Chaos Experiments

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MURI Review Meeting
8 June, 2002

Report Documentation Page

Form Approved
OMB No. 0704-0188

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	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**UU**	**22**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

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

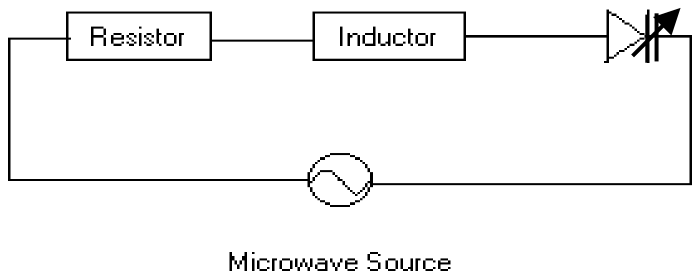
Identify novel ways to introduce low frequency signals into circuits using nonlinear dynamics

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

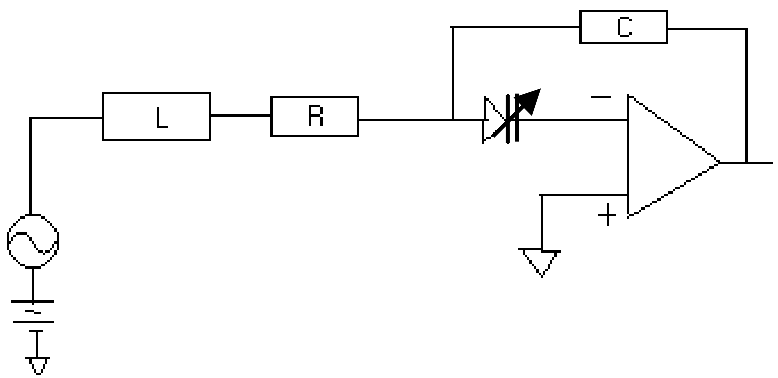
Are there qualitatively new failure modes of circuits than can be exploited using nonlinear dynamics?

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?

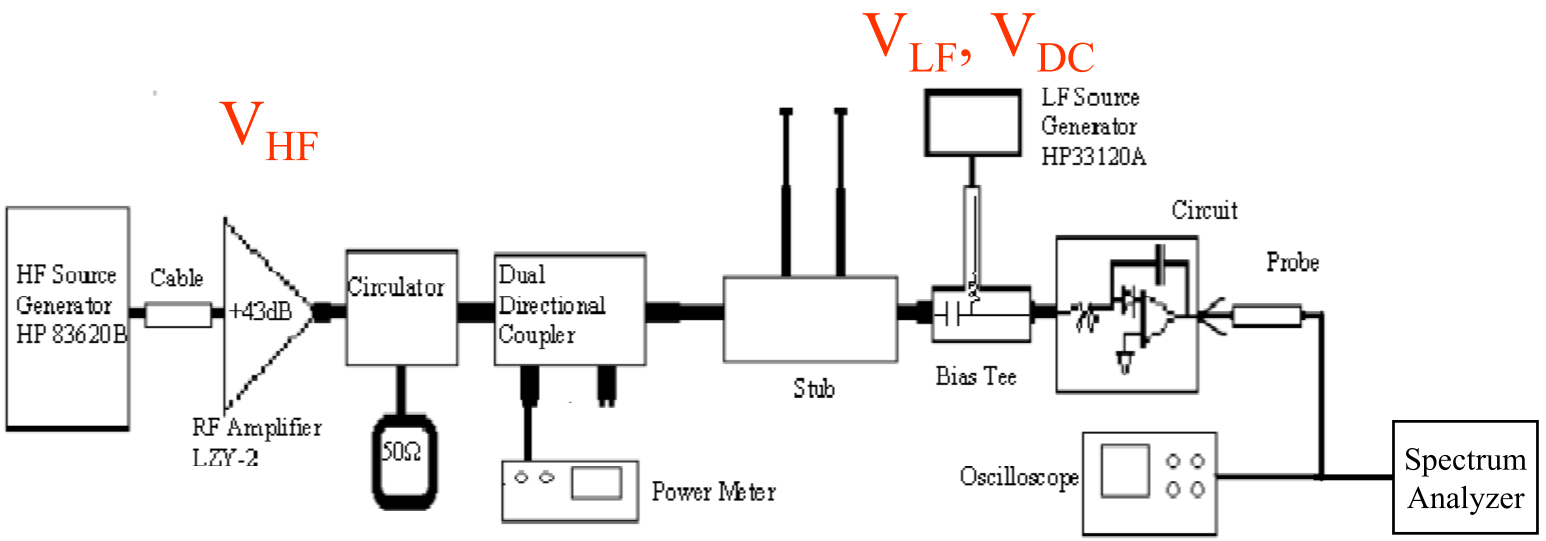
Given the absence of irreversible changes in the RLD/Op-Amp circuit, can we identify other effects of nonlinear dynamics on circuit behavior?

