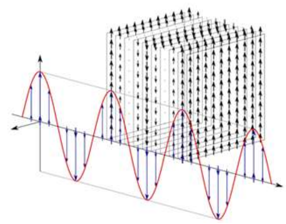
# Experimental Setup



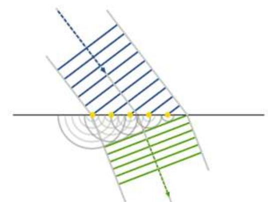

This is a rough diagram of my experimental setup, consisting of a computer to control data acquisition, connected to a vector network analyzer with a pair of multiplexed antenna arrays connected to the inputs. An object under test, such as my own hand, is then placed between the two parallel antenna arrays and the network analyzer determines the electromagnetic properties between the two antennas.

# Electromagnetic Overview

- Plane-wave approximation
  - Imaging subject located in far-field of antenna array
    - perpendicular to propagation of waves
  - Simplifies analysis at expense of system size



- Scattering through media
  - A result of multiple layers of diffraction and refraction
    - Organic tissue is a complex system

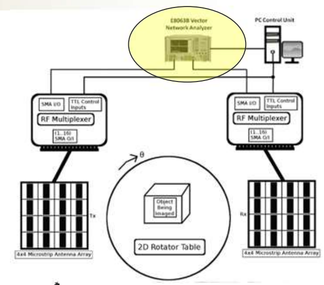


Images courtesy of:
http://en.wikipedia.org/wiki/File:Linear.Polarization.Linearly.Polarized.Light_plane.wave.svg
http://commons.wikimedia.org/wiki/File:Huygens_brechung.png

A brief overview of how electromagnetic radiation interacts through matter and space begins with the fact that on the surface of a radiating antenna, the electromagnetic fields have a spherical distribution, but at a certain distance away from the surface, the far-field distance, the electromagnetic fields can be considered a plane wave, which helps to simplify the processing of the data and thus speed up the production of microwave images. As this electromagnetic radiation passes through the medium of an object under test, the waves undergo a complex series of diffraction and refraction.

# Network Analyzer

- **Measures a Two Port Network**
  - Returns S-Parameters (*Scattering Parameters*)
    - S11 – Return Loss
    - S21 – Insertion Loss




- **Parallel antennas connected to ports**
  1. Calibrate response
  2. Place object between antennas
  3. Result is how the object affected the electromagnetic fields between the two antennas
     - Software algorithms calculate dielectric properties

The network analyzer works by determining the electromagnetic properties of the network between its two connection ports across a user-defined range of frequencies, and the data it provides are what is known as the scattering parameters of the network. In the simplest imaging system, two identical antennas are connected to the network analyzer ports. First, data will be collected about the system with no object between the antennas, and then it will be compared to data collected with an object present. Software algorithms written in Matlab will process this data in order to visualize it as graphs and models that we can see on a computer screen.

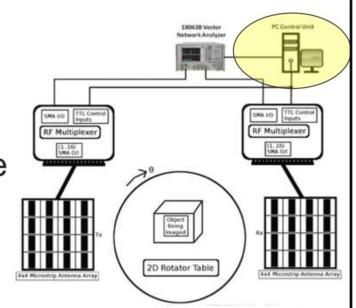
# Inverse Scattering Solution

- **Repeat with multiple antennas** (4x4 array, in this case)
  - Result is a set of matrixes of scattering parameters for a 32-port network (for a range of frequencies!)
    - Can be manipulated to produce a discretized graphical representation of the dielectric properties in different regions between antenna arrays
    - Interpolation used to produce a 3-dimensional model
- **Inverse Scattering Problem** – <u>Microwave Tomography</u>
  - We know the forward transmitted radiation (aka Incident Fields)
  - We have information about the received fields (aka Scattered Fields)
  - Now we want to know what made them change!
    - Very complex calculations that are demanding of computing resources
    - Fortunately, much research has been published that has mathematically and/or computationally simplified the solution process (relatively)

With more antennas collecting data from discrete different points in space, such as on a planar 4 by 4 array of 16 antennas, the result is a significantly larger amount of data which can be used to create higher resolution images. Add the fact that the data will be across a range of frequencies and at different angles relative to the rotated object, and we have plenty of data to use to reconstruct 3-dimensional models of the object on the computer screen! This process is what is known as inverse scattering tomography and requires to the use of complex equations to process the collected data.

# Automated Data Analysis

- **National Instruments' *Labview***
  - Automate collection of data
  - Several colleagues have worked out the details
    - Rotation mechanism –***Miguel Rivera***
    - TTL communication (for multiplexer) – ***Julio Vasquez***
  - AMEL – Motorized system finalized
- ***Matlab***
  - Process data from Network Analyzer
  - Numerous published algorithms to be implemented and tested




The data collection automation will be helped by research from colleagues of mine, such at the Labview-assisted automated rotation system by Miguel Rivera and the multiplexer communication interface made by Julio Vasquez.

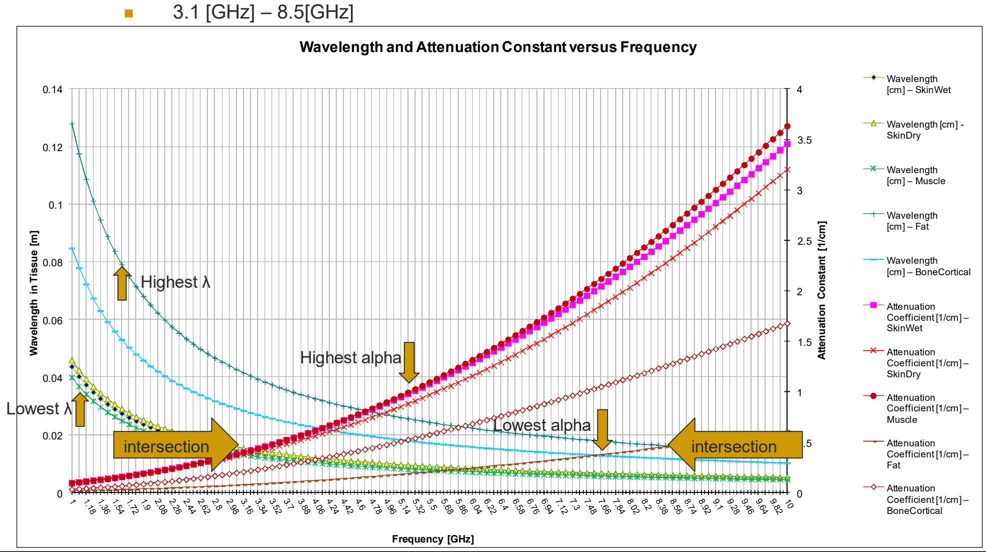
# Frequency Selection

- Limited by technology of hardware (Switch and/or Antenna Bandwidth)
- Biomedical focus – human tissues
- Estimates vary, best to come up with your own and justify accordingly
- Begin with what spectrum is available
  - Federal Communications Commission ("FCC") Guidelines;
  - *"Medical Systems: These devices must be operated in the frequency band **3.1-10.6 GHz**. A medical imaging system may be used for a variety of health applications to "see" inside the body of a person or animal. Operation must be at the direction of, or under the supervision of, a licensed health care practitioner."*
    - *http://transition.fcc.gov/Bureaus/Engineering_Technology/Orders/2002/fcc02048.pdf*
- Electromagnetic properties of the Human Body
  - Database of dielectric properties of numerous types of tissue available from Italian National Research Council site:
    - http://niremf.ifac.cnr.it/tissprop/

Now, the first main system characteristic I needed to determine is the range of frequencies to use for microwave imaging, which are significantly limited by the technology of the antennas and switches used in the design relative to the spectrum allocated by the FCC for medical systems research. There is no concrete answer to this and I determined it would be best to justify this on my own, basing it on research found in a paper published in 1985 which referenced data from the early 1970s. Since I wanted to focus on biomedical objects for imaging, I found a database with recently-collected electromagnetic properties of many different kinds of human tissues and put together a graph to help with the selection process.

