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IREAP

Chaotic microwave systems based on traveling-wave tube (TWT) amplifiers

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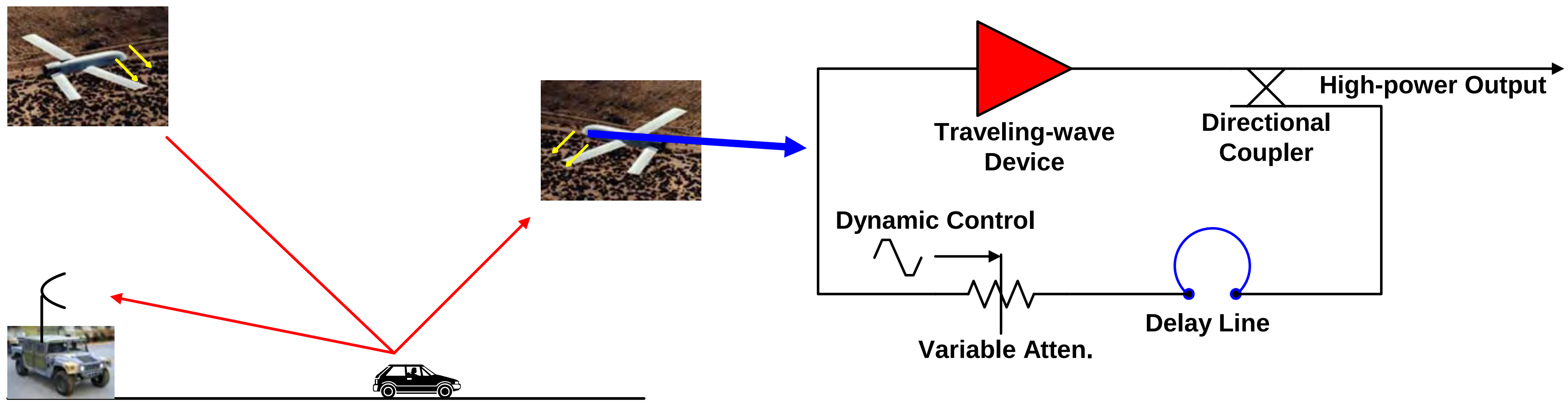
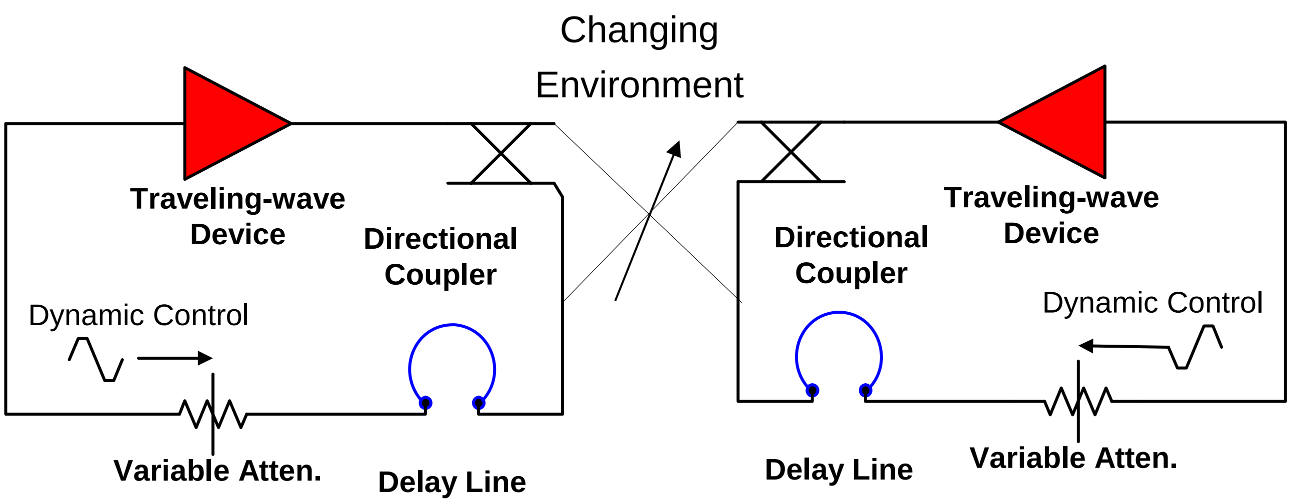
Concept: Networks of coupled chaotic time-delayed oscillators (TDO)



•The radiation scattered off objects will couple in varying strengths to the various nodes of the network and modulate its dynamics.

Basic Research Questions

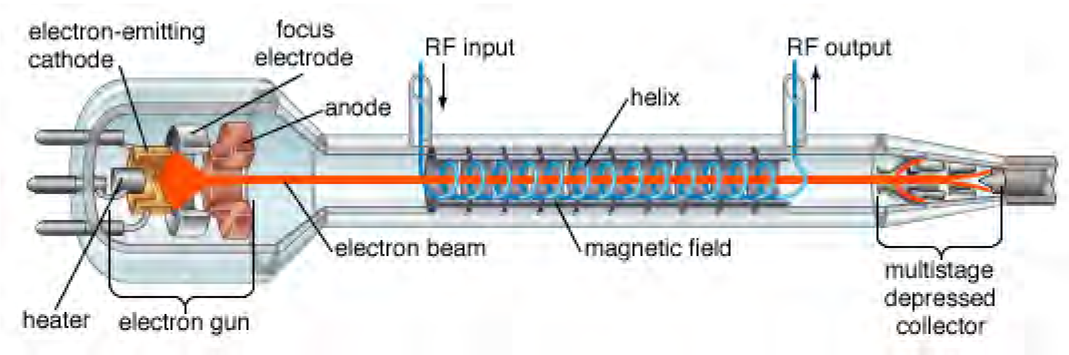
- How robust would synchronization in the network be in the presence of:
  - Noise
  - Mismatch in the dynamical parameters of the nodes
  - Interference or jamming
  - Complexity of the environment

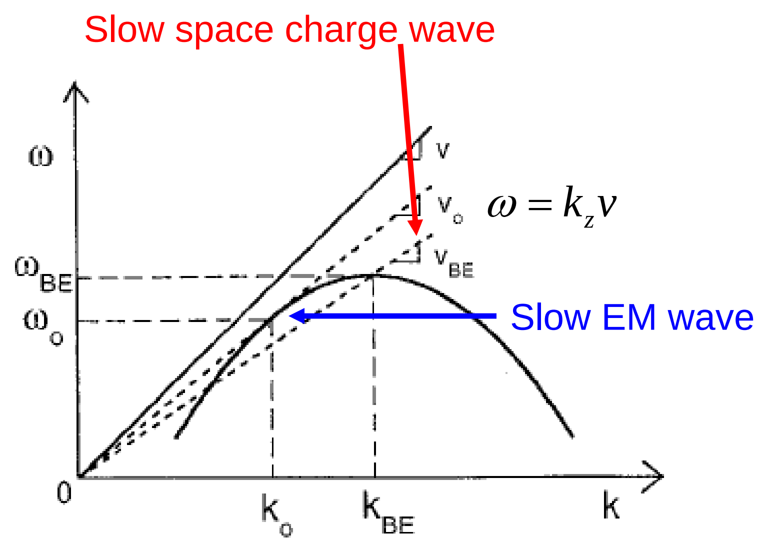


Outline

- Basic characteristics of the traveling-wave tube (TWT)
- TWT nonlinearity
- Saturation models
- Results of previous simulations
- Results of experiments on TWT's with time-delayed feedback
- Digital control of the time-delayed system
- Future research

TWT Basics





TWT Dispersion Diagram

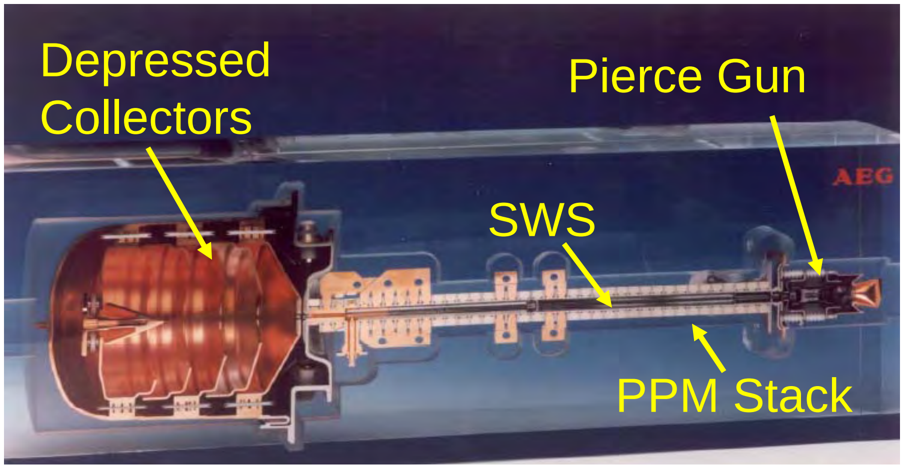
- Properties:

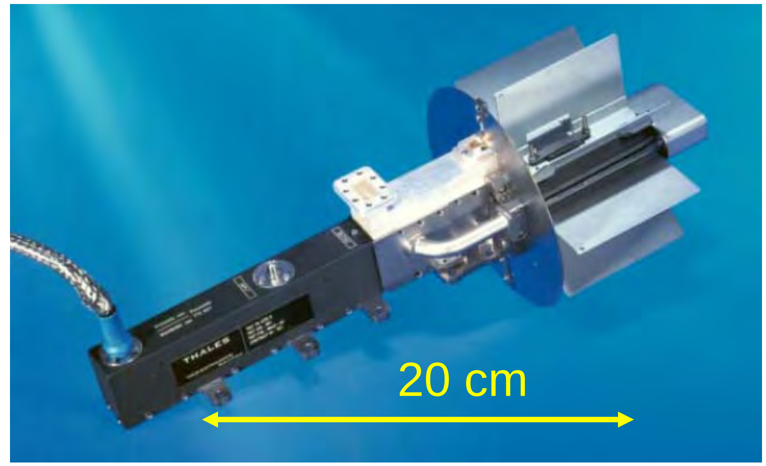
  High gain, wideband, good linearity and efficiency

- Applications:

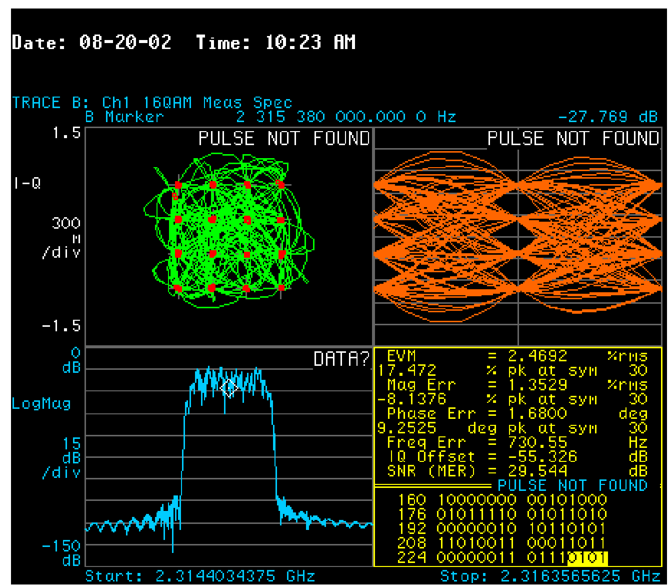
  Space communications, secure LOS, cell phones, radar, EW

