OPTIARB: WIDEBAND OPTICAL ARBITRARY WAVEFORMS USING FOURIER COMPOSITION

Generate electrical pulses from low phase noise oscillator→filter harmonics→vector modulate each→combine & amplify→drive external modulator

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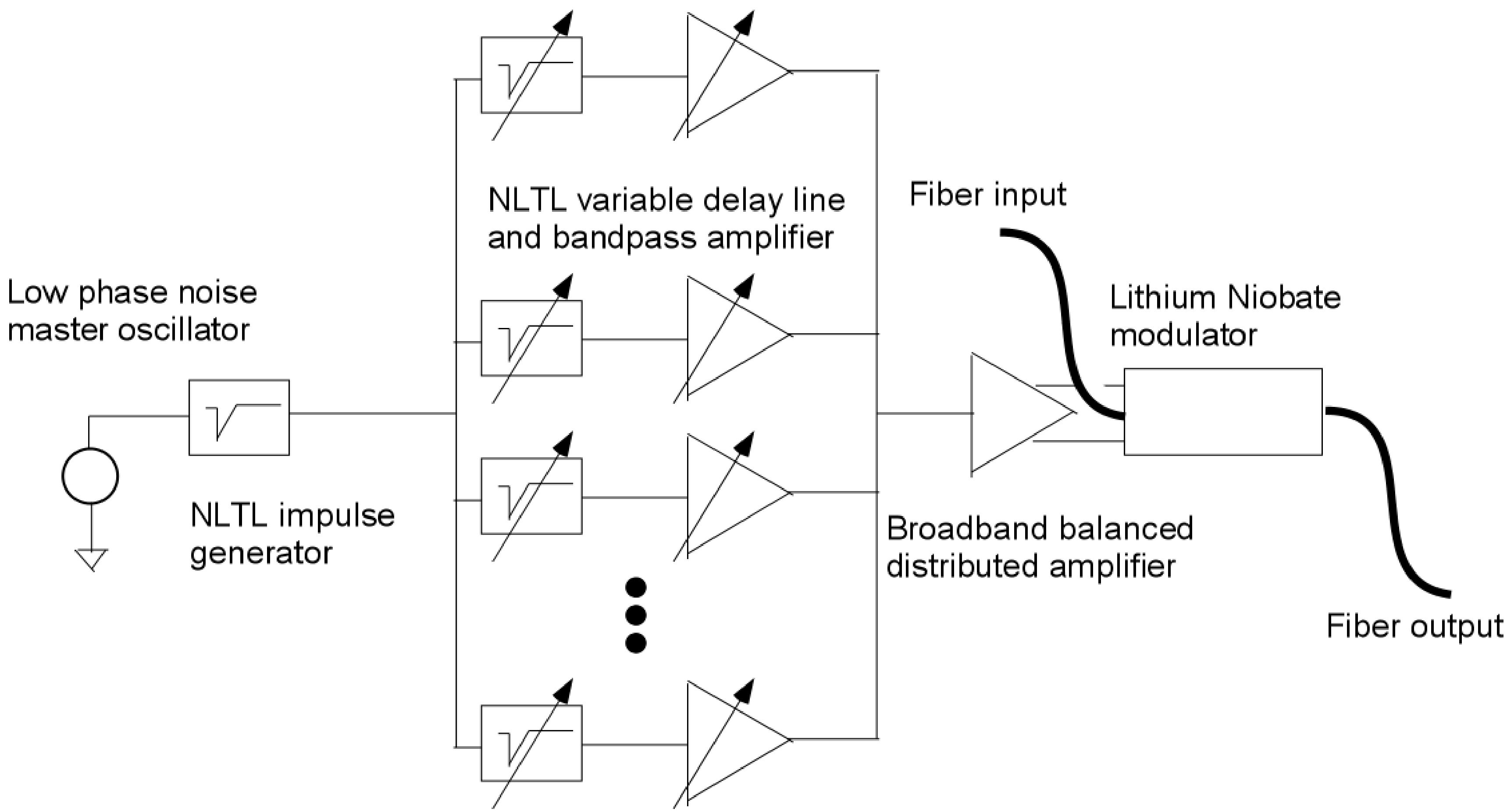
Defense Advanced Research Projects Agency DARPA

