

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



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Thanks to Alexander Glasser, Marshal Miller, John Rodgers, Todd Firestone

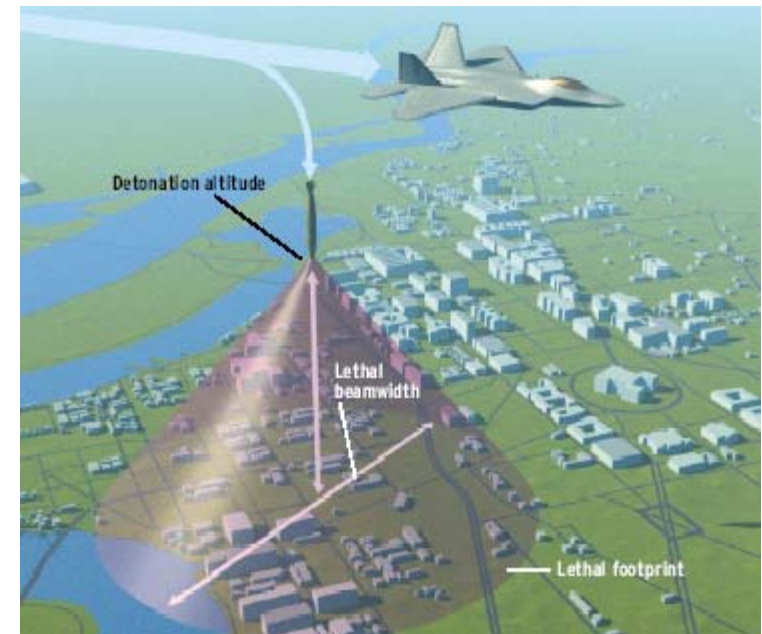


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HPM Effects on Electronics



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

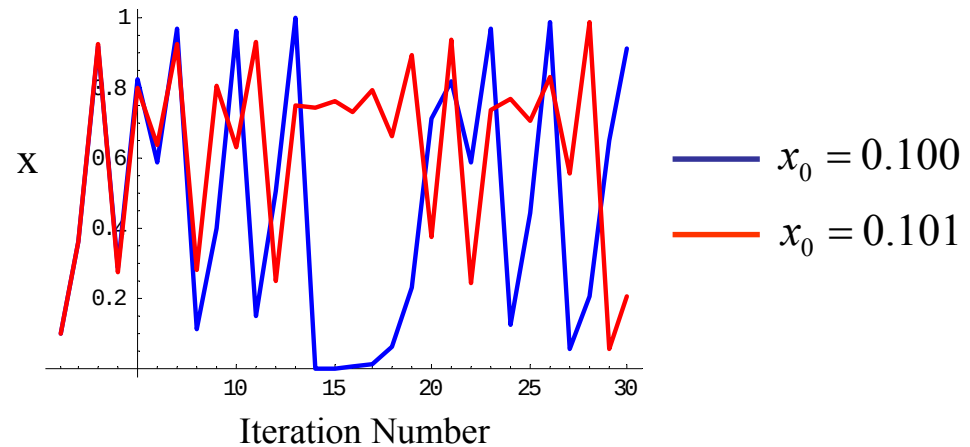


Classical: Extreme sensitivity to initial conditions

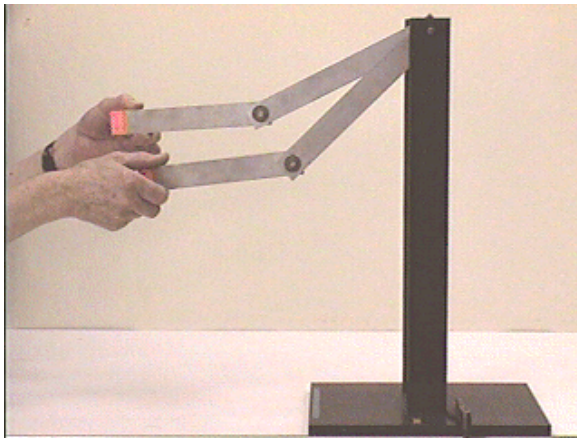
The Logistic Map:

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

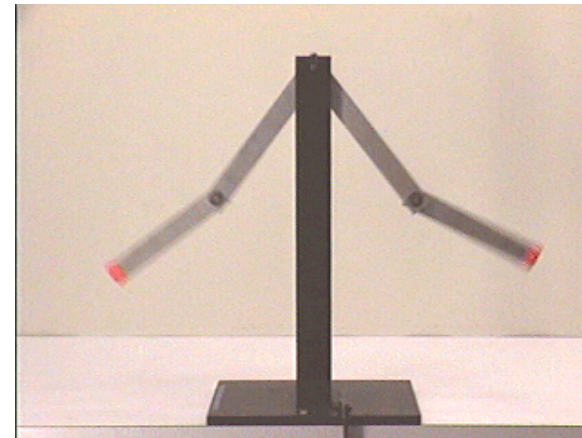
$$\mu = 1.0$$



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

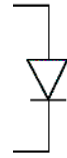
- ...

- 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)

