Novel Antenna Modulation and Size Reduction Techniques Using Integrated High-Speed Semiconductor Switching Devices

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Prepared for the Duke University Department of Electrical and Computer Engineering
Ph.D. Preliminary Exam

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April 5, 2007
10:00AM – 12:00AM

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   - PIN diode selection / placement
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   - Next steps

Overview

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   - General concept
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Introduction

Thesis Research Objective

To explore the integration of modern semiconductor switching devices with a communication system antenna in an effort to enhance the system bandwidth and reduce the size and signature of the antenna structure while still maintaining high radiation efficiency.

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Thesis Research Objectives

Objective 1

- To extend the information bandwidth beyond the resonant bandwidth of a communication system antenna using modern semiconductor switching technology

Technique being considered:

- Direct antenna modulation (DAM)
  - Novel antenna modulation technique utilizing fast-switching PIN diodes integrated into an antenna structure and driven with an information signal encoded in pulse-train format

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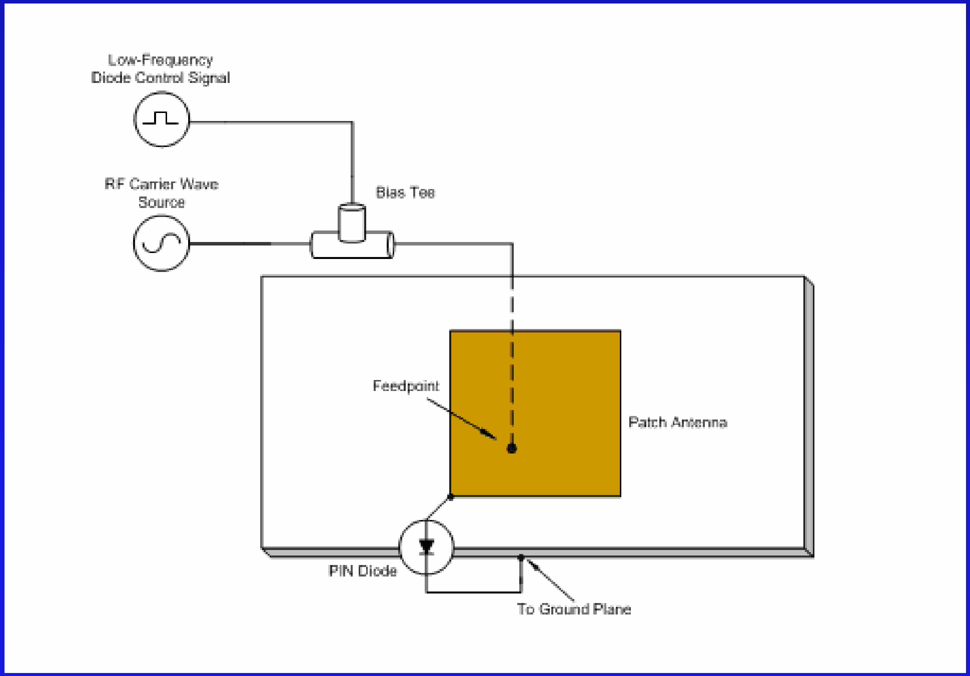
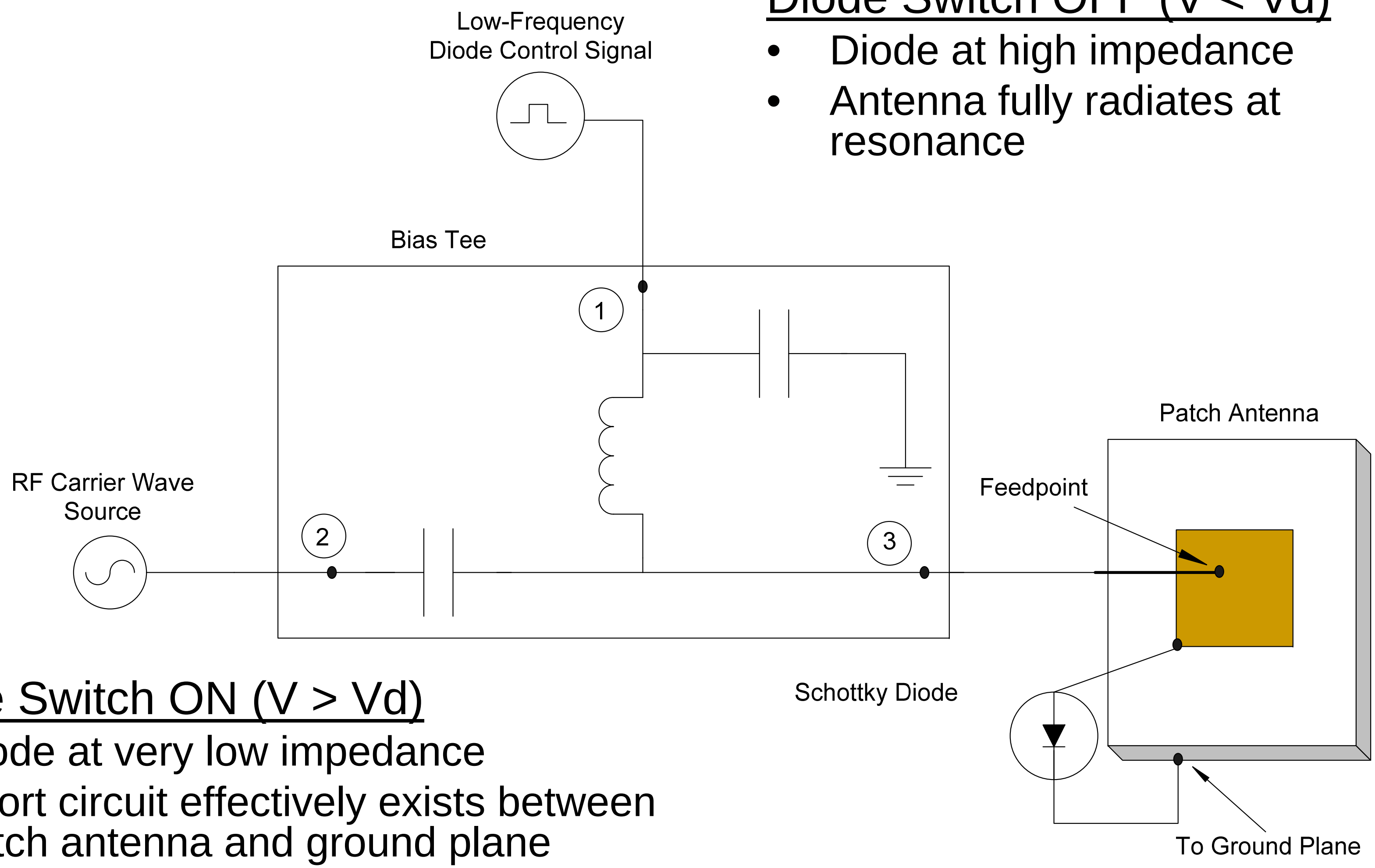
DAM General Concept



Adapted from [2], Allerton Antenna Applications Symposium 2006

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

Direct Antenna Modulation



Diode Switch OFF (V < Vd)

- Diode at high impedance
- Antenna fully radiates at resonance

Diode Switch ON (V > Vd)

- Diode at very low impedance
- Short circuit effectively exists between patch antenna and ground plane
- Antenna radiation is significantly hindered and effectively ceases

DAM Historical Review

Two papers explicitly explore direct antenna modulation:

<u>Fusco and Chen [5]</u>

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

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

<u>Yao and Wang [1]</u>

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

• Potential information bandwidth increase of 6-10x the resonant antenna bandwidth

• Concluded that smaller carrier lifetime (related to switching speed) of Schottky diodes could lead to improved modulation responses and further bandwidth increases

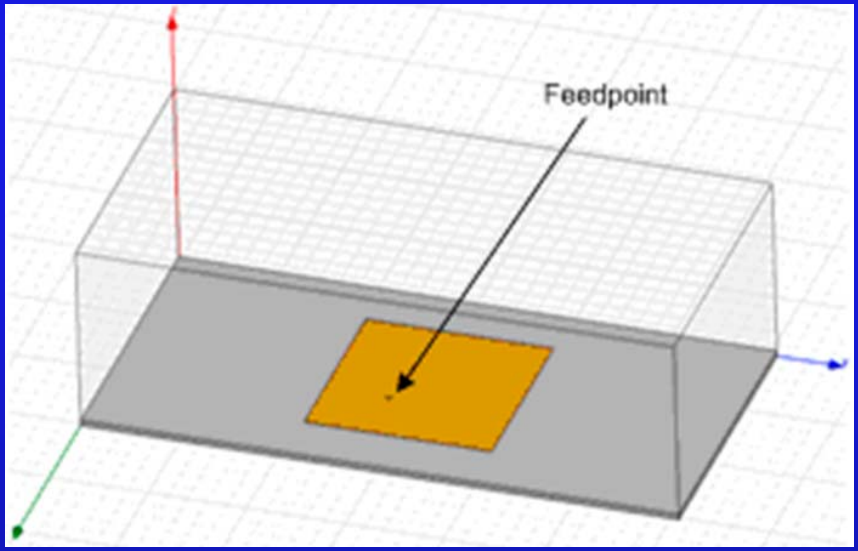
DAM Experiment

Objectives:

