Chaos Experiments at Microwave Frequencies

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Two Types of Experiments

"Quantum Chaos"

Basic study of wave dynamics in enclosed boxes

Relevant to EM interference and damage mechanisms

"Classical Chaos", addressing the question:

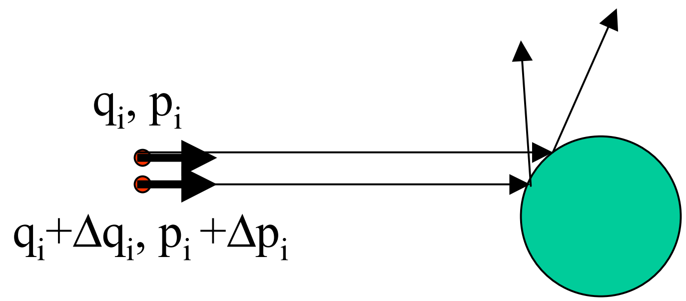
Does chaos enhance the susceptibility of electronic circuits to damage at low power levels?

Continuation of work funded by STEP/STIC project

Chaos

Classical: Extreme sensitivity to initial conditions

$$\dot{q}_i = \partial H / \partial p_i$$
$$\dot{p}_i = -\partial H / \partial q_i$$



Manifestations of classical chaos:

Chaotic oscillations, difficulty in making long-term predictions, sensitivity to noise, etc.

Quantum: ???

Heisenberg Uncertainty principle limits knowledge of initial conditions

$$\Delta p \, \Delta q > h/2\pi$$

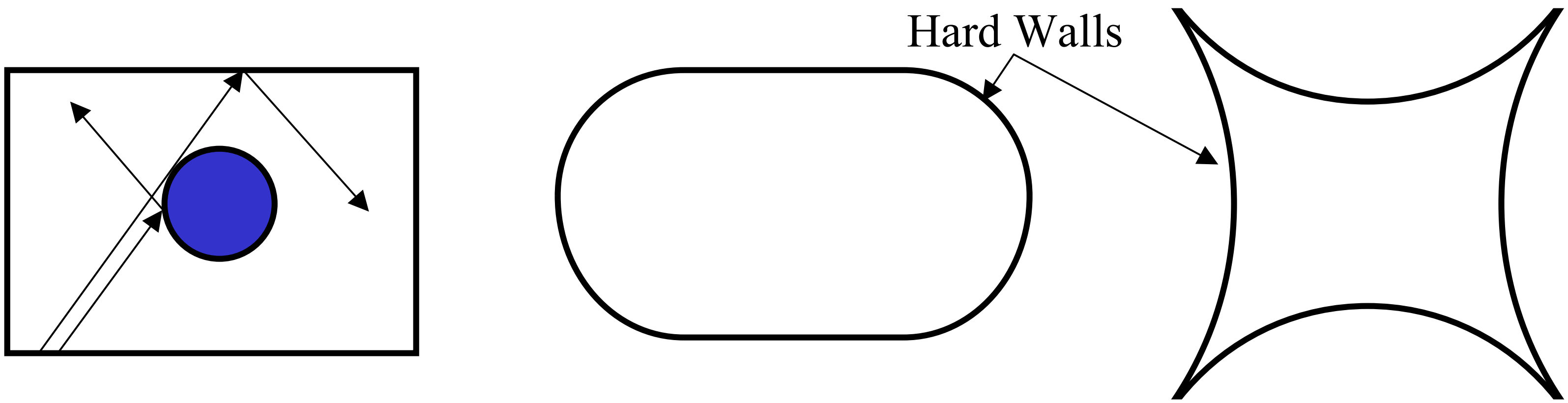
$$\frac{1}{2m}\left(-i\hbar\nabla - qA\right)^2 \Psi + V\Psi = i\hbar\frac{\partial \Psi}{\partial t}$$

Manifestations of quantum chaos:

Breaking of degeneracy, Scars, Strong eigenfunction fluctuations

Wave Chaos in Bounded Regions

Consider a two-dimensional infinite square-well potential (i.e. a box) which shows chaos in the classical limit:



