

Chaos Experiments

Steven M. Anlage

Renato Mariz de Moraes

Tom Antonsen

Ed Ott

Physics Department

University of Maryland, College Park



UNIVERSITY OF
MARYLAND

MURI Review Meeting

8 June, 2002

Report Documentation Page			Form Approved OMB No. 0704-0188			
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.						
1. REPORT DATE JUL 2006		2. REPORT TYPE N/A		3. DATES COVERED -		
4. TITLE AND SUBTITLE Chaos Experiments				5a. CONTRACT NUMBER		
				5b. GRANT NUMBER		
				5c. PROGRAM ELEMENT NUMBER		
6. AUTHOR(S)				5d. PROJECT NUMBER		
				5e. TASK NUMBER		
				5f. WORK UNIT NUMBER		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Physics Department University of Maryland, College Park				8. PERFORMING ORGANIZATION REPORT NUMBER		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)		
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)		
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release, distribution unlimited						
13. SUPPLEMENTARY NOTES The original document contains color images.						
14. ABSTRACT						
15. SUBJECT TERMS						
16. SECURITY CLASSIFICATION OF:				17. LIMITATION OF ABSTRACT UU	18. NUMBER OF PAGES 22	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified				



Chaos Experiments

Two Approaches

Classical Chaos

Nonlinear Circuits

Is there premature circuit failure due to nonlinear dynamics?

Wave Chaos

Statistical properties of waves trapped in irregular enclosures

Effects of breaking time-reversal symmetry

Effects of coupling



Motivation

Classical Chaos

Identify novel ways to introduce low frequency signals into circuits using nonlinear dynamics

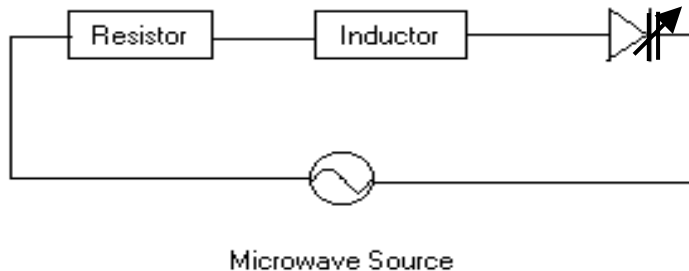
Does nonlinear dynamics and chaos create new opportunities to modify circuit behavior?

Are there qualitatively new failure modes of circuits than can be exploited using nonlinear dynamics?

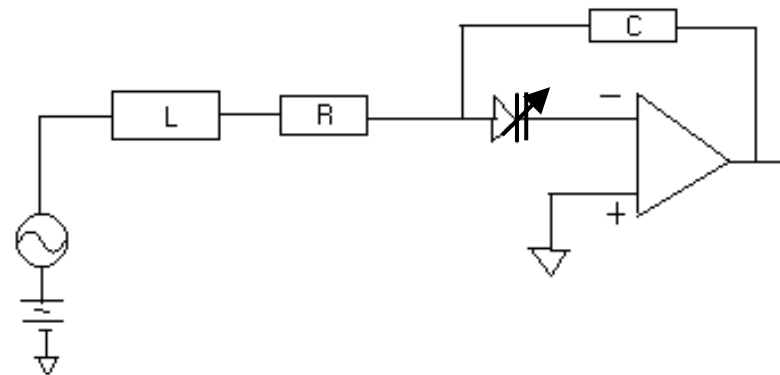


Focus

Experimental investigation of the driven Resistor-Inductor-Diode (RLD) series circuit with and without a TransImpedance Amplifier (TIA)



Driven RLD



Driven RLD/TIA



Are There Other Effects of Nonlinear Dynamics?

Given the absence of irreversible changes in the RLD/Op-Amp circuit, can we identify other effects of nonlinear dynamics on circuit behavior?



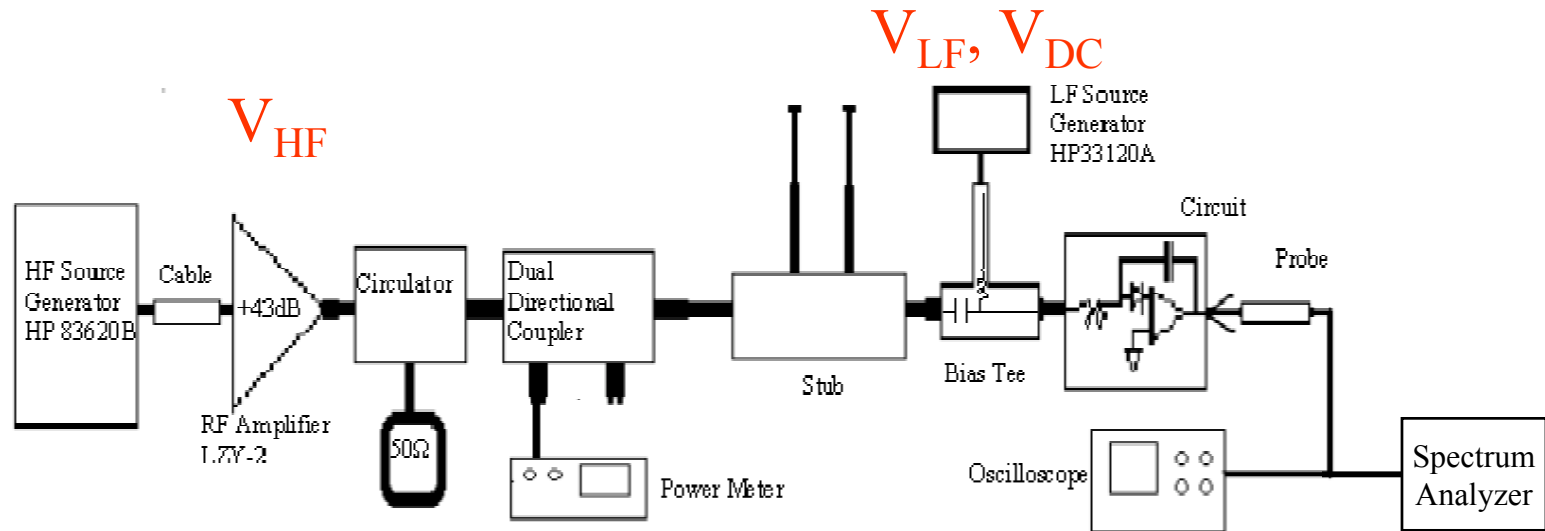
Two-Tone Irradiation of Nonlinear Circuits