- Verify the feasibility of the direct antenna modulation technique with an L-band patch antenna
- Observe the upper limit to information bandwidth and compare the performance of a directly-modulated signal with that of an externally-modulated signal

Antenna:

- Symmetric L-band patch antenna
- $f_r \approx 1.5$ GHz
- Coaxial feed
- G-10 epoxy glass substrate, $\varepsilon r \approx 4.24$
- Modeled using *Ansoft* HFSS [3]



Adapted from [2], Allerton Antenna Applications Symposium 2006

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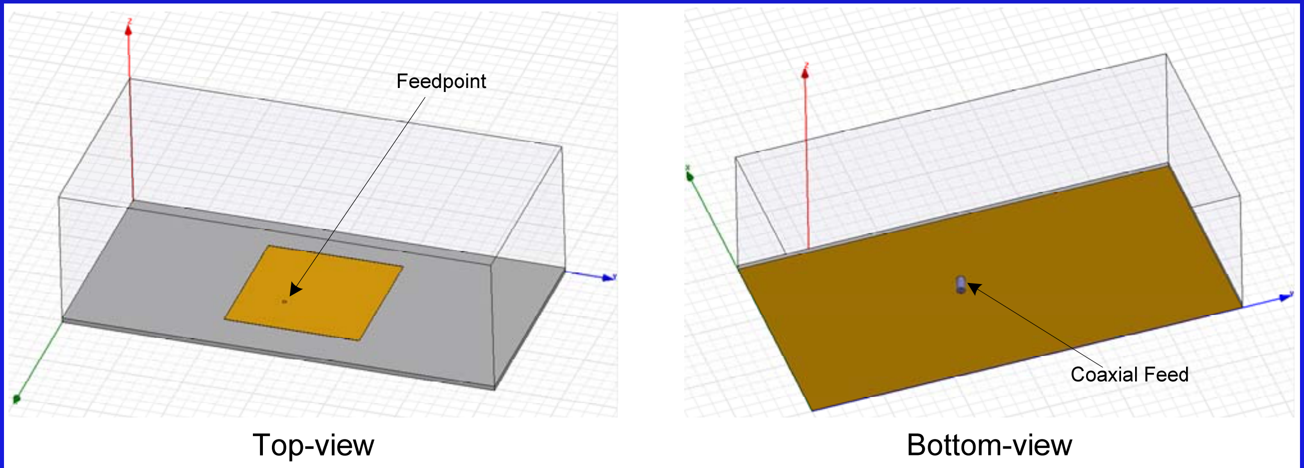
Patch Antenna HFSS Simulation

• HFSS simulation conducted to optimize patch antenna design and PIN diode placement



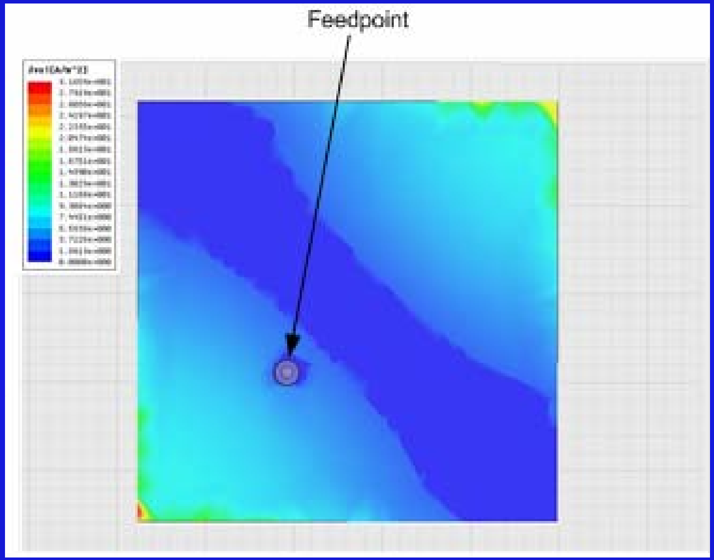
Adapted from [2], Allerton Antenna Applications Symposium 2006

<u>Simulation Details</u>:

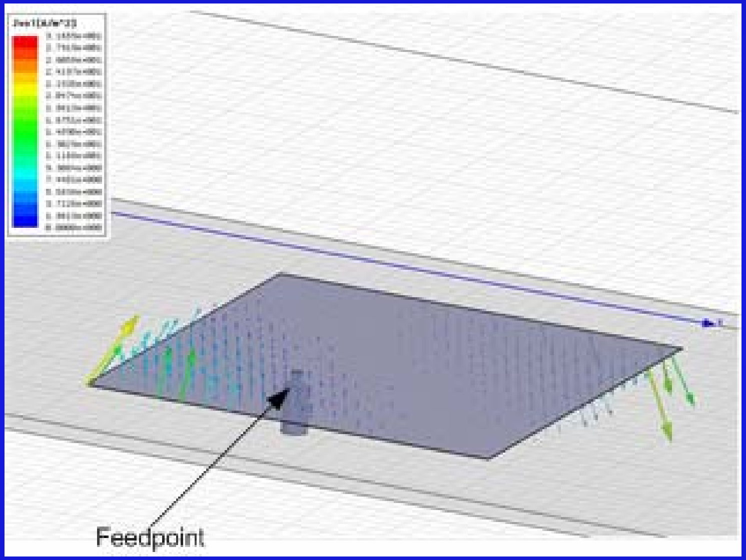
- <u>Sweep</u>: Fast Sweep from 1 GHz to 2 GHz
- <u>Center frequency</u>: 1.5 GHz

Use HFSS To Optimize Diode Placement

- Maximum volume current density points occur at the corners along the feedpoint diagonal



J_{vol} Magnitude Plot
(Bottom View of Patch Antenna)



J_{vol} Vector Plot
(Angled Top View of Patch Antenna)

Adapted from [4], IEEE AP-S International Symposium 2006

- Diodes should be placed at these points for maximum effect on radiated signal

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Diode Characteristics Are Critical

- SMP1340 (*Skyworks Solutions*) [8] has low junction capacitance (0.3 pF) at 0V forward bias
  - Looks like an open circuit at 1.5 GHz

$$Z = \frac{1}{j\omega C} = \frac{1}{j \cdot 2\pi \cdot 1.5 \cdot 10^{9} \cdot 0.3\,pF} = j354\Omega$$

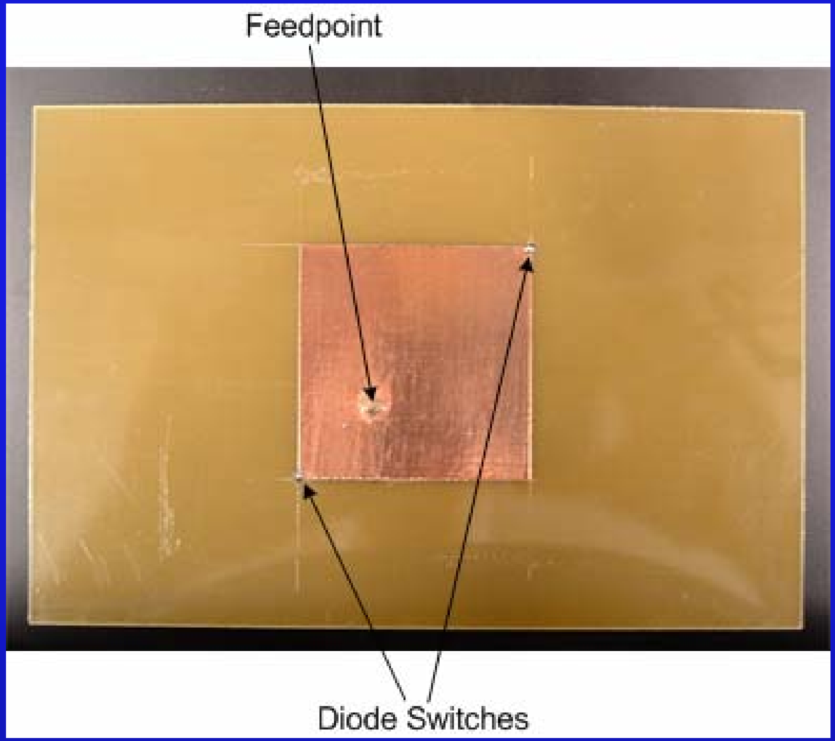
- The SMP1340 is also a very fast-switching PIN diode (short carrier lifetime of ~100 ns) which enables high modulation rates

Prototype Antenna

- Diodes soldered between patch antenna and ground
  - Located at the corners along the feedpoint diagonal

<u>Final Patch Dimensions</u>

- ~4.6 x 4.6 cm
- Feedpoint placed ~1.95 cm along the diagonal
- Good return loss (-23.2 dB) achieved at ~ 1.56 GHz