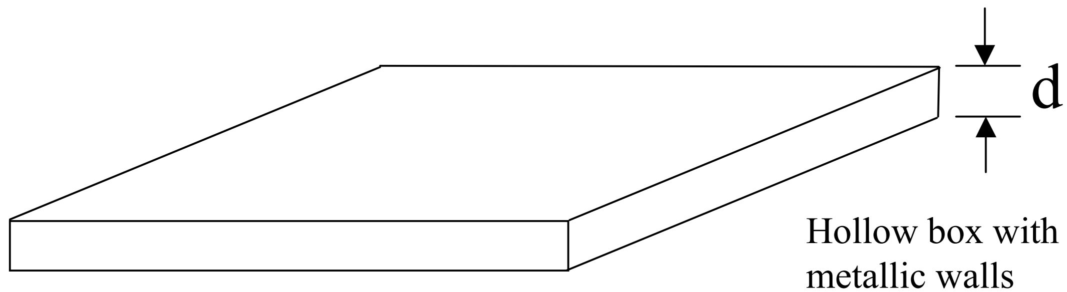
Now solve the electromagnetic wave equation (or Schrodinger equation) in the same potential well

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

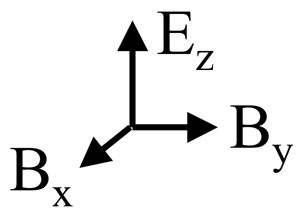
What will happen?

Principle of Measurement

- Exploit the Helmholtz - Schrodinger Analogy in a "two-dimensional" electromagnetic resonator



Only transverse magnetic (TM) propagate for $f < c/2d \sim 19$ GHz, in our case



$$\nabla^2\psi_n+2m(\varepsilon_n-V)/\hbar^2\psi_n=0$$

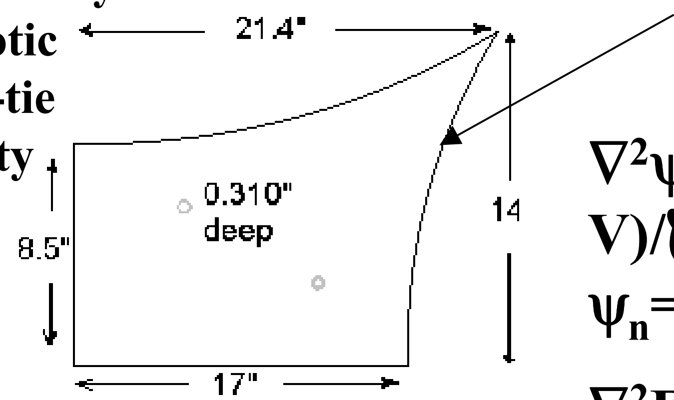
$\psi_n = 0$ at boundaries

$$\nabla^2 E_z+k_i^2 E_z=0$$

$E_z = 0$ at boundaries

Experiment

Classically Chaotic Bow-tie Cavity



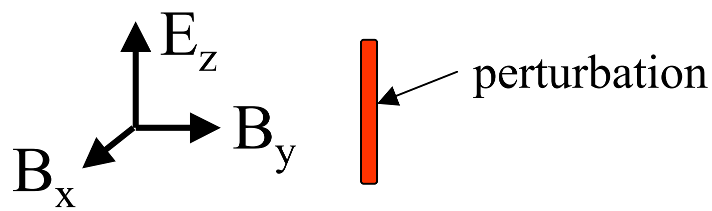
$$\nabla^2\psi_n + 2m(\varepsilon_n - V)/\hbar^2\psi_n = 0$$

$\psi_n = 0$ at boundaries

$$\nabla^2 E_z + k_i^2 E_z = 0$$

$E_z = 0$ at boundaries

- **Excite an eigenmode of the cavity with frequency ω_o**
- **Scan Perturbation through the cavity**
- **Measure ω at each point**
- **Use : $\omega^2 = \omega_o^2 \left(1 + \int (|B|^2 - |E|^2) dV_p\right)$, to get $|E|^2$ (Slater)**



