Introduction to Direct Modulation of a Symmetrical Half-Wavelength Patch Antenna Using Integrated Schottky Diodes

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Ph.D. Qualifying Exam

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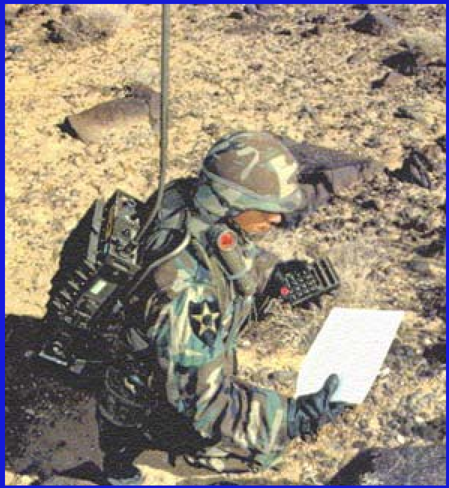
Presentation Overview

1. Army Research Office (ARO) Proposal
   - Motivation for research
   - Main research objective
2. Direct Antenna Modulation
   - General Concept
   - Brief historical review
   - Experiment Details
3. Patch Antenna Design Process
   - Patch antenna theory/design
   - HFSS Simulations
   - Construction and testing
4. Conclusion
   - Recap of completed research and experimentation
   - Future research plans

ARO Proposal

Research Motivation

- 80% of Army ground mobile communications occurs in the HF - UHF bands [6]
  - Low frequency: 3 MHz – 1 GHz
  - Long wavelength: 30 cm – 100 m



Manpack Radio Set AN/PSC-3
Adapted from www.tobyhanna.army.mil

M577A3 Tracked Command Post Carrier
Adapted from sill-www.army.mil

– Results in long, visually-compromising and cumbersome antennas

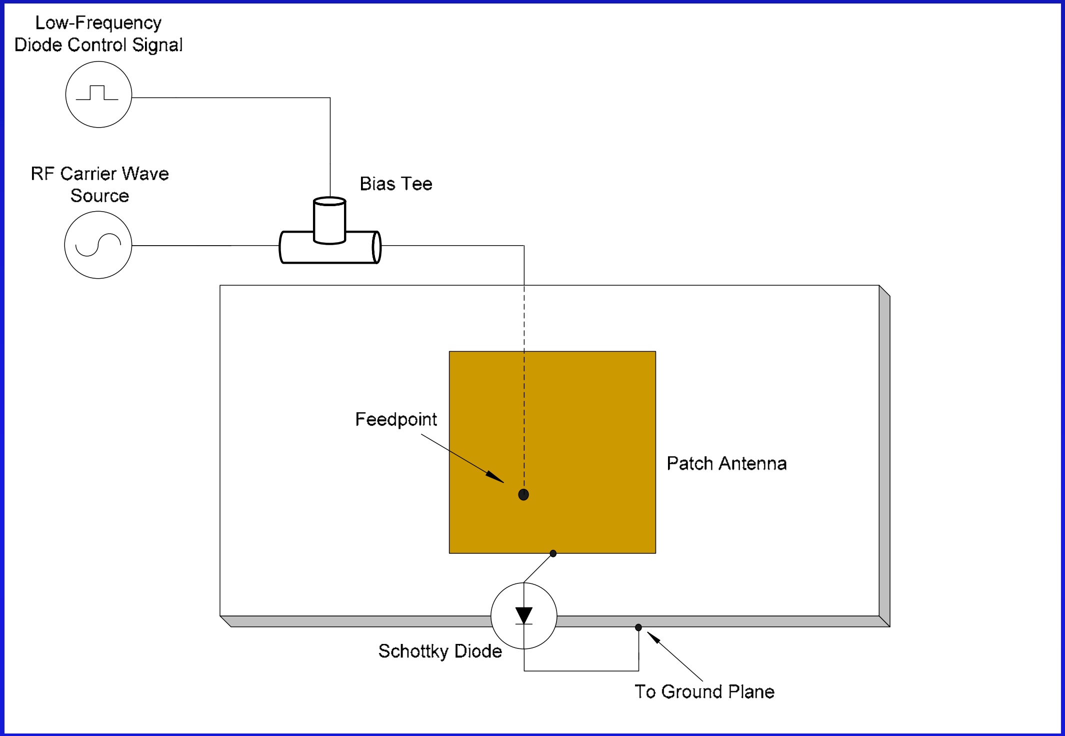
ARO Proposal

Main Research Objective

To investigate direct antenna modulation (DAM) as a technique to [6]:

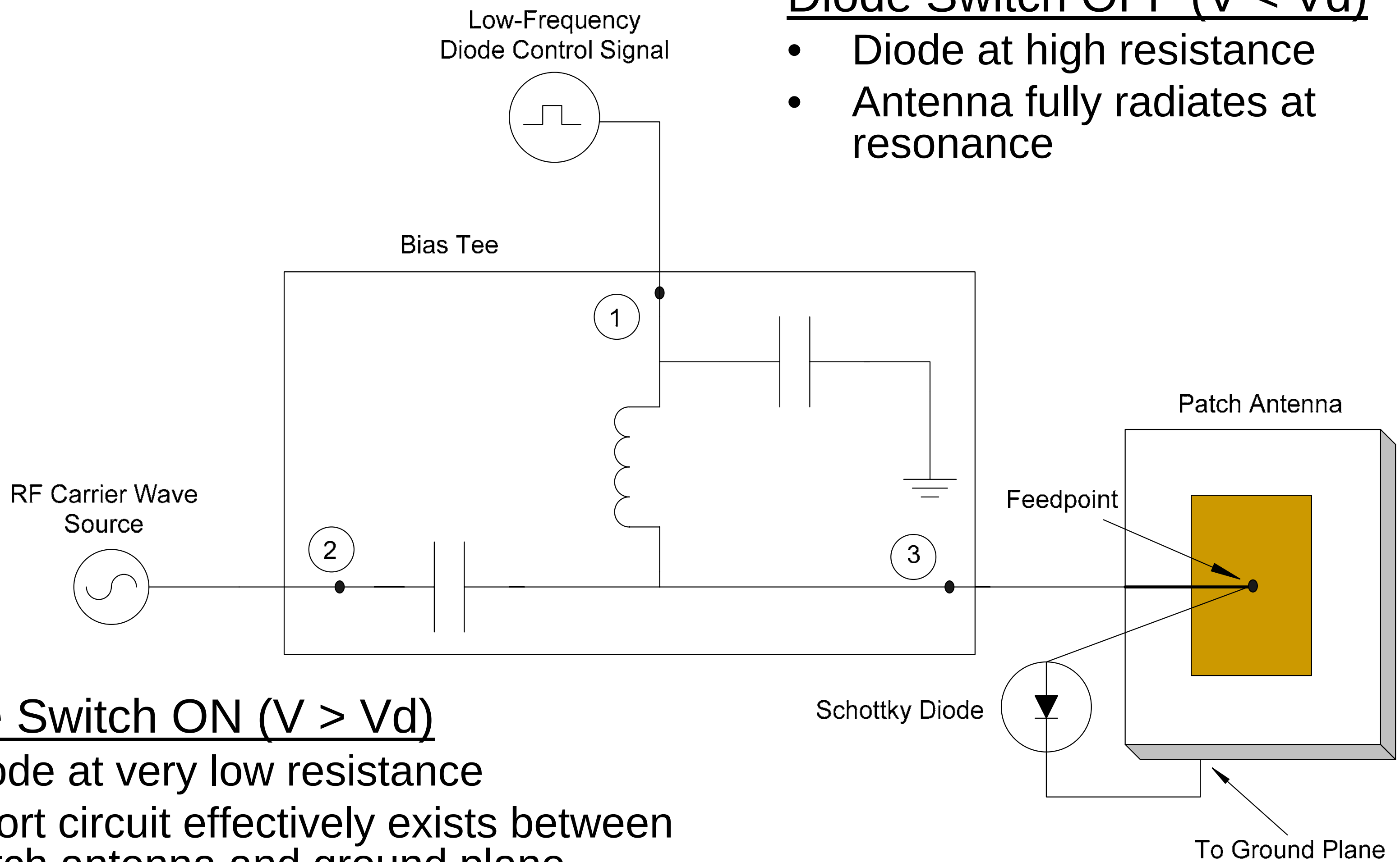
- Increase information bandwidth of Army comm. system antennas
- Maximize radiation efficiency of Army comm. system antennas
- Reduce the size/visual signature of Army comm. system antennas