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



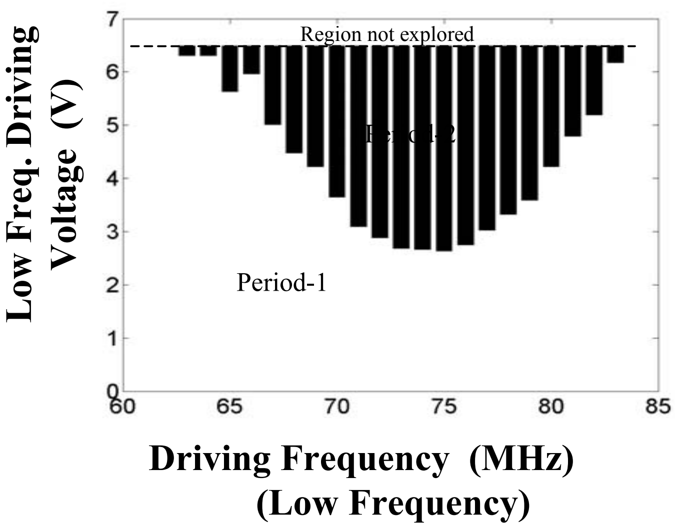
Circuit $f_0 \sim 10$ MHz

V_{LF} at 5.5 MHz

V_{HF} at 800 MHz

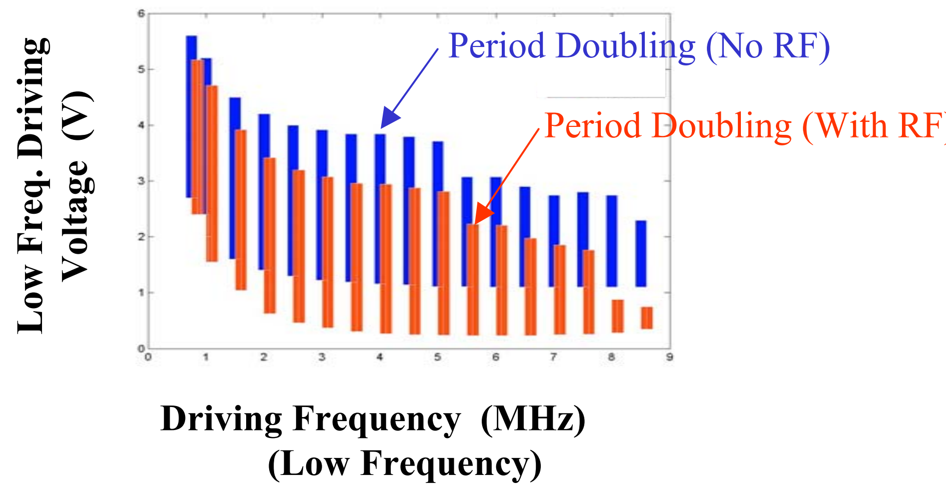
Two-Tone Irradiation of Nonlinear Circuits

