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# Susceptibility of Circuits and Systems to HPM Pulses

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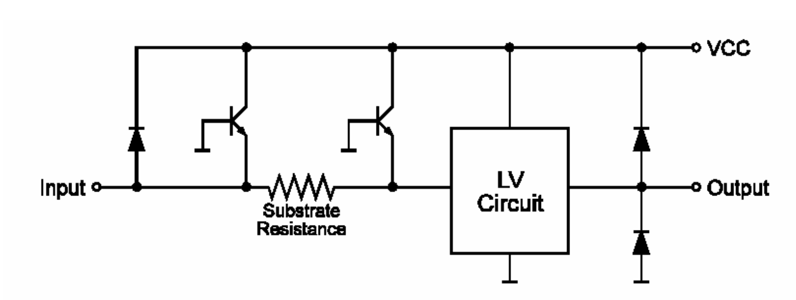
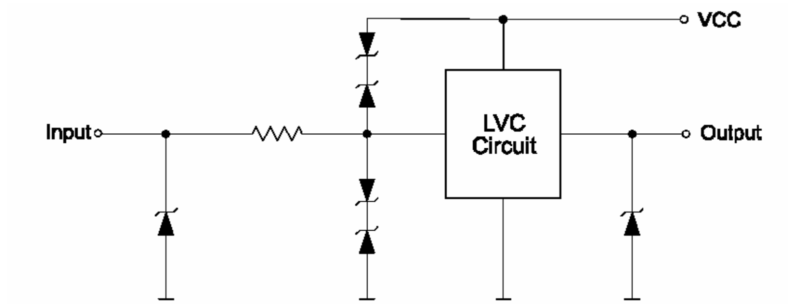
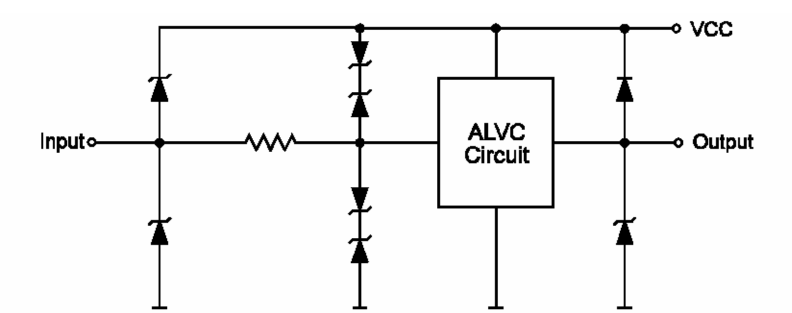
# Outline

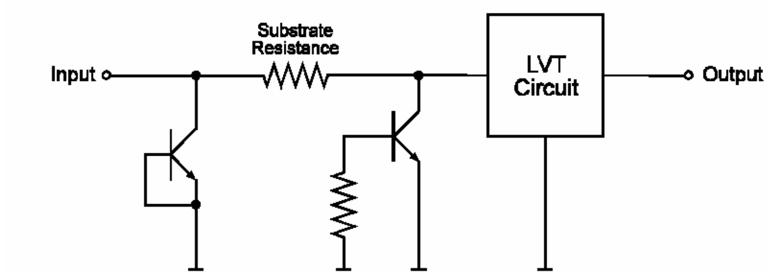
- Review of previous results
  - RF Rectification by electrostatic discharge (ESD) protection diodes
  - Effects in logic, discrete and analog circuits
- Systems susceptibility
  - Resonant circuits within resonant cavities
  - RF fields in complicated structures
  - DC feedback controllers: An “Achilles Heel” in electronic systems
- Wideband sources

# Examples of ESD protection in integrated circuits



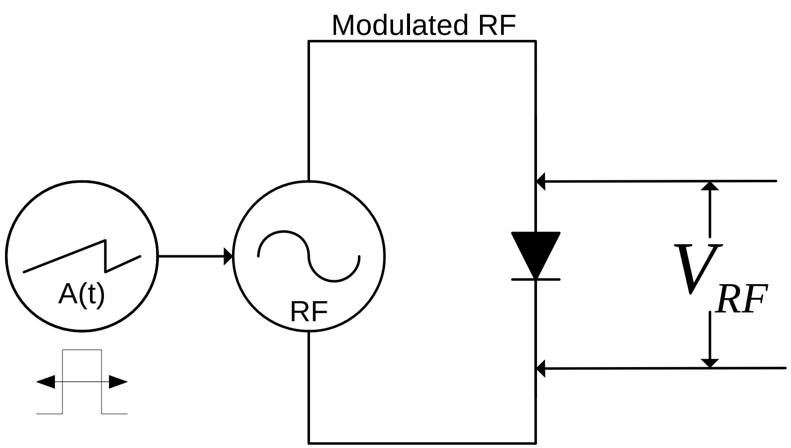



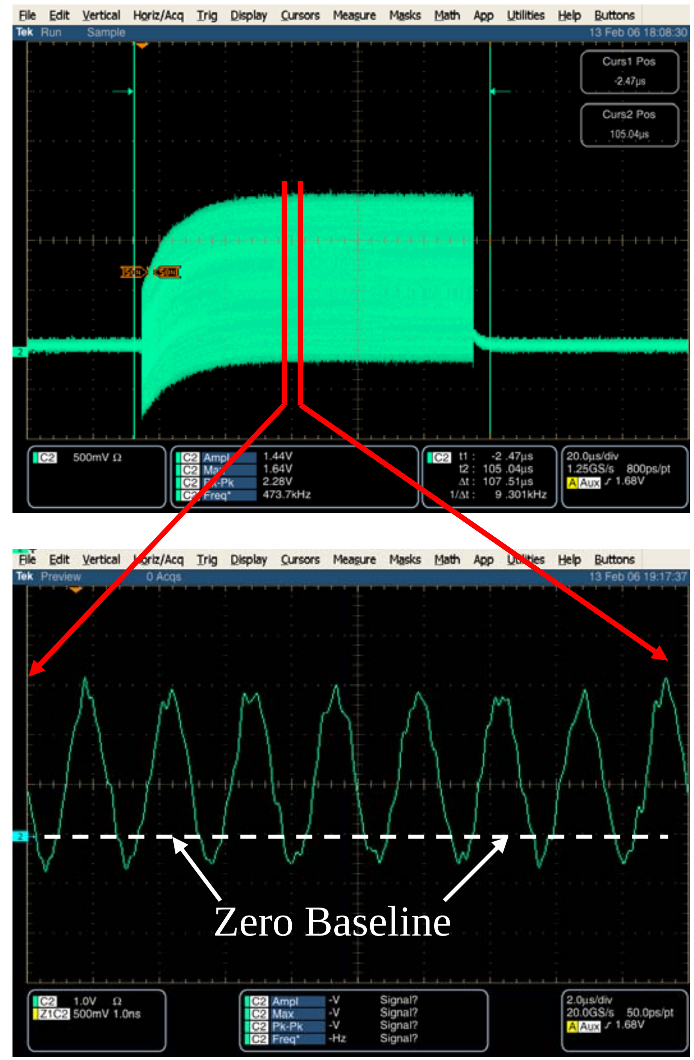




Electrostatic discharge protection devices are integrated into nearly all chips: discrete, logic, analog, RFIC, mixed signal

# Waveforms of the RF Voltage Across a Typical ESD Diode Excited with a Pulsed 850 MHz Carrier

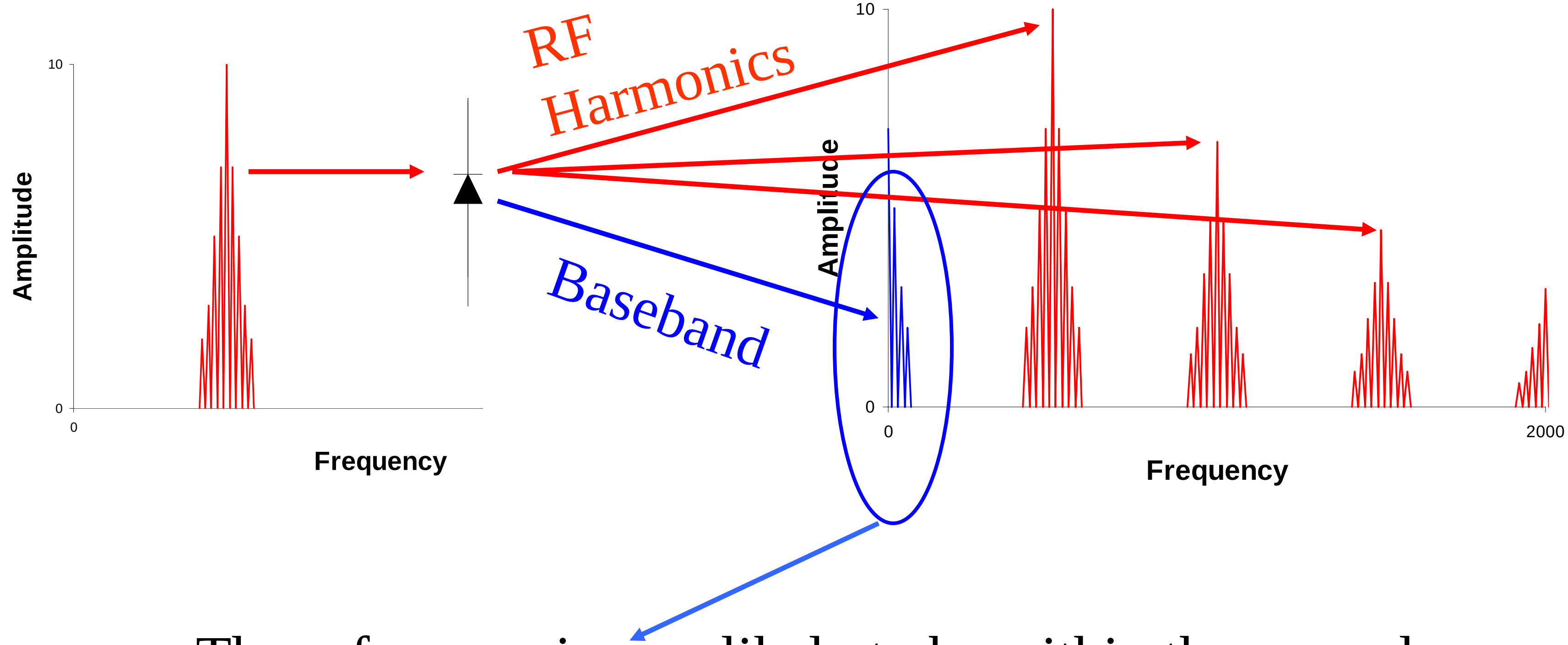



Expanded view showing actual RF cycles.

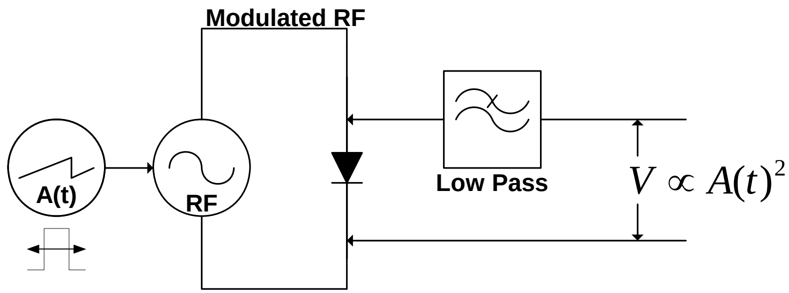
The 20 Gs/sec sample rate was not high enough to capture the very high odd harmonics in the waveform which are necessary to reproduce clipping as the diode forward conducts.

