Passive Intermodulation Distortion, Part 2

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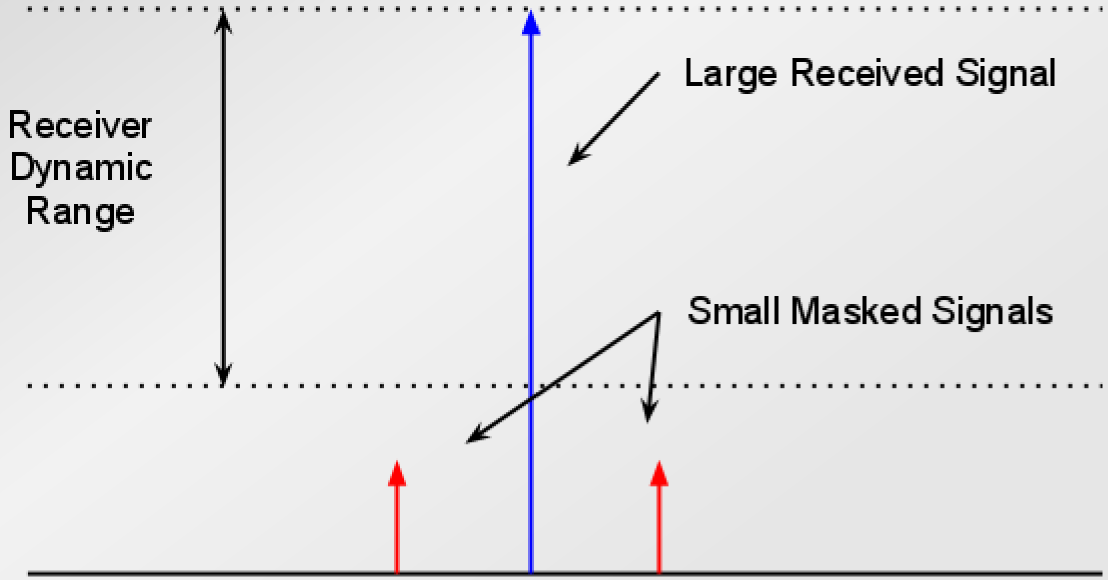
Outline

- Background
- Passive Intermodulation Distortion (2 parts)
  - Part 1, PIM effects, Electro-Thermal PIM
    - Test Equipment, Microwave Circuits / Antennas
  - Part 2, PIM effects
    - Non Electro-Thermal PIM, Filter PIM
- Behavioral Modeling
  - Behavioral model
  - Measurement Equipment
- Simulation and Modeling of Large Systems
  - Part 1, New circuit concepts
  - Part 2, fREEDA

PIM Measurement System (Analog Canceller)

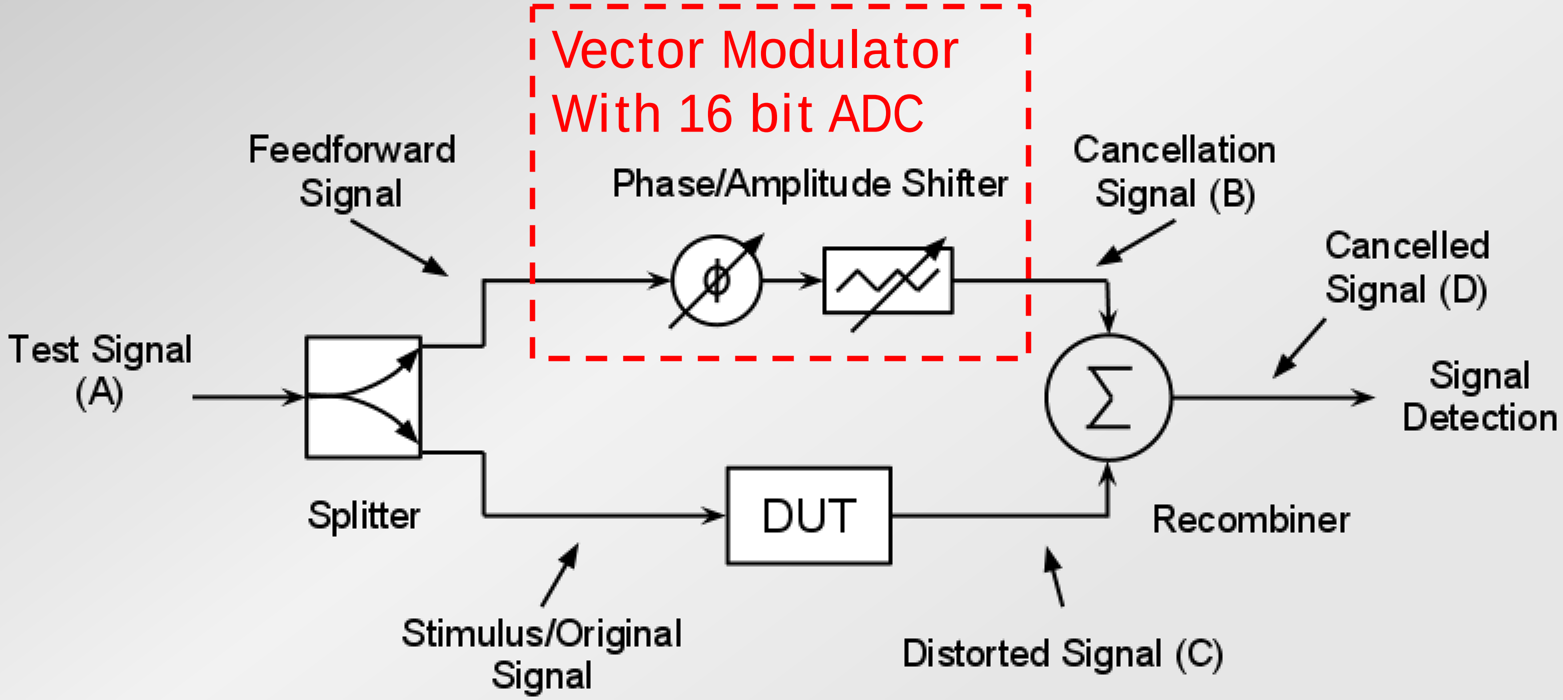
Problem

- Need to measure small signals in the presence of large signals.
  - E.g. GPS receiver, radar, distortion measurement



Cancellation Theory

- Sum with equal amplitude/anti-phase signal of original signal



Cancellation Theory

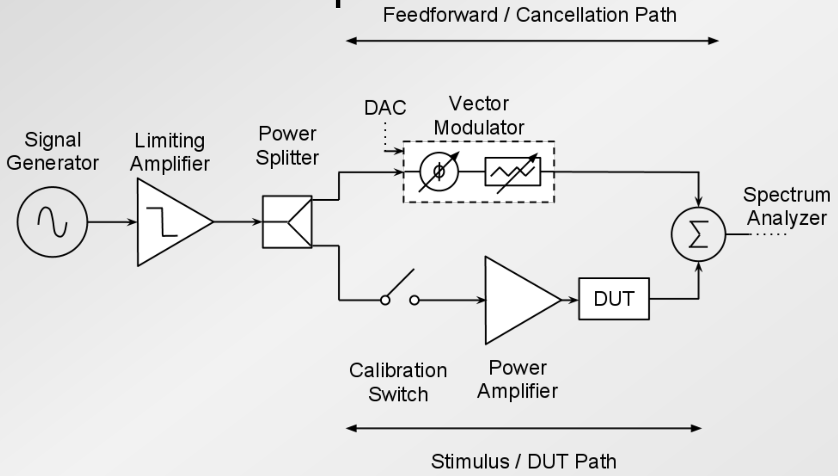
- Amplitude Measurements Only
- Non Newton-Based Iteration

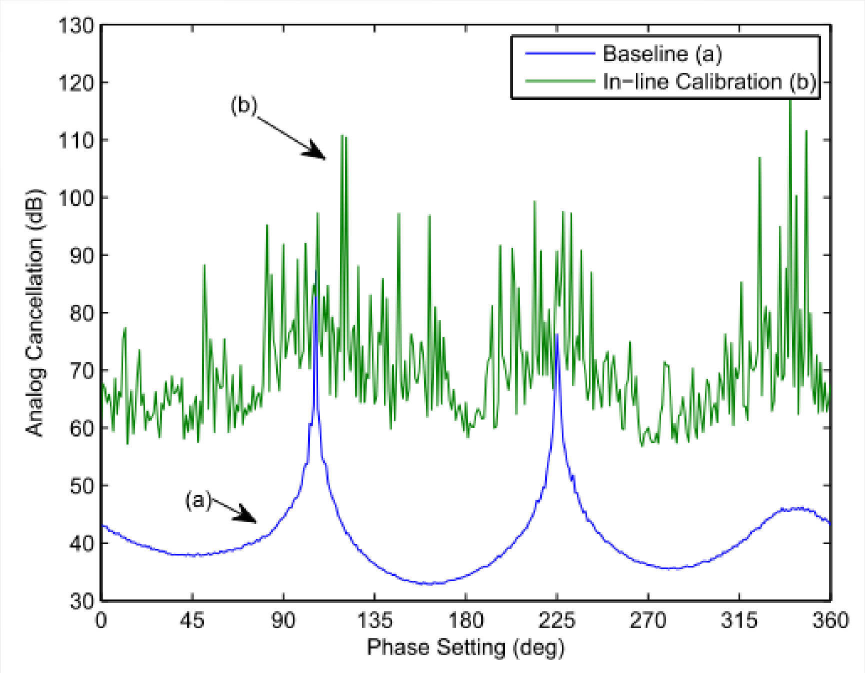
Cancellation Errors

- Phase error:
  - Mostly result of errors in β and α in θ_S equation
  - Dependent on phase separation of signals
  - Can be minimized in iteration
- Amplitude error:
  - Results from path non-linearities
  - Dependent on phase, frequency, time
  - More sensitive than phase errors due to sole reliance on amplitude measurement
  - Minimized through path amplitude calibration

Amplitude Calibration

- Standard (baseline): Generate calibration matrix: Ampl. vs. Freq.
  - Occurs pre-test
  - Does not capture time-dependent or phase-dependent effects
  - Only needs to be done once (ideally)
  - Speed depends on density of matrix
  - Inherent interpolation error
- In-line: Perform calibration on-the-fly
  - Occurs during cancellation
  - Minimizes time-dependency
  - Very fast: single measurement
  - No interpolation error

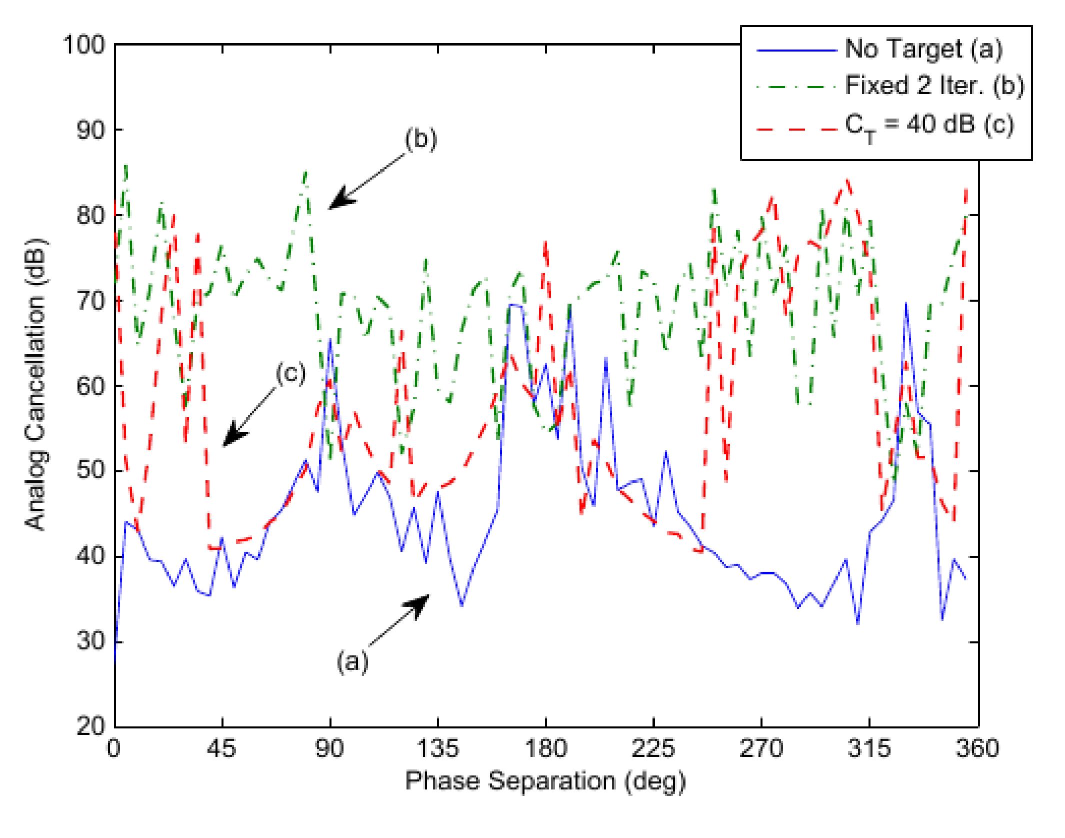




Analog Cancellation

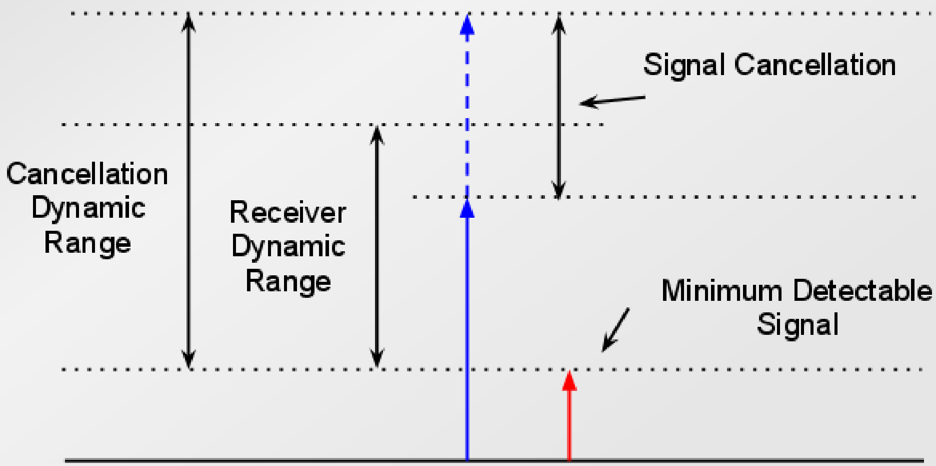
- Initial cancellation is statistical
  - Cancellation converges to 70-90 dB

