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

Steven M. Anlage, Vassili Demergis, Renato Moraes, Edward Ott, Thomas Antonsen

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

AFOSR MURI Final Review

Research funded by the AFOSR-MURI and DURIP programs
**1. REPORT DATE**  
JUL 2006

**2. REPORT TYPE**  
N/A

**3. DATES COVERED**  
-

**4. TITLE AND SUBTITLE**  
Delayed Feedback and GHz-Scale Chaos on the Driven Diode-Terminated Transmission Line

**5a. CONTRACT NUMBER**  
-

**5b. GRANT NUMBER**  
-

**5c. PROGRAM ELEMENT NUMBER**  
-

**5d. PROJECT NUMBER**  
-

**5e. TASK NUMBER**  
-

**5f. WORK UNIT NUMBER**  
-

**6. AUTHOR(S)**  
-

**7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)**  
Institute for Research in Electronics Applied Physics

**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:**  

<table>
<thead>
<tr>
<th>a. REPORT</th>
<th>b. ABSTRACT</th>
<th>c. THIS PAGE</th>
<th>d. ABSTRACT</th>
<th>e. THIS PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>unclassified</td>
<td>unclassified</td>
<td>unclassified</td>
<td>unclassified</td>
<td>unclassified</td>
</tr>
</tbody>
</table>

**17. LIMITATION OF ABSTRACT**  
UU

**18. NUMBER OF PAGES**  
21

**19a. NAME OF RESPONSIBLE PERSON**  
-

---

According to the OMB control number, the estimated public reporting burden for the collection of information is 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

The original document contains color images.
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
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:

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

\[ \mu = 1.0 \]

**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


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

Delay differential equations for the diode voltage

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

2) \[ V_{ref}(t) = V(t) - V_{inc}(t) \]

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

\[
\frac{d}{dt} V(t) = -\frac{(1+Z_0g)}{Z_0C(V(t))} V(t) + g \frac{(1-Z_0g)}{Z_0C(V(t))} V(t-2T) + \frac{-\rho_g C(V(t))}{C(V(t-2T))} \frac{d}{dt} V(t-2T) + \frac{V_g \tau_g}{Z_0C(V(t))} \cos(\omega(t-T))
\]
Chaos in the Driven Diode Distributed Circuit

Simulation results

\[ V_g = 0.5 \text{ V} \]  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

\[ f = 700 \text{ MHz} \]

\[ T = 87.5 \text{ ps} \]

\[ R_g = 1 \text{ } \Omega \]

\[ Z_0 = 70 \text{ } \Omega \]

\[ \text{PLC, } C_r = C_f / 1000 \]
Chaos in the Driven Diode Distributed Circuit

Simulation results

\[ f = 700 \text{ MHz} \]
\[ T = 87.5 \text{ ps} \]
\[ R_g = 1 \Omega \]
\[ Z_0 = 70 \Omega \]
\[ \text{PLC, } C_r = C_f/1000 \]

http://arxiv.org/abs/nlin.cd/0605037
Experiment on the Driven Diode Distributed Circuit

<table>
<thead>
<tr>
<th>Diode</th>
<th>Reverse Recovery Time (ns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BAT 86</td>
<td>4</td>
</tr>
<tr>
<td>1N4148</td>
<td>4</td>
</tr>
<tr>
<td>1N5475B</td>
<td>160</td>
</tr>
<tr>
<td>1N5400</td>
<td>7000</td>
</tr>
</tbody>
</table>
Experimental Bifurcation Diagram
BAT41 Diode @ 85 MHz
T ~ 3.9 ns, Bent-Pipe
Distributed Transmission Line Diode Chaos at 785 MHz

17 dBm input

19 dBm input

21 dBm input

NTE519
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? $\rightarrow$ 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
- Two-tone driving lowers threshold for chaotic onset

Noise-induced Chaos:

Resonant perturbation waveform
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


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

Results

Simple Experiment
Phase Diagram

Period 2 or more complicated

1N4148 Diode
\( \tau_{RR} = 4 \text{ ns} \)
\( Z_0 = 75 \, \Omega \)
\( T \sim 8.6 \text{ ns} \)
\( ED \sim 2.3 \text{ ns} \) (-0.7 m)

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
\( \rho = -0.2, \tau = 0.8 \)

