LA-UR- 11-01464

Approved for public release;
distribution is unlimited.

Title:	Metamaterial Based Terahertz Emitter
Author(s):	Reiten, Matthew T. Roy Chowdhury, Dibakar Earley, Laurence Taylor, Antoinette O'Hara, John F. Azad, Abul
Intended for:	2011 IC Postdoctoral Fellowship Research Colloquium

Los Alamos
NATIONAL LABORATORY
EST. 1943

Form 836 (7/06)

Abstract for "Metamaterial Based Terahertz Emitter" presentation for 2011 IC Postdoctoral Research Fellowship Colloquium, 4-7 April 2011, Tysons Corner VA

Responsible Author: Matthew T. Reiten, Z# 235241

The objective of this research is the development of a metamaterial based terahertz (THz) emitter capable of operating at room temperature with only an applied DC bias voltage as power source. The current THz spectrum is underutilized and many applications exist for a compact metamaterial THz emitter (metamitter.) The concept is to integrate a negative differential resistance component into a split ring resonator in order to drive current and subsequent radiation. An ordered array of these gain-loaded elements will increase total emitted power. The present state of development of the metamitter device has encountered a technical hurdle with the micro-fabrication of the air-bridge connector for the resonant tunneling diode gain component. Concurrent research utilizing GHz scale analogs and passive THz frequency metamaterial arrays has been pursued in support of the metamitter design process. The GHz scale analogs have shown bias leads and frequency mixing to impact intended performance. The passive THz metamaterial response has shown that inter-element coupling greatly impacts the frequency and bandwidth of the measured resonances.

Metamaterial Based Terahertz Emitter

M. T. Reiten

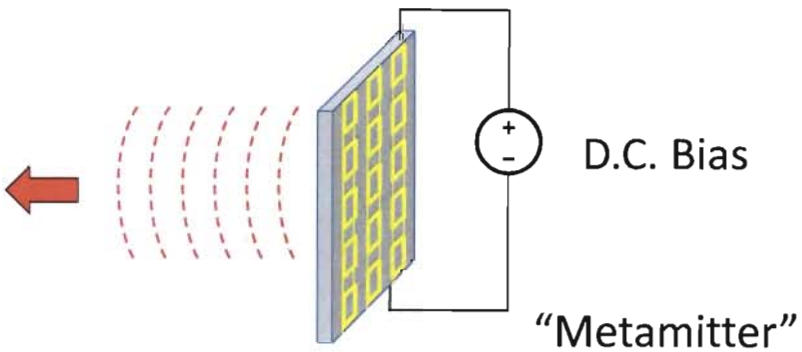
J. O'Hara, D. Roy Chowdhury, L. Earley, A. Azad, and A. Taylor

Los Alamos

NNSA

Objective

Design, simulate, fabricate, and characterize active metamaterial based THz emitter (*metamitter*) capable of operating at room temperature with only an applied DC bias voltage as power source.



Los Alamos

NNSA

Motivation

- Current THz spectrum is underutilized due to scarcity of sources, detectors, and natural limitations.

Approach	Operational frequency (THz)	Typical power (W)	Advantages	Disadvantages
Optical heterodyne	0.1-3.0	10^{-6}-10^{-5}	Relatively simple concept	Poor power
Quantum cascade laser	0.1-5	10^{-3}	Good power	Difficult fabrication. Needs cryogenic cooling
Gas laser	0.1-10	10^{-3}-10^{+1}	High power	Large. Fixed operating frequencies
Tube sources	0.1-1.0	10^{-3}-10^{3}	Excellent power	Fabrication difficulty. Requires huge magnetic fields for high power
Free-electron laser	0.1-10	10^{3}-10^{6}	Excellent power	Building-sized system
Solid-state	< 1	10^{-6}-10^{0}	Stable. Reliable. Compact	Power very low approaching 1 THz

- THz spectroscopy (and imaging) has been confined to the laboratory and/or controlled environments.

Los Alamos NATIONAL LABORATORY

NNSA

Metamitter Applications

- Compact continuous wave THz emitter
  - Non-invasive imaging source
  - Targeted spectroscopy using tuned arrays for:
    - Security (explosive and chemical detection)
    - Pharmaceutical
    - Bio Applications
- Potential to lead to THz focal plane array

Los Alamos NATIONAL LABORATORY

NNSA

Concept

- Integrate negative differential resistance component (RTD) into metamaterial element in order to drive current oscillation and subsequent radiation.
- Create ordered array of radiating elements to increase total emitted power.
- Potential to shape the radiation pattern by modifying the array.

Los Alamos NNSA

Metamaterials

- **Metamaterials:** Engineered materials with derived from the composite properties of the structure and the surrounding material that can exhibit a tailored effective medium behavior. The Split Ring Resonator (SRR) can serve as a metamaterial element which has both electric and magnetic response.[1,2]

Potential of metamaterials: Negative Index Materials→ Cloaking Screens, Perfect Lenses; Ability to tune parameters

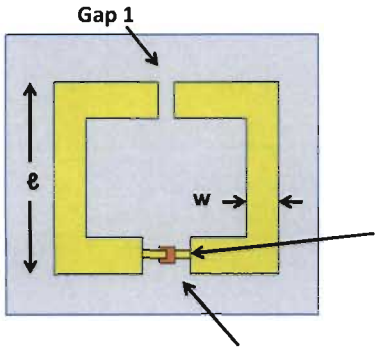
*[1] J.B. Pendry et al., "Extremely Low Frequency Plasmons in Metallic Mesostructures," PRL **76**, 4773 (1996)*

*[2] J.B. Pendry et al., "Magnetism from conductors and enhanced nonlinear phenomena," IEEE Trans. Microwave Tech. **47**, 2075 (1999)*

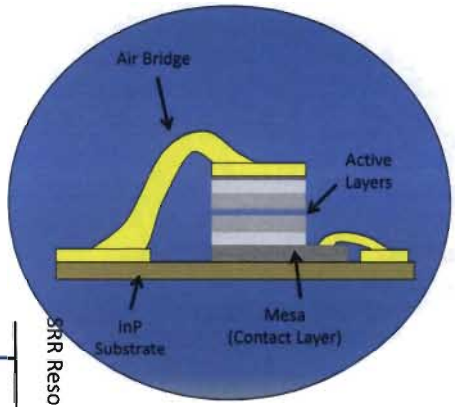
Los Alamos NNSA

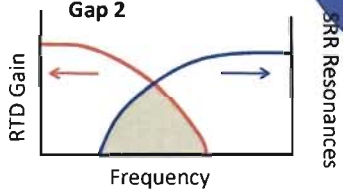
Metamitter Element

Tank circuit provides feedback



RTD is active gain element



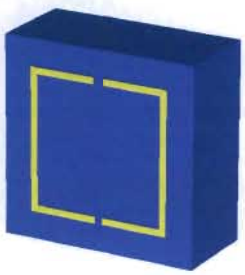


Los Alamos

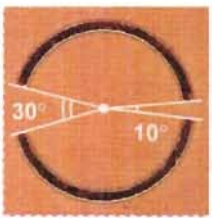
NNSA

SRR

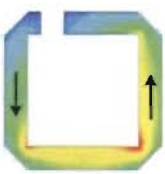
Split Ring Resonator (SRR)



- Asymmetry important for radiation coupling from fundamental resonance
  - Gap ratio
  - Gap placement
- Two gaps required for bias



Fedotov, et. al., PRL **99**, 147401 (2007)



Al-Naib, et. al., APL **94**, 153505 (2009)

