Delayed Feedback and GHz-Scale Chaos on the Driven Diode-Terminated Transmission Line

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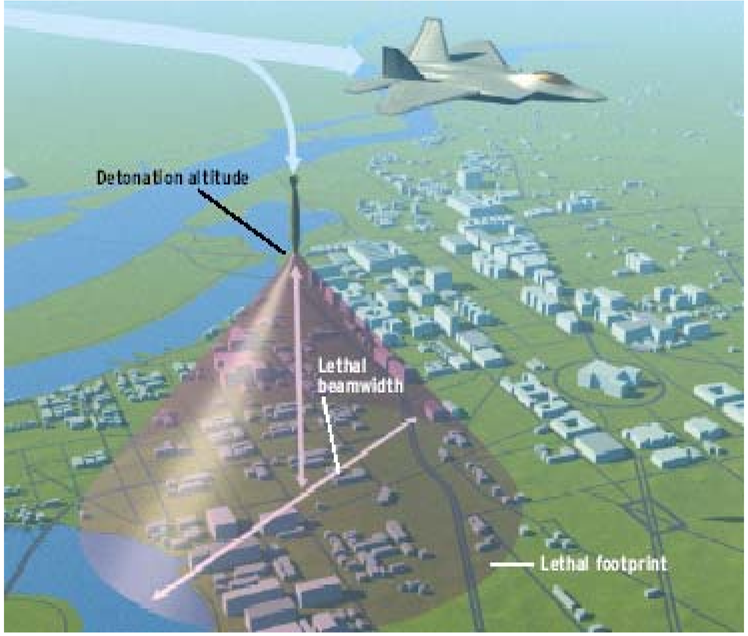
HPM Effects on Electronics



What role does **Nonlinearity** and **Chaos** play in producing HPM effects?

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 systematic framework 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?

These questions are difficult to answer conclusively…

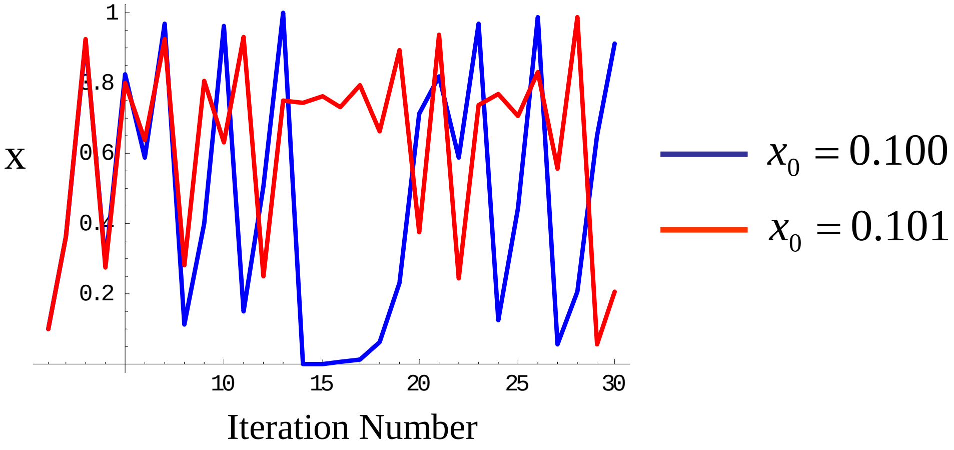
Chaos

Classical: Extreme sensitivity to initial conditions

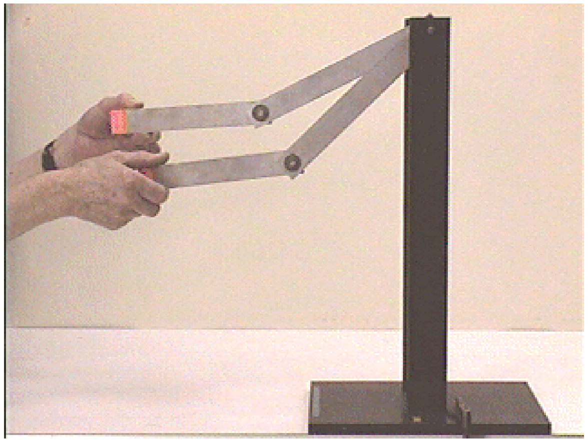
The Logistic Map:

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

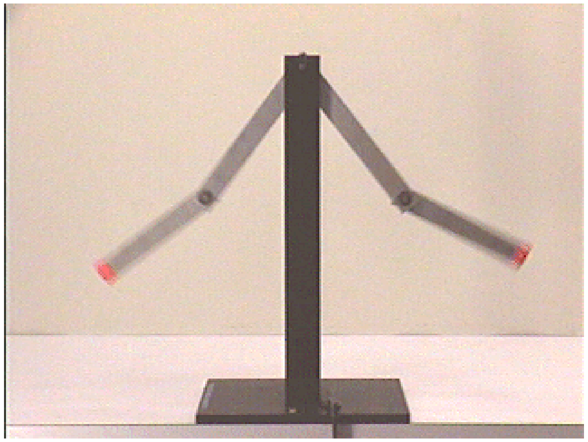
$$\mu = 1.0$$



Double Pendulum



later



Manifestations of classical chaos:

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

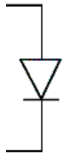
Chaos in Nonlinear Circuits

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)