Overview

- *Goals*
  - *Build and deliver an OPTIARB*
    - *Achieve > 10 bit resolution*
    - *Achieve 10 GHz instantaneous bandwidth*
- *Approach*
  - *Simulate entire system using accurate device models derived from foundry process measurements*
  - *Develop, fabricate nonlinear transmission lines for pulse generators*
  - *Develop, fabricate voltage-variable delay lines*
  - *Brassboard scale-model 1 GHz system*
  - *Scale down to chip-level 10 GHz instantaneous/100 GHz total bandwidth*
- *Team*
  - *Graduate students*
    - *Circuit design: Sung-Jin Ho, Kae-Oh Sun, Jorg Yen*
    - *Device modeling: Sung-Jin Ho, Min-Ki Choi*
    - *IC layout: Kae-Oh Sun, Jorg Yen, Sung-Jin Ho*
    - *Fabrication: Min-Ki Choi, Dong-Hwan Kim, Hong-Joon Kim*
    - *Signal processing, programming: Hong-Joon Kim, Min-Ki Choi*
    - *Optics integration: Sung-Jin Ho, <Adriana Reyes>*

System emphasizes electrical generation and harmonic vector modulation



Goals

- *12-18 months*
  - *System design, simulation in Advanced Design System (ADS)*
  - *Device model extraction from InGaP/GaAs HBT process*
  - *Brassboard 1 GHz system*
- *19-36 months*
  - *Verifying brassboard with ADS*
  - *4-6 bit 10 GHz multi-chip module (MCM)*
  - *> 10 bit MCM*

Milestones

Year	Milestones	Duration
1	Lay out models for ~~SiGe~~ fabrication	3 months
1	Extract high-frequency device models, perform comprehensive system simulations, design and simulate low-voltage $LiNbO_3$ traveling wave modulator	6 months
1	Lay out and submit component designs for Run II	3 months
2	Test second round fabrication, programming	4 months
2	Brassboard components including segmented $LiNbO_3$ traveling wave modulator	8 months
2	Layout and submit Round III	3 months
3	Test brassboard (multiple scale models), programming	6 months
3	Fourth round layout and fabrication	5 months
3	Assemble and test OPTIARB system	2 months
	Total	36 months

Deliverables

Deliverables associated with this work specifically include the following:

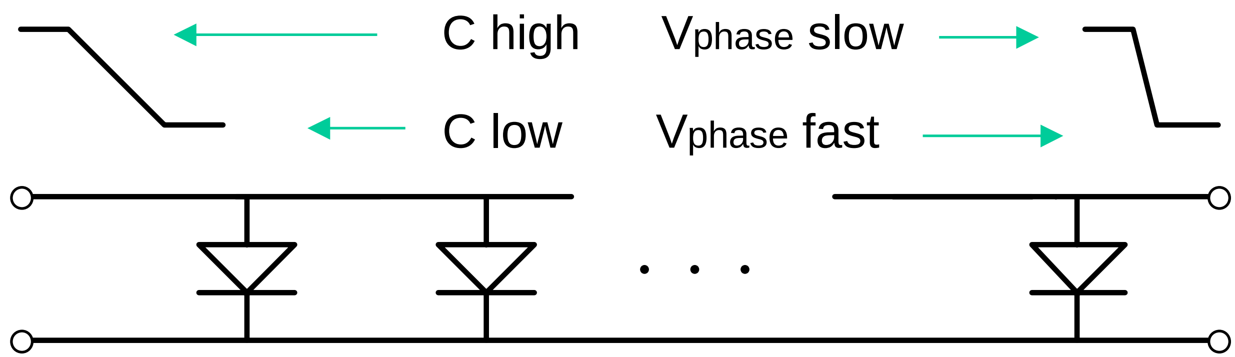
- 100 GHz device models from the HBT process
- NLTL's executed in our own GaAs process
- Ridge waveguide low-voltage $LiNbO_3$ traveling wave modulators
- Broadband pulsed drive electronics
- Broadband power amplifiers
- Comprehensive simulations of both subsystems and the OPTIARB system
- Low-voltage $LiNbO_3$ traveling wave modulators