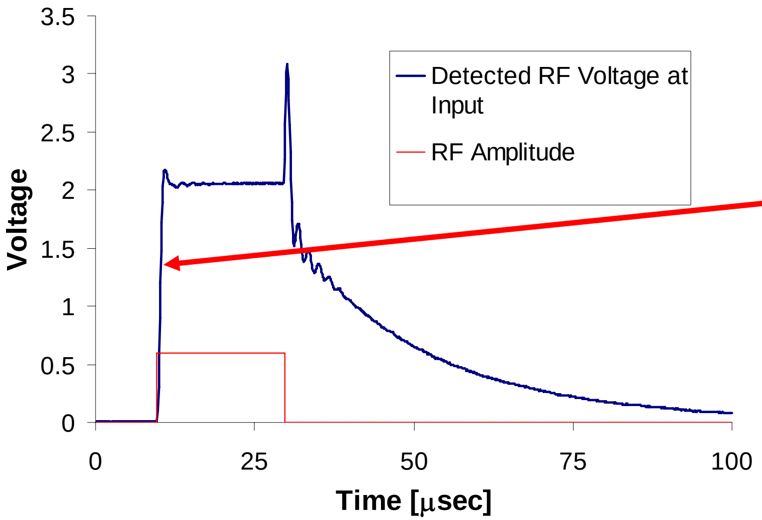
# The ESD down-converts the modulation frequencies off the microwave carrier and behaves like an RF detector




These frequencies are likely to be within the normal operating range of the circuit.

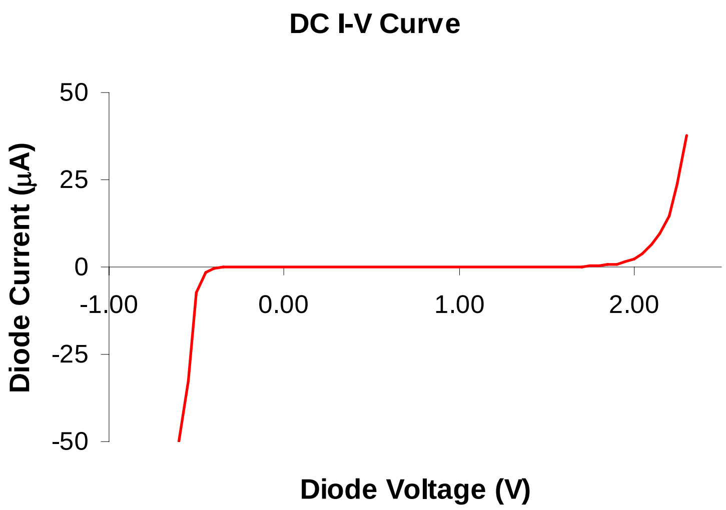
# Bandwidth limited voltage measured at the input of a CMOS circuit when excited by a microwave pulse (Frequency = 1.4 GHz)




- Good dynamic characteristics indicated by sharp rise and short delay.
- The transient response in RF detector diodes is described by the junction capacitance and a "video" resistance.

# Small-signal analysis of ESD diodes as "square law" RF detectors




$$V_d = Z_L I_d(V) =$$

$$V_0 + Z_L \sum_{n=0}^{\infty} \frac{v_{rf}^{n+1}}{(n+1)!} \frac{d^n G_d}{dV^n}$$

$$v_{det} = \frac{I_s}{4V_t^2} \frac{R_L R_V}{R_L + R_V} v_{RF}^2$$

Basic High-Frequency Diode Parameters

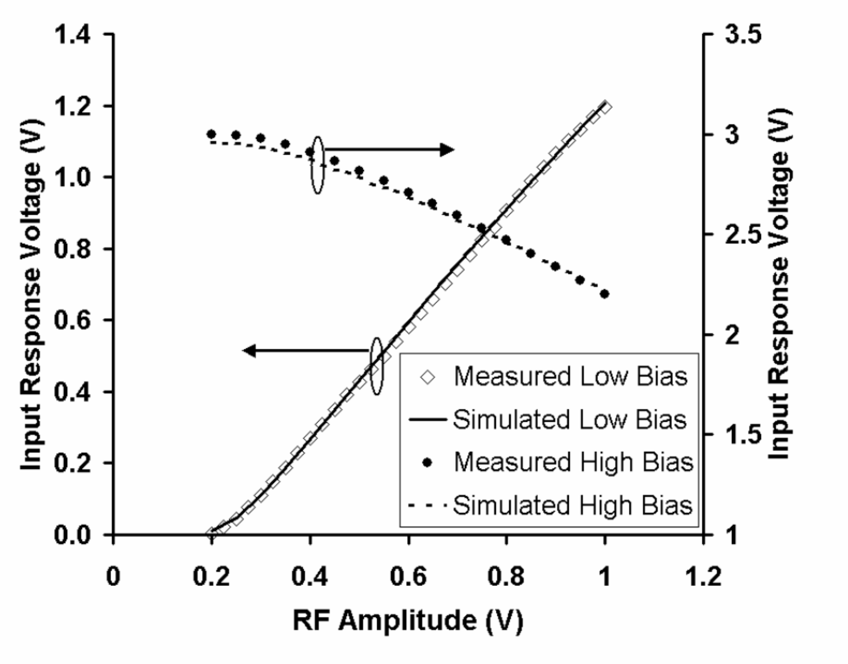
Where:

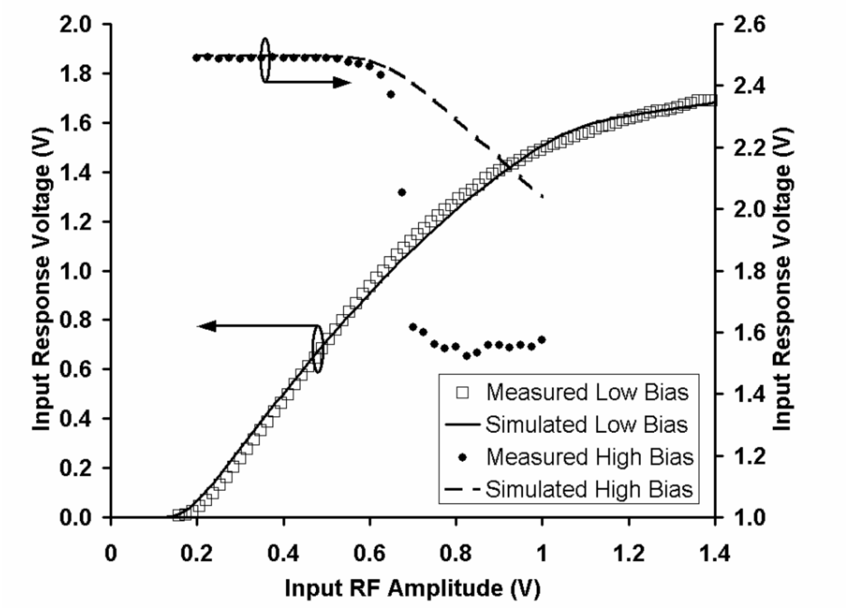
$G_d = \partial I / \partial V$ is the diode conductance

$R_V = V_T / I_S = 1 / G_d$ is the video resistance

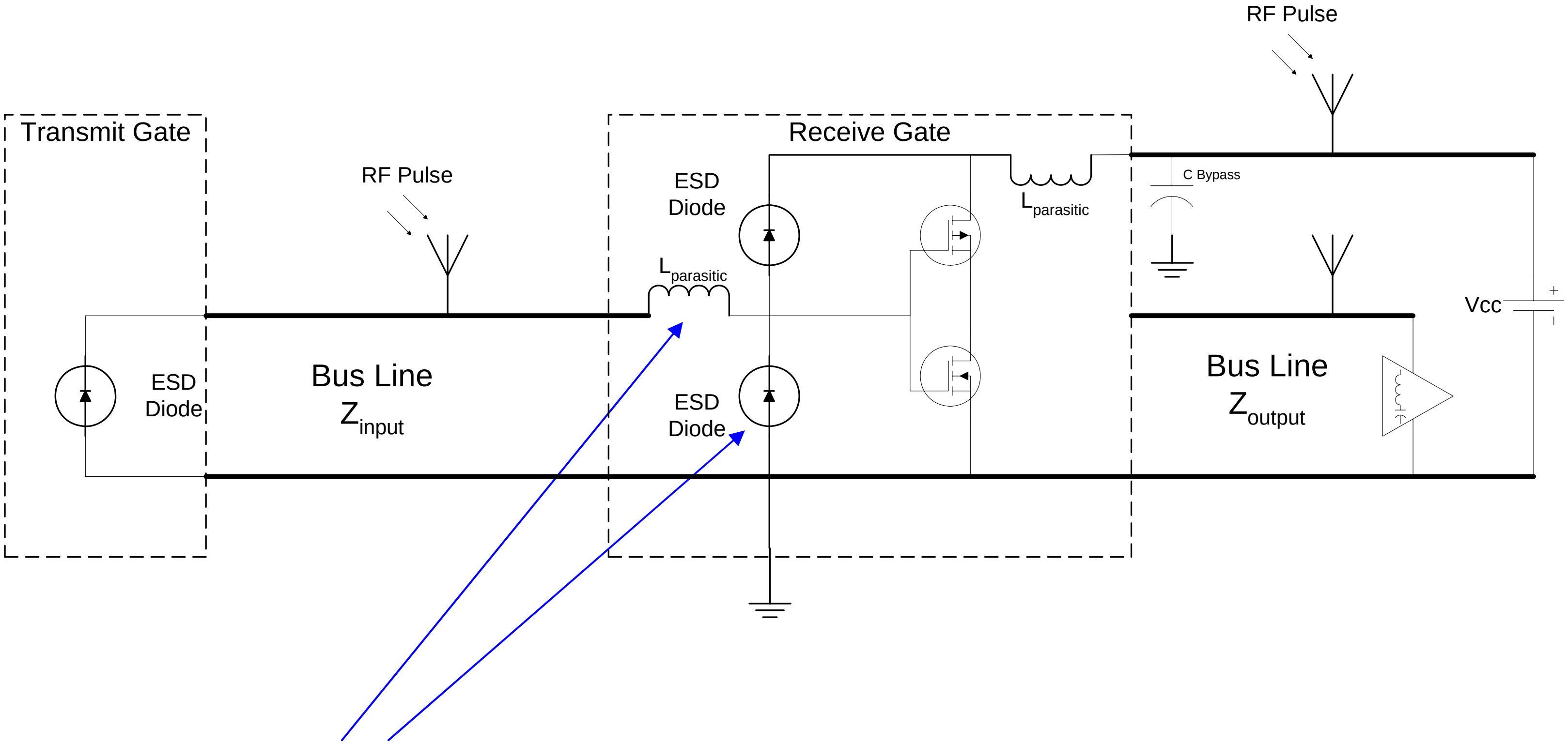
$V_T = kT / e$ is the thermal voltage

# Comparison of measured and simulated ESD diode response to RF Pulses



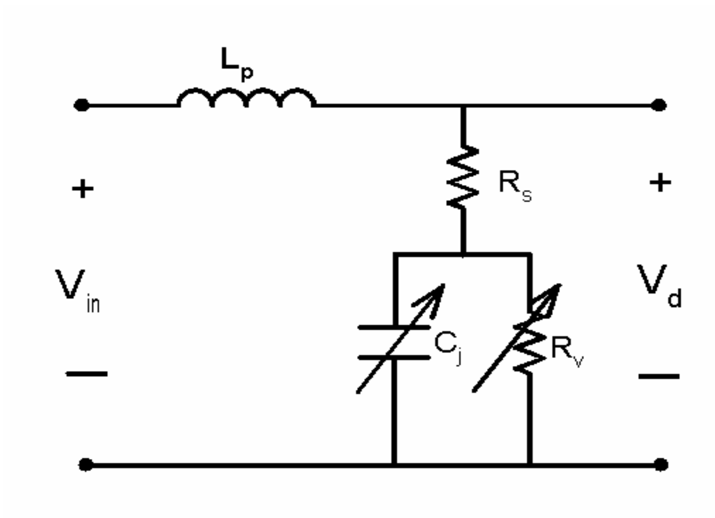



# Simplified Schematic of a CMOS Circuit




LC parasitic elements form resonant circuits

# Resonance at microwave frequencies in the series RLC circuit formed by the parasitic inductance and ESD junction capacitance