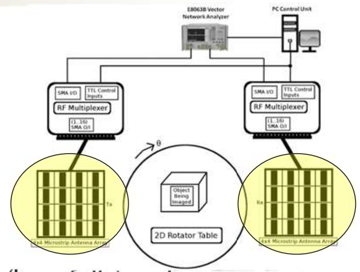
# Dielectric Properties Database

- Skin (wet and Dry), Muscle, Fat, and Bone
  - Major constituents of most body parts
- 3.1 [GHz] – 8.5[GHz]



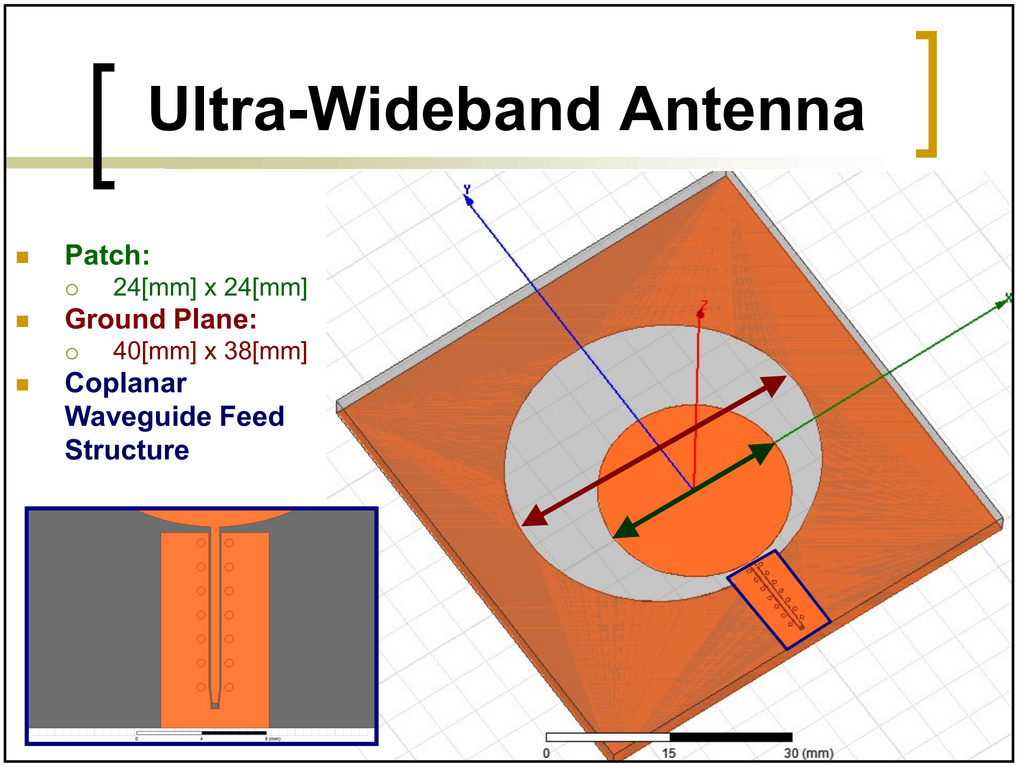

This graph compares the frequency-dependent wavelength and attenuation constants of wet and dry skin, muscle, fat, and bone, which I considered to generalize the majority of the human body. I took the ideal bandwidth of my system to be represented by where the extremes of the two sets of curves crossed, which is between 3.1 and 8.5[GHz].

# Ultra-Wideband Antenna



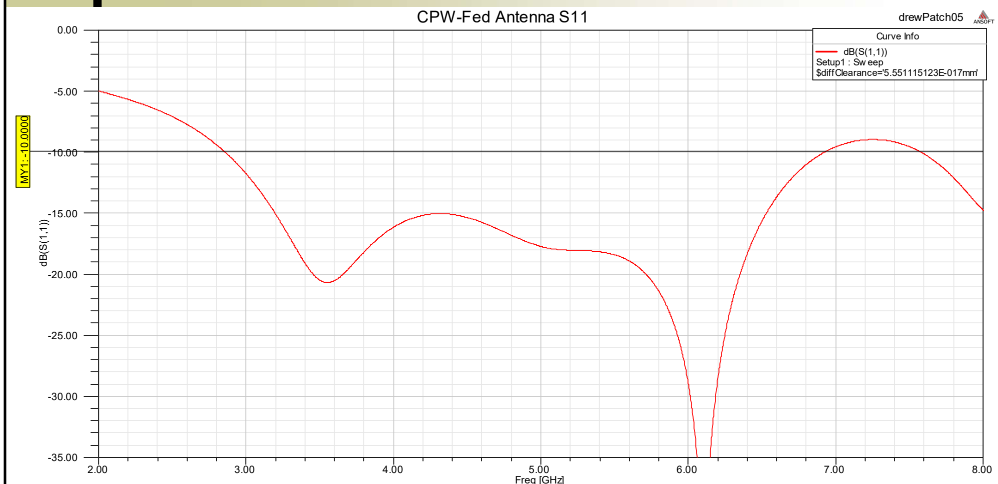

- Two-port network theory
  - One-port input network, in this case
  - $S_{11}$ measures "return-loss" [dB]
    - Lower is better, -10[dB] indicates half of the input power is lost to the network
    - Return Loss is power radiated from antenna (hopefully) and other losses.
- Bandwidth is measured where $S_{11}$ < -10[dB]
  - Design is UWB when (Bandwidth / $Freq_{center}$) >= 25%
- Many designs researched and simulated
  - Interest in fractal-based designs
  - Unable to design something better

For the design of the ultra-wideband antenna, I went with a planar patch design as my focus in order to be able to produce the array using standard printed circuit board construction techniques. As far as the network analyzer is concerned, my antenna is a device which accepts input electromagnetic radiation and "loses" it to the surrounding space; one way to measure the performance of this antenna is to determine the frequency bandwidth for which 10 decibels (or half of the input power) is lost to the antenna. I had a particular interest in fractal based designs and spent a lot of time researching and simulating various designs but eventually I decided to go with a circular design with a larger elliptical discontinuity in the ground plane beneath the radiating surface.




This is the design I created in HFSS; the forward-facing component of the antenna is a 24 by 24 millimeter copper patch with a a 40 by 38 millimeter ground plane discontinuity behind it. The antenna is fed by a co-planar waveguide feed structure, which I will be explaining later in this presentation.

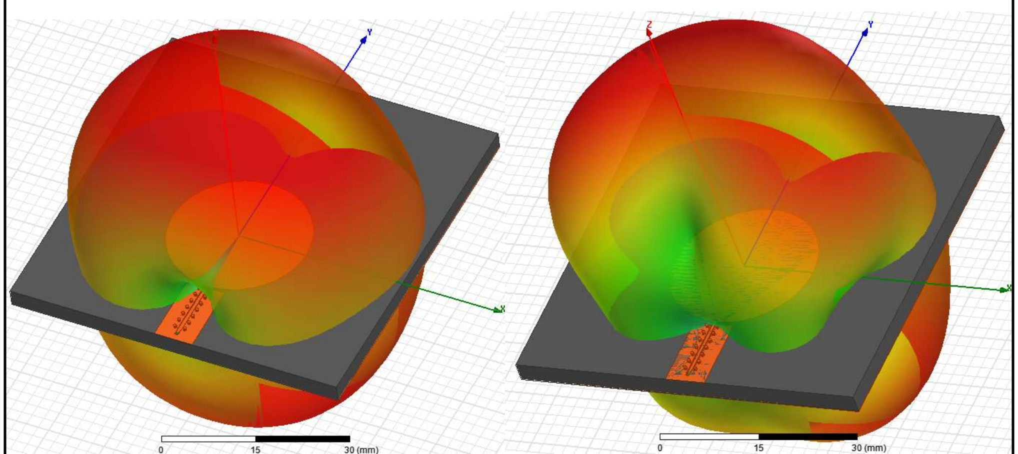
# UWB Antenna Simulation




- **Bandwidth:** 2.9 [GHz] to 6.9 [GHz]
  - **BW / $F_{center}$** = 4 [GHz] / 4.9 [GHz] = 81.63%
- Ultra-Wideband response, mostly below -15 [dB]

This is a graph of the frequency-dependent S11 return loss of the antenna, as simulated in HFSS. It indicates an 85% bandwidth between 2.9 and 6.9 gigahertz, with an added bonus of being below -15 dB across that spectrum.