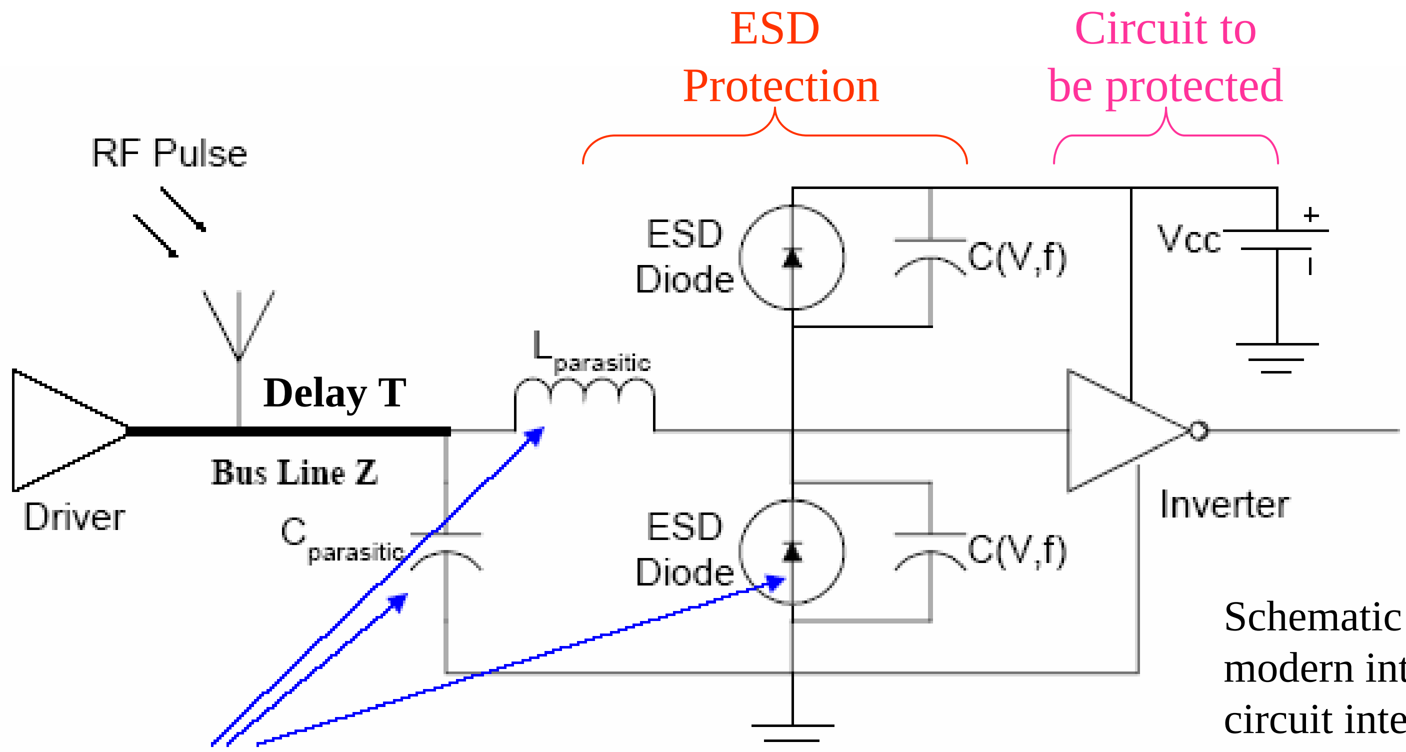
HPM input can induce Chaos through several mechanisms

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

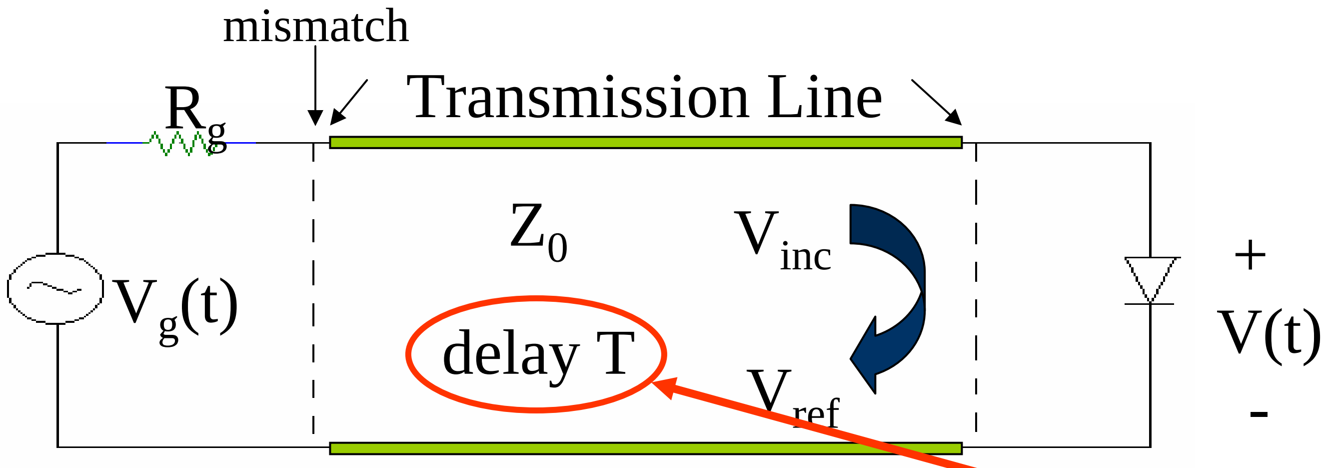


Schematic of modern integrated circuit interconnect

Typical circuit values are resonant at microwave frequencies

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

$$1)\quad 2V_{inc}(t) = V(t) + Z_0\left[gV + \frac{d}{dt}Q(V(t))\right]$$

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

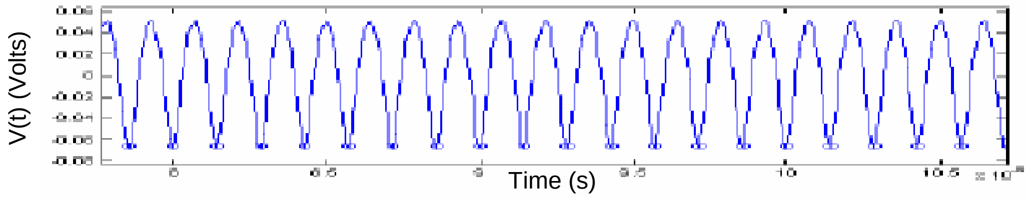
$$3)\quad V_{inc}(t) = V_{ref}(t-2T) + V_g(t-T)$$

$$\frac{d}{dt}V(t) = \frac{-(1+Z_0 g)}{Z_0 C(V(t))}V(t) + \frac{\rho_g(1-Z_0 g)}{Z_0 C(V(t))}V(t-2T) + \frac{-\rho_g C(V(t))}{C(V(t-2T))}\frac{d}{dt}V(t-2T) + \frac{V_g \tau_g}{Z_0 C(V(t))}\cos(\omega(t-T))$$

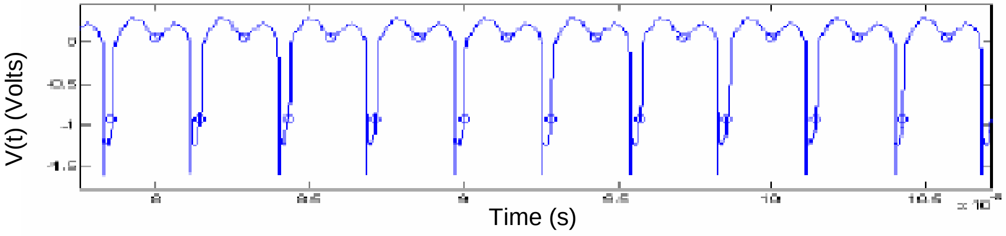
Chaos in the Driven Diode Distributed Circuit