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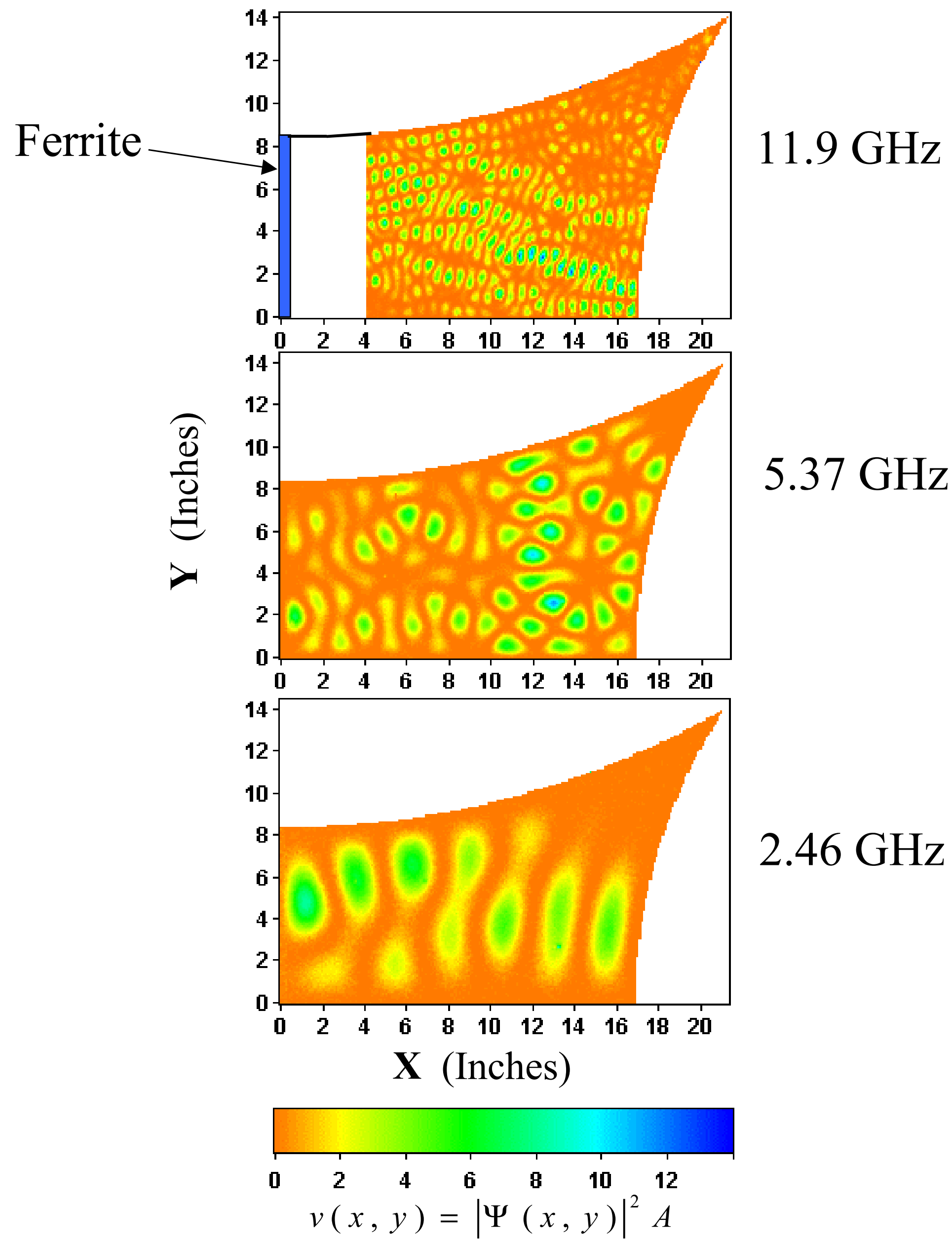