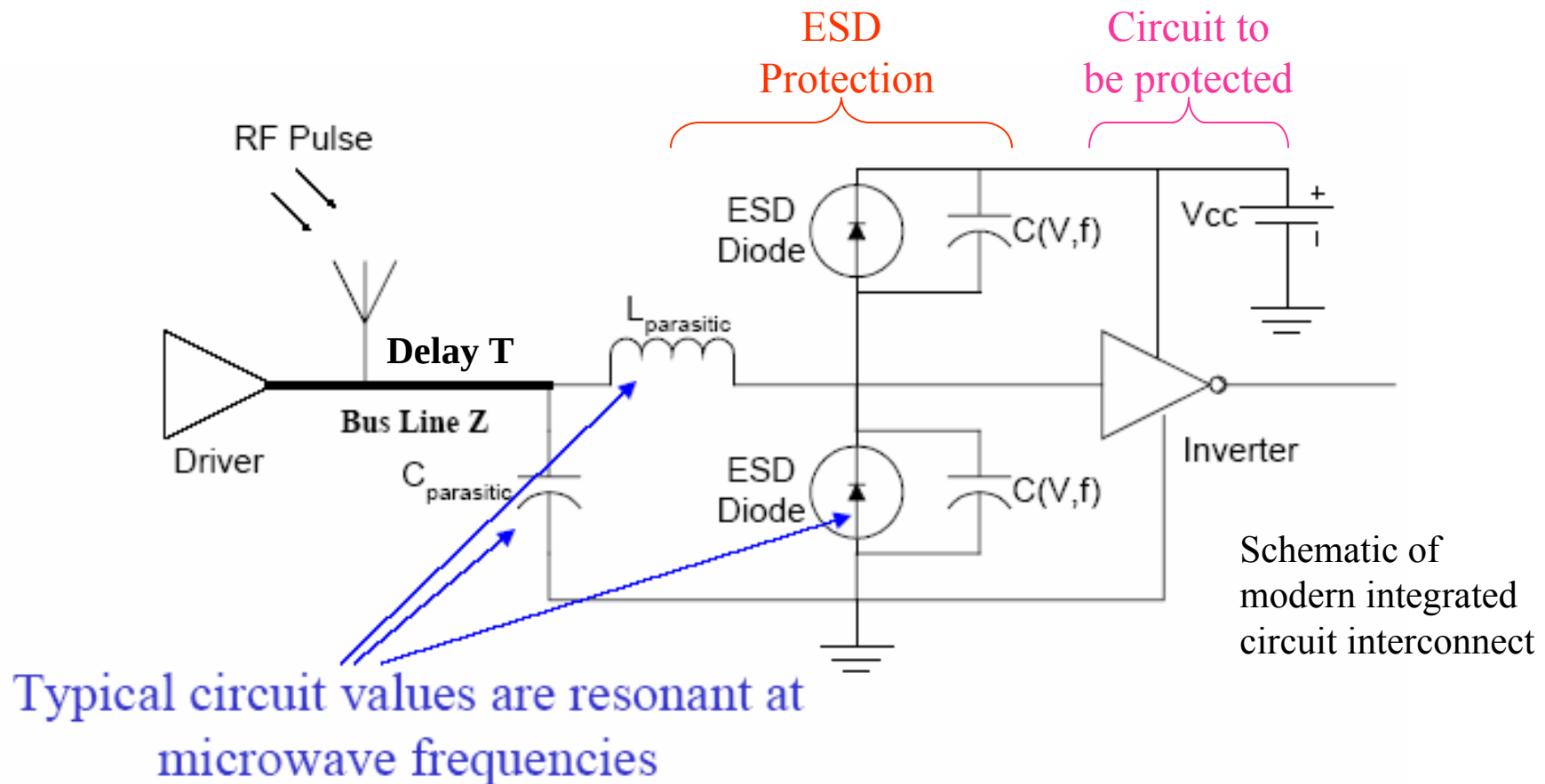
HPM input can induce Chaos through several mechanisms

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).

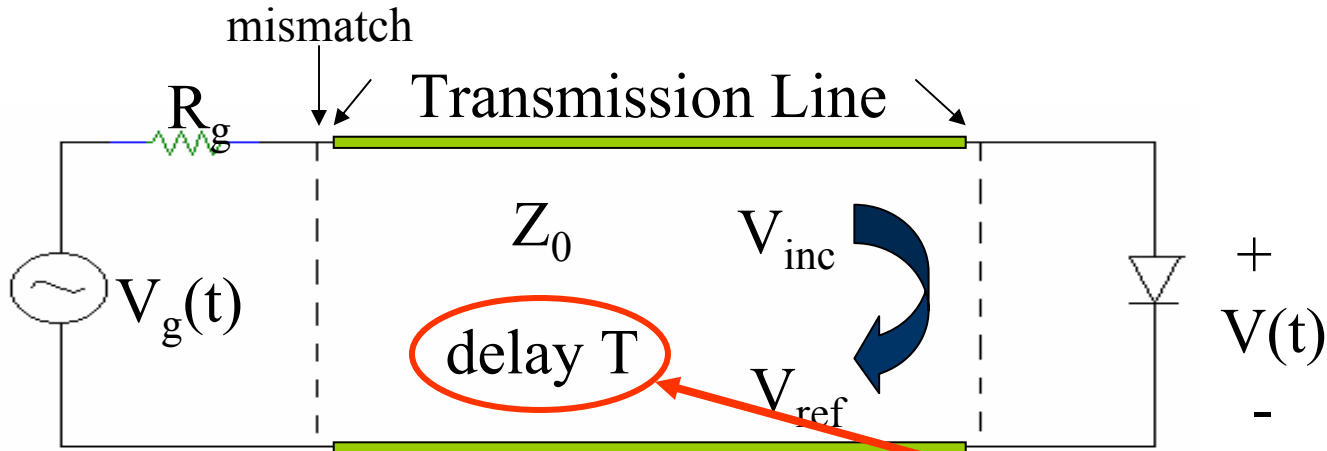
Electrostatic Discharge (ESD) Protection Circuits

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



The “Achilles Heel” of modern electronics

Chaos in the Driven Diode Distributed Circuit

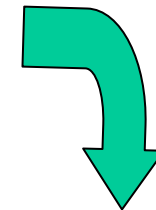


A simple model of p/n junctions in computers

**New
Time-Scale!**

Delay differential equations for the diode voltage

$$\left. \begin{aligned} 1) \quad 2V_{inc}(t) &= V(t) + Z_0 \left[gV + \frac{d}{dt} Q(V(t)) \right] \\ 2) \quad V_{ref}(t) &= V(t) - V_{inc}(t) \\ 3) \quad V_{inc}(t) &= V_{ref}(t - 2T) + V_g(t - T) \end{aligned} \right\}$$



