RF Upset and Chaos in Circuits: Basic Investigations

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IEEE
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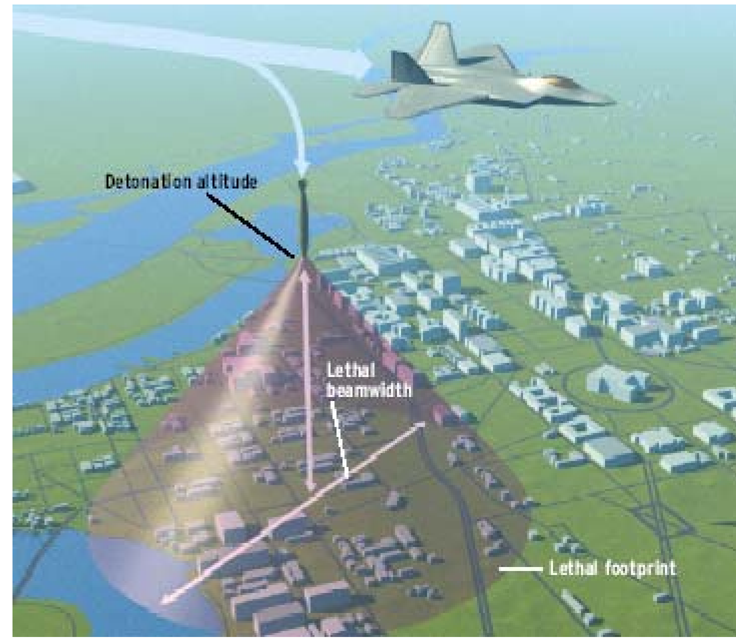

Detonation altitude
Lethal beamwidth
Lethal footprint

OVERVIEW

HPM Effects on Electronics

Are there systematic and reproducible effects?

Can we predict effects with confidence?

Evidence of HPM Effects is spotty:

Anecdotal stories of rf weapons and their effectiveness

Commercial HPM devices

E-Bomb (IEEE Spectrum, Nov. 2003)

etc.

Difficulty in predicting effects given complicated coupling, interior geometries, varying damage levels, etc.

Why confuse things further by adding chaos?

New opportunities for circuit upset/failure

A <u>systematic framework</u> in which to quantify and classify HPM effects

Overview/Motivation
"The Promise of Chaos"

- Can Chaotic oscillations be induced in electronic circuits through cleverly-selected HPM input?
- Can susceptibility to Chaos lead to degradation of system performance?
- Can Chaos lead to failure of components or circuits at extremely low HPM power levels?
- Is Chaotic instability a generic property of modern circuitry, or is it very specific to certain types of circuits and stimuli?

Chaos

Classical: Extreme sensitivity to initial conditions

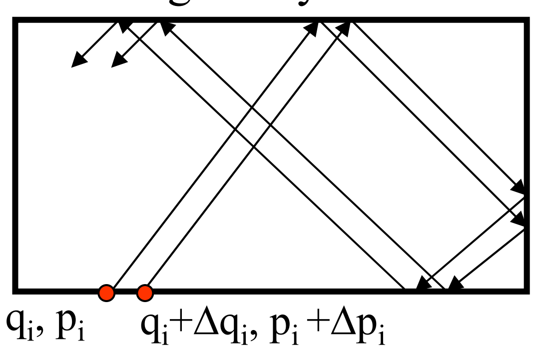
$$\dot{q}_i = \partial H / \partial p_i$$

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

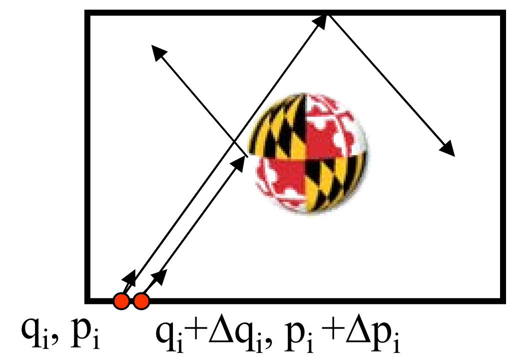
$$H = T + V \quad \text{Hamiltonian}$$

Best characterized as "extreme sensitivity to initial conditions"

Regular system



Chaotic system



Manifestations of classical chaos:

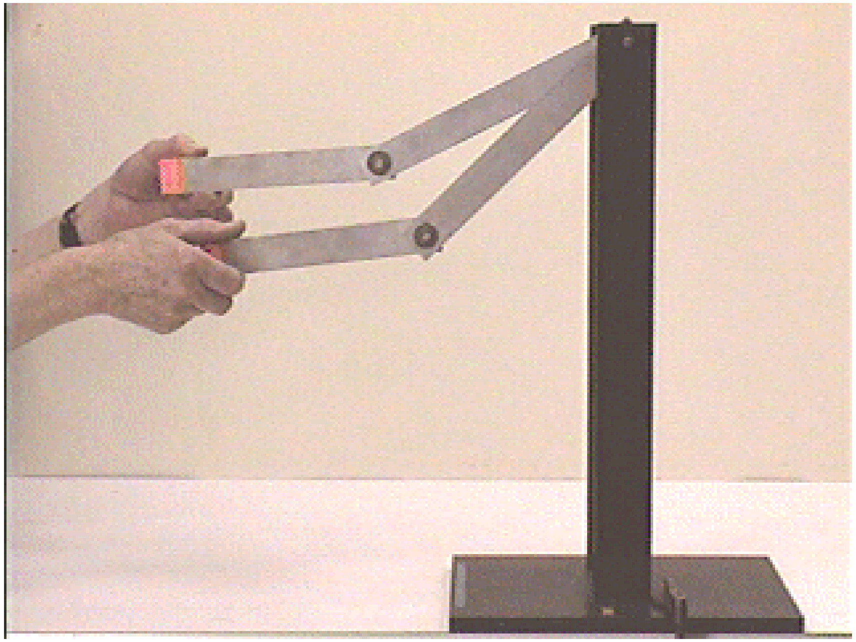
Chaotic oscillations, difficulty in making long-term predictions, sensitivity to noise, etc.