Numerical
\( V_0 = 0.6 \) Volts
21 dBm
T = 10.9 ns
Cr = 3 pF
\( \rho = -0.35, \tau = 0.8 \)
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
V₀ = 0.6 Volts
21 dBm
T = 19.5 ns
Cr = 3 pF
ρ = -0.35, τ = 0.8
### Summary of Results

<table>
<thead>
<tr>
<th>Diode</th>
<th>$\tau_{rr}$ (ns)</th>
<th>$C_j^0$ (pf)</th>
<th>Experiment</th>
<th>Delay Time T (ns)</th>
<th>Result</th>
<th>Min. Pow. to PD</th>
<th>$\approx f$ Range for Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>1N4148</td>
<td>4$^*$</td>
<td>0.7</td>
<td>Part. Reflecting</td>
<td>8.6, 17.3</td>
<td>PD</td>
<td>~20 dBm</td>
<td>0.4–1.0 GHz periodically</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Bent-Pipe</td>
<td>3.0, 3.5, 3.9, 4.1, 4.4, 5.5, 7.0</td>
<td>PD, Chaos*</td>
<td>~14 dBm</td>
<td>0.2–1.2 GHz</td>
</tr>
<tr>
<td>BAT86</td>
<td>4$^*$</td>
<td>11.5</td>
<td>Part. Reflecting</td>
<td>8.6, 17.3</td>
<td>Per 1 only</td>
<td>---</td>
<td>20-800 MHz</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Bent-Pipe</td>
<td>3.0, 3.5, 3.9, 4.1, 4.4, 5.5, 7.0</td>
<td>Per 1 only</td>
<td>---</td>
<td>0.4-1.0 GHz</td>
</tr>
<tr>
<td>BAT41</td>
<td>5$^*$</td>
<td>4.6</td>
<td>Part. Reflecting</td>
<td>8.6, 17.3</td>
<td>Per 1 only</td>
<td>---</td>
<td>40 MHz</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Bent-Pipe</td>
<td>3.0, 3.5, 3.9, 4.1, 4.4, 5.5, 7.0</td>
<td>PD, Chaos</td>
<td>~25 dBm</td>
<td>43 MHz</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>~17 dBm</td>
<td>85 MHz</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>---</td>
<td>20-800 MHz</td>
</tr>
<tr>
<td>NTE519</td>
<td>4$^*$</td>
<td>1.1</td>
<td>Part. Reflecting</td>
<td>8.6, 17.3</td>
<td>Per 1 only</td>
<td>---</td>
<td>0.4–1.0 GHz periodically</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Bent-Pipe</td>
<td>3.0, 3.5, 3.9, 4.1, 4.4, 5.5, 7.0</td>
<td>Per 1 only</td>
<td>---</td>
<td>0.5-1.2 GHz</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>PD, Chaos*</td>
<td>~16 dBm</td>
<td></td>
</tr>
<tr>
<td>NTE588</td>
<td>35</td>
<td>116</td>
<td>Part. Reflecting</td>
<td>8.6, 17.3</td>
<td>Per 1 only</td>
<td>---</td>
<td>0.02 - 1.2 GHz</td>
</tr>
<tr>
<td>MV209</td>
<td>30</td>
<td>66.6</td>
<td>Part. Reflecting</td>
<td>8.6, 17.3</td>
<td>Per 1 only</td>
<td>---</td>
<td>0.02 - 1.2 GHz</td>
</tr>
<tr>
<td>5082-2835</td>
<td>&lt;15</td>
<td>0.7</td>
<td>Part. Reflecting</td>
<td>8.6, 17.3</td>
<td>Per 1 only</td>
<td>---</td>
<td>0.02 - 1.2 GHz</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Bent-Pipe</td>
<td>3.0, 3.5, 3.9, 4.1, 4.4, 5.5, 7.0</td>
<td>Per 1 only</td>
<td>---</td>
<td></td>
</tr>
<tr>
<td>5082-3081</td>
<td>100</td>
<td>2.0</td>
<td>Part. Reflecting</td>
<td>8.6, 17.3</td>
<td>Per 1 only</td>
<td>---</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Bent-Pipe</td>
<td>3.0, 3.5, 3.9, 4.1, 4.4, 5.5, 7.0</td>
<td>Per 1 only</td>
<td>---</td>
<td></td>
</tr>
</tbody>
</table>

*Highest Frequency Chaos @ 1.1 GHz

*With dc bias.