## Antenna Radiation Pattern

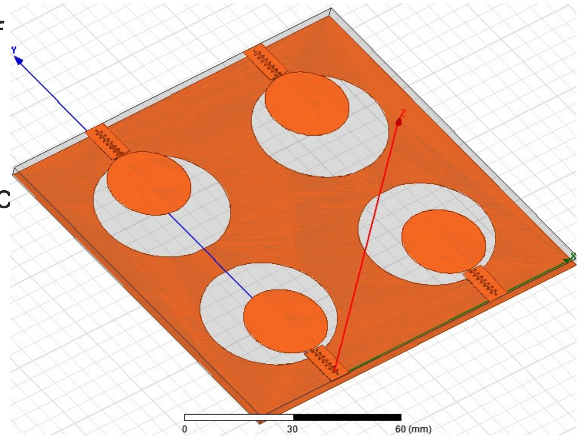



3.0 - 5.0 [GHz] 6.0 [GHz]

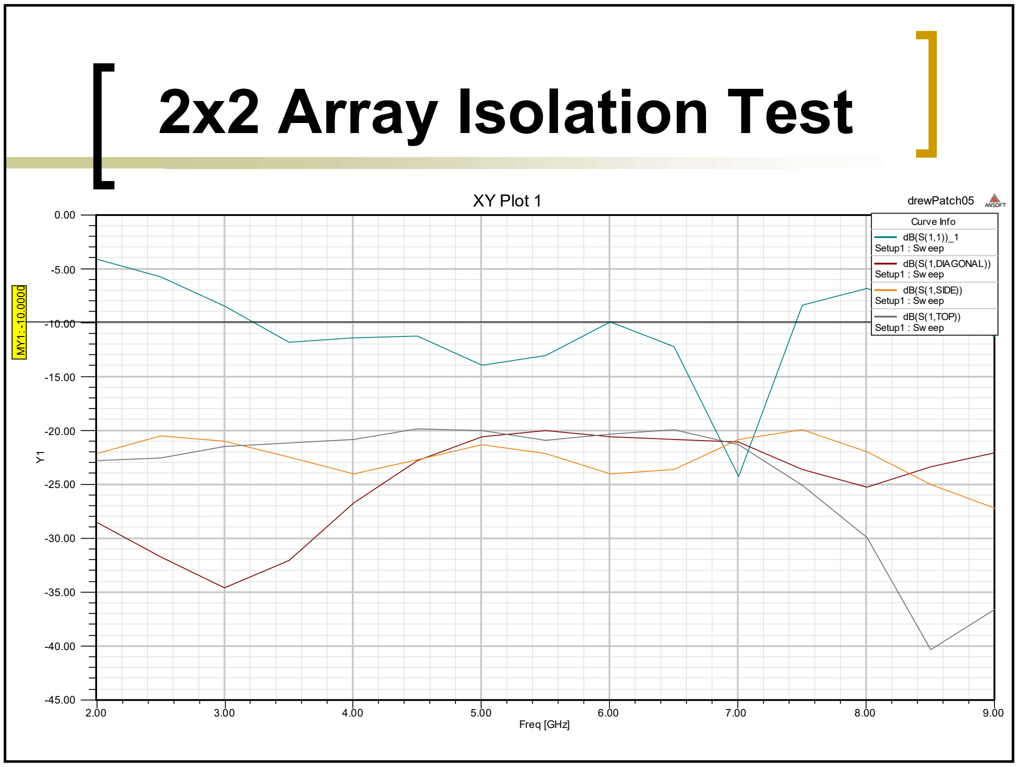
The radiation pattern indicates that the design has a close approximation of an ideal hemispherical distribution . If the design were to suffer from severe non-surface-normal directivity, it would make the antenna very hard to work in a planar array.

# Array Coupling Tests

- Need to minimize size of array
  - Mainly limited by spacing between each antenna
- 2x2 Array with symmetric spacing (50mm)
  - HFSS Simulation
  - 4-port symmetric network
  - Less than -20[dB] transmission between antenna elements



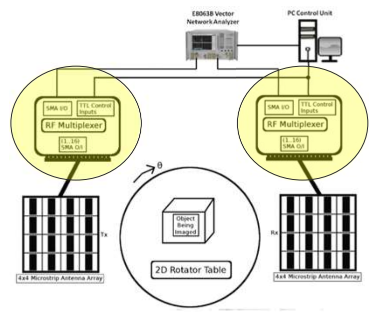

I then took that design and simulated a 2 by 2 array of antennas in order to find the minimum spacing I could allow between them for my eventual system design. Since the antennas radiate in a nearly hemispherical distribution, some of the radiation from one antenna can reach another, which is known as “coupling”, which is to be avoided. A good number for determining how much coupling can be permitted is -20 decibels, as above that indicates that there will be difficulty in determining which antenna is actually radiating at any given time. By varying the distance between the antennas in HFSS and comparing the coupling between them, I was able to determine a minimum distance between them as being three quarters of the wavelength of the lowest frequency used in the system.



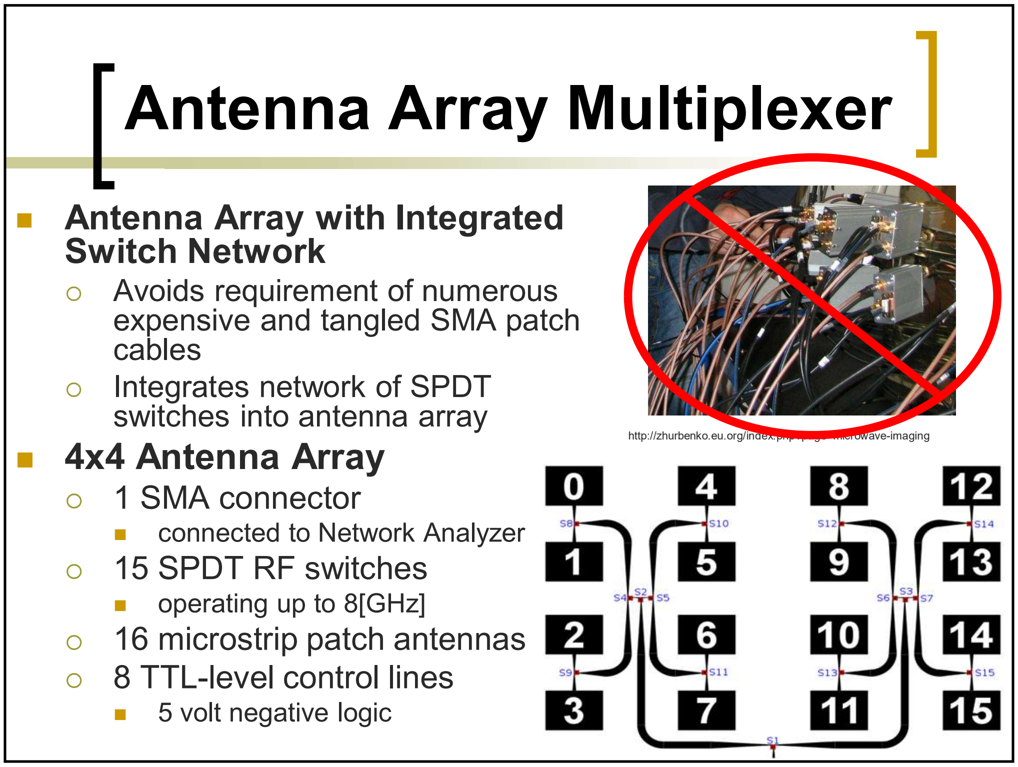

Which this graph demonstrates by showing the coupling between the four antennas shown on the previous slide. This graph indicates that for the frequency range I am using, there is a good measure of isolation between each antenna.