Time series, iterated maps, Lyapunov exponents, etc.

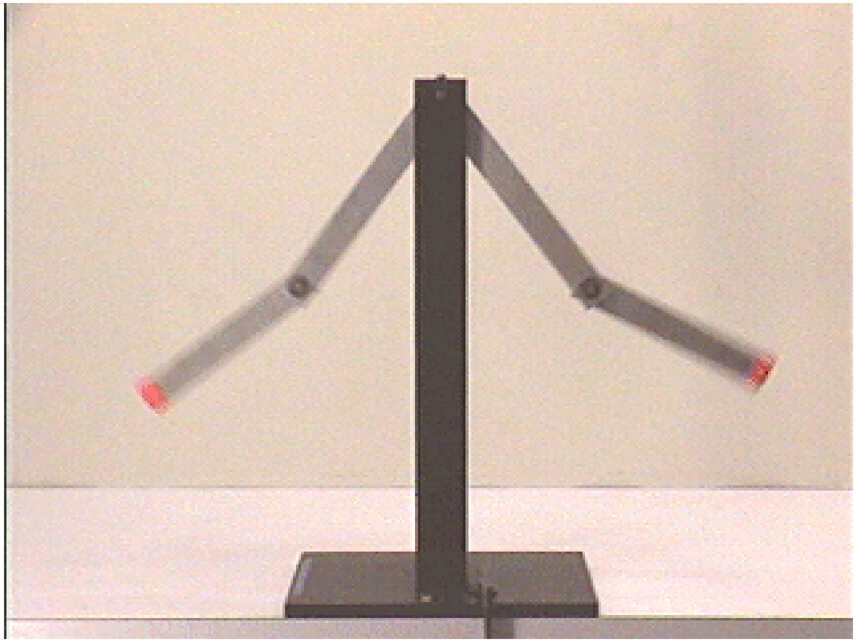
Extreme Sensitivity to Initial Conditions

Double Pendulum Demo

Start with similar initial conditions



The motion of the two pendula diverge



G1-60: CHAOS - TWO DOUBLE PHYSICAL PENDULA

DESCRIPTION: The two pendula are started into apparently identical oscillations, but their motion soon diverges. No matter how closely the motions of the two pendula are started, they eventually must undergo virtually total divergence. This illustrates the modern meaning of "chaos."

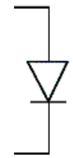
Chaos in Nonlinear Circuits

Many nonlinear circuits show chaos:

- Driven Resistor-Inductor-Diode series circuit
- Chua's circuit
- Coupled nonlinear oscillators
- Circuits with saturable inductors
- Chaotic relaxation circuits
- Newcomb circuit
- Rössler circuit
- Phase-locked loops
- …
- Synchronized chaotic oscillators and chaotic communication

Here we concentrate on the most common nonlinear circuit element that can give rise to chaos due to external stimulus: the p/n junction

The p/n Junction



The p/n junction is a ubiquitous feature in electronics:

- Electrostatic-discharge (ESD) protection diodes
- Transistors

Nonlinearities:

- Voltage-dependent Capacitance
- Conductance (Current-Voltage characteristic)
- Reverse Recovery (delayed feedback)