$$A_V = \frac{V_d}{V_{in}} = \frac{1 + sC_jR_S}{1 + s^2L_PC_j + sC_jR_S}$$

$$A_V(\omega_R) = 1 - j\sqrt{L_P / C_j(V_D)} / R_S$$

$$Q = \sqrt{L_p / C_j(V_D)} / R_s$$

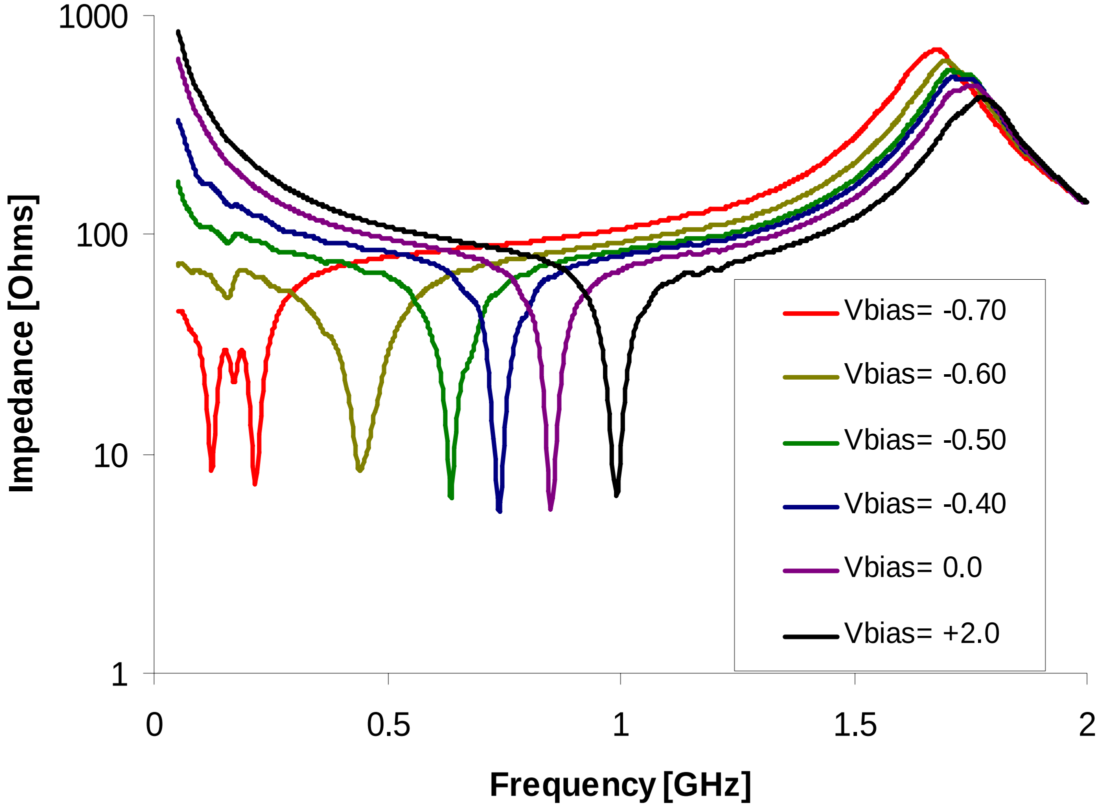
Typical values:

$$C_{j0} \simeq 3\,pF$$
$$L_P \simeq 10\,nH$$
$$R_V \simeq 1\,M\Omega$$
$$R_S \simeq 10\,\Omega$$

Give:

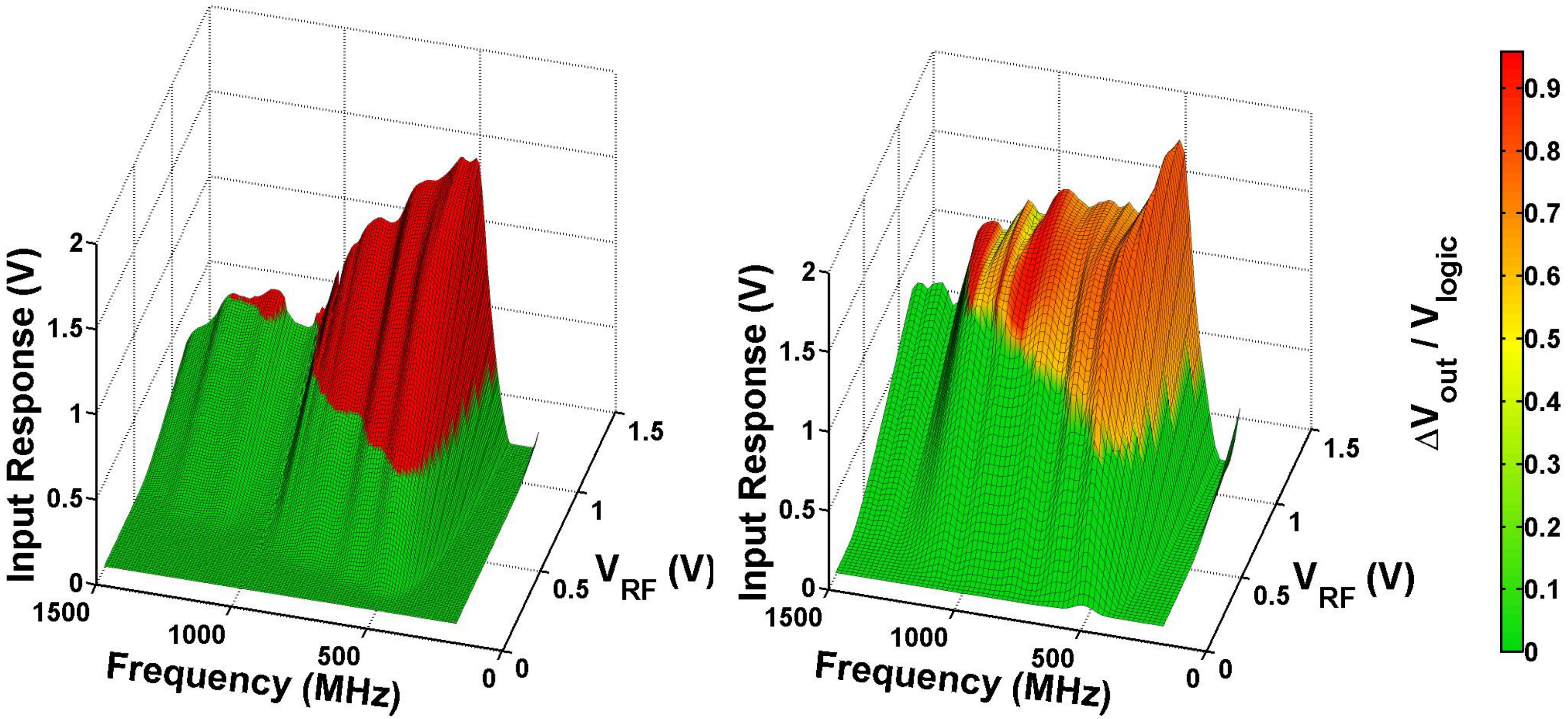
$$0.5 < f_R < 3\,GHz$$
$$2 < Q < 6$$
$$1.5 < |A_V| < 6$$

# Impedance (small-signal) at the Input of a CMOS w/ ESD Protection at Microwave Frequencies




•When driven at resonance, the diode current and the rectified voltage increase.

# Contours of measured large-signal response in advanced CMOS

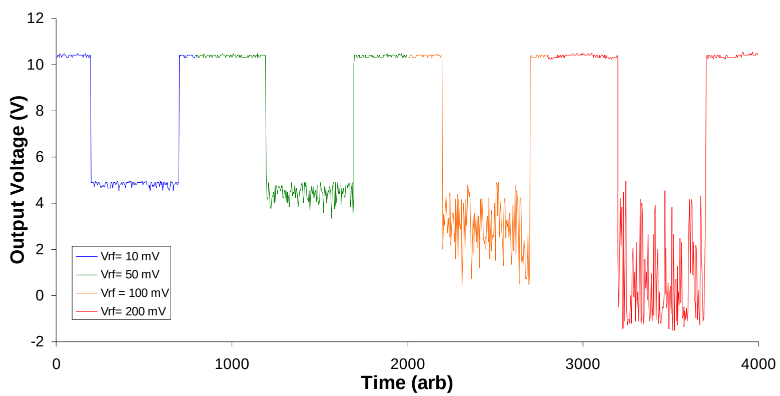


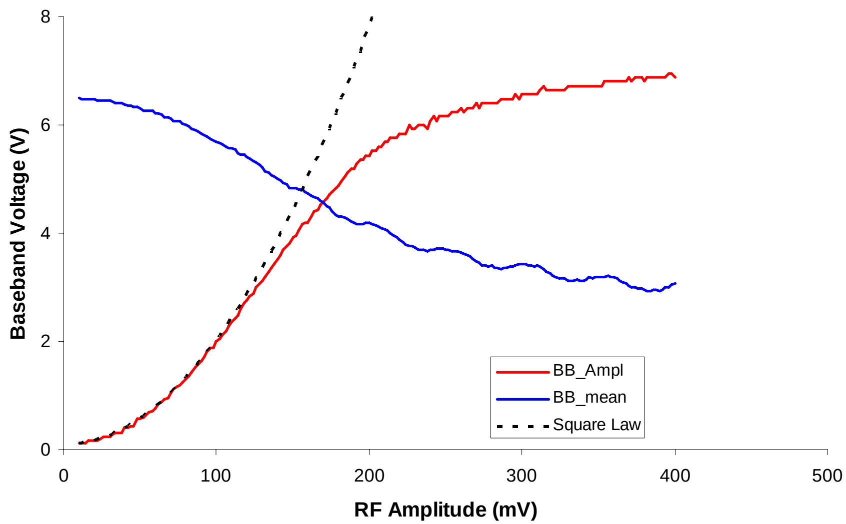

HCT

ALVC

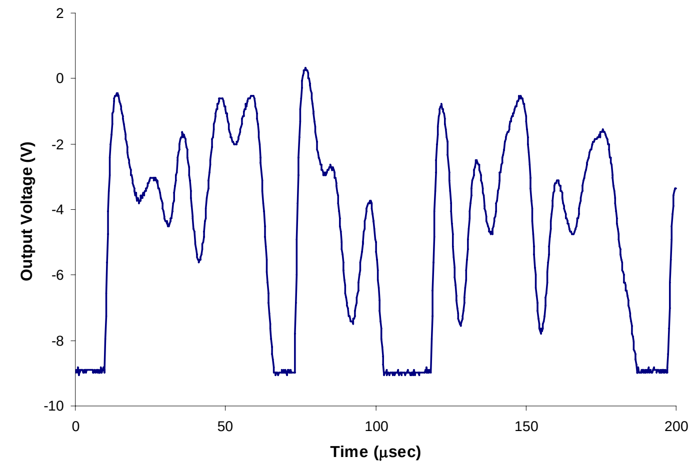
# This behavior has been observed and studied in a wide variety of circuits.