Driven **RLD** Circuit



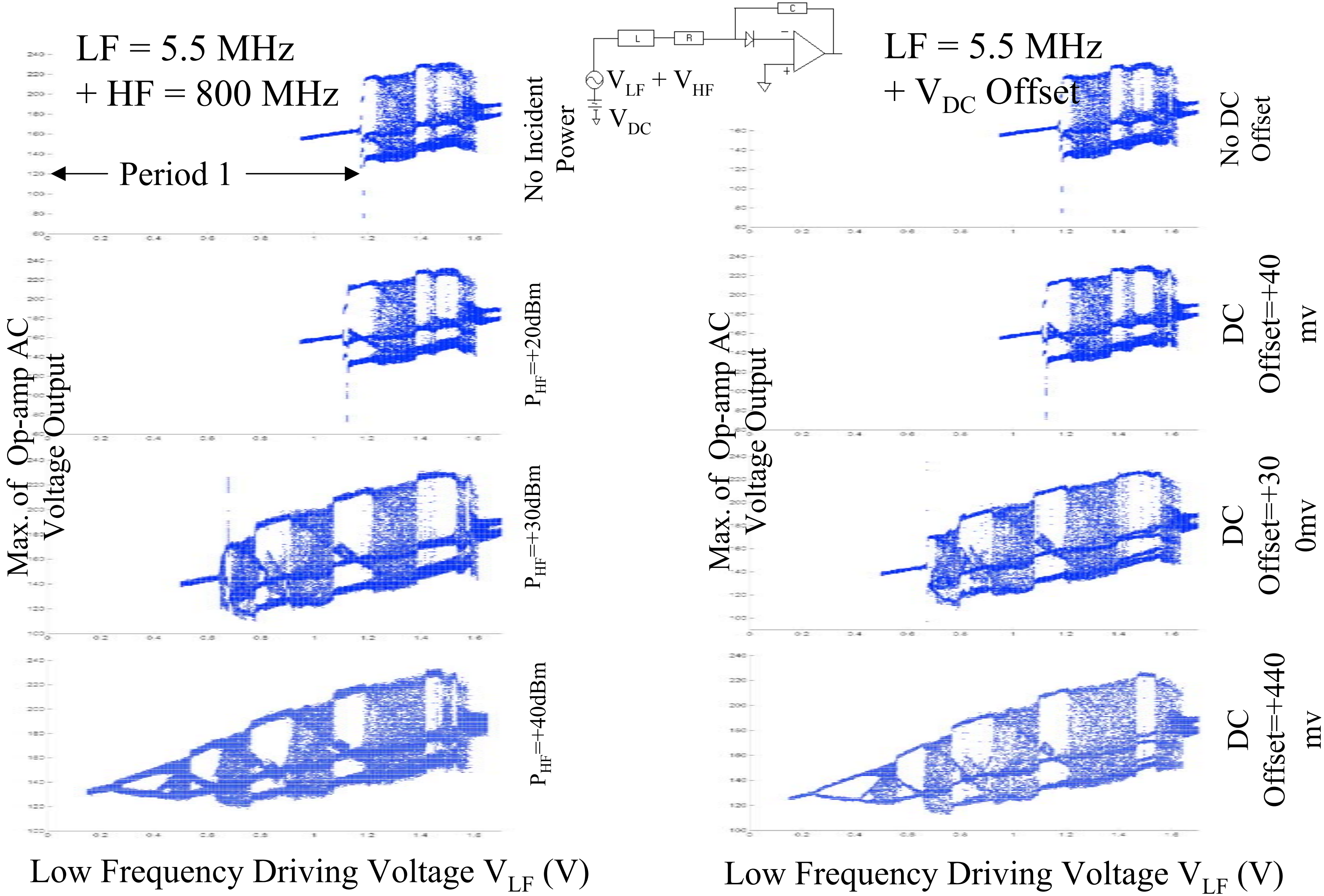
No change in period doubling behavior with or without RF

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



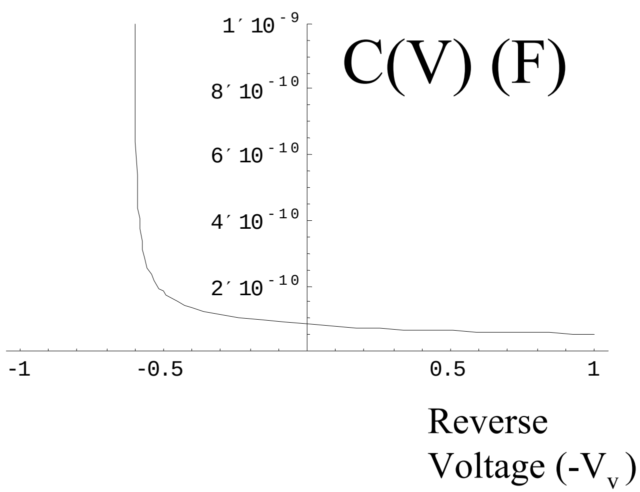
RF Illumination and Chaos In the RLD/TIA Circuit

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 => period doubling and eventually chaos

This DC offset is VERY SMALL in the driven RLD circuit => 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

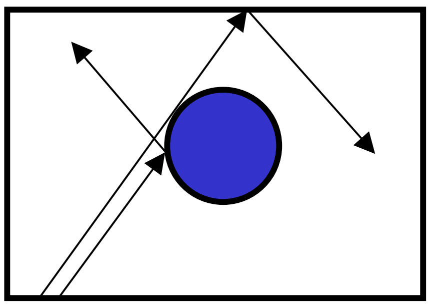
Does chaos lower the threshold for irreversible change to electronic components?

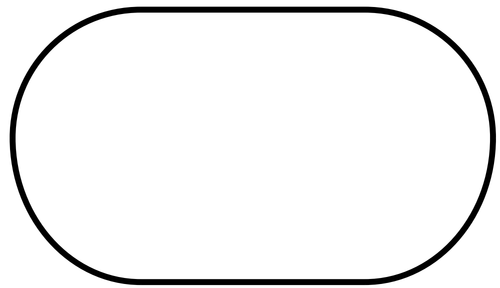
To what extent do modern IC p/n junctions exhibit nonlinear capacitance and period doubling bifurcations?