DAM General Concept



- External carrier wave passes through bias tee and drives patch antenna at resonance
- Fast-switching diode (e.g. Schottky) connected between patch antenna and ground plane
- Baseband information signal passes through bias tee to feedpoint and controls diode switching
- Diode switching directly controls antenna radiation, resulting in a modulated carrier wave signal

DAM General Concept



Diode Switch OFF (V < Vd)

- Diode at high resistance
- Antenna fully radiates at resonance

Diode Switch ON (V > Vd)

- Diode at very low resistance
- Short circuit effectively exists between patch antenna and ground plane
- Oscillating charges on antenna radiation slots flow through diode to ground plane
- Antenna radiation effectively ceases

DAM Historical Review

Two papers explicitly explore direct antenna modulation:

Fusco and Chen [2]

• Designed an X-band patch antenna with integrated Schottky diode on silicon substrate

• Concluded that direct antenna modulation is possible by integrating a high-speed diode structure with an antenna and biasing it with a signal

Yao and Wang [7]

• Designed an S-band patch antenna with discrete Schottky diodes on low-loss substrate

• Potential information bandwidth increase above 6.5x the resonant antenna bandwidth

• Concluded that faster rise/fall times of Schottky diodes could lead to improved modulation responses and further bandwidth increases

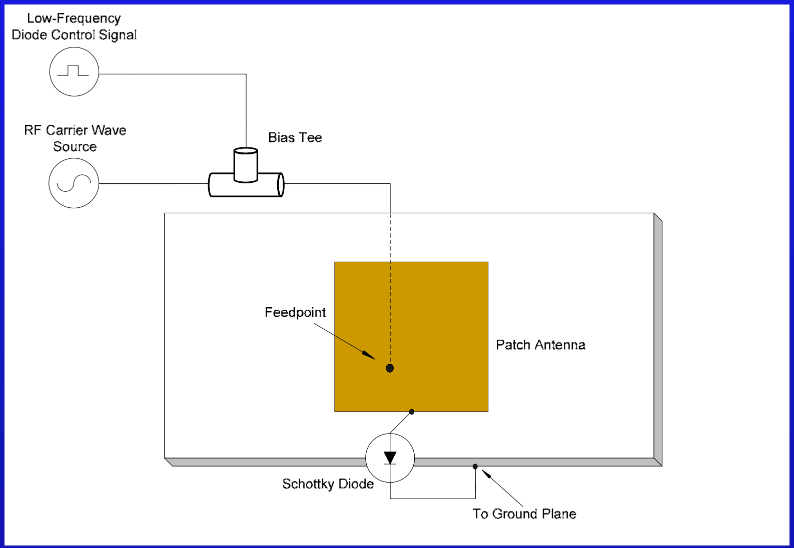
1st DAM Experiment

Objectives:

- Verify the feasibility of the direct antenna modulation technique
- Observe the upper limit to information bandwidth and compare to that of a basic amplitude-modulated system, limited by its resonant antenna bandwidth
- Explore modulation improvements from faster rise/fall time characteristics of Schottky diodes

Step 1:

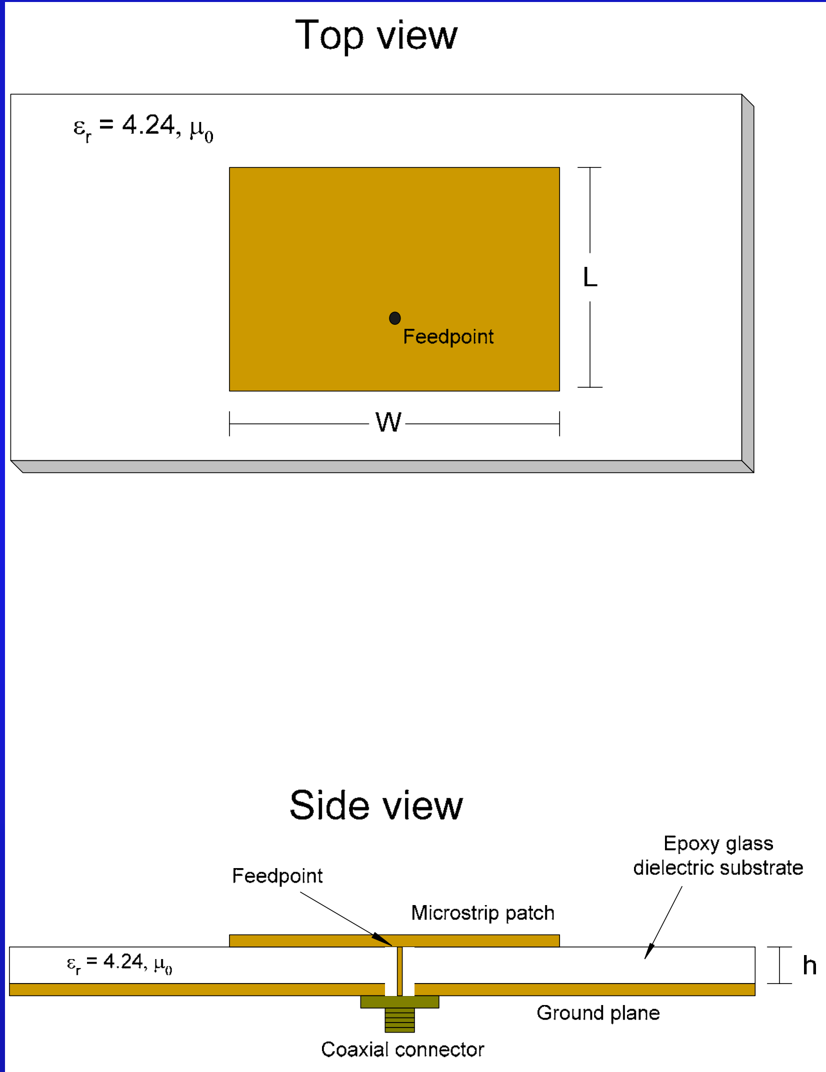
- Design patch antenna for experiment



Patch Antenna Design Process

Antenna Design

- Symmetric 1.5 GHz patch antenna
- G-10 epoxy glass substrate, $\varepsilon_r \sim 4.24$
- ~15 to 20 MHz Bandwidth (narrowband)



$$L \approx \frac{\lambda_0}{2}$$

W = variable

$$h = \tfrac{1}{16}"$$

Patch Antenna Theory

Length/Width Calculation for Symmetric Antenna

- For symmetric patch antenna,

$$L_0 = W_0 = \frac{\lambda_0}{2} = \frac{1}{2 \cdot f_c \cdot \sqrt{\mu \varepsilon_r}} = \frac{1}{2 \cdot 1.5 \cdot 10^9 \cdot \sqrt{4\pi \cdot 10^{-7} \cdot 4.24 \cdot 8.854 \cdot 10^{-12}}} \approx 4.85cm$$