Simulation results

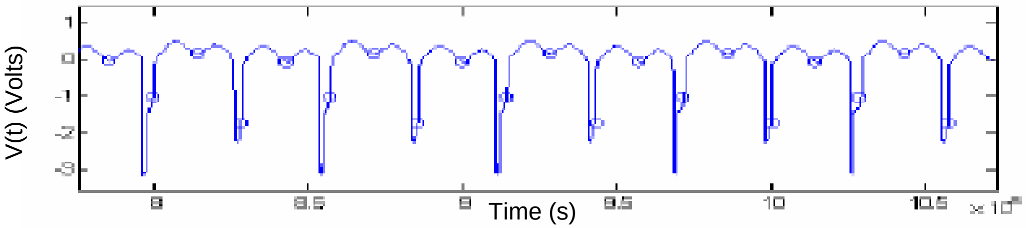
V_g = .5 V **Period 1**



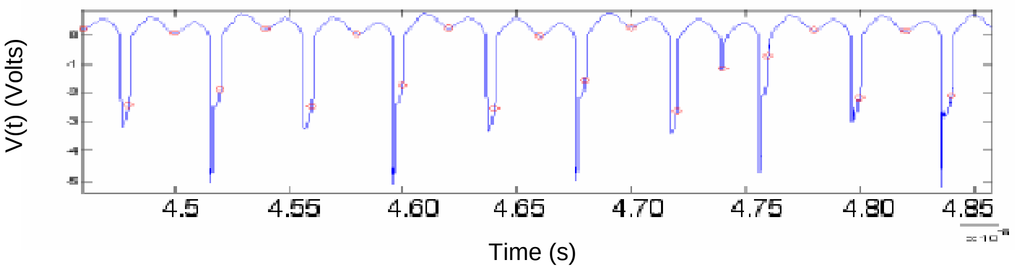
V_g = 2.25 V **Period 2**



V_g = 3.5 V **Period 4**



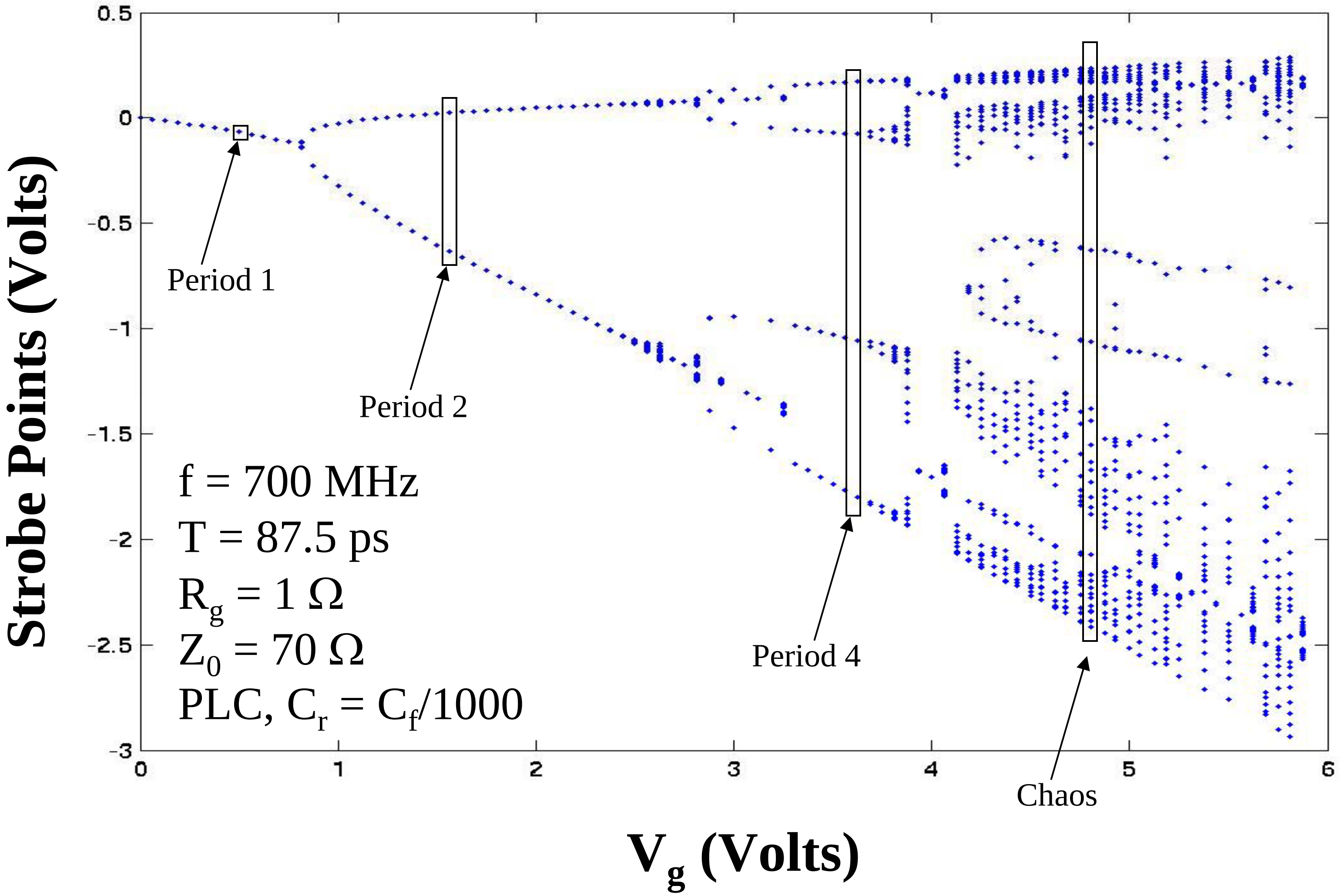
V_g = 5.25 V **Chaos**



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