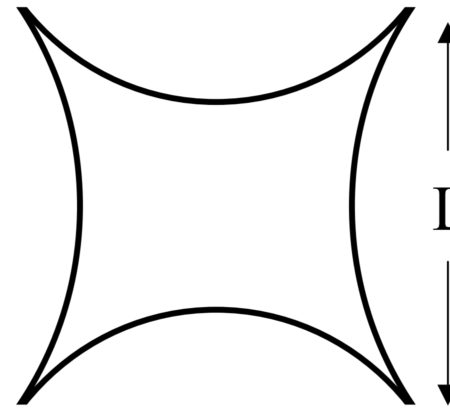
Funding provided by STIC/STEP and Air Force MURI

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:

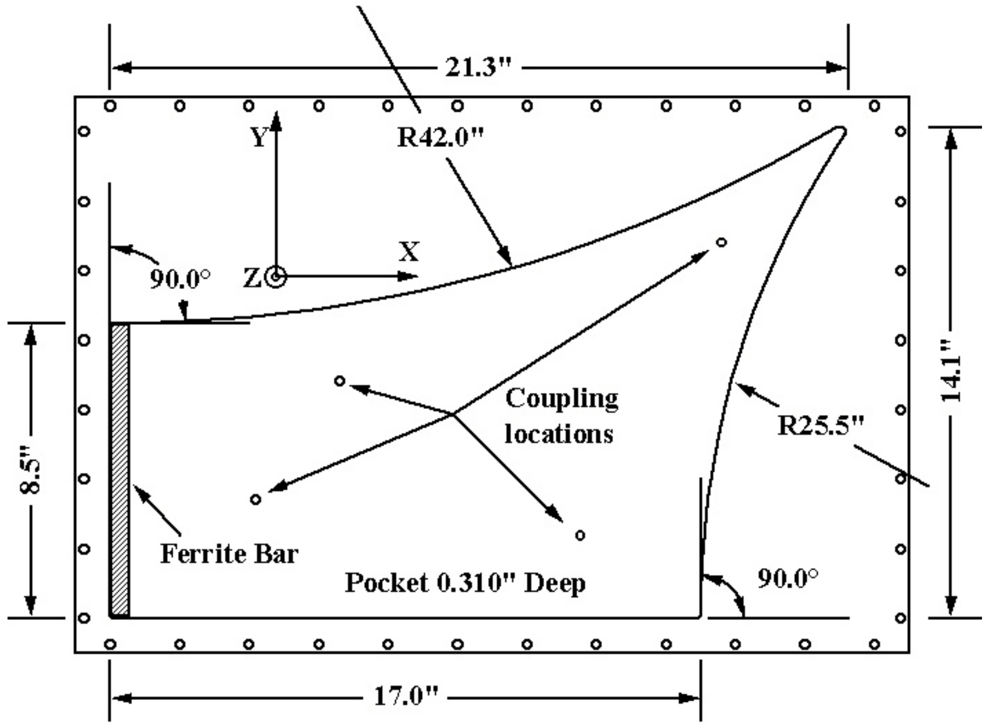
- Time-Reversal Symmetric (GOE)
- Broken Time-Reversal Symmetry (GUE)
- Symplectic (Spin-1/2) Symmetry (GSE)

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

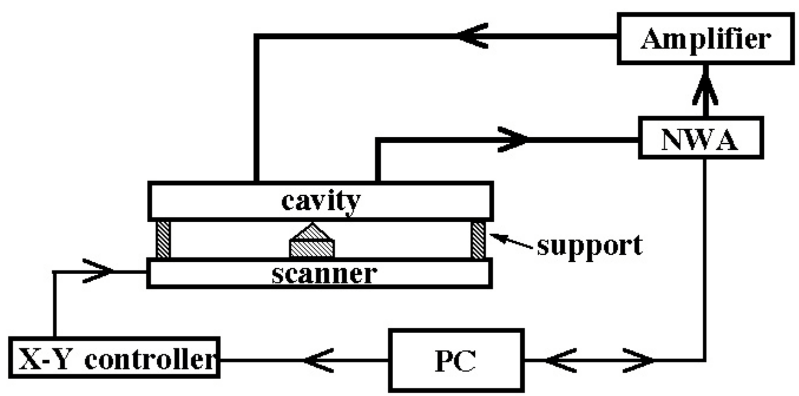
➨ TRSB modifies the eigenfunctions

How do we Perform the Experiment?