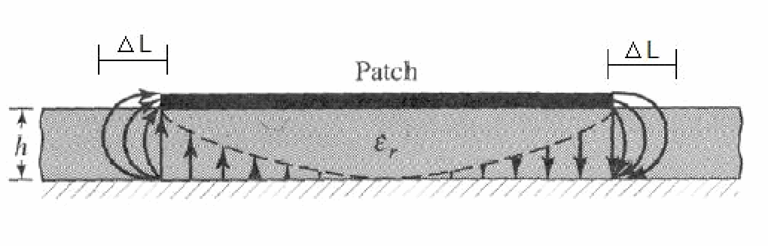
- However, fringing field effects must be considered,

$$\Delta L = 0.412 \cdot h \cdot \frac{(\varepsilon_{eff} + 0.3) \cdot \left(\frac{W}{h} + 0.264\right)}{(\varepsilon_{eff} - 0.258) \cdot \left(\frac{W}{h} + 0.8\right)}$$

These two formulas [1] were empirically determined and cannot be formally derived

where,

$$\varepsilon_{eff} = \frac{4.24 + 1}{2} + \frac{4.24 - 1}{2} \cdot \left[1 + 12 \cdot \frac{h}{W}\right]^{-0.5}$$



Adapted from [1]

Patch Antenna Theory

<u>Length/Width Calculation for Symmetric Antenna</u>

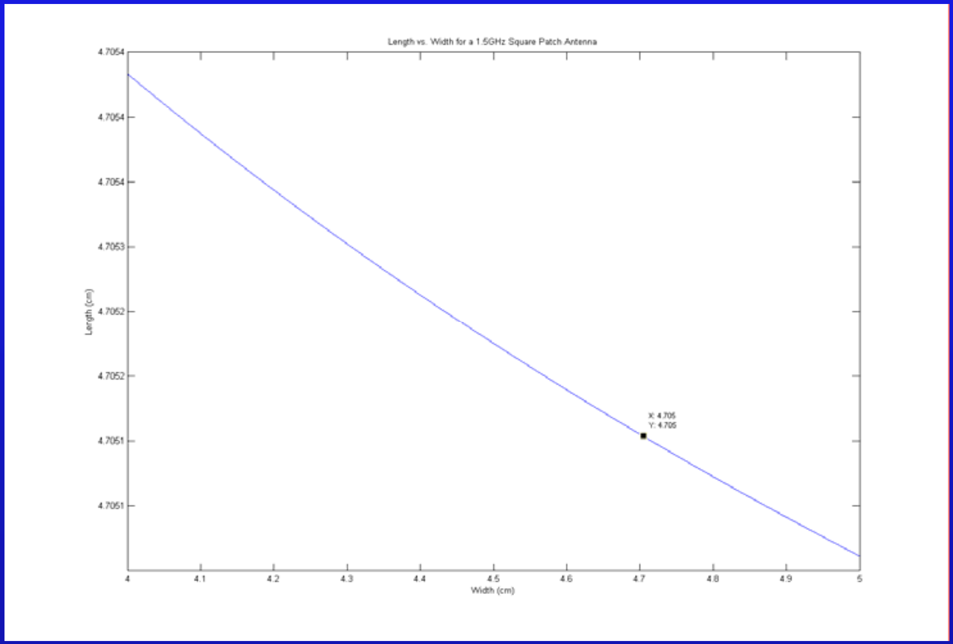
- Having determined the fringing field length, solve the following using MATLAB:

$$L = W = L_0 - 2 \cdot \Delta L = \frac{\lambda_0}{2} - 2 \cdot \Delta L$$

- According to theory,

L = W = 4.71 cm

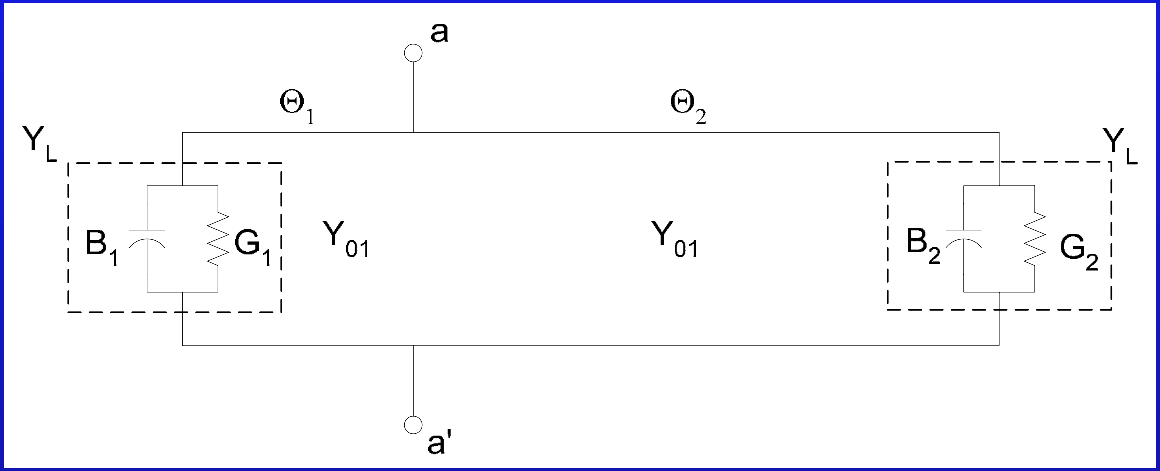
will yield an optimal square patch antenna with a center frequency of 1.5 GHz



Patch Antenna Theory

<u>Transmission Line Approximation</u>

- Patch antenna can be represented by a two radiating apertures separated by a transmission line with dimensions equal to that of the antenna
- Use transmission line theory to find feedpoint location (a,a') where Z = 50Ω



Patch Antenna Theory

Transmission Line Approximation

- According to transmission line theory,

$$Y_{aa'} = Y_{01} \cdot \frac{Y_L + jY_{01}\tan(\theta_1)}{Y_{01} + jY_L\tan(\theta_1)} + Y_{01} \cdot \frac{Y_L + jY_{01}\tan(\theta_2)}{Y_{01} + jY_L\tan(\theta_2)},$$

$$\theta_1 = \beta \cdot \ell_1, \qquad \theta_2 = \beta \cdot \ell_2$$

$$\beta = \frac{2\pi}{\lambda_0}$$

- Y_L can be approximated by [1],

$$Y_L \approx G_L = \frac{W}{120 \cdot \lambda_0}\left[1 - \frac{1}{24} \cdot (\beta_0 \cdot h)^2\right], \quad \beta_0 = \omega\sqrt{\mu\varepsilon}$$