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

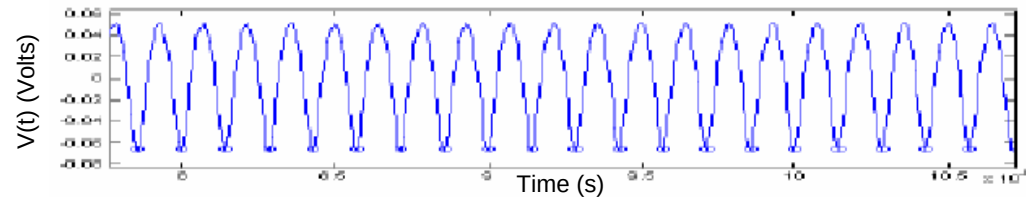
Chaos in the Driven Diode Distributed Circuit



Simulation results

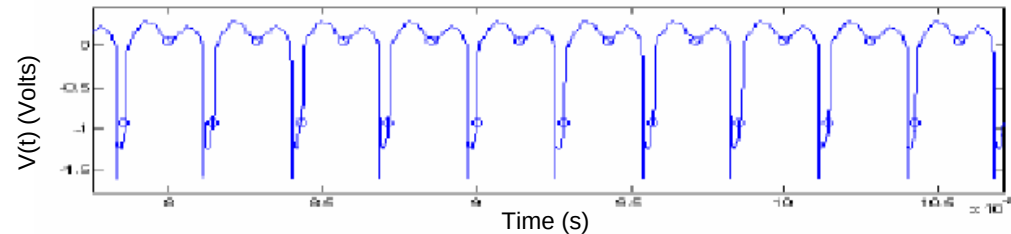
$$V_g = .5 \text{ V}$$

Period 1



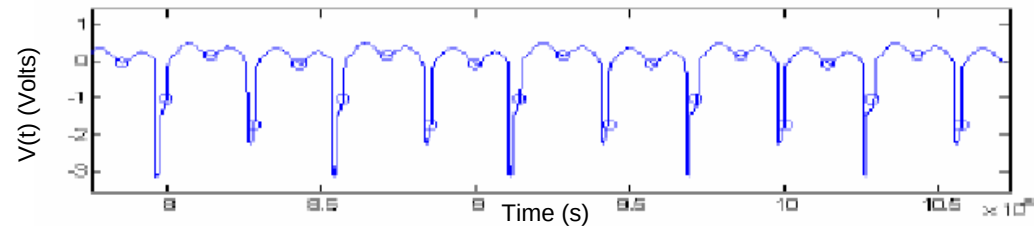
$$V_g = 2.25 \text{ V}$$

Period 2



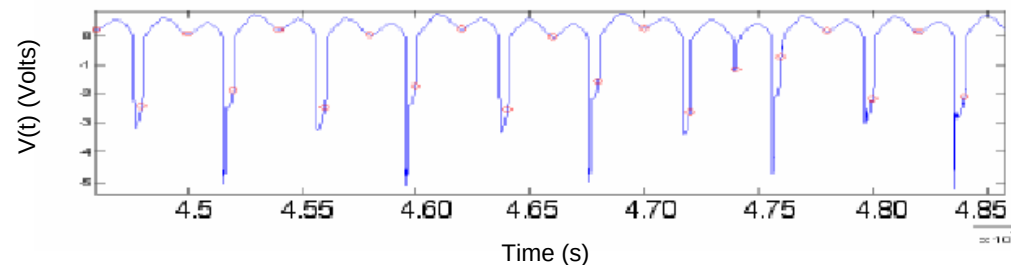