Target C_T (dB)	Iterations				Meas. analog cancellation (dB)			
	Av.	Max	Md.	σ	Av.	Max	Min	σ
0	1.00	1	1	0.00	45.0	69.7	27.3	9.5
30	1.01	2	1	0.12	46.4	79.3	31.2	10.4
40	1.31	2	1	0.46	56.9	84.5	40.5	13.3
50	1.72	3	2	0.48	67.0	84.5	50.3	10.0
60	2.01	4	2	0.49	73.5	87.6	62.5	4.9
70	2.63	11	2	1.24	75.3	90.0	70.3	4.0
–	Forced 2 Iter.				68.6	85.8	48.3	8.7



High Dynamic Range Measurement

- Cancellation Dynamic Range (DR_C):
  - Ratio of the highest-power signal that can be cancelled to the minimum detectable signal (MDS) after cancellation
  - Not simple combination of C_A and DR_R

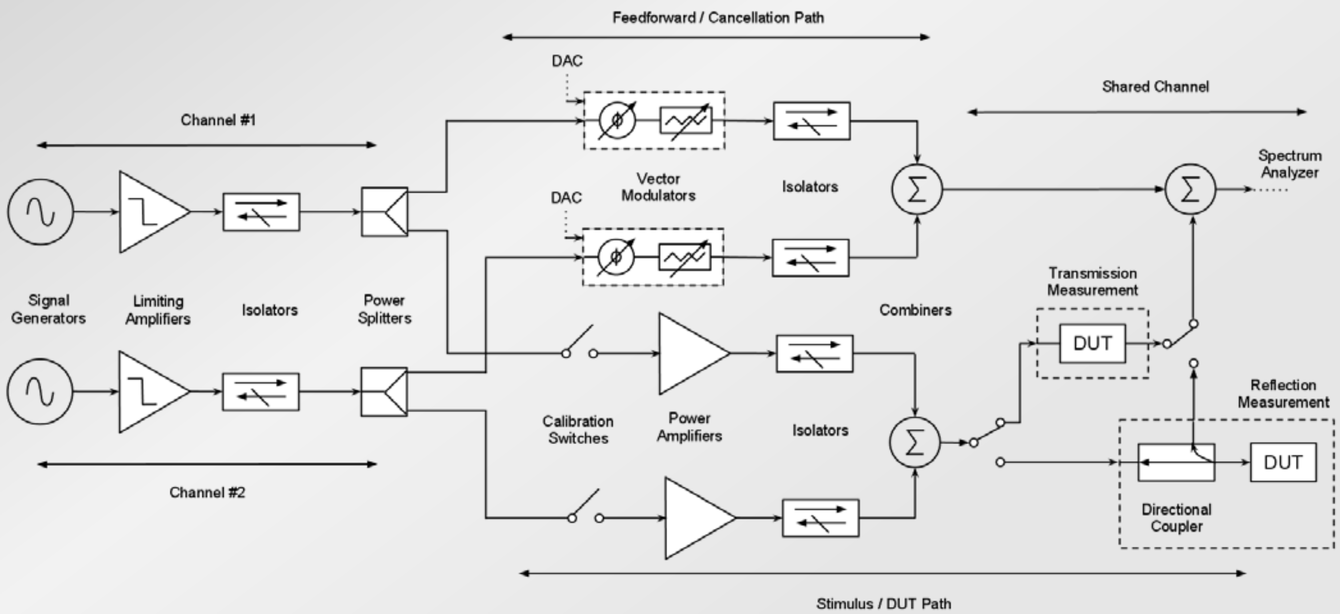


High Dynamic Range Measurement

- Limits on Dynamic Range:
  - RF signal source spurious leakage
    - Suppressed inherently through cancellation
  - Coupling of external RF emissions
    - Suppressed through RF shielding/isolation
  - AC power supply leakage
    - Eliminate by using DC power (i.e. batteries)
  - System thermal noise
- Ultimate limit on cancellation: quantization error
  - Quantization in DAC leads to finite resolution for VM output step
    - Can be improved with attenuation at a cost to dynamic range
  - Quantization in receiver leads to finite resolution for measurement
    - Calibration accuracy cannot exceed measurement accuracy

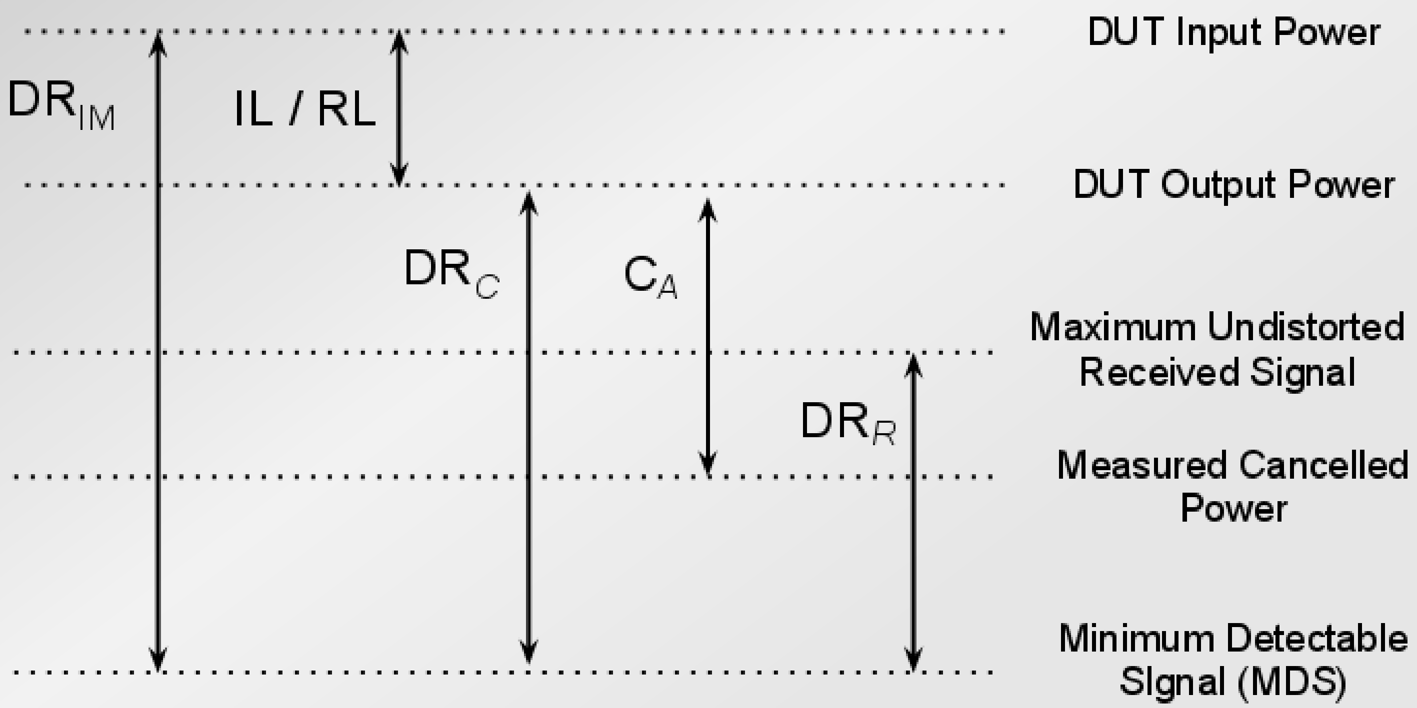
Two-Tone IMD Measurement

- Two-tone IMD measurement system built using separate cancellers for each channel
- Can be used for transmission or reflection



Intermodulation Dynamic Range, DR_{IM}

- The change in reference makes DR_{IM} theoretically independent of DUT characteristics and system configuration.

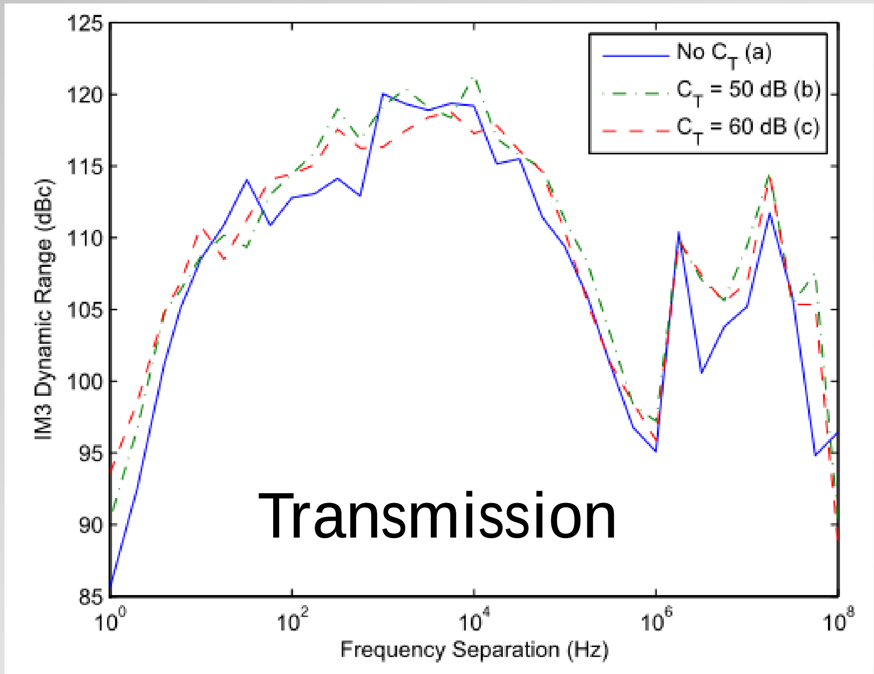


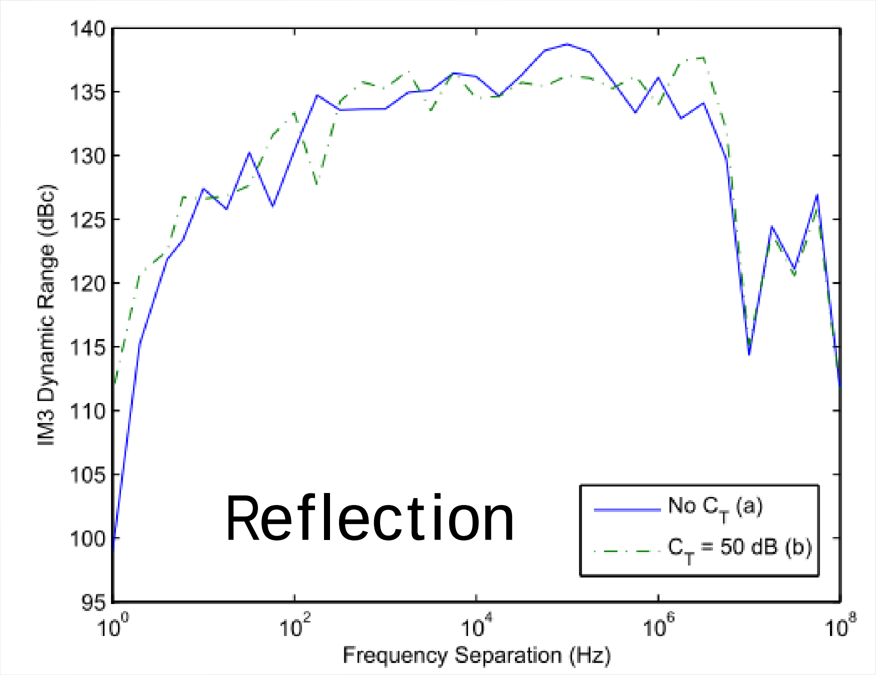
Two-Tone IMD Measurement

- Key to high dynamic range: linearity
  - Isolators reduce undesired mixing of channels through reverse path
  - Minimize external spurious content
    - External RF coupling, AC supply leakage
  - Low-PIM components:
    - Silver-plated
    - Physically large
    - Distributed implementations
- Bandwidth Limitations:
  - Isolators (typically half-octave):
    - Narrowest bandwidth in system, but only limits frequency range of a single channel
  - Shared channel components
    - Wider bandwidth than isolators but must include entire frequency range from lower IM product to upper IM product
  - Bandwidth limitations only affect maximum tone separation; system emphasis is on very small tone separation (to 1 Hz)

Measured Results (DR_{IM3})

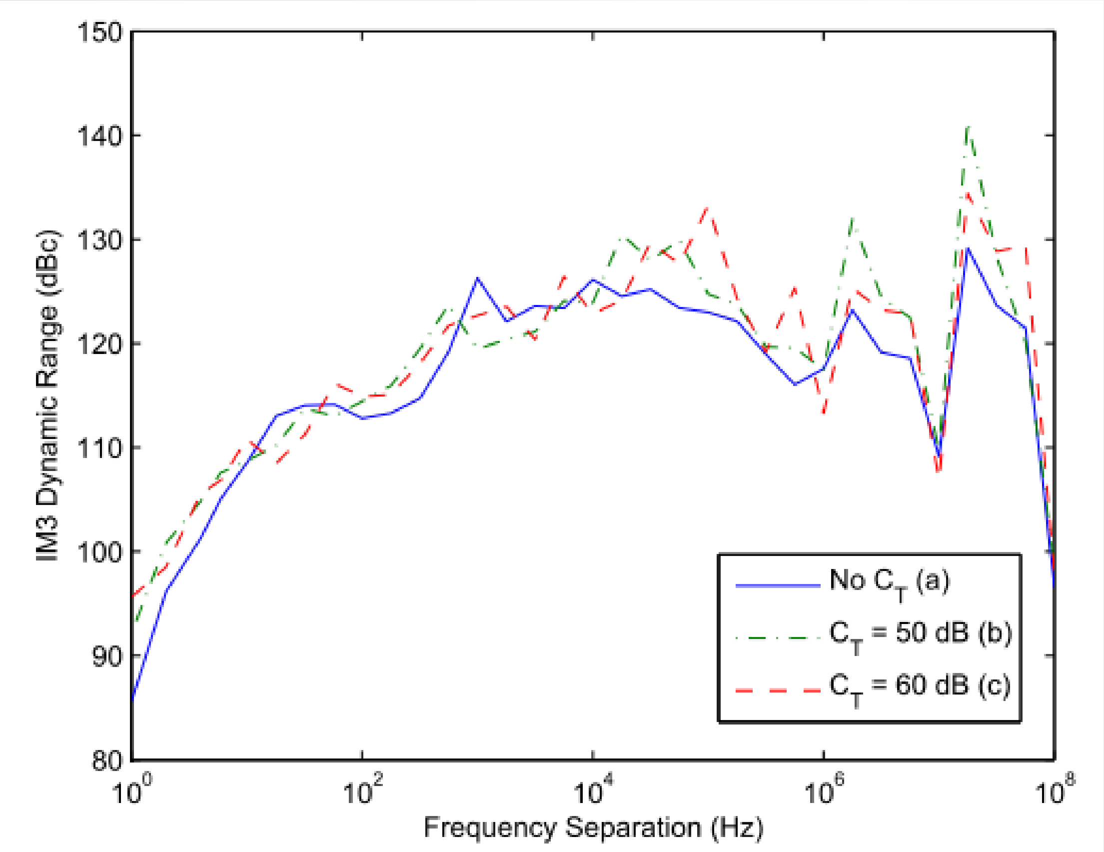
- 460 MHz with an input power of 26 dBm.