1 GHz static RAM multiplexed to 12-bit voltage controllers for both amplitude and phase of each waveform component

Approach

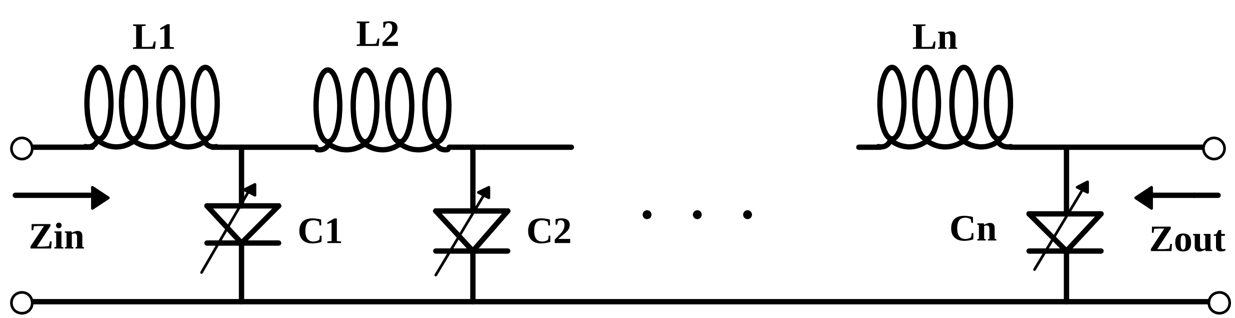
- *Pulse generation with NLTLs*
  - *NLTL concept, design*
  - *Driver amplifier design*
- *Vector modulation of harmonics using delay lines/variable-gain amplifiers*
  - *Frequency translator, applications*
  - *New delay line device design*
- *Broadband balanced distributed amplification to modulate light using $LiNbO_3$*

Nonlinear transmission lines (NLTLs) create fast edges from sinusoidal inputs, and can also be used for frequency translation