Adapted from [2], Allerton Antenna Applications Symposium 2006

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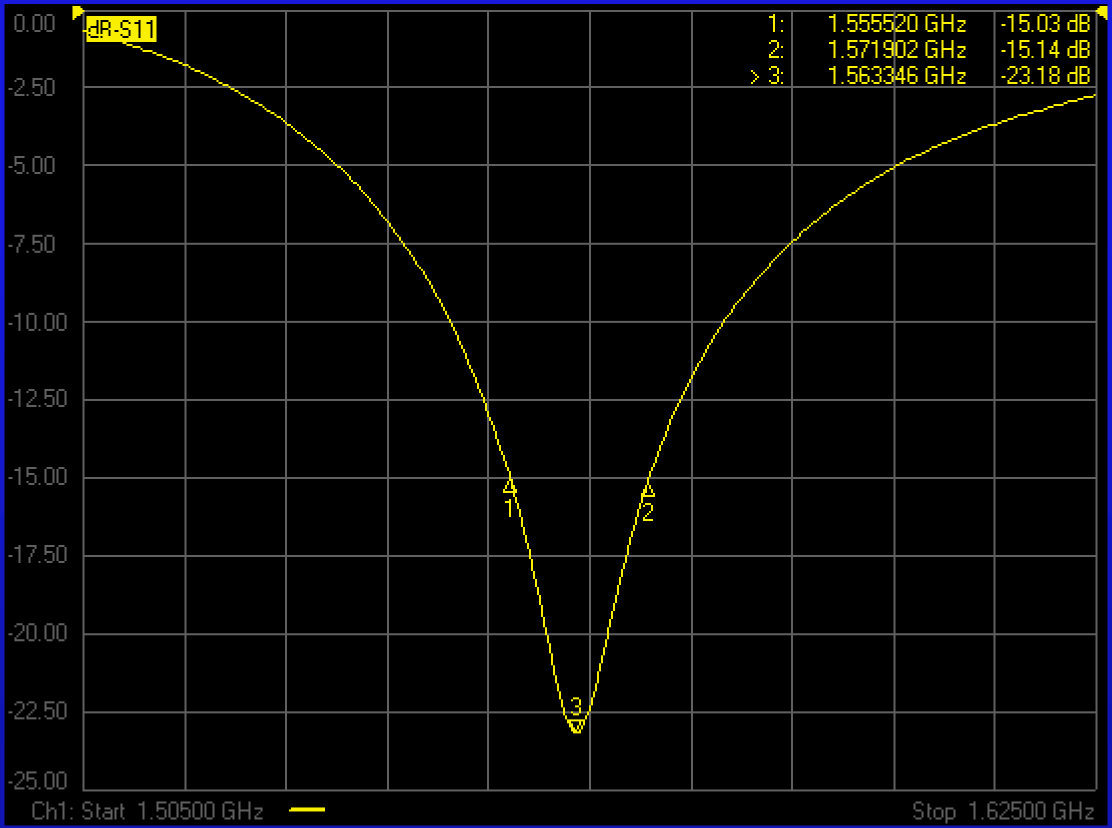
Prototype Antenna

Center frequency: 1.56 GHz

Bandwidth: 16 MHz ($S_{11} \leq -15$ dB)

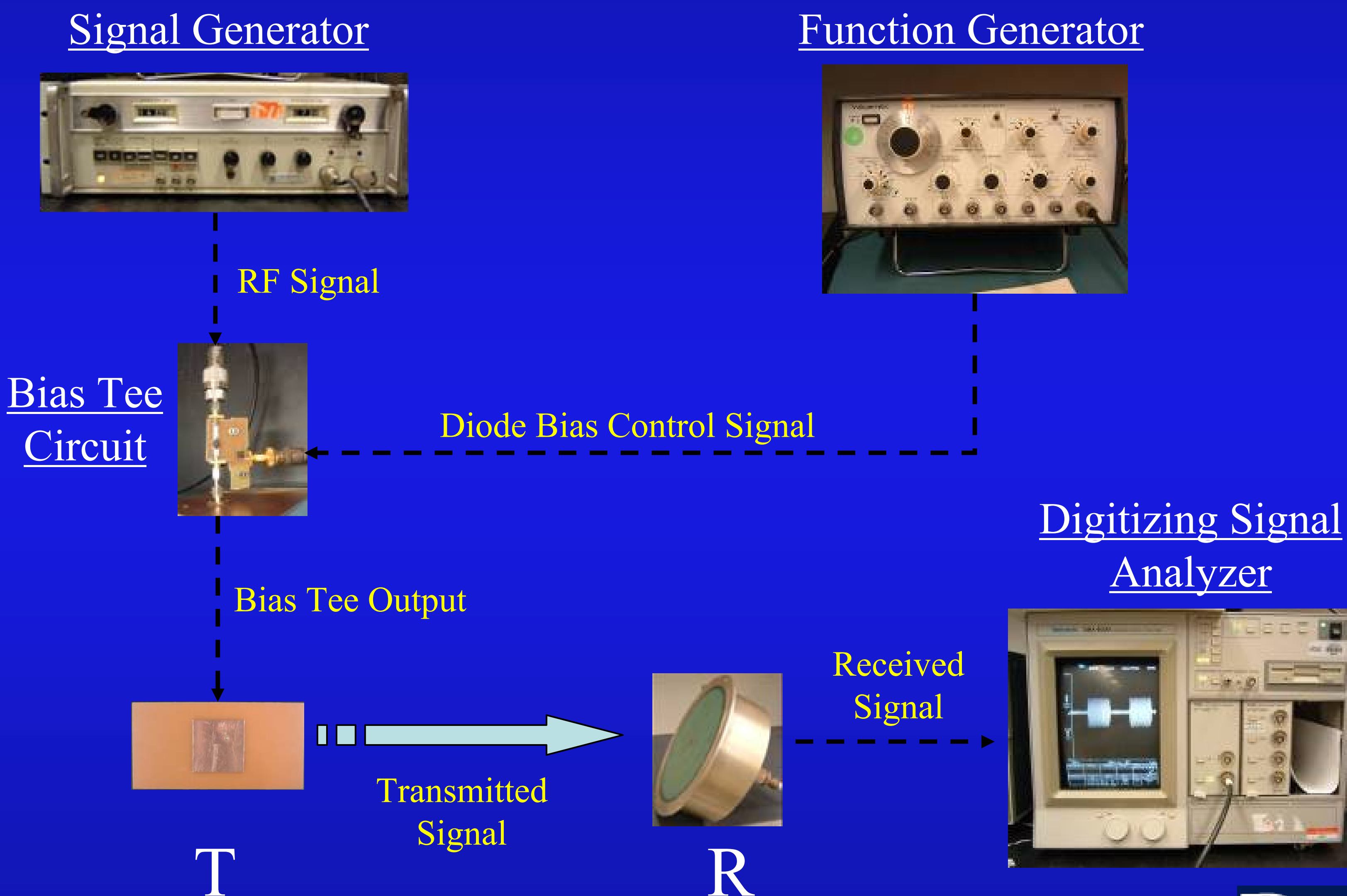
28 MHz ($S_{11} \leq -10$ dB)



- Narrowband system

  (~1-2% Bandwidth)

Signal Flow



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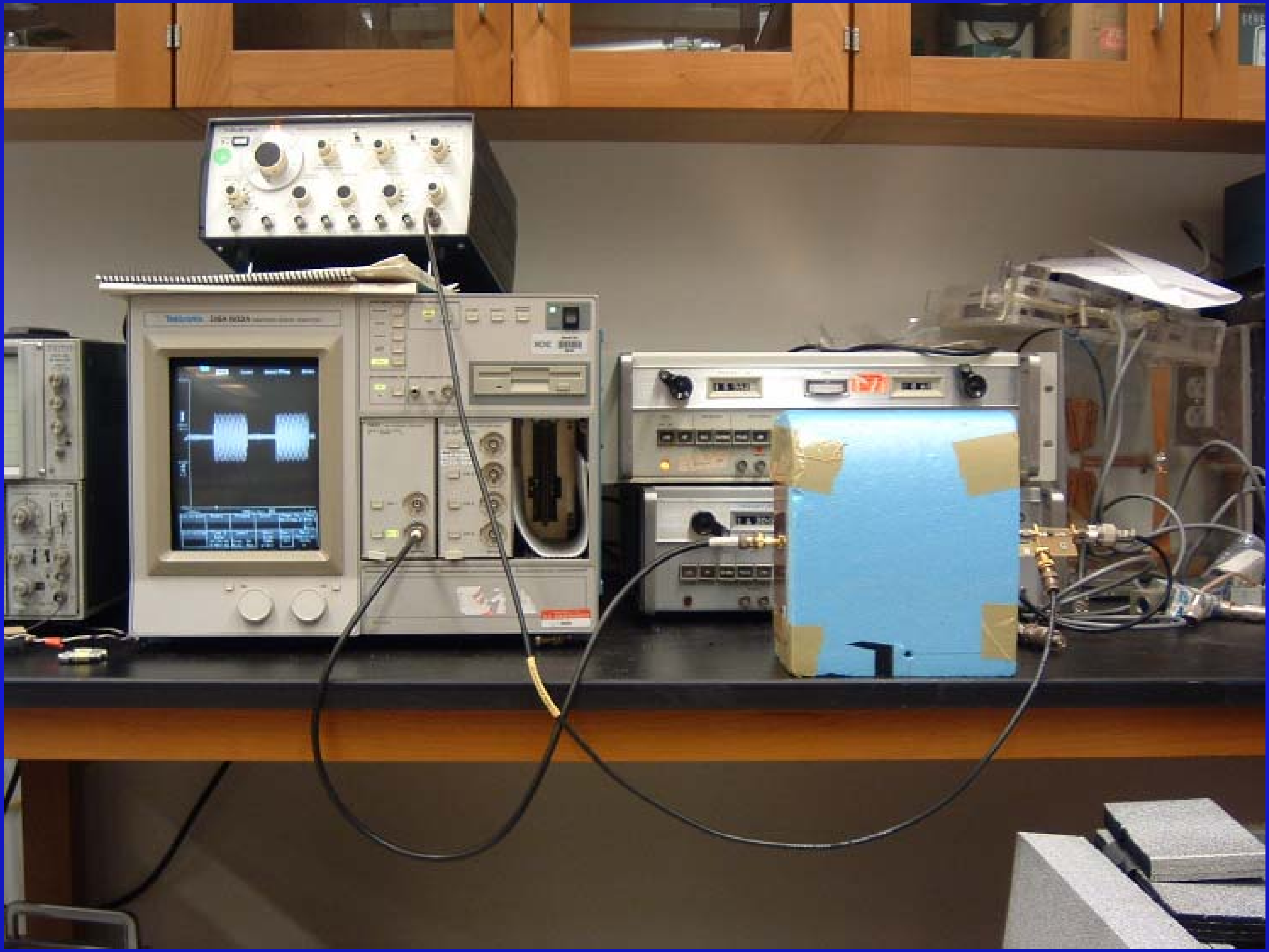
Experimental Setup