$$V_g = 3.5 \text{ V}$$

Period 4



$$V_g = 5.25 \text{ V}$$

Chaos



$$f = 700 \text{ MHz}$$

$$T = 87.5 \text{ ps}$$

$$R_g = 1 \Omega$$

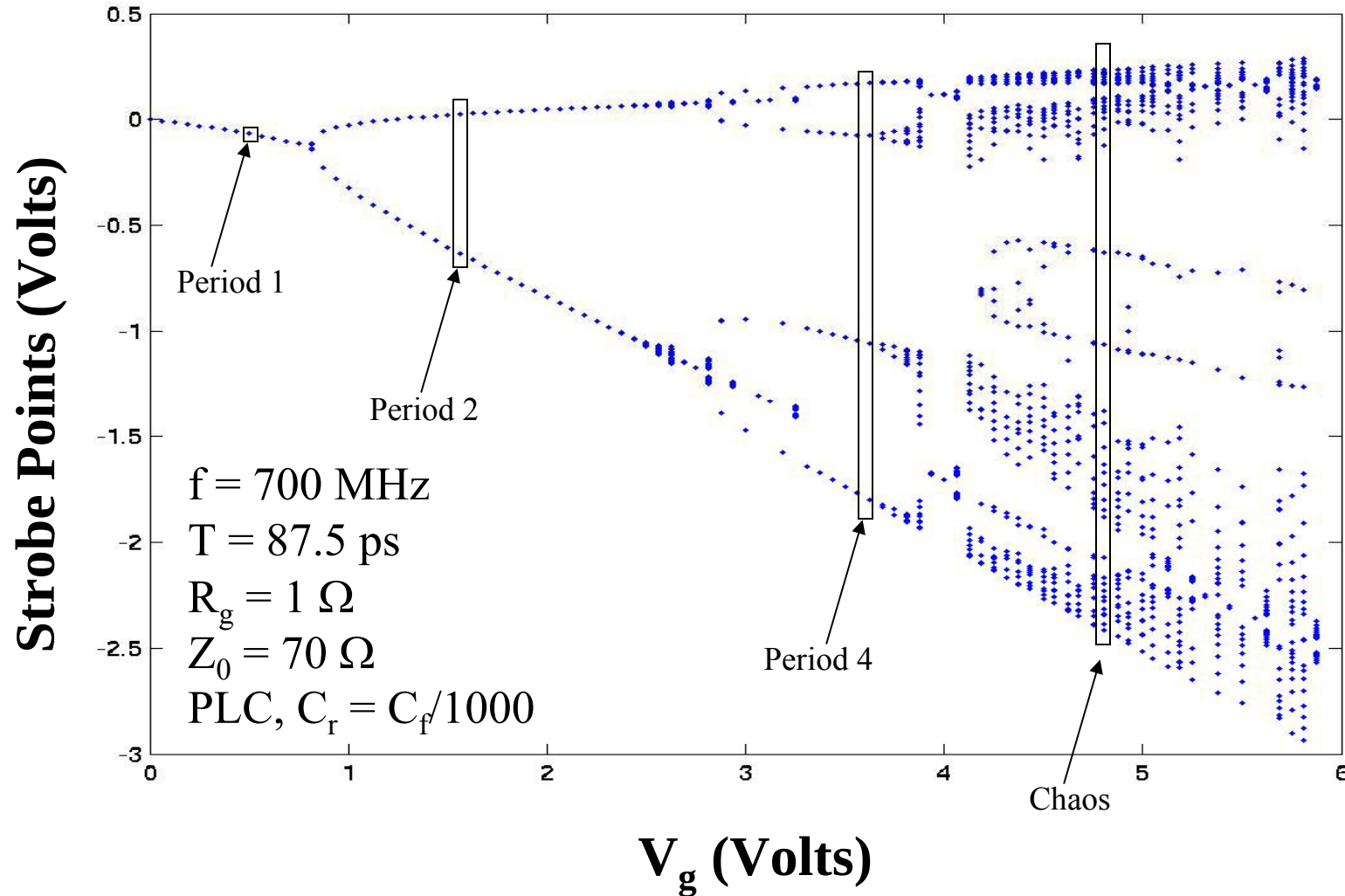
$$Z_0 = 70 \Omega$$

$$10 \text{ PLC, } C_r = C_f/1000$$

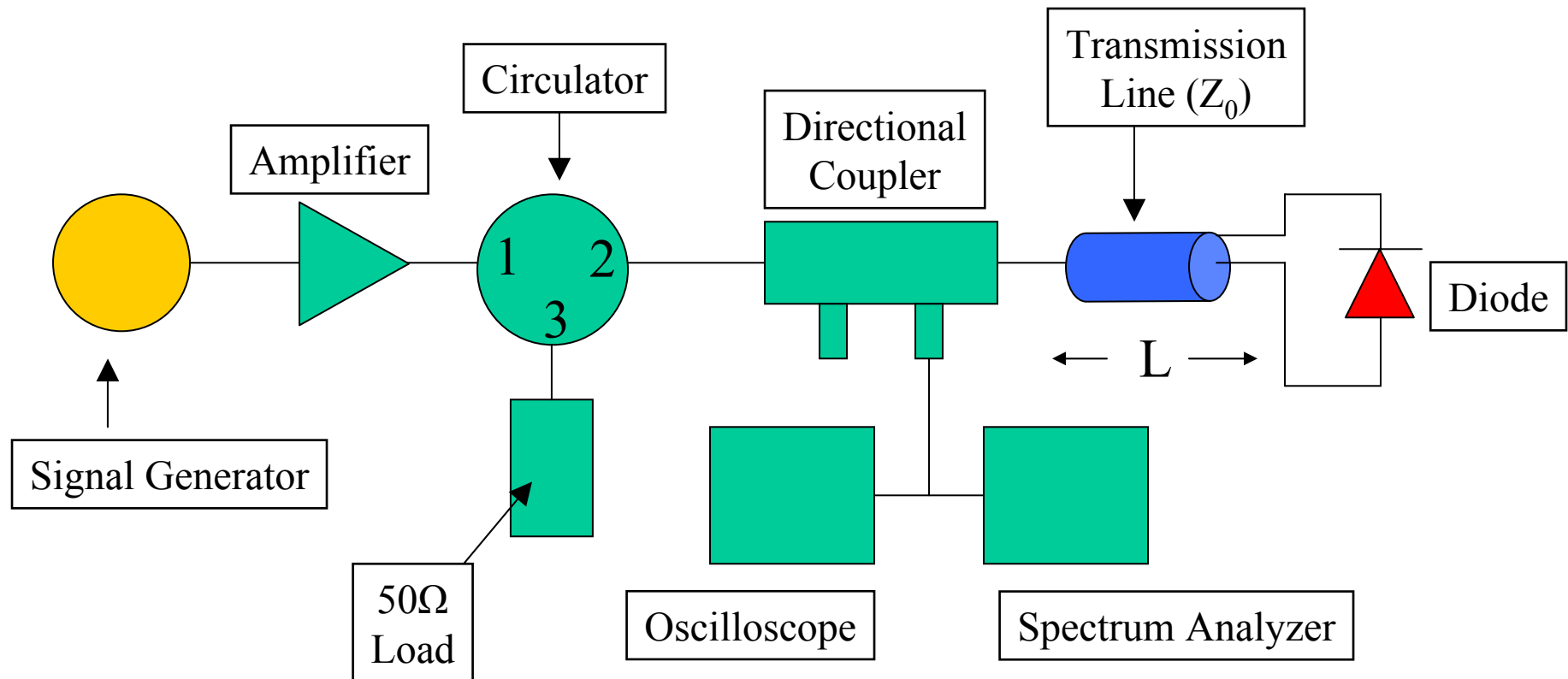
Chaos in the Driven Diode Distributed Circuit