Can the presence of a “high frequency” signal increase the susceptibility of a “low frequency” circuit to go into chaos?

Can two-tone injection increase the susceptibility of a circuit to go into chaos? Vavriv (Kharkov)



Two Tone (Hi/Lo) Injection Of RLD/Op-Amp Circuit



Circuit $f_0 \sim 10$ MHz

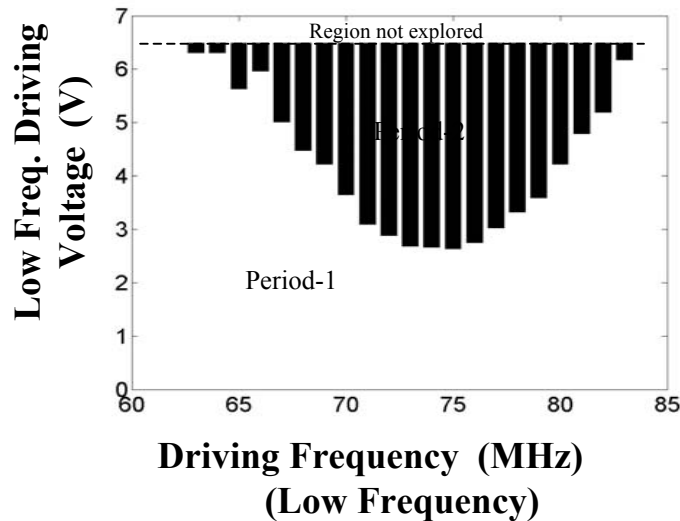
V_{LF} at 5.5 MHz

V_{HF} at 800 MHz



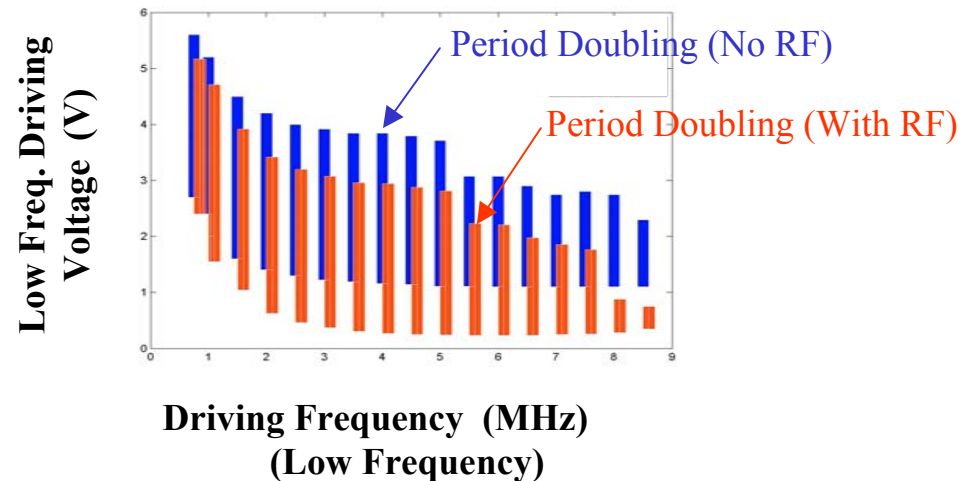
Two-Tone Irradiation of Nonlinear Circuits