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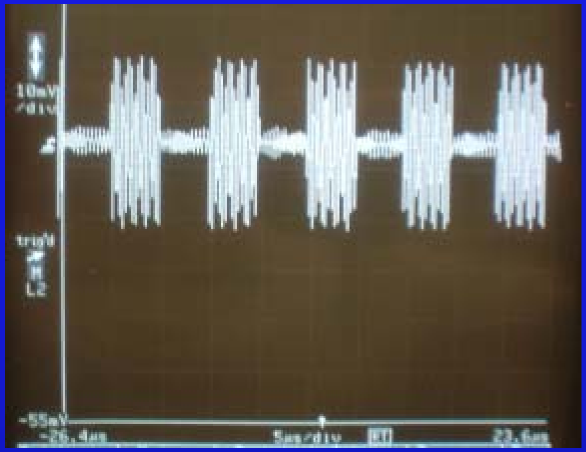
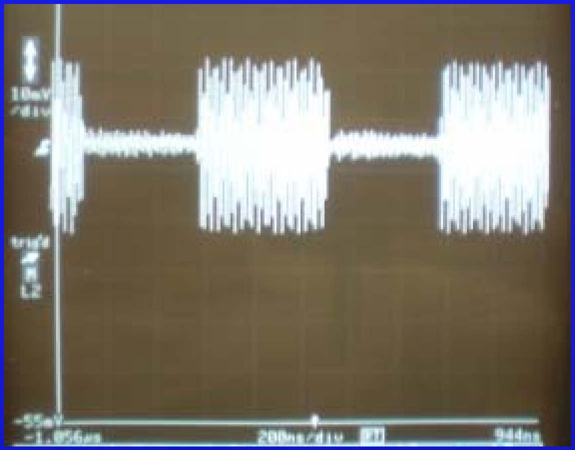
Modulation Results

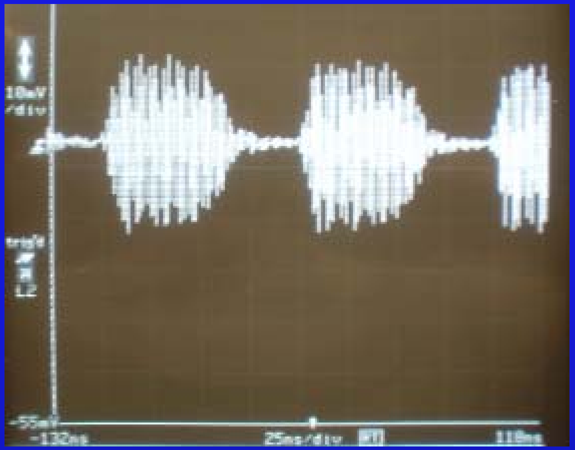
- Received waveform demonstrates direct antenna modulation effect



10 kHz



1 MHz



10 MHz

Adapted from [2], Allerton Antenna Applications Symposium 2006

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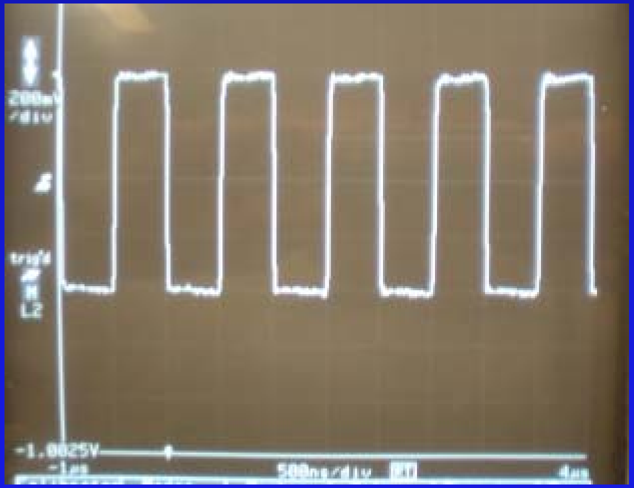
Received Signal Details

<u>Received Modulated CW</u>:

~ 40 mV peak-to-peak

- Since diode has low, but not zero impedance when in forward bias, ~5 mV received signal leakage occurs

- This leakage is minimal, however, yielding a signal high-to-low ratio of ~ 8:1



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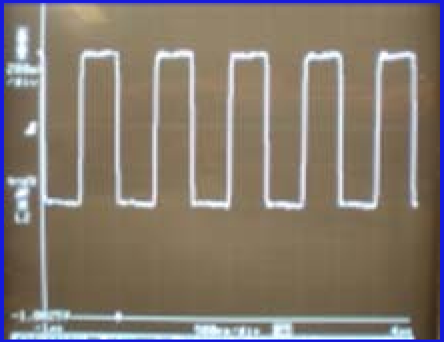
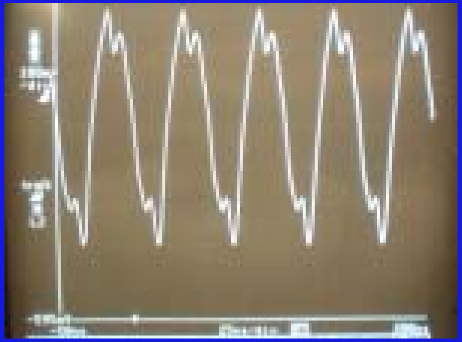
Function Generator Limits Performance

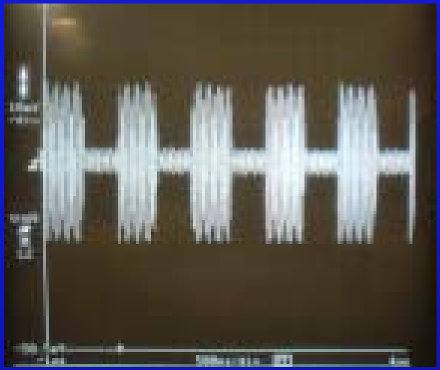
- Above 10 MHz, received waveform is distorted by degradation in the *Wavetek* Model 145 function generator (20 MHz limit) bias signal

1 MHz | 20 MHz





Bias Signal



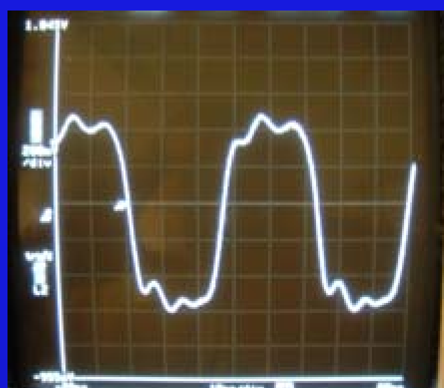
Received Waveform

Adapted from [2], Allerton Antenna Applications Symposium 2006

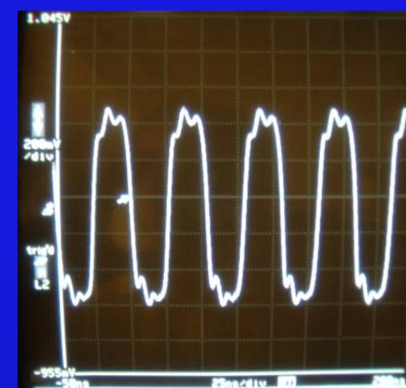
Results with Better Function Generator

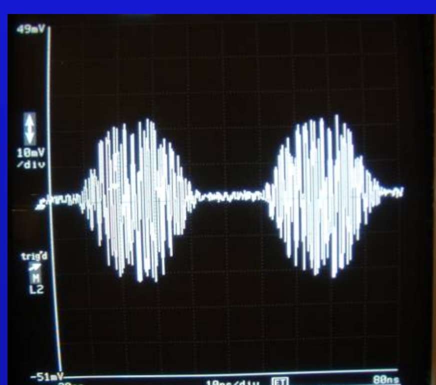
- With the *Wavetek* Model 801 function generator (50 MHz limit), received directly-modulated waveform looks better at 20+ MHz