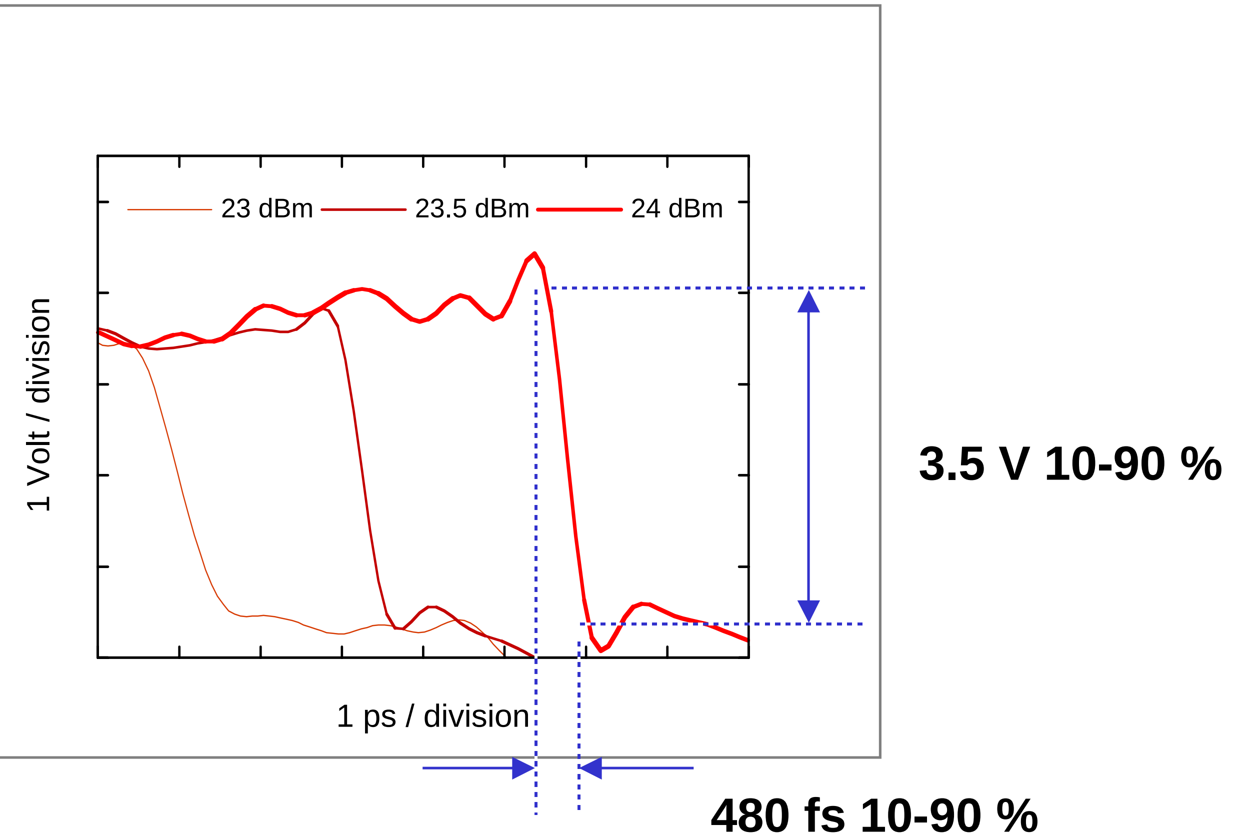


$$\Delta Vp = \frac{1}{\sqrt{LC(v)}}$$

The diodes create a voltage-dependent propagation velocity for a wave on the line