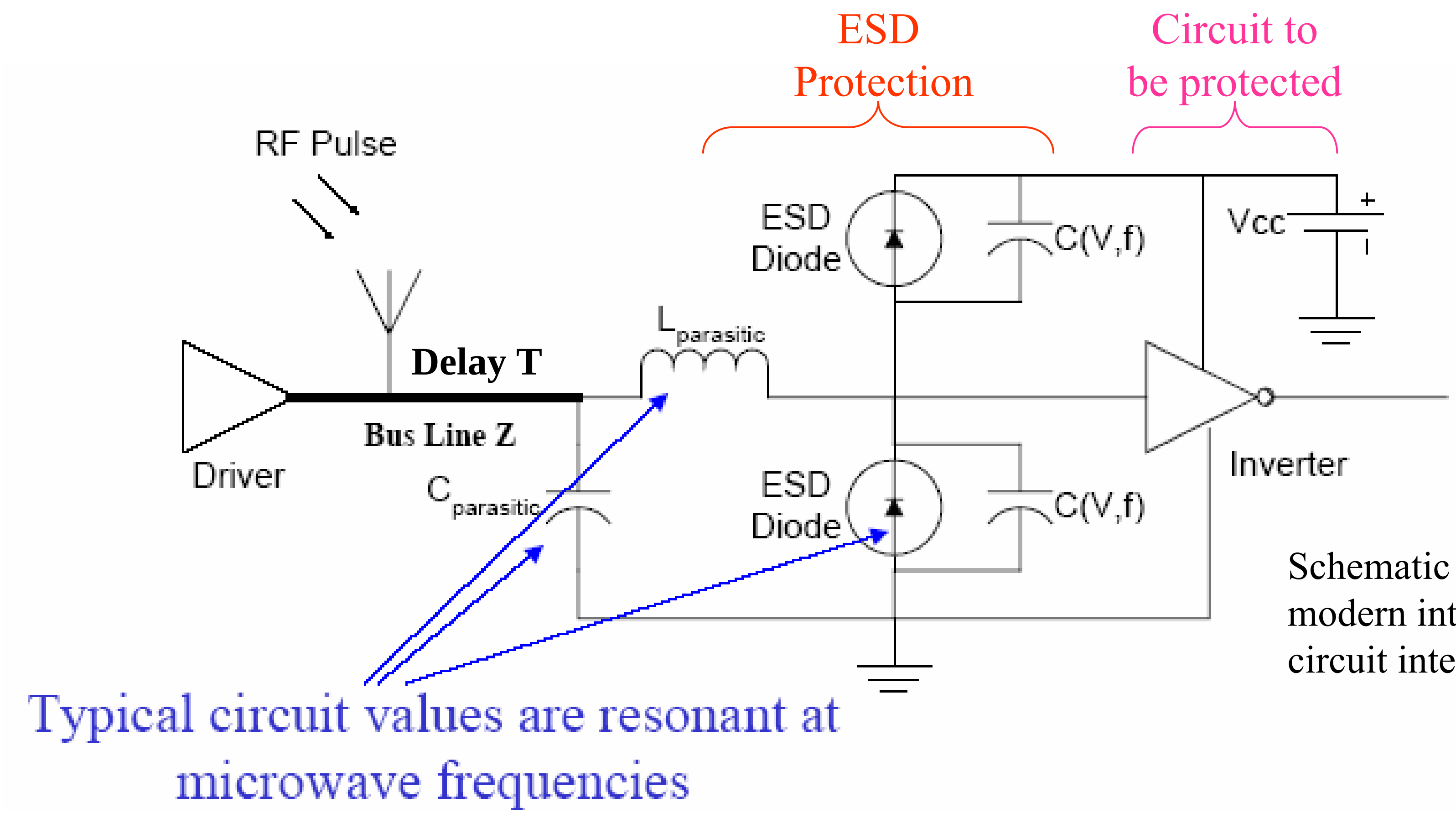
HPM input can induce Chaos through several mechanisms

Renato Mariz de Moraes and Steven M. Anlage, **"Unified Model, and Novel Reverse Recovery Nonlinearities, of the Driven Diode Resonator,"** Phys. Rev. E **68**, 026201 (2003).

Renato Mariz de Moraes and Steven M. Anlage, **"Effects of RF Stimulus and Negative Feedback on Nonlinear Circuits,"** IEEE Trans. Circuits Systems I: Regular Papers, **51**, 748 (2004).

Electrostatic Discharge (ESD) Protection Circuits

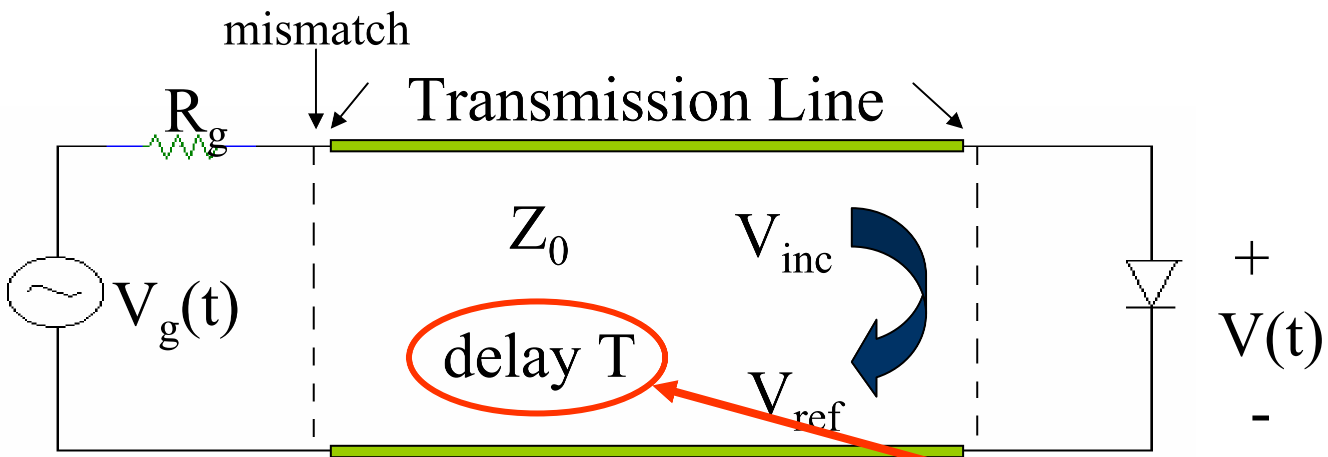
A New Opportunity to Induce Chaos at High Frequencies in a distributed circuit



Schematic of modern integrated circuit interconnect

The "Achilles Heel" of modern electronics

Chaos in the Driven Diode **Distributed** Circuit



A simple model of p/n junctions in computers

New Time-Scale!