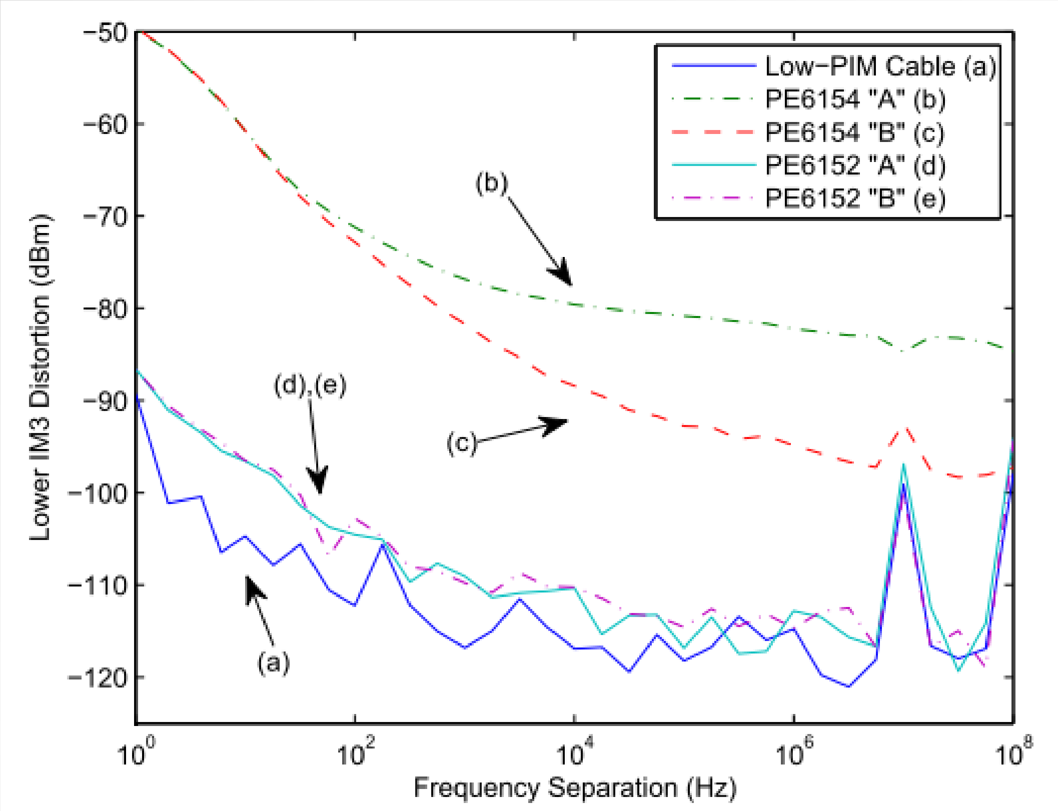
Measured Results (DR_{IM3})

- Spurious tone at 1 MHz only shows up in upper IM3 in transmission
  - Source currently unknown



Measured Results (PIM)

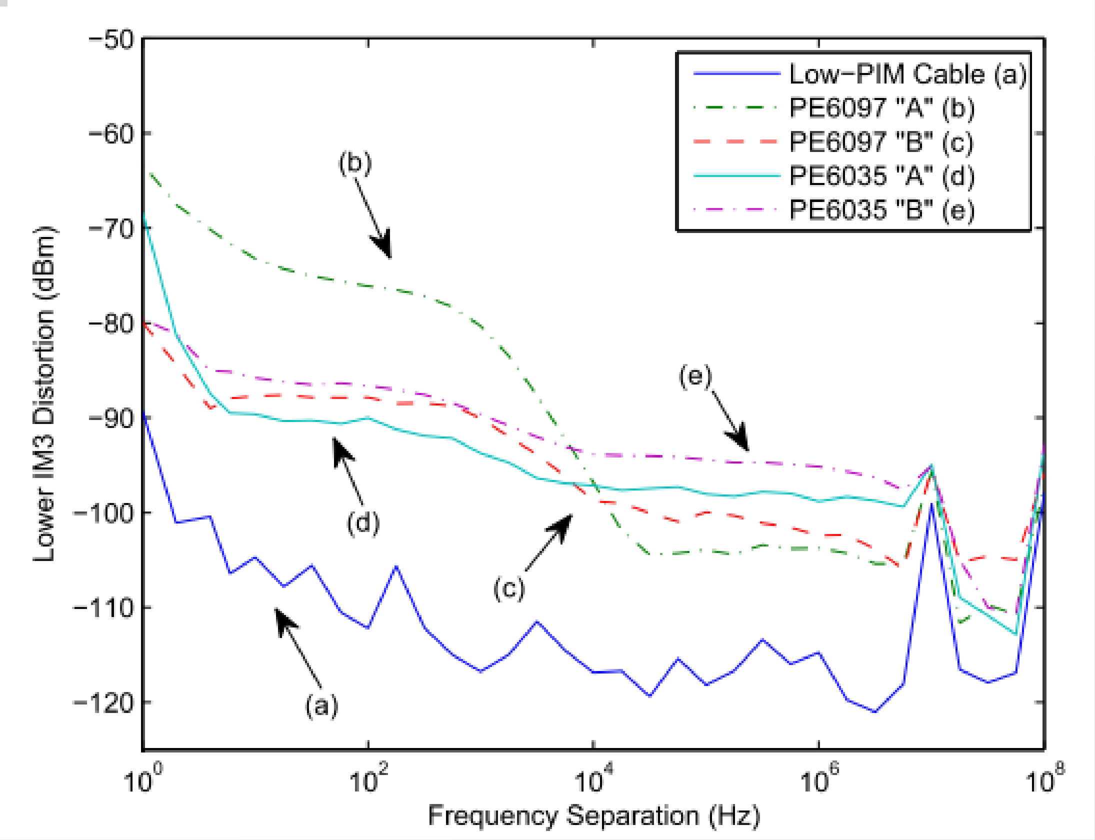
- Pasternack PE6154, PE6152
  - Standard 2W terminations, similar form-factor



Lower IM3

Measured Results (PIM)

- Pasternack PE6097 (5W), PE6035 (10W)
  - High power, terminations with large “finned” aluminum heatsinks



Lower IM3

Summary PIM Measurement

- Analog Canceller
  - Minimum DR_{IM3} :
    - Transmission: 94 dBc at 1 Hz (C_T = 60 dB)
    - Reflection: 111 dBc at 1 Hz (C_T = 50 dB)
  - Minimum DR_{IM3} between 100 Hz – 30 kHz:
    - Transmission: 113 dBc (C_T = 60 dB)
    - Reflection: 130 dBc (C_T = 50 dB)
  - Limited improvement with additional cancellation except at $\Delta f < 10$ Hz
    - At these tone separations, the MDS is the phase noise off the carrier signals: extra cancellation directly reduces the MDS, improving DR_{IM3}
  - Spurious tones reduce performance at 10 MHz, and 100 MHz
    - Sources currently unknown

References

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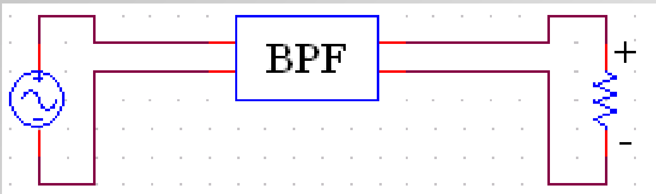
- A. Christianson and W. Chappell, “Measurement of ultra low passive intermodulation with ability to separate current/voltage induced nonlinearities,” *2009 IEEE MTT-S Int Microwave Symp Digest*, 7-12 June 2009, pp. 1301-1304.
- J. R. Wilkerson, K. G. Gard, and M. B. Steer, “Automated broadband high-dynamic-range nonlinear distortion measurement system,” *IEEE Trans. Microwave Theory and Techniques*, vol. 58, no. 5, pp. 1273-1282, May 2010.
- J. Henrie, A. Christianson, W. J. Chappell, “Prediction of passive intermodulation from coaxial connectors in microwave networks," *IEEE Trans. Microwave Theory and Techniques*, vol. 56, no. 1, pp. 209-216, Jan. 2008.
- J. R. Wilkerson, K. G. Gard, A. G. Schuchinsky, and M.B. Steer, “Electro-thermal theory of intermodulation distortion in lossy microwave components,” *IEEE Trans. Microwave Theory and Techniques*, vol. 56, no. 12, pp. 2717-2725, Dec. 2008.
- J. R. Wilkerson, P. G. Lam, K. G. Gard, and M.B. Steer, “Distributed passive intermodulation distortion on transmission lines,” *IEEE Trans. Microwave Theory and Techniques*, vol. 59, no. 5, pp. 1190-1205, May. 2011.
- J. R. Wilkerson, K. G. Gard, and M.B. Steer, “Electro-thermal passive intermodulation distortion in microwave attenuators," *Proc. 36th Eur. Microwave Conf.*, 10-15 Sept. 2006, pp. 157-160

Time-Frequency Effect Filter PIM

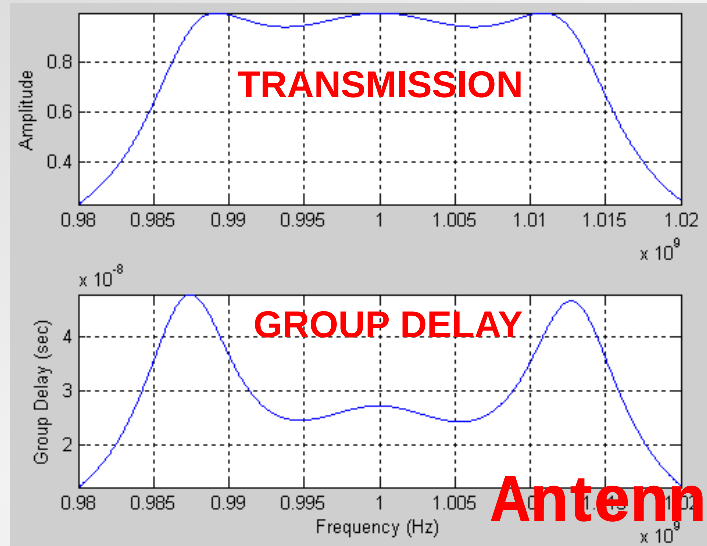
Delay Effects in Filters

BANDPASS FILTER



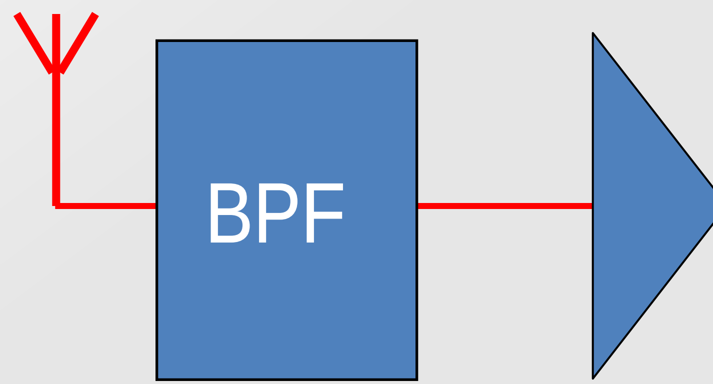
SOURCE

LOAD

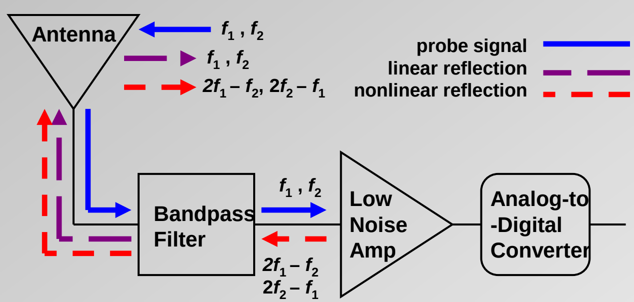


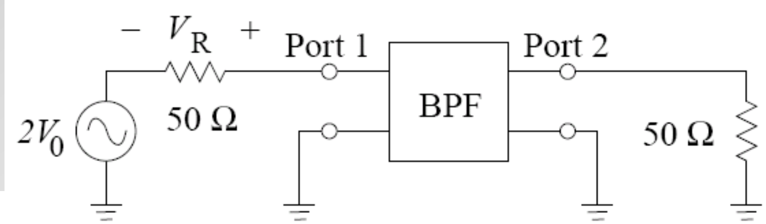
Thesis:
Can we use variation in group delay to develop an optimum waveform to create large nonlinear effects.