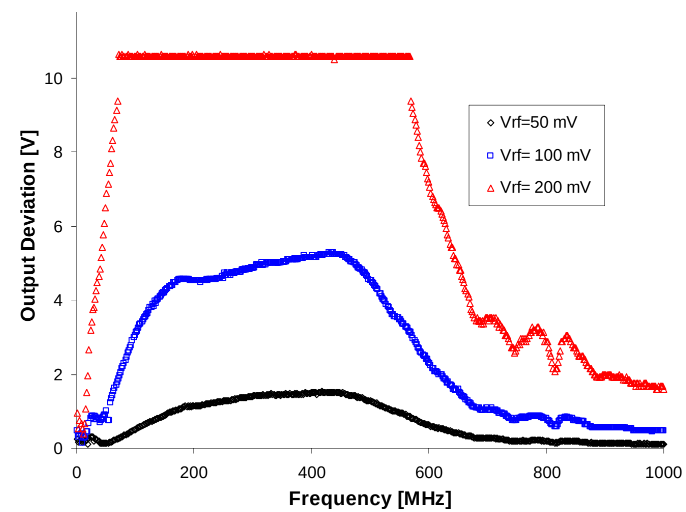
## Discrete (JFET)



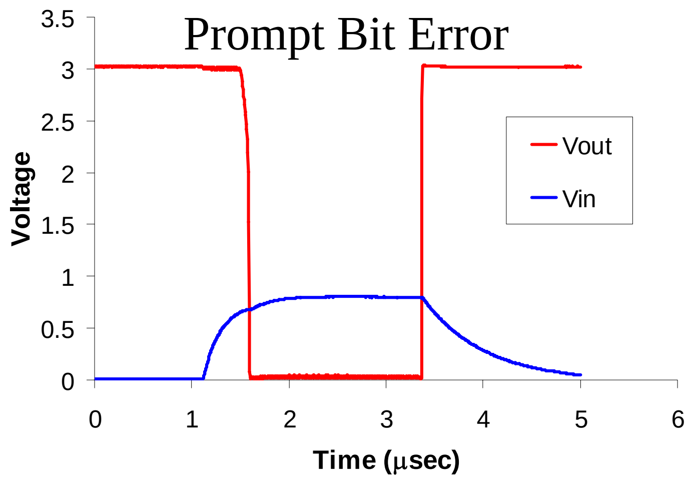



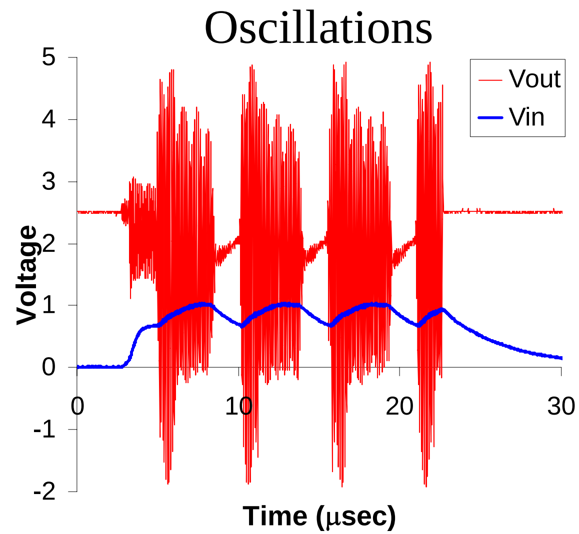

## Analog (Op Amp)

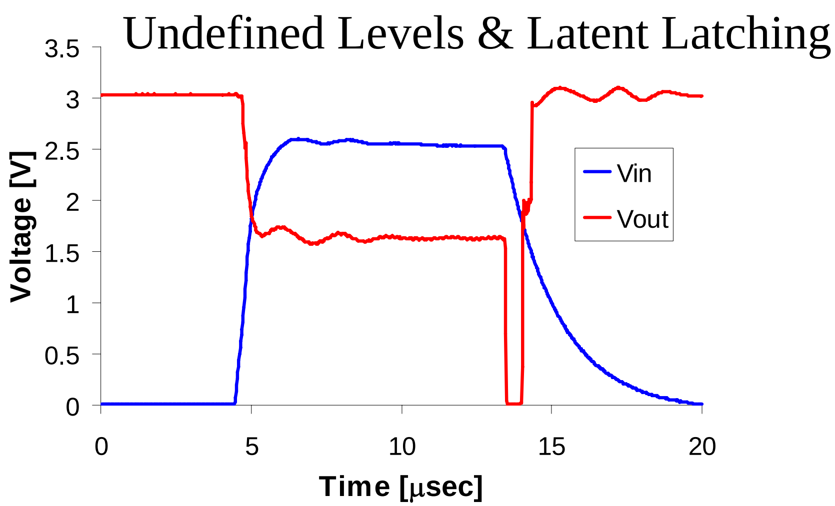


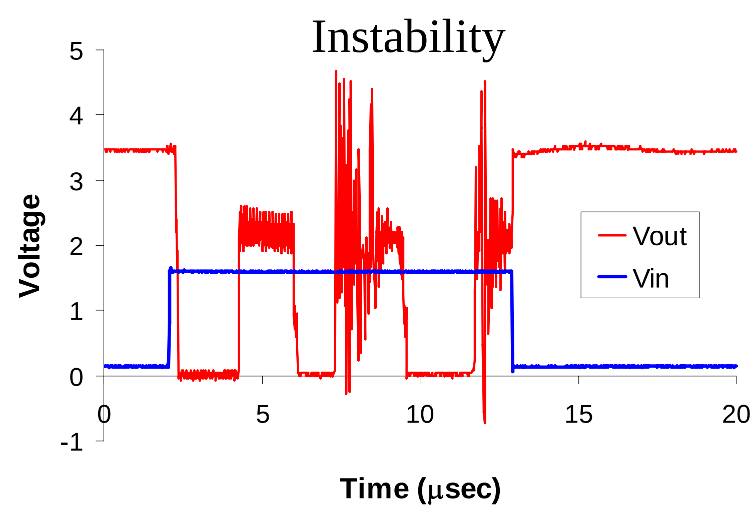



# Effects in Advanced CMOS when Driven Near Resonance



# Distribution of parasitic resonant frequencies and quality factors in a digital communications system

View of the IC layout on the motherboard of a programmable LAN switch

**I/O**

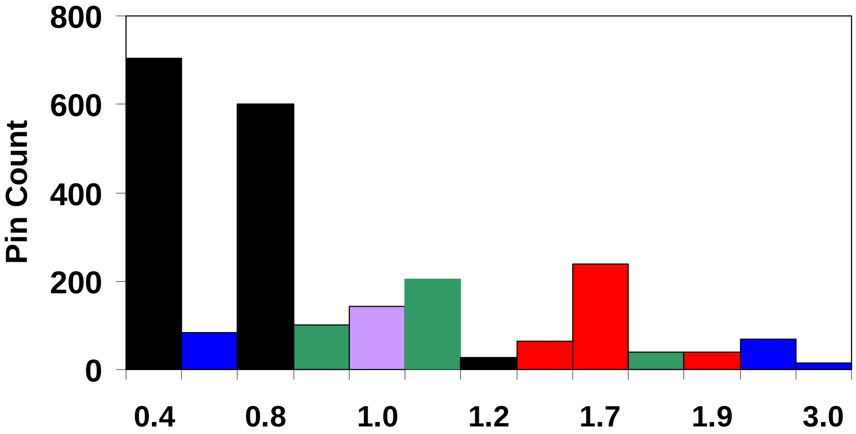
**Logic**

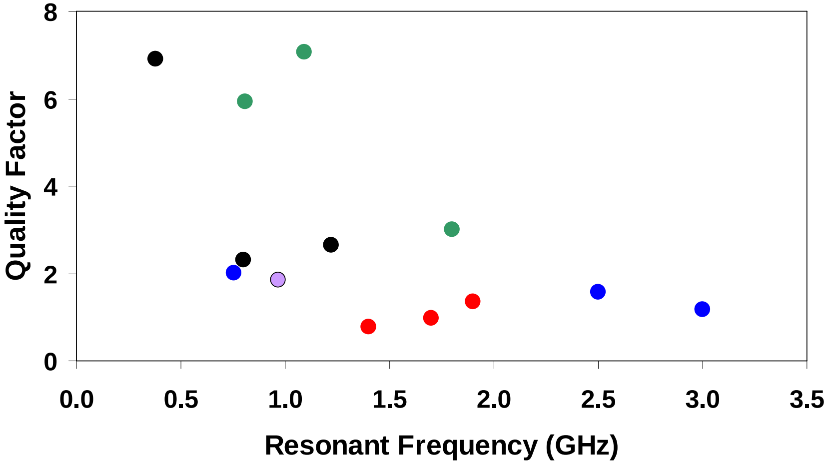
**System Controller**

**CPU**

**Memory**

Results from small-signal measurements of parasitic resonances in the IC's of a functional set



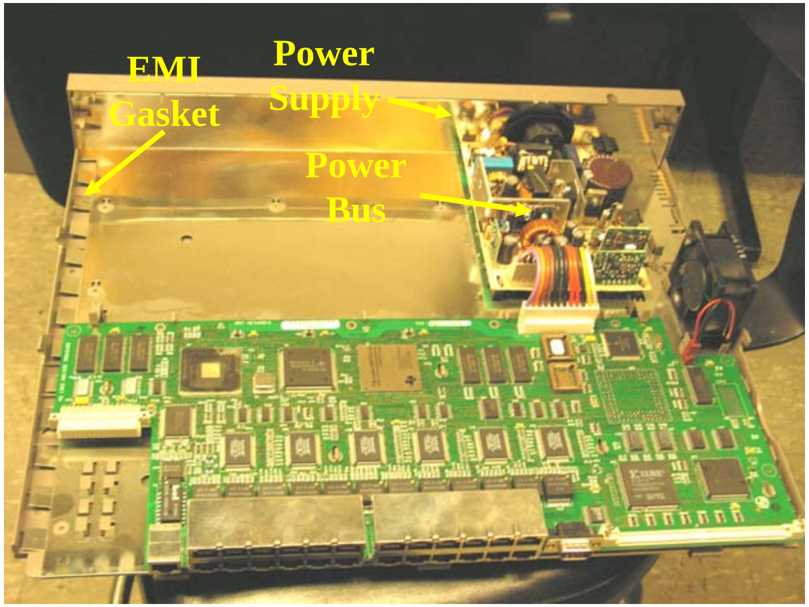



# Overview of studies of HPM upset in electronic systems

•Systems consist of many circuits with internal resonances interconnected within cavities.

•What parts of the system are most likely to be upset once RF penetrates the enclosure?