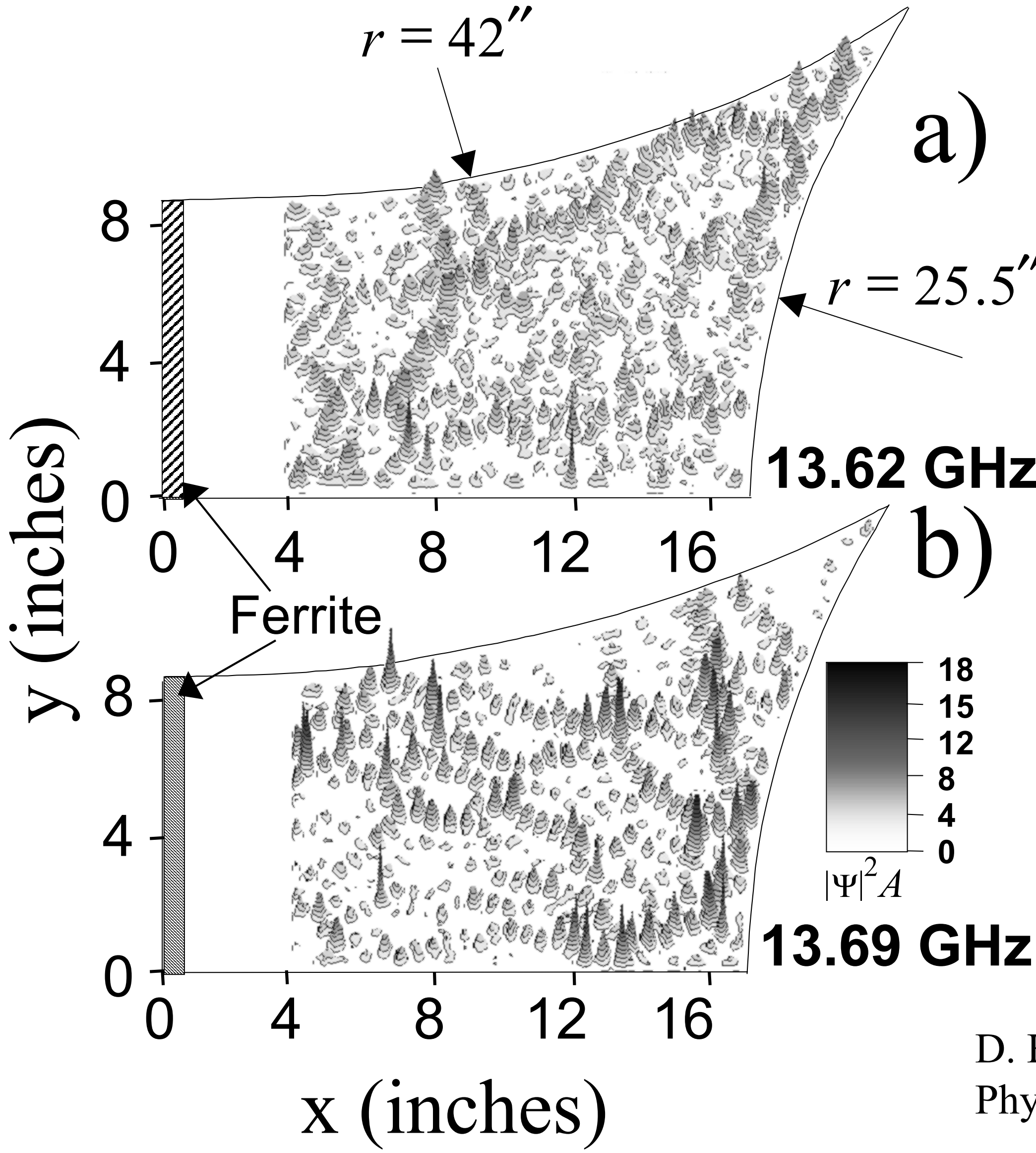
Eigenfunctions