## Multiplexer vs Switch Network

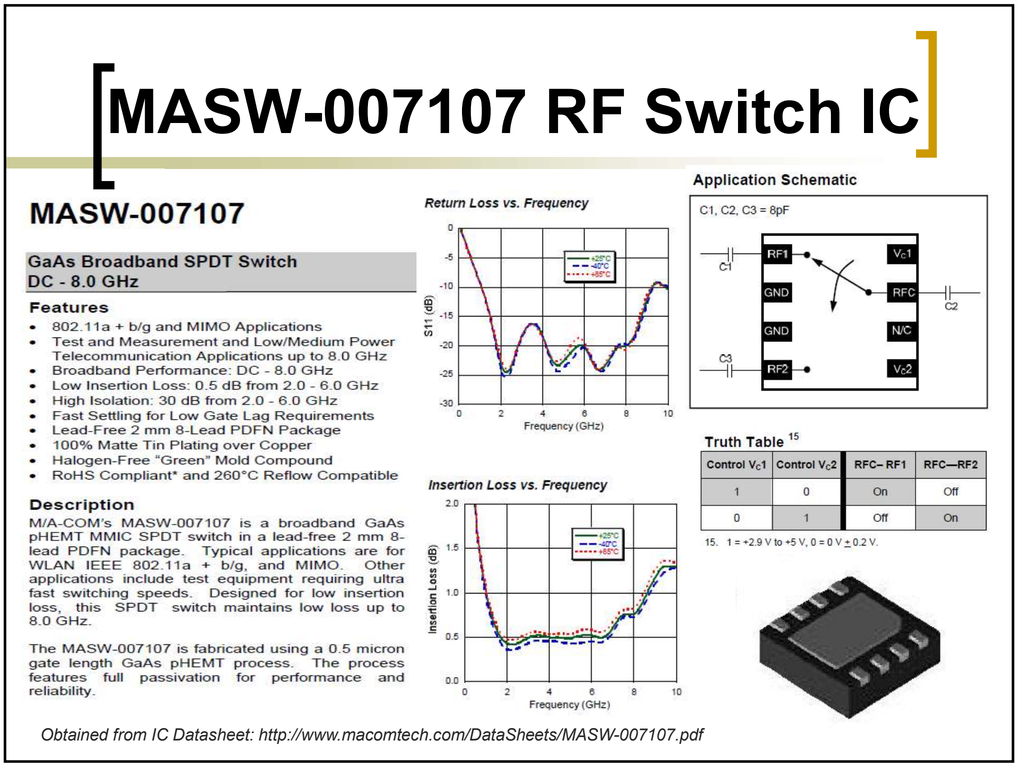
- Fully featured DC-12[GHz] multiplexer
  - $700 ~ $1700
- Single SPDT DC-8[GHz] RF Switch IC
  - < $1 each
  - M/A-COM technology solutions
    - MASW-007107
    - Pros
      - Distributed by Mouser
      - Inexpensive!
    - Cons
      - Small package size ~ (2[mm] x 2[mm])



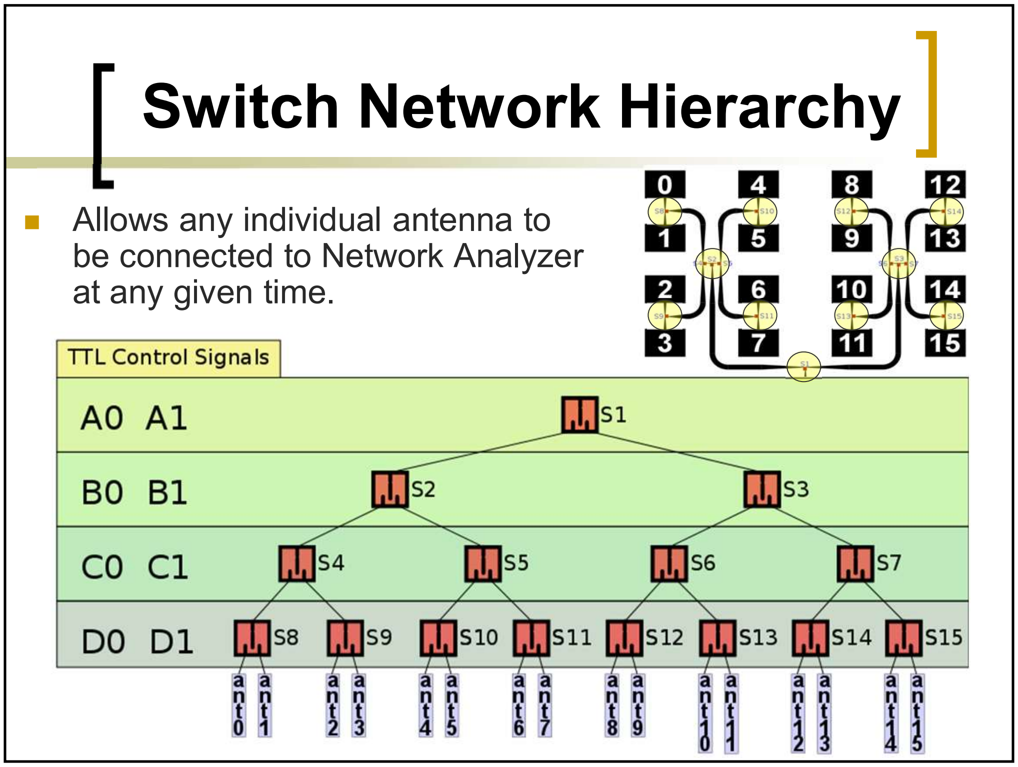

The next design hurdle was whether to go with a commercial multiplexer device or to design my own switching network for electronically switching between individual antennas in the array to connect to the network analyzer at any given time. A commercial multiplexer device can cost anywhere between $600 up to $1700, which is well beyond my $300 budget, so I decided to instead find some very inexpensive RF switch ICs and integrate a switching network onto the surface of my antenna array. The devices I chose cost less than $1 each and I only need 15 of them for each 4 by 4 array, keeping costs very low for my project. However, they are incredibly small, at 2mm by 2mm, but I successfully learned how to solder these for my project using a combination of hand-soldering and a hot-air rework station.



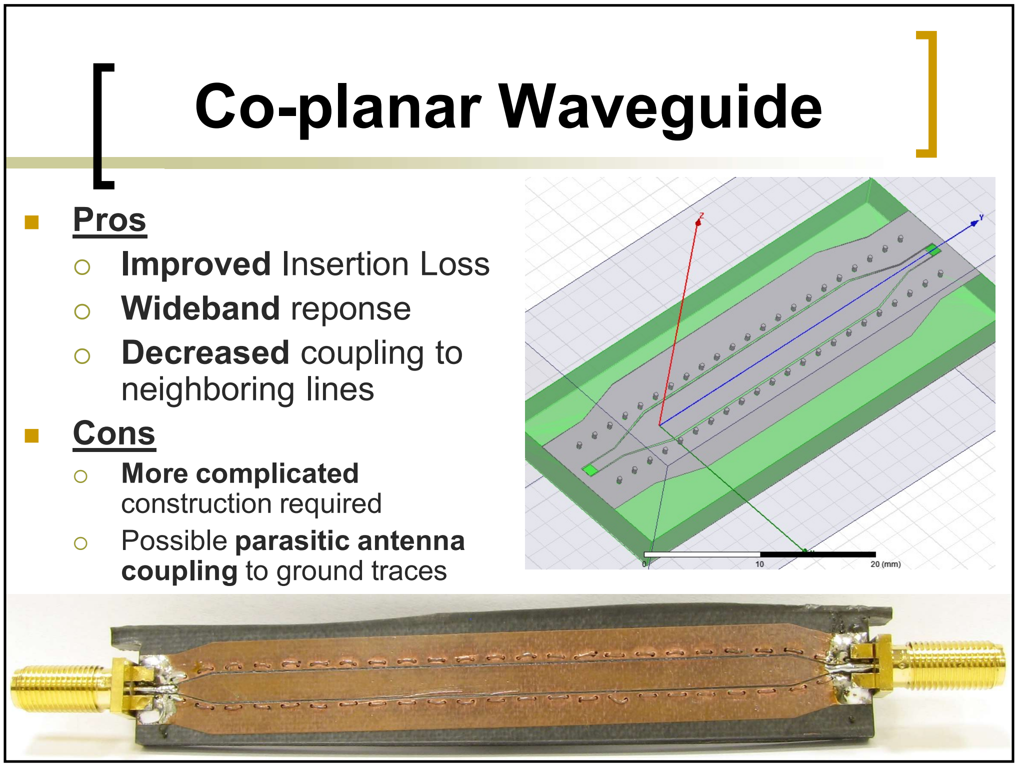

I put together a simple connection diagram to illustrate how my switching network will be integrated into the antenna array in the lower right corner of this slide. This choice freed me from even more additional costs, as I would no longer need a large number of cables to connect each of an external multiplexer's outputs to each of my antennas in the array, and would instead be able to connect my antenna array directly to the network analyzer. This did, however, make the design and construction of my array significantly more difficult.