Chaos in the Driven Diode Distributed Circuit

Simulation results



f = 700 MHz

T = 87.5 ps

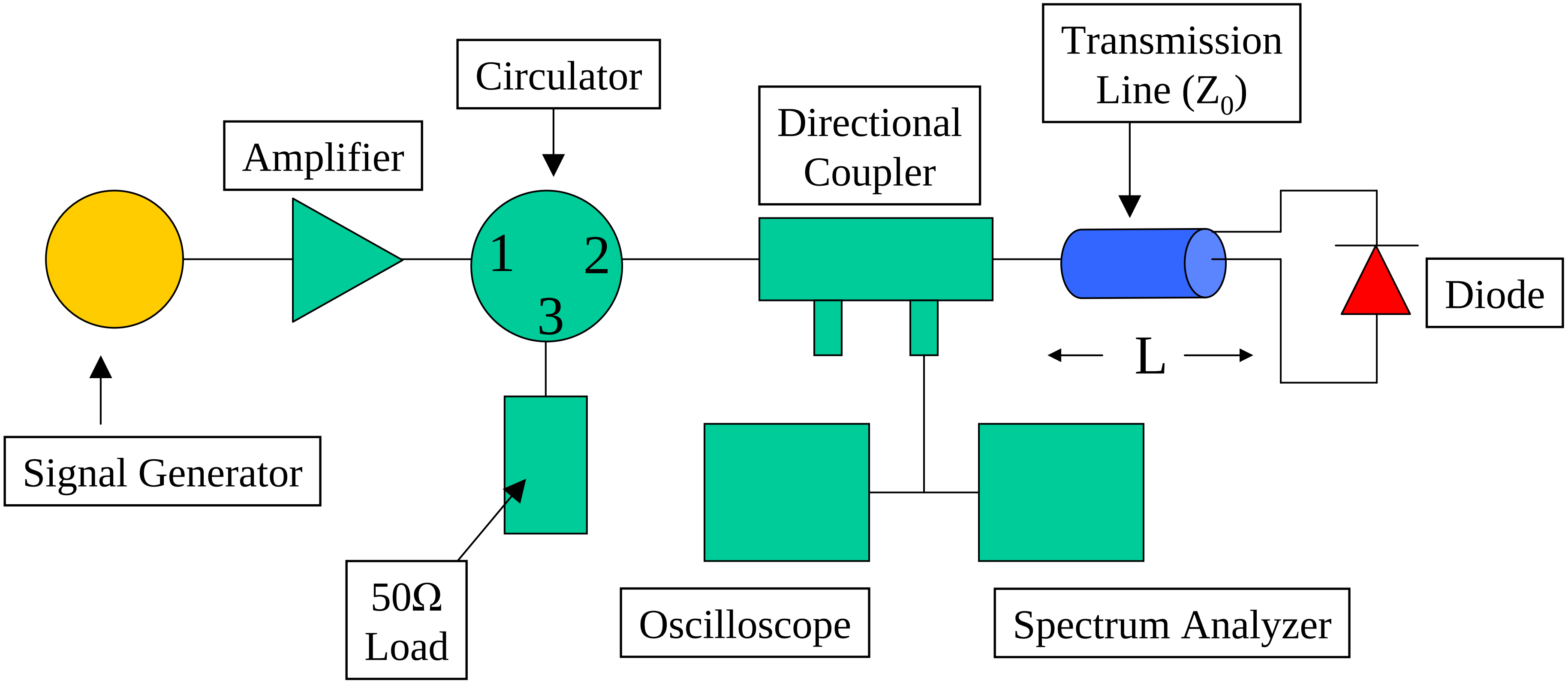
$R_g = 1\ \Omega$

$Z_0 = 70\ \Omega$

PLC, $C_r = C_f/1000$

http://arxiv.org/abs/nlin.cd/0605037

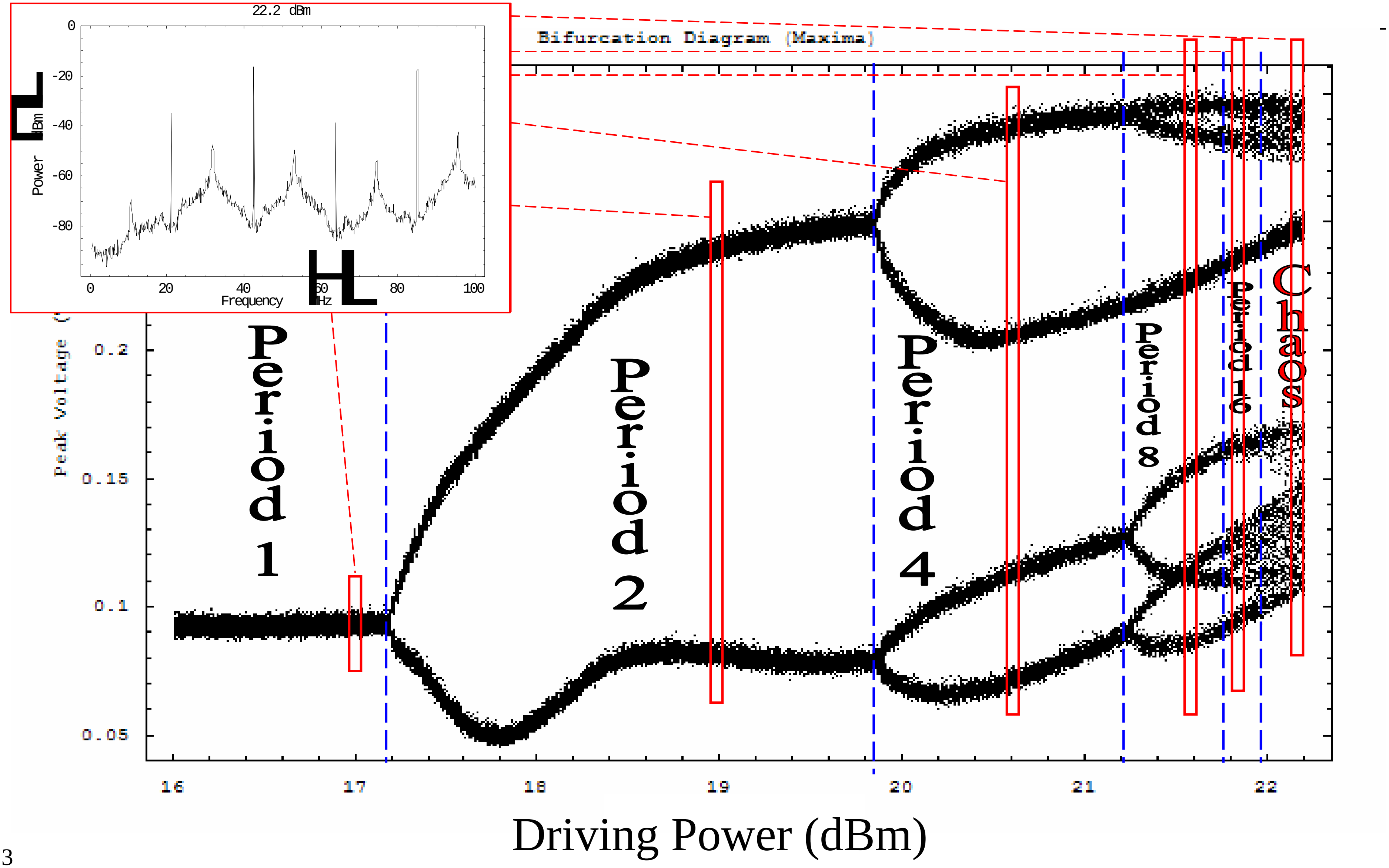
Experiment on the Driven Diode Distributed Circuit