Simulation results



Experiment on the Driven Diode Distributed Circuit

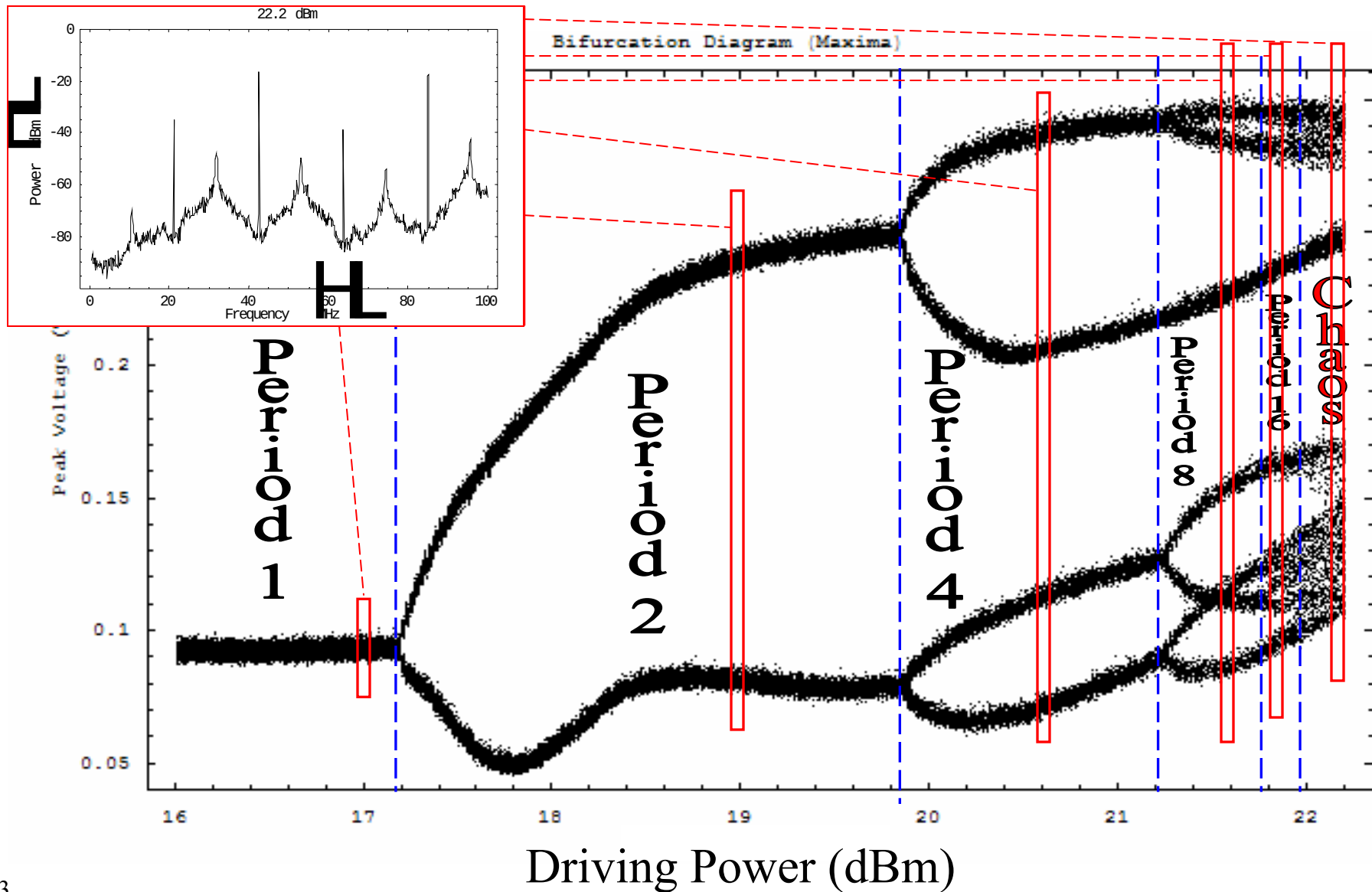


Diode	Reverse Recovery Time (ns)
BAT 86	4
1N4148	4
1N5475B	160
1N5400	7000

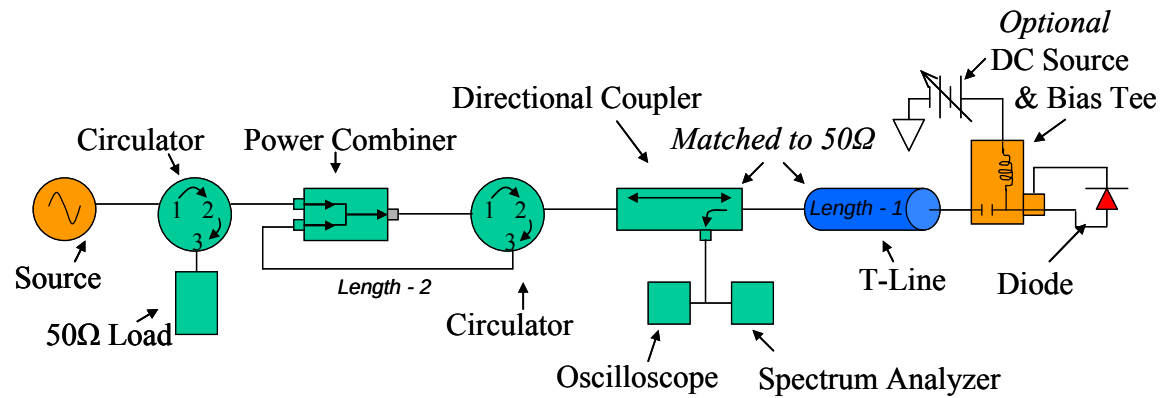
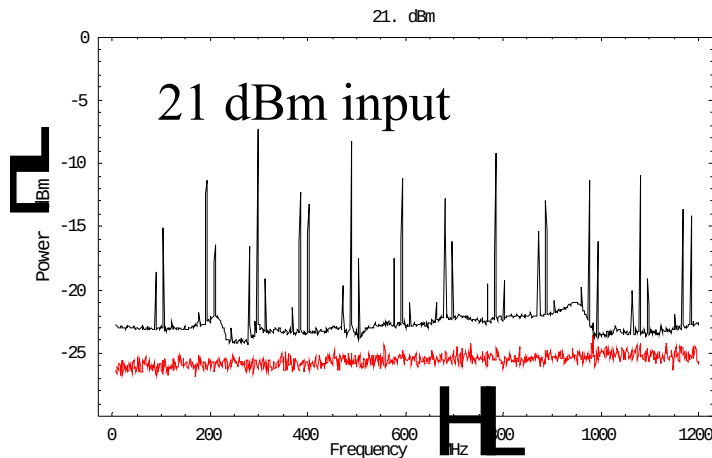
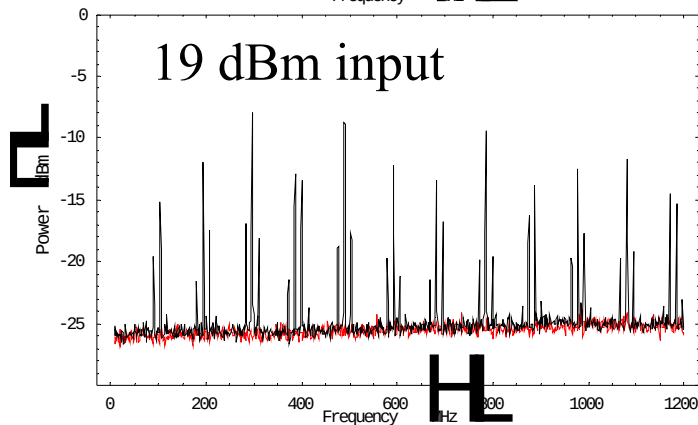
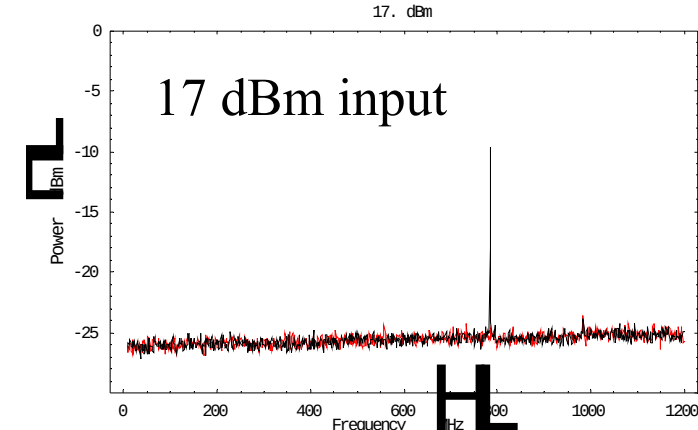
Experimental Bifurcation Diagram BAT41 Diode @ 85 MHz T ~ 3.9 ns, Bent-Pipe