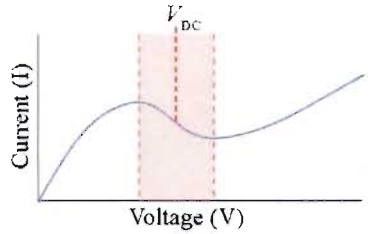
Los Alamos

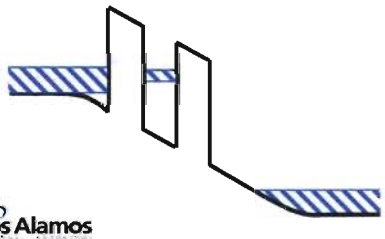
NNSA

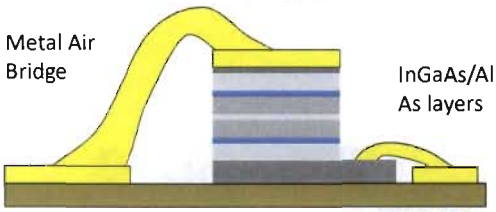
RTD

Resonant Tunneling Diode (RTD)

- Negative Conductance Device
- Resonant Tunneling
  - Two barriers leads to 100% transmission
  - High Frequency Response







Los Alamos

NNSA

Metamitter Fabrication

Bare InP Wafer

MBE Layer-by-Layer Growth

Etching Pillars for RTDs

Metalization SRR + Bias Lines

Electroplating of Air Bridges

Dicing and Testing

Los Alamos

NNSA

Development Plan

Frequency	Isolated Element	Multielement Array
1 GHz	30 *mm*	1 × 2
100 GHz	300 μm	3 × 3
300 GHz	100 μm	4 × 4
1 THz	30 μm	END STATE

Los Alamos

NNSA

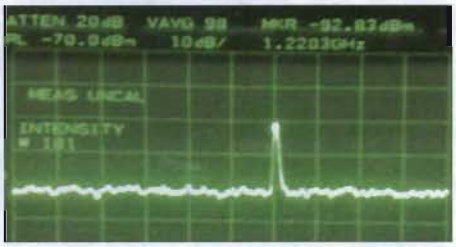
Concurrent Investigations

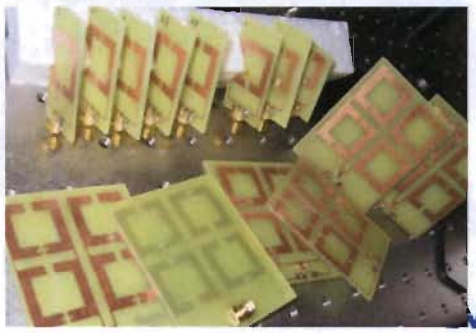
- Gain Loaded Metamitter Elements
  - GHz frequency scale analogs
  - Commercially available tunnel diodes
- Passive Micron Scale Metafilm Arrays
  - THz frequency response
  - Test design concepts in response to observations from GHz elements

Los Alamos

NNSA

GHz Metamitters



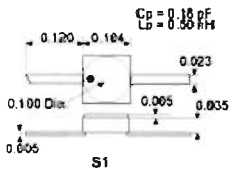


Los Alamos NATIONAL LABORATORY

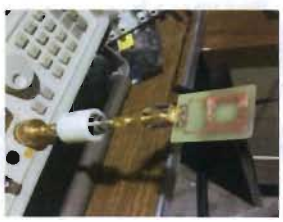
NNSA

Tunnel Diodes

- Meant to be a GHz frequency stand in for THz RTDs
  - Exhibits same negative differential resistance
  - Low threshold voltage
- Can the nonlinearity of the TD account for all the frequency mixing behavior?



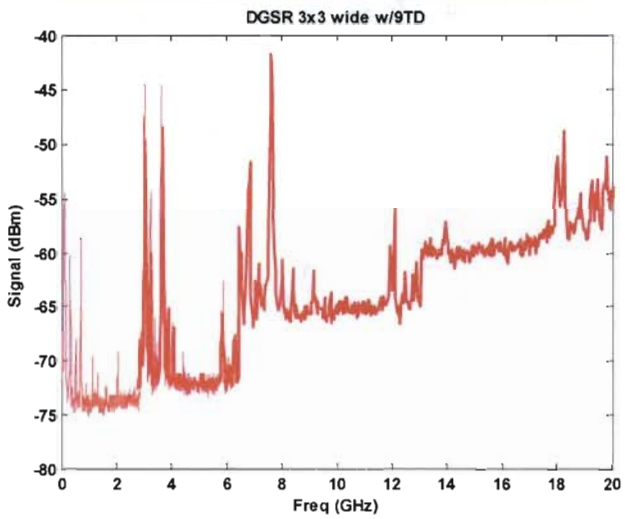
http://www.mpulsemw.com/Tunnel_Diode.htm



Los Alamos NATIONAL LABORATORY

NNSA

3x3 Array

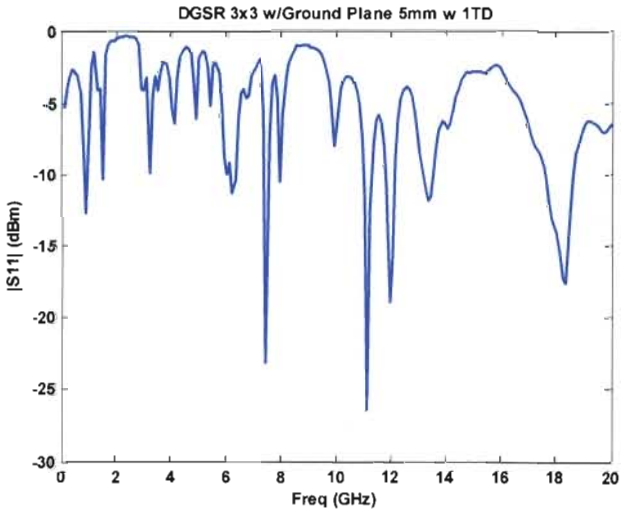


Individual SRR should be resonant @ ~ 6 GHz

Los Alamos

NNSA

3x3 DGSR

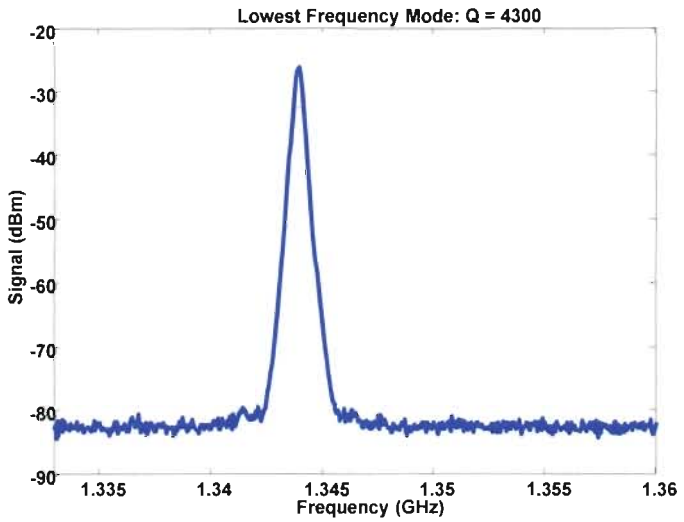


Simplify: one TD
Include ground plane.