Patch Antenna Theory

Transmission Line Approximation

- To solve for Y_{01}, note that:

$$Z_{01} = \sqrt{\frac{L}{C}}$$

- From a Schwarz-Christoffel transformation applied to a standard microstrip transmission line,

$$C = \varepsilon \cdot F(g), \quad L = \frac{\mu}{F(g)}$$

$$F(g) = \frac{2 \cdot W}{h} + \frac{2}{\pi} + \frac{2}{\pi} \cdot \ln\left(1 + \frac{\pi \cdot W}{h}\right)$$

- Finally, Y_{01} is solved for as:

$$Y_{01} = \frac{1}{Z_{01}} = \sqrt{\frac{C}{L}} = \sqrt{\frac{F(g)^2}{\mu/\varepsilon}} = \frac{\frac{2 \cdot W}{h} + \frac{2}{\pi} + \frac{2}{\pi} \cdot \ln\left(1 + \frac{\pi \cdot W}{h}\right)}{\sqrt{\mu/\varepsilon}}$$

Patch Antenna Theory

Feedpoint Calculation for Symmetric Antenna

- Having determined the equations for Y_{01} and Y_L in terms of h and W (set to 4.71 cm), set $Y_{aa'} = 1/50\Omega$ and solve the original transmission line equation for Θ_1, using MATLAB:

$$Y_{aa'} = Y_{01} \cdot \frac{Y_L + jY_{01}\tan(\theta_1)}{Y_{01} + jY_L\tan(\theta_1)} + Y_{01} \cdot \frac{Y_L + jY_{01}\tan(\theta_2)}{Y_{01} + jY_L\tan(\theta_2)}$$

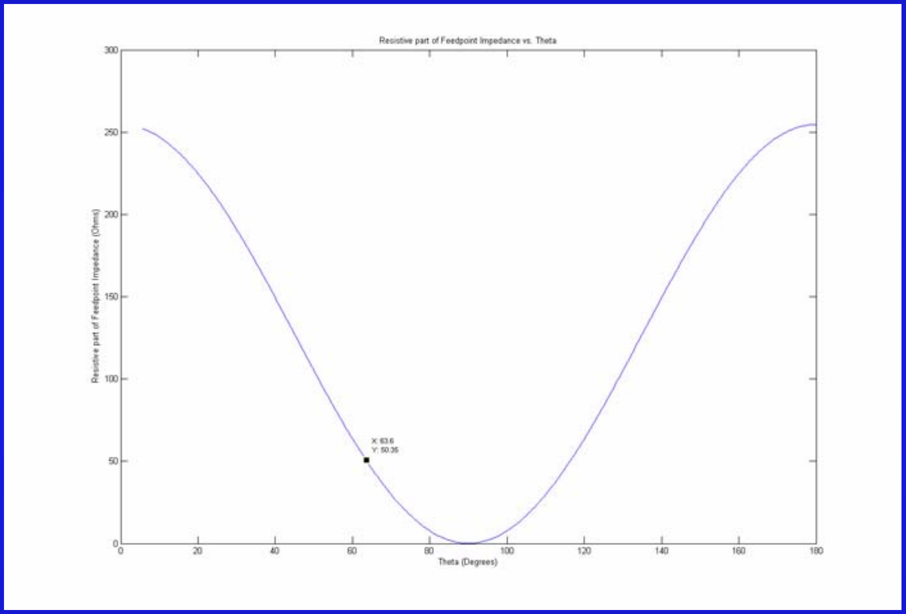
- Note that $\Theta_2 \approx 180^\circ - \Theta_1$, since this is a half-wavelength antenna design
- According to theory,

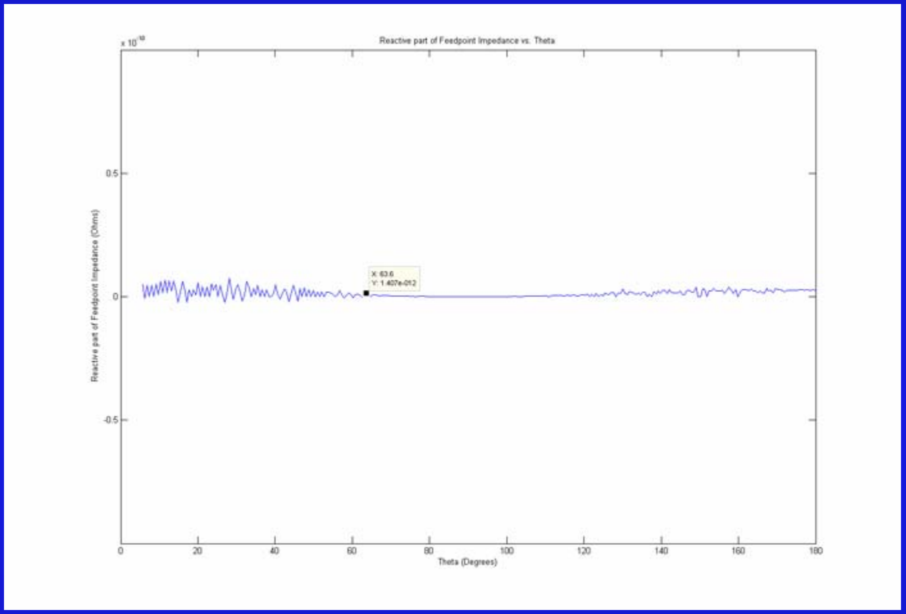
$$\mathbf{\Theta_1 \approx 63.7^\circ}$$

will yield an optimal ~50Ω impedance-matched feedpoint

Patch Antenna Theory

Feedpoint Calculation for Symmetric Antenna





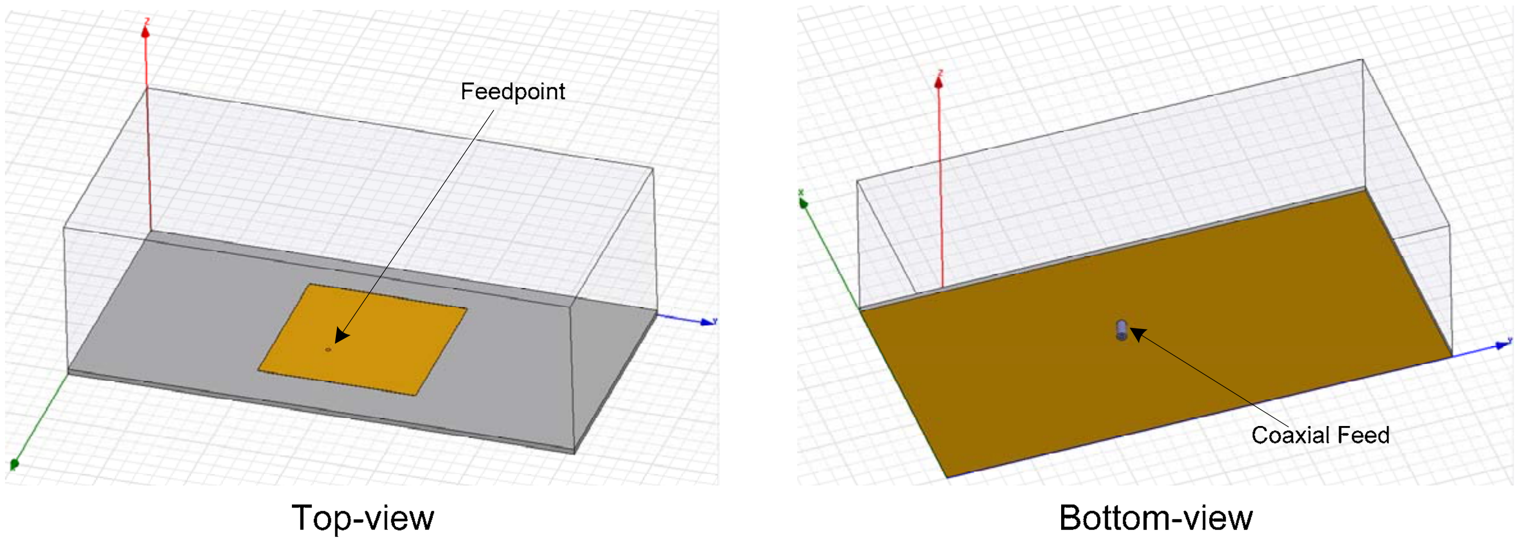
- The resulting feedpoint location along the patch diagonal was determined as follows,