Typical characteristics of the TWTA

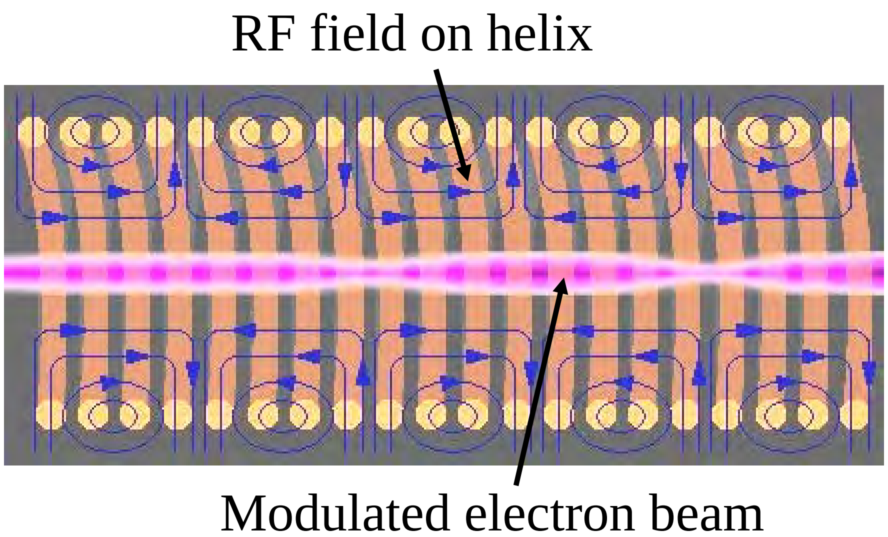


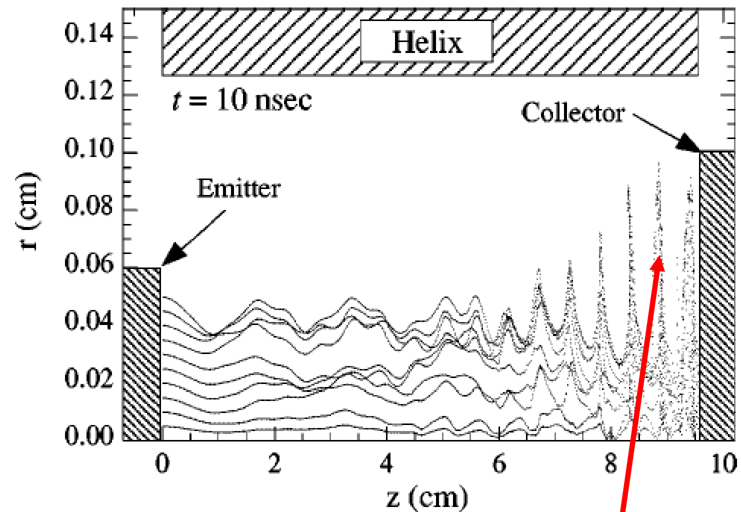


- •High gain 40-60 dB
- •Wideband >2 octaves
- •Compact m~ kg, L< 12 cm
- •Efficient >80% (Dep. Coll.)
- •High Frequency >50 GHz
- •Modest Voltage ~few kV



Nonlinearity in TWT's (1-D Model)





Equation of Motion $\frac{\partial v}{\partial t} = -v\frac{\partial v}{\partial z} - \frac{e}{m}\frac{\partial (V_W + V_{SC})}{\partial z}$

Continuity $\frac{\partial \rho}{\partial t} = -\frac{\partial (\rho v)}{\partial z}$

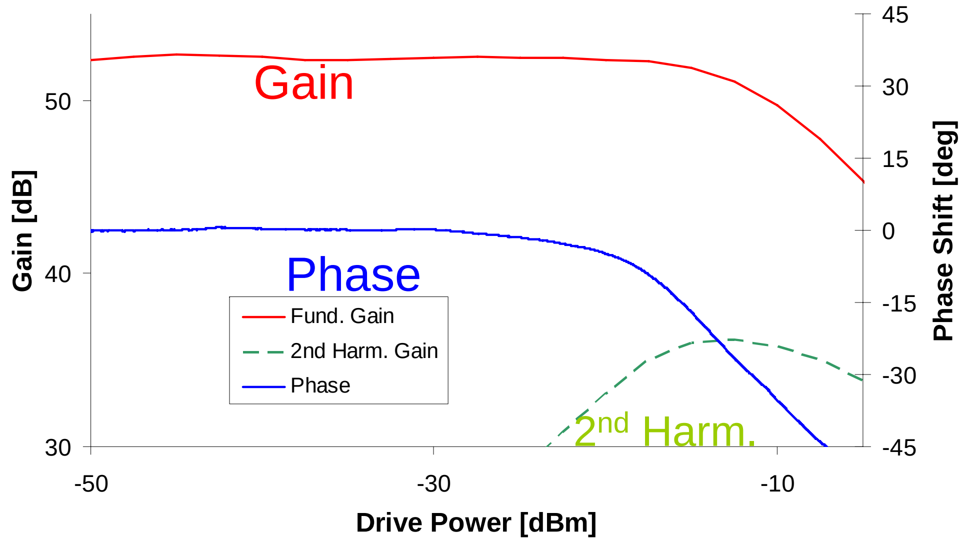
Gauss's Law $\frac{\partial^2 V_{SC}}{\partial z^2} = -\frac{\rho}{\varepsilon_0}$

Wave Equation $\frac{\partial^2 V_W}{\partial t^2} - c^2\frac{\partial^2 V_W}{\partial z^2} = cZ_0 A\frac{\partial^2 \rho}{\partial t^2}$

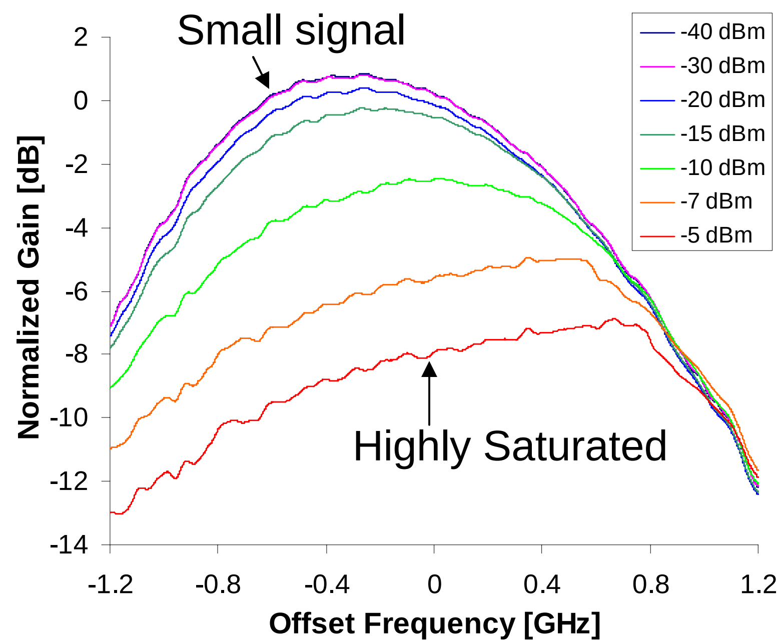
Over-modulation of the beam increases space-charge forces which saturate the amplifier.

TWT Gain Saturation

Gain and Output Phase vs. Input Power



Gain-Bandwidth



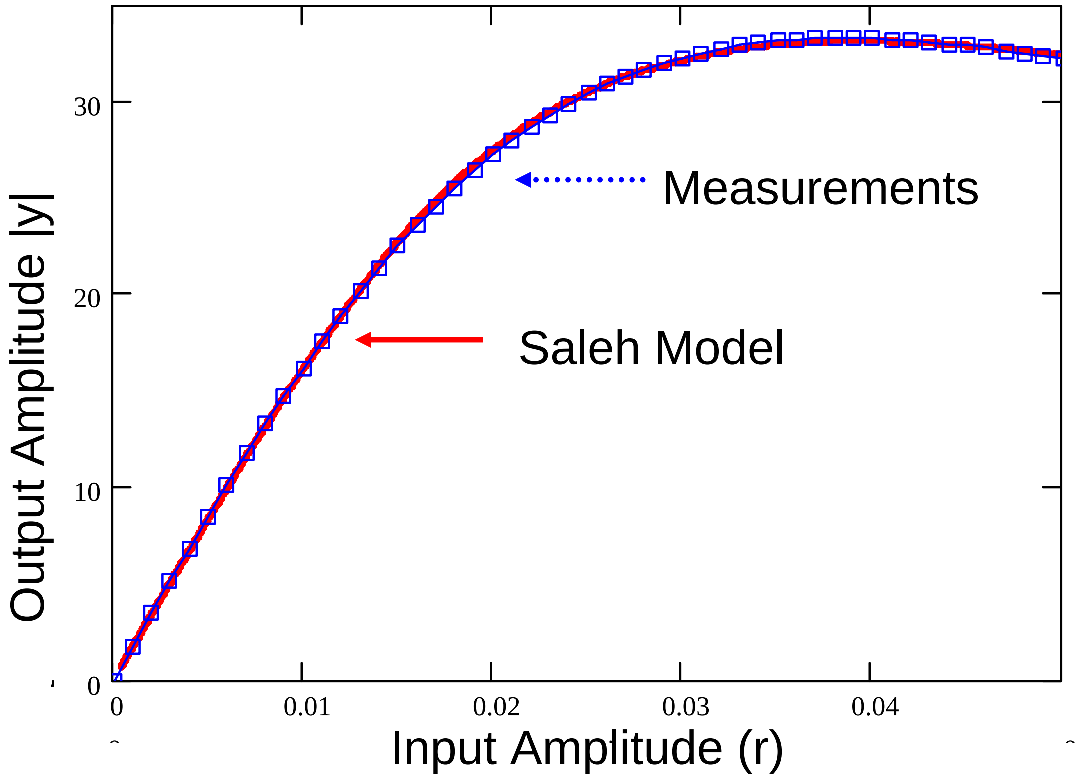
In some TWT's, saturation is well described as a quadratic function the of input amplitude and the small-signal bandwidth as a first-order band pass filter (BPF).

Comparison of measured TWT drive curve with best fit to Saleh[1] model

$$y = A(r)e^{-j\Phi(r)}$$

$$A(r) = \frac{\alpha_a r}{1+\beta_a r^2}$$

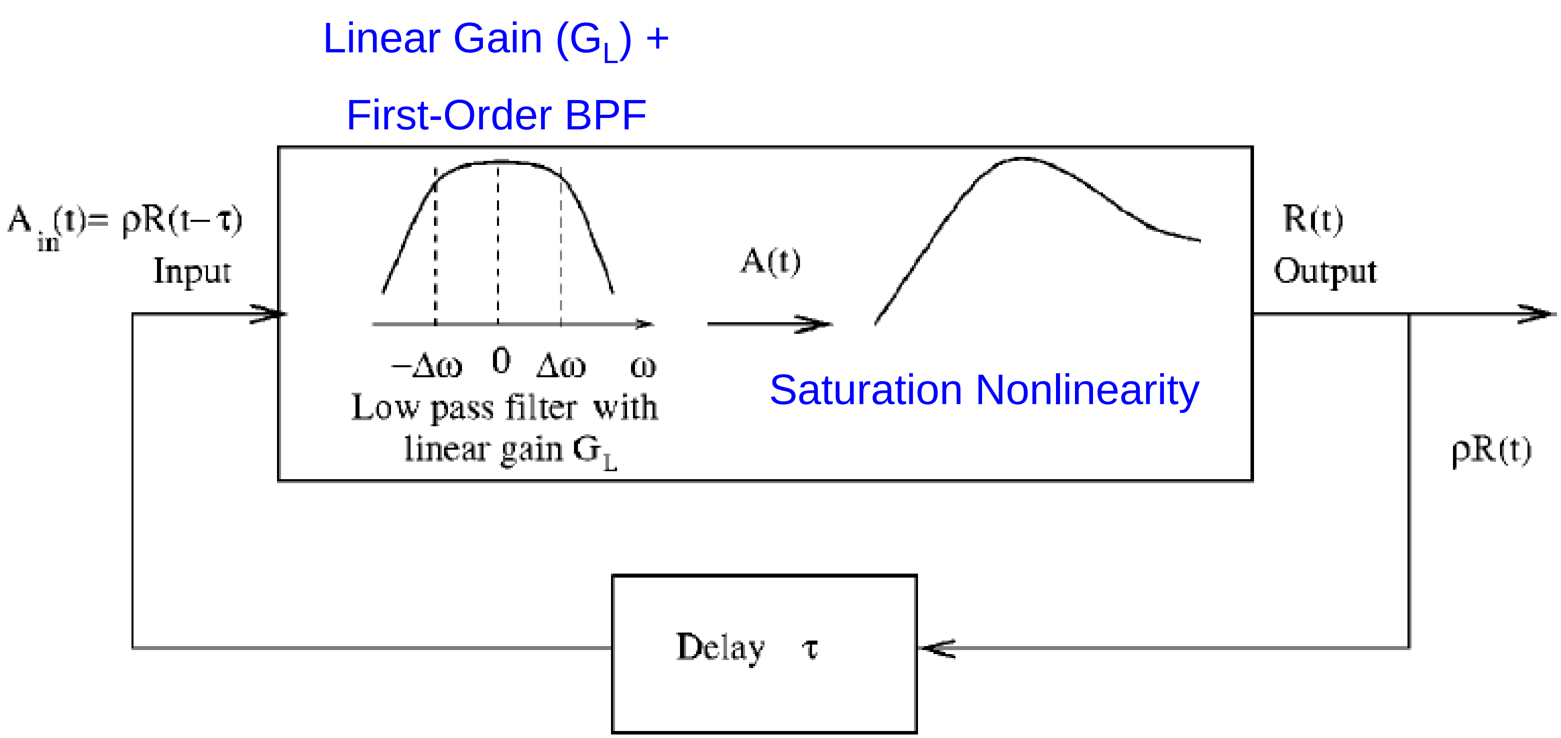
$$\Phi(r) = \frac{\alpha_\phi r^2}{(1+\beta_\phi r^2)^2}$$