Los Alamos

NNSA

Harmonics

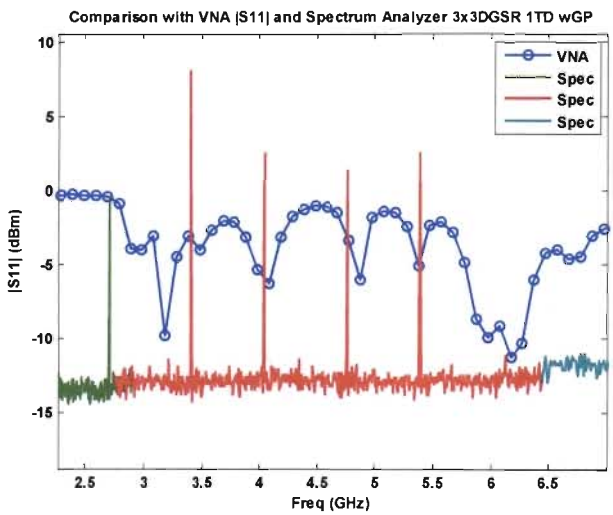


f1 = 1.33 GHz
f2 = 3.4 GHz
f3 = 7.15 GHz
f4 = 14.9 GHz

Los Alamos

NNSA

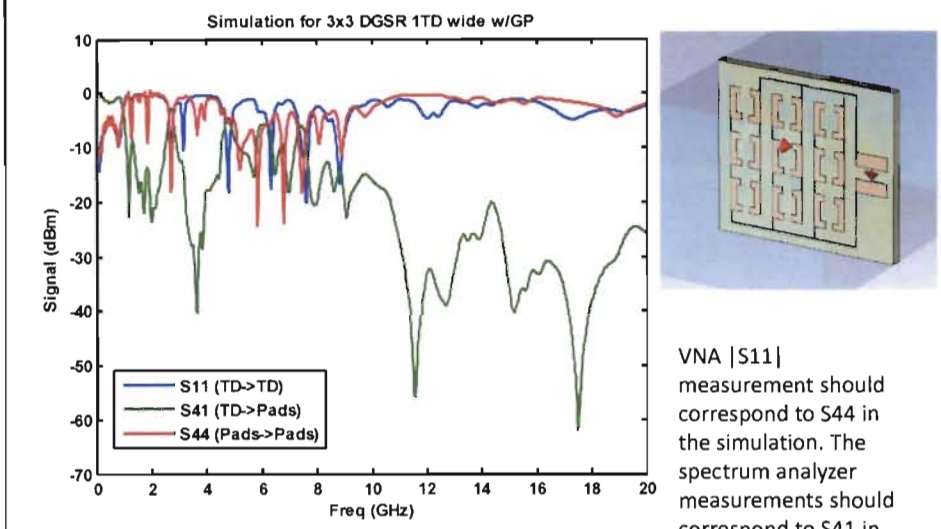
VNA vs Spectrum



Los Alamos

NNSA

Simulation

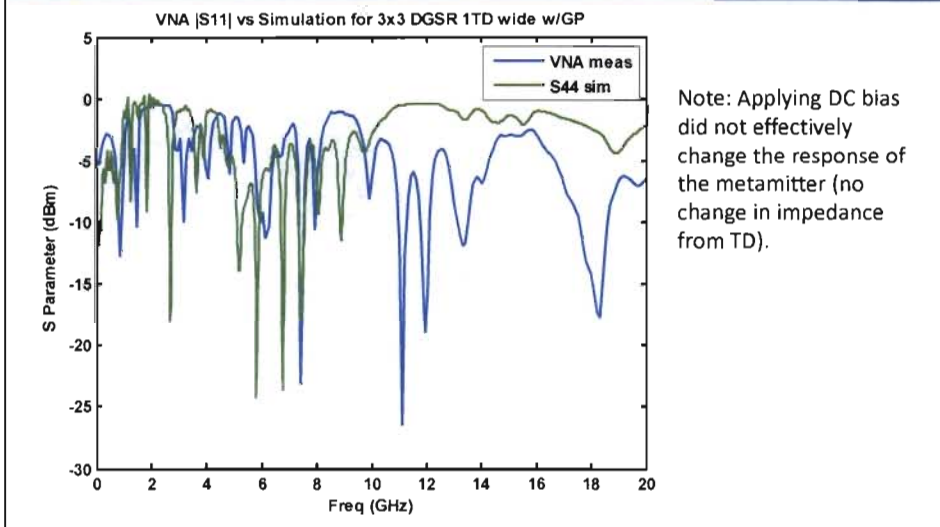


VNA |S11| measurement should correspond to S44 in the simulation. The spectrum analyzer measurements should correspond to S41 in the simulation.

Los Alamos

NNSA

VNA vs Simulation

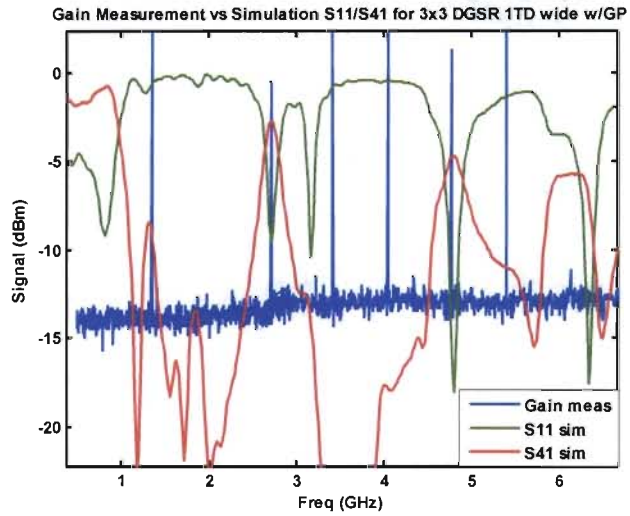


Note: Applying DC bias did not effectively change the response of the metamitter (no change in impedance from TD).

Los Alamos

NNSA

Gain Spectrum vs. Simulation



Possible correlation between gain and resonances at:

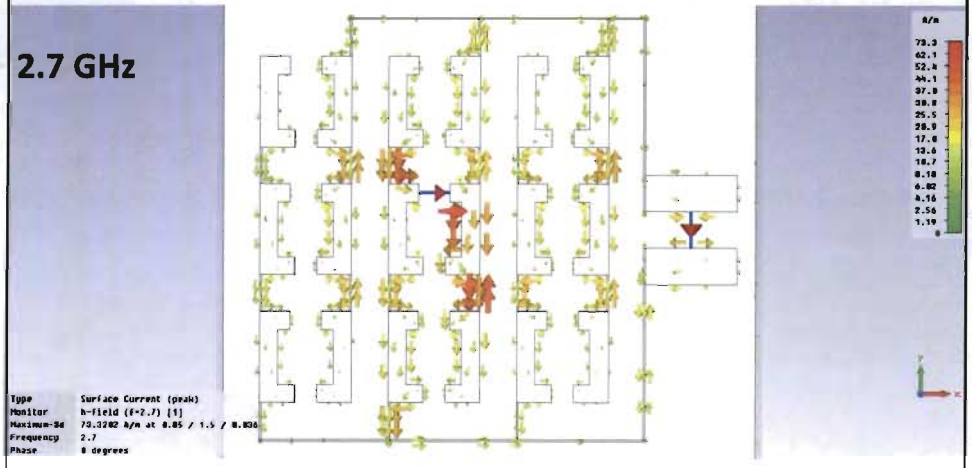
1.35 GHz
2.7 GHz
4.8 GHz

The rest??