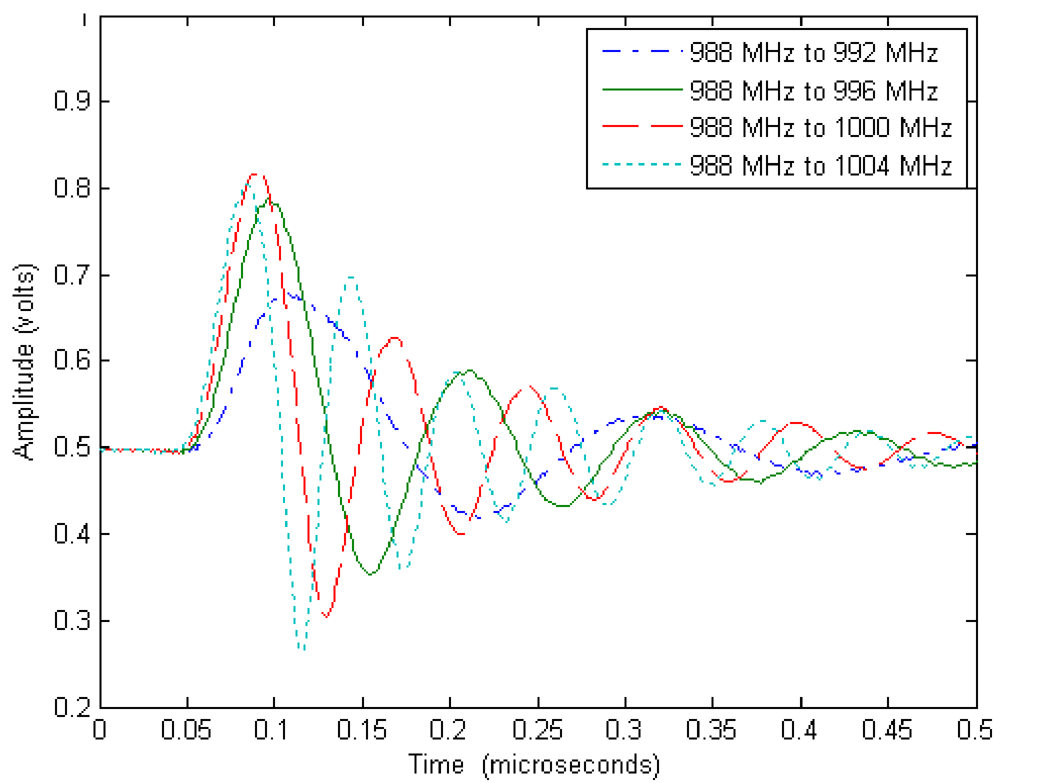
Antenna

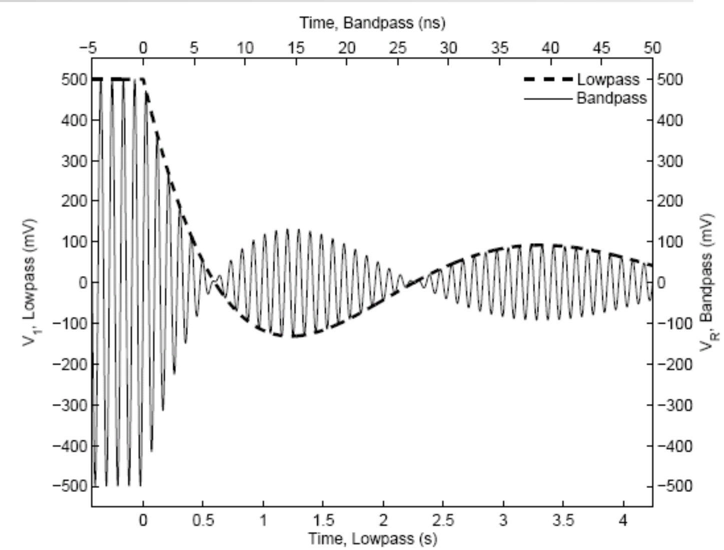


Switched Tone Response of a Filter

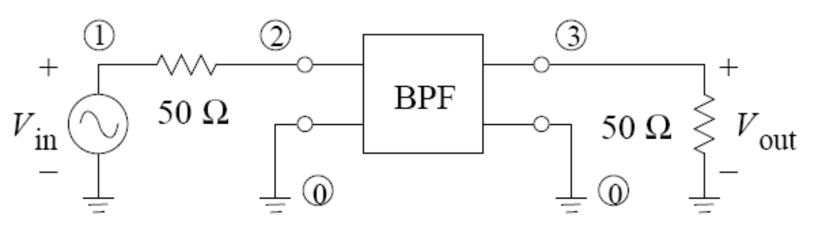


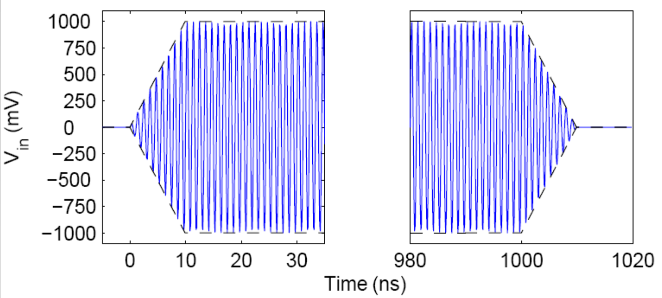


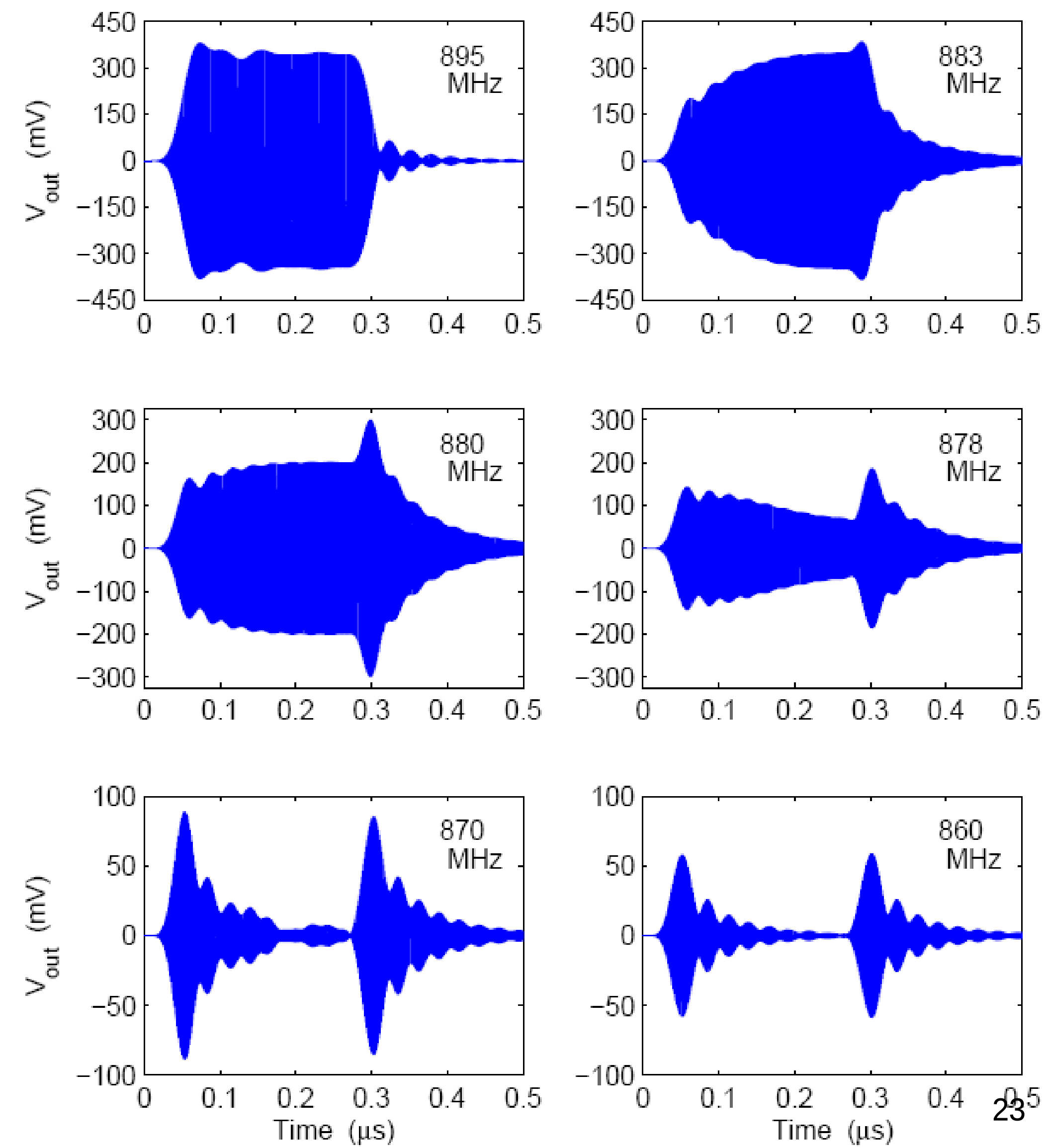




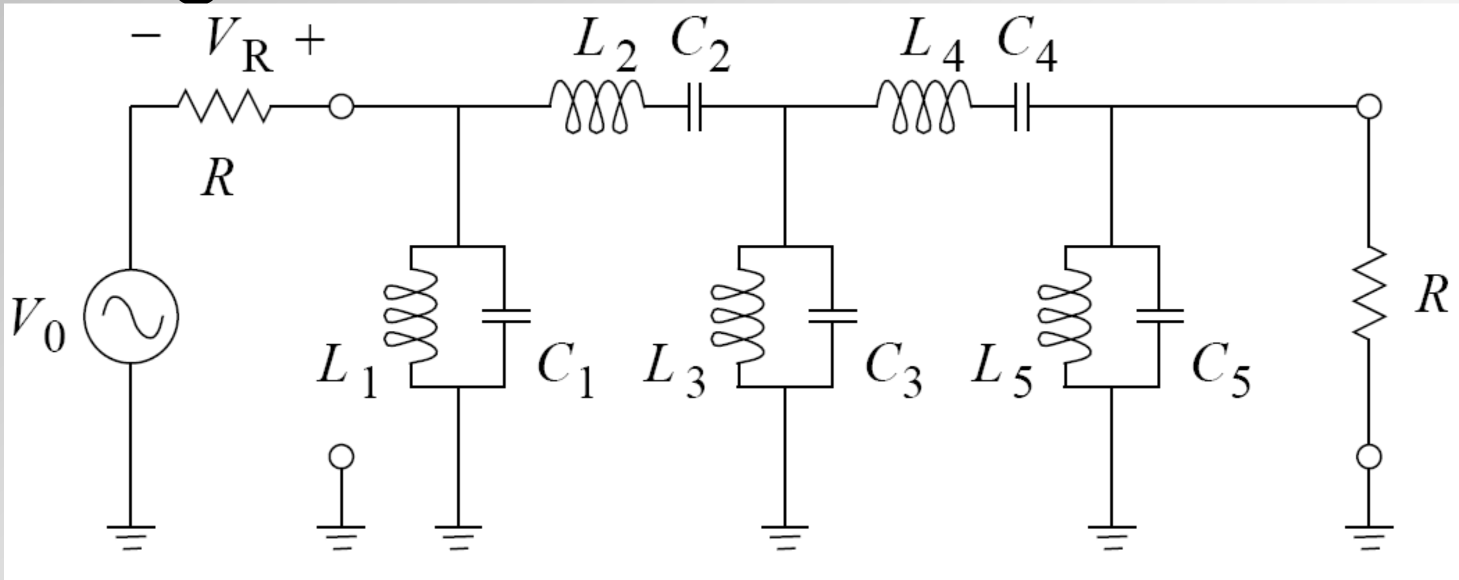
Time-Frequency Response of a Filter

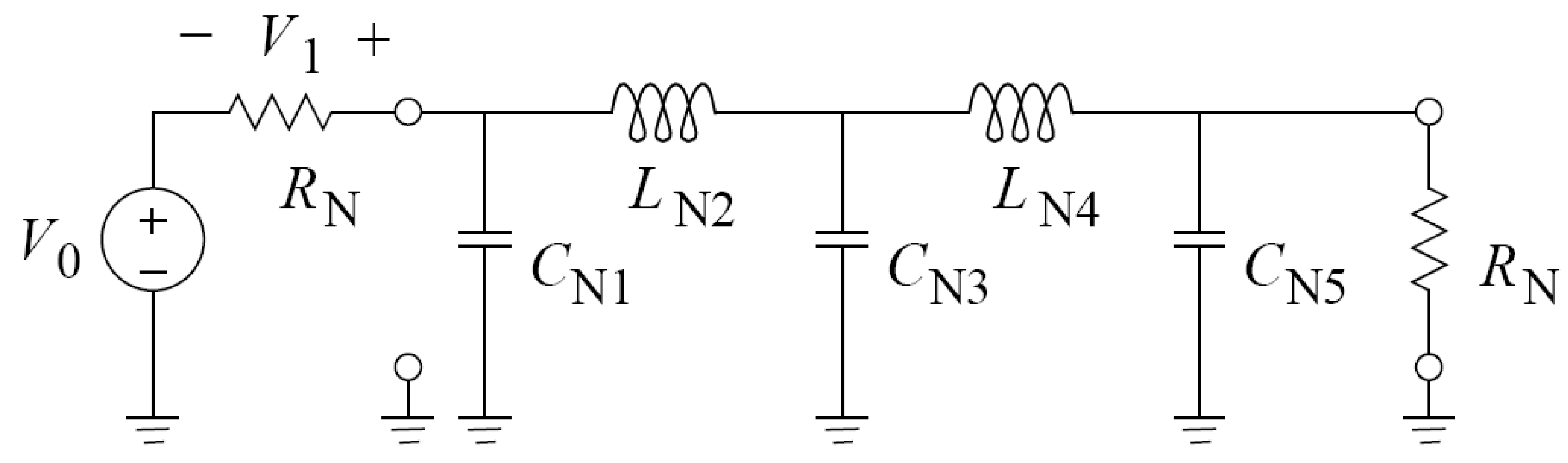




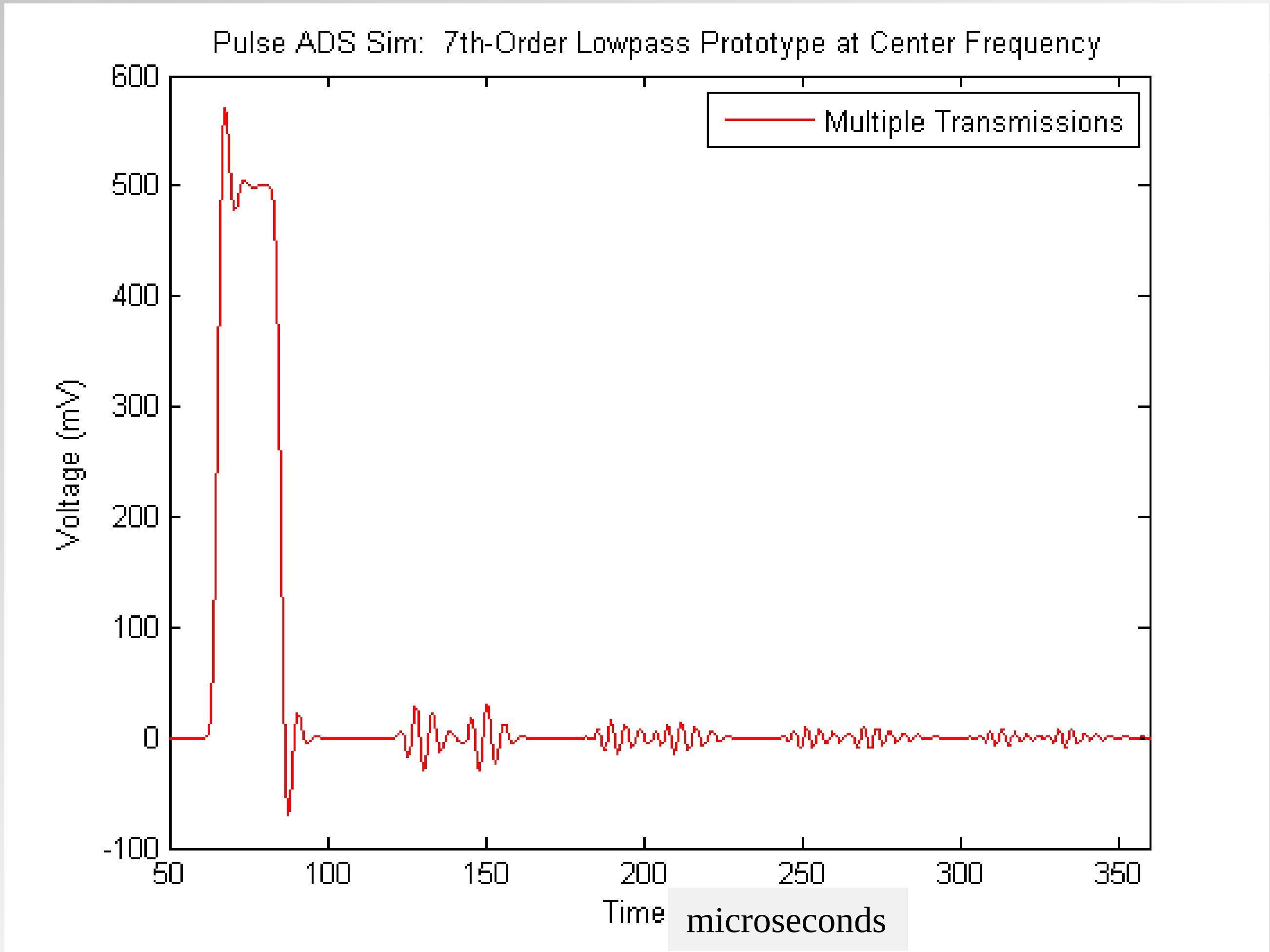


Modeling





Memory Effect



Linear PIM