Driven RLD Circuit



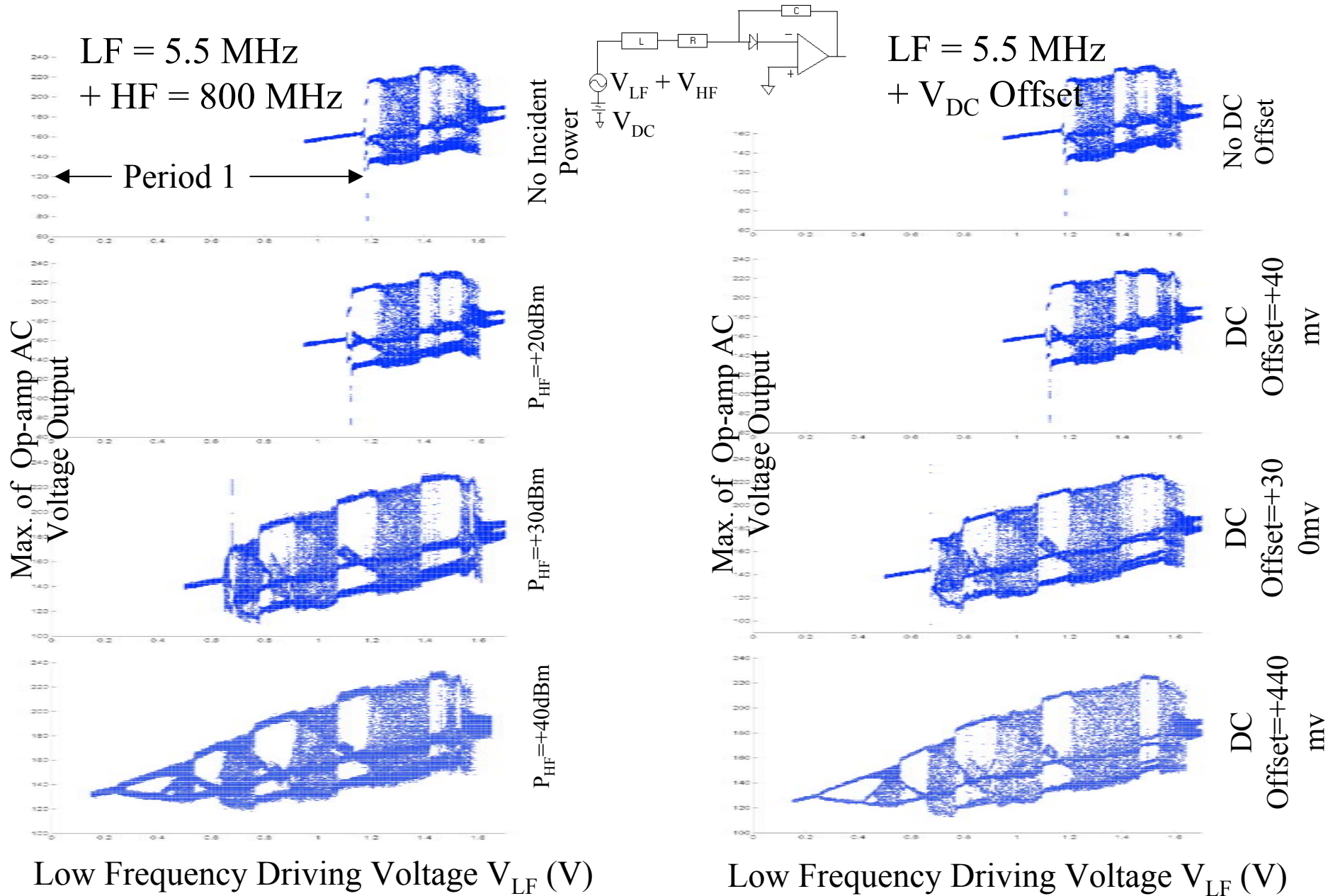
No change in period doubling behavior with or without RF

Driven RLD/TIA Circuit



RF irradiation causes significant drop in driving amplitude required to produce the period-doubling transition!

RF Irradiation Lowers the Threshold for Chaos in Driven RLD/TIA





RF Illumination and Chaos In the RLD/TIA Circuit

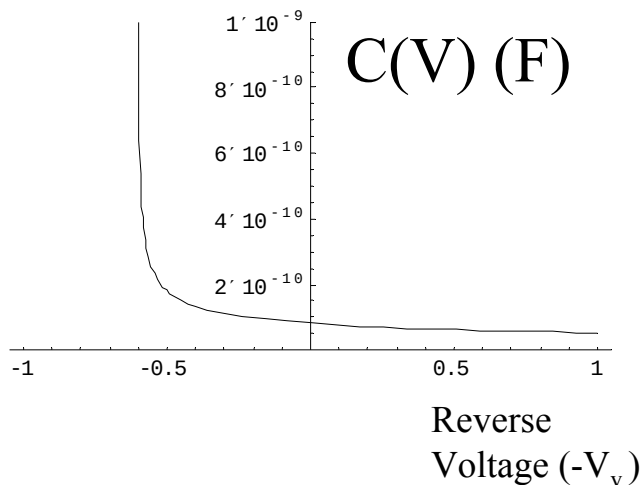
800 MHz signal lowers the threshold for chaos at 5.5 MHz dramatically

Results consistent with a DC offset generated by rectification in the diode
(the sign depends on the polarity of the diode)

DC offset changes the bias point on the $C(V)$ curve

Higher $C \Rightarrow$ period doubling and eventually chaos

This DC offset is VERY SMALL in the driven RLD circuit $\Rightarrow$ no change



$$f_0 = \frac{1}{2\pi\sqrt{LC(V_{DC})}}$$



Conclusions And Open Questions



Two-Tone (Hi/Lo frequency) injection lowers the threshold for chaos in the RLD circuit followed by a trans-impedance amplifier

“Embedded” nonlinear circuits may cause more trouble than we expect on the basis of their behavior in isolation

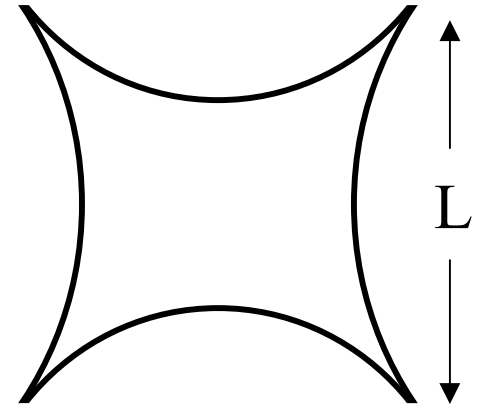
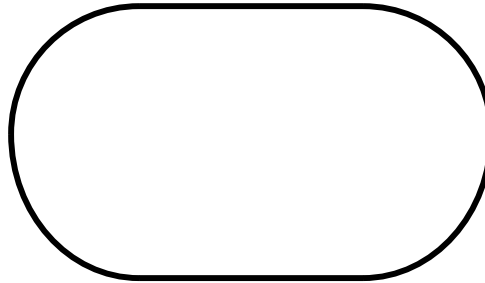
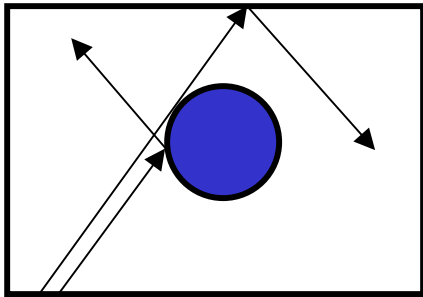
Does chaos lower the threshold for irreversible change to electronic components?