The switch IC I chose to use for my switching network is manufactured by MA-COM Technology Solutions, and works from DC all the way up to 8[GHz] and features a minimal insertion loss of 0.5 decibel. In January, I built my first test board on FR-4 substrate in order to test my ability to design and construct a circuit using these ICs; the performance beyond 1 GHz was terrible, but I learned many lessons from it, in particular, the fact that FR-4 is a very lossy substrate above 3 GHz and is not a good choice for my project.



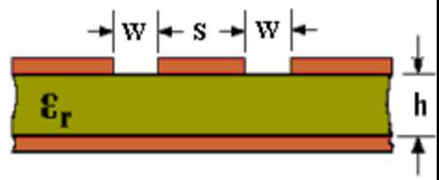

Each of these switches is arranged in a branched network of connections and requires only an 8-bit logic control signal to select which antenna will be connected to the vector network analyzer at any given time. Since the signal must pass through a total of four switches between the network analyzer and the antenna patch, there is a minimum of 2 decibels lost in the switches alone (not taking into account the losses of transmission lines connecting all of them).

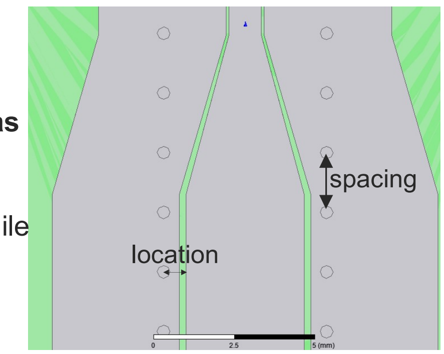



To route the signal between each of the switches in the switching network, I chose to use a coplanar waveguide structure, which can be constructed on the same surface as the antenna array and thus makes the layout of the array fairly straightforward. It has the benefits of very wideband performance compared to microstrip transmission lines and increased isolation between components. I am also able to intrinsically vary the width of the center conductor, allowing me to interface with the small, 0.25[mm]x0.35[mm] pins of the switch IC I chose to use. At the bottom of the slide is a prototype I made to test my design and construction of the waveguide.

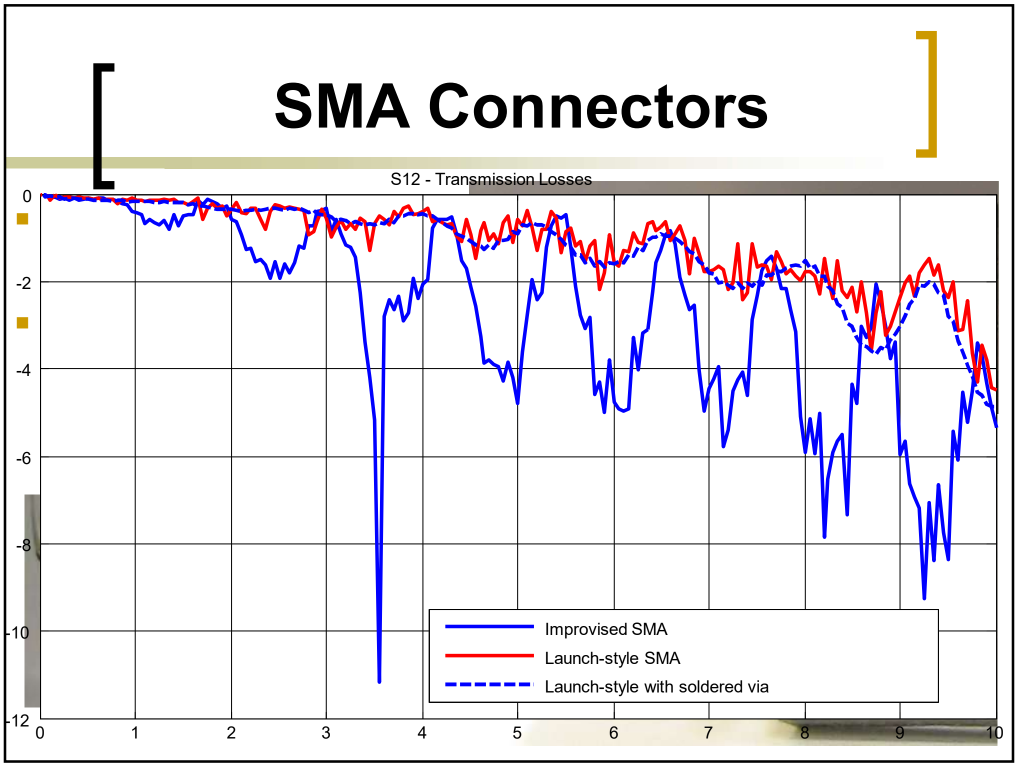
# Coplanar Waveguide

- **Initial dimensions determined from online calculator**
  - W = 0.1[mm]
  - S = 2.285[mm]
  - Small tweaks based on HFSS simulation results
    - Automated optimization
- **Adjust spacing/number of ground vias**
  - Affects wideband response of transmission line
  - Optimized to give best response while reducing construction complexity



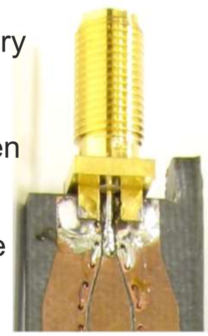

Through a series of computer simulations using HFSS, I was able to determine the best design characteristics of my coplanar waveguides in order to match the wideband nature of my design. I discovered many things that could be varied to optimize my design and construction process, such as the spacing and location of the ground vias on the side conductor ground planes.




Finally, the SMA connectors needed to be worked out. They are the one connection point between the antenna array's main connection and the Network Analyzer, and represent the point where the radiation changes from a coaxial to a planar transmission. I initially used some SMA connectors that Dr. Zhou had available, but I found out that the performance with my coplanar waveguide prototype was very lossy. After doing some research on the topic, I discovered that what I actually needed was a "launch style" connector, where the central connector is surrounded in a fashion similar to the coplanar waveguide. Tests confirmed that when I soldered some spare copper wire to my connectors, the performance was greatly improved. After I purchased some launch style connectors, the performance was finally close to what my HFSS simulations indicated they should be, as shown in the red curve.

# Antenna Array with integrated Multiplexer

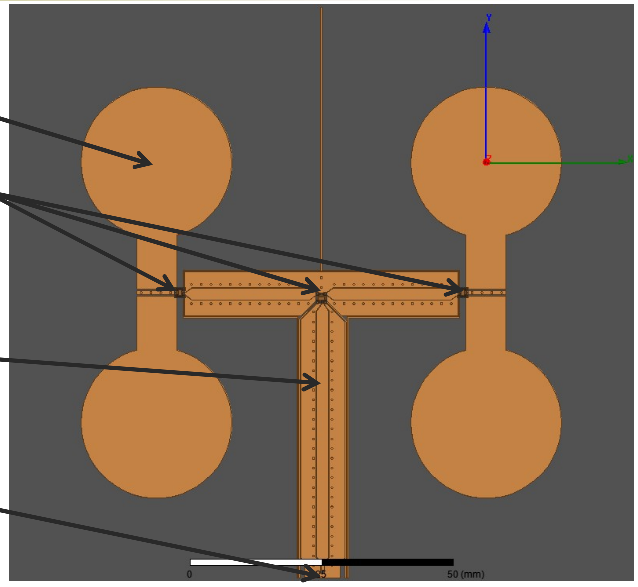
- Substrate
  - Rogers Corp RT/Duroid 5880 (3.175[mm] thickness)
- Antenna
  - Size: ( 24[mm] x 24[mm] ) + 5[mm] coplanar feed
  - Bandwidth roughly 3[GHz]-7[GHz]
- Switch ICs
  - MASW007107
    - Inexpensive, no external components necessary
- Grounded Coplanar Waveguides
  - Routes signal between components
    - Broadband, low-loss, inherent isolation between lines
- SMA connector
  - “Launch-Style” integrates with coplanar waveguide
  - Expensive, but necessary



So, the last choice I am left with is my antenna array substrate, and I decided to use what was available on hand from Dr. Zhou and it turned out to be a good choice for my project, Rogers RT Duroid 5880. I have my ultra wideband antenna design, my switch ICs, coplanar waveguides for feeding the signal between switch ICs, and my SMA connectors. I set out to design a 2 by 2 antenna array with an integrated switching network in order to test all that I had simulated and built small test boards for up to this point.