20 MHz



Bias Signal





Received Waveform

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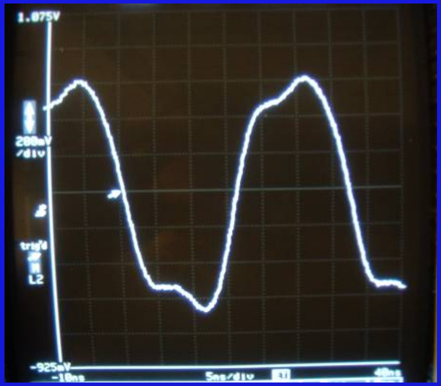
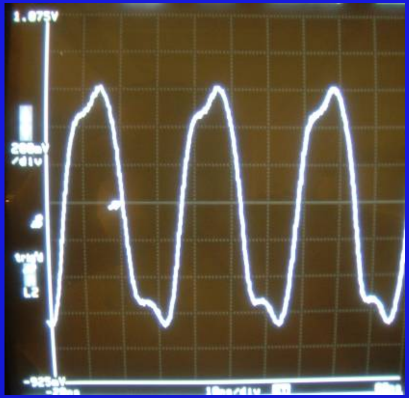
Results with Better Function Generator

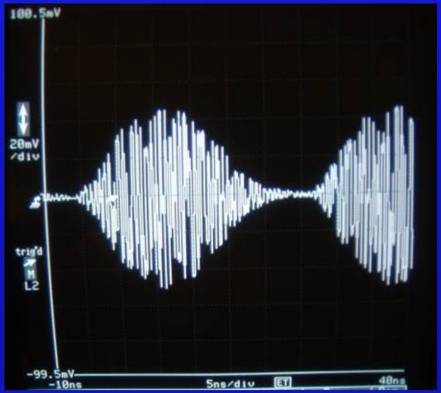
- Received directly-modulated signal degrades as the modulation frequency approaches the 50 MHz function generator limit, since the pulse output itself becomes increasingly distorted

30 MHz

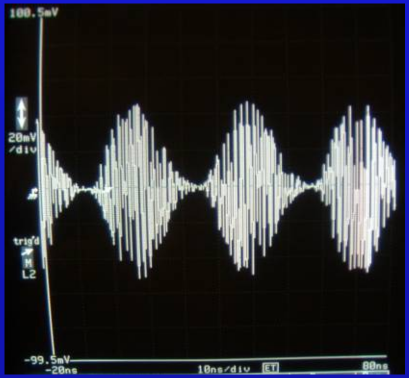


Bias
Signal





Received
Waveform



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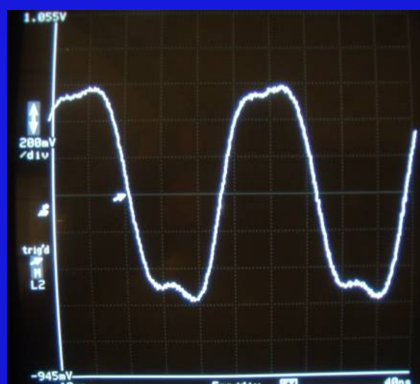
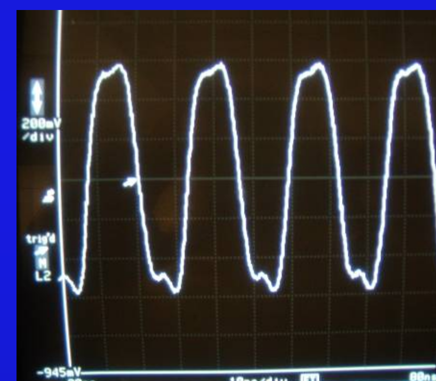
Results with Better Function Generator

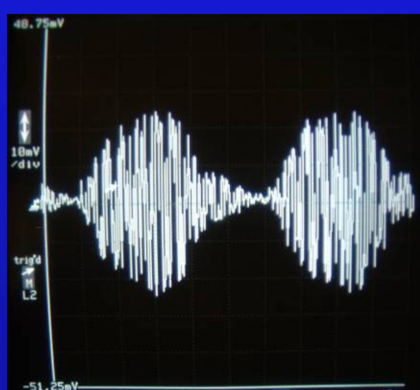
- Received directly-modulated signal degrades as the modulation frequency approaches the 50 MHz function generator limit, since the pulse output itself becomes increasingly distorted

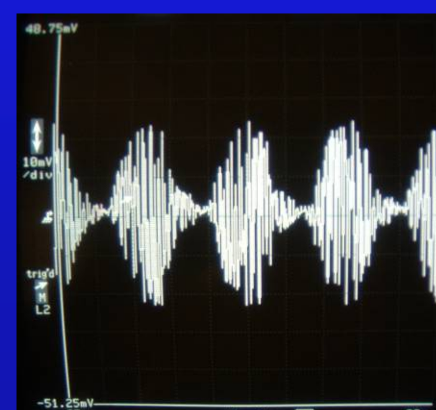
40 MHz





Bias Signal



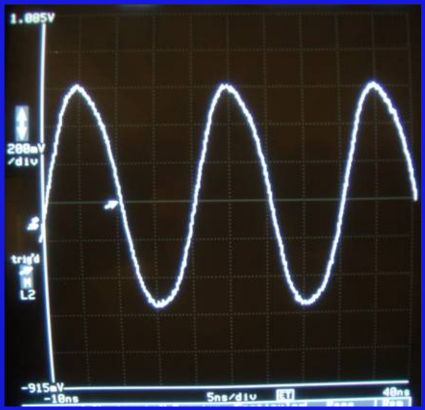


Received Waveform

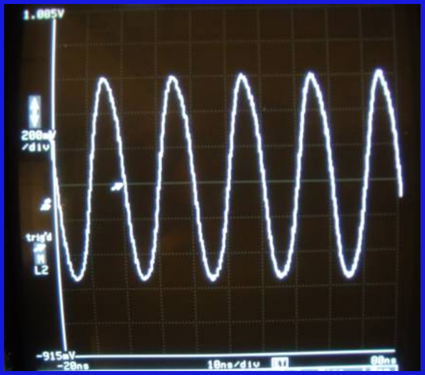
Results with Better Function Generator

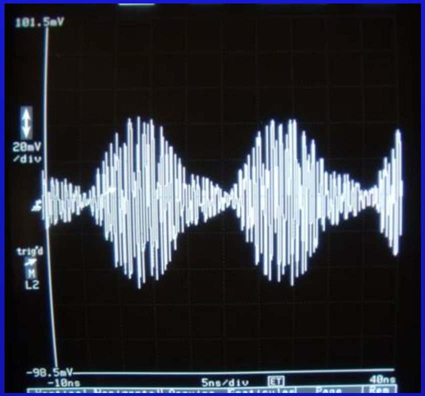
- Results at 50 MHz with the *Wavetek* Model 801 FG (50 MHz upper limit) look similar to results at 20 MHz with the *Wavetek* Model 145 FG (20 MHz upper limit)

50 MHz

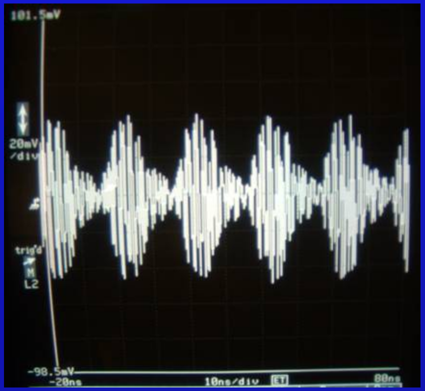


Bias Signal





Received Waveform



DAM Experiment Conclusions

- Direct Antenna Modulation is an effective technique for transmitting pulse-modulated signals from a patch antenna with information bandwidth extended beyond the resonant bandwidth of the antenna

- Diode selection and placement is critical
  - Fast switching speed, low junction capacitance
  - Placed at field strength maxima on the antenna for strongest effect

- Sharp pulse output of function generator is

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Next Steps in DAM Experiment

1. Obtain improved function generator
   - Capable of providing sharp 50+ MHz pulse train
   - Explore the upper limit to the information bandwidth provided by the DAM comm. system and compare with a standard amplitude-modulated comm. system with the same antenna structure

2. Examine the spectrum of received directly-modulated signal
   - New spectrum analyzer will hopefully be purchased in the next 3-6 months
   - Examine any detrimental spurious radiation that may arise from the PIN diode switching harmonics