View of the assembled LAN switch



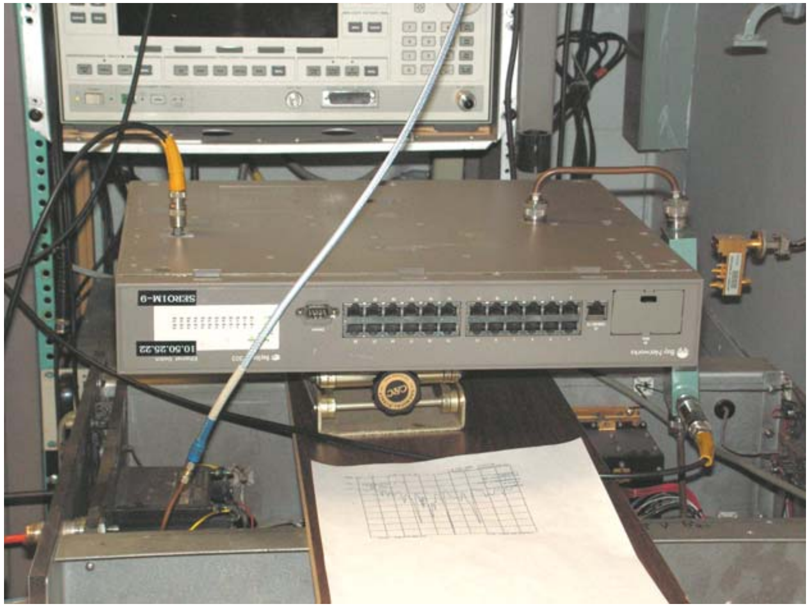

Chassis cover removed

# Characteristics of electronic systems

• Most electronic systems contain modular components that are packaged according to standardized form factors (4U, 19” bays, ATX, etc.)

•Does this present any universal conditions or likely avenues for HPM attack?

•The enclosures are clearly natural microwave resonators.

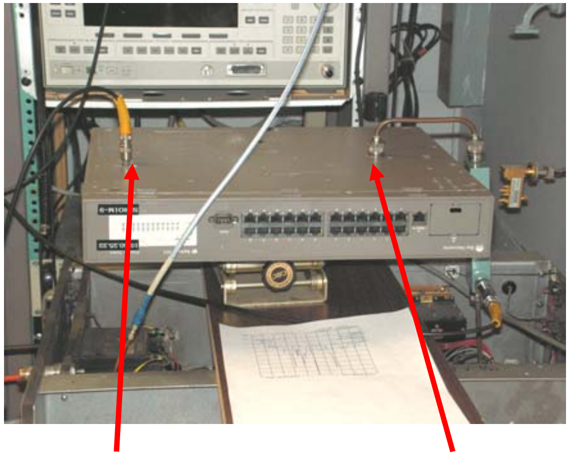


LAN switch with coaxial RF ports

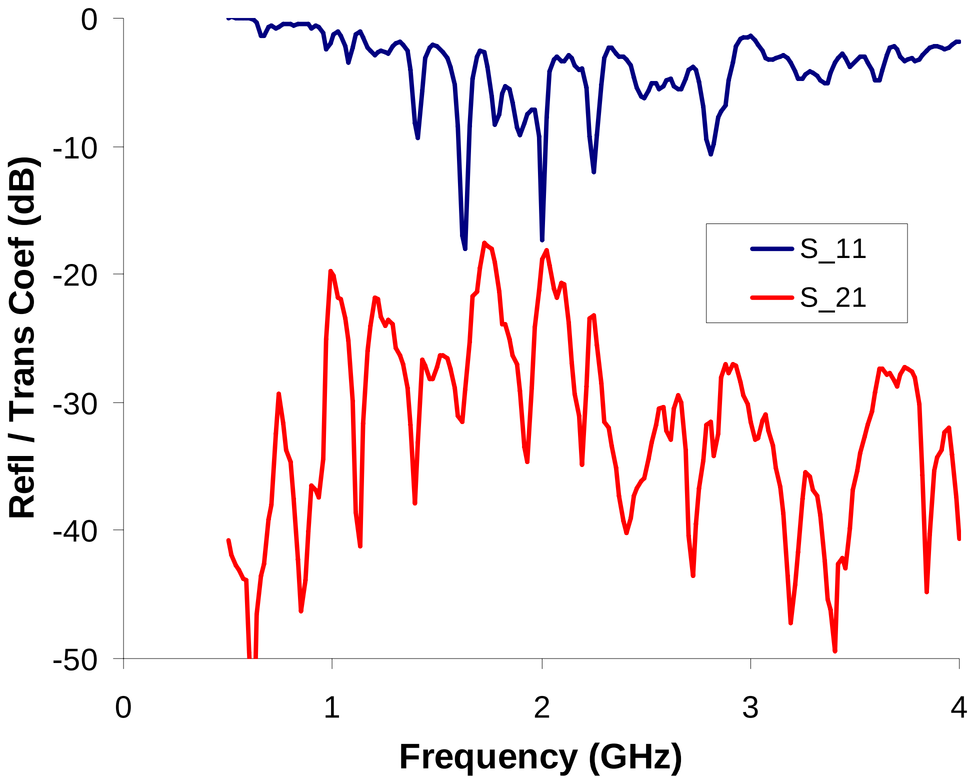

PC with waveguide port

# Results of S-parameter measurements in an operating LAN switch

- Port #1 is a dipole launching antenna and port #2 is connected to the main +12 VDC power bus on the motherboard



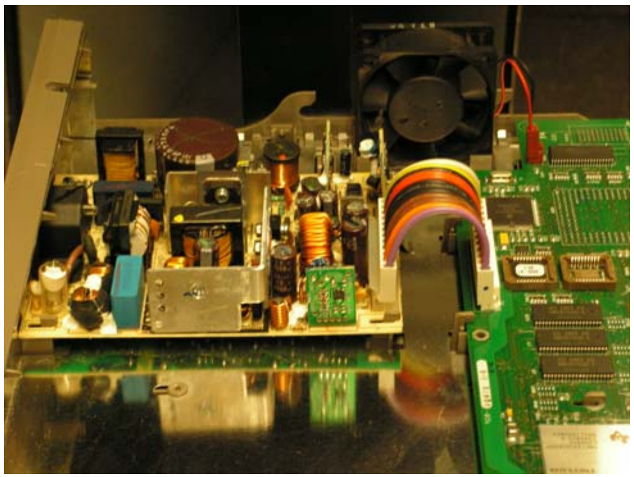
Port #2 Port #1

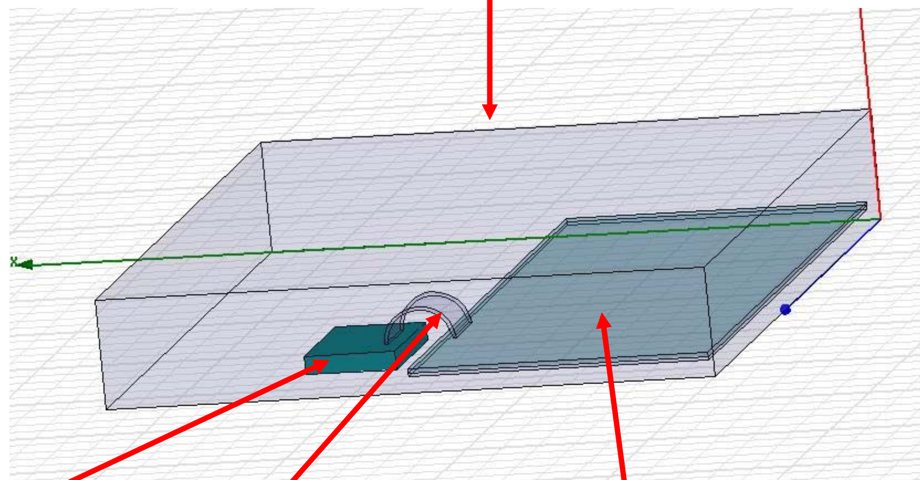



- Strong resonances are observed across L-band (~1-2 GHz)

# Simulation of resonances in LAN switch using HFSS eigenmode solver

EMI Enclosure





Lossy Block
(Power Supply)

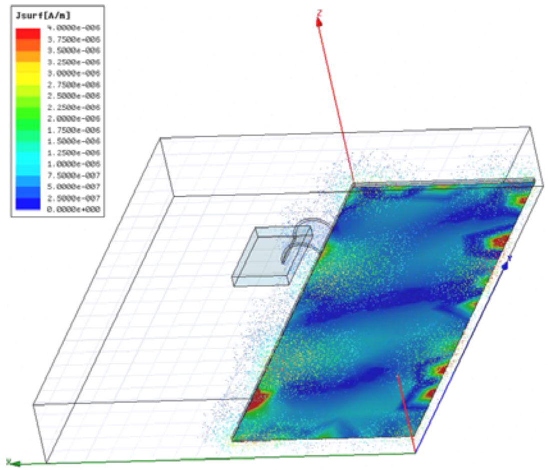
Power Cable

Epoxy board bottom-clad
w/ thin copper sheet
(ground Plane)

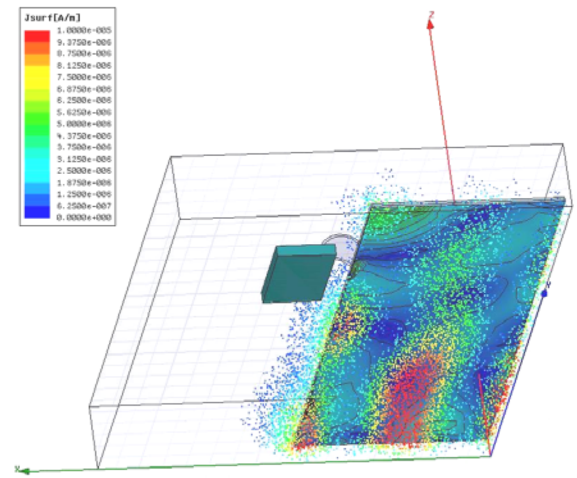
- Power cable is modeled as a copper half-cylinder with its edges in contact with the board and a lossy block.

- Typically, all power lines originate at DC filter capacitors which are lossy at microwave frequencies.