To what extent do modern IC p/n junctions exhibit nonlinear capacitance and period doubling bifurcations?

Funding provided by STIC/STEP and Air Force MURI

Wave Chaos in Bounded Regions

Consider a two-dimensional infinite square-well potential box that shows chaos in the classical limit:



Now solve the Schrodinger equation in the same potential well
These solutions can be mapped to those of the Helmholtz equation
for electromagnetic fields in a 2D cavity

Examine the solutions in the semiclassical regime:
wavelength $\lambda \ll$ system size L

What will happen?

An Important Issue: Time Reversal Symmetry Breaking

Theory tells us that there are only three distinct classes of Wave Chaotic systems:

Time-Reversal Symmetric (GOE)

Broken Time-Reversal Symmetry (GUE)

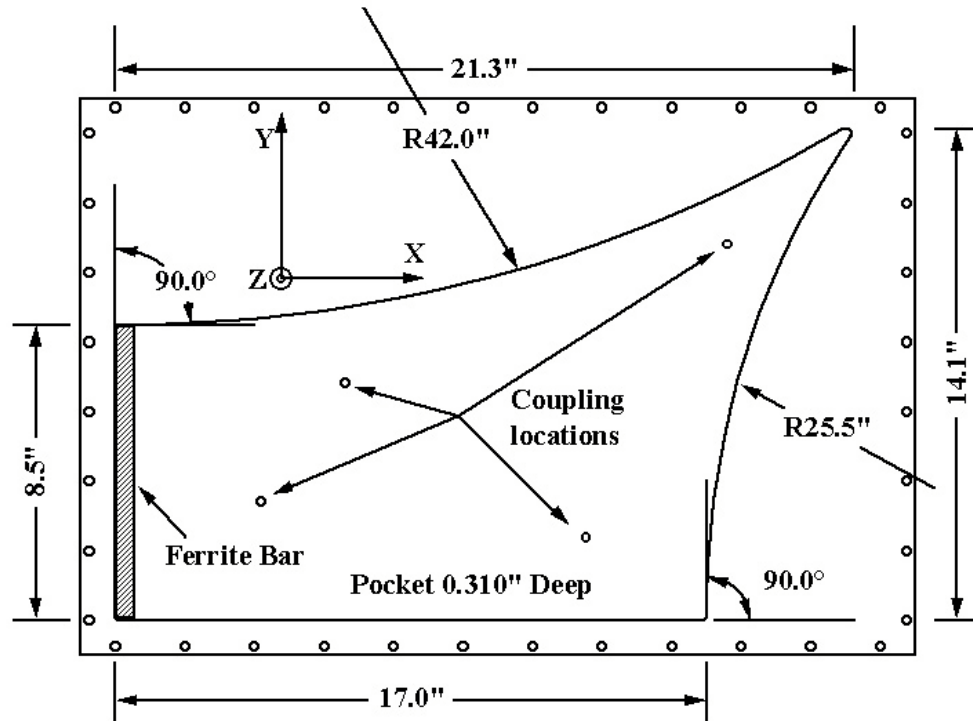
Symplectic (Spin-1/2) Symmetry (GSE)

Our Goal: Investigate electromagnetic wave chaotic systems in the Time-Reversal Symmetric (TRS) and TRS-Broken (TRSB) states, and for states in between.

➡ TRSB modifies the eigenvalue spectrum

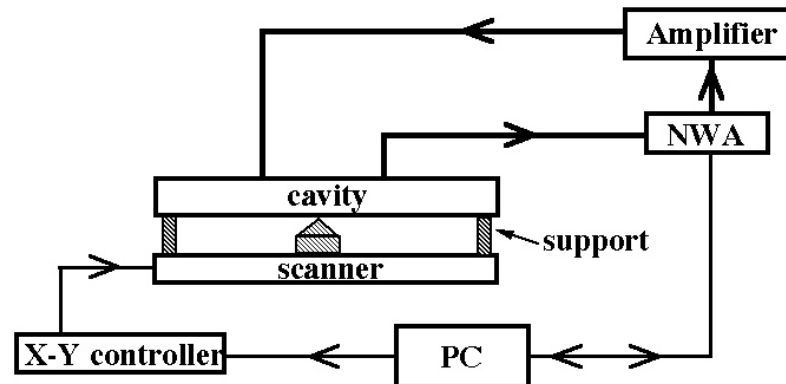
➡ TRSB modifies the eigenfunctions

How do we Perform the Experiment?