Quarter bow-tie cavity

A magnetized ferrite (top Fig.) breaks time-reversal symmetry for the microwaves



Wave Chaotic Eigenfunctions with and without Time Reversal Symmetry

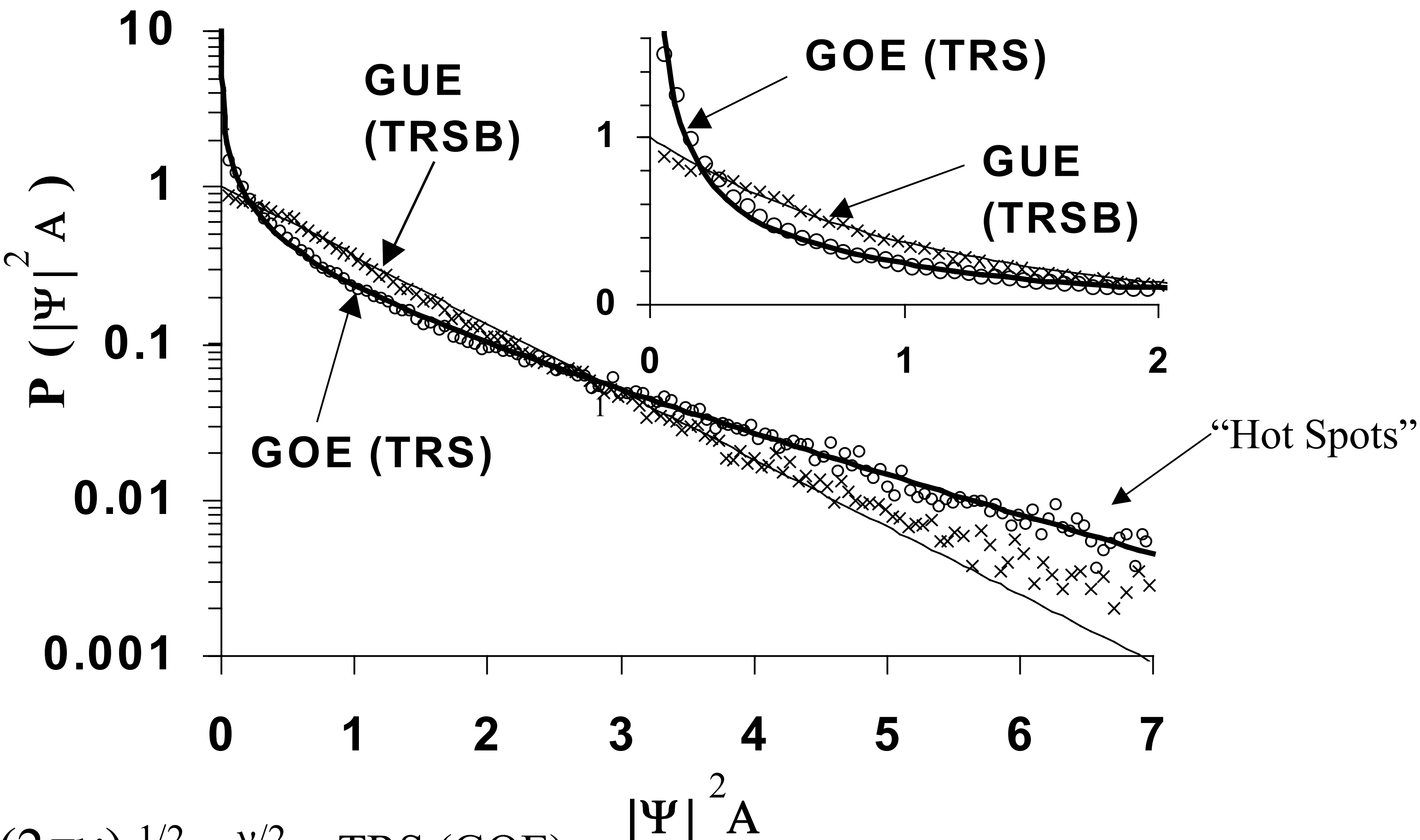


TRS Broken (GUE)

TRS (GOE)

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

Probability Amplitude Distribution with and without Time Reversal Symmetry

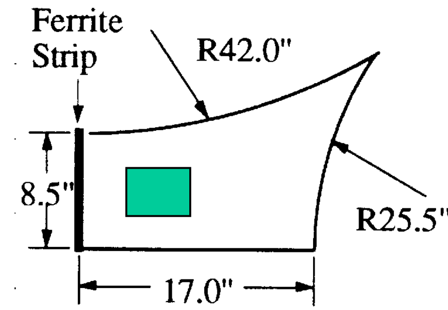


$$P(\nu) = \begin{cases} (2\pi\nu)^{-1/2}\, e^{-\nu/2} & \text{TRS (GOE)} \\ e^{-\nu} & \text{TRSB (GUE)} \end{cases}$$

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

Wave Chaos Experiments

Cavity with dielectric slab



Investigate wave chaos at the length scale
of a pc board
Ray splitting
Fields confined mainly in slab
Image $|E_z|^2$ under and around the slab
Add loss to the slab: when does the eigenfunction picture break down?

Make a connection to device-level studies:
start with low-loss dielectric
⇒ blank pc board
⇒ pc board with Cu ground plane
⇒ pc board with interconnects, passive circuit elements
⇒ pc board with active elements (nonlinear circuits!)

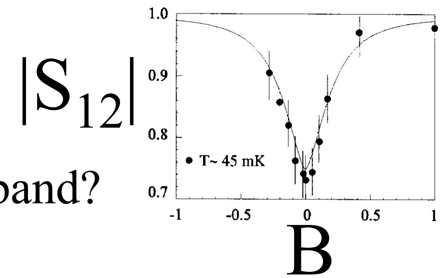
Other Wave Chaos Experiments

Magnetic Field Dependence of Standing Wave Characteristics

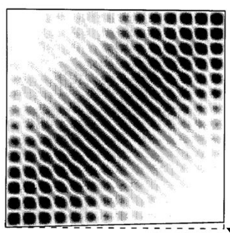
How are the $|E|^2$ maxima decreased with applied B?

"Weak Localization"

Can the standing wave suppression be made broad-band?