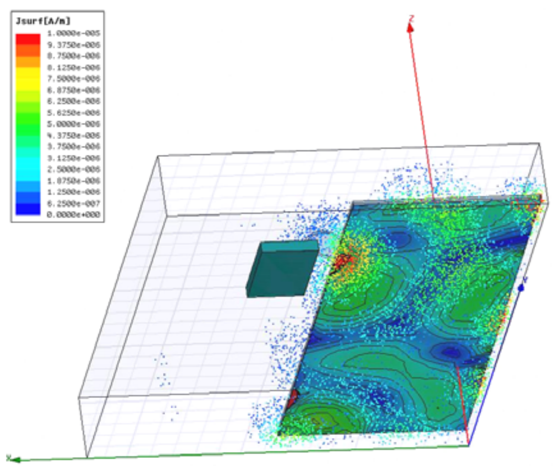
# Plots of RF Field Intensity and Surface Current Density for Various TEM Eigenmodes on the Board



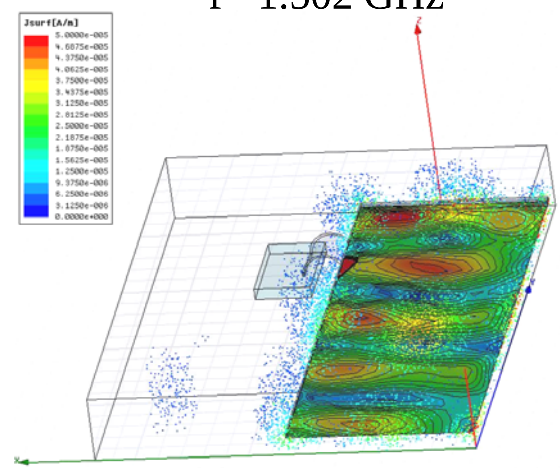
f= 1.284 GHz



f= 1.502 GHz

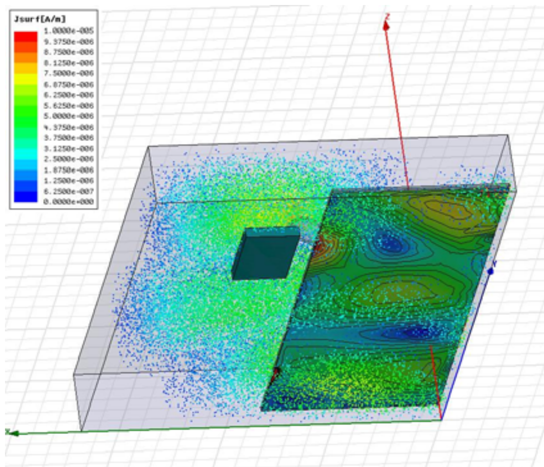


f= 1.591 GHz

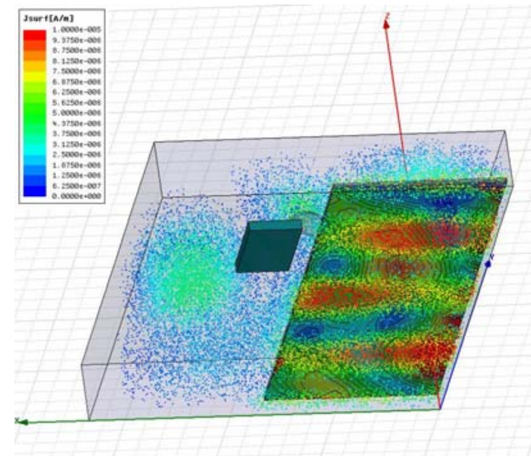


f= 1.654 GHz

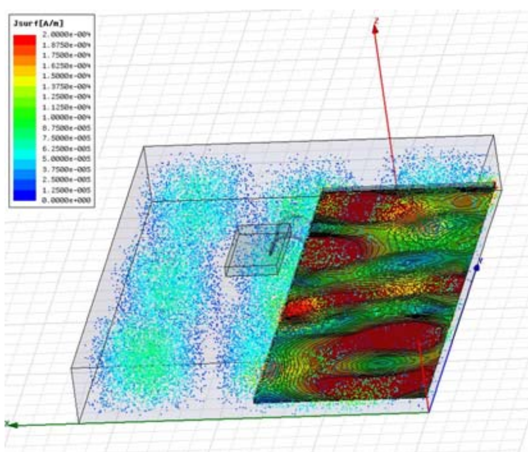
# Plots of RF Field Intensity and Surface Current Density for Various TE Eigenmodes on the Board



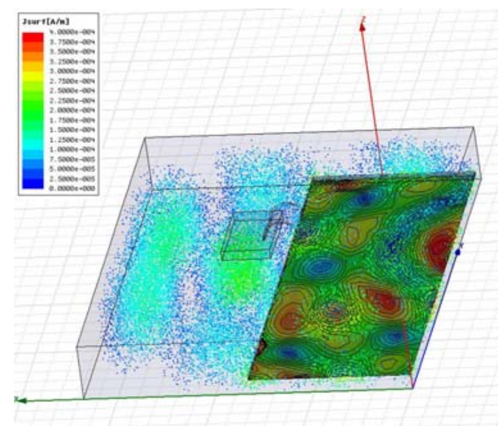
f= 1.117 GHz



f= 1.353 GHz



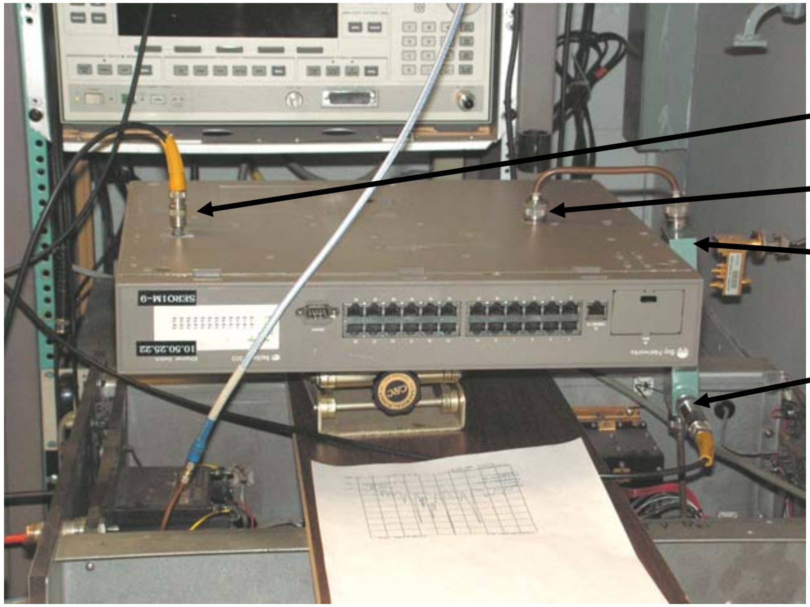
f= 1.678 GHz



f= 1.768 GHz

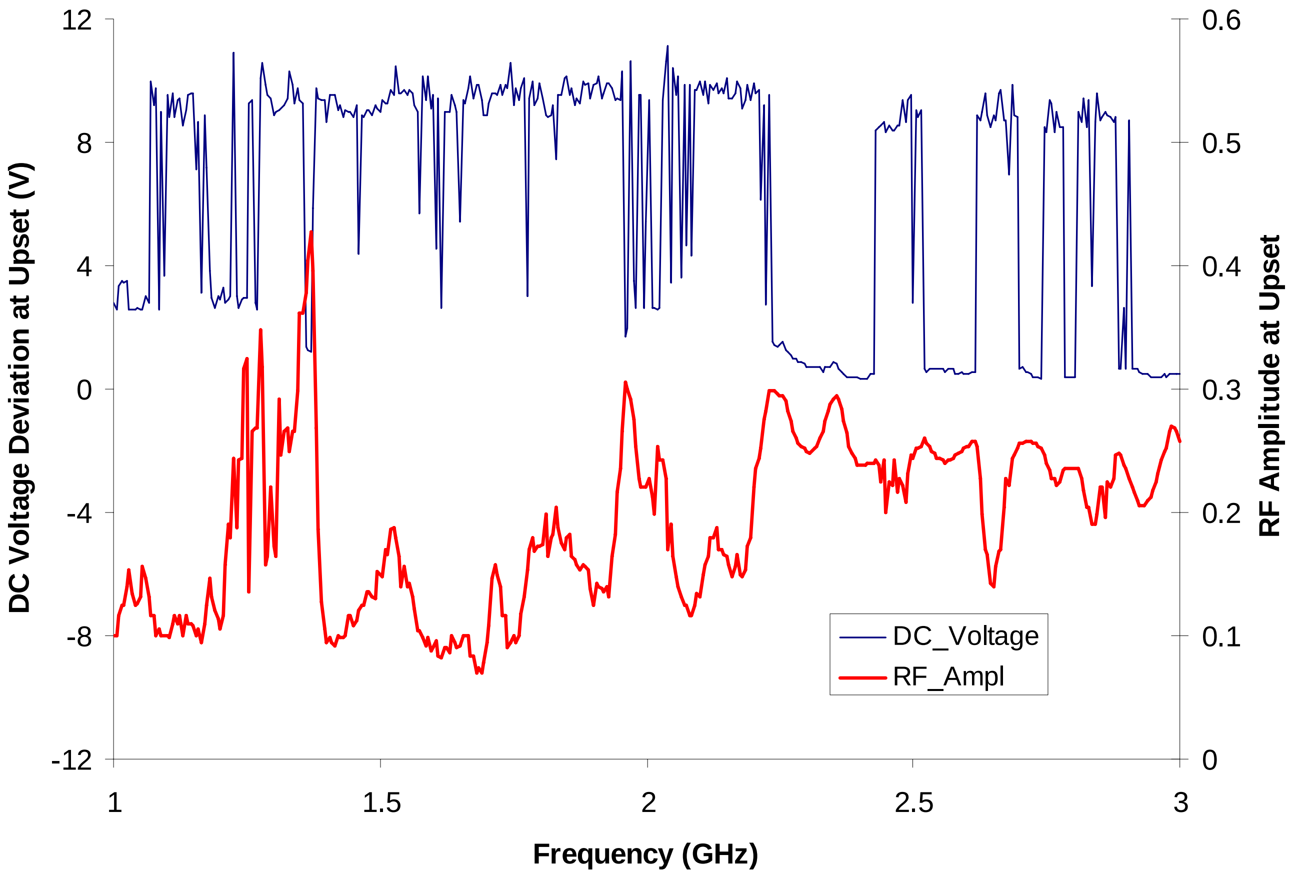
# Studies of Pulsed RF Upset in a Programmable LAN Switch

- RF was injected into Port #1 while the +12 VDC power bus was monitored at Port #2 in an operating LAN switch.
- For each frequency step from 1.0 to 3.0 GHz, the RF amplitude was increased until the system was upset.
- At upset, the deviation in DC voltage and the RF amplitudes were recorded.




LAN switch upset testing

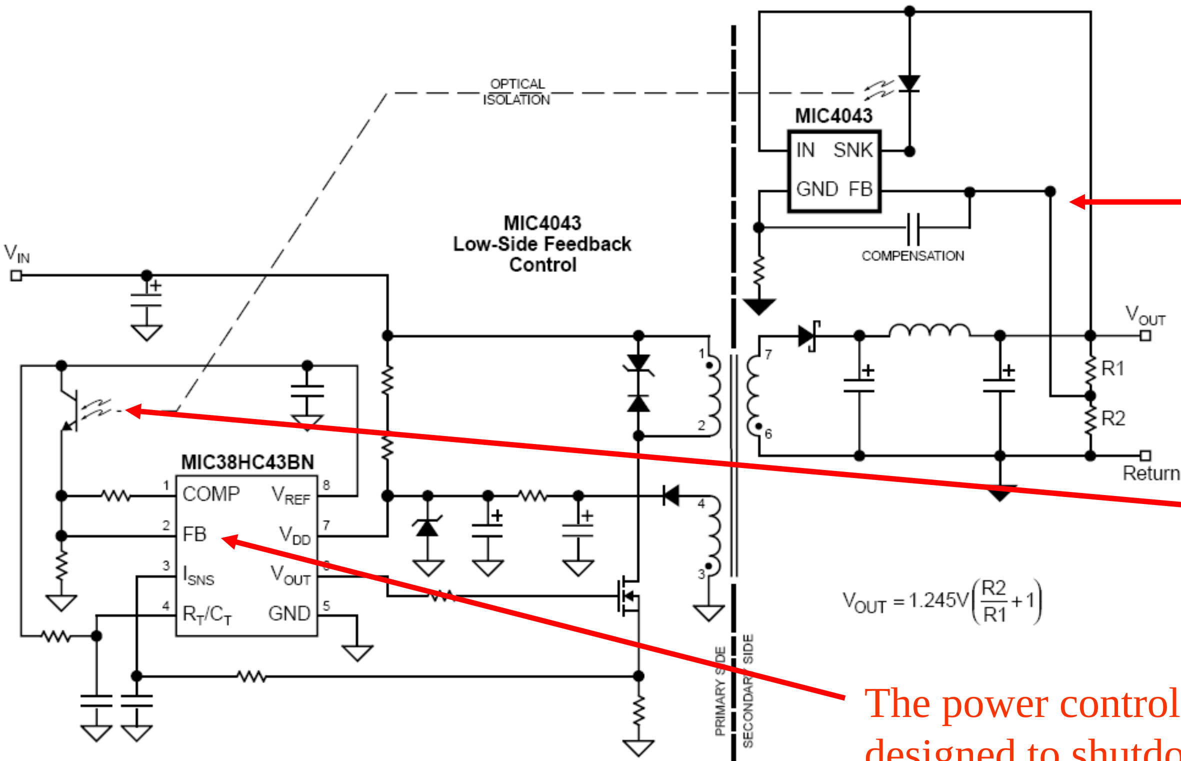
# Results from Upset Studies in a LAN Switch




- At upset, the RF caused the switching power supply to either completely shut down or output the incorrect voltage for times that were 100 – 1000 times the RF pulse width.