Los Alamos

NNSA

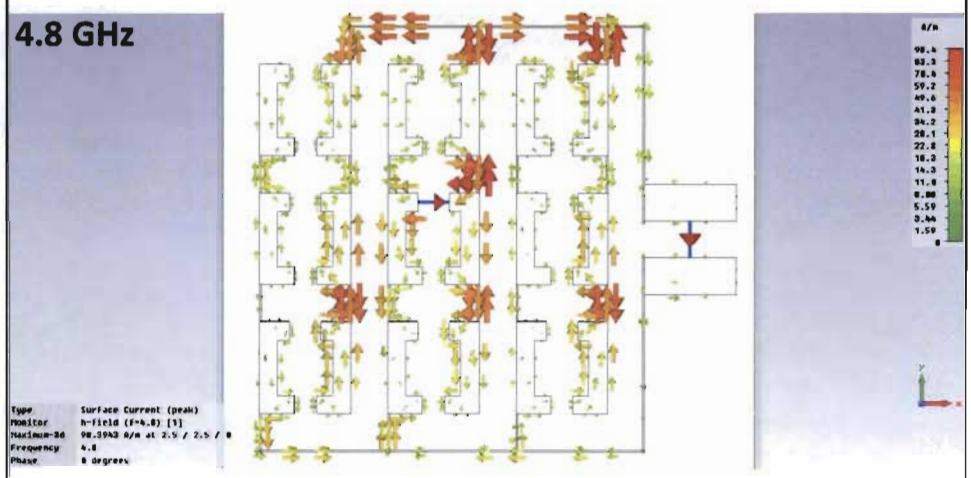
Simulation Current Densities



Los Alamos

NNSA

Simulation Current Densities (cont)

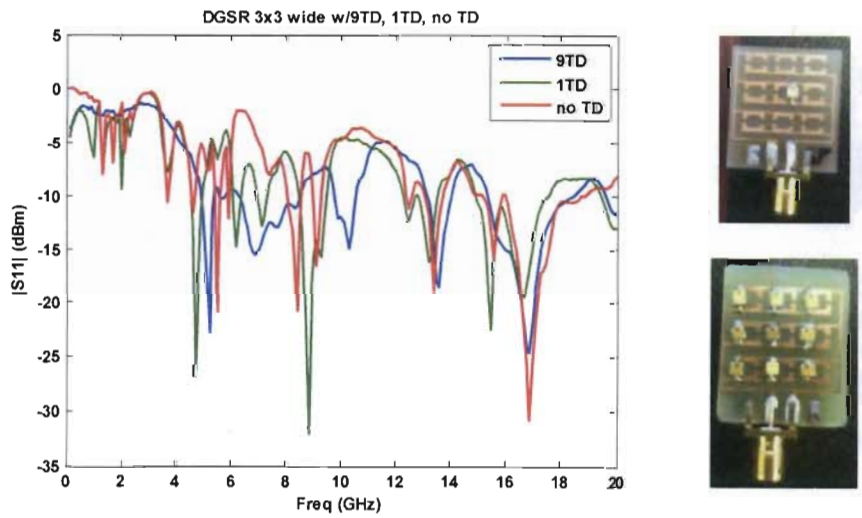


Bias leads like to oscillate...

Los Alamos

NNSA

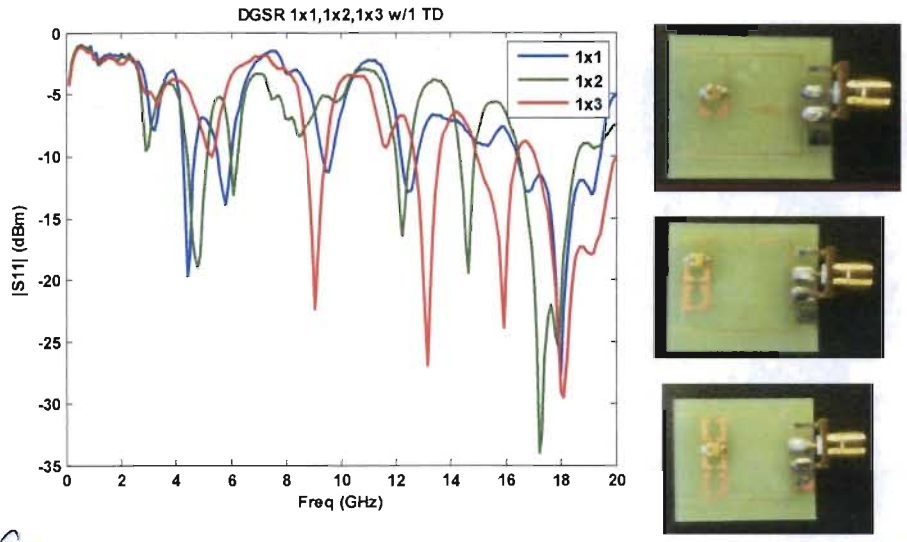
Effect of Loading DGSR?



Los Alamos

NNSA

1xn DGSR Comparison



Los Alamos

NNSA

Identified Challenges

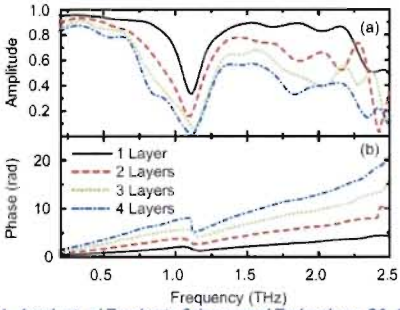
- DC Bias Lines?
  - Had wanted to avoid lumped elements for scaling
  - Introduction of lossy elements inconclusive
- Measurement
  - |S11| misleading as designed
  - Coupling to free space may be best
- Coupled Oscillators
  - General result: *n* oscillators → *n* resonances (may be degenerate if weakly coupled)
- Multiple Frequency Components
  - Resonant Feedback to Stabilize Oscillators?

Los Alamos

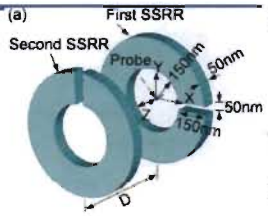
NNSA

Interaction Between Layers

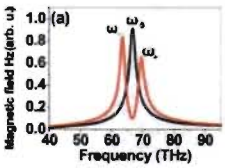
$d \sim \lambda_{res}/5$

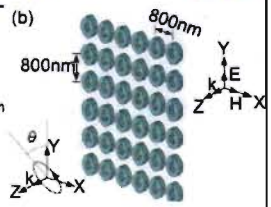


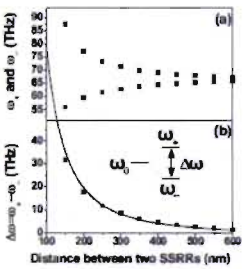
A. Azad, et. al Terahertz Science and Technology, **94**, 15 (2009)



$d \sim \lambda_{res}/50$





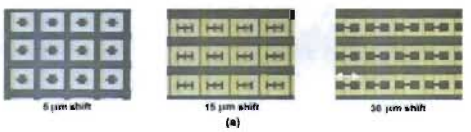


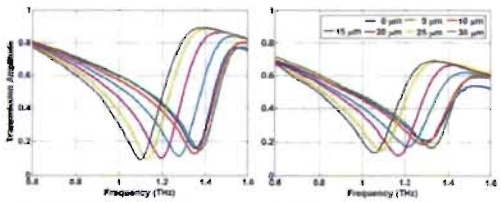
H. Liu, et. al Phys. Rev. **76**, 073101 (2007)

Los Alamos

NNSA

Other Coupling Geometries

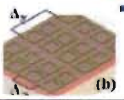


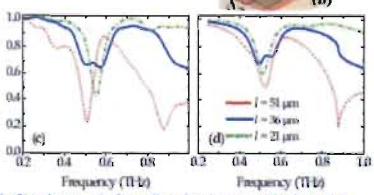


E. Ekmekci, et. al, Frequency-tunable metamaterials using broadside-coupled split ring resonators, arXiv:1008:2195 (2010)

$d \sim \lambda_{res}/60$

Planar Coupling





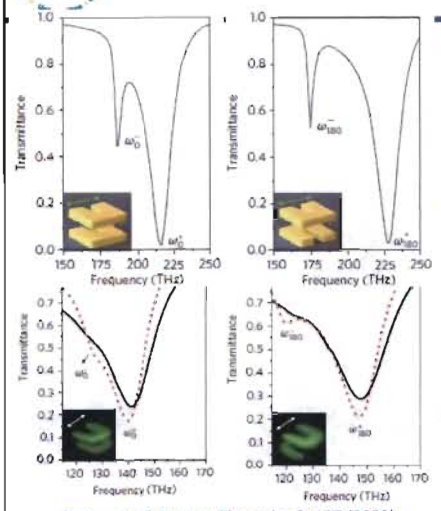
R. Singh, et. al. Coupling between a dark and a bright eigenmode in a terahertz metamaterial, Phys Rev B **79** 085111, 2009