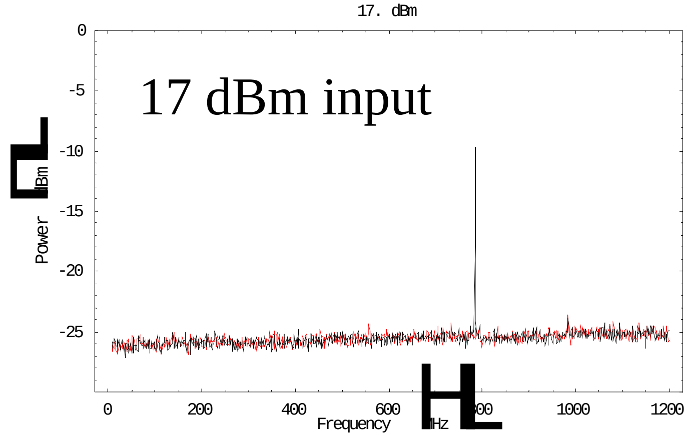
Diode	Reverse Recovery Time (ns)
BAT 86	4
1N4148	4
1N5475B	160
1N5400	7000

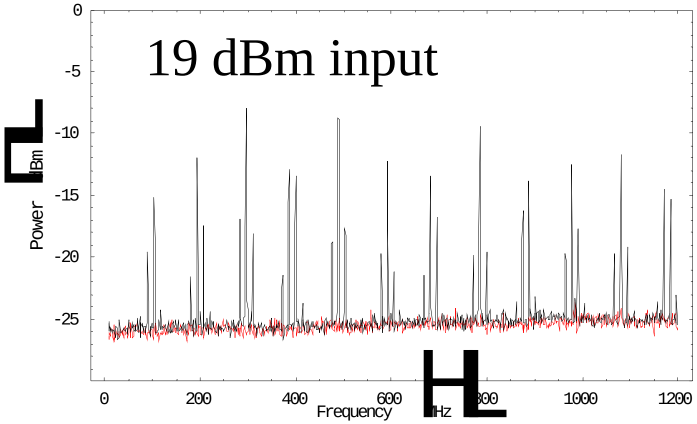
Experimental Results

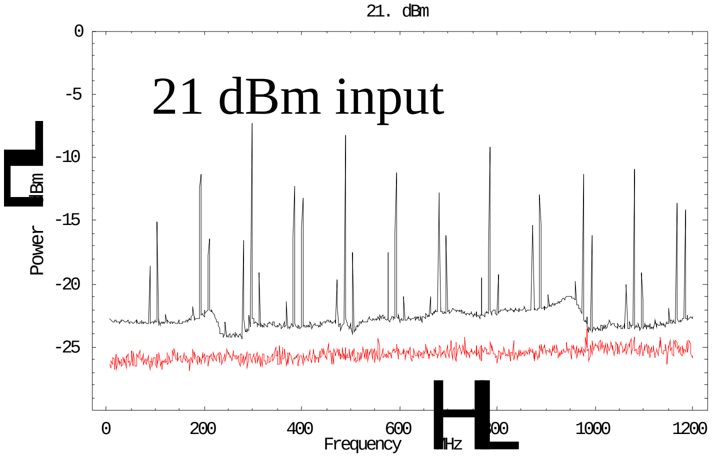
Experimental Bifurcation Diagram
BAT41 Diode @ 85 MHz
T ~ 3.9 ns, Bent-Pipe

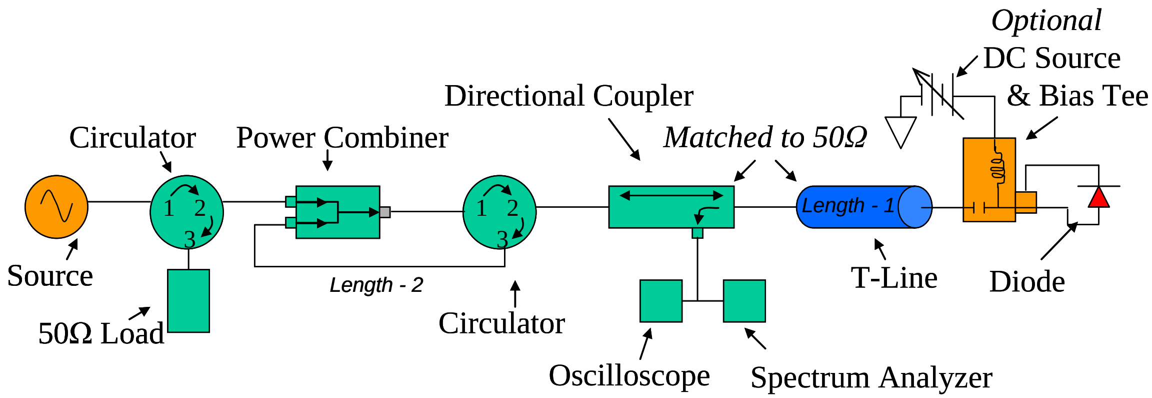


Distributed Transmission Line Diode Chaos at 785 MHz









Optional
DC Source
& Bias Tee
Directional Coupler
Matched to 50Ω
Circulator
Power Combiner
Source
50Ω Load
Length - 2
Circulator
Length - 1
T-Line
Diode
Oscilloscope
Spectrum Analyzer

<u>NTE519</u>

785 MHz

T ~ 3.5 ns

DC Bias=6.5 Volts

http://arxiv.org/abs/nlin.cd/0605037

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?

Are nonlinearity and chaos the correct organizing principles for understanding HPM effects?

Effects of chaotic driving signals on nonlinear circuits

(challenge – circuits are inside systems with a frequency-dependent transfer function)

Unify our 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).

A. Hübler, PRE (1995): Aperiodic time-reversed optimal forcing function

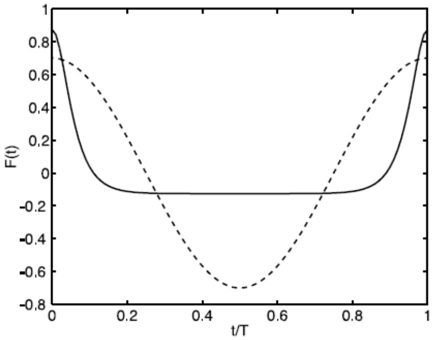


Figure 2. Comparison of the waveform for the optimal forcing function of least power for a weakly damped, weakly forced pendulum of period: $T = 1$ (dashed curve); $T = 25$ (solid curve).