1. A. M. Saleh, *IEEE Trans. Comm.,* Vol. 29, No. 11, (1981), pp. 1715-1720.

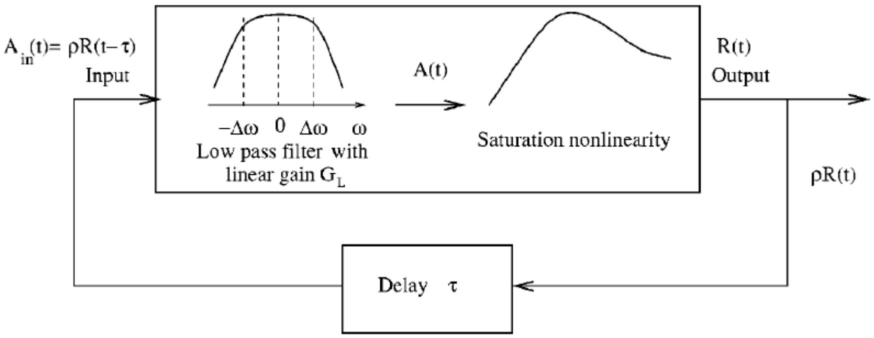
Model of a Time-delayed Feedback Oscillator Using Linear and Nonlinear Blocks to Describe the TWT

(see poster presented by Wai-Shing Lee)



2. V. Dronov, M. Hendry, T. M. Antonsen, Jr., and E. Ott, *Chaos,* Vol. 14, No. 1, pp. 30-35, 2004.

Nonlinear Dynamics



$$Loop\,Gain: \quad k = \rho G_L$$

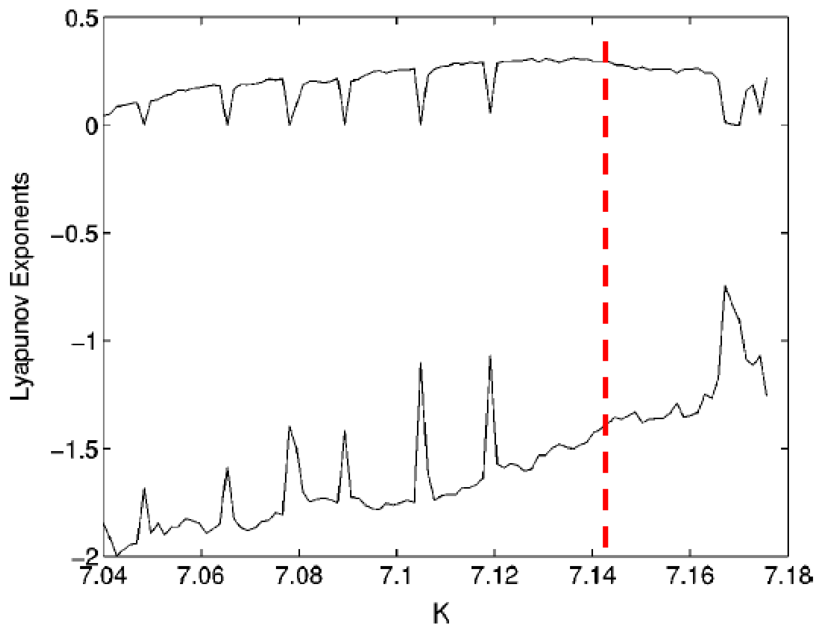
$$Output: \quad R(t) = A(t)\frac{e^{i\eta|A(t)|^2}}{1+|A(t)|^2}$$

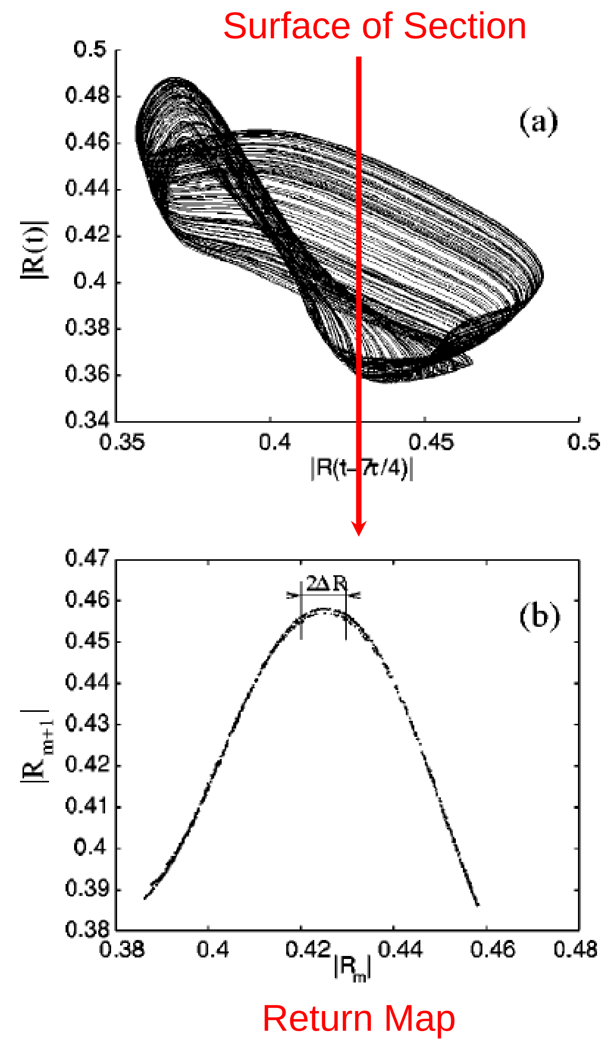
$$Dimensionless\,Time: \quad t \to t\Delta\omega, \tau \to \tau\,\Delta\omega$$

$$DDE: \quad \frac{dA(t)}{dt} + A(t) = kA(t-\tau)\frac{e^{i\eta|A(t-\tau)|^2}}{1+|A(t-\tau)|^2}$$

Quadratic Saturation Model

Numerical Results Using Quadratic Saturation Model





System Parameters:

$$k = 7.142$$

$$\tau = 0.530$$

$$\eta = 1$$

2. V. Dronov, M. Hendry, T. M. Antonsen, Jr., and E. Ott, *Chaos,* Vol. 14, No. 1, pp. 30-35, 2004.

Characteristics of 276HA TWT Driver Amplifier for Satellite Communications

Frequency: 3-4 GHz

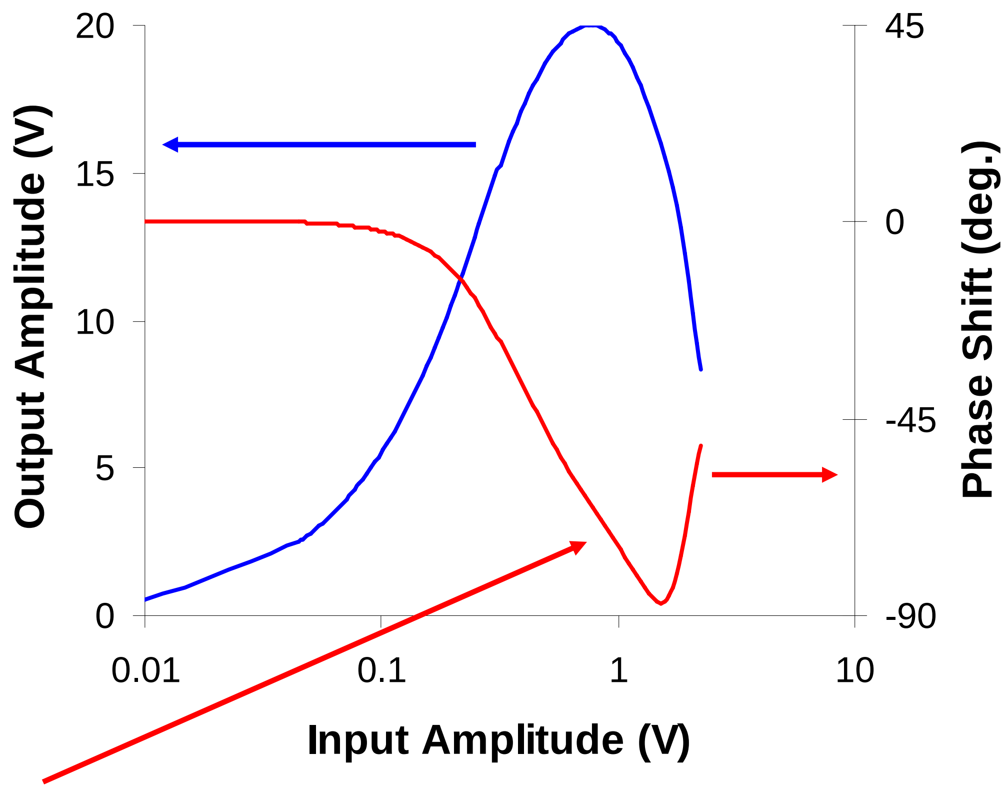
Output Power: 0.6 W

Gain: 35 dB

Bandwidth: 1 GHz

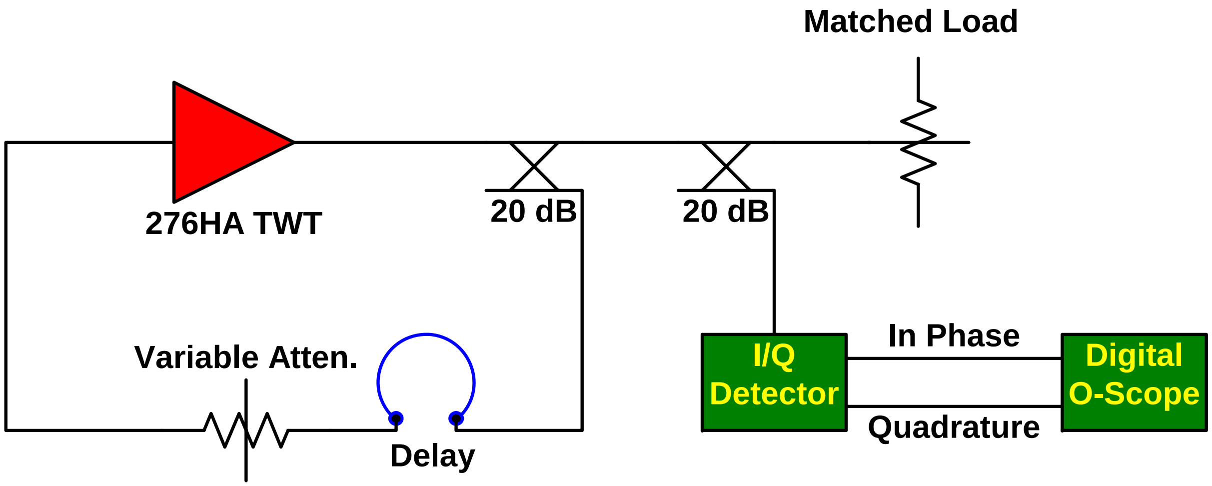
Efficiency: 70%

(Multi-Stage Depressed Collector Design)



Phase becomes periodic for large input amplitudes!