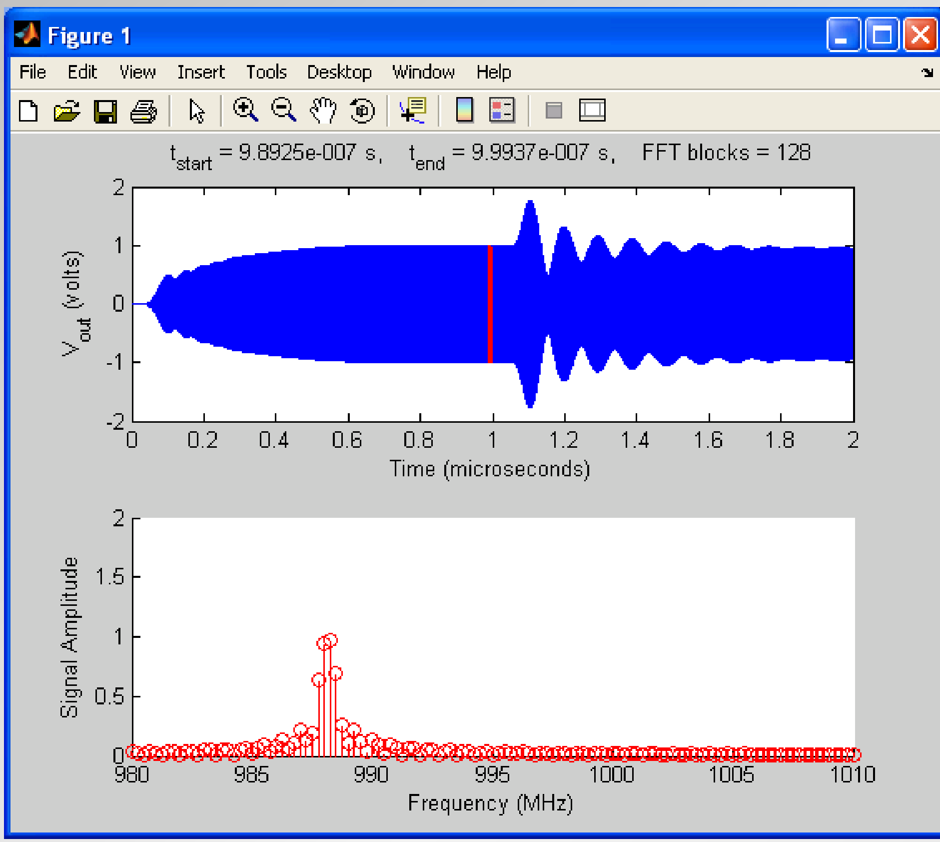


Figure 1
File Edit View Insert Tools Desktop Window Help
t_start = 9.8925e-007 s, t_end = 9.9937e-007 s, FFT blocks = 128
V_out (volts)
Time (microseconds)
Signal Amplitude
Frequency (MHz)

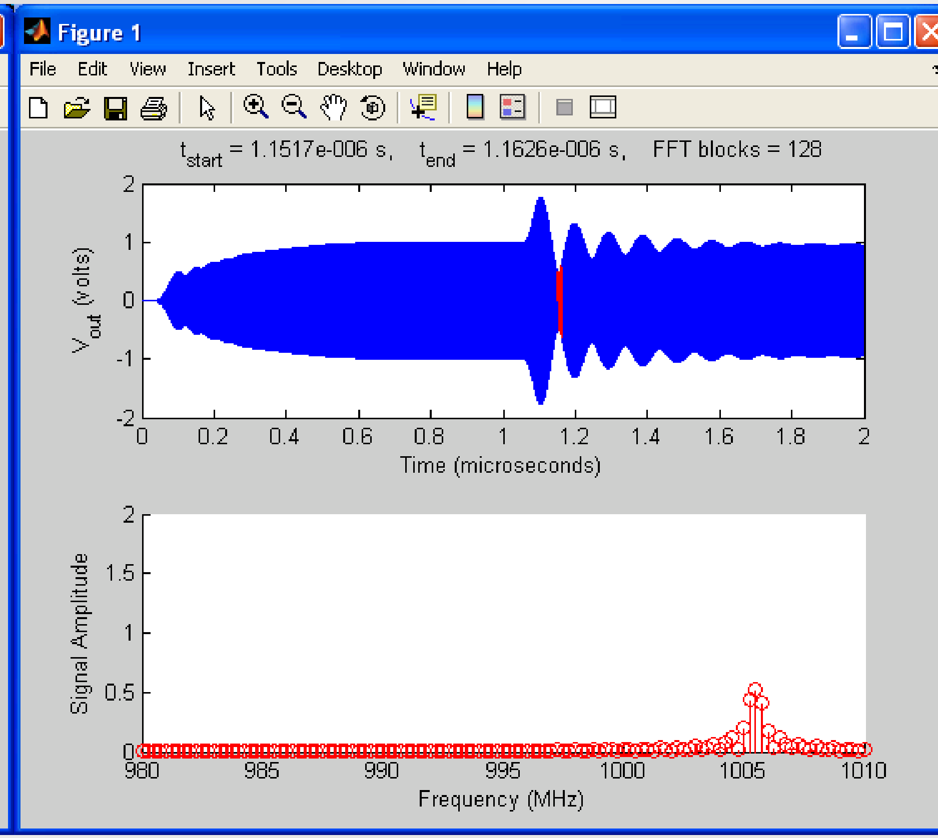
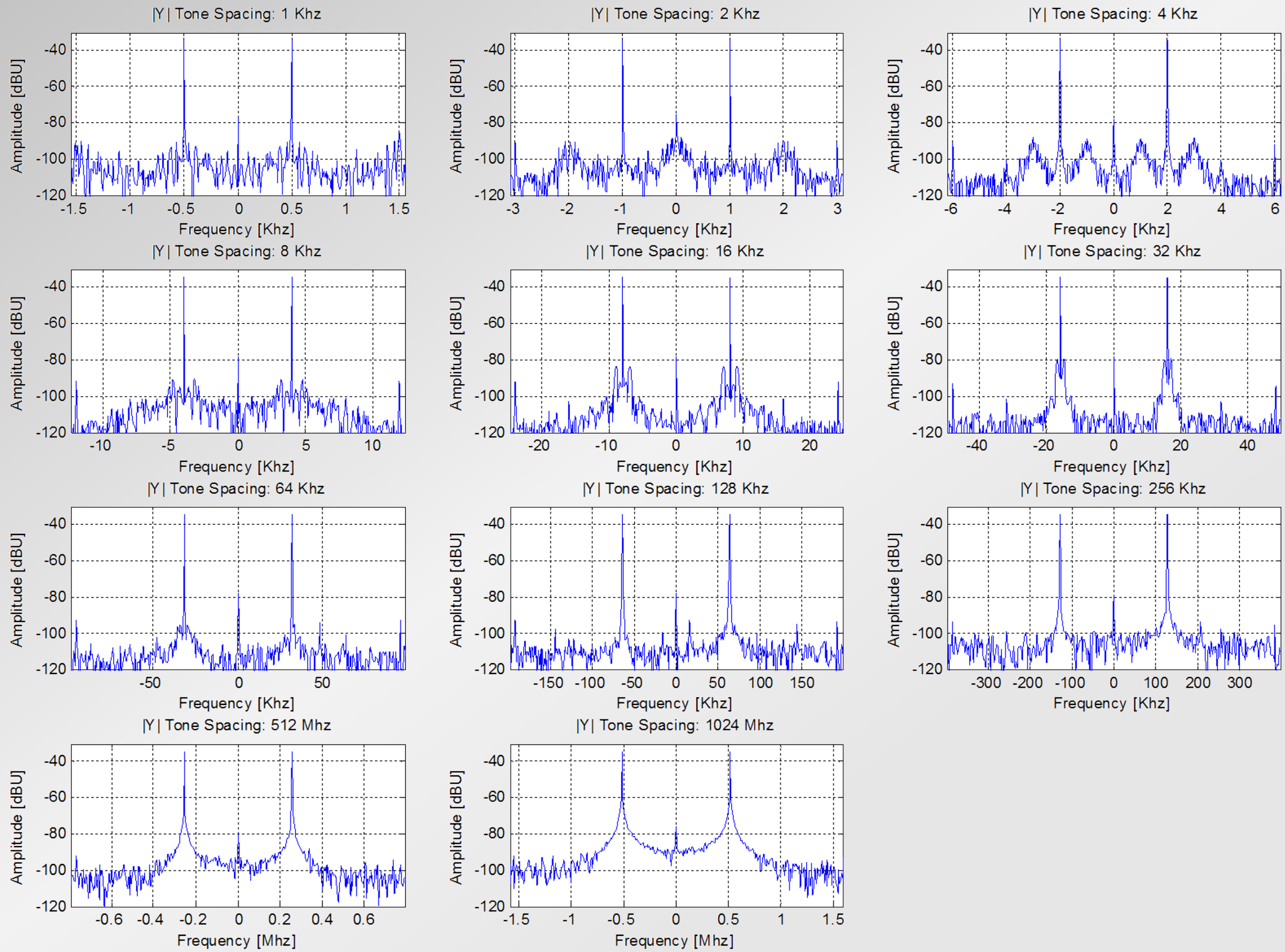


Figure 1
File Edit View Insert Tools Desktop Window Help
t_start = 1.1517e-006 s, t_end = 1.1626e-006 s, FFT blocks = 128
V_out (volts)
Time (microseconds)
Signal Amplitude
Frequency (MHz)