Chaotic Driving Waveforms

Chaotic microwave sources

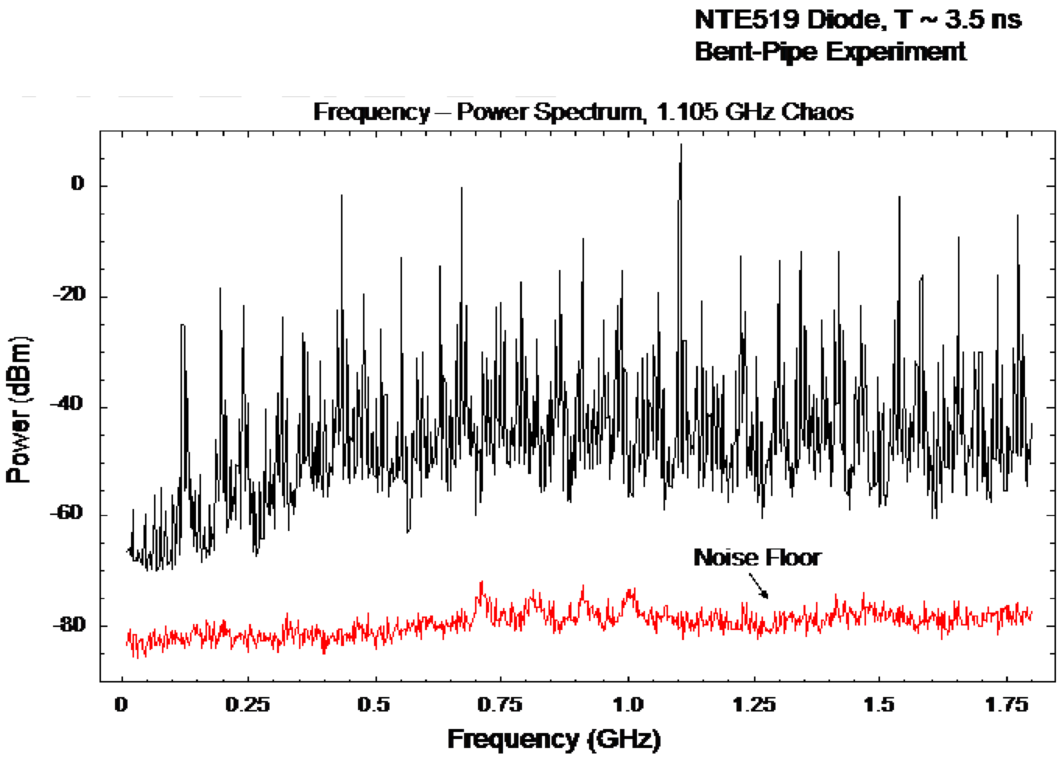
Conclusions

The p/n junction offers many opportunities for HPM upset effects

Instability in ESD protection circuits (John Rodgers)

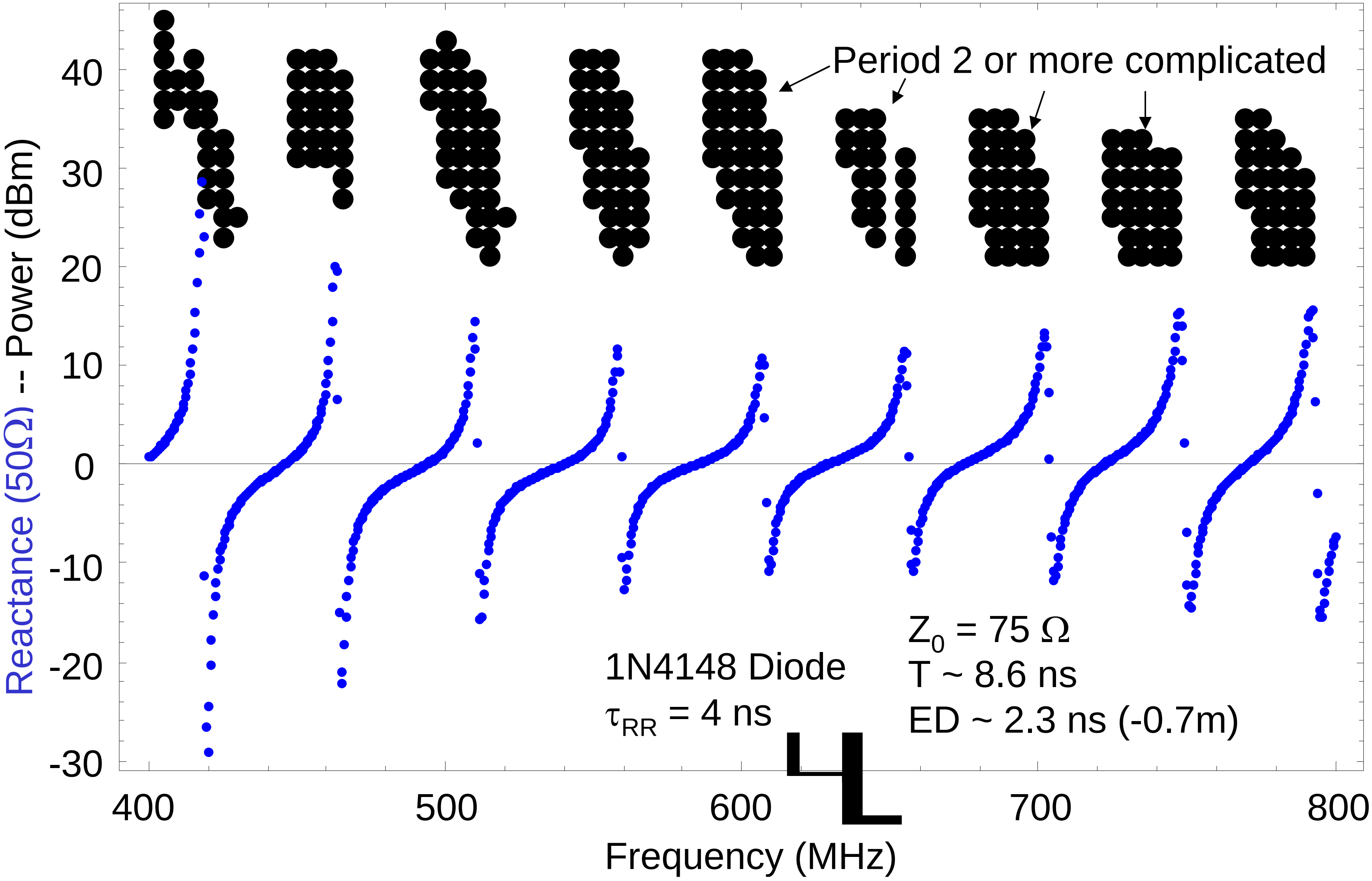
Distributed trans. line / diode circuit → GHz-scale chaos