D. Roy Chowdhury, et. al. Passive tuning of the terahertz metamaterial response via coupled resonators, TBP (2010)

Los Alamos

NNSA

Previously Observed Resonance Shifts



The Lagrangian of an isolated SRR

$$\mathcal{L} = \frac{L\dot{Q}^2}{2} - \frac{Q^2}{2C} \qquad \omega_0 = \sqrt{1/LC}$$

The Lagrangian of coupled SRRs

$$\mathcal{L} = \frac{L\dot{Q}_1^2}{2} - \frac{Q_1^2}{2C} + \frac{L\dot{Q}_2^2}{2} - \frac{Q_2^2}{2C} + M_H\dot{Q}_1\dot{Q}_2 + M_E\omega_0^2 Q_1 Q_2 \cos\varphi$$

Solving Euler-Lagrange equation

$$\frac{d}{dt}\left(\frac{\partial \mathcal{L}}{\partial \dot{Q}_i}\right) - \frac{\partial \mathcal{L}}{\partial Q_i} = 0, \quad i = 1,2$$

$$\omega_{\pm} = \omega_0 \sqrt{\frac{1 \mp \frac{M_E}{L}\cos\varphi}{1 \mp \frac{M_H}{L}}}$$

Where did C go in this process?

Wrapped up in $\omega_o = 1/\sqrt{LC}$

N. Liu, et. al. Nature Photonics 3, 157 (2009)

$d \sim \lambda_{res}/50$

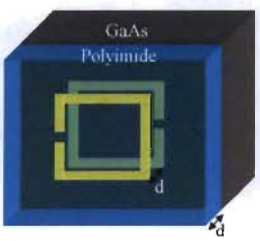
$d \sim \lambda_{res}/500$?

Los Alamos

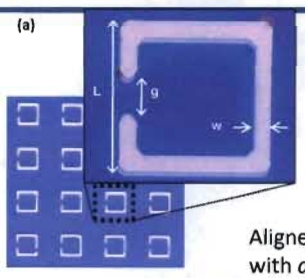
NNSA

Our Experiment

Sample Fabrication

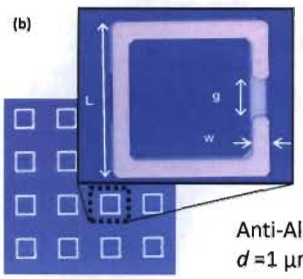


- Standard photolithography
- Substrate SI-GaAs
- Spacing Layer *d* Polyimide
- SRR: 200 nm Au
- Unit Cell: 98 µm
- Thickness: *d* = ~1 and 4 µm



L = 48 µm
g = 12 µm
w = 5 µm

Aligned SRRs with *d* =1 µm



Anti-Aligned SRR with *d* =1 µm

Los Alamos

NNSA

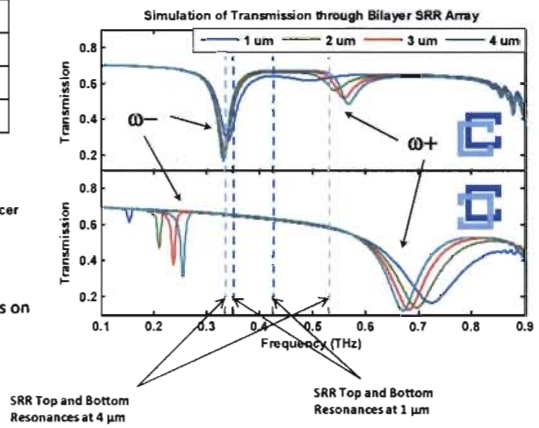
Simulation for Bilayer Arrays Varying *d*

Lower Resonances ω− and isolated SRR resonances

Polyimide Layer	1 μm (sim)	4 μm (sim)
Aligned	0.34	0.33
Anti-aligned	0.15	0.25
SRR Top Only	0.42	0.53
SRR Bottom Only	0.35	0.34

Consequence of inhomogeneity is the SRRs on top and bottom will experience different dielectric environments and will have different uncoupled resonances.

CST Microwave Studio 2009 Time Domain Solver (FDTD) used to simulate the THz TDS experiment.



Los Alamos NNSA

Eigenfrequencies for Inhomogenous Bilayer

$$\Gamma = \frac{L_1}{2}\left(\dot{Q}_1^2 + \omega_1^2 Q_1^2\right) + \frac{L_2}{2}\left(\dot{Q}_2^2 + \omega_2^2 Q_2^2\right) + M_H \dot{Q}_1 \dot{Q}_2 \pm M_E Q_1 Q_2$$

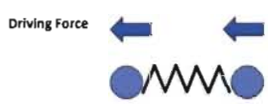
Solving Euler-Lagrange eqn..., realizing that $L_1 = L_2$,...assuming a harmonic oscillator solution $Q_n = B_n e^{i\omega t}$ and then taking the determinant of the resulting coupled differential equations yields:

$$\left(\omega^2 - \omega_1^2\right)\left(\omega^2 - \omega_2^2\right) - \left(\frac{M_H}{L}\omega^2 \pm \frac{M_E}{L}\right)^2 = 0$$

Los Alamos NNSA

Elementary Coupled Oscillators

- General result: *n* coupled oscillators = *n* resonant frequencies
  (may be degeneracies)
- Consider simplest case of two coupled "mass on a spring" oscillators attached to a fixed surface with a spring constant of κ_{self} (not pictured) and coupled with spring constant of $\kappa_{coupling}$



Symmetric
(lower energy)

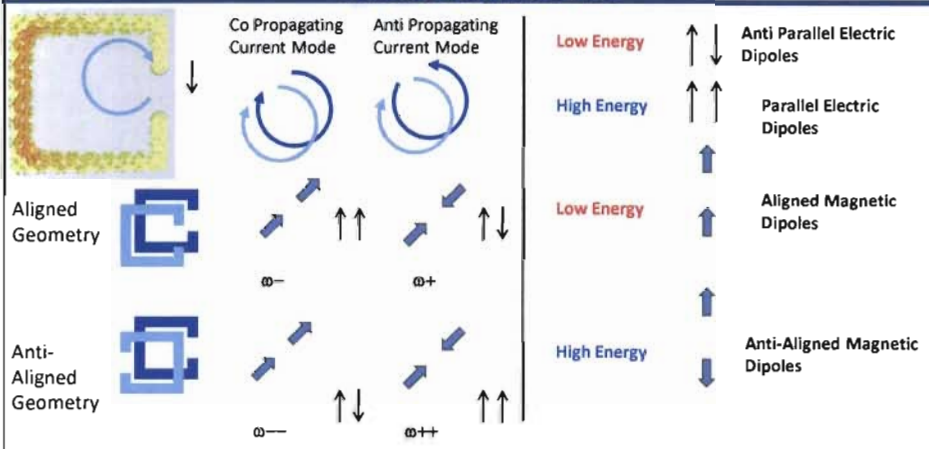
$$\omega- = \sqrt{\frac{\kappa_{self}}{m}}$$

Anti-symmetric
(higher energy)

$$\omega+ = \sqrt{\frac{\kappa_{self} + 2\kappa_{coupling}}{m}}$$

Los Alamos NNSA

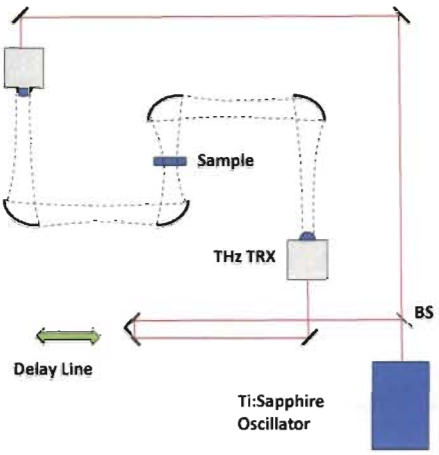
Current Modes and Coupling Mechanisms



With a single coupling mechanism it is relatively easy to identify the "symmetric" and "anti-symmetric" modes. Two competing coupling mechanisms complicate the process.