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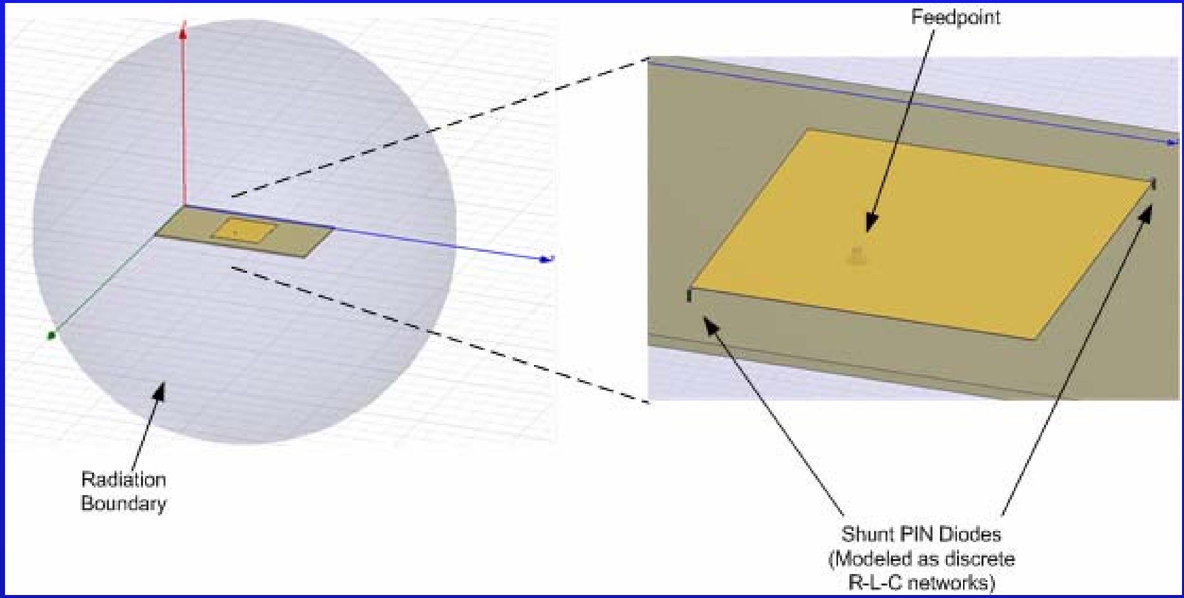
DAM HFSS Simulation

Objectives:

- Understand the physical mechanisms behind the direct carrier wave modulation
- Explore the radiation characteristics of a directly-modulated L-band patch antenna as a first step towards modeling Direct Antenna Modulation



Adapted from [7], IEEE AP-S International Symposium 2007

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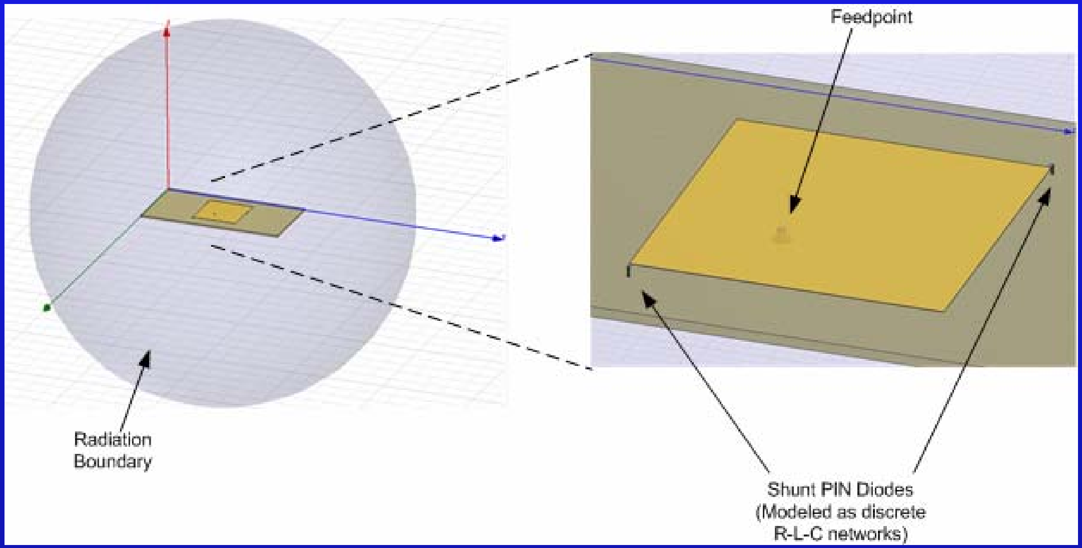
SMP1340 PIN Diode

Diode Model

- SMP1340 PIN diode modeled as an R-L-C circuit:
  - Parallel RC circuit in series with an inductance, L, for the zero/reverse bias region
  - Series R-L circuit for the forward bias region
- Discrete R/L/C values determined for diode bias voltage levels between 0 V and 0.8 V (SMP1340 PIN diode impedance measured by *Skyworks Solutions* engineers)



Adapted from [7], IEEE AP-S International Symposium 2007

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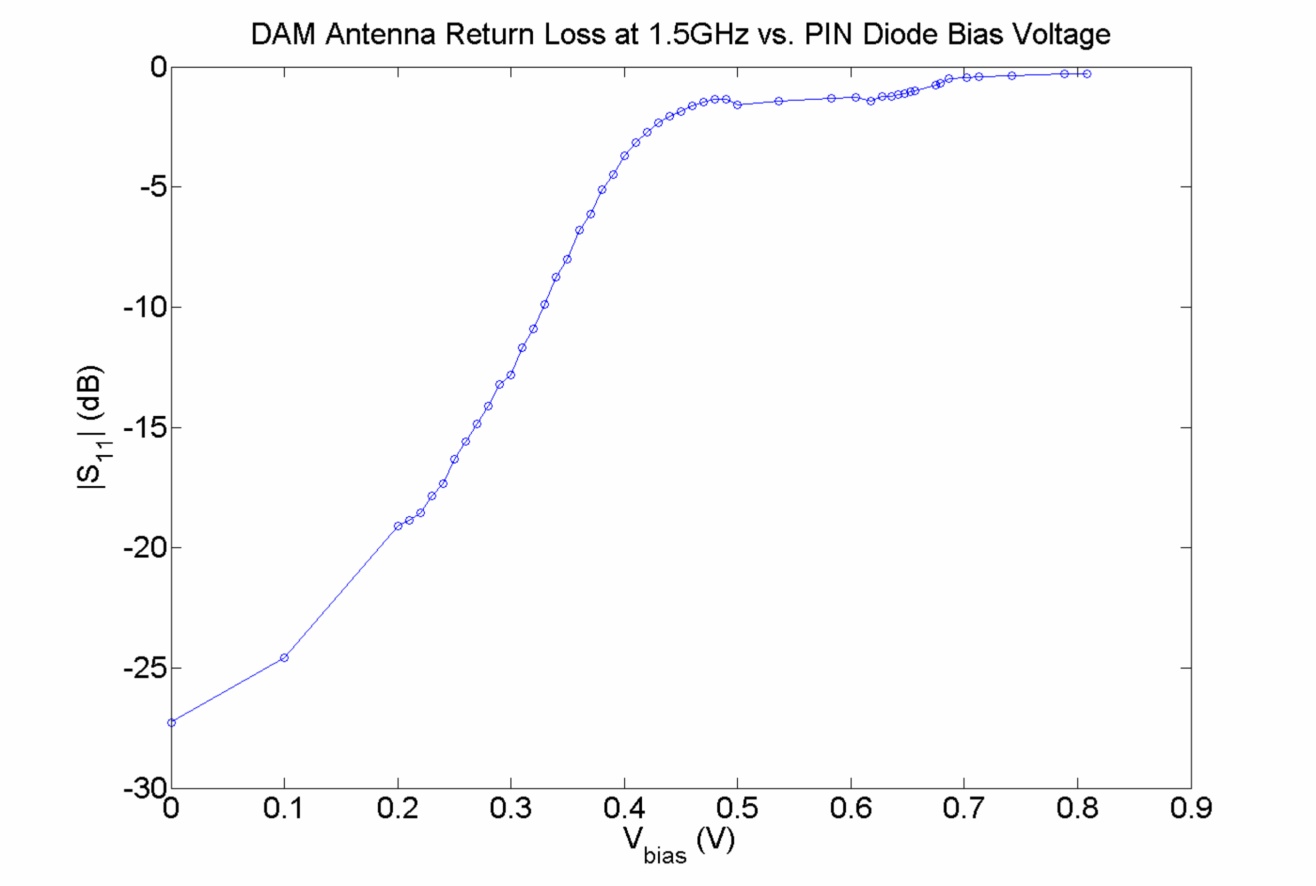
DAM Electromagnetic Simulation

<u>HFSS Simulation Details</u>

- Same patch antenna in DAM experiment used in HFSS model
  - Spherical radiation boundary set ~10λ away from patch to ensure a far-field radiation pattern
- Discrete sweep run from 1.4 to 1.8 GHz
- 51 simulations carried out
  - L set to 1.48 nH based on data in [8]
  - R and C values updated for each simulation to represent the PIN diode model values at a discrete bias voltage level, V_b