GHz chaos paper: **http://arxiv.org/abs/nlin.cd/0605037**



Results

Simple Experiment
Phase Diagram



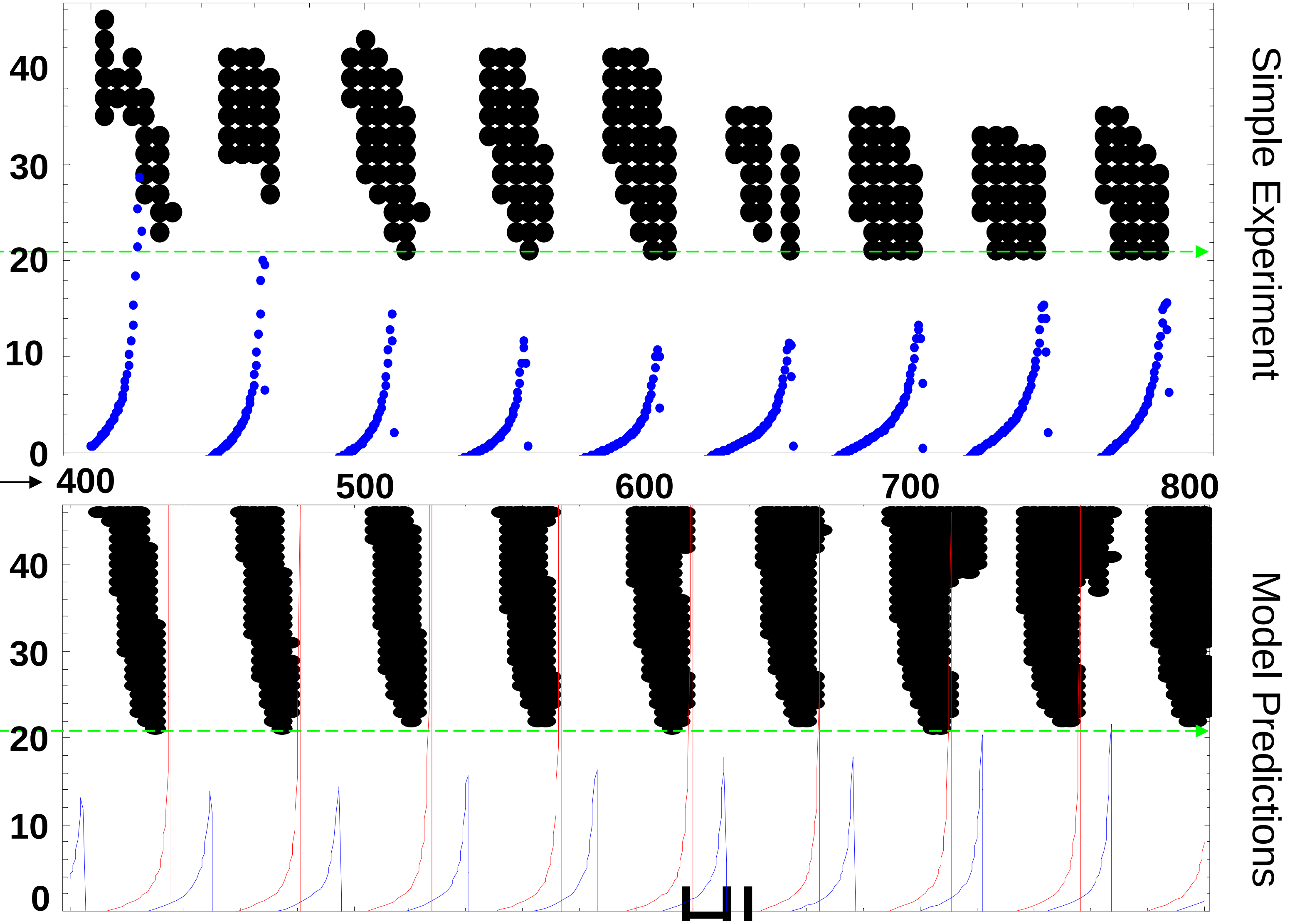
1N4148 Diode
τ_{RR} = 4 ns

Z_0 = 75 Ω
T ~ 8.6 ns
ED ~ 2.3 ns (-0.7m)