Los Alamos NNSA

8F THz Time Domain Spectroscopy System

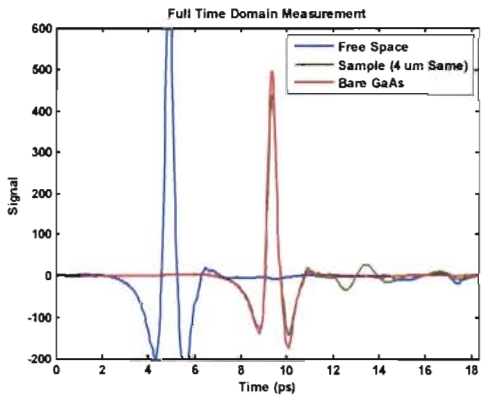


- Photoconductive Switch System
- Sample placed at frequency independent focus
- 2:3 Imaging at focus
- Beam illuminated ~ 2500 SRR pairs
- Etalon pulses limit measurement window to 18.33 ps (Sample substrate & transmitter chip GaAs with thickness of 500 µm)

Los Alamos

NNSA

Measurement Results



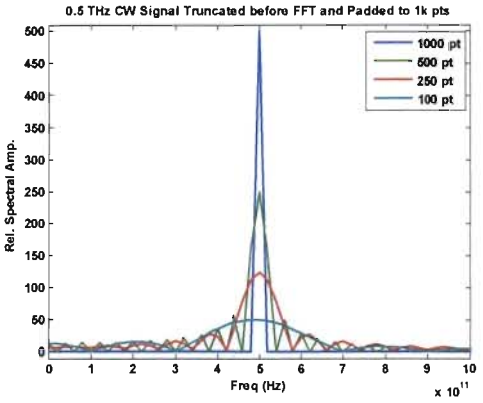
Windowed to remove etalon pulses

- Using the Free Space measurement for the reference spectrum in this case for comparison with CST Microwave Studio simulation results.

Los Alamos

NNSA

Time Windowing Effect on Spectra



Perfect Sine Wave at 0.5 THz
$\Delta t = 0.01$ ps
N = 1000 pts

For low frequency resonances, few cycles will be captured in a finite time window.

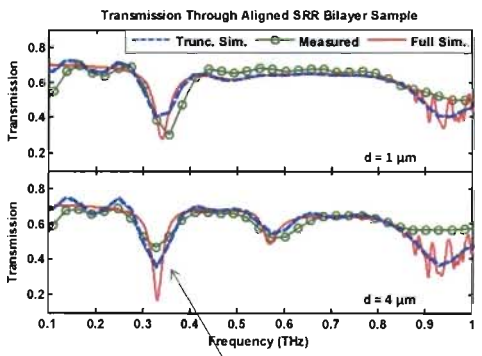
Zero padding doesn't add signal, but it does make the result look more continuous.

May add artifacts in analysis.

Los Alamos

NNSA

Sim. vs. Meas. for Aligned SRR



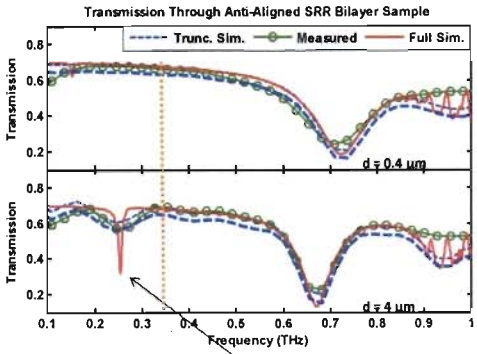
$Q = f_o/\Delta f \approx 12$ from simulation

- Measurement data zero padded to 36.66 ps (2x time window)
- |S21| response adjusted for additional Fresnel losses
- Structure beyond ~0.85 THz likely due to higher order dipoles and interaction with boundary conditions/waveguide modes.
- Truncated time domain analyzed like measurement (18.33 ps window, 2x zero padded)

Los Alamos

NNSA

Sim. vs. Meas. for Anti-Aligned SRR



$Q = f_o/\Delta f \approx 30$ from simulation

- Performing the same analysis as for the aligned SRR geometry.

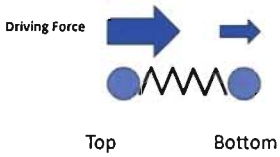
- From the fit to the truncated simulated data, we can infer a sharper resonance for the coupled case than can be measured.

Los Alamos

NNSA

Symmetric vs. Asymmetric Modes

- Asymmetric excitation can result in activating both normal resonances
  - Not typically seen in planar structures→preferred mode only is driven.
- Perhaps due to "shadowing" where the top SRR is preferentially excited by incident field.



Los Alamos

NNSA

Coupled Oscillator Research

- Coupled oscillators follow fundamental physics. Identifying and isolating the coupling mechanisms can be a challenge in order to make use of the fundamental physics to gain further insight.
- Applied: Have method to enhance Q by coupling resonators which may lead to more efficient oscillators and have red shifted the resonance which may lead to more effective electrically small antennas.
- Experimental: In order to resolve high Q resonances, the time window available must be increased for measurements.
- Future: Working toward extracting the relative strength of the electric and magnetic dipole coupling as a function of *d* for various geometries.

Los Alamos NNSA

GHz Metamitter Elements

DGSR (Large)
20 mm x 20 mm
2 mm gap
5 mm width
fo ≈ 2.4 GHz

DGMR
25 mm x 25 mm outer
16 mm x 19 mm mid
9 mm x 12 mm inner
6/2/1 mm gaps
1.5/1.5/ 2 mm widths
fo ≈ 1 GHz (approx)

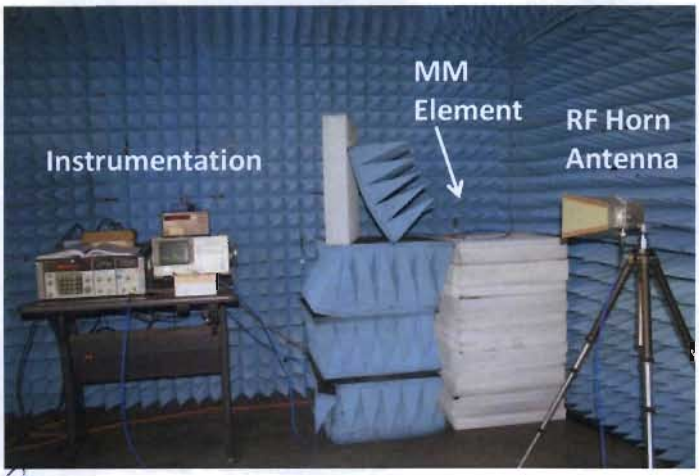
DGDR
25 mm x 25 mm
outer
16.3 mm x 16.3 mm
inner
1/1.75 mm gaps
2 mm width
fo ≈ 1 GHz

DGSR+SGSR
25 mm x 25 mm
DGSR
15 mm x 15 mm
SGSR
2/4 mm gaps
2 mm width
fo ≈ 1 GHz