- This forced the microcontroller to completely reboot the system.

# Schematic of a typical switching power supply

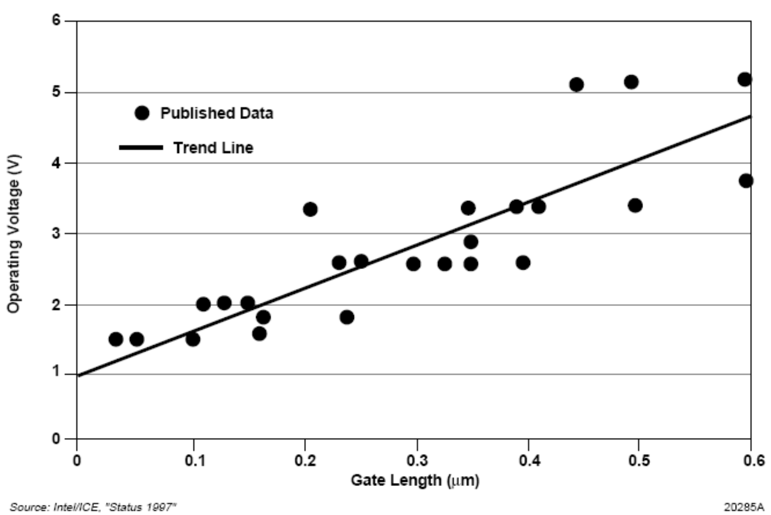



200kHz DC-DC Flyback Converter

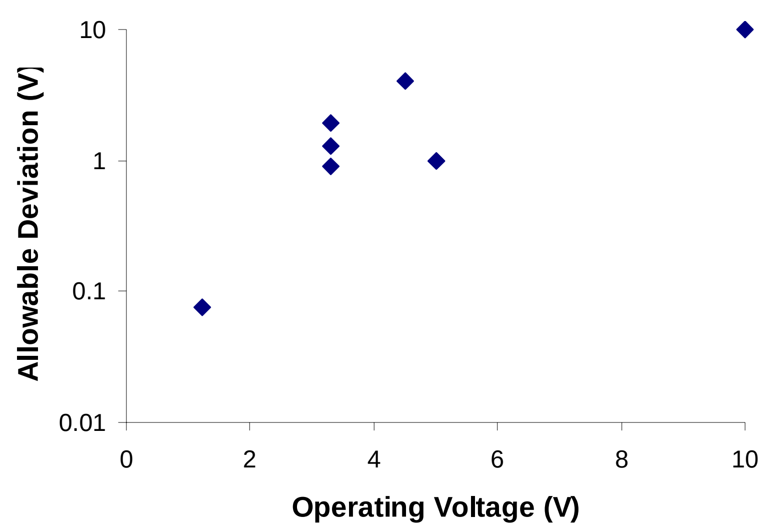
Rectified RF voltage at the feedback pin fools the comparator into detecting an over-voltage condition. It then sends a shutdown signal to the power controller via an opto-isolator

The power controller feedback is designed to shutdown the system (~ 30 sec) even if the "fault" is momentary (microseconds).

As IC technology has advanced, operating voltages have dramatically decreased and power regulation has become a critical issue creating a serious HPM vulnerability.




More advanced



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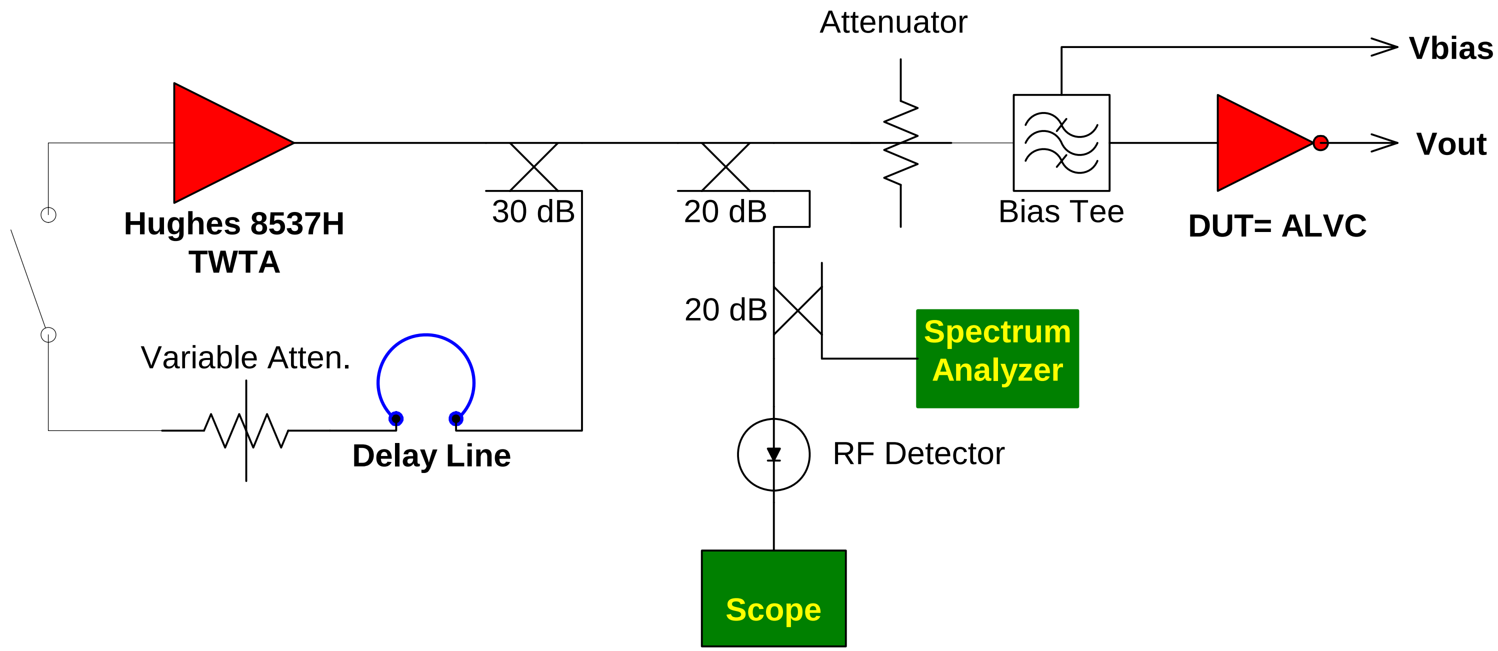
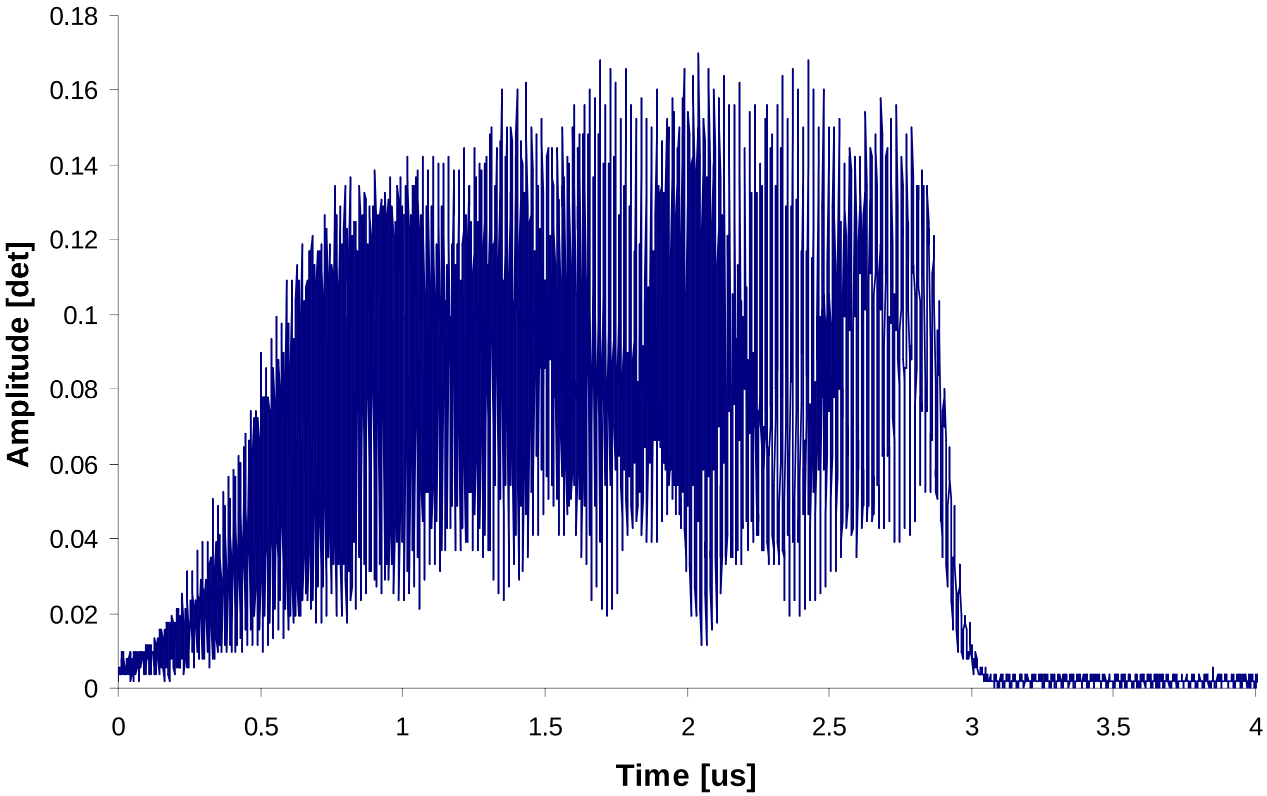
# Schematic of Chaotic Oscillator Circuit