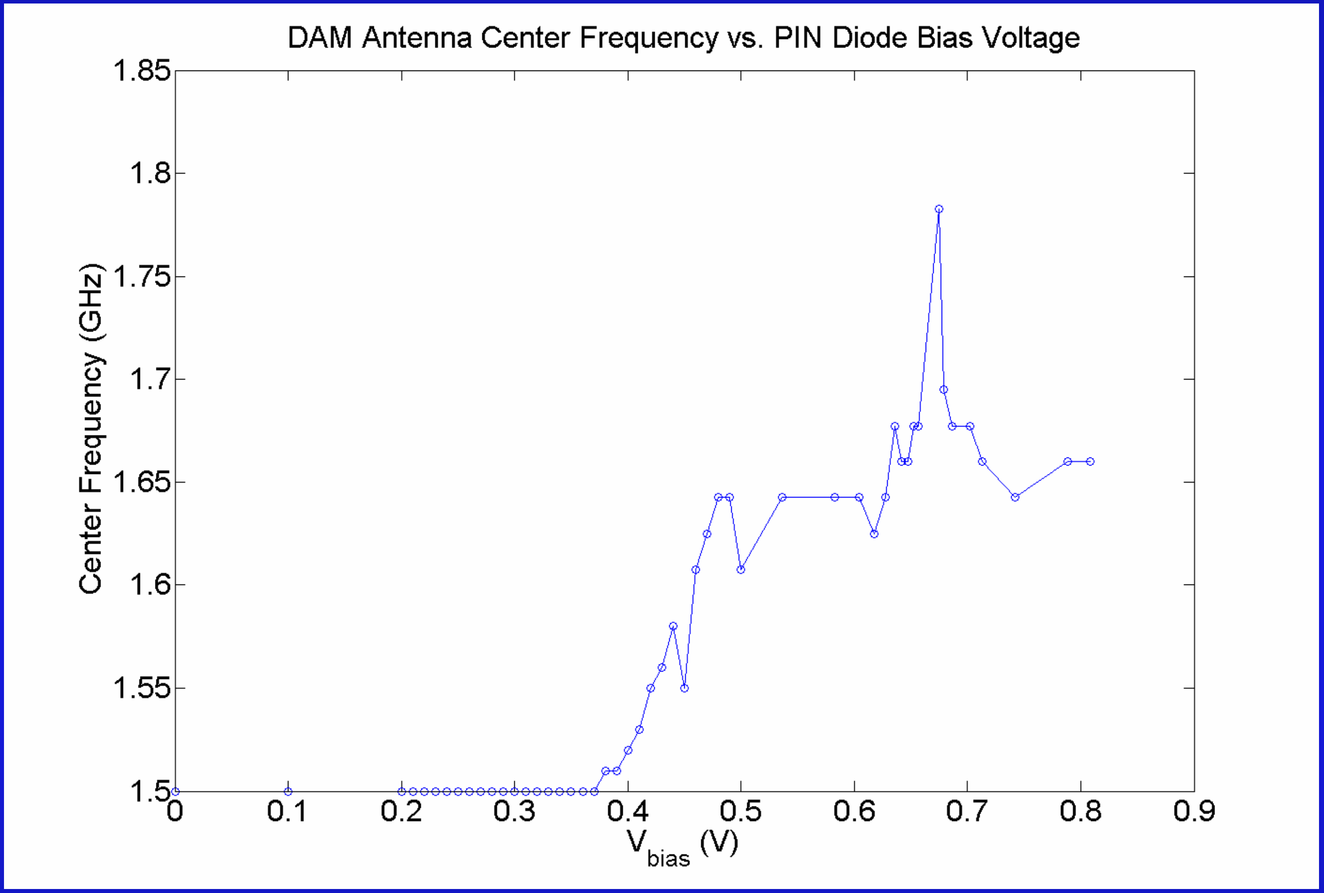
DAM HFSS Simulation Results



Adapted from [7], IEEE AP-S International Symposium 2007

- Steady increase in return loss as diode bias voltage, V_b, is increased from 0 V to 0.8 V
- Return loss reaches -3dB at $V_b \approx 0.415$ V

DAM HFSS Simulation Results



Adapted from [7], IEEE AP-S International Symposium 2007

- When $V_b \approx 0.38$ V, patch antenna center frequency steadily increases above its original value of 1.5GHz as V_b increases to 0.8 V
- Center frequency settles between ~1.65 and 1.68 GHz when $V_b > 0.48$ V
  - Shift of ~150 to 200 MHz from original center frequency

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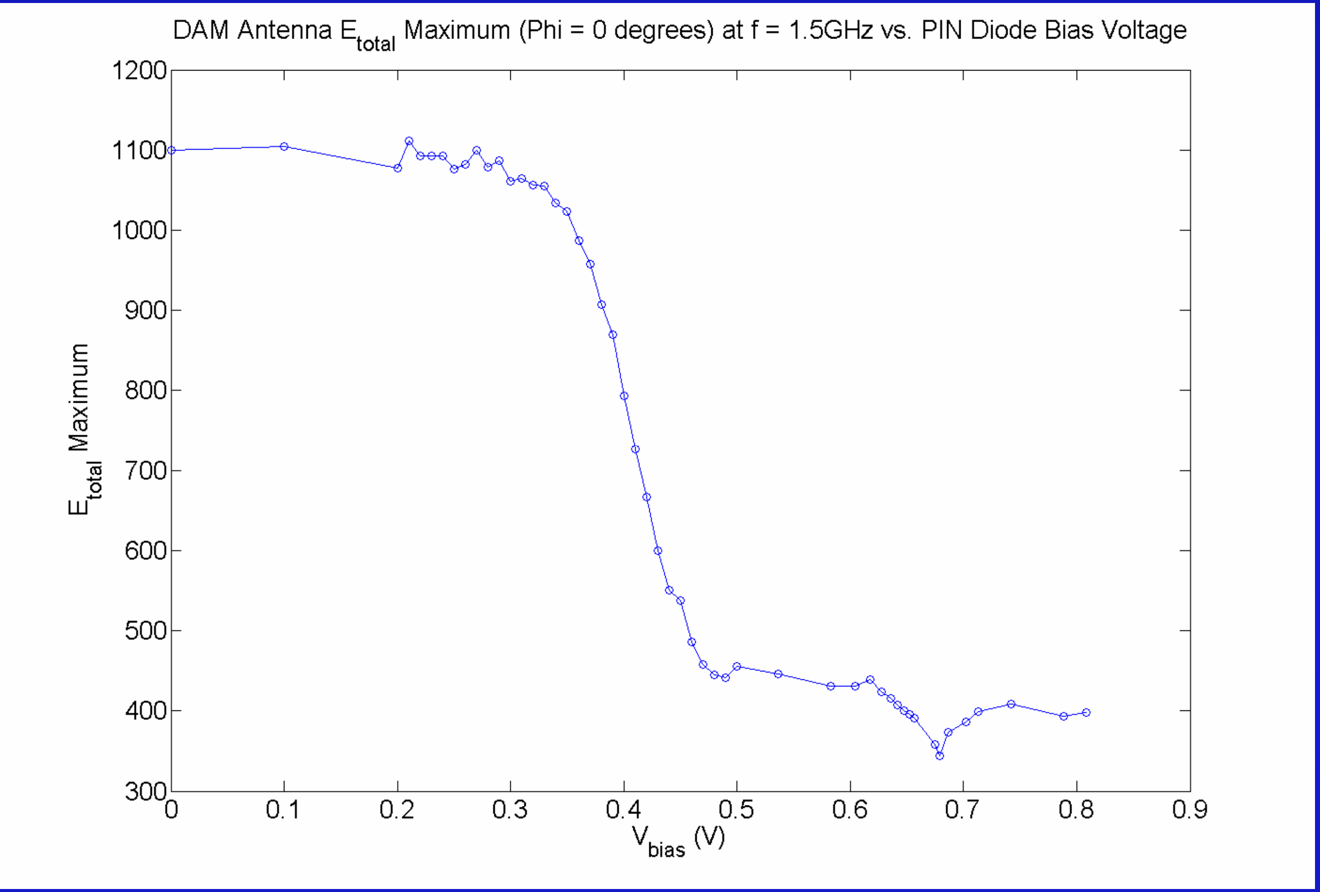
DAM HFSS Simulation Results



- Far-field total electric field maximum steadily decreases between $V_b = 0.3$ V and $V_b = 0.5$ V
- Total electric field maximum at $V_b = 0.8$ V is reduced to ~35% of its original value at $V_b = 0$ V

DAM Simulation Conclusions

- Two distinct mechanisms involved in antenna radiation reduction as diode bias voltage, V_b, is increased:
  1. Antenna return loss significantly increases as V_b is increased, resulting in less power being delivered for antenna radiation
  2. Antenna center frequency shifts to ~150-200 MHz higher than the zero-bias ($V_b = 0$) center frequency, f = 1.5 GHz
- Diode bias signal, V_b, must be larger than ~0.4 V to significantly increase the antenna return loss / shift the antenna center frequency and minimize antenna radiation
  - Pulse train with sharp edges (very short rise/fall times) is essential to properly control antenna radiation with the PIN diode switches

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Next Steps in DAM Simulation

- Create animation of 3-D polar plot of the total electric field as V_b increases from 0 V to 0.8 V
  - Excellent demonstration of the effect that the switched PIN diode has on the patch antenna radiation
- Run set of simulations with different numbers of diodes and with diodes placed at other locations within the antenna structure
  - Compare these results to determine optimal implementation of the DAM technique