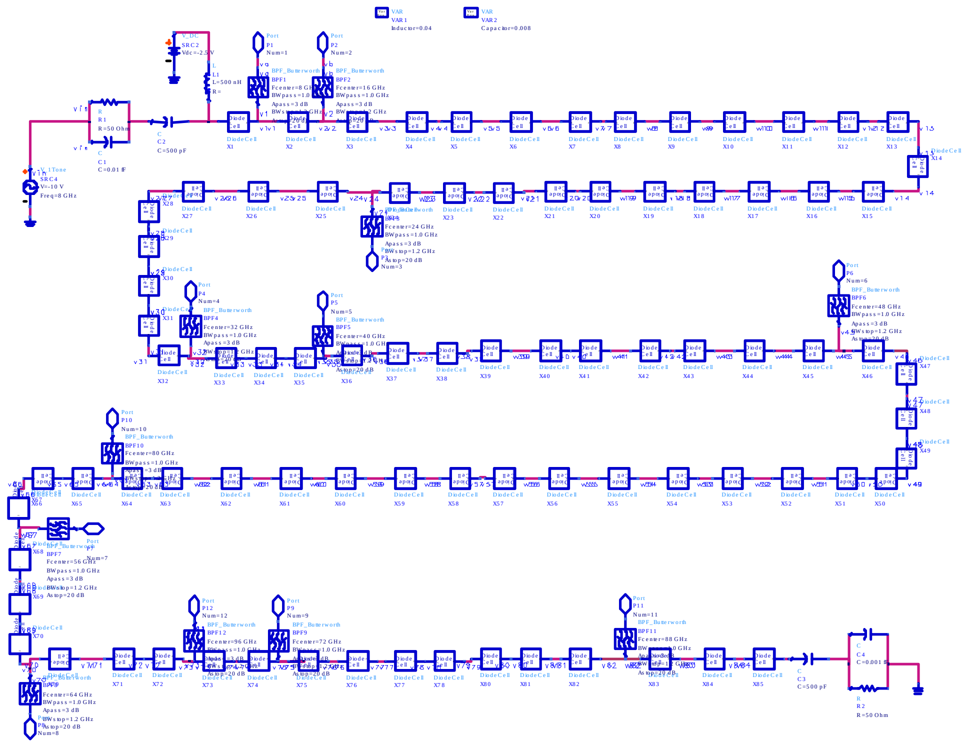


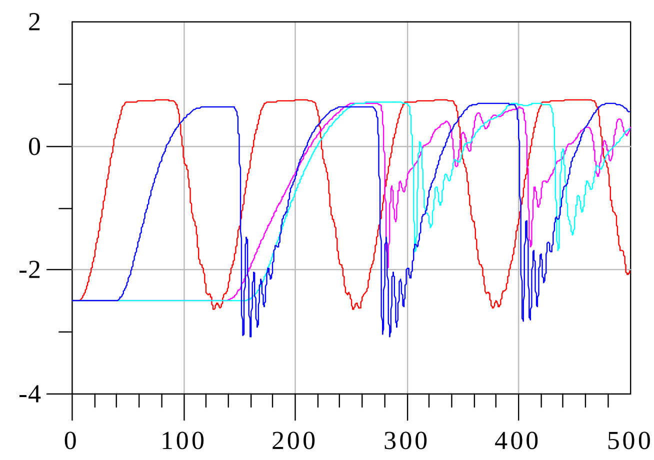
We have made NLTLs on GaAs that can produce < 1 ps edges