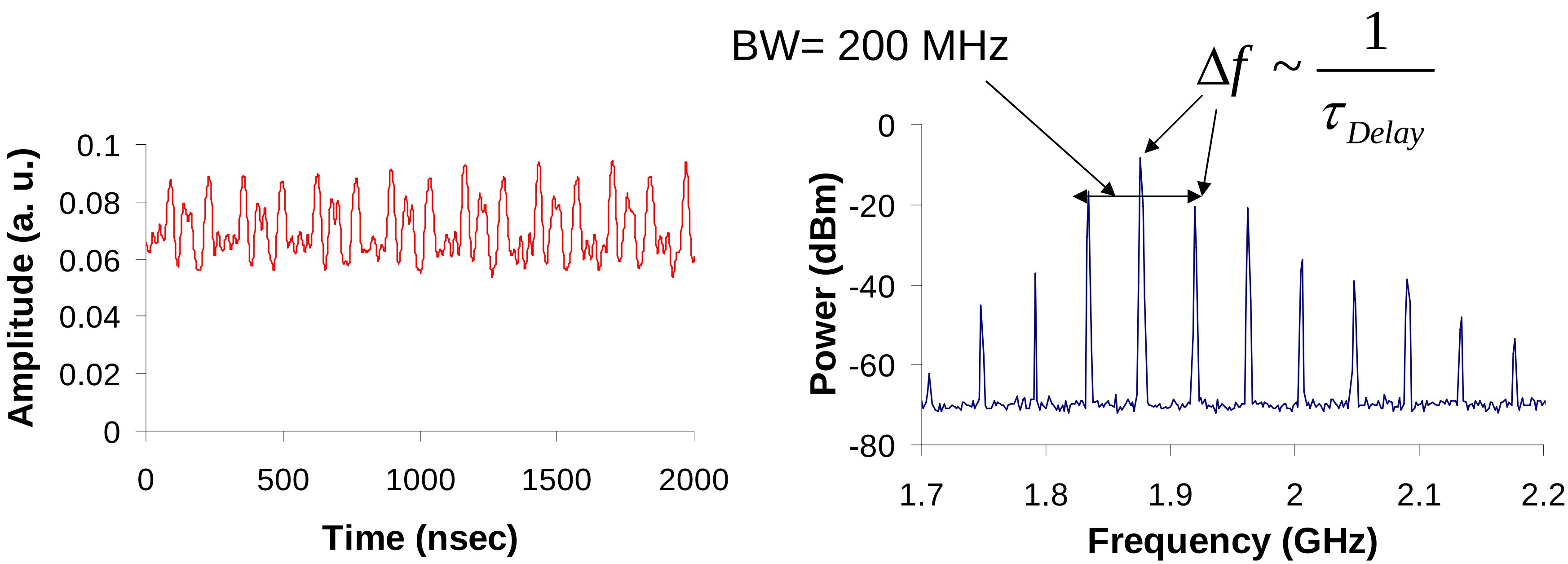
Time-delayed Feedback Oscillator Experiment (Wideband)



Model	Experiment
$\eta = 1.0$	$\eta = 3.4$
$\tau_{Norm} = 0.530$	$\tau_{Norm} = (5\,ns)(2\pi * 1GHz) = 10\pi$
$k = 7.142$	$\Phi \neq quadratic\ function\ of\ \lvert A_{in} \rvert$

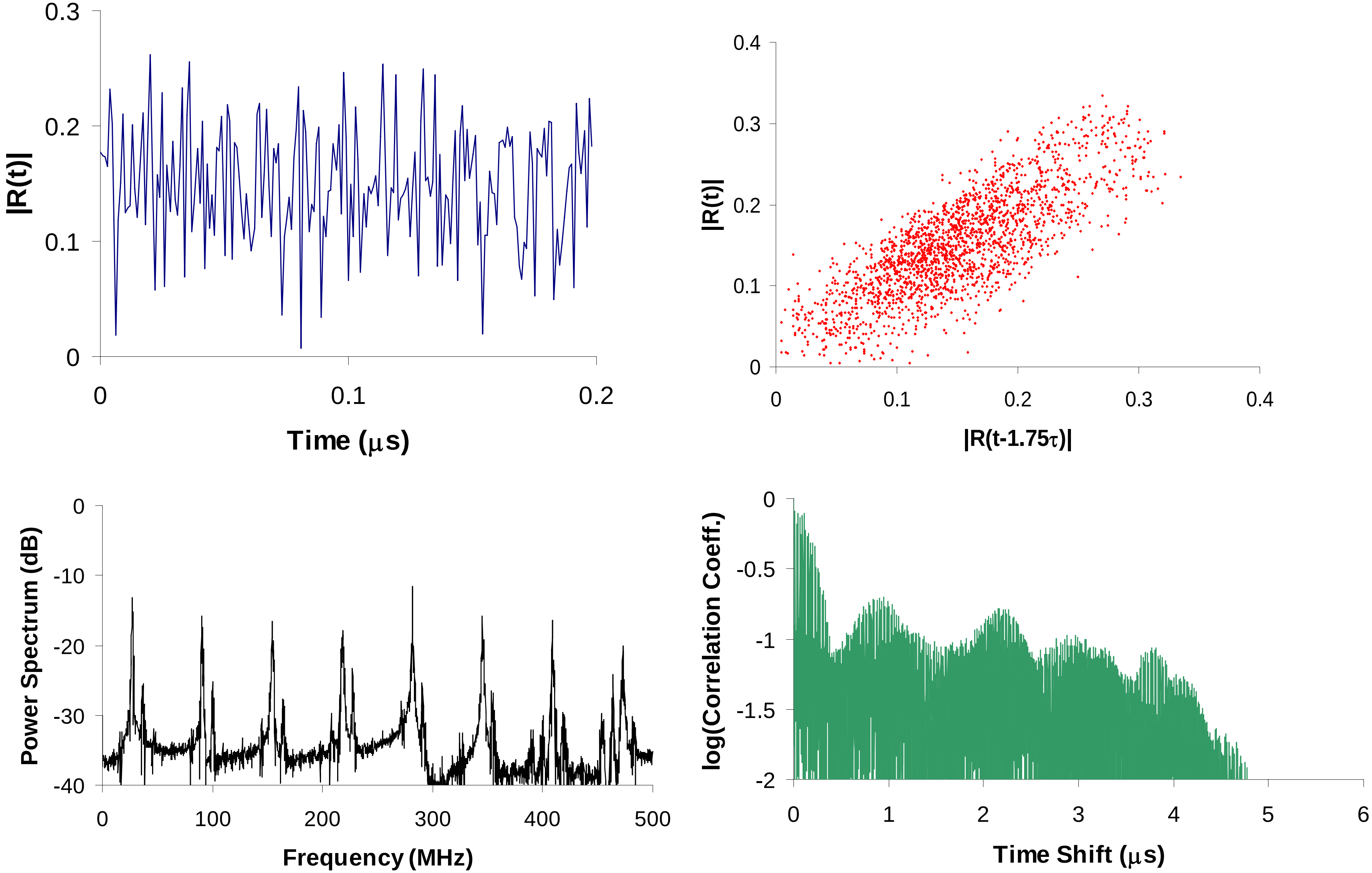
Caution: Our system has much longer memory!

Typical quasi-periodic behavior at low loop gains

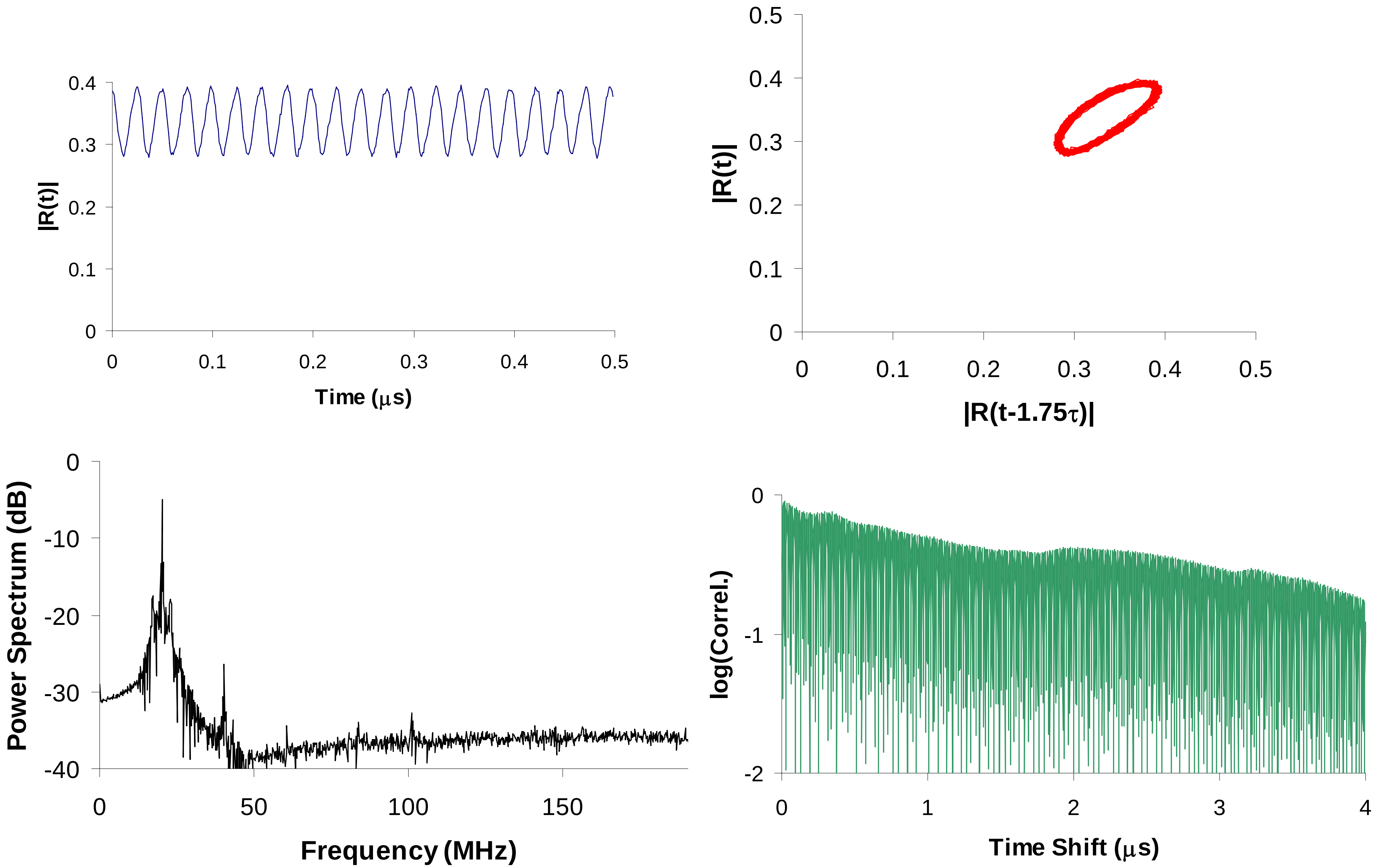


Experimental results from an L-band TWT with a short feedback delay (τ_D = 20 ns).