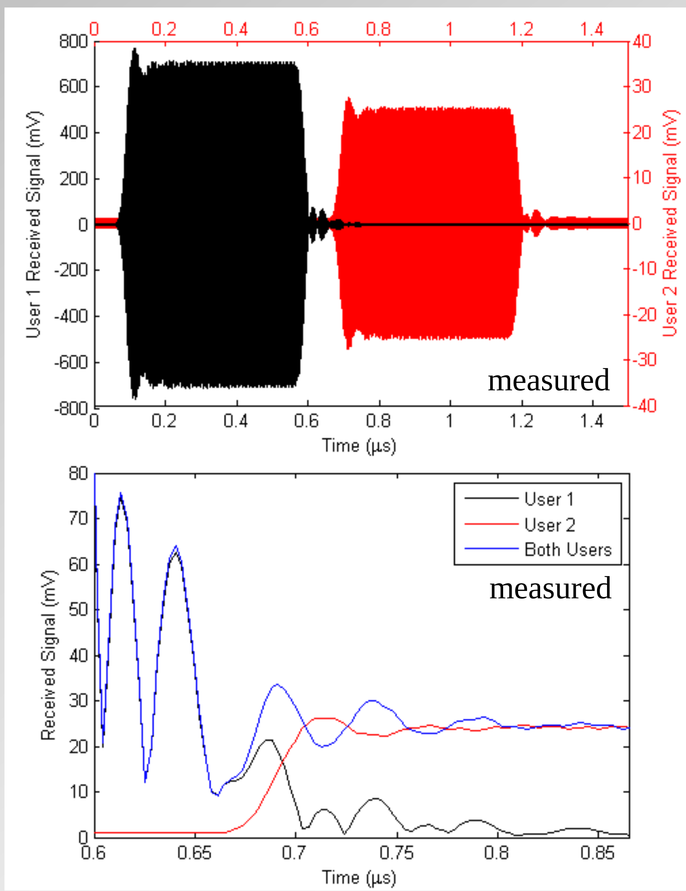
Stepped Two-tone Signals

Frequency separation stepped logarithmically from 1 kHz to 1 MHz

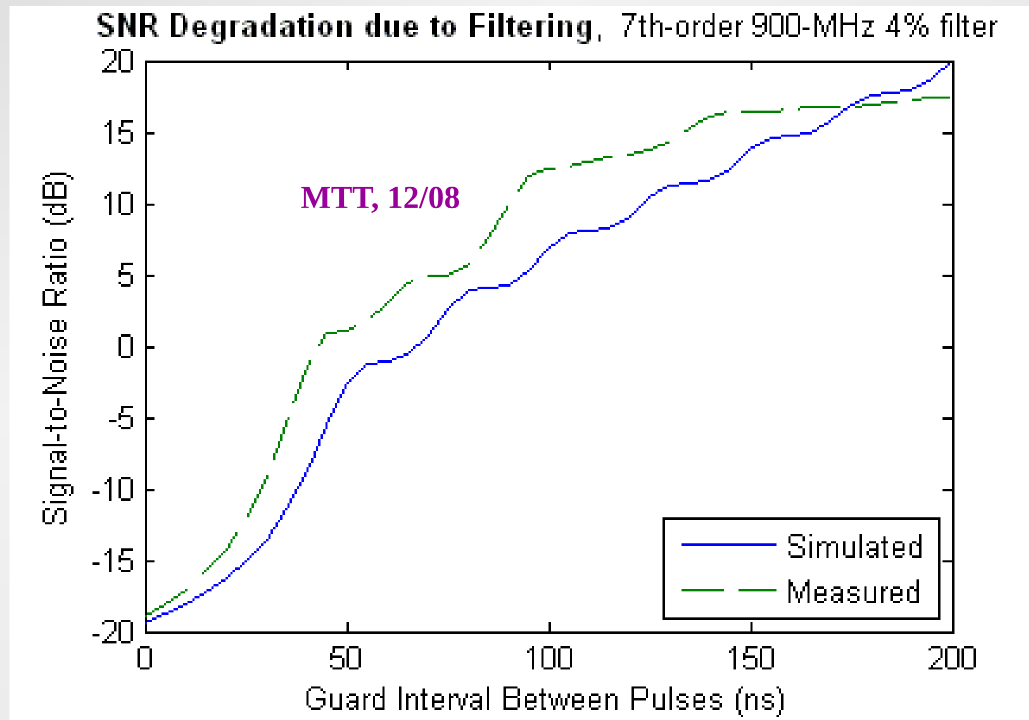


Time-Frequency Effects: Linear Transient Distortion

- What are the effects of these transients on wireless communications?
  - ➢ sharp filtering can degrade received signal-to-noise ratio



Filtered <u>frequency-hopping</u> pulses, 900-MHz 4% filter
User 1 at 10 dBm, User 2 at -20 dBm
900 MHz, 100 ns guard interval



Nearest work:
Chohan/Fidler (1973) -- impact on FSK & PSK, no metric

Time-Frequency Effects: Linear Metrology

- How do we measure parameters of coupled resonator circuits?
  - the Q factor of the outer resonators in a chain may be determined with time-domain analysis

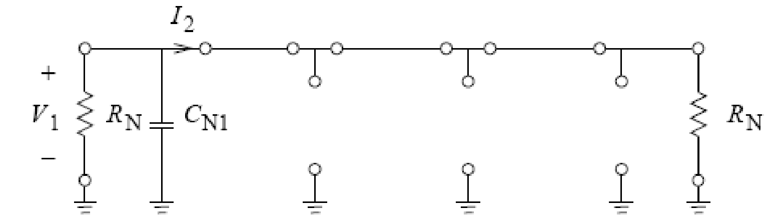
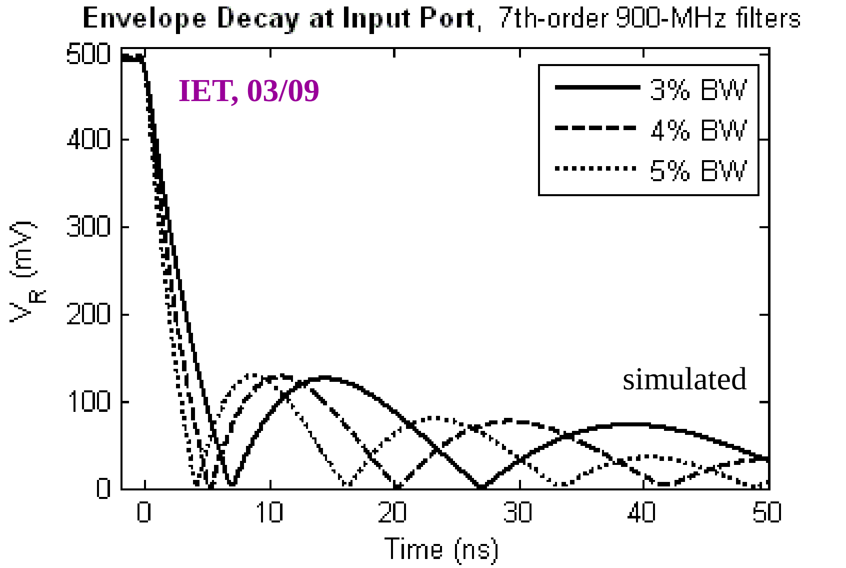


Figure 5: Equivalent lowpass circuit after source is zeroed

$$\frac{dV_1(0)}{dt_N} = -\frac{V_1(0)}{R_N C_{N1}} - \frac{I_2(0)}{C_{N1}} = -\frac{2}{R_N C_{N1}} V_1(0)$$

$$\tau = \frac{t}{\ln\left(V_0^2\right) - \ln\left(V_R^2(t)\right)}$$



900-MHz stimulus tone turned off at t = 0 ns

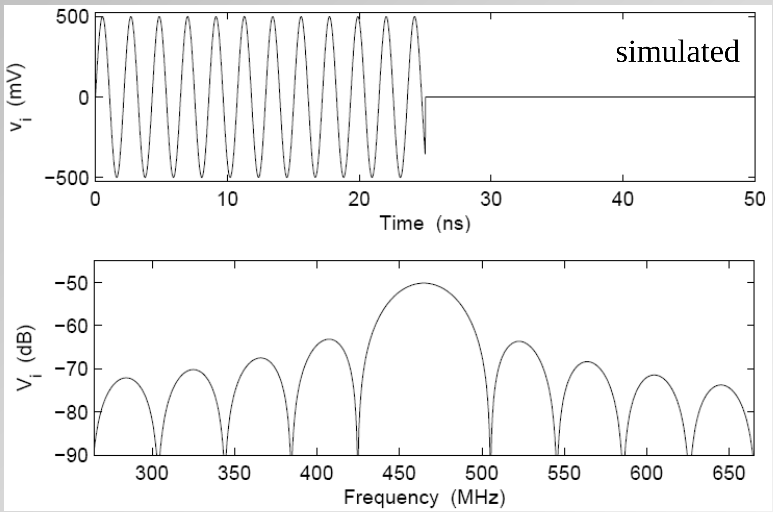
Table 2: Measured Q-Value Estimation, 900 MHz Chebyshev Design

Filter Order	BW	Passband Ripple (dB)	2-Port Q Value	1-Port Q Value
7	4%	0.01	23.3	24.6
	5%	0.01	18.4	20.1

Nearest prior work:
Pereda (1992) -- Prony analysis, dielectric resonators, not a 'coupled' structure

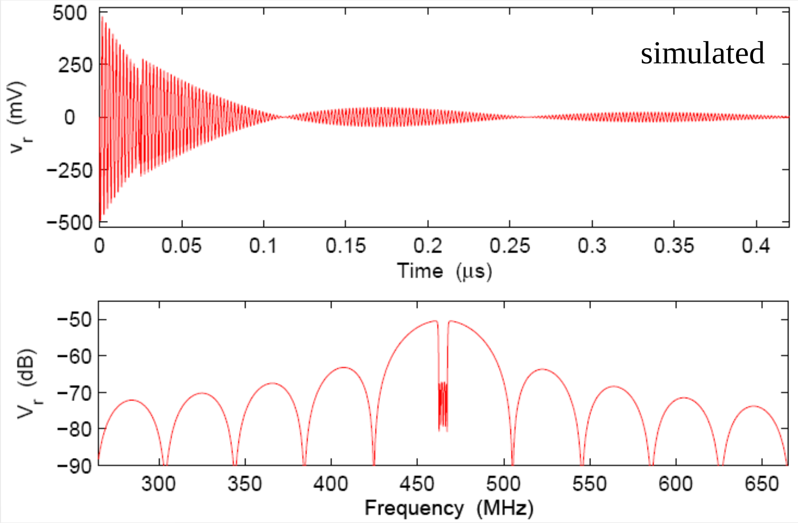
Time-Frequency Effects: Linear Metrology

- How else can we exploit transients for metrology?

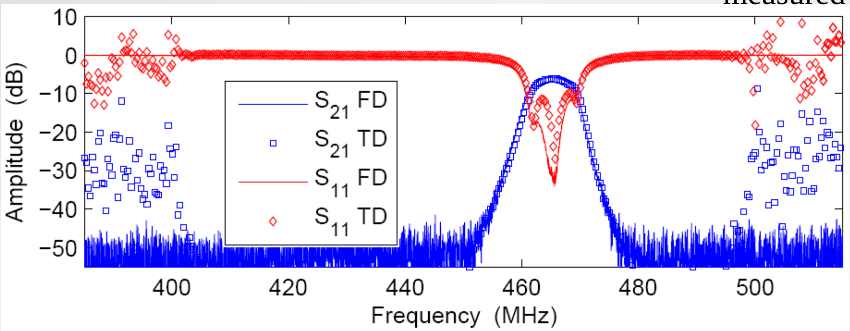


Time- & frequency-domain views, short pulses
465-MHz 1% Chebyshev filters

➢ 2-port *S*-parameters can be extracted from short-pulse time-domain responses



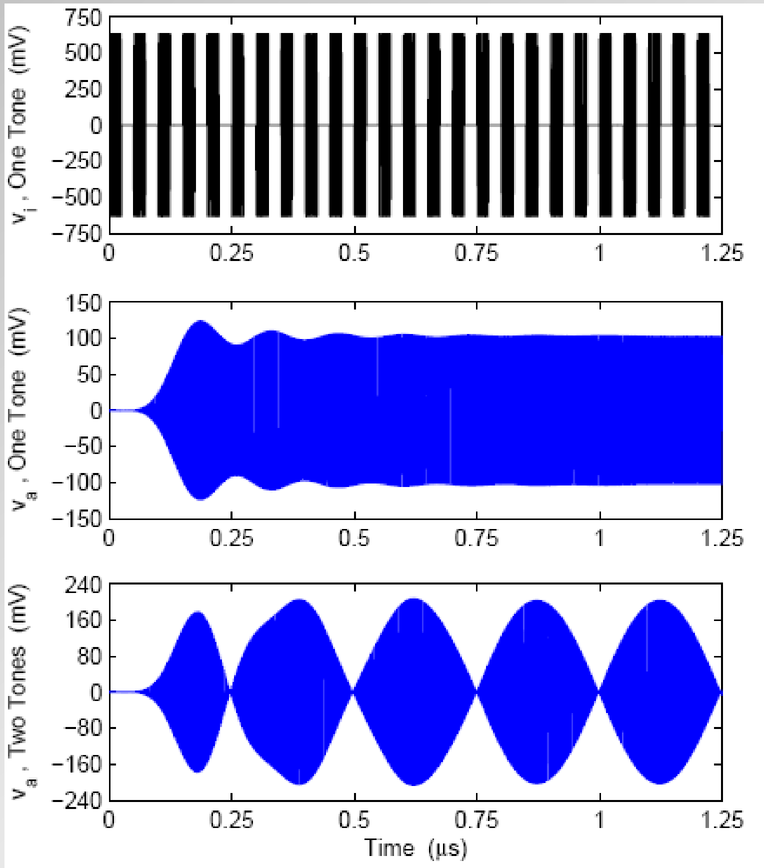
measured



Nearest prior work:
Courtney (1999) –
permittivity measurements,
nanosecond impulses

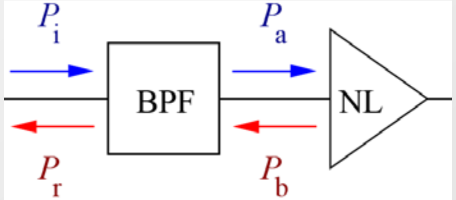
Time-Frequency Effects: Nonlinear Metrology

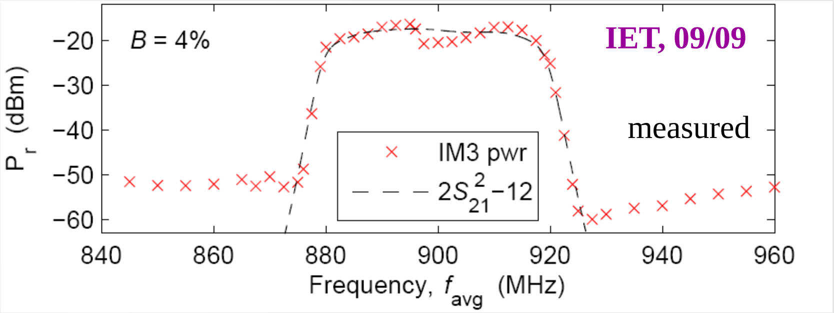
- **Can we exploit filter properties for <u>nonlinear</u> measurements?**



Simulated fast-switching filter response
7th-order 465-MHz Chebyshev design
(a) input, 1 tone, (b) output, 1 tone, (c) output, 2 tones