Thesis Research Objectives

<u>Objective 2</u>

- To reduce the size and signature of Army mobile ground communication system antennas using modern semiconductor switching technology while maintaining high radiation efficiency

Technique being considered:

- Digitally-driven antenna (DDA) system
  - Novel antenna-driving technique based on concepts developed for Class-D power amplifiers that utilizes high-speed transistor switches to digitally drive a communication system antenna with a pulse-width modulated signal

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Motivation

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

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

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

Typical antenna designs yield:

- ***Cumbersome size***
- ***Visually-compromising signature***

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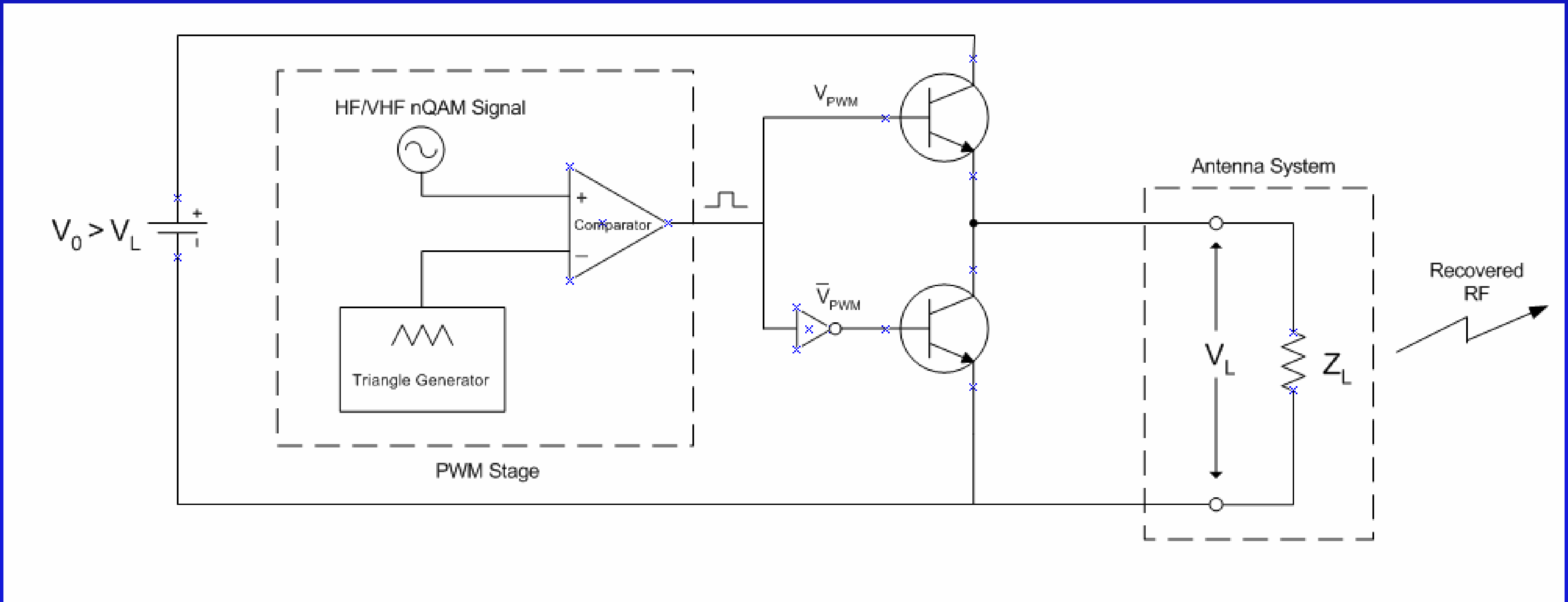
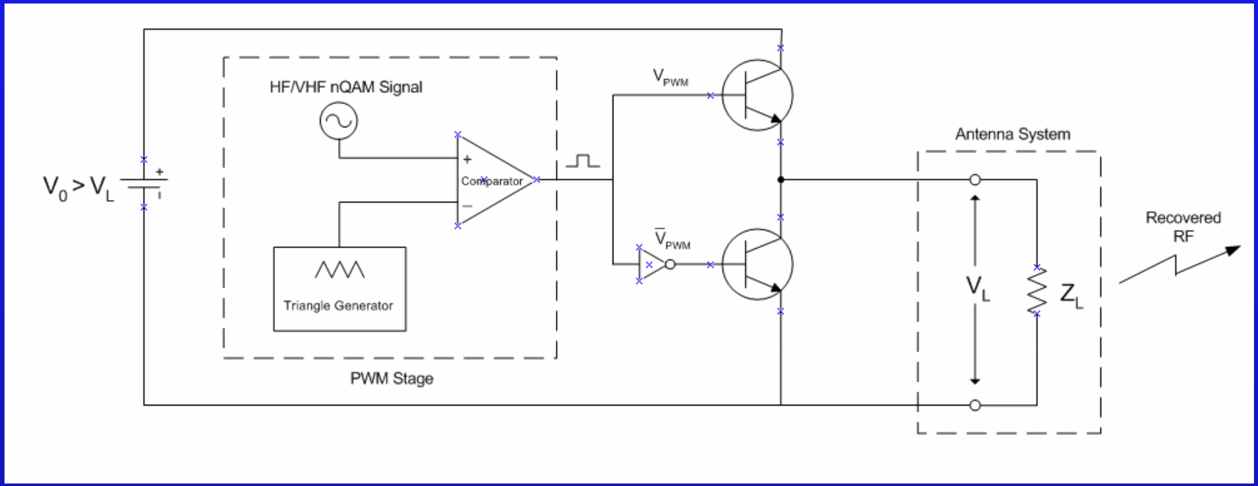
DDA System Layout



- HF/VHF signal pulse-width modulated by comparing the signal with a triangle or sawtooth wave
  - When HF/VHF signal is larger than triangle/sawtooth wave, comparator output is HIGH
  - When HF/VHF signal is smaller than triangle/sawtooth wave, comparator output is LOW
  - For good sampling, triangle/sawtooth wave frequency should be 5-10 times the HF/VHF signal frequency

DDA System Layout

- PWM signal controls output of high-speed transistor switches
  - Signal sent to base of BJT push-pull circuit
  - Amplified version of PWM signal sent to antenna structure
- Transistor switch output integrated by antenna system reactance to recover original RF signal
- Original RF signal radiated by antenna system at high efficiency with resonant matching circuitry circumvented



DDA Example

As an example, we may use this technique to radiate a 20 MHz (HF) amplitude-modulated signal:

- Traditional half-wavelength dipole antenna designed for this frequency would be:

$$\lambda = \frac{c}{f} = \frac{3 \cdot 10^8}{20 \cdot 10^6} = 15m \quad , \quad \frac{\lambda}{2} = 7.5m$$

- With a DDA system, a PWM signal of at least 5-10x the original 20 MHz signal will be sent to the antenna by the transistor switching circuit:

$$\lambda' = \frac{c}{f'} = \frac{3 \cdot 10^8}{10 \cdot 20 \cdot 10^6} = 1.5m \quad , \quad \frac{\lambda'}{2} = 0.75m = \frac{\lambda}{20}$$

- Potential to transmit HF signal at high radiation efficiency with an antenna 5-10x smaller than a traditionally-designed communication system antenna

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Areas to Explore

- Carry out the previous example to demonstrate the feasibility of the DDA technique
  - This works for audio amplifier systems…can it be applied to an antenna system much smaller than a ½ or ¼ wavelength and still result in high radiation efficiency?
- Details of RF signal recovery
  - Is the antenna reactance all that is needed to recover the original signal or are other passive components necessary?
  - Is the fidelity of the original signal well-preserved after signal is radiated?
- Higher-frequency spectral content
  - The use of a high-speed transistor switch may yield spurious radiation at harmonics well above the HF/VHF/UHF radiated signal…how detrimental is this radiation to the overall communication system? Is there a good way to suppress this?

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Summary of Research Progress

- Experimentally demonstrated DAM with L-band patch antenna
- Conducted electromagnetic simulation of L-band DAM antenna
- Proposed digitally-driven antenna system and planned experiment to demonstrate its feasibility

<u>Presentations / Publications</u>

- IEEE Antennas and Propagation Society International Symposium, July 2006
- Allerton Antenna Applications Symposium, September 21, 2006 (Student Paper Finalist)
- 2006-2007 Defense University Research Instrumentation Program award (currently in negotiation phase – have received news of the intent to award)
- IEEE Antennas and Propagation Society International Symposium, June 2007

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Plan for Remaining Thesis Research

- Fully explore the improvement that DAM can offer to the information bandwidth of a communication system antenna
  - Will be conducted when better pulse/function generator is obtained

- Run more iterative HFSS simulations of the L-band DAM patch antenna
  - Determine optimal diode numbers/locations of integration within the patch antenna structure
  - Generate a large pool of data by which a general model of this technique may be developed

- Carry out proposed DDA system
  - Demonstrate feasibility of this technique and its ability to reduce the size and signature of an HF/VHF antenna
  - Explore the applicability of this technique to Army mobile ground communication systems

- Publish results of these experiments in IEEE Transactions on Antennas and Propagation journal and present results at future antenna/microwave symposiums

- Complete dissertation summarizing this research

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Questions?

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