Delay differential equations for the diode voltage

1) $2\,V_{inc}(t) = V(t) + Z_o[gV + \frac{d}{dt}Q(V(t))]$

2) $V_{ref} = V(t) - V_{inc}(t)$

3) $V_{inc}(t) = V_{ref}(t-2T) + V_g(t-T)$

$$\frac{d}{dt}V(t) = \frac{-(1+Z_o g)}{Z_o C(V(t))}V(t) + \frac{\rho_g(1-Z_o g)}{Z_o C(V(t))}V(t-2T) + \frac{-\rho_g C(V(t))}{C(V(t-2T))}\frac{d}{dt}V(t-2T) + \frac{V_g \tau_g}{Z_o C(V(t))}\cos(w(t-T))$$

Chaos in the Driven Diode Distributed Circuit

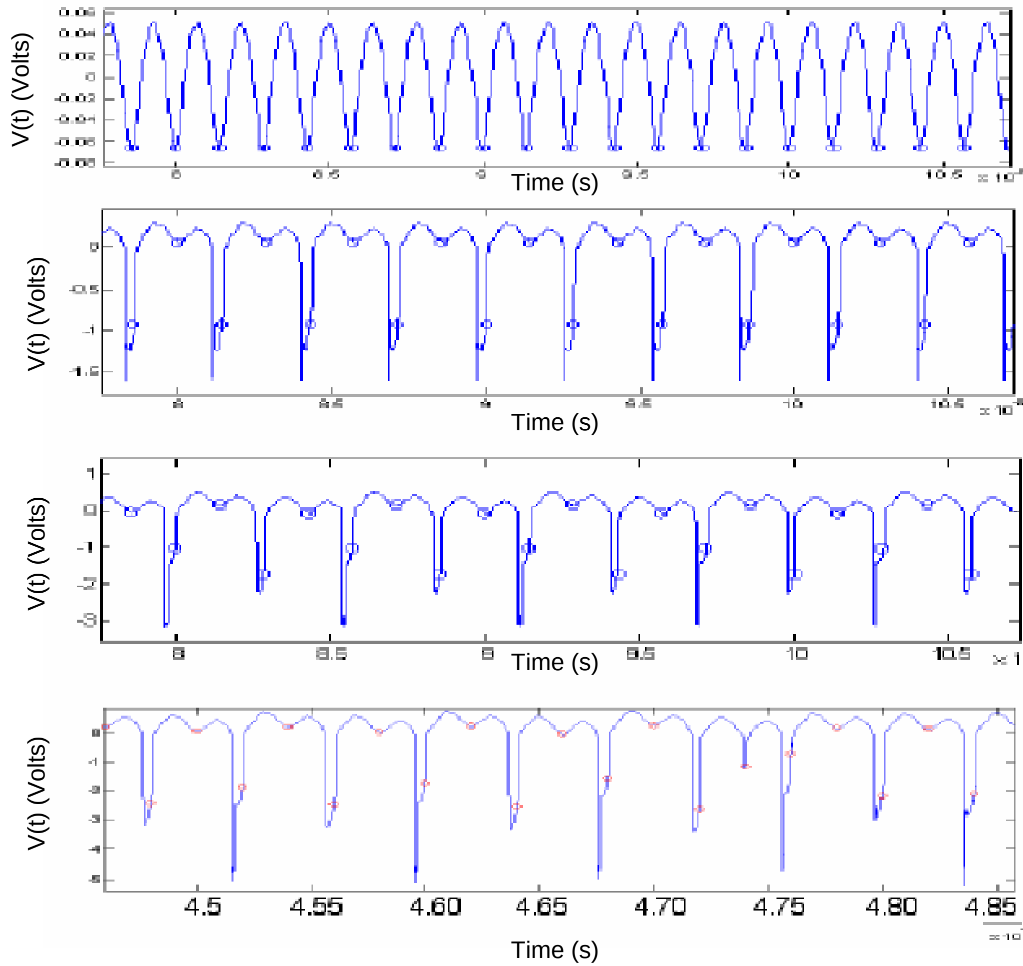
Simulation results

V_g = .5 V **Period 1**

V_g = 2.25 V **Period 2**

V_g = 3.5 V **Period 4**

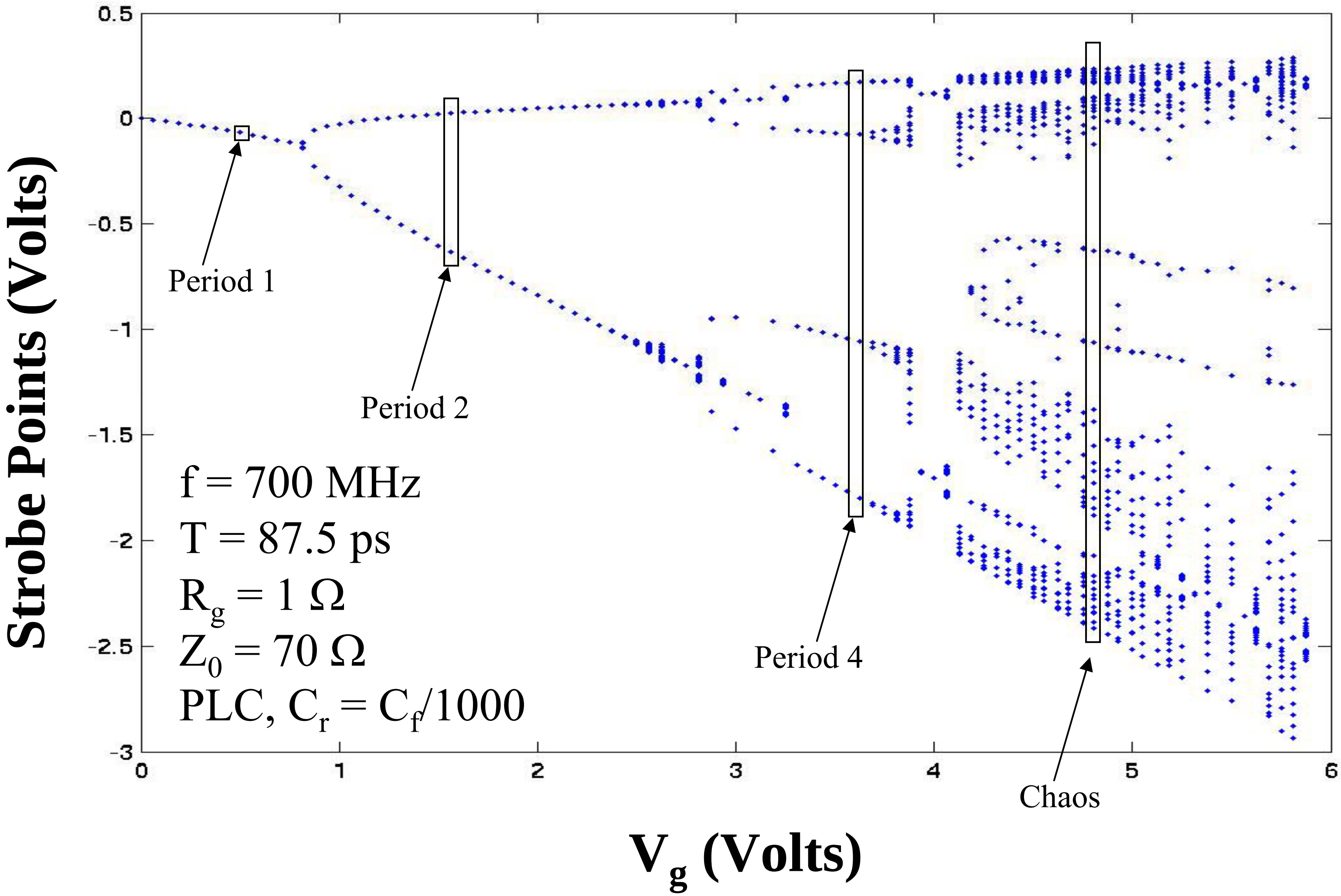
V_g = 5.25 V **Chaos**



f = 700 MHz
T = 87.5 ps
$R_g = 1\ \Omega$
$Z_0 = 70\ \Omega$
PLC, $C_r = C_f/1000$

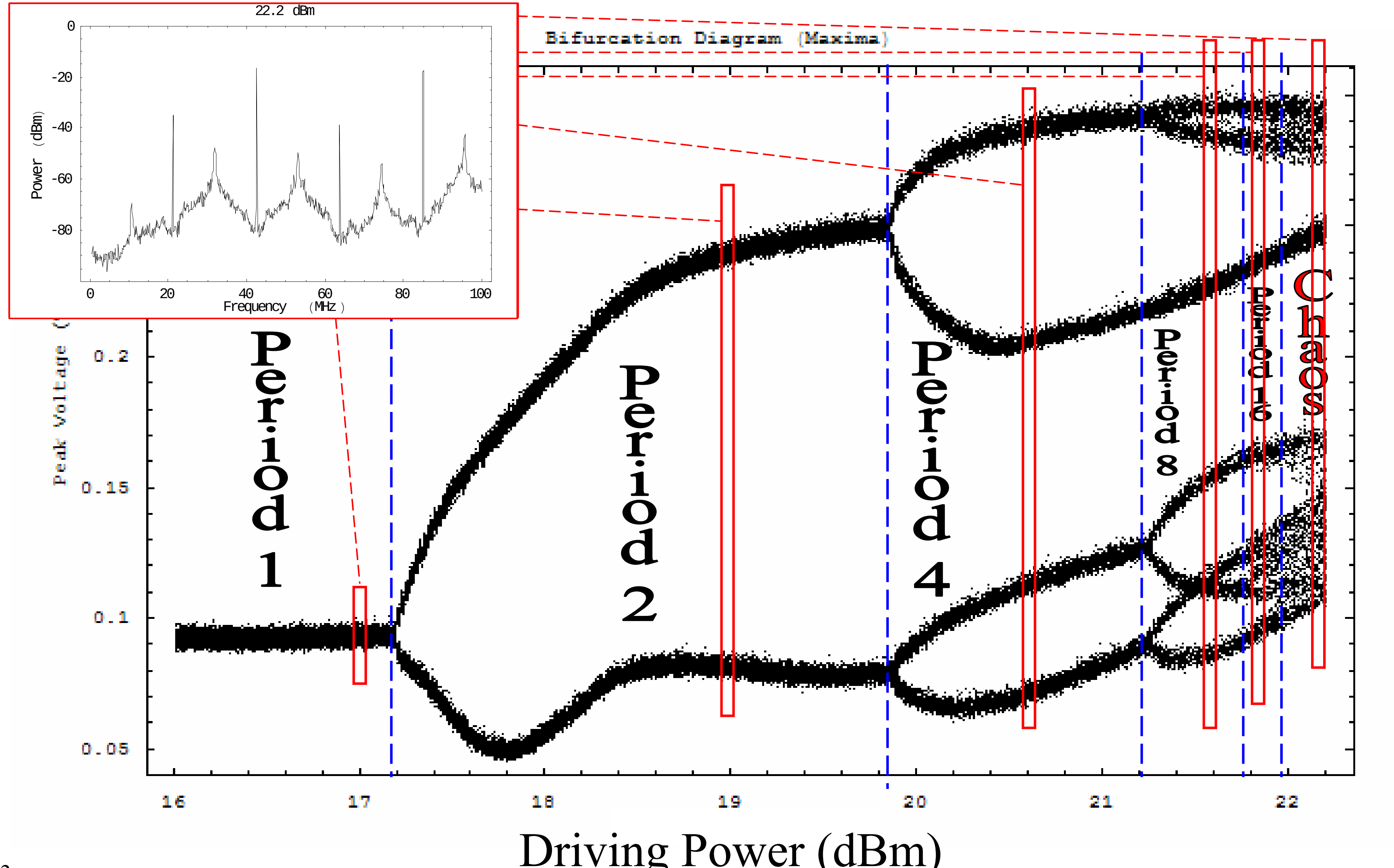
Chaos in the Driven Diode Distributed Circuit