Experimental Results



Distributed Transmission Line Diode Chaos at 785 MHz



NTE519

785 MHz

$T \sim 3.5$ 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

Chaotic Driving Waveforms

Chaotic microwave sources

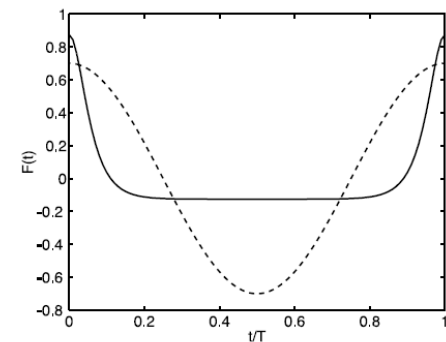


Figure 2. Comparison of the waveform for the optimal forcing function of least power for a weakly damped, weakly forced pendulum of period: $T = 1$ (dashed curve); $T = 25$ (solid curve).

Conclusions

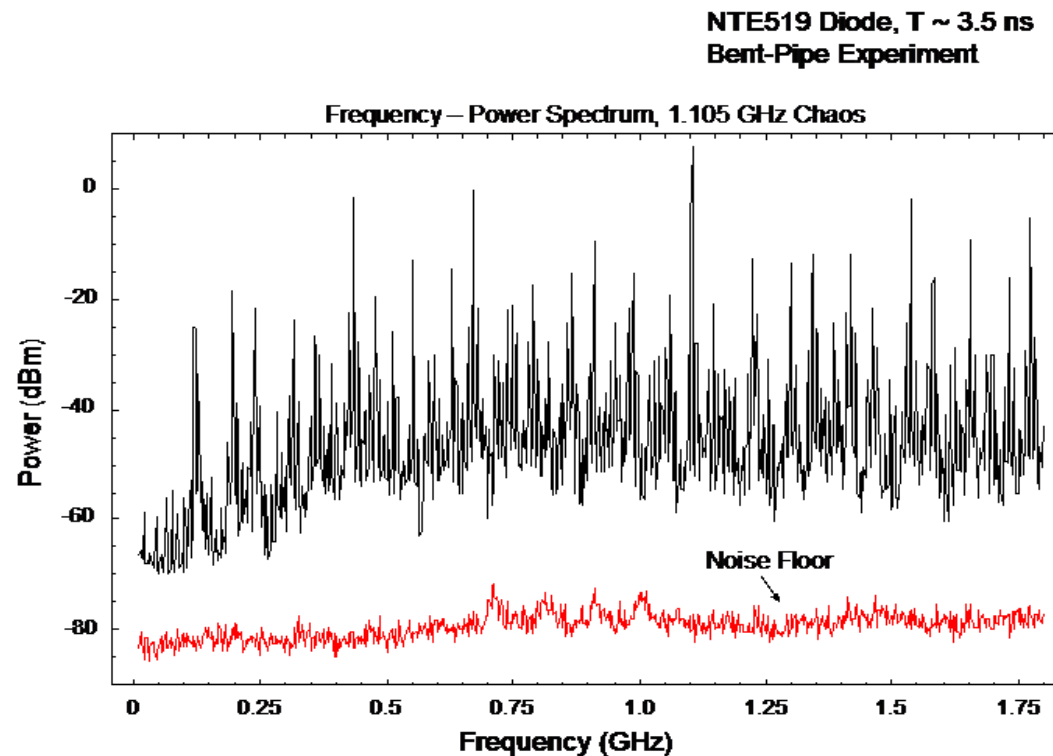


The p/n junction offers many opportunities for HPM upset effects

Instability in ESD protection circuits (John Rodgers)