# 2x2 Antenna Array Layout

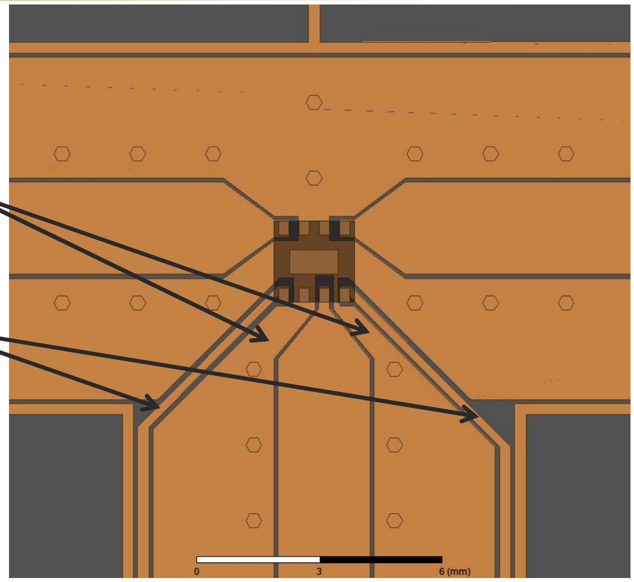
- Antenna
- RF Switch ICs
  - MASW007107
- Coplanar Waveguide
- SMA Connector Feed-point



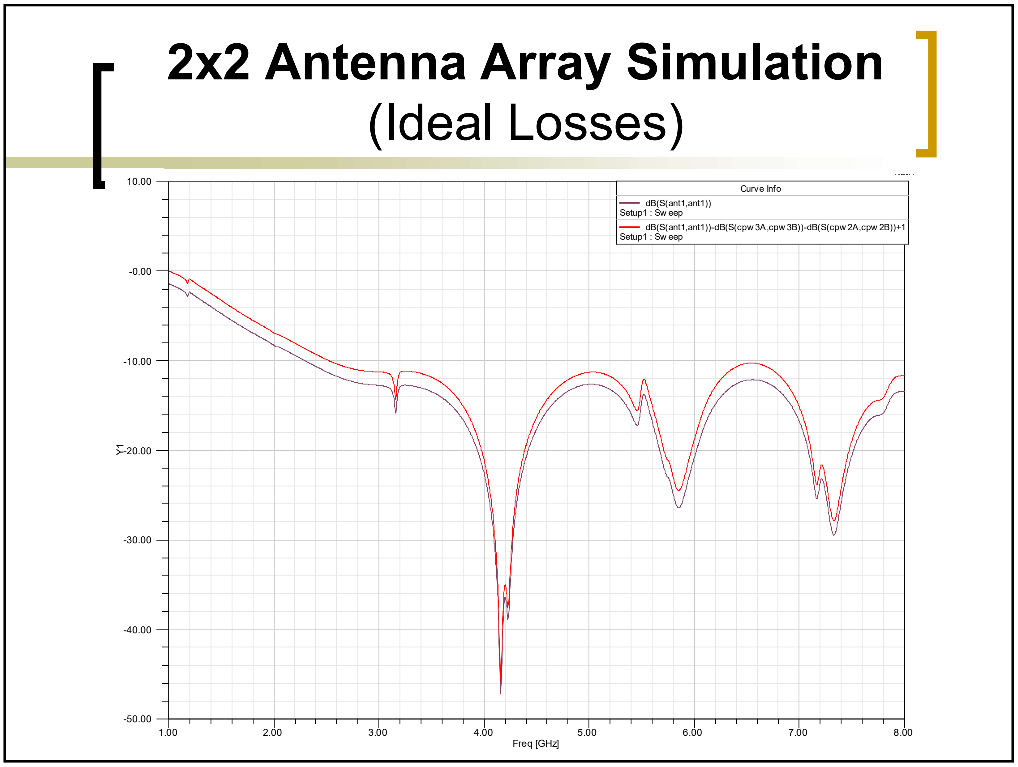
This is the arrangement I came up with in HFSS for my first prototype. You can see the four antennas, the three RF switch ICs, and coplanar waveguides, and the SMA connector feed point.

# 2x2 Antenna Array Layout

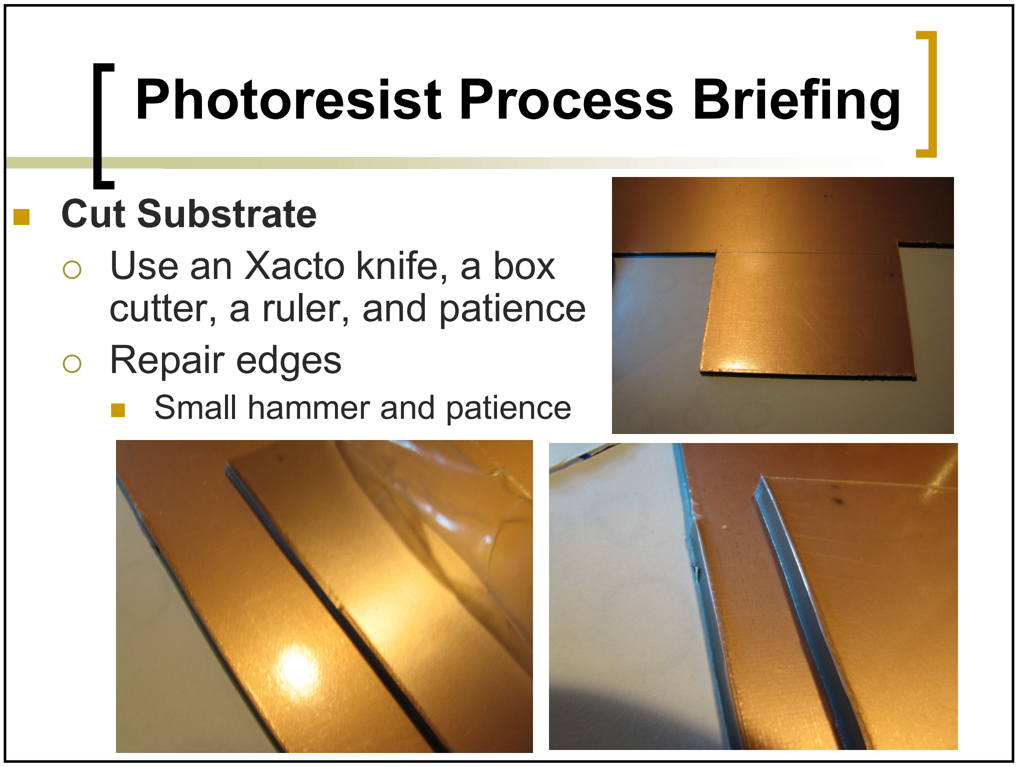
- Difficulties
  - Coplanar waveguide ground planes
  - Switch logic control lines
- Some level of artistic creativity required




When you zoom in on the central switch IC, you can see where some level of artistic creativity is required to interface the coplanar waveguides with the switch IC.