Los Alamos NNSA

Experimental Set Up

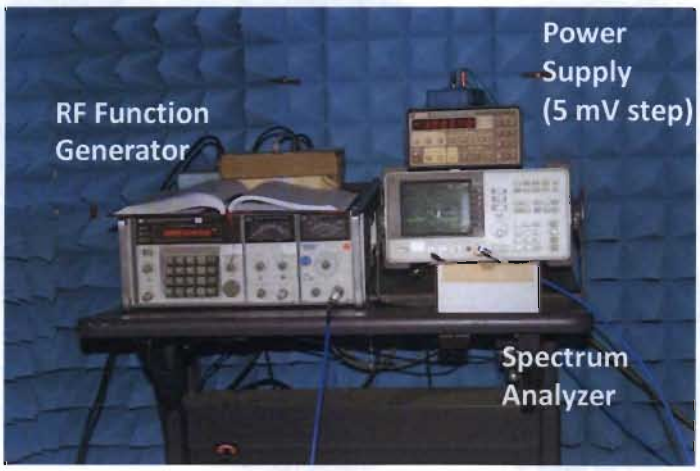
External free space RF excitation experiment



All external RF measurements were taken with magnetic excitation of the metamaterial element. No contribution expected from the

(Photo Courtesy Larry Earley)

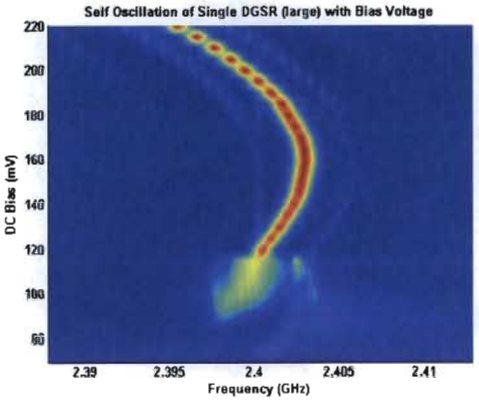
Instrumentation



Self oscillation measured with power supply and output on the spectrum analyzer.

(Photo Courtesy Larry Earley)

DGSR Metamitter



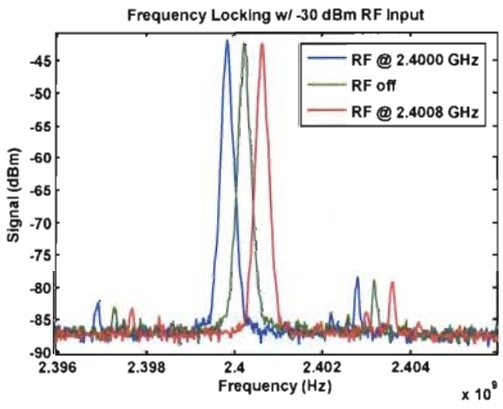
Note onset of sidebands with increasing bias.

Frequency shifting is most likely due to variation in the gain (slope = dI/dV) of the negative differential resistance.

Los Alamos

NNSA

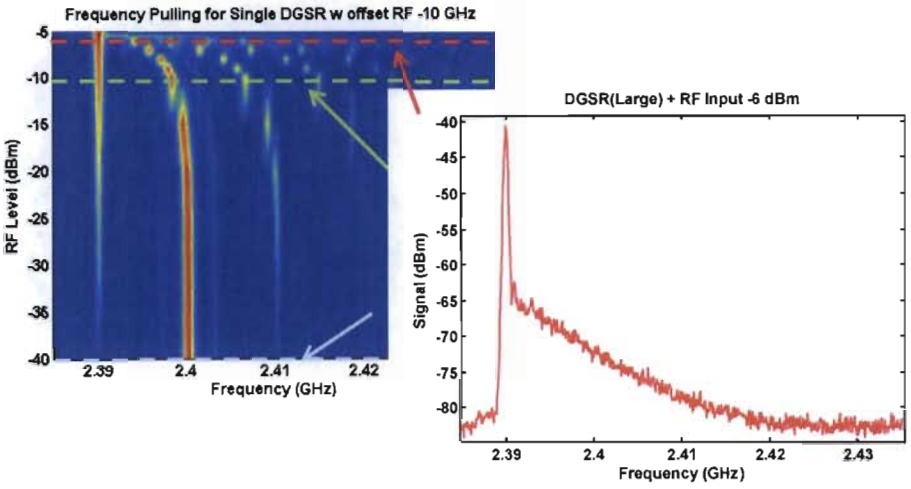
Frequency Locking



Los Alamos

NNSA

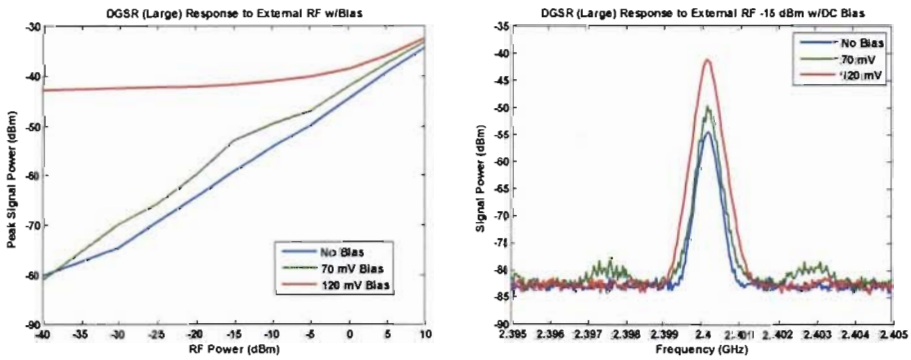
Frequency Pulling



Los Alamos

NNSA

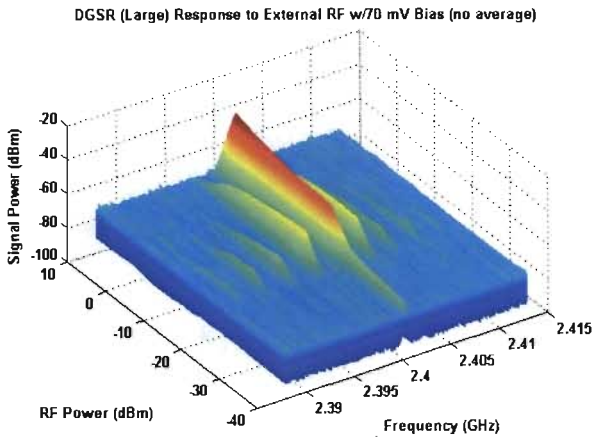
Gain



Los Alamos

NNSA

Frequency Mixing

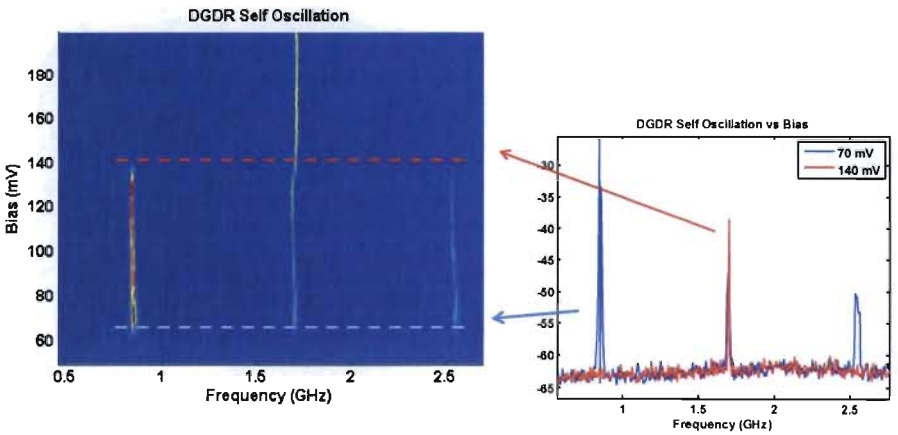


Unaveraged signal is noisy but shows more dramatic response with RF input for sub oscillation dc bias. The side bands are very jittery and apparently so is the peak response. Notice the sudden onset at -20 dBm RF power.