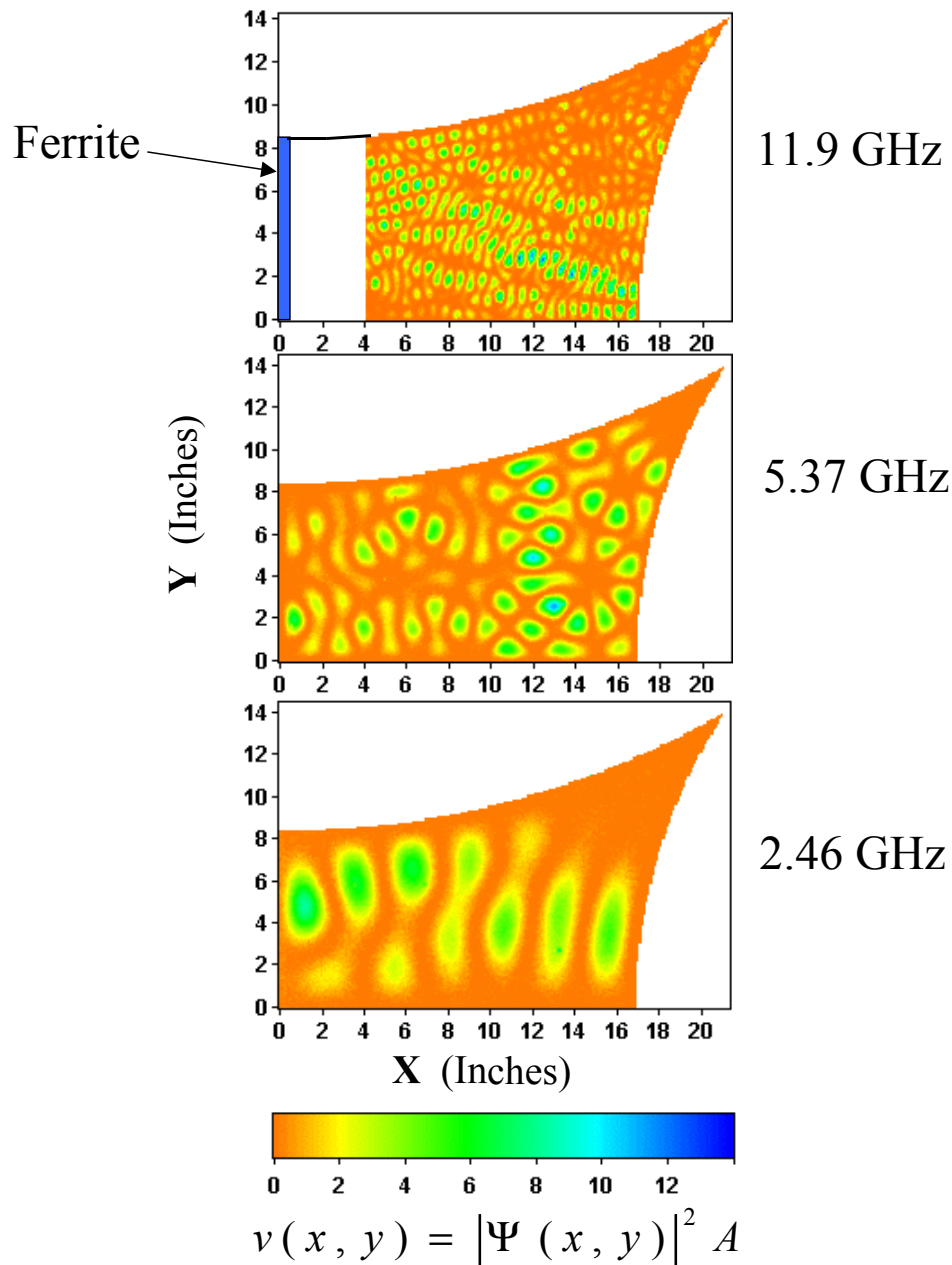


Quarter bow-tie
microwave
resonator

Measurement
setup



Eigenfunctions



A. Gokirmak and S. M. Anlage,
Rev. Sci. Instrum. 69, 3410 (1998).

and

D. H Wu and S. M. Anlage,
Phys. Rev. Lett. 81, 2890 (1998).

A Magnetized Ferrite in the Cavity Produces Time-Reversal Symmetry-Breaking

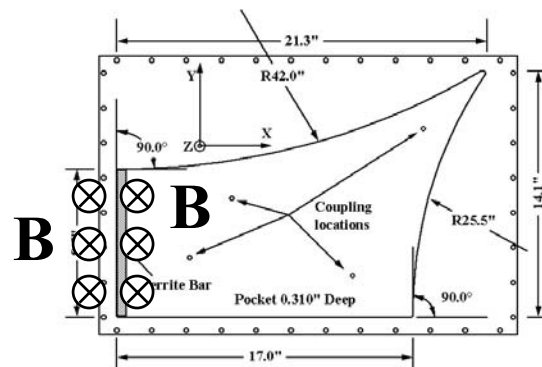
Analogous to a QM particle in a magnetic field

Schrödinger equation for a charged particle in a magnetic field

$$\nabla^2 \Psi - \frac{i2q}{\hbar} \vec{A} \cdot \nabla \Psi + \frac{2m}{\hbar^2} \left[E - \frac{q^2}{2m} \vec{A}^2 \right] \Psi = 0$$