Simulation results

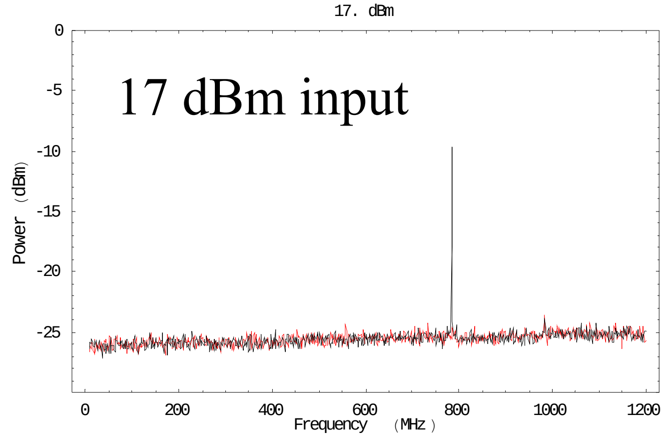


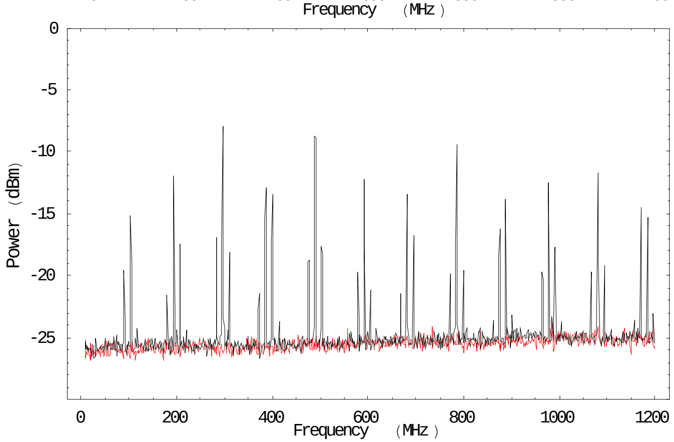
Experimental Results

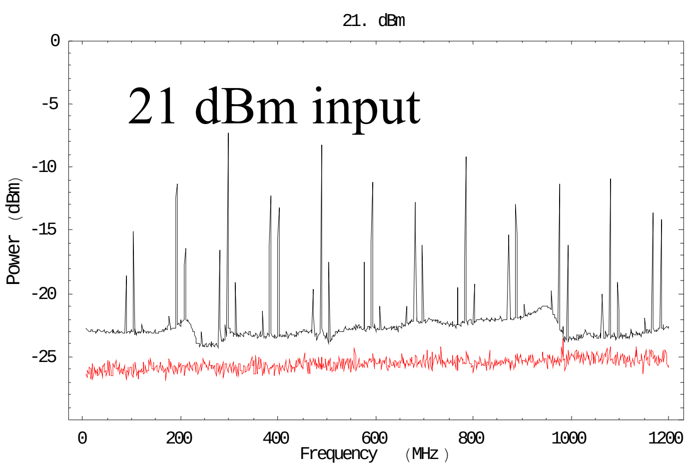
Experimental Bifurcation Diagram
BAT41 Diode @ 85 MHz
T ~ 3.9 ns, Bent-Pipe

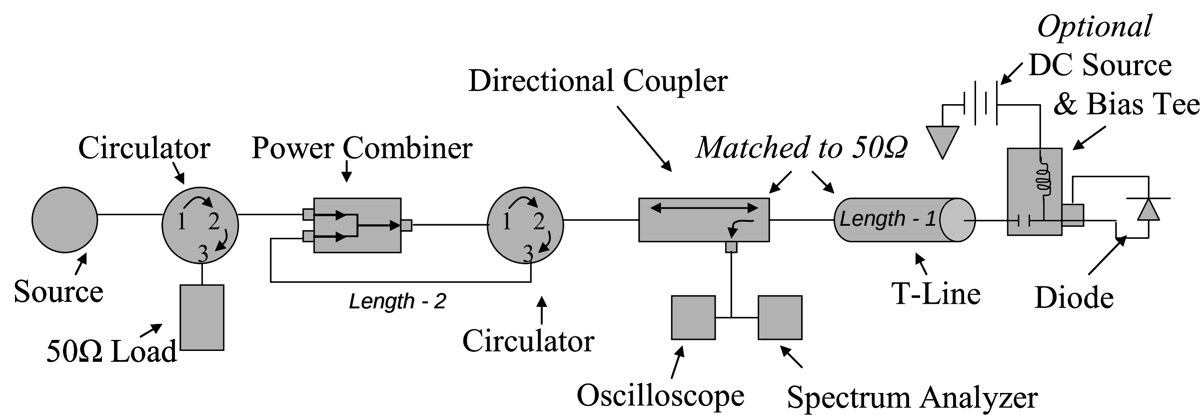


Distributed Transmission Line Diode Chaos at 785 MHz









NTE519

785 MHz

T ~ 3.5 ns

DC Bias=6.5 Volts

Chaos and Circuit Disruption
What can you count on?