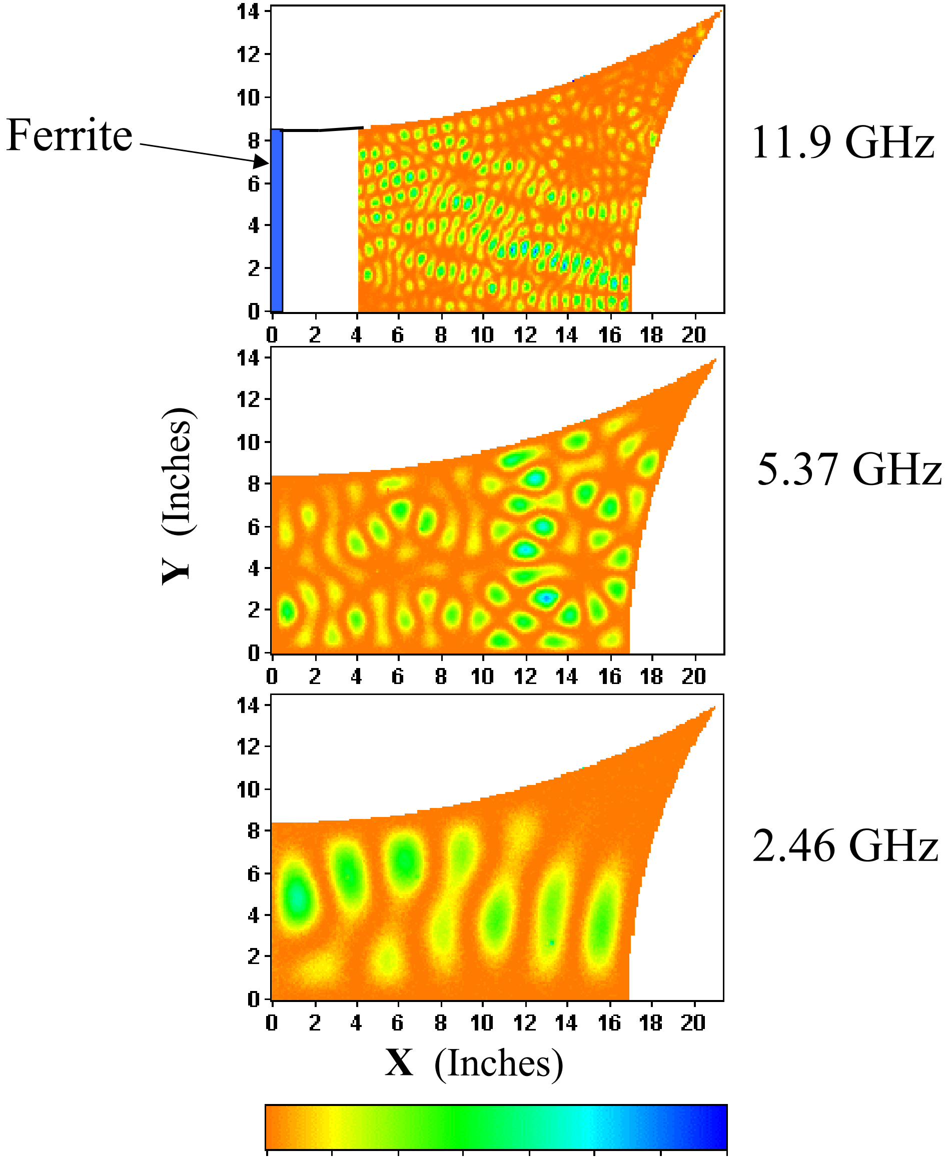


Quarter bow-tie microwave resonator

Measurement setup



Eigenfunctions



$$v(x,y) = |\Psi(x,y)|^2 A$$

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

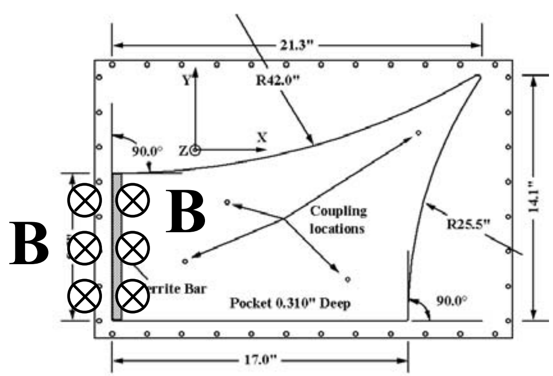
Analogous to a QM particle in a magnetic field