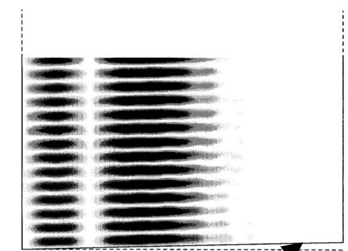
Localized modes in trapezoidal cavities



Investigate the effects of slight irregularities in the shape

Square/rectangular cavity + wedge

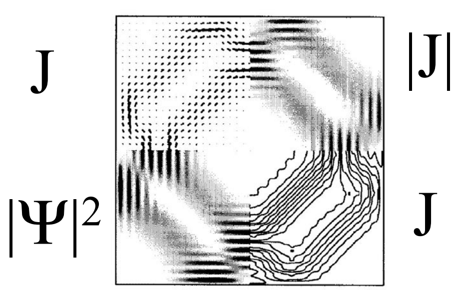
Enhanced $|E_z|^2$ mode near wedge - calculated by Prange

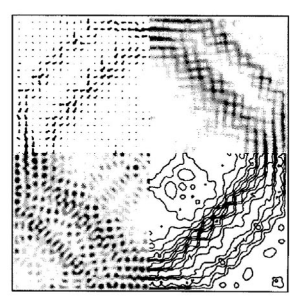


Calculated by Zaitsev, *et al.*

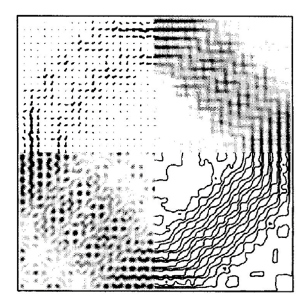
Circulating modes in cavities with magnetized ferrite

Square cavity + magnetized ferrite show circulating currents





Diamagnetic



Diamagnetic

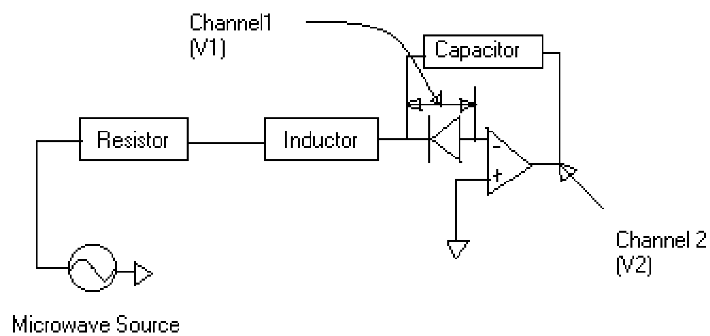
Calculated by Narevich. PRE 2000

Objectives of Classical Chaos Experiments

- Investigate the idea that chaos suppresses the threshold for damage in nonlinear circuits
  - Continue to examine the series R-L-Diode-Op-Amp circuit
    - Does period doubling lead to damage of components?
- Investigate the effects of high power rf signals on nonlinear circuits
  - RF-induced chaos may bring about a lowering of damage thresholds of electronic devices.
- Simulate the behavior of nonlinear circuits under these conditions

Brief History of the Problem

- C. Wallace (TRW) claims that period-doubling transition in this circuit leads to op-amp failure at absorbed power levels far below thermal failure limits:



900 MHz
100 W input
70 mW absorbed

Wallace's observation: "violent chaotic oscillation state and failure of the op-amp, in which the output voltage went to zero and stayed there while the diode remained perfectly functional."

- Our experiments on a similar circuit at 10 - 60 MHz, 0.1 W input showed period-doubling and chaos, but no component failure.
- Jaycor/MRC examined a similar circuit up to 3 W and found no period-doubling or chaos, but did observe op-amp and diode burnout due to thermal effects

Classical Chaos Experiments in Progress

Understand why the results are so sensitive to measurement conditions, power levels, etc. Arrive at a consensus

Employ high-impedance voltage probes to minimize perturbation of circuit

Establish 100 W, 900 MHz measurement setup

Monitor op-amp supply voltage and current. Preliminary results show significant changes at the onset of period-doubling

Identify a simpler circuit which shows the essential behavior

Conclusions

Wave Chaos offers insights into the effects of microwaves in enclosures

- Statistical properties of eigenvalues and eigenfunctions
  - Most results independent of box shape
- Benefits of breaking Time-Reversal Symmetry
- Ray Splitting

Does chaos lower the threshold for damage to electronic components?

- Develop a consensus on experimental results
- Is there a simpler circuit which shows the effect unambiguously?
- Generalize the results

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