$$\ell = \frac{\theta_1}{180°} \cdot W = \frac{63.7°}{180°} \cdot 4.71 = 1.67cm$$

$$\ell_{diagonal} = \sqrt{\ell^2 + \ell^2} = \sqrt{2 \cdot 1.67^2} = 2.36cm$$

HFSS Simulation

- HFSS simulation conducted to optimize patch antenna design



<u>Simulation Details</u>:

- <u>Sweep</u>: Fast Sweep from 1 GHz to 2 GHz

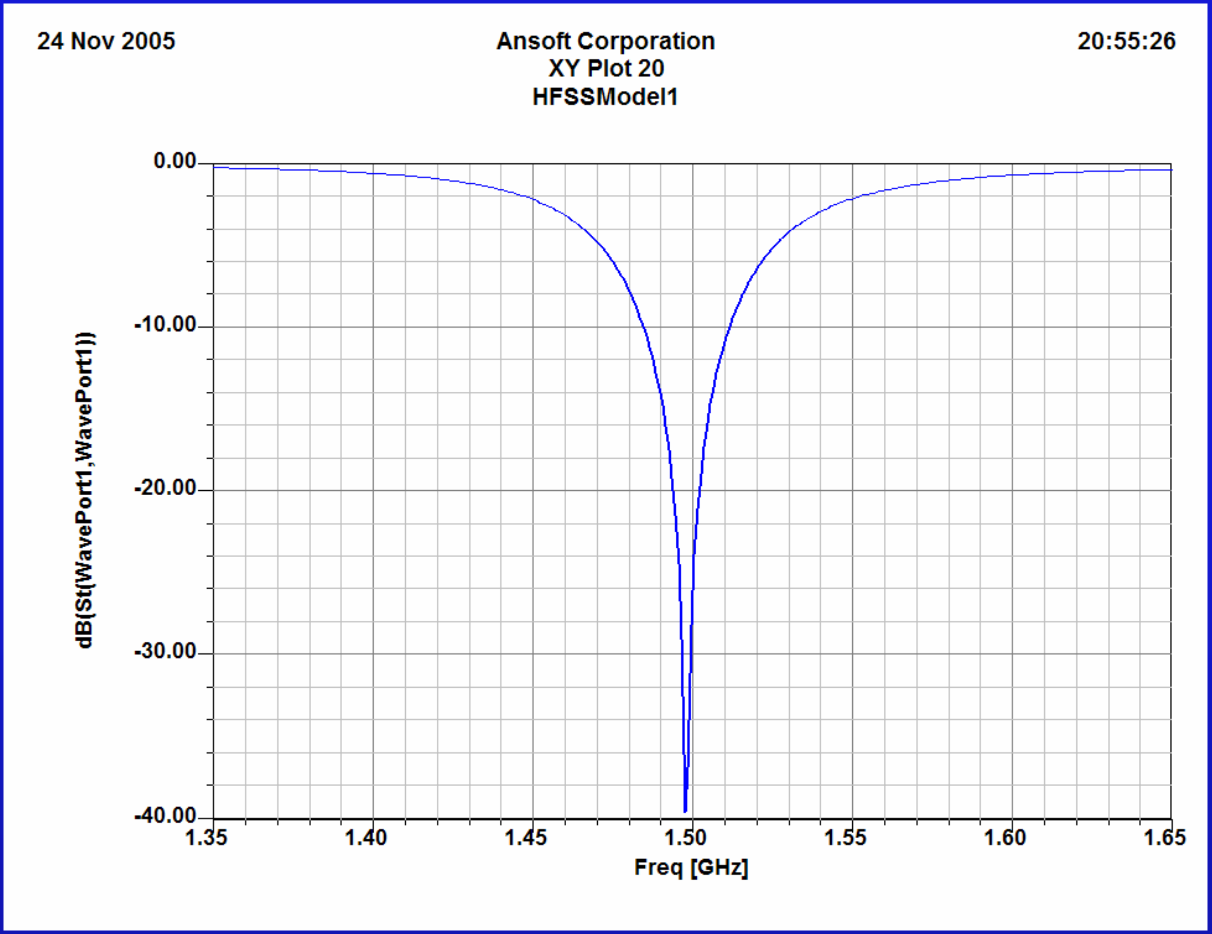
- <u>Center frequency</u>: 1.5 GHz

•<u>Antenna Dimensions (Optimized)</u>: 4.76 x 4.76 cm w/ feedpoint ~2.38 cm along patch diagonal

HFSS Simulation

S11 Response

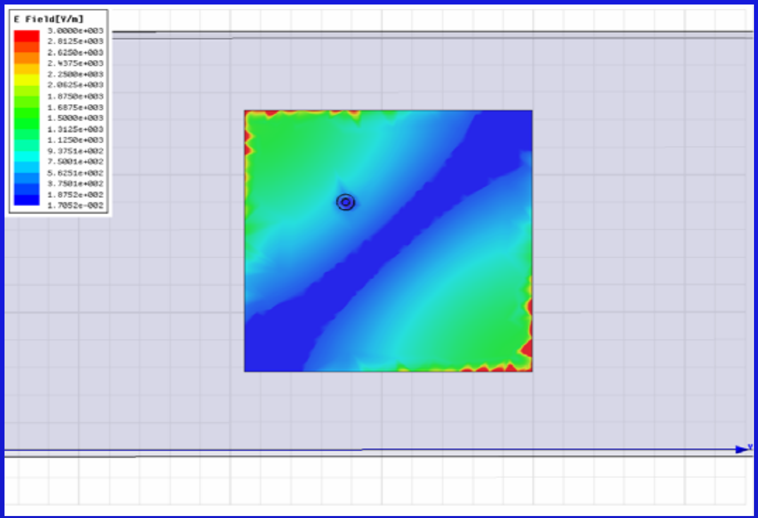
Center Frequency: -39.5 dB at ~1.496 GHz



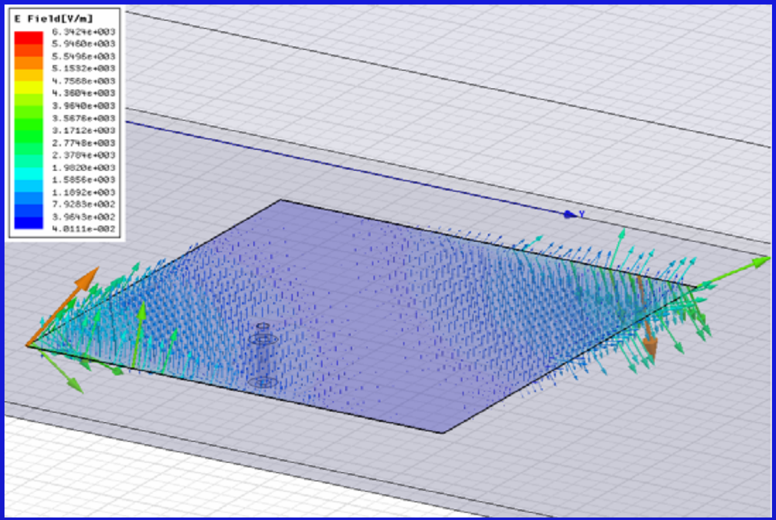
HFSS Simulation

Optimal Diode Locations

- For optimal direct antenna modulation, diodes should be placed at points of greatest electric field strength