Schrödinger equation for a charged particle in a magnetic field

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

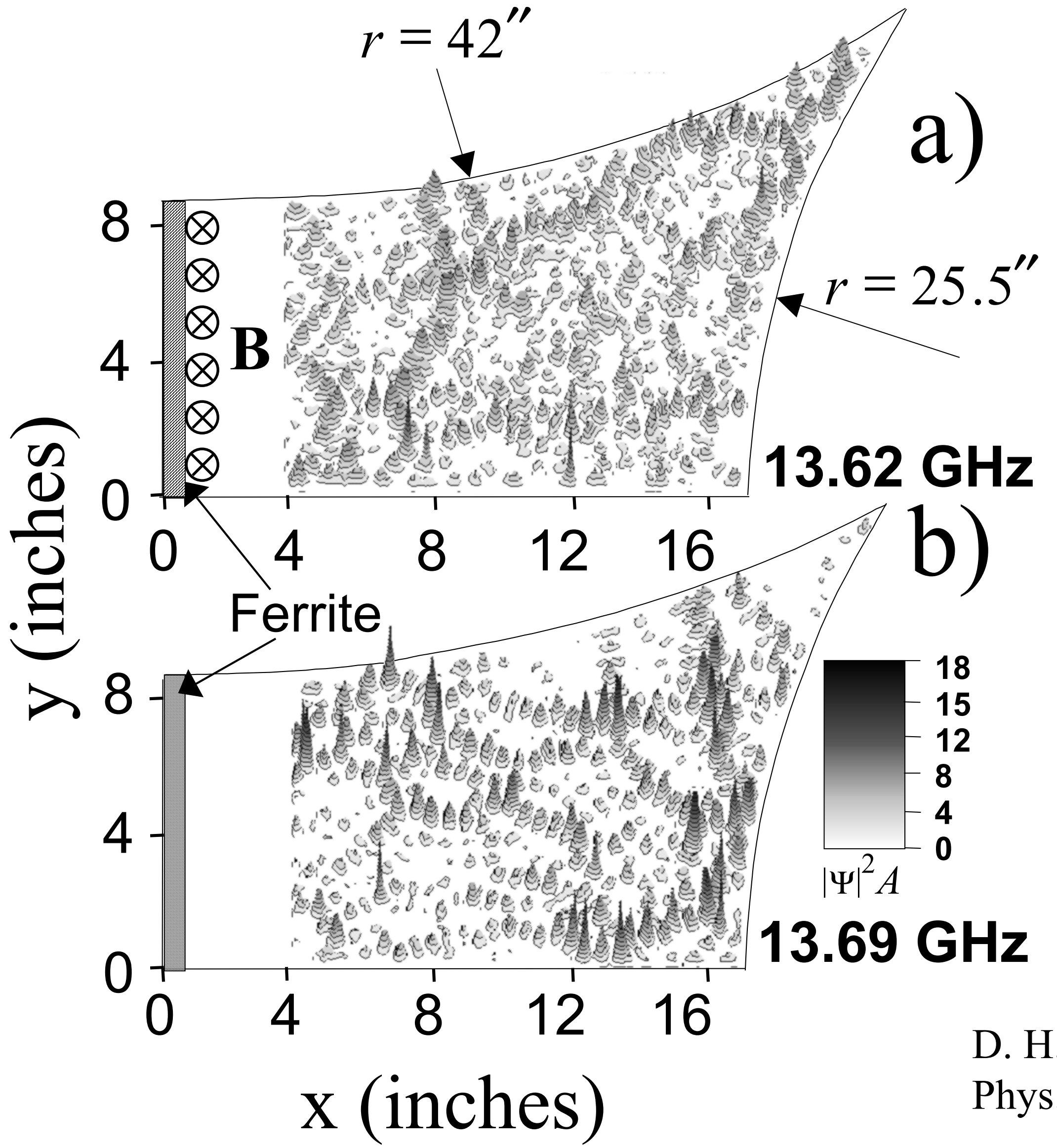
Helmholtz equation for a microwave cavity including a magnetized ferrite