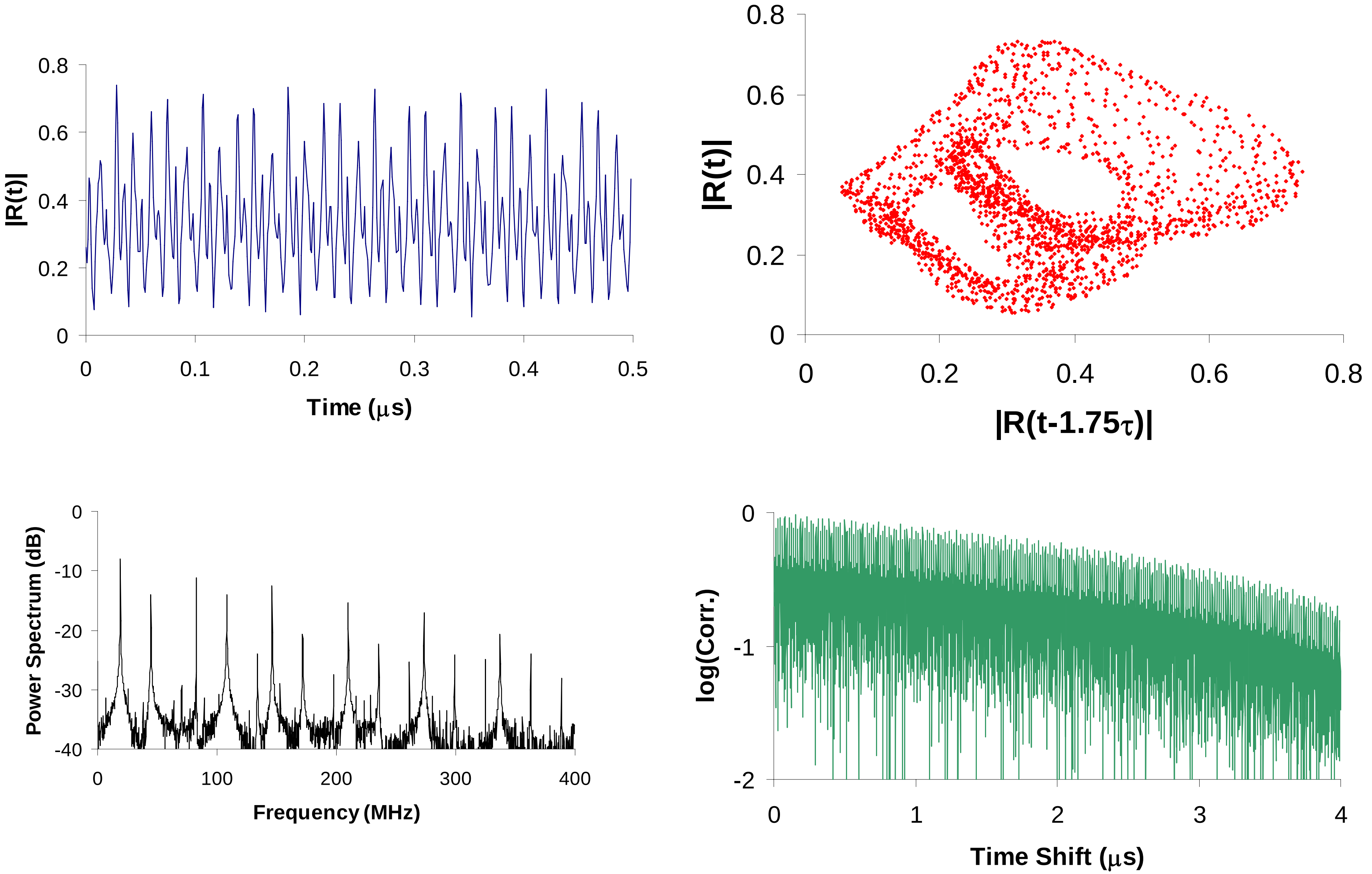
Full Band Case: Loop Gain, k = 1.12



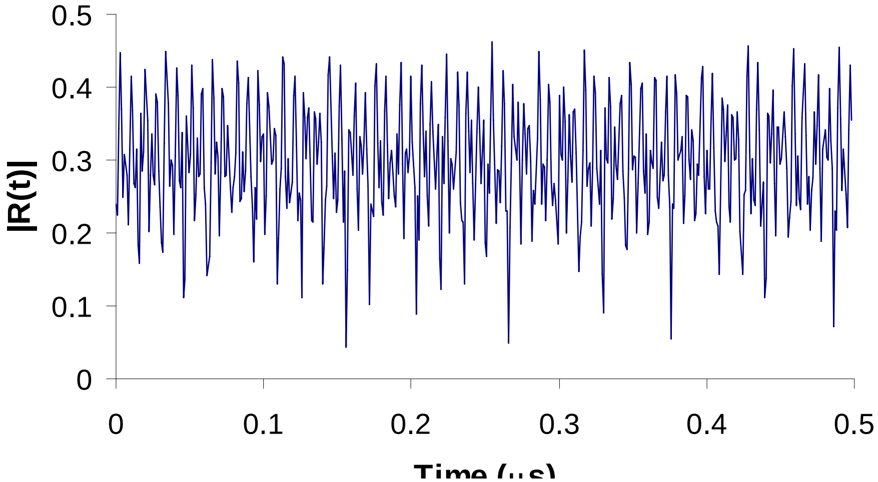
Loop Gain, k = 1.41

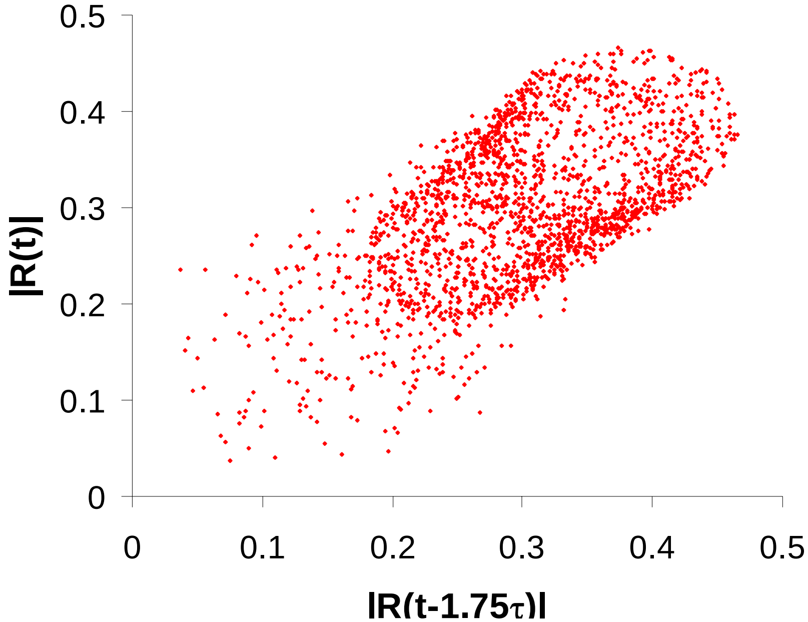


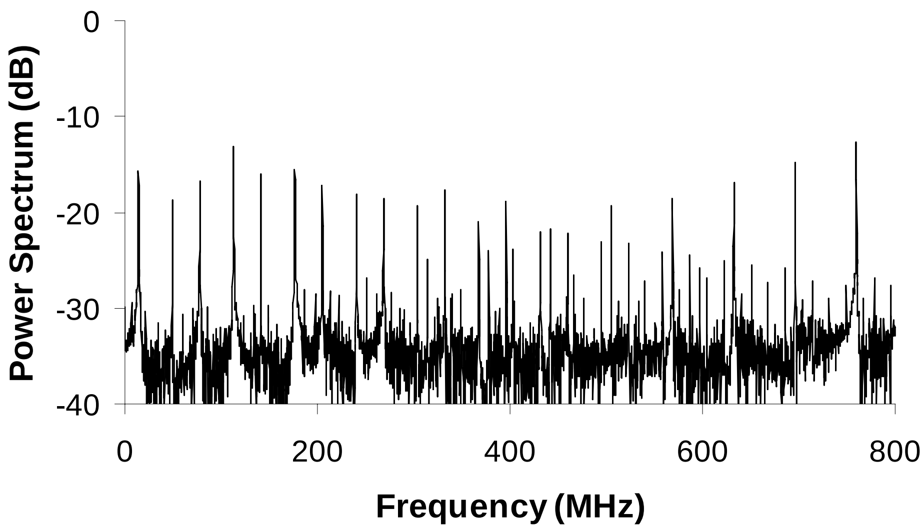
Loop Gain, k = 1.60

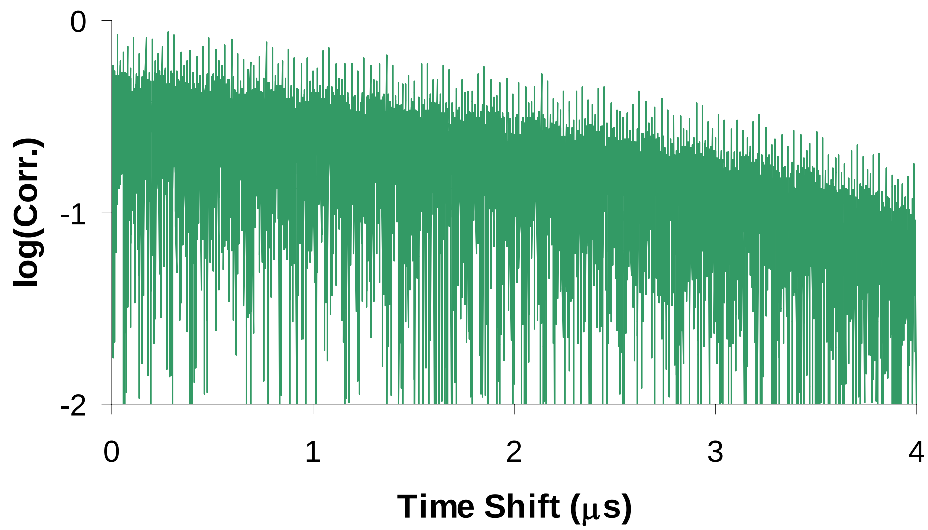


Loop Gain, k = 4.0

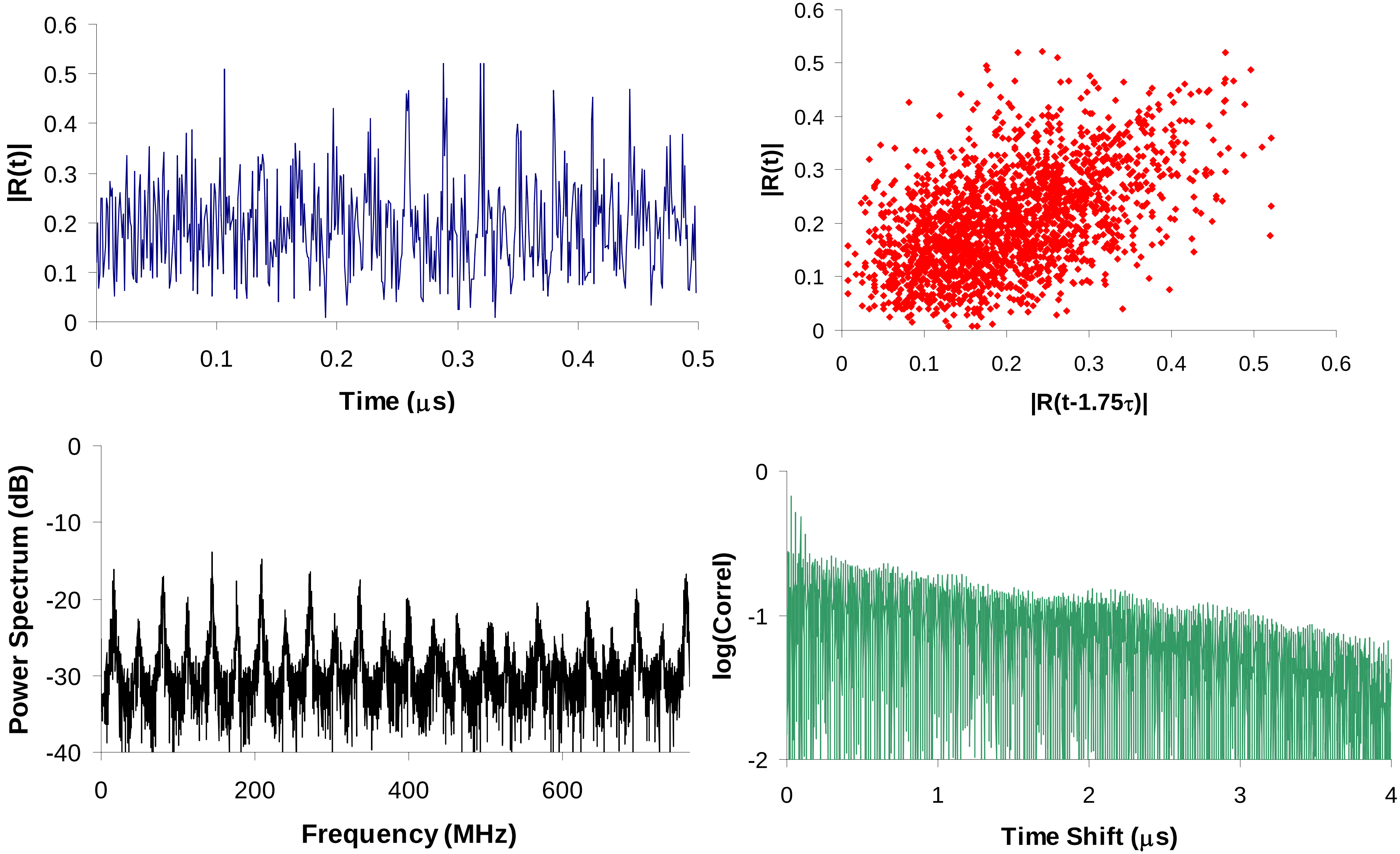




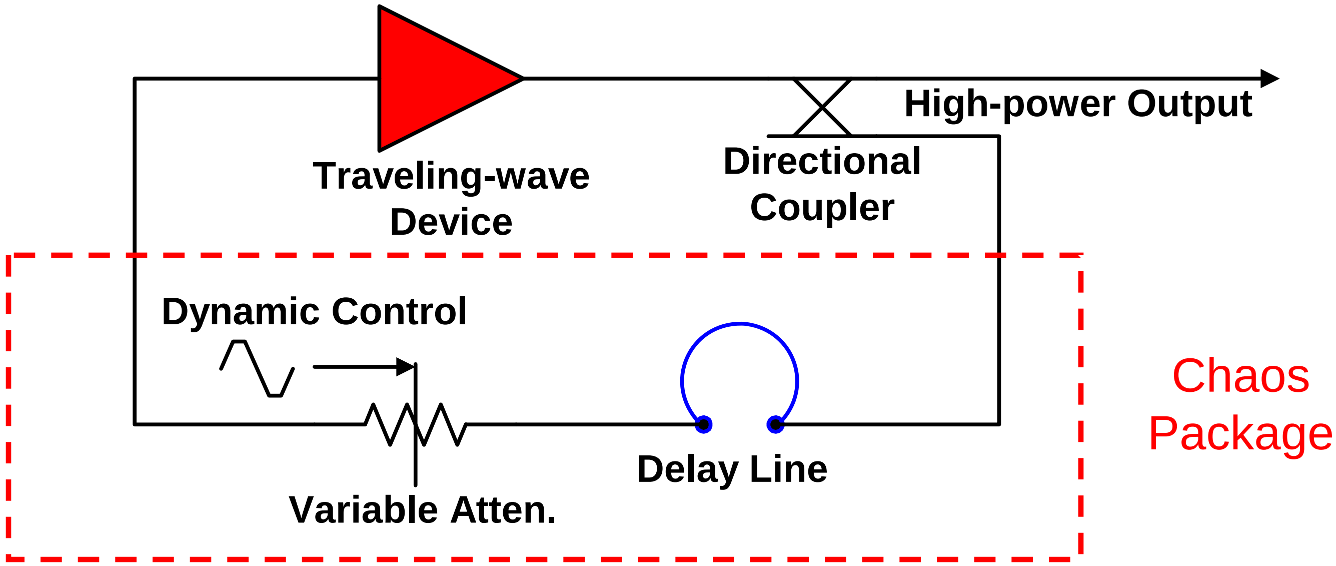




Loop Gain, k = 7.94