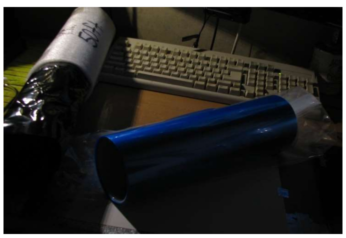

The purple curve in the graph shows the simulated ideal performance of my ultra-wideband antenna, while the red curve shows the simulated ideal performance of the antenna after incorporating the losses that would be due to the feeding and switching network. You can see that the switching network impacts the effective bandwidth of the antennas, and this is why having the return loss as high as possible is very important to the performance of the system.

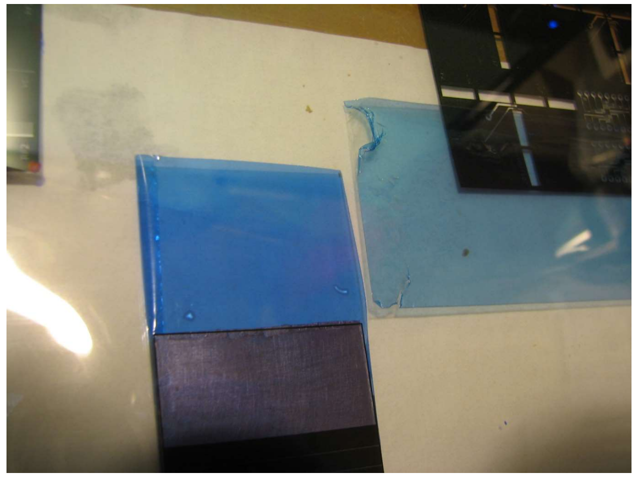


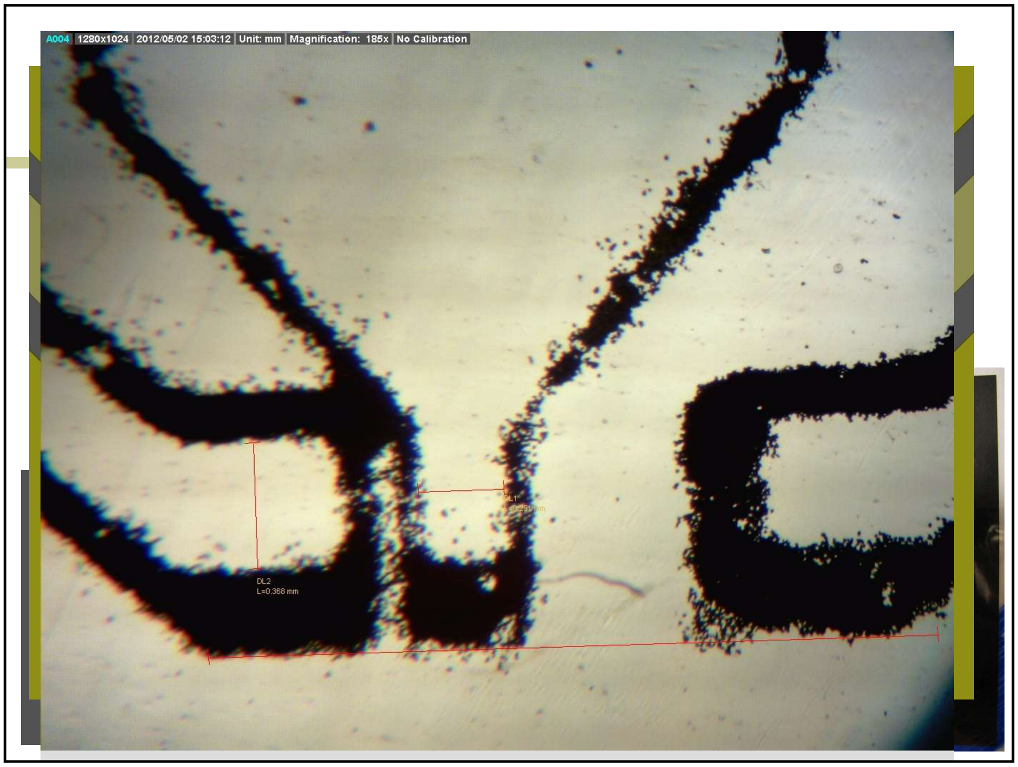

In order to actually construct the prototypes, I used a photoresist process. Compared to the more traditional method of toner transfer, using a photoresist method is generally much more precise and accurate in its reproduction of designs made on a computer. I determined that the minimum feature size on the etched copper that I can reliably reproduce with my setup is 0.1mm, but my design has a few features around the IC pins that are actually down to 0.08 mm.

# Apply Photoresist Film

- Practice, practice, and practice some more.



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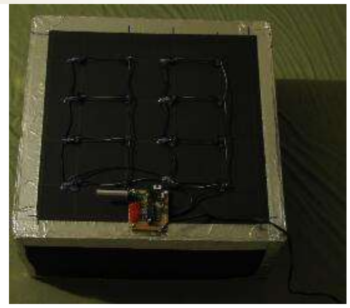
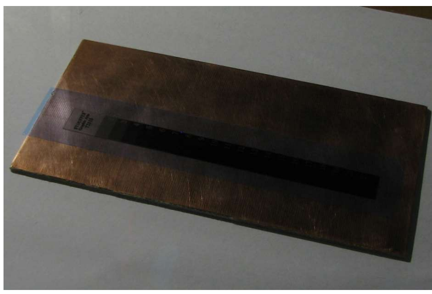
# Expose to Ultraviolet Light and Develop

- **UV LED Light Box**
  - Small project for this purpose
  - PIC Microcontroller for Timer
  - Needs to be calibrated (*Stouffer Guide*)
    - Once per roll of Photoresist Film
- **6 minutes exposure time per side**
  - Varies depending on mask opacity