Helmholtz equation for a microwave cavity including a magnetized ferrite

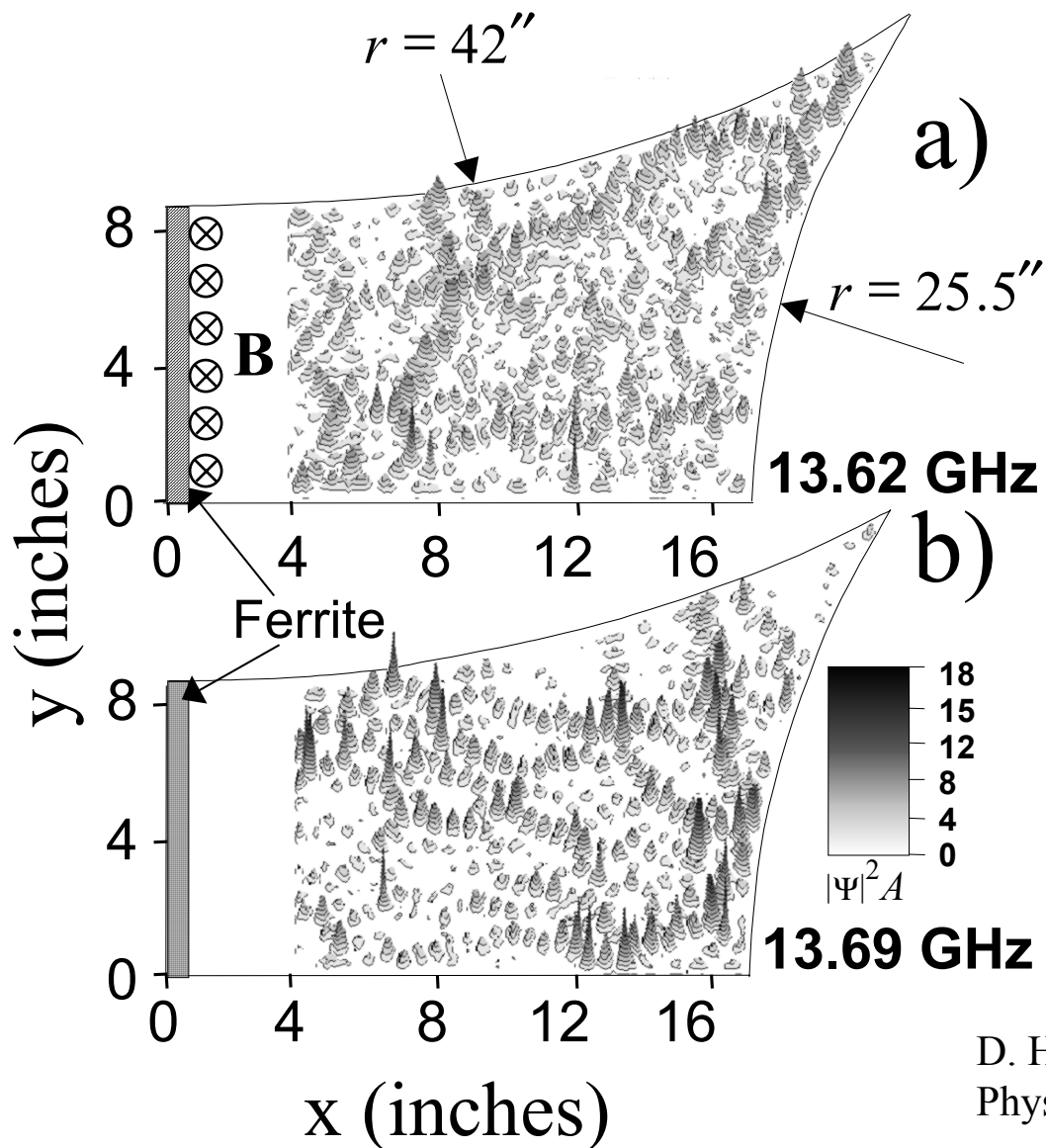
$$\nabla \cdot [(1 + \mu_{\parallel}) \nabla E_z] - i(\hat{z} \times \nabla \kappa) \cdot \nabla E_z + k^2 E_z = 0$$



- ➡ The magnetized ferrite problem and the magnetized Schrödinger problem are in the same TRSB universality class (GUE)