Los Alamos

NNSA

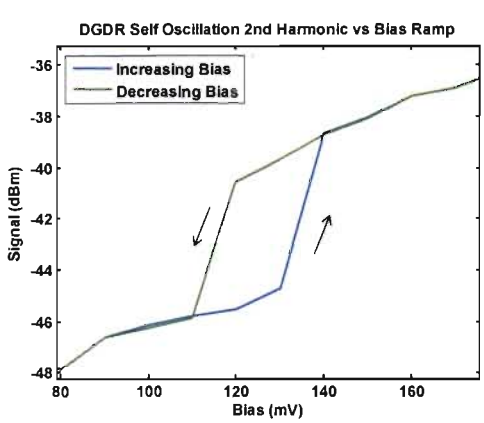
Double Gap Double Ring

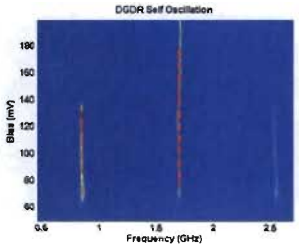


Los Alamos

NNSA

DGDR Hysteresis

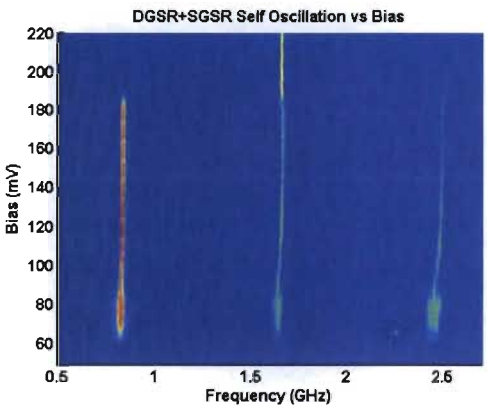




Los Alamos

NNSA

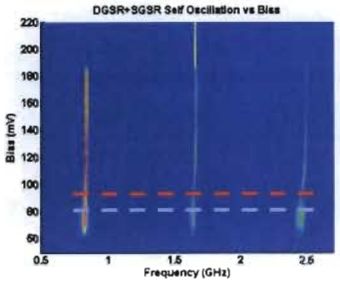
DGSR + SGSR

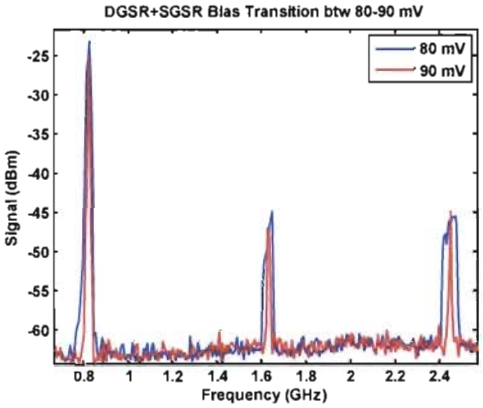


Los Alamos

NNSA

Line Narrowing

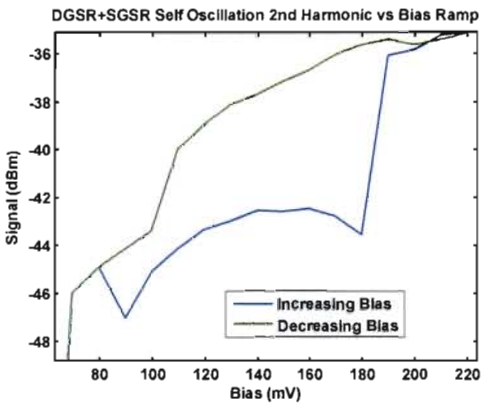


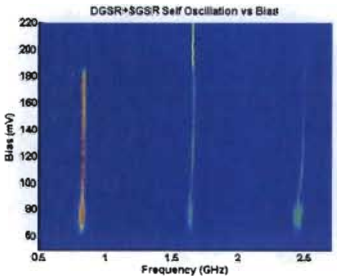


Los Alamos

NNSA

Hysteresis





Los Alamos

NNSA

Double Gap Multi-Ring

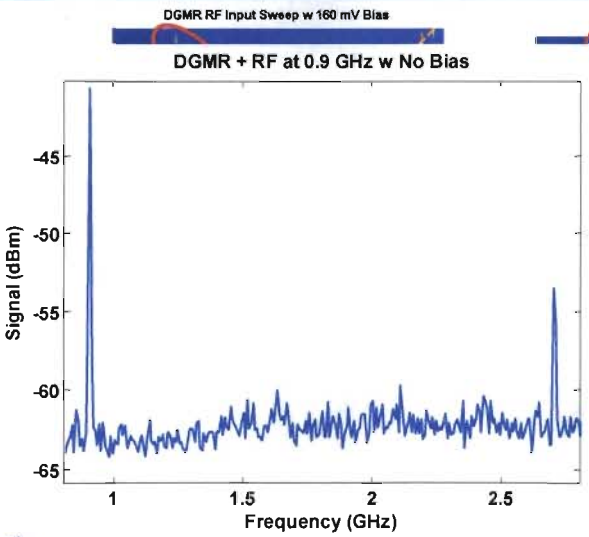
No self oscillation observed...

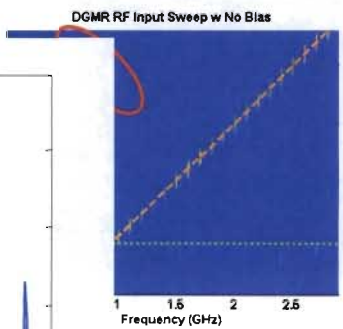
at least below 2.9 GHz.

Los Alamos

NNSA

RF Sweep of DGMR



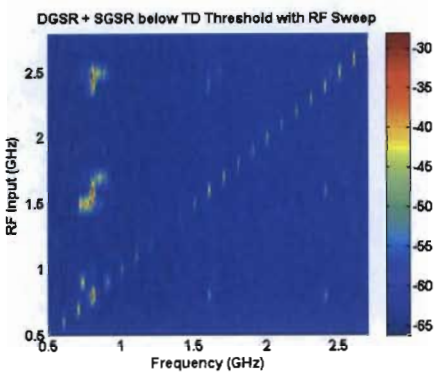


3rd Harmonic frequency of driving field w/o bias across TD.

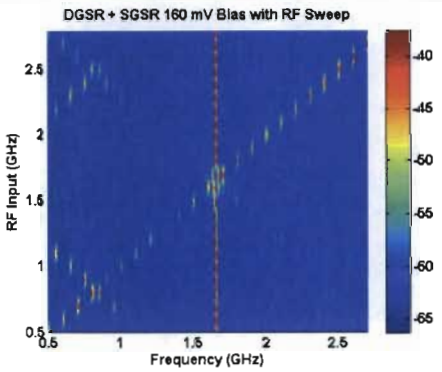
Los Alamos

NNSA

RF Sweep of DGSR+SGSR



When RF input is on a sustained harmonic resonance, all 3 harmonics are observed.



Bias was above transition to support only 2nd harmonic self oscillation.

Los Alamos NATIONAL LABORATORY

NNSA

Overall Conclusion

- Continuing working on development of THz Metamitter
  - Technical hurdle with air-bridge for RTD fabrication
- Interaction of coupled oscillators
  - Spin off results applicable to electrically small antennas
  - Potential to push SRR resonances higher for metamitter
- Frequency mixing as an asset
  - Hysteresis
  - Heterodyne detection (focal plane array)

Los Alamos NATIONAL LABORATORY

NNSA