D.W. van der Weide, APL ***65*** *(7) 881, 1994*

ADS simulations of NLTL

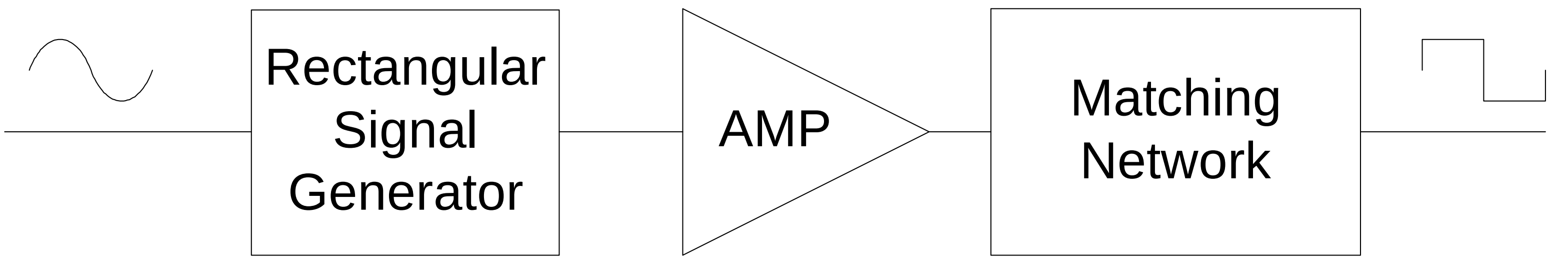




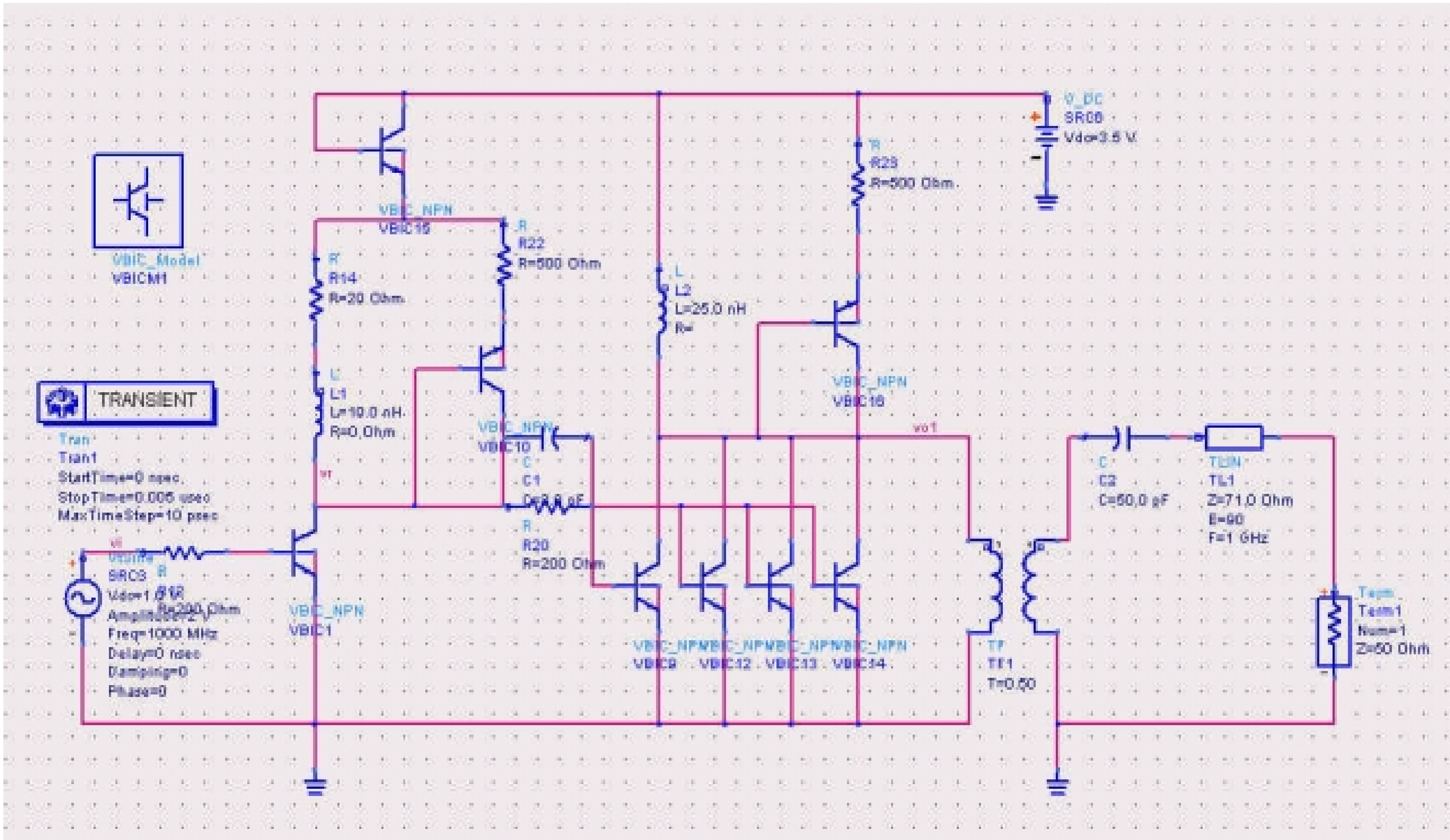
Amplifier design drives NLTLs efficiently