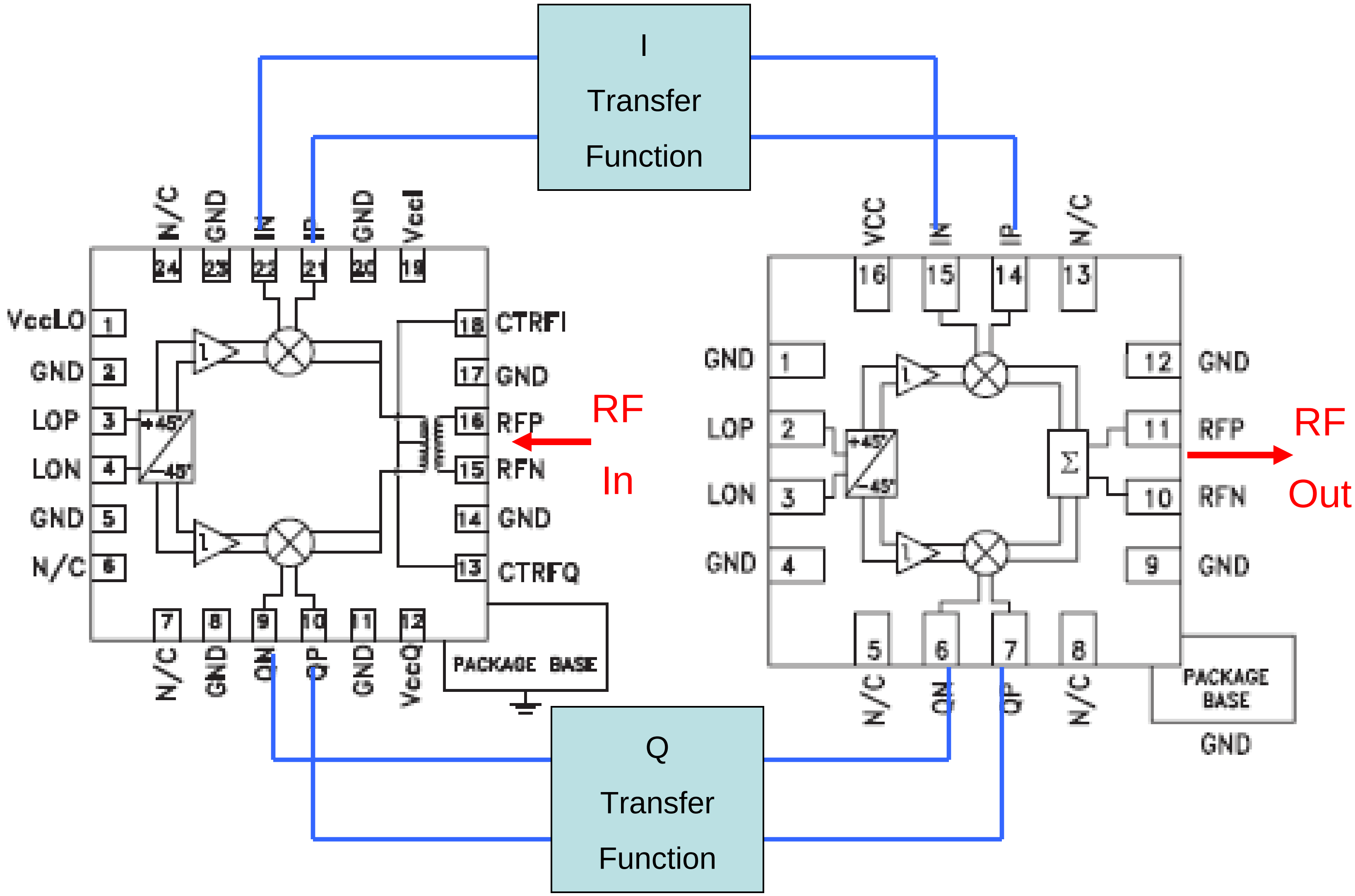


Deliverable: Develop an "dynamics package" that could be integrated into existing RF transmitters

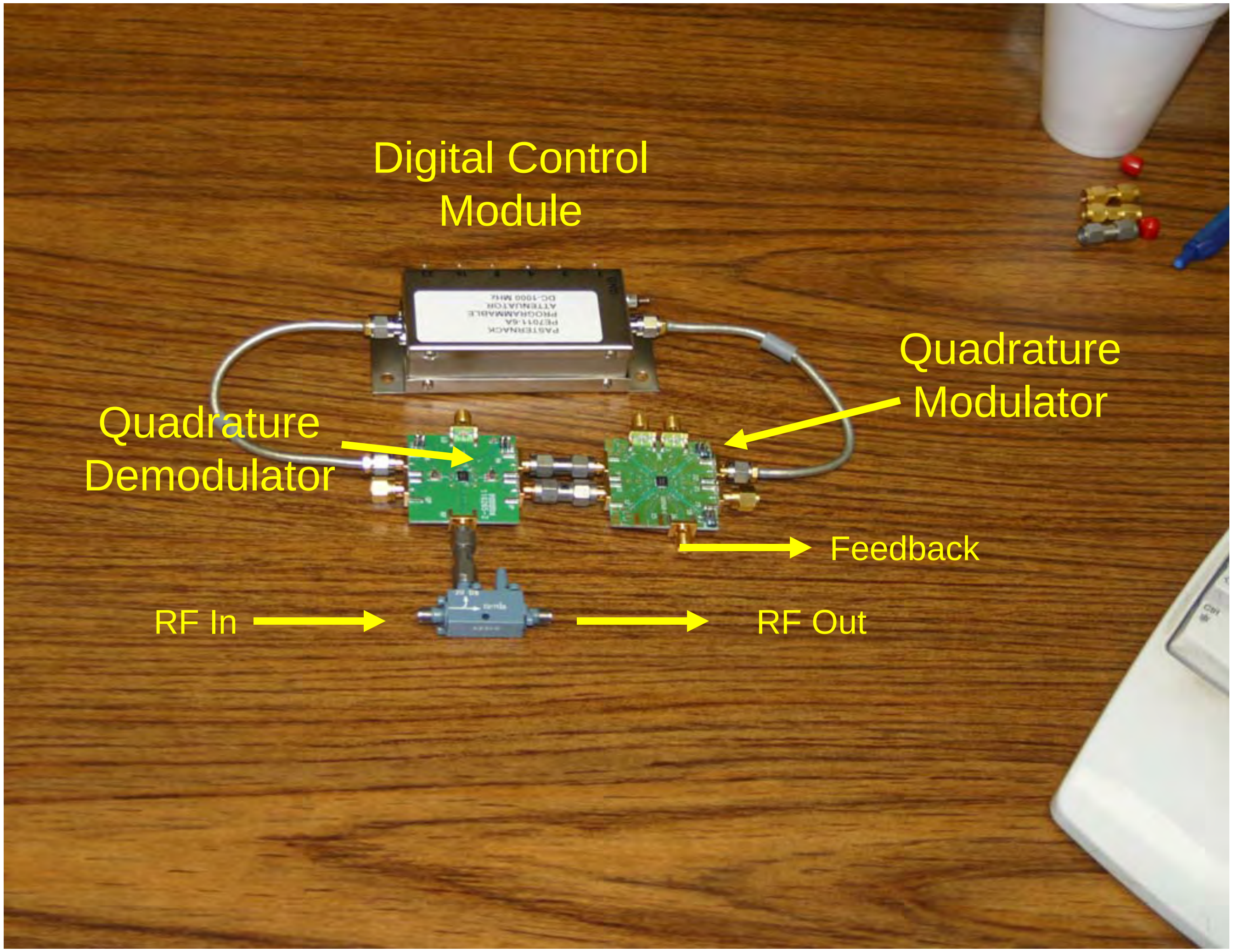


- Simple construction
- Uses existing technology that is deployed in a wide variety of military systems.
- Generates power levels and frequencies that would be useful for covering wide areas (e. g. urban environments).