Data

Results

Simple Experiment & Model Phase Diagram Comparison



1N4148 Diode

Si Contact Potential ~0.6 Volts

21 dBm

T ~ 8.6 ns
ED ~ 2.3 ns
Cj(0) ~ 4 pF
ρ = -0.2, τ = 0.8

Freq (MHz) →

Numerical

V_0 = 0.6 Volts

21 dBm

T = 10.9 ns
Cr = 3 pF
ρ = -0.35, τ = 0.8

Results

Simple Experiment & Model Phase Diagram Comparison

1N4148 Diode

Si Contact Potential ~0.6 Volts

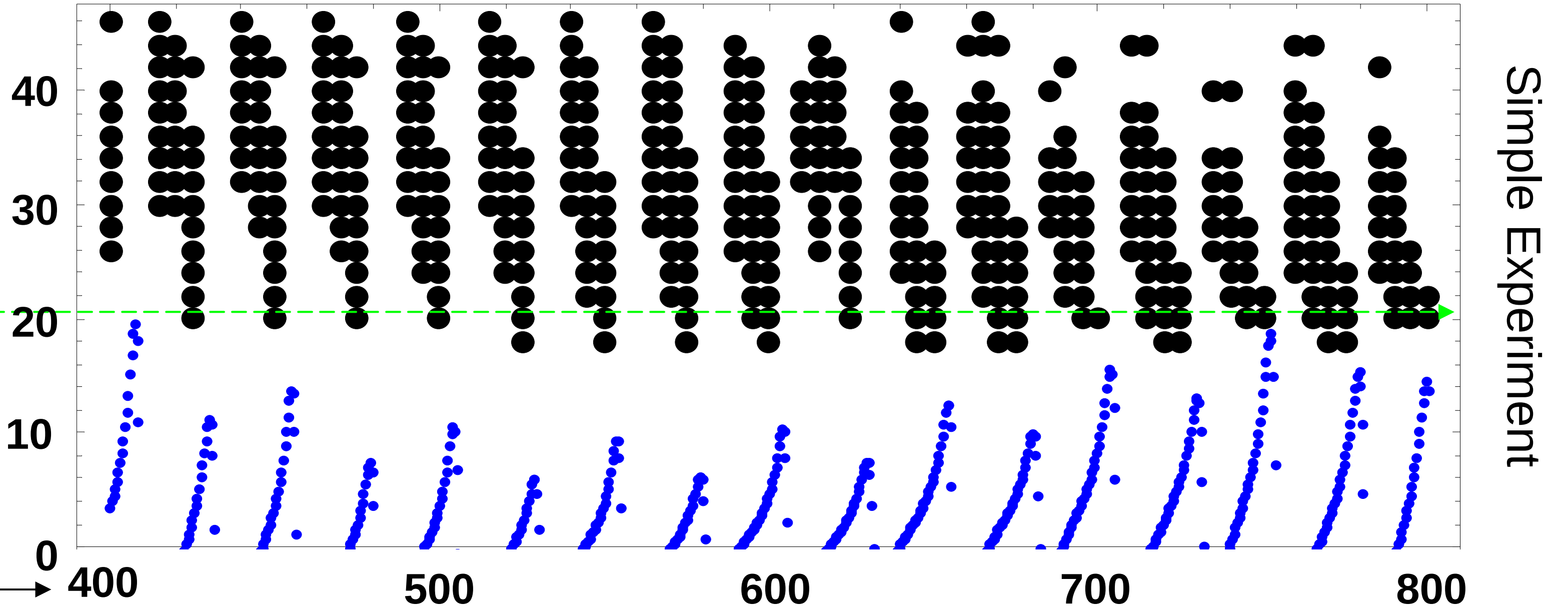
21 dBm

T ~ 17.3 ns

ED ~ 2.3 ns

Cj(0) ~ 4 pF

ρ = -0.2, τ = 0.8



Numerical

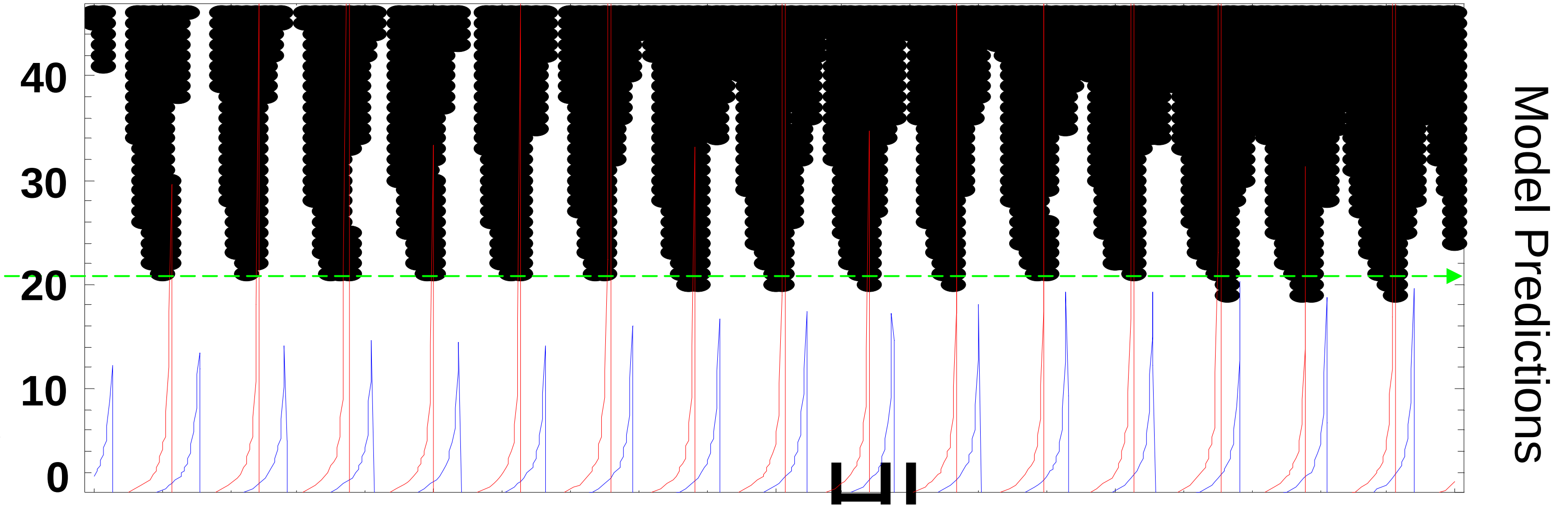
V_0 = 0.6 Volts

21 dBm

T = 19.5 ns

Cr = 3 pF

ρ = -0.35, τ = 0.8



Summary of Results

Diode	τ_{rr} (ns)	$C_{j}0$ (pf)	Experiment	Delay Time T (ns)	Result	Min. Pow. to PD	~*f* Range for Result
1N4148	4®	0.7	Part. Reflecting	8.6, 17.3	PD	~20 dBm	0.4–1.0 GHz periodically
			Bent-Pipe	3.0, 3.5, 3.9, 4.1, 4.4, 5.5, 7.0	PD, Chaos*	~14 dBm	0.2–1.2 GHz
BAT86	4®	11.5	Part. Reflecting	8.6, 17.3	PD	~ 35 dBm	0.4–1.0 GHz periodically
			Bent-Pipe	3.0, 3.5, 3.9, 4.1, 4.4, 5.5, 7.0	Per 1 only	---	20-800 MHz
BAT41	5®	4.6	Part. Reflecting	8.6, 17.3	Per 1 only	---	0.4-1.0 GHz
			Bent-Pipe	3.9	PD, Chaos	~ 25 dBm	43 MHz
						~ 17 dBm	85 MHz
				3.0, 3.5, 4.1, 4.4, 5.5, 7.0	Per 1 only	---	20-800 MHz
NTE519	4®	1.1	Part. Reflecting	8.6, 17.3	PD	~25 dBm	0.4–1.0 GHz periodically
			Bent-Pipe	3.0, 3.5, 3.9, 4.1, 4.4, 5.5, 7.0	PD, Chaos*	~16 dBm	0.5-1.2 GHz
NTE588	35	116	Part. Reflecting	8.6, 17.3	Per 1 only	---	0.02 - 1.2 GHz
			Bent-Pipe	3.0, 3.5, 3.9, 4.1, 4.4, 5.5, 7.0			
MV209	30	66.6	Part. Reflecting	8.6, 17.3	Per 1 only	---	0.02 - 1.2 GHz
			Bent-Pipe	3.0, 3.5, 3.9, 4.1, 4.4, 5.5, 7.0			
5082-2835	<15	0.7	Part. Reflecting	8.6, 17.3	Per 1 only	---	0.02 - 1.2 GHz
			Bent-Pipe	3.0, 3.5, 3.9, 4.1, 4.4, 5.5, 7.0			
5082-3081	100	2.0	Part. Reflecting	8.6, 17.3	Per 1 only	---	0.02 - 1.2 GHz
			Bent-Pipe	3.0, 3.5, 3.9, 4.1, 4.4, 5.5, 7.0			

*With dc bias.

Highest Frequency Chaos @ 1.1 GHz