- ➢ IP3 of an amplifier can be measured using a filter & switched-tone source
- ➢ a device's passband can be extracted from 1 port



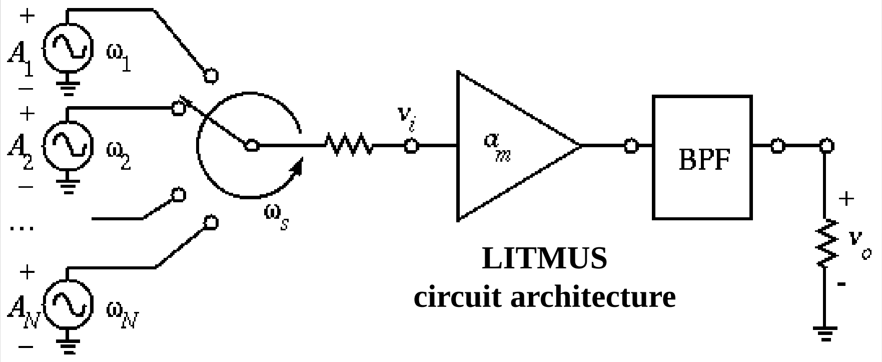


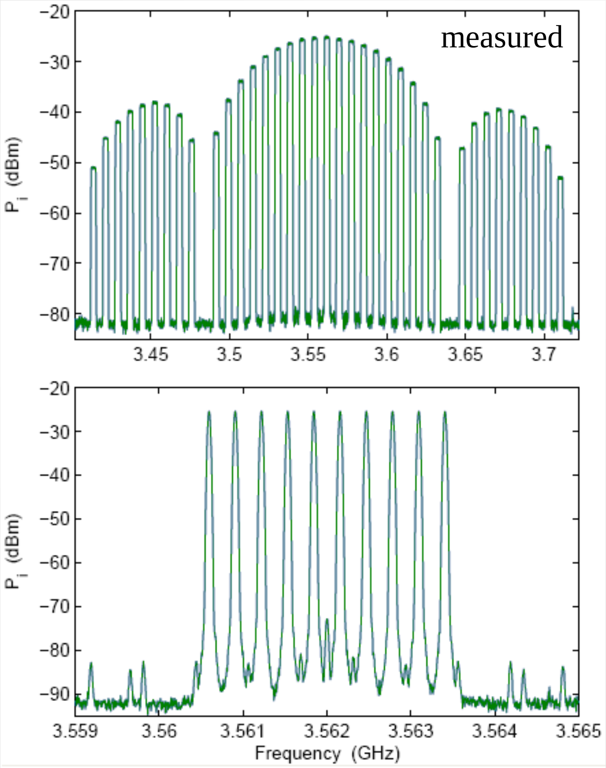
Passband extraction for bandpass filter
7th-order 900-MHz Chebyshev design

Nearest prior work: **Walker** (2005) – steady-state two-tone testing

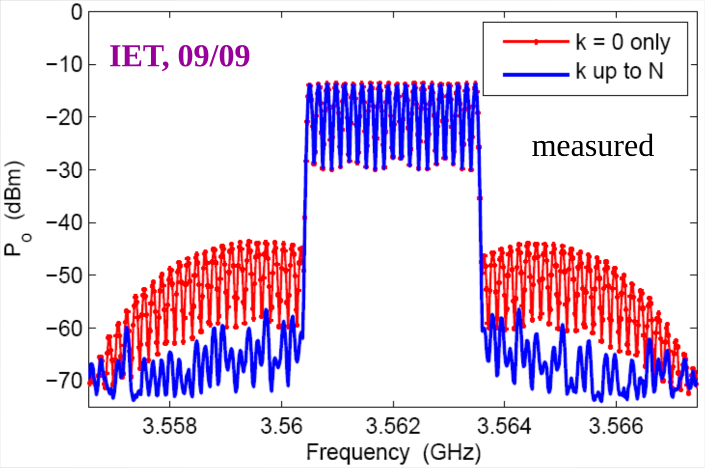
Linear Amplification by Time-Multiplexed Spectrum

- **How can we improve linearity by applying time-frequency techniques?**





Wideband & narrowband spectra for $N = 10$
generated by Agilent N6030A + QM3337A modulator



Distortion reduction for $N = 20$
non-multiplexed (red) vs. multiplexed (blue)
Ophir 5162 amplifier

➢ the IMD associated with amplitude modulation can be reduced by trading signal bandwidth for smaller Peak-to-Amplitude Ratio

Summary: Time-Frequency Effects

Narrowband transients last longer than expected.

co-site interference

(a) identified resonant cascade as a source of long tails
(b) developed a differential-equation simplification
(c) showed frequency-dependence of the tails causes pulse overlap
(d) evaluated ISI and IMD for frequency-hopping scenarios

Used filter transients to develop new measurement techniques:

non-destructive testing

(a) *Q*-factor of a single resonator
(b) bandwidth, without *S*-parameters
(c) broadband *S*-parameters from a single time-domain trace
(d) device passband from a single input port

Time-multiplexing & filtering — LITMUS:

reduces IMD associated with amplitude modulation

transmitter linearity

Summary

- High dynamic range measurement system
- Time-Frequency effects produce apparent PIM

Review of Time-Frequency Effects

Time-Frequency Effects: Tucker/Eaglesfield (1946)

- **commonly-used 6-element bandpass filter**

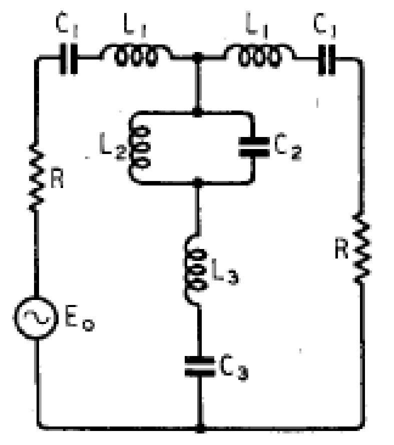


Fig. 3. *6-element symmetrical filter.*

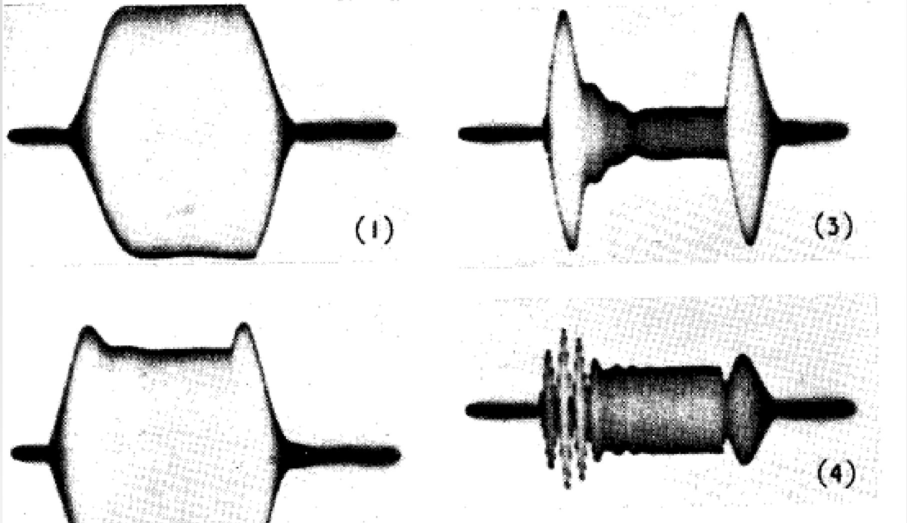


Fig. 6. *Pulse waveforms in 6-element filter section (bandwidth = 100 c/s); applied frequencies,* (1) 2,650 c/s = *mid-band,* (2) 2,600 c/s, (3) 2,550 c/s, (4) 2,400 c/s.

Filtered Pulse Responses

- while analyzing *non-ideal* (transmission-characteristic) filters…
- oscilloscopes can capture filtered pulse envelopes
- differential operators (precursor to Laplace Transforms) can be used to solve for analytical forms for pulse responses

"Transient response of filters," *Wireless Engineer*, Vol. 23, pp. 36-42 & 84-90, Feb-Mar. 1946

Time-Frequency Effects: Hatton (1951) & McCoy (1954)

- amplitude transients
  & frequency transients
  for a single resonator

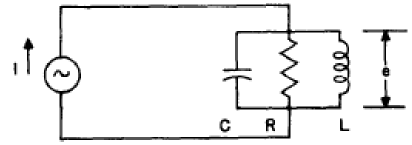


Fig. 1

Circuit used in calculations. $i(t) = \cos \omega_1 t$, $t < 0$; $i(t) = \cos \omega_2 t$, $t > 0$; center frequency of tuned circuit $= \omega_3$; bandwidth of tuned circuit $= 2/T$; $\omega_1 = \omega_3 - k_1/T$; $\omega_2 = \omega_3 + k_2/T$.

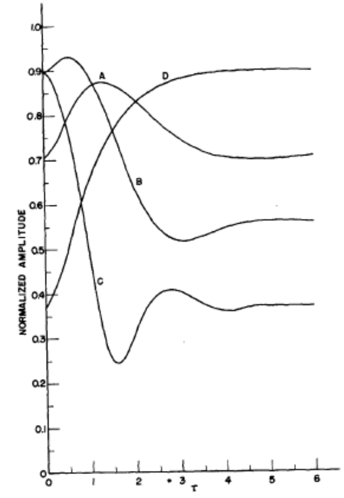


Fig. 6

Typical amplitude transient accompanying the frequency transients for various amounts of decentering. All jumps have size 2/T. Curve A: decentering = 0. Curve B: decentering = + 1/2. Curve C: decentering = + 1 1/2. Curve D: decentering = - 1 1/2.

Normalized Amplitude Transients

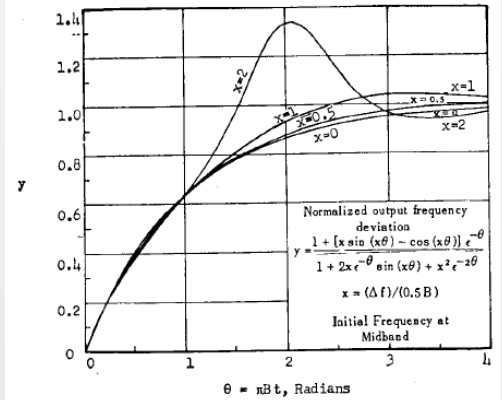


Fig. 2—Response of a single tuned circuit to a rectangular-step frequency shift, starting at midband frequency.

Normalized Frequency Transients

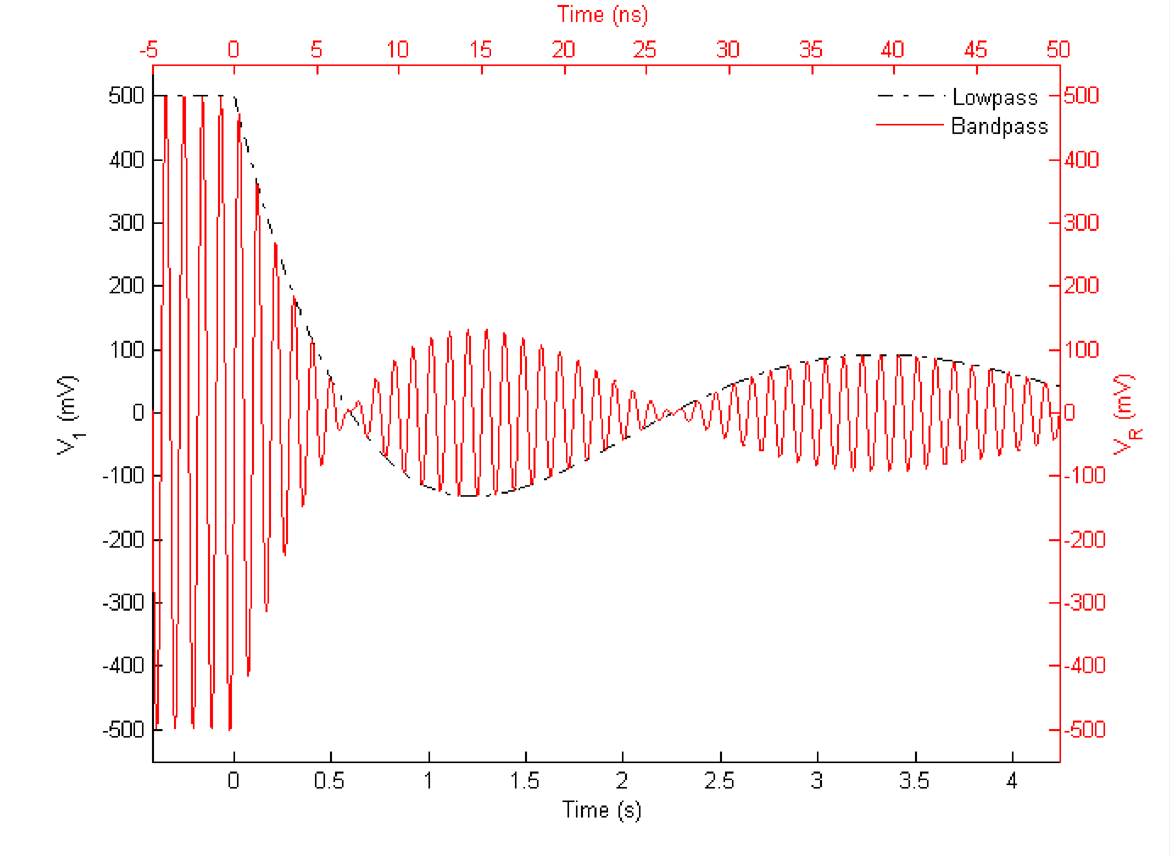
- while comparing frequency-modulation to amplitude-modulation…
- overshoots in amplitude & frequency are possible
  for input frequency transitions within a filter's passband

"Simplified FM transient response," MIT, Cambridge, MA, Tech. Rep. 196, Apr. 1951
"FM transient response of band-pass circuits," *Proc. IRE*, vol. 42, no. 3, pp. 574-579, Mar. 1954

Time-Frequency Effects: Blinchikoff (2001)

- Lowpass vs. bandpass transient responses

$$u_b(t) \approx u_l(t_N)\cos(\omega_0 t + \theta)$$



- ➢ transient response at midband is a time-scaled version of the lowpass turn-on response

Filtering in the Time and Frequency Domains, Raleigh, NC: SciTech Publishing, Inc., 2001.