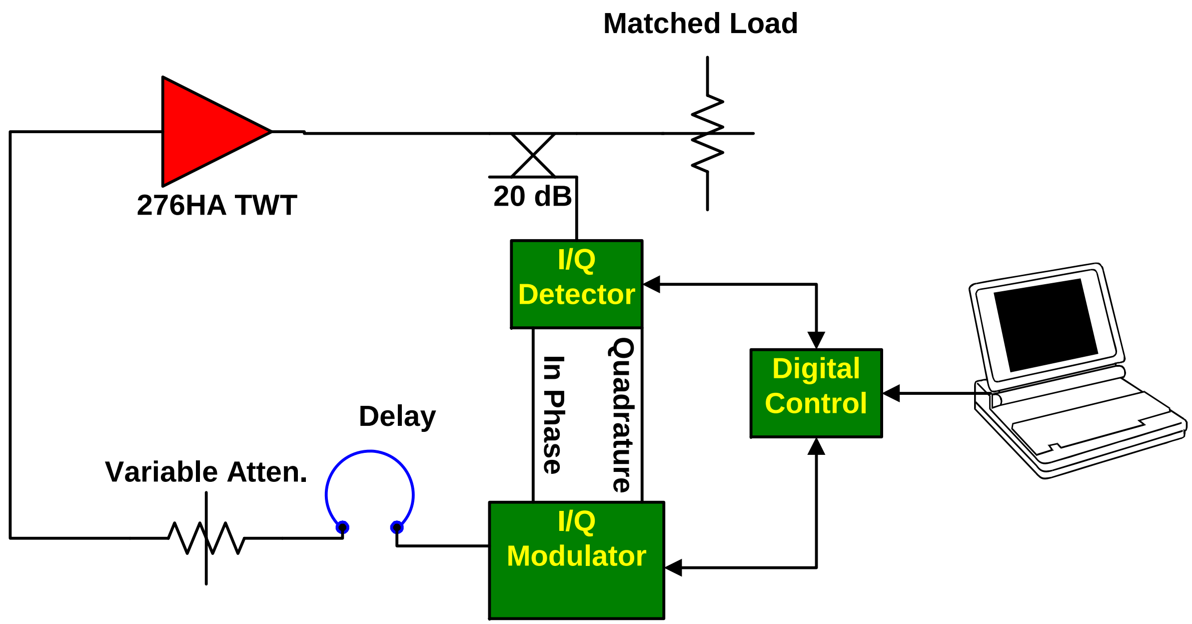
Digital control of dynamical states using quadrature feedback



Components of the dynamics control package



Digital Control of System State



- Adjustable loop gain/dynamics
- Apply new transfer functions to the feedback
- Automated setup of dynamics