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



➨ 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

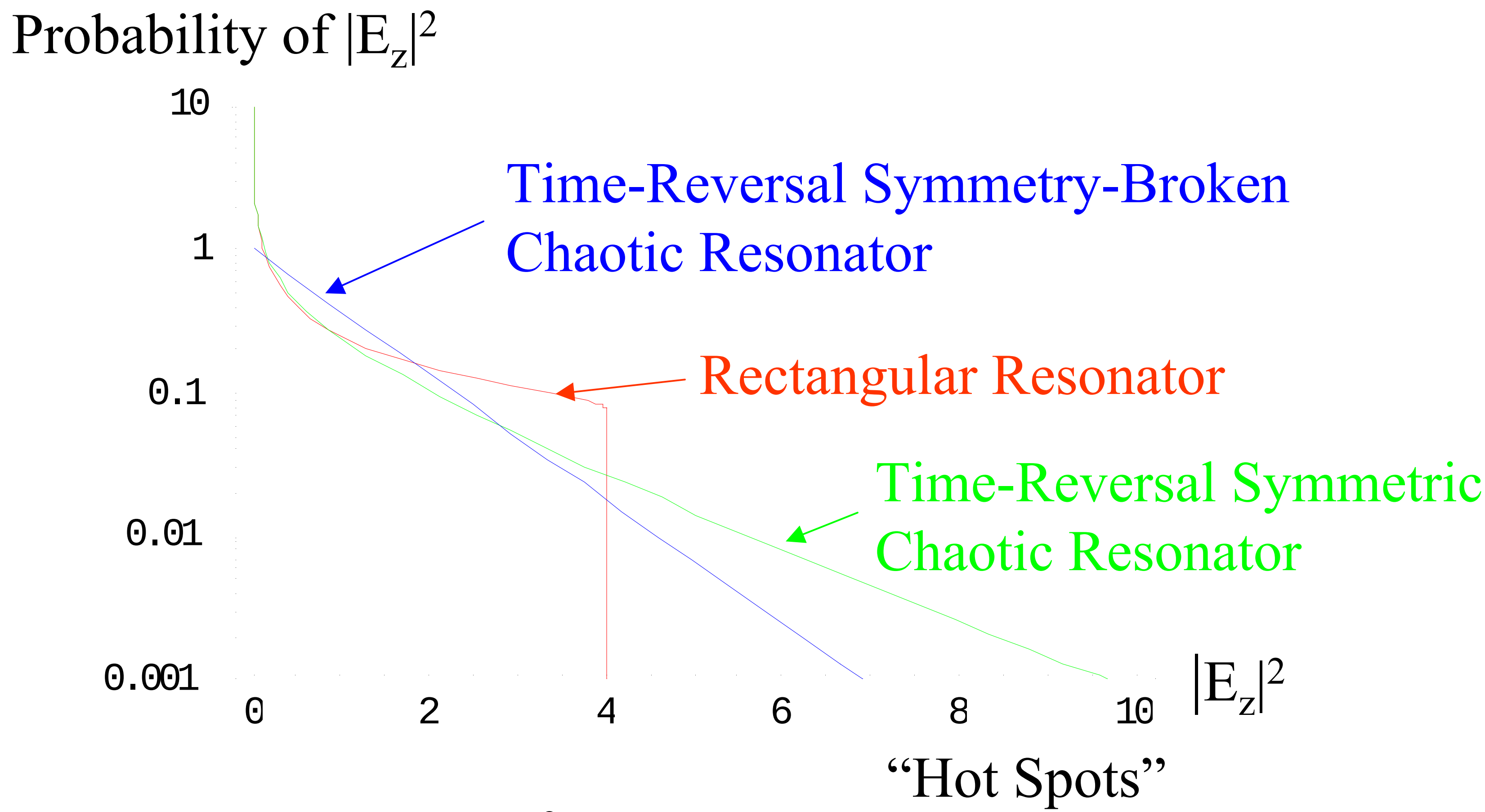


TRS Broken (GUE)

TRS (GOE)

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



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

Based on H. Ishio, *et al*., Phys. Rev. E **64**, 056208 (2001).

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

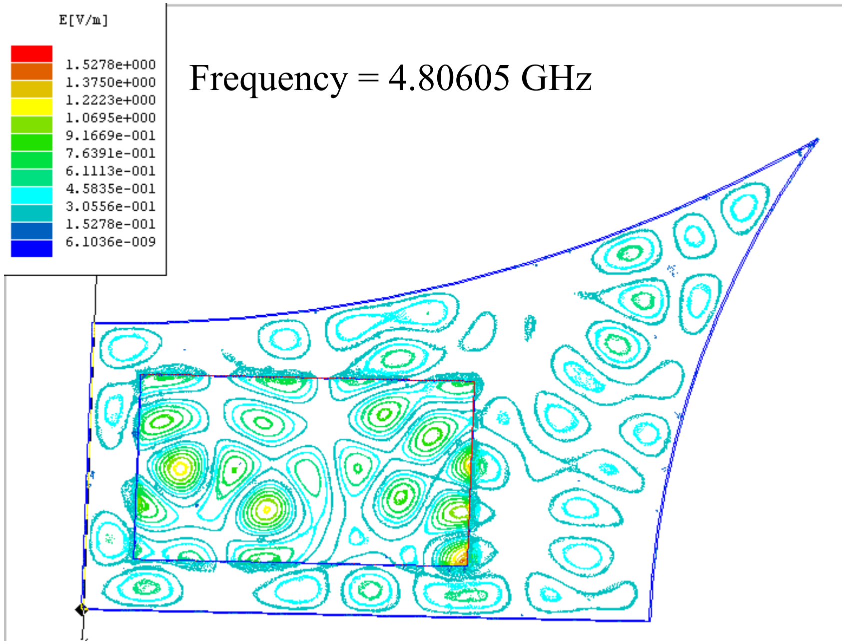
- Image the complex E_z (or Ψ) directly, instead of $|E_z|^2$