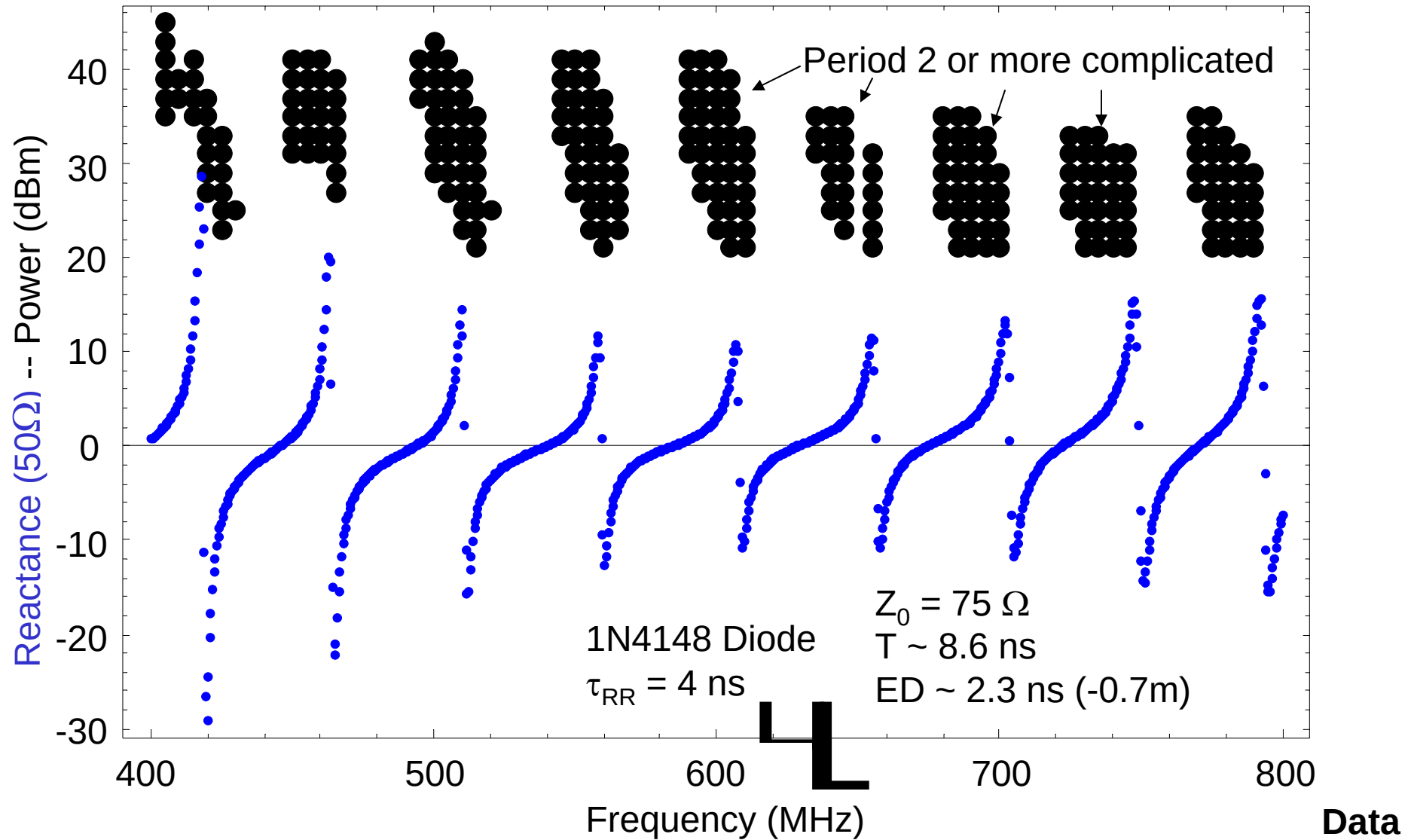
Distributed trans. line / diode circuit → GHz-scale chaos