Electric Field Magnitude Plot
(Bottom View of Patch Antenna)

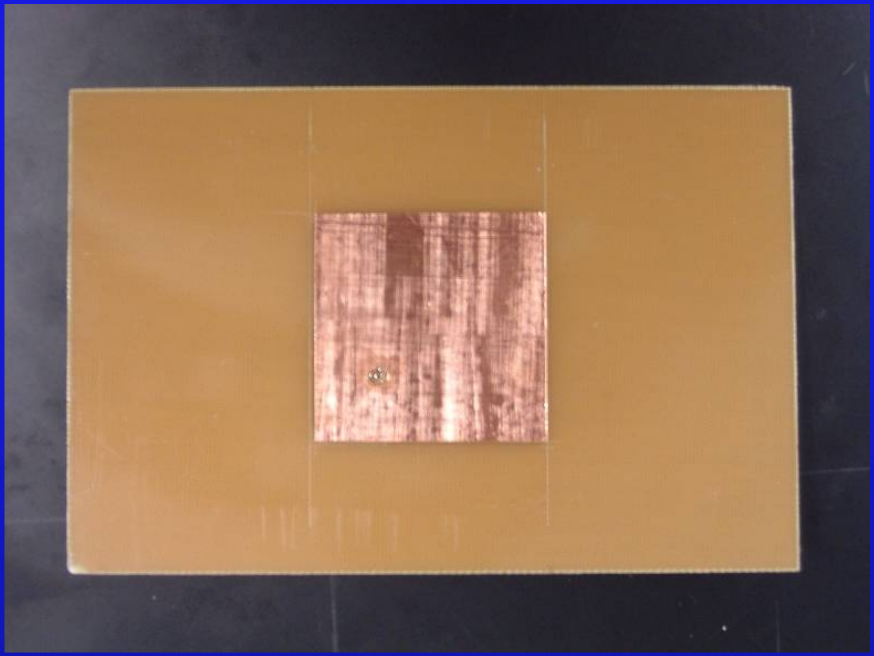


Electric Field Vector Plot
(Angled Top View of Patch Antenna)

- Highest electric field points occur near patch antenna corners along the feedpoint diagonal

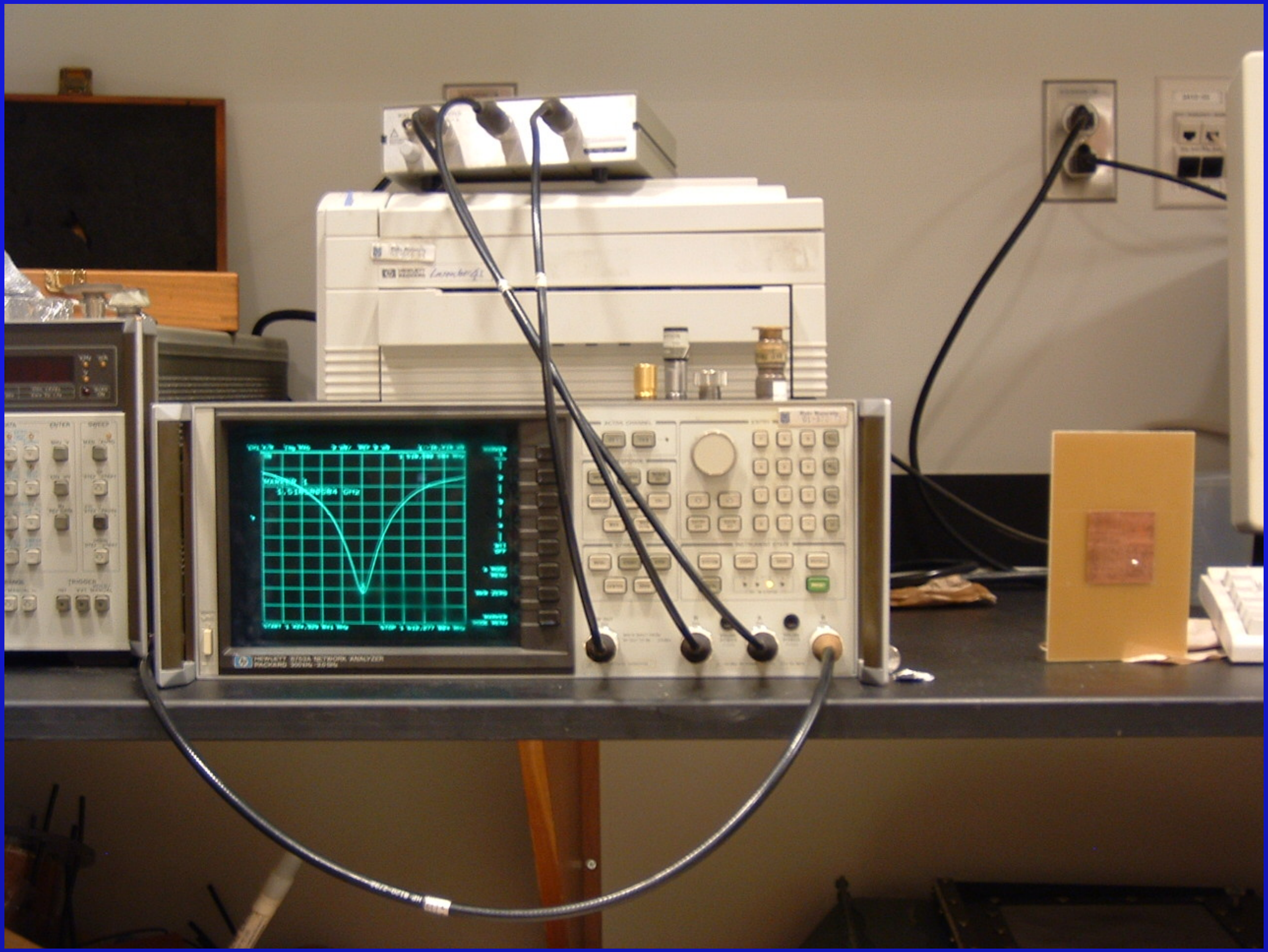
Construction and Testing

- Dielectric Substrate: 10.1 x 15.2 cm G-10 epoxy glass ($\varepsilon_r \sim 4.24$)
- Antenna Dimensions: 4.8 x 4.8 cm with feedpoint ~1.84 cm along patch diagonal