- *Drive NLTL(Non Linear Transmission Line)*
- *Use GaAs HBT (Knowledge-on Inc.)*
- *Rectangular signal output*
- *Fall time < 100 ps*
- *1W Output Power*

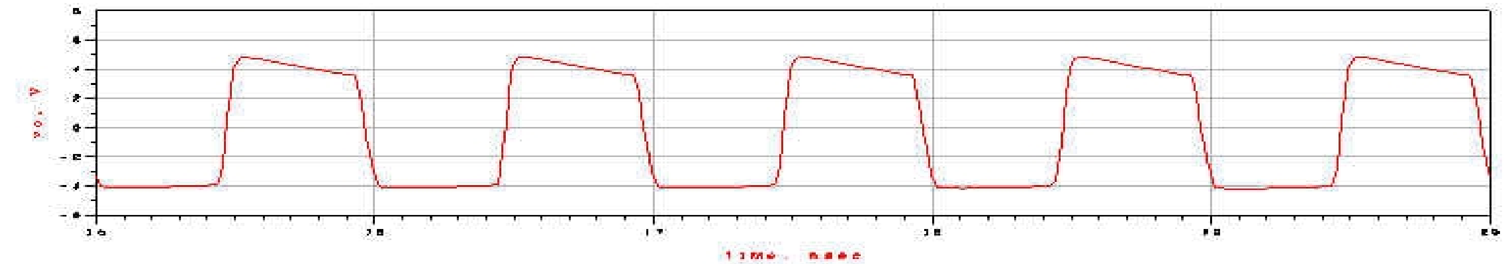
Block diagram



Driver amplifier schematic



Output waveforms

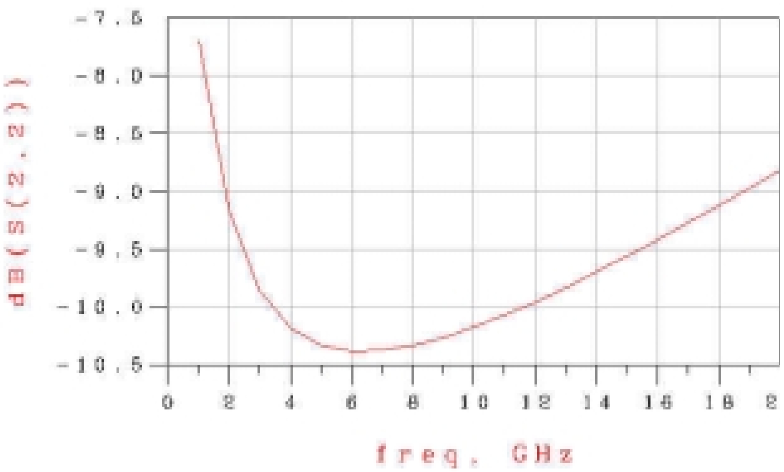


< Output Voltage >

- *Voltage Fall Time = 70 pS*

< Output Current >

Output matching



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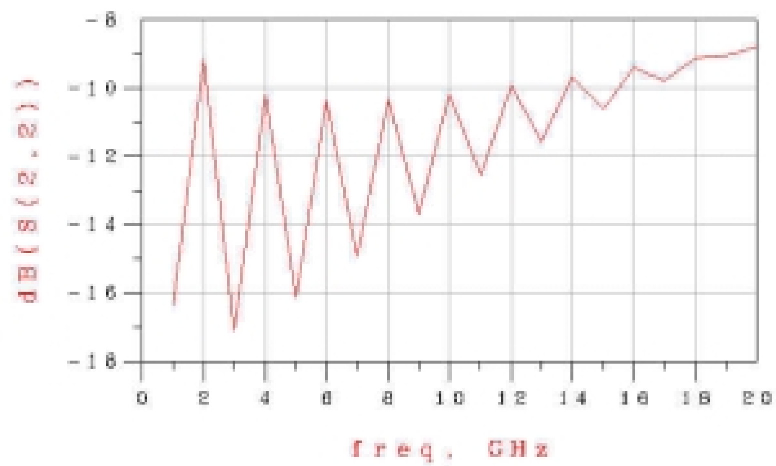
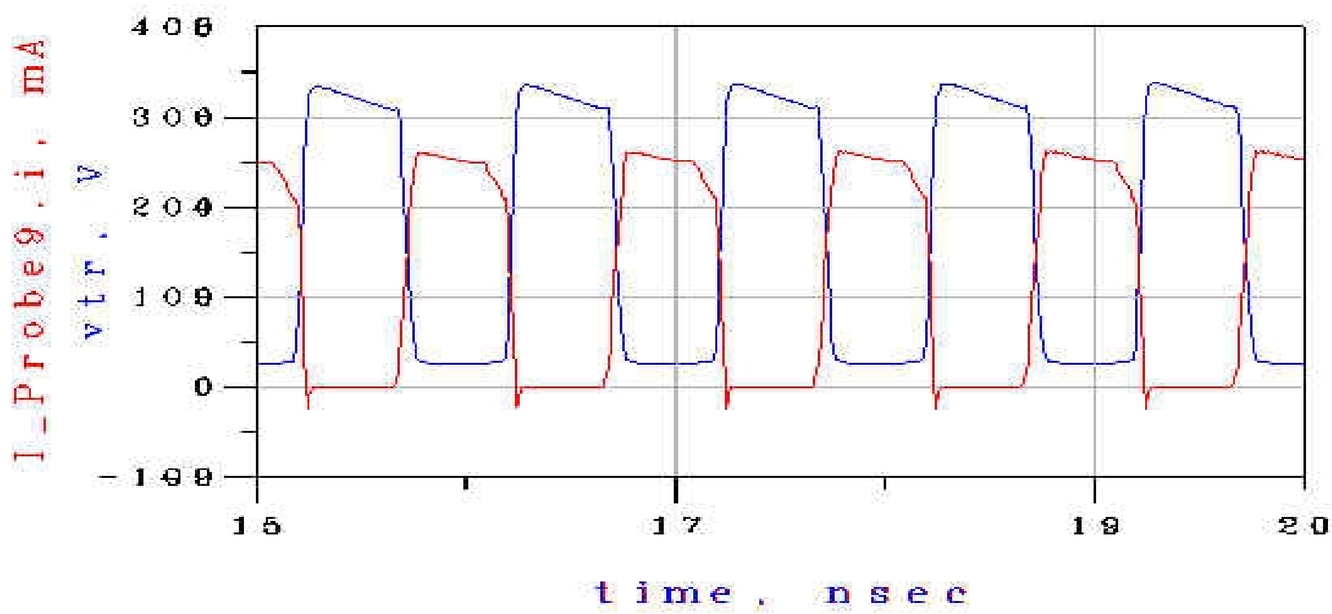


< After >

- *Used quarter wave length transmission line to match odd harmonics of rectangular output waveform*