Bottom Line on HPM-Induced circuit chaos

What can you count on? → p/n junction nonlinearity

Time scales!

Windows of opportunity – chaos is common but not present for all driving scenarios

ESD protection circuits are ubiquitous

Manipulation with “nudging” and “optimized” waveforms.

Quasiperiodic driving lowers threshold for chaotic onset

D. M. Vavriv, Electronics Lett. 30, 462 (1994).

Two-tone driving lowers threshold for chaotic onset

D. M. Vavriv, IEEE Circuits and Systems I 41, 669 (1994).

D. M. Vavriv, IEEE Circuits and Systems I 45, 1255 (1998).

J. Nitsch, Adv. Radio Sci. 2, 51 (2004).

Noise-induced Chaos:

Y.-C. Lai, Phys. Rev. Lett. **90**, 164101 (2003).

Resonant perturbation waveform

Y.-C. Lai, Phys. Rev. Lett. **94**, 214101 (2005).

What needs further research?

Is chaos the correct organizing principle for understanding HPM effects?

Effects of chaotic driving signals on nonlinear circuits
(challenge – circuits are inside systems with a frequency-dependent transfer function)

Unify UMD circuit chaos and wave chaos research

Uncover the "magic bullet" driving waveform that causes maximum disruption to electronics

S. M. Booker, "A family of optimal excitations for inducing complex dynamics in planar dynamical systems," Nonlinearity 13, 145 (2000).

Example of optimized waveform

Chaotic Driving Waveforms

Chaotic microwave sources

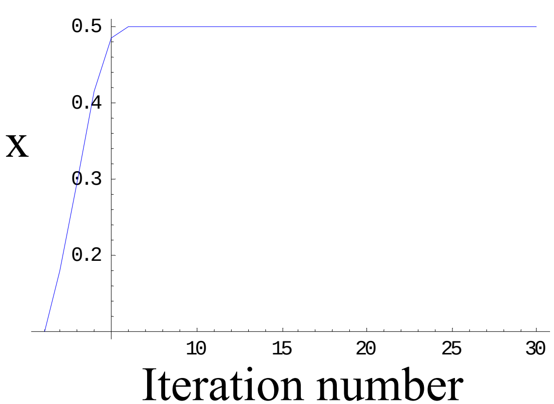
Simple Chaos
1-Dimensional Iterated Maps