# TWT Output Amplitude vs. Time



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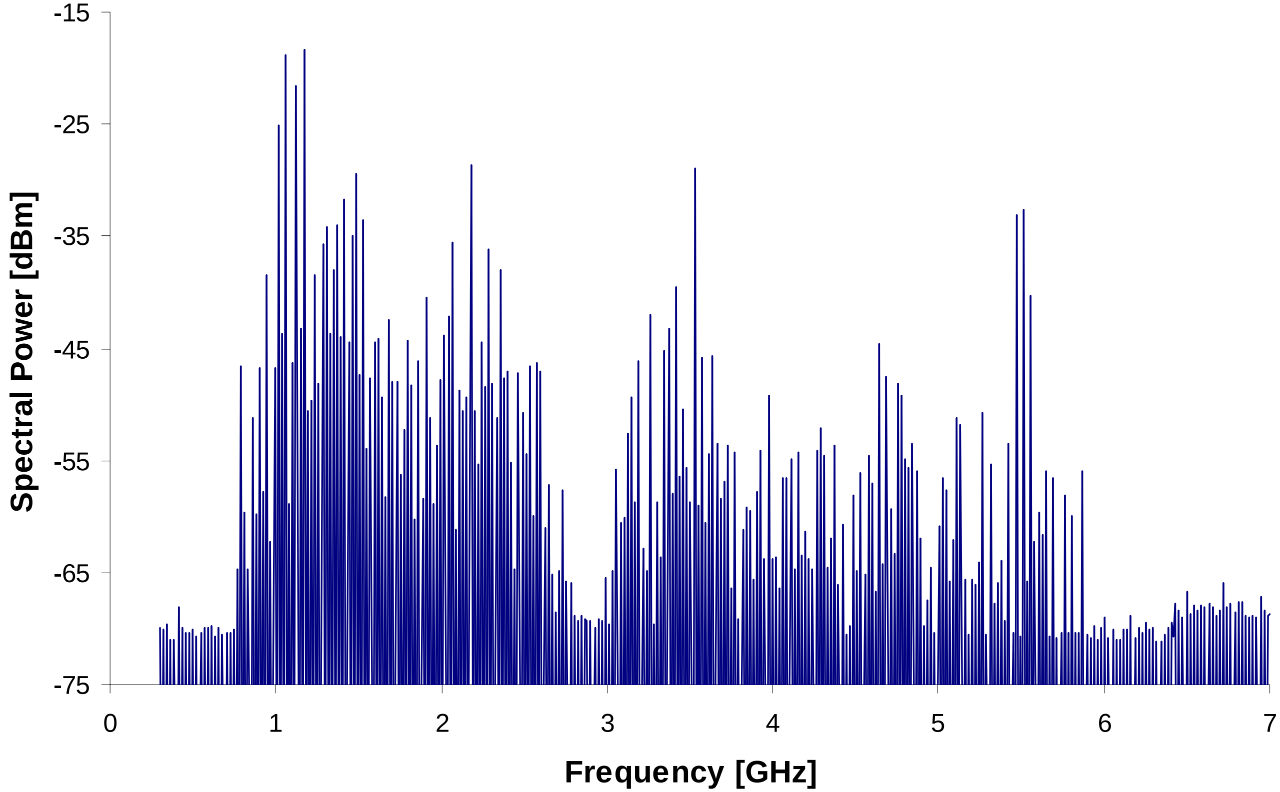
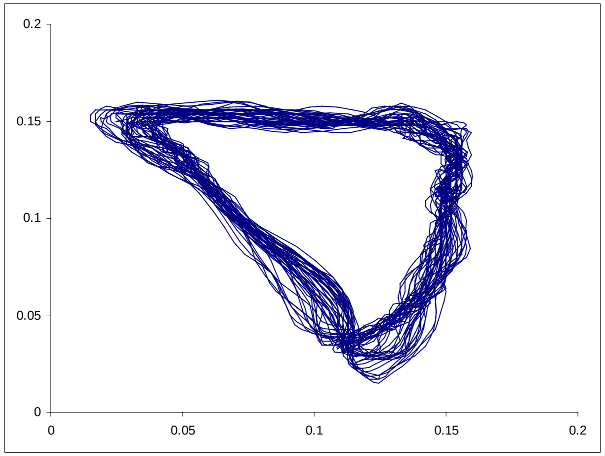
# Time-averaged Spectrum of Wideband Oscillations in TWT

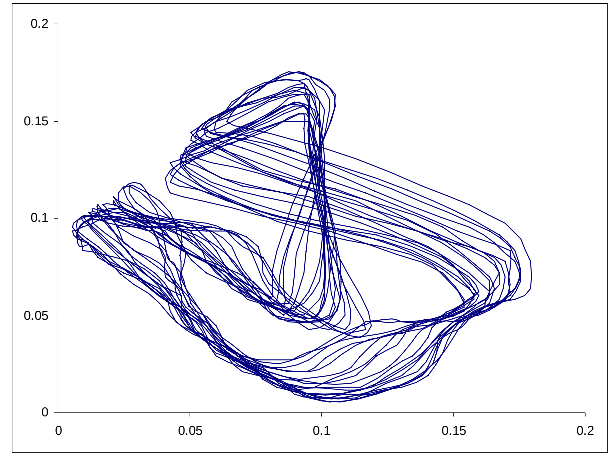


# Sequence of Attractor Maps of TWT Amplitude as Feedback Gain is Increased

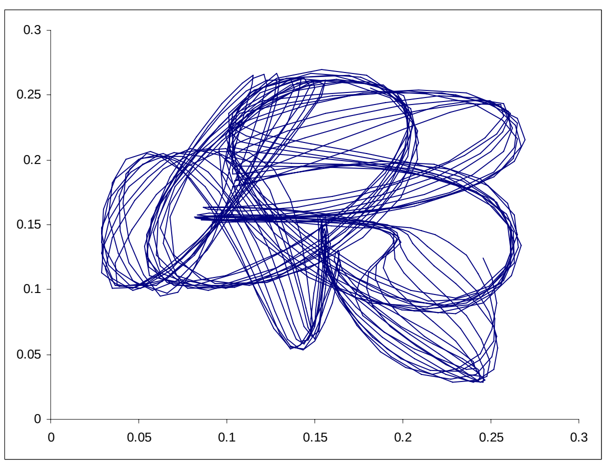
0.2 dB



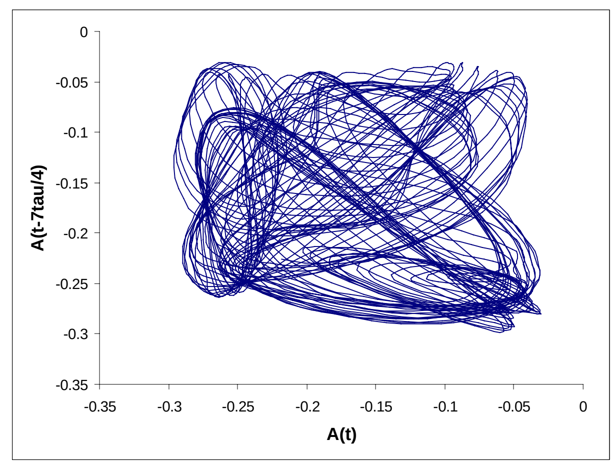

0.5 dB



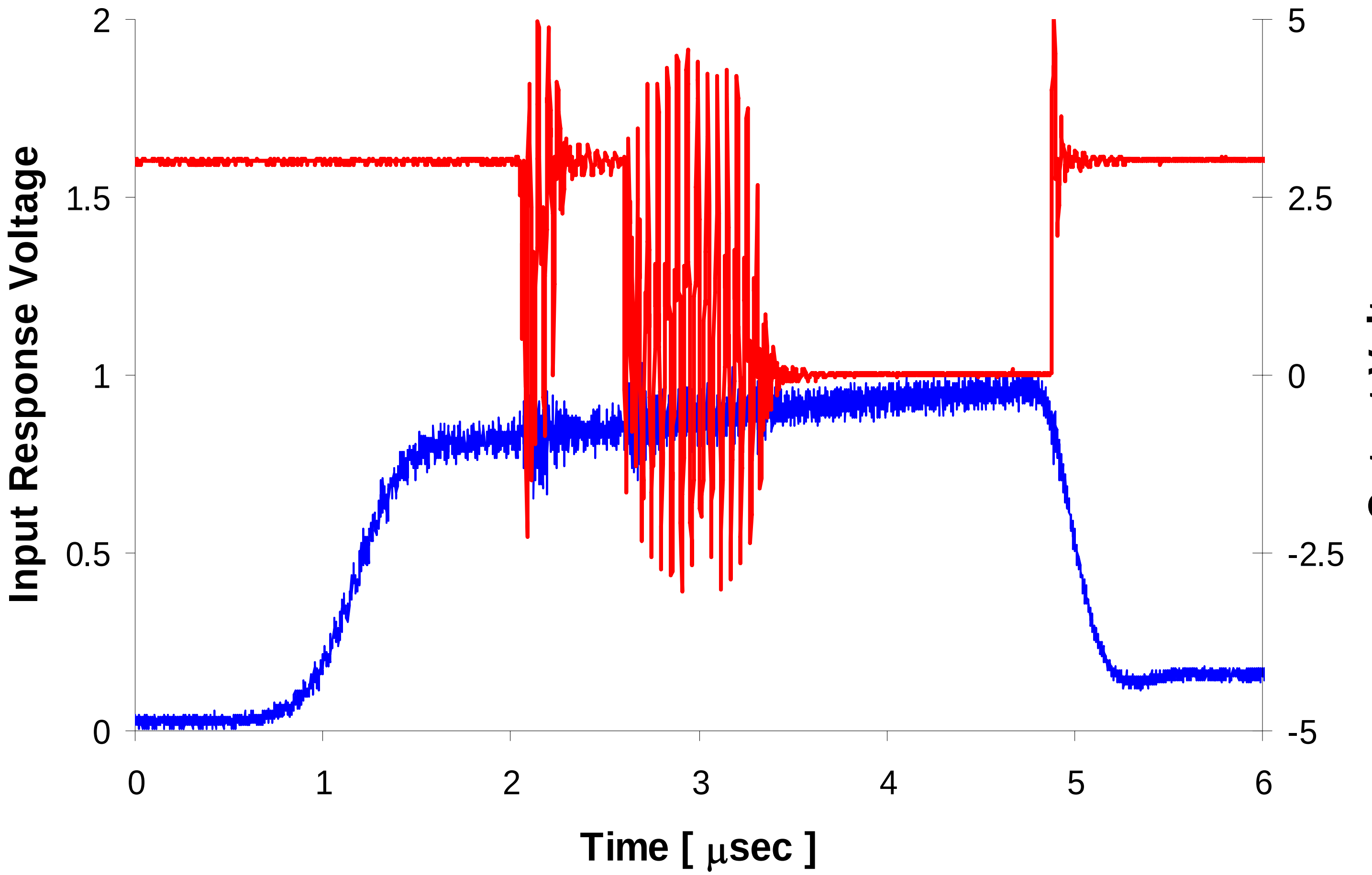

0.7 dB




2.0 dB



# Response of Advanced Low-Voltage CMOS to wideband RF source (RF amplitude = 450 mV)



# Conclusions

- RF rectification by ESD protection diodes and parasitic resonances have been identified as major susceptibility issues.
- The RF characteristics of these devices can be accurately described using lumped-element circuit models with simple high-frequency diode parameters.
- Upset can be easily predicted in terms of the high-frequency transfer characteristics of the circuit and the RF voltage, frequency and modulation at the circuit terminals.
- In systems, the problem requires an EM or RCM treatment.
- Power controllers with feedback have been identified as a major and universal problem.
- An informed basis for developing effects sources:
  - L-band
  - Wideband or chaotic modulation
  - 10-100 MW Power levels