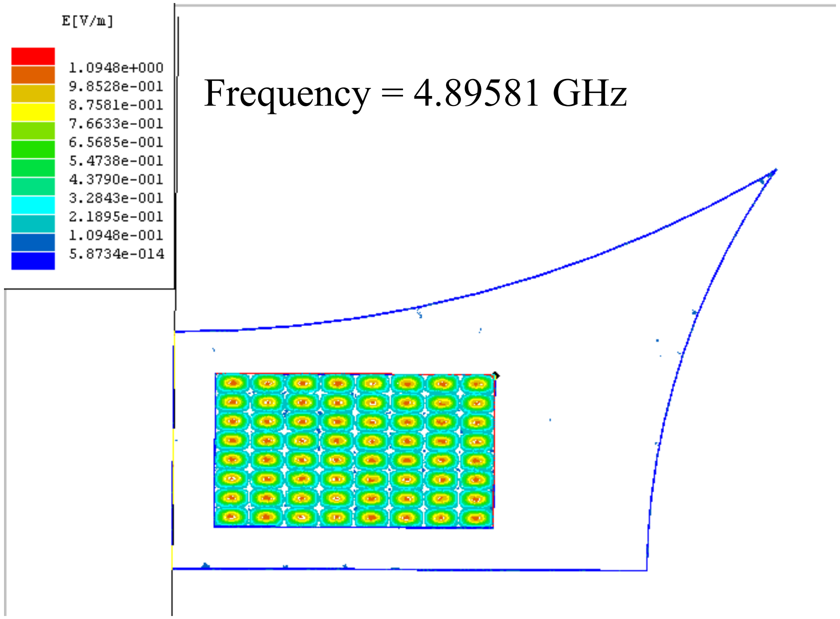
Numerical Results

- 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
$\varepsilon_r = 4.0$, $\tan\delta = 0$

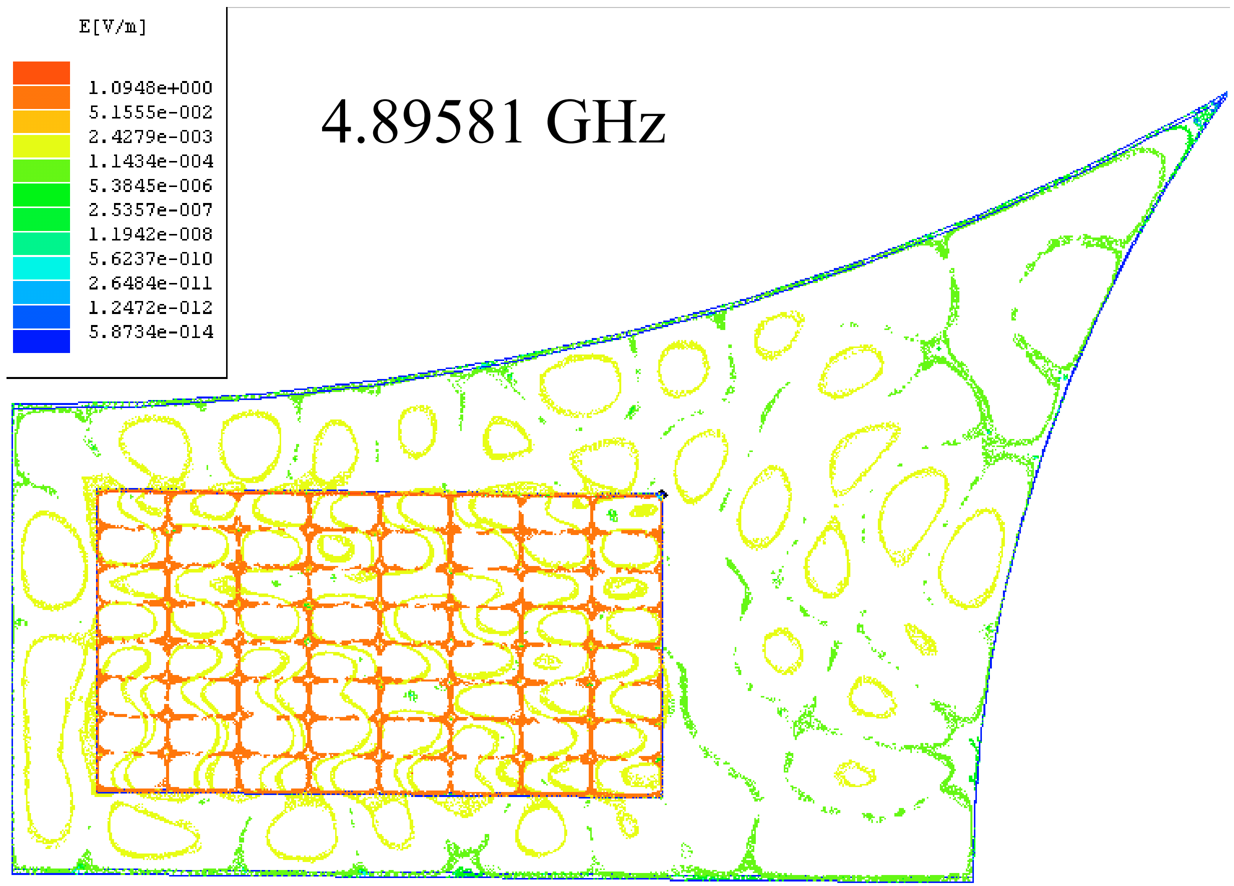
Dielectric Slab Mode (8 x 8) in Bow Tie Resonator

HFSS Calculation

Dielectric slab 10” x 5.5” x 0.2”, attached to lid

$\varepsilon_r = 4.0$, $\tan\delta = 0$

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