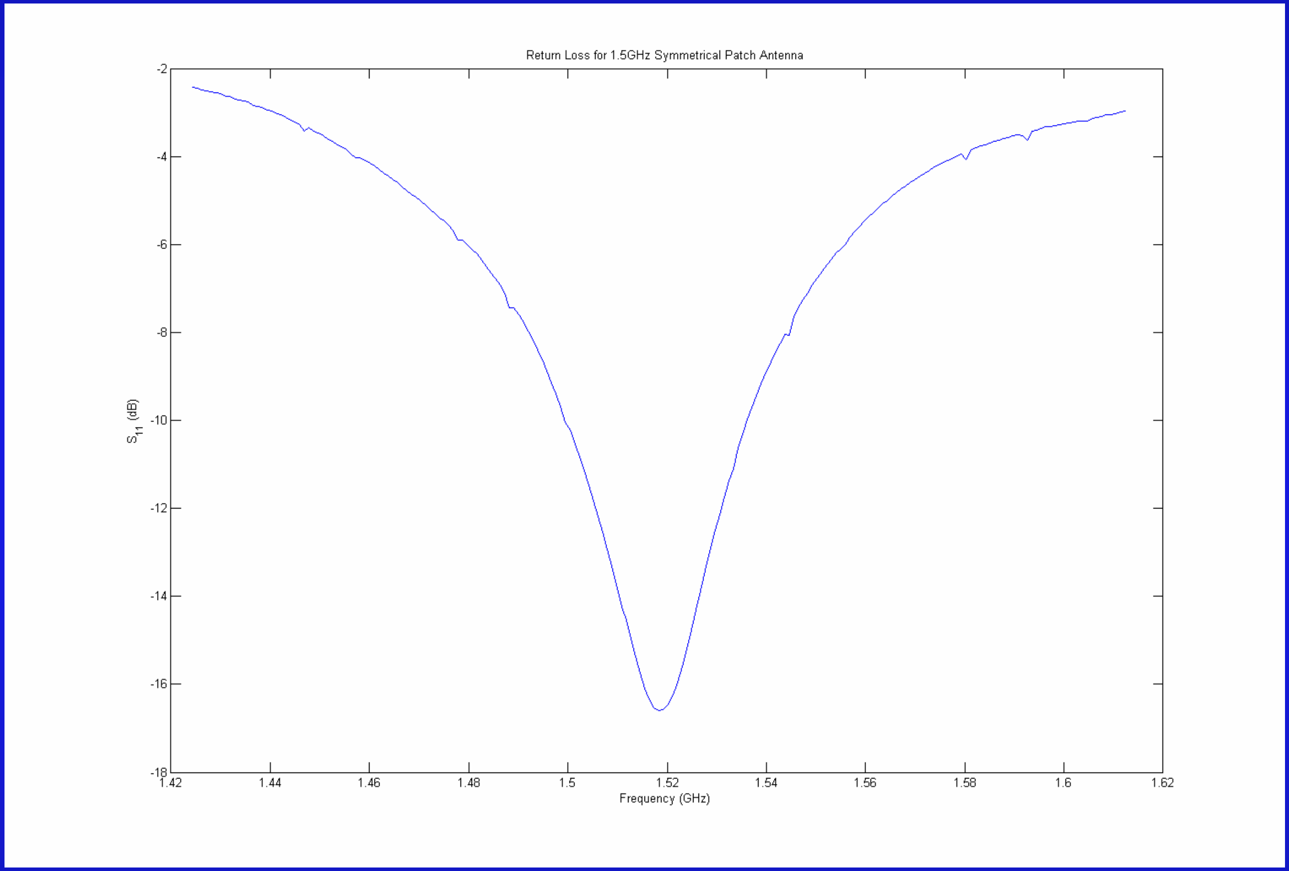


Construction and Testing

- Hewlett-Packard 8753A Network Analyzer used for patch antenna S11 return loss measurement