The Logistic Map: $x_{n+1} = 4\mu\, x_n(1 - x_n)$

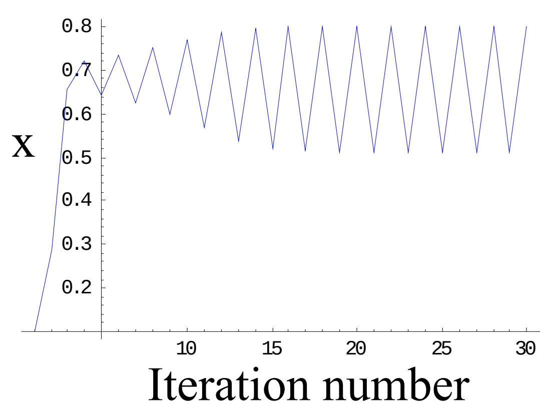
Parameter: μ Initial condition: x_0

$$x_0 = 0.100$$

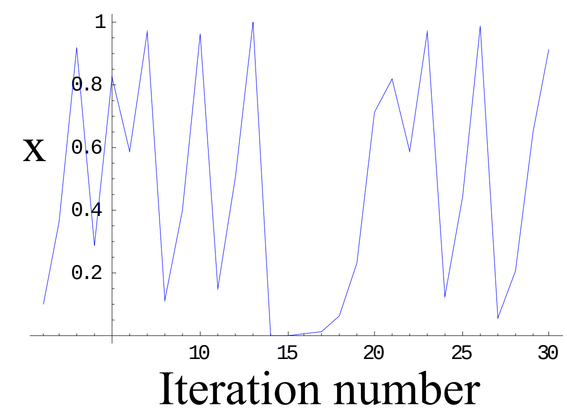
$\mu = 0.5$



$\mu = 0.8$



$\mu = 1.0$



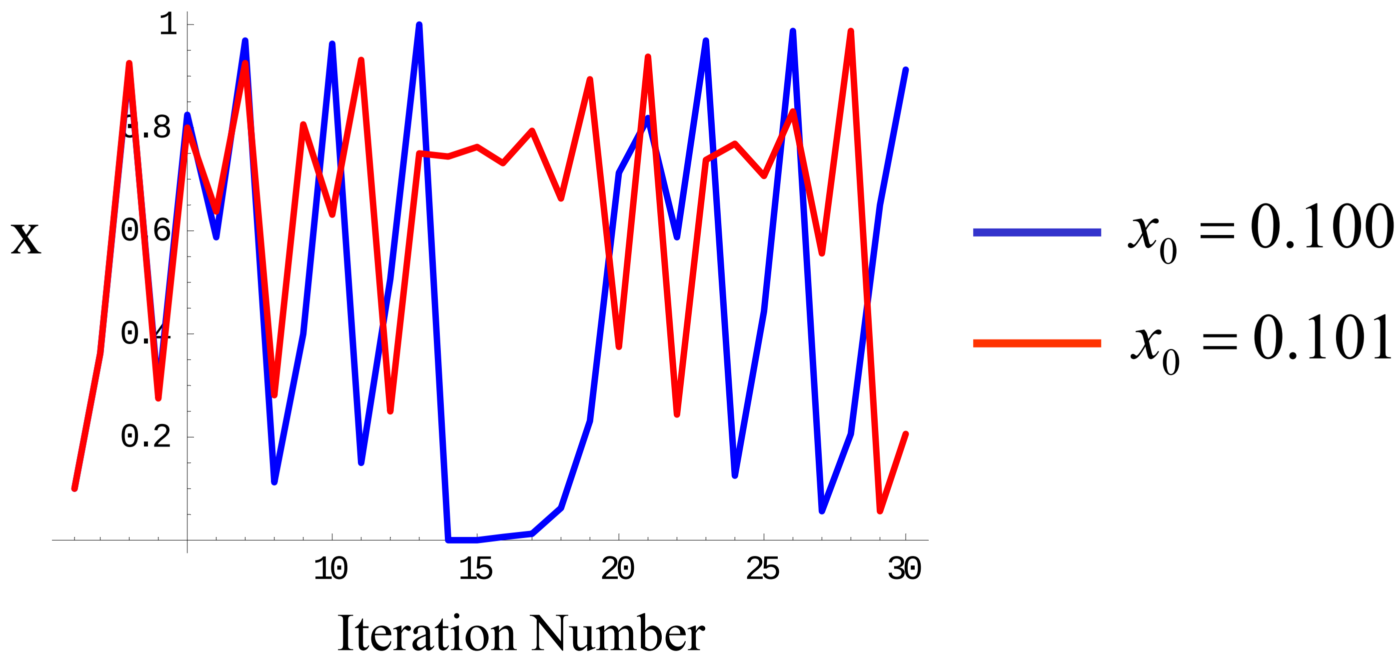
Extreme Sensitivity to Initial Conditions

1-Dimensional Iterated Maps

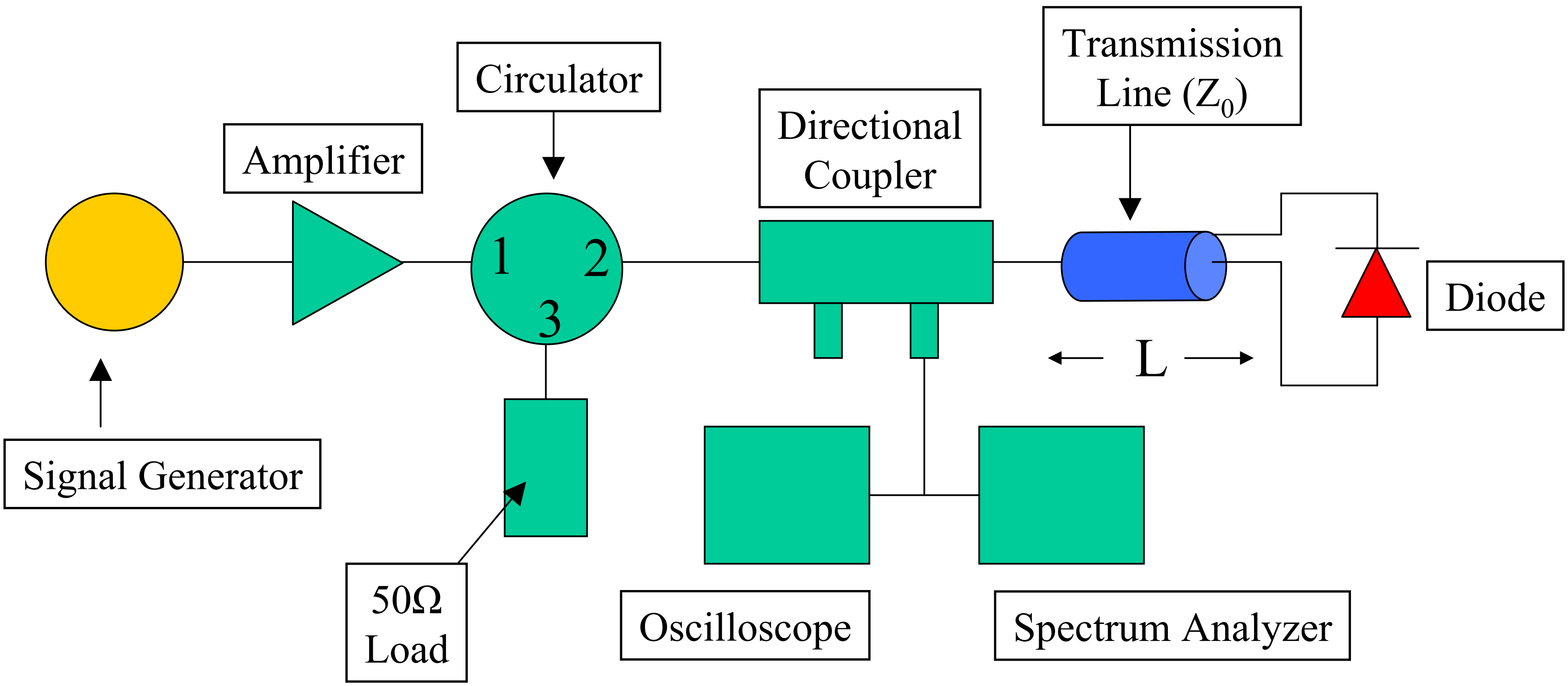
The Logistic Map: $x_{n+1} = 4\mu\, x_n (1 - x_n)$

$$\mu = 1.0$$

Change the initial condition (x_0) slightly…



Experiment on the Driven Diode Distributed Circuit



Diode	Reverse Recovery Time (ns)
BAT 86	4
1N4148	4
1N5475B	160
1N5400	7000