Driver V-I waveforms



- Small overlap between V_{C-E} and I_C

  -> Low power consumption

  -> High Efficiency

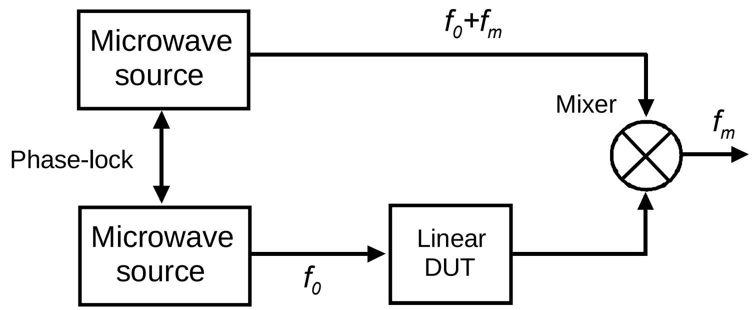
Scanning the delay of a NLTL enables phase modulation and even frequency translation for small signals

- *Vector modulation of harmonics in OPTIARB*
- *To make a reflection or transmission system inexpensive and practical for arrays, we need low-cost integrated frequency translation*
- *This circuit shows very high carrier suppression*
- *Only phase noise is added by scanner circuit—not intrinsic to phase modulator*

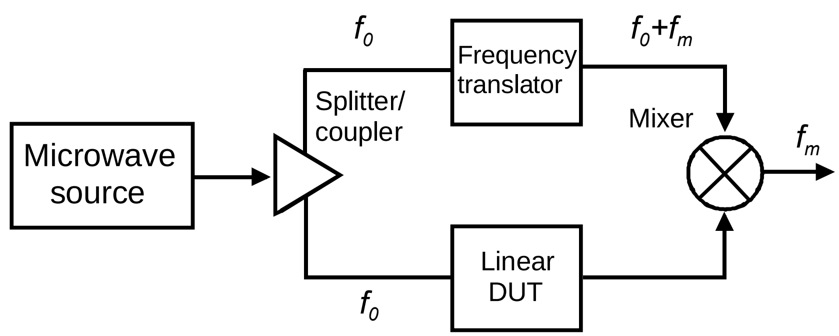
Frequency translators replace dual microwave sources at much lower cost

Coherent measurement systems

Present day

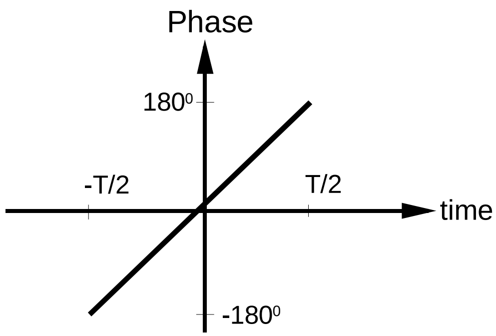


We propose

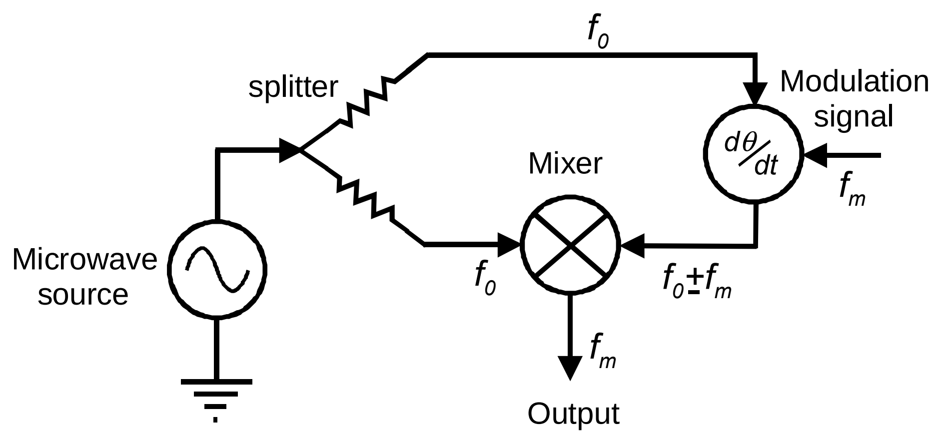