Wave Chaotic Eigenfunctions with and without Time Reversal Symmetry

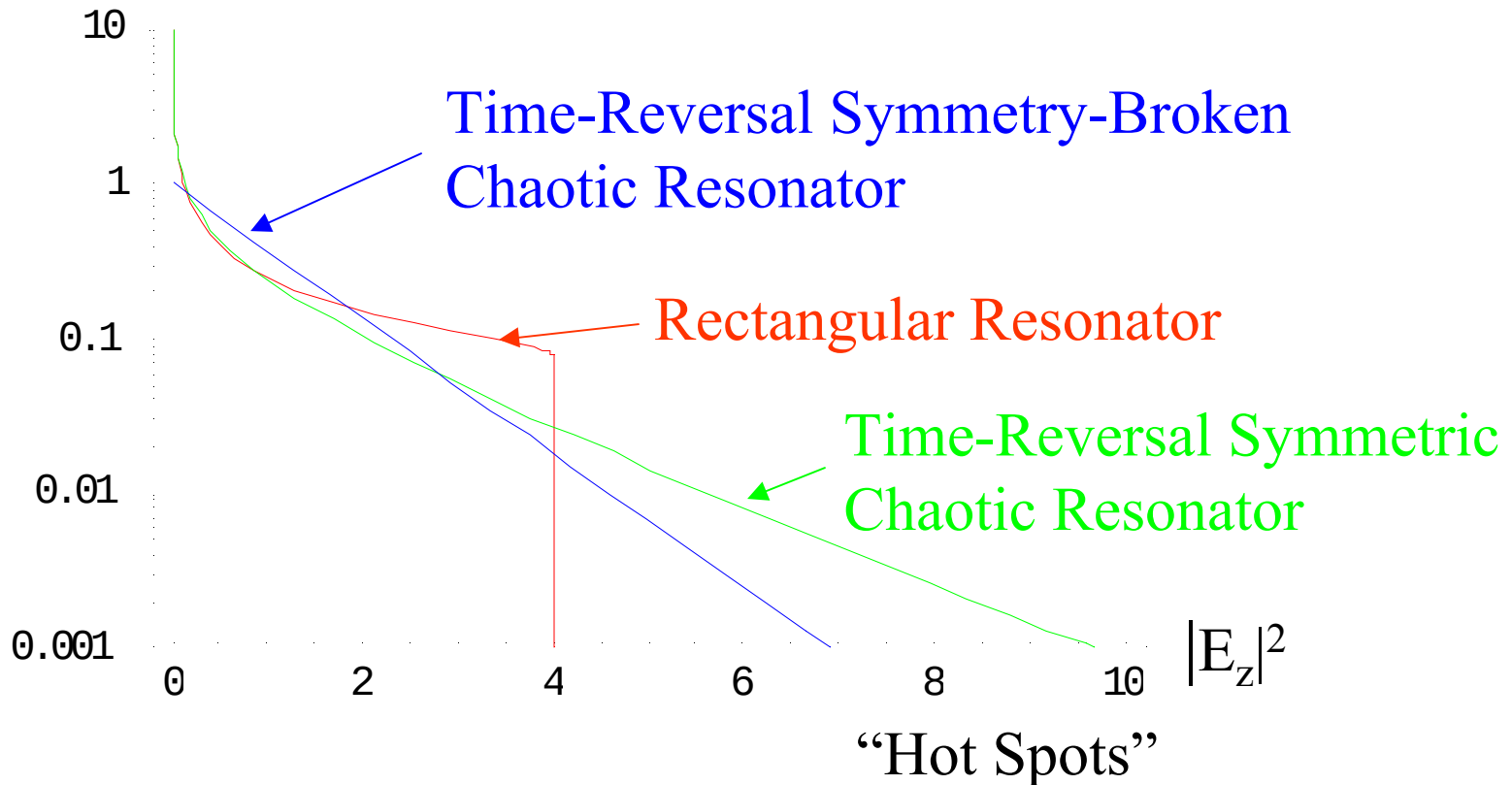


D. H. Wu and S. M. Anlage,
Phys. Rev. Lett. 81, 2890 (1998).

Eigenvalue Fluctuations in Electromagnetic Cavities

Effects of Chaos and Time-Reversal Symmetry Breaking

Probability of $|E_z|^2$



These cavities obey $\Downarrow |E_z|^2 dA = 1$

Experiments in Progress

The bow-tie cavity now has an electromagnet so the degree of time-reversal symmetry-breaking can be tuned.

Image eigenmodes as TRS is destroyed

Statistical properties of the cavity vs. TRSB

Weak Localization (Increase in $|S_{21}|$ with B)

Variable coupling capability

New Analysis

Calculate $|J|^2$ from $|\Psi|^2$

Statistical measure of scars

New Imaging Methods

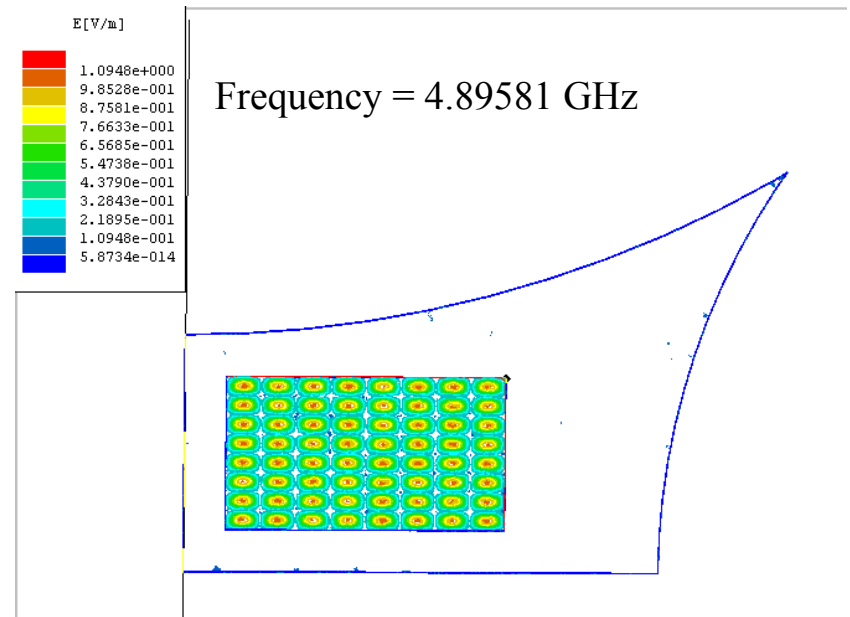
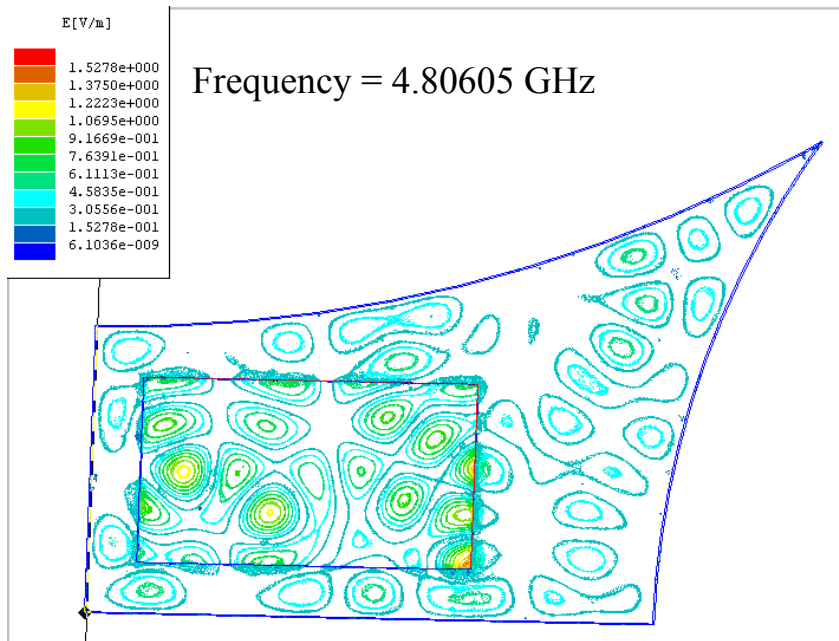
Image the complex E_z (or Ψ) directly, instead of $|E_z|^2$