Time-Frequency Effects: Chohan/Fidler (1973)

- **frequency transients, steps of phase/frequency at filter input**

➢ while investigating filtering effects on FSK- and PSK-type signals…

➢ generalized earlier narrowband Laplace methods for any order & any Q value

"Generalised transient response of bandpass transfer functions to FSK and PSK-type signals," *Electronics Letters*, vol. 9, no. 14, pp. 320-321, July 1973.

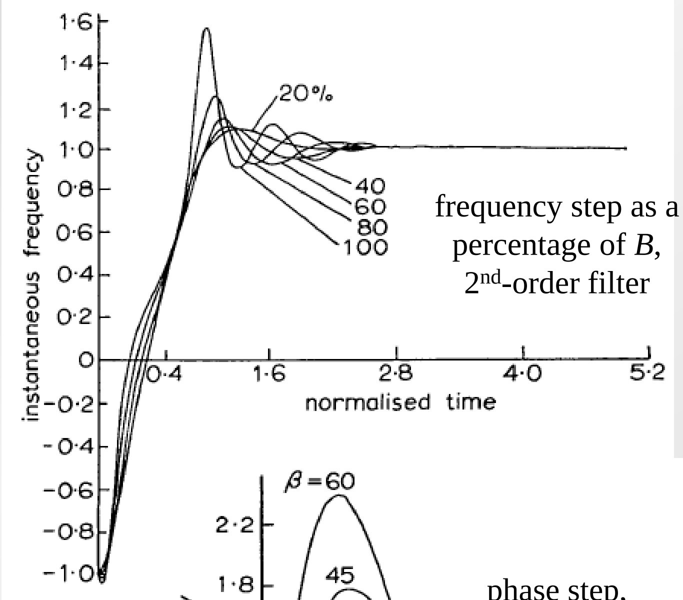


Fig. 1

frequency step as a percentage of *B*, 2nd-order filter

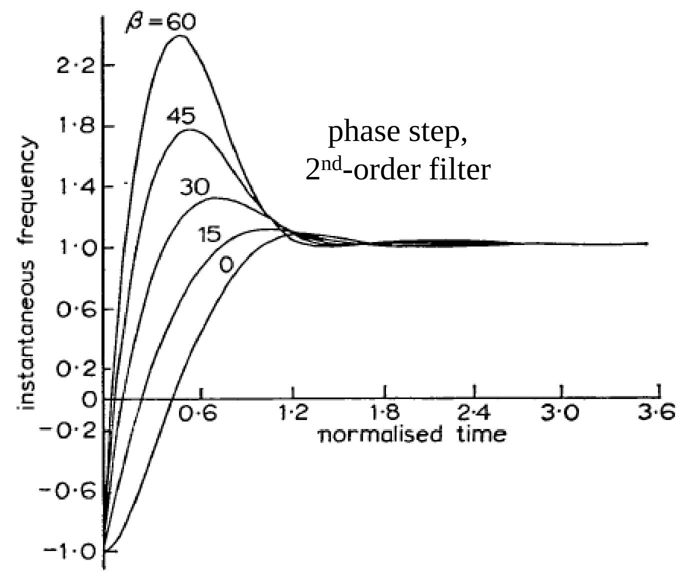


Fig. 2

phase step, 2nd-order filter

Normalized Frequency Transients

Time-Frequency Effects: Vendik/Samoilova (1997)

- resonators: transmission line & microstrip

  - attributed nonlinearities to
    (a) crystalline structure
    (b) charge carrier density
    (c) Abrikosov vortices

  - resistance is a function of current

$$R_1(x,t) = R_1\left[1 + \frac{I^2(x,t)}{I_0^2}\right]$$

"Nonlinearity of superconducting transmission line and microstrip resonator"
IEEE Trans. Microw. Theory Tech., vol. 45, no. 2, pp. 173-178, Feb. 1997.

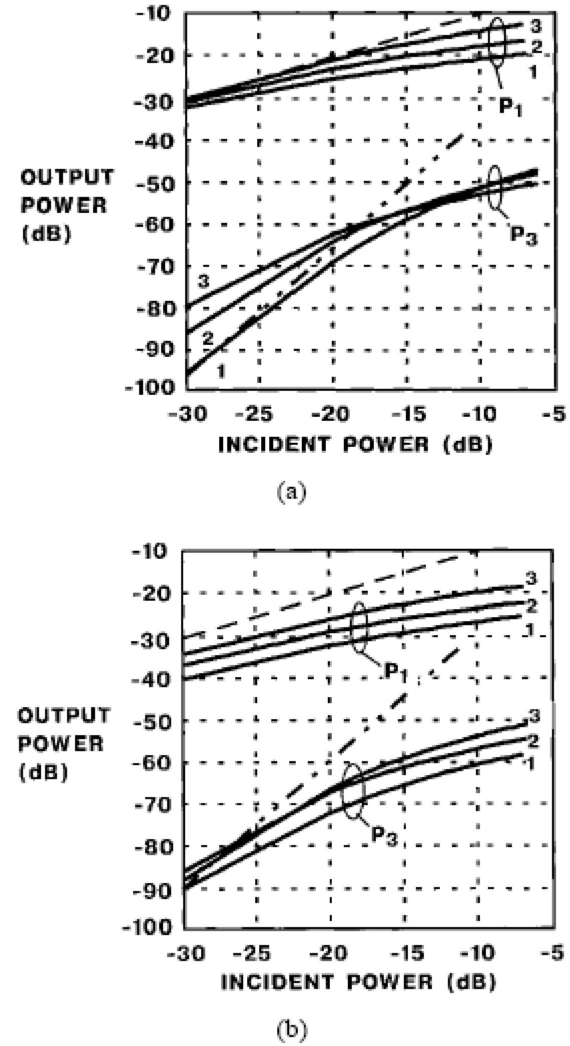


Fig. 7. Output power of first (P_1) and third (P_3) harmonics as functions of incident power P_{incid}. The power is normalized to the characteristic power P_0. (a) Q_u=10 000; Q_e: 1: 500, 2: 1000, 3: 2000; (b) Q_u=1000; Q_e: 1: 500, 2: 1000, 3: 2000. In the figure, dashed line corresponds to the slope of power 1; dashed-dotted line corresponds to the slope of power 3.

Time-Frequency Effects: Pereda (1992)

- estimation of quality factor from resonant decay

$$S(n\Delta t) = \sum_{i=1}^{p} A_i \exp\left((\alpha_i + j2\pi f_i) n\Delta t\right) \quad \text{for } n = 0, \cdots, N-1, \qquad (1)$$

Prony analysis

- while investigating resonance in dielectric resonators…
- reduced time to compute resonant frequencies and quality factor using FDTD and Prony analysis

TABLE I-A
COMPARISON OF THE RESONANT FREQUENCIES AND Q-FACTORS OF THE SIX LOWEST MODES OF AN ISOLATED DR OBTAINED BY VARIOUS METHODS. AXISYMMETRIC MODES

	TE_{01}		TM_{01}		TE_{02}	
	F(GHz)	Q	F(GHz)	Q	F(GHz)	Q
Moment Method [9]	4.829	45.8	7.524	76.8		
Null-Field Method [8]	4.8604	40.819	7.5384	76.921	8.3311	301.02
Measured [10]	4.85	51	7.60	86		
Present Method	4.862	47	7.524	71	8.320	302

"Computation of resonant frequencies and quality factors of open dielectric resonators by a combination of finite-difference time-domain and prony's methods," *IEEE Microwave and Guided Wave Letters*, vol. 11, no. 2, pp. 431-433, Nov. 1992.

Time-Frequency Effects: Dunsmore (1999)

- Time-domain coupled-resonator filter tuning
  - while working at Hewlett-Packard Microwave Instruments Division…
  - showed how to tune individual resonators using time-domain return loss

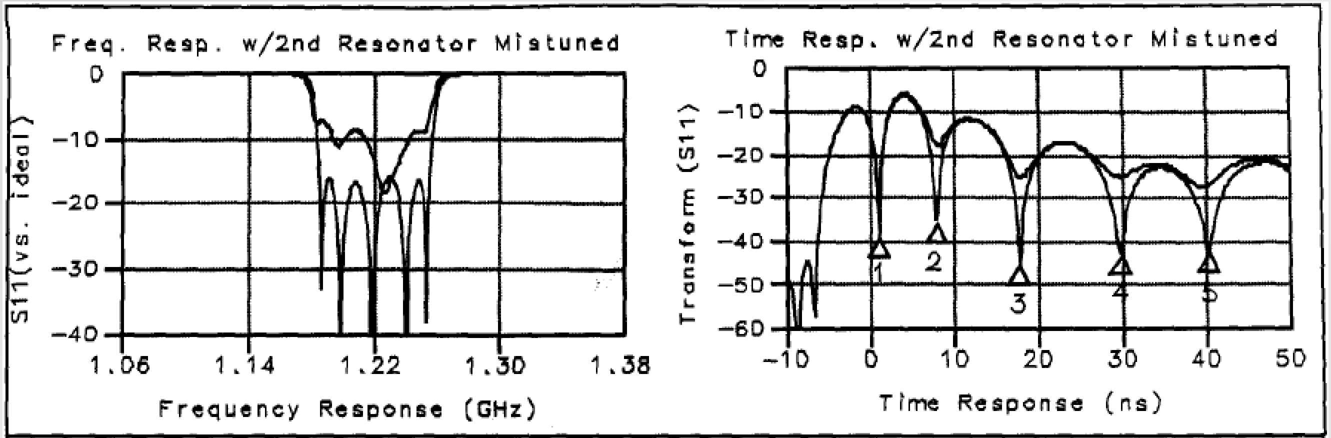


Figure 2: Frequency response (left) and time domain response (right) of the return loss (S11) of a perfectly tuned filter (lighter trace) and a filter with the second resonator mis-tuned (darker trace).

"Tuning band pass filters in the time domain,"
IEEE MTT-S Int. Microw. Symp., Anaheim, CA, June 1999, pp. 1351-1354.

Time-Frequency Effects: Courtney (1999)

- Frequency measurements from time-domain traces

➢ while trying to determine broadband permittivity and permeability of a sample material…

➢ found a way to measure T and Γ by time-domain-reflectometry with nanosecond impulses

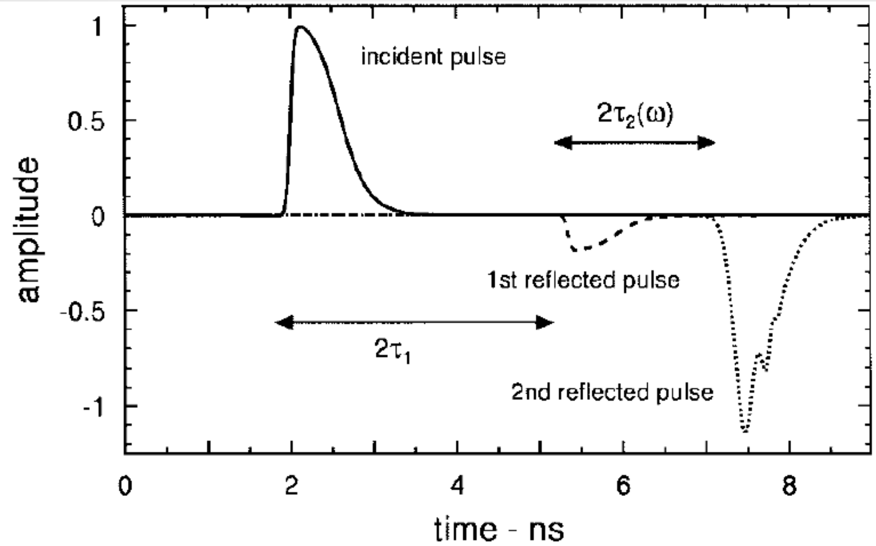


Fig. 3. The simulated incident and computed first and second reflected waveform components.

"One-port time-domain measurement of the approximate permittivity and permeability of materials" *IEEE Trans. Microw. Theory Tech.*, vol. 47, no. 5, pp. 551-555, May 1999.

NC STATE UNIVERSITY

Time-Frequency Effects: Hung et. al. (2002)

- Nonlinear distortion reduction by time-multiplexing

➢ working with optical cable television transmission…

➢ found a way to reduce IMD by transmitting subcarrier frequencies in different time slots

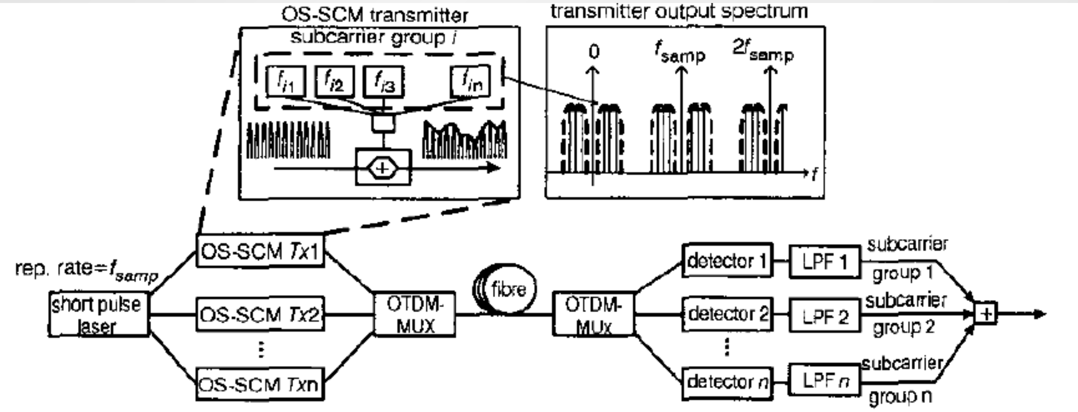


Fig. 1 *Nonlinear distortion reduction scheme using OS-SCM and OTDM*

Subcarriers are divided into M groups, each group may contain up to N subcarriers, $M > N$, $i \leq M$, $n < N$

“Optical sampled subcarrier multiplexing scheme for nonlinear distortion reduction in lightwave CATV networks,” *Electronics Letters*, vol. 38, no. 25, pp. 1702-1704, Dec. 2002.