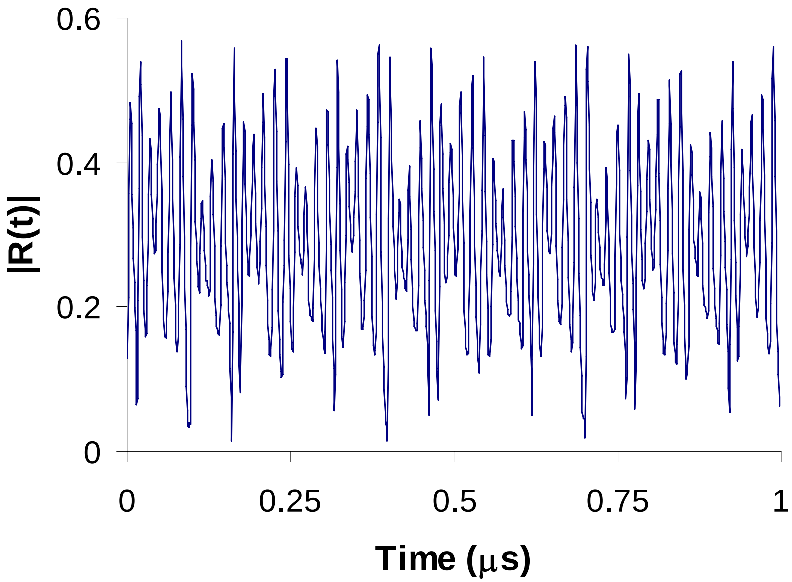
$$s = \pm I \pm iQ$$

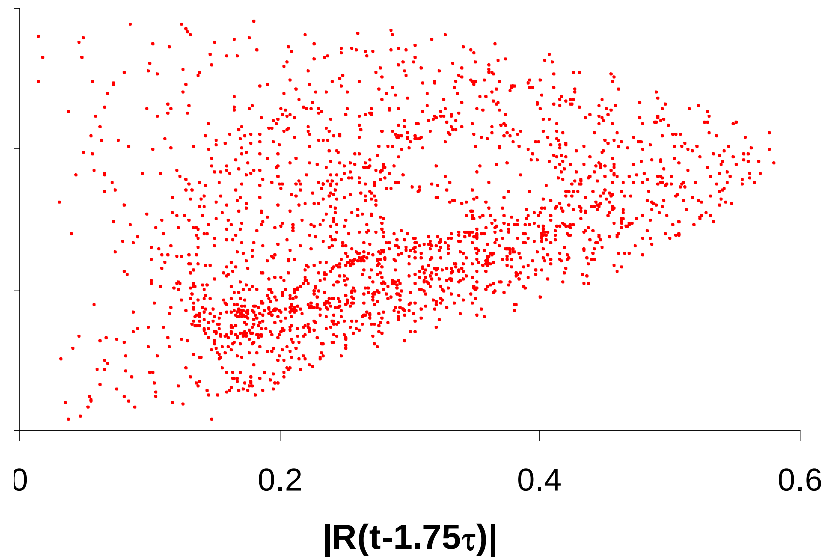
$$s = \overline{s}$$

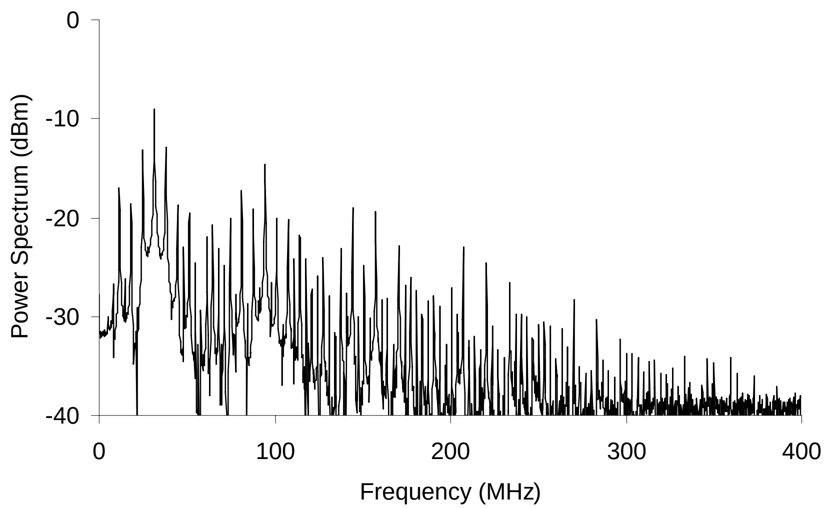
$$s = I^n \pm iQ^n$$

$$s = I \rightarrow Q, Q \rightarrow I$$

Complex Feedback Transfer Functions







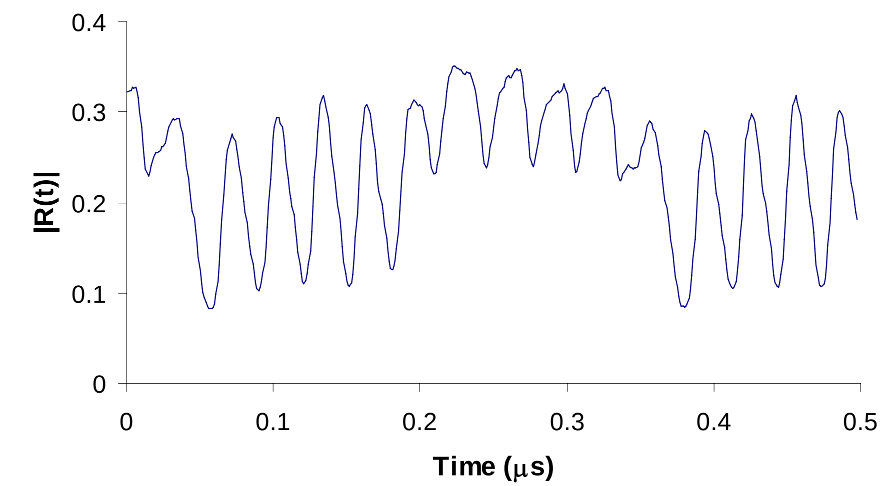
$$s = \overline{s}$$

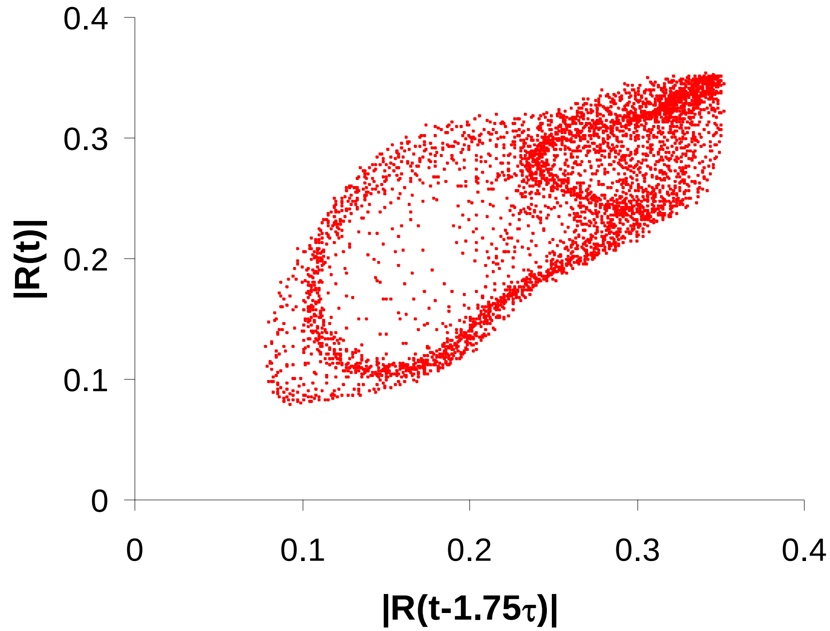
$$\Delta\omega = 2\pi(40\,MHz)$$

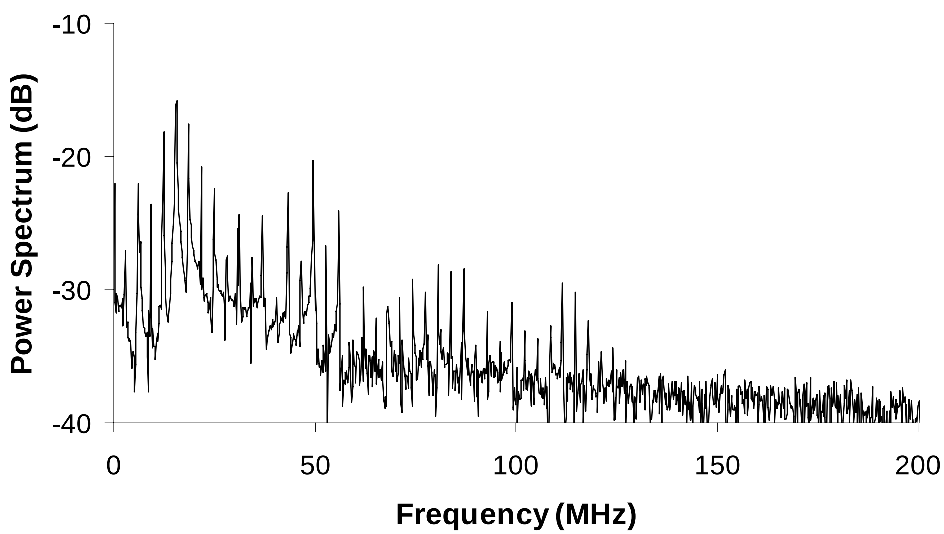
$$\tau_{Norm} = 1.25$$

$$k = 2.88$$

Complex Feedback Transfer Functions





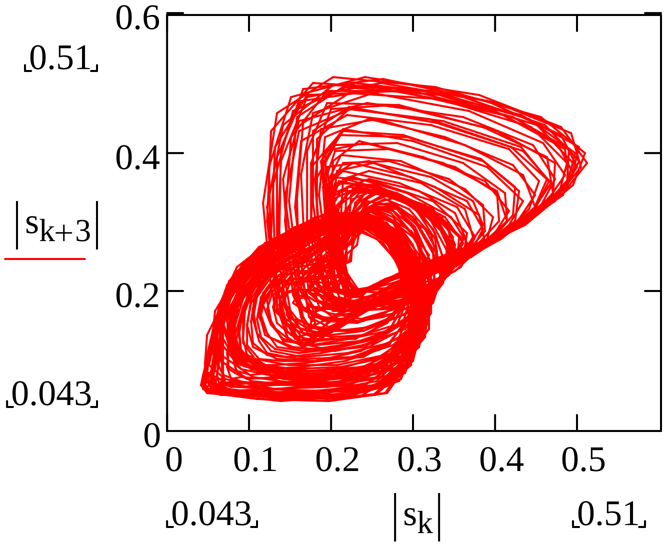


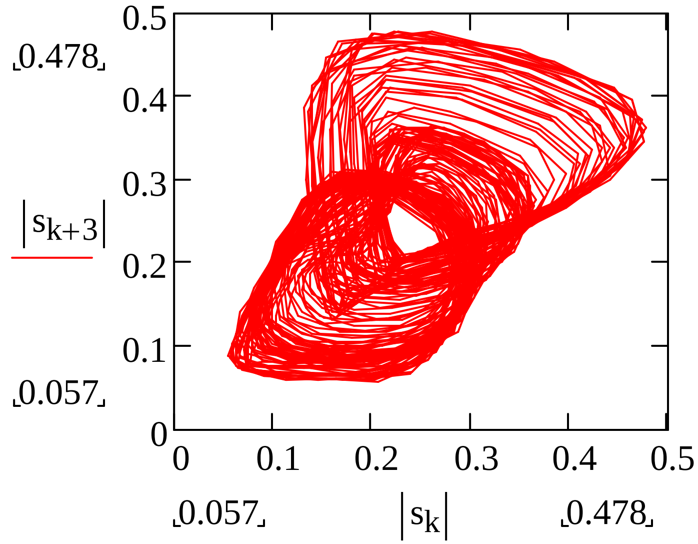
$$s = -s$$

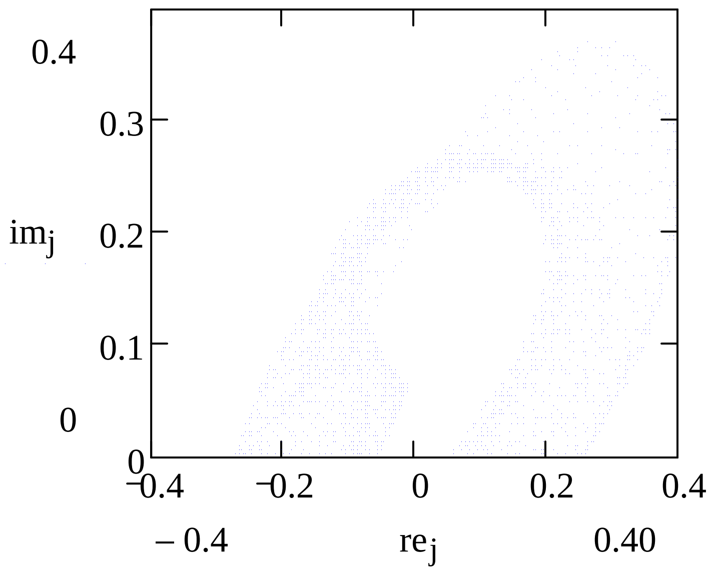
$$\Delta\omega = 2\pi(40\,MHz)$$

$$\tau_{Norm} = 1.25$$

$$k = 5.01$$







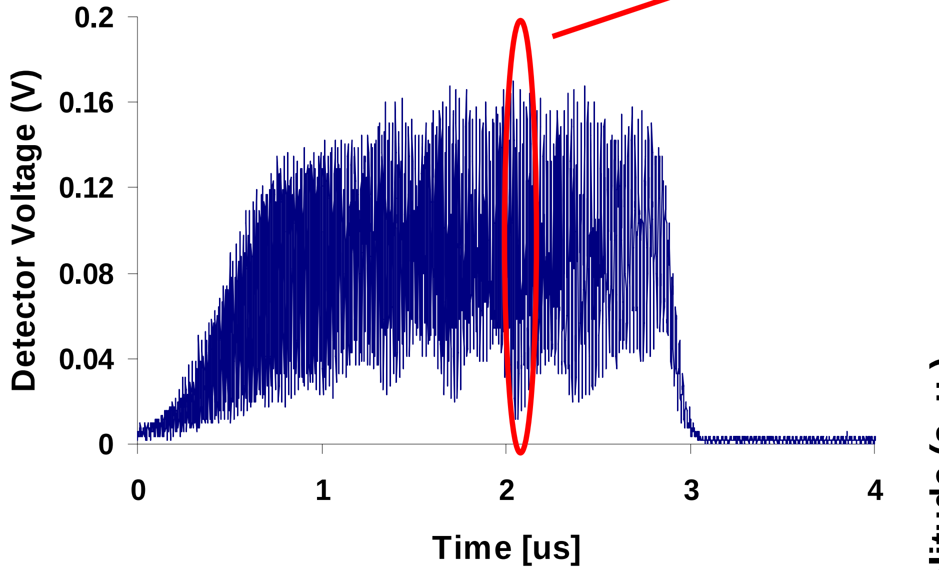
$$s = I - iQ$$

$$\Delta\omega = 2\pi(40\, MHz)$$

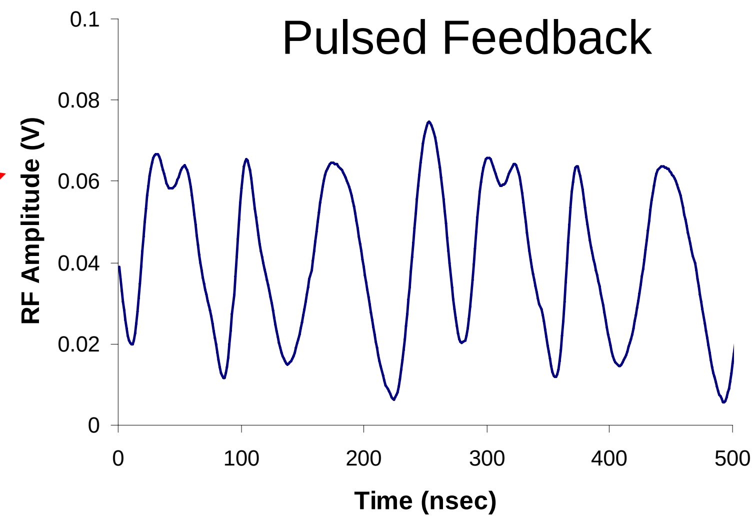
$$\tau_{Norm} = 1.25$$

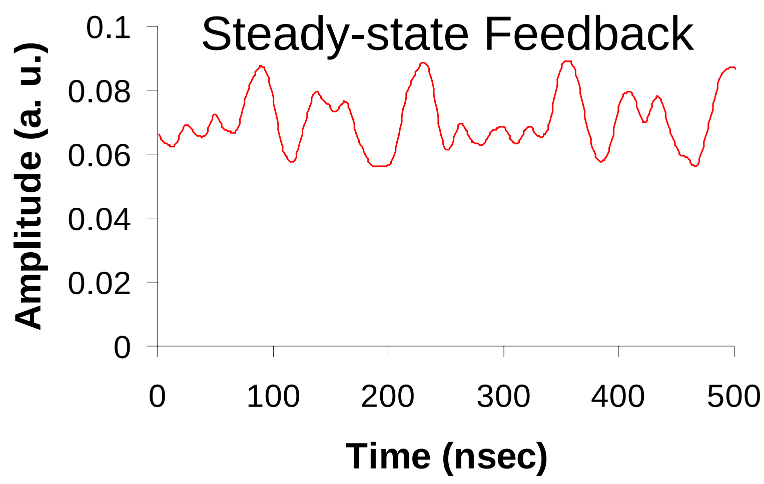
$$k = 2.2, 5.01$$

Transient chaos in a TWT (pulsed beam or feedback)

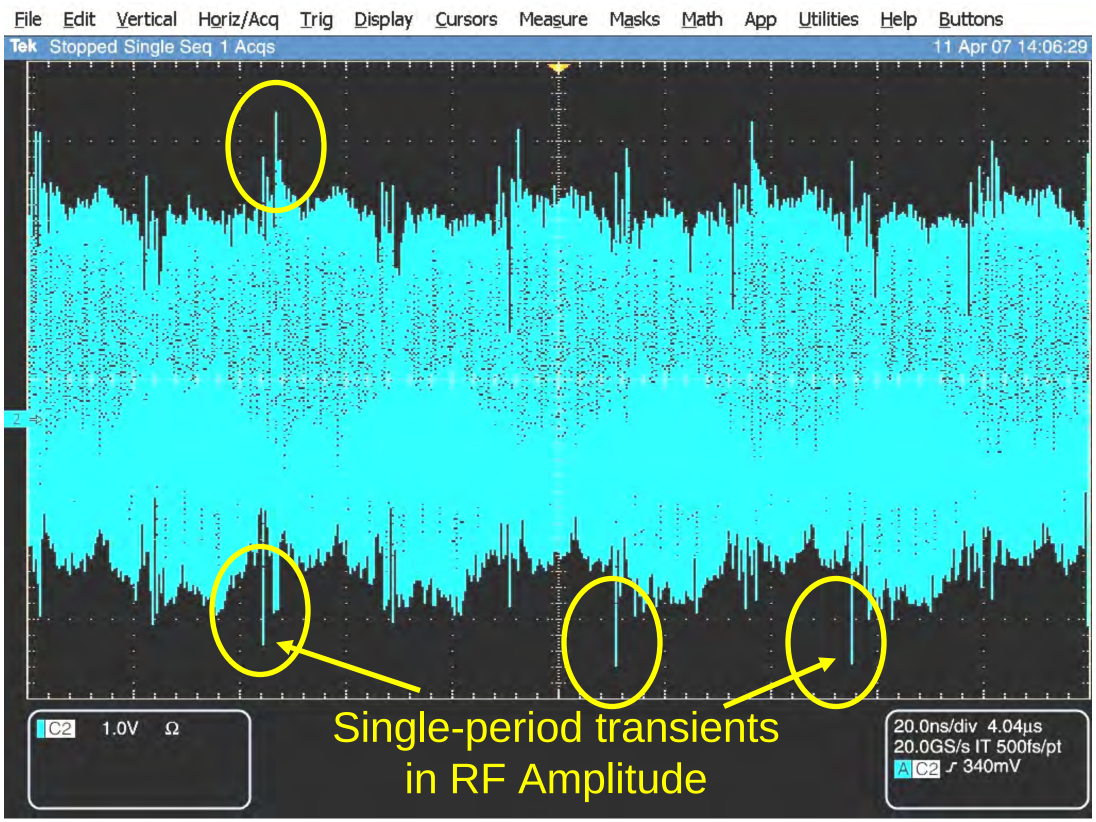


Very deep amplitude modulation





- Transients in TWT TDO's



Time series of chaotic TWT output voltage (measured)

Summary of 2008 Results

- Basic characterization of TWT TDO's at frequency bands relevant to Navy hardware:
  - L-band (1-2 GHz)
  - C-band (3-4 GHz)
  - X-band (8-12 GHz)
  - Ku-band (12-18 GHz)
- Demonstrated a simple method to control the state of the TWT TDO
  - Flexibility: the system can be adapted for various missions

Future Work (2009)

- Investigate synchronization in mutually coupled TWT TDO's
- Construct a network of TWT devices
  - Demonstrate digital state control of the network
  - Study network dynamics w/ static coupling
  - TDO network dynamics when coupled through complex, time-dependent environments