Numerical Results

Dielectric resonator modes of “pc-board” in cavity

Electromagnetic Simulations of 2D Cavities in HFSS

Quarter bow-tie resonator with a dielectric slab inside Eigenmode Solver



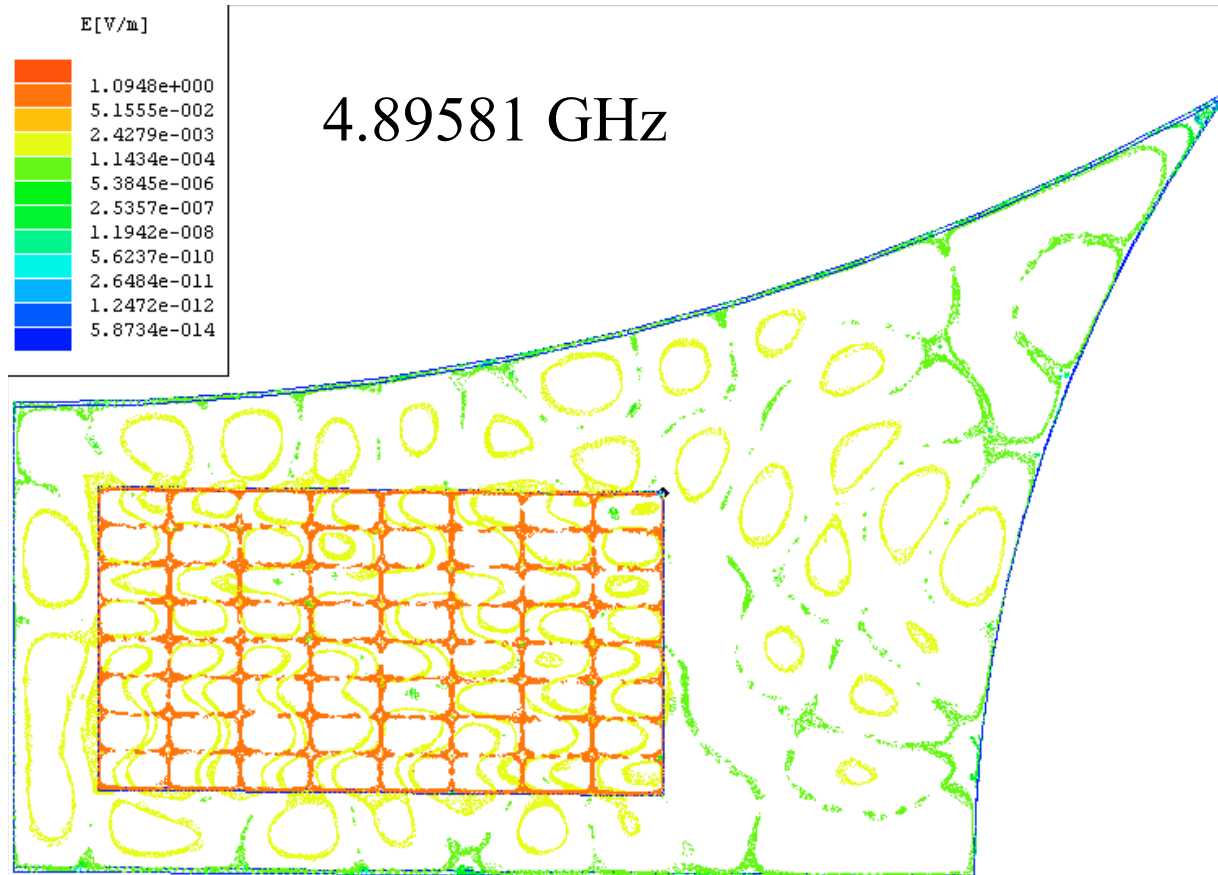
Dielectric slab 10'' x 5.5'' x 0.2'', attached to lid
 $\epsilon_r = 4.0$, $\tan\delta = 0$

Dielectric Slab Mode (8 x 8) in Bow Tie Resonator

HFSS Calculation

Dielectric slab 10" x 5.5" x 0.2", attached to lid
 $\epsilon_r = 4.0$, $\tan\delta = 0$

logarithmic
scale





Conclusions



The statistical Properties of non-trivial electromagnetic resonators can be Understood from the perspective of wave chaos

Time-Reversal Symmetry (TRS) has important consequences for eigenmode properties:

- Stronger “Hot Spots” and more “Dead Spots” in TRS eigenmodes

- More “smoothed out” character of TRSB eigenmodes

- Weaker spatial correlations in TRSB modes

- ➡ Breaking TRS reduces the number of “Hot Spots” in chaotic eigenmodes

New Capabilities and Directions:

- Variable Magnetic field -> Variable degree of Time-Reversal Symmetry Breaking

- Variable coupling -> move from resonator with discrete resonances to a continuum transfer function

Funding provided by Air Force MURI