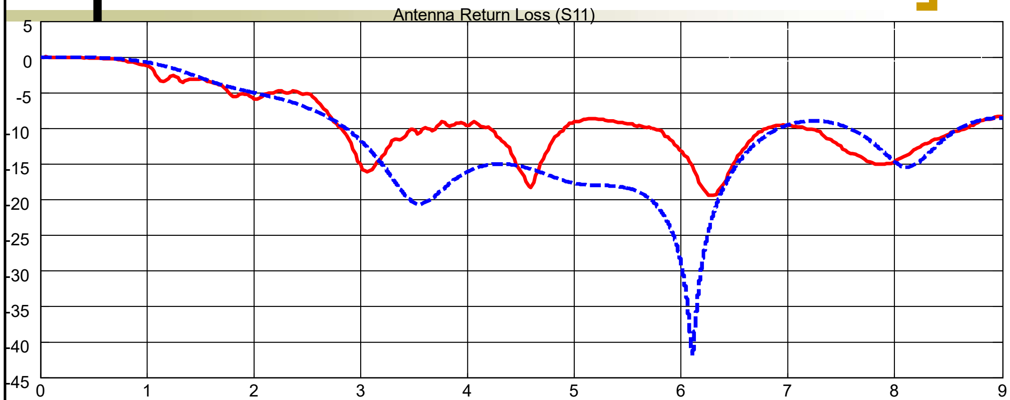


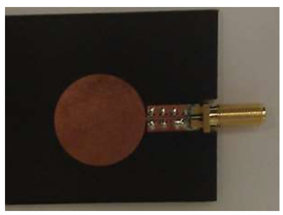


# Develop Film and Etch

- 1% Sodium Hydroxide Solution
  - 2-3 minutes

# UWB Antenna Prototype

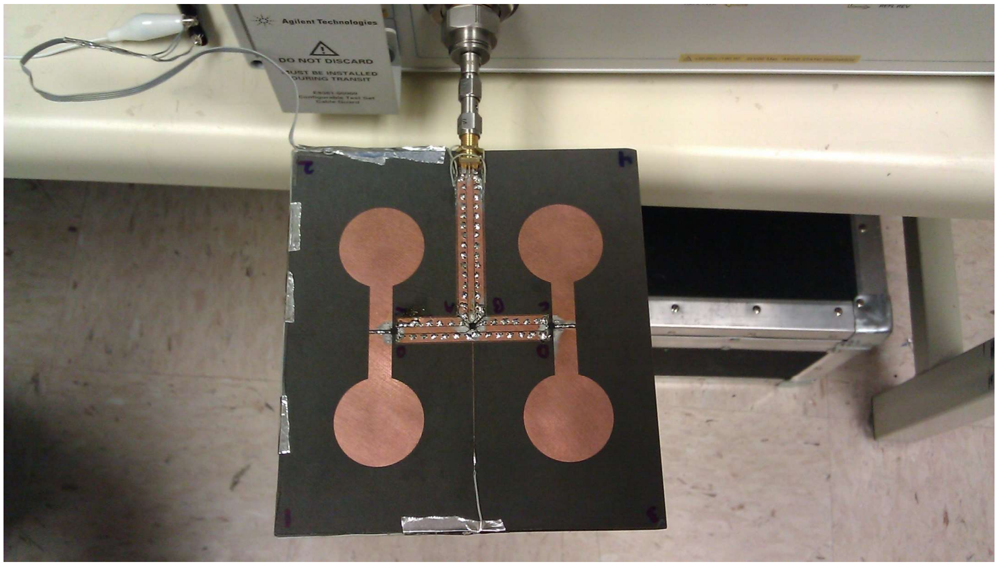


- **Bandwidth:** 2.9 [GHz] to 6.9 [GHz]
  - **BW / Fc** = 4.3 [GHz] / 5.05 [GHz] = 85.15%
- Extra losses due to mistake in design of coplanar feed structure.

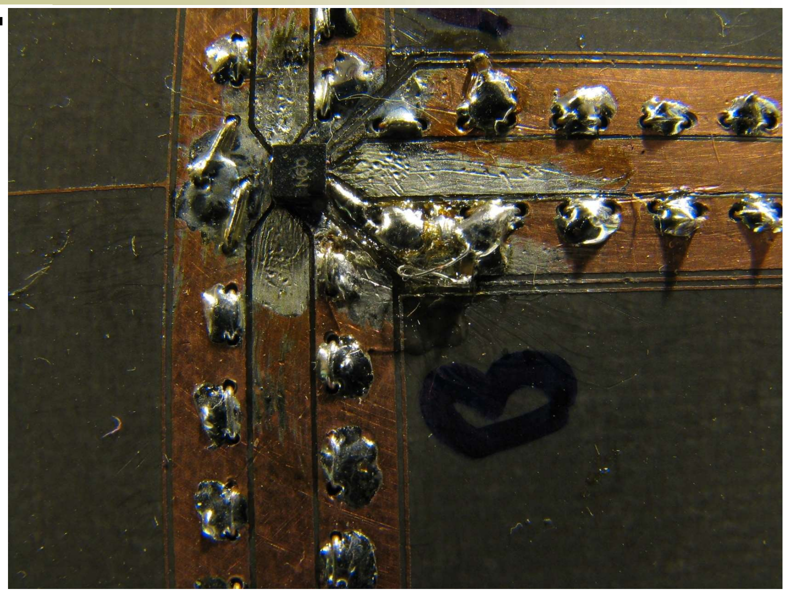
Here are the results of the first prototype I made of the antenna. Tests with the network analyzer indicated that the bandwidth was very similar to what was simulated, but the prototype suffers from a geometry mistake I made in the coplanar feed structure, and a new prototype will be constructed soon to confirm this.

# 2x2 Antenna Array Prototype



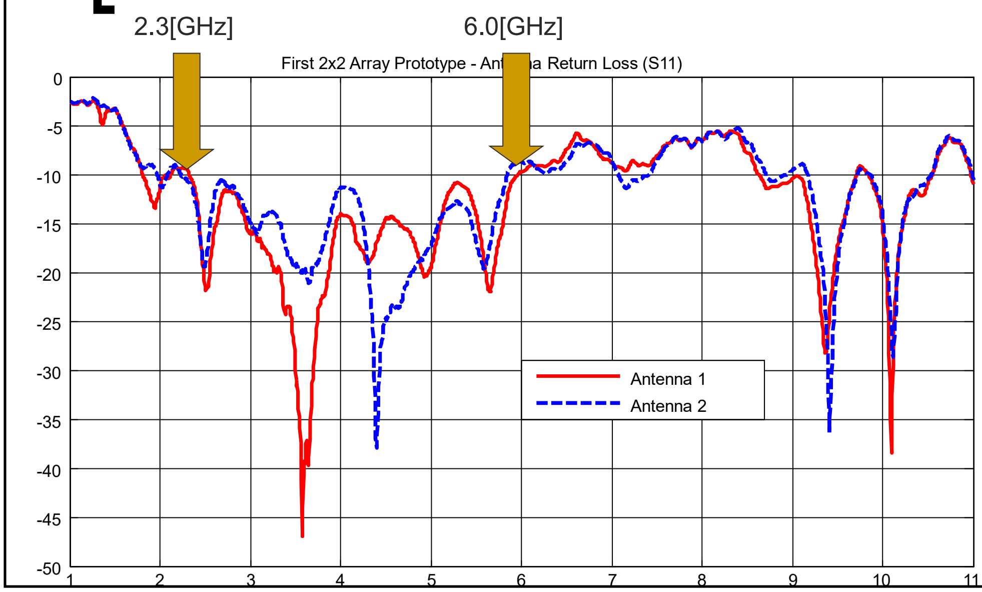

This is the constructed 2 by 2 antenna array prototype, from which I learned many things about how to optimize my design and construction process. These lessons will first be used in constructing a second 2 by 2 array prototype and culminate in my design and construction of a 4 by 4 antenna array soon.

# **2x2 Antenna Array Prototype** (close-up)



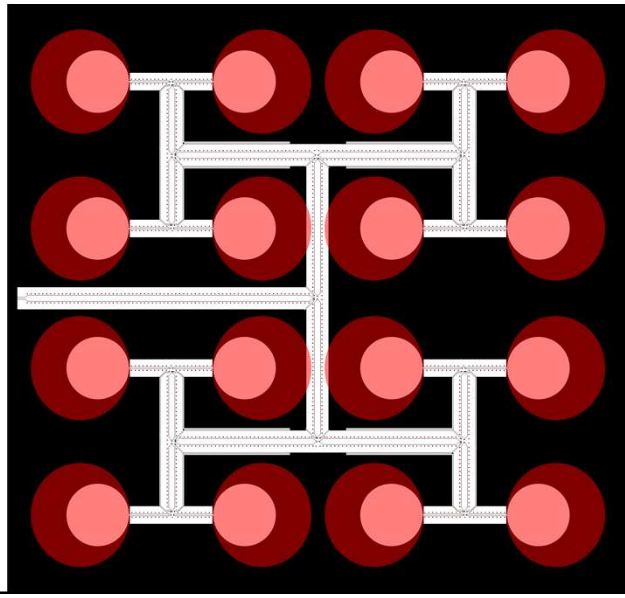
This close-up image of the prototype shows just how ugly things can get when working at these scales. Fortunately, the prototype worked as intended.

# 2x2 Antenna Array Prototype




This is the performance of one of the antennas in my array with the losses due to the switching network. It is not what I ideally wanted, but I expect significantly better results from my next prototype.

# 4x4 Antenna Array Design

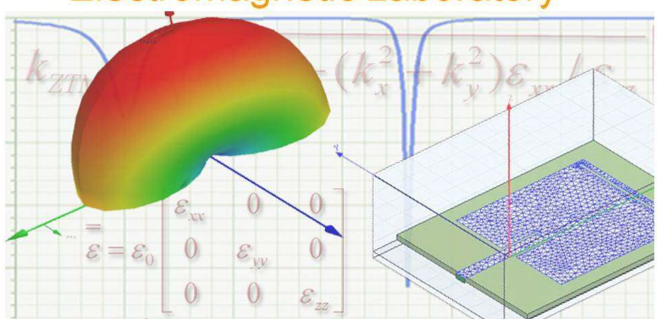


This is the performance of one of the antennas in my array with the losses due to the switching network. It is not what I ideally wanted, but I expect significantly better results from my next prototype.

# Thank You
# For Your Attention

Department of Engineering

Applied Microwave & Electromagnetic Laboratory



Located in SETB 1.240

- Questions?

I would like to conclude by stating that none of this project would have been possible without the existence of the Applied Microwave and Electromagnetic Laboratory, located in SETB 1.240. Thank you for your attention, do you have any questions?