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



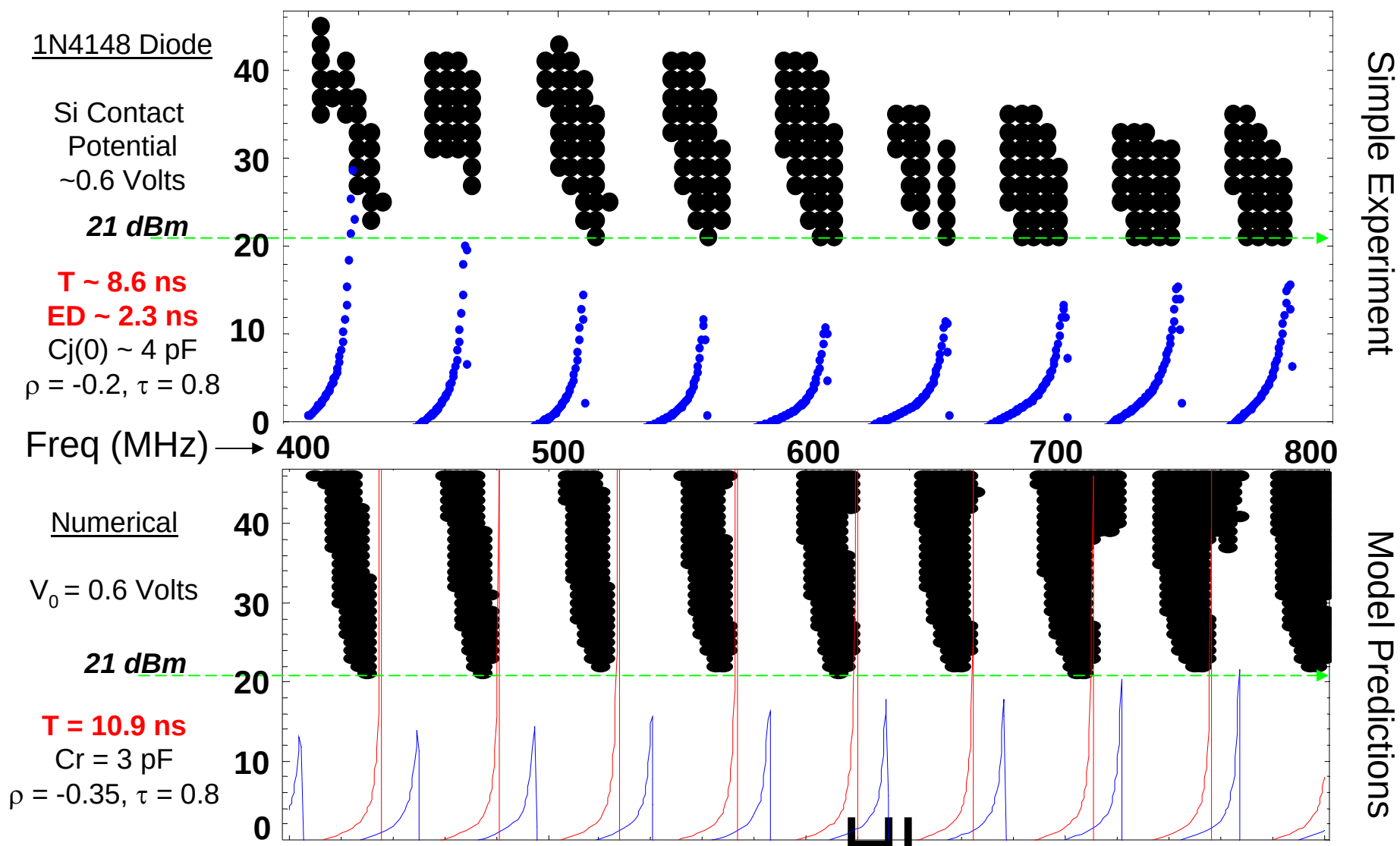
Results

Simple Experiment
Phase Diagram



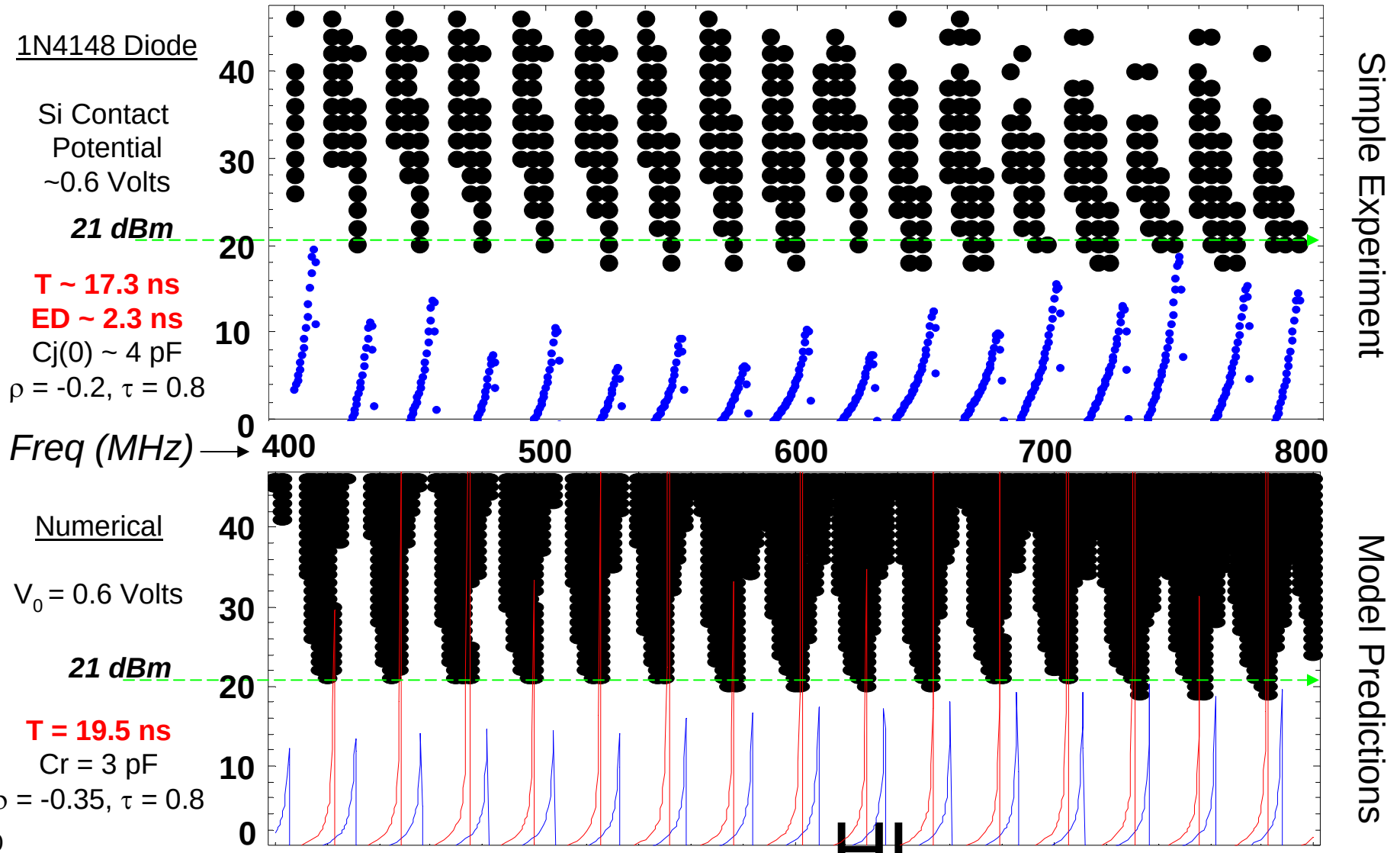
Results

Simple Experiment & Model Phase Diagram Comparison



Results

Simple Experiment & Model Phase Diagram Comparison



Summary of Results



Diode	τ_{tr} (ns)	C_{j0} (pf)	Experiment	Delay Time T (ns)	Result	Min. Pow. to PD	$\sim f$ 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
				3.0, 3.5, 4.1, 4.4, 5.5, 7.0	Per 1 only	~ 17 dBm	85 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			

21 Highest Frequency Chaos @ 1.1 GHz

*With dc bias.