Construction and Testing

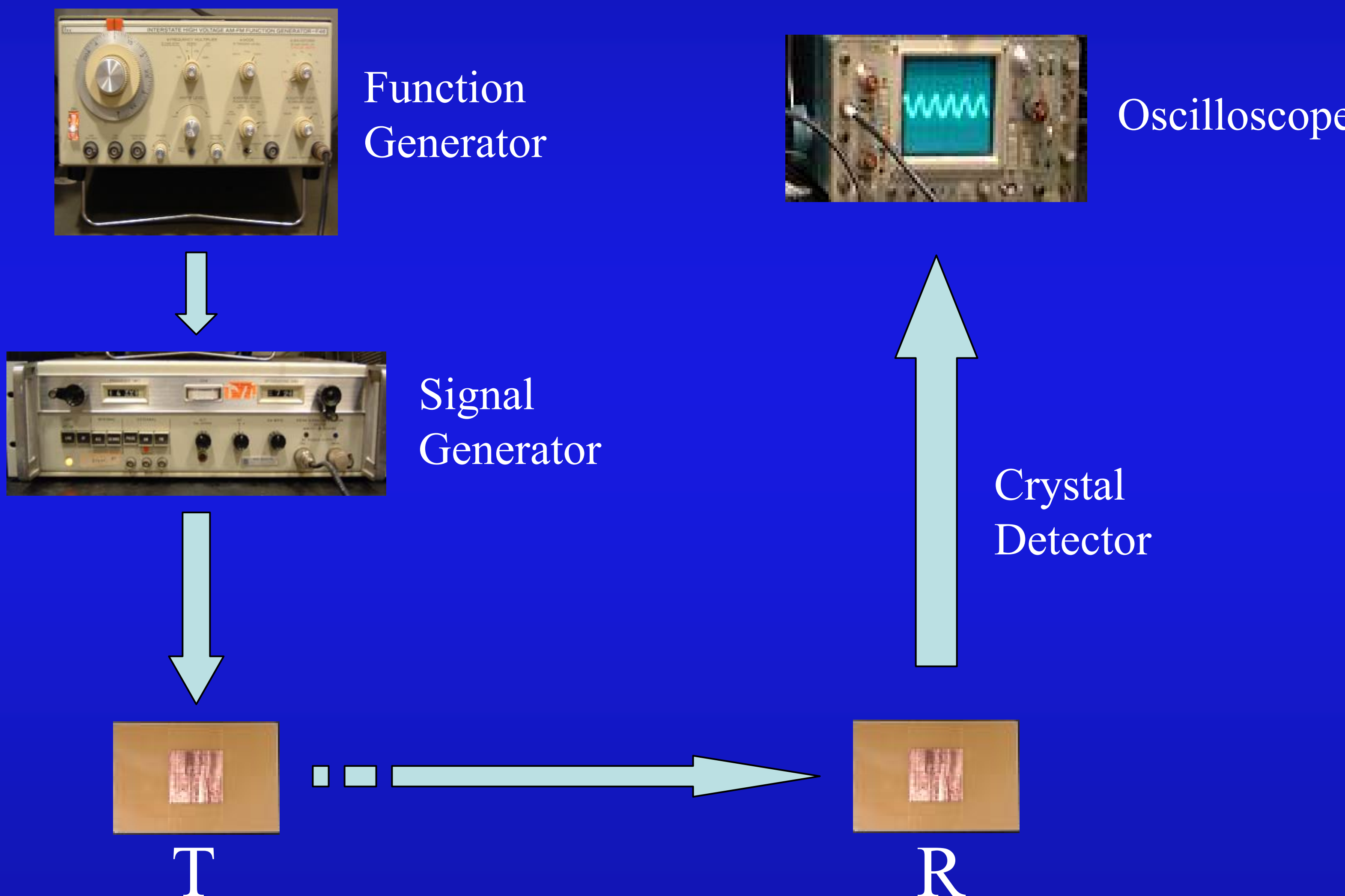


<u>Center Frequency</u>: -16.43 dB at ~1.518 GHz

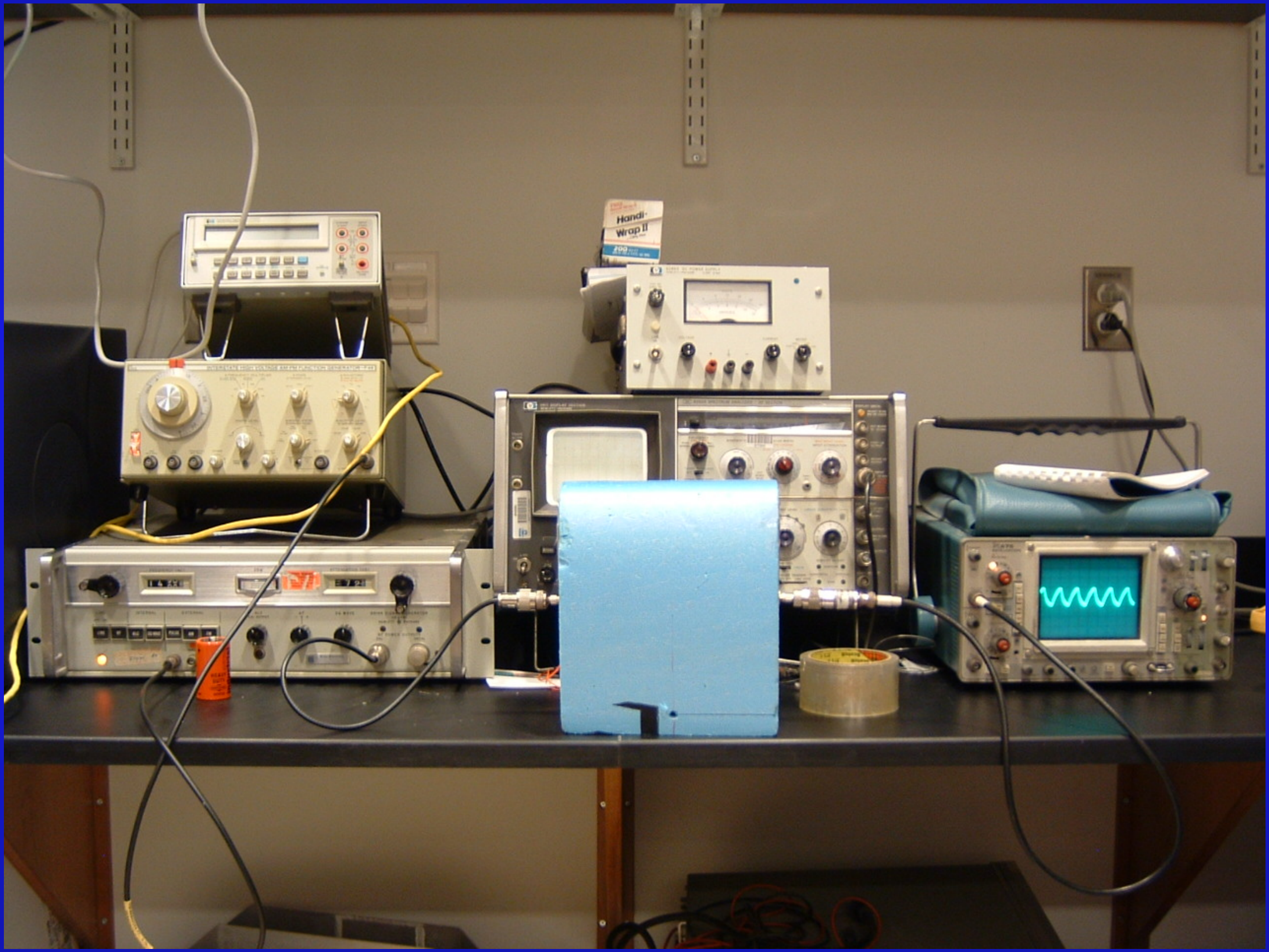
<u>Bandwidth</u>: 1500.07 MHz - 1536.23 MHz = 36.16 MHz (10 dB return loss standard)

1513.11 MHz - 1524.18 MHz = 11.07 MHz (15 dB return loss standard)

Basic Communication System

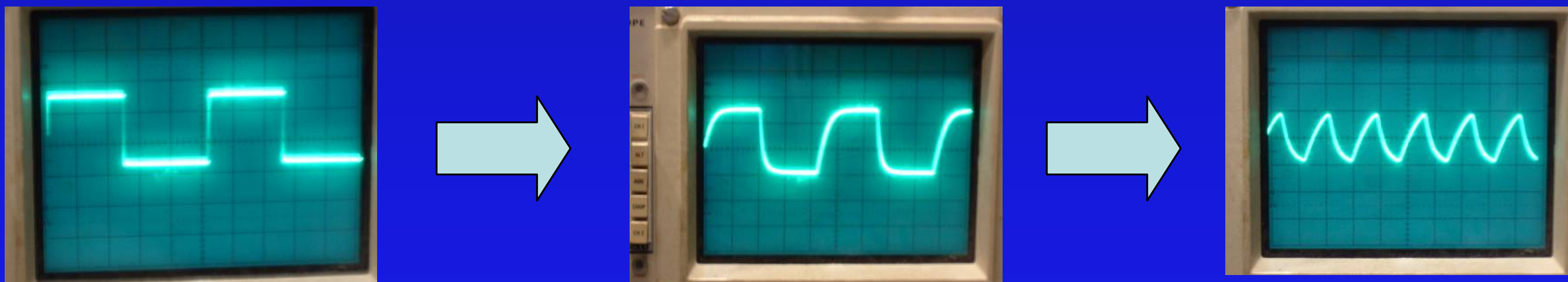


Basic Communication System



Measurement Bandwidth Limit

1kHz, 30mV 185 kHz, 15mV



- As the modulating baseband information signal frequency increases, received demodulated waveform becomes increasingly distorted and peak-to-peak voltage decreases
- Currently, the signal is becoming significantly degraded with a modulating information signal frequency of just ~110 kHz
- Signal degradation is most likely associated with the useable bandwidth of the crystal detector and is not due to the bandpass effect of the antenna

Basic Communication System

Modifications to Equipment

- Order better crystal detector to view demodulated received waveform
- Use sampling oscilloscope to view the modulated 1.5 GHz carrier wave

Expected Observations

- Signal will become increasingly noisy as frequency of baseband information signal increases
- For basic T/R case, information signal bandwidth will be limited by the bandpass effect of the patch antenna (should become quite noisy beyond 15-20 MHz)
- For Direct Antenna Modulation case, information signal bandwidth will only be limited by the switching speed of the diode (hope to achieve an upper bound of at least 100-200+ MHz) [7]

Future Research

1. Explore feasibility of direct antenna modulation to produce nQAM and QPSK modulation schemes in addition to amplitude and pulse-code/pulse-width modulation

2. Develop computational and potentially nonlinear circuit models to analyze and predict direct antenna modulation performance

3. Apply direct antenna modulation to HF/VHF/UHF antennas to test applicability of technique to Army communication systems (typically less than 1 GHz carrier wave)

References

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5. C. M. Montiel, L. Fan, and K. Chang, "A Novel Active Antenna with Self-Mixing and Wideband Varactor-Tuning Capabilities for Communication and Vehicle Identification Applications," IEEE Trans. Microwave Theory and Techniques, vol. 44, no. 12, pp. 2421 – 2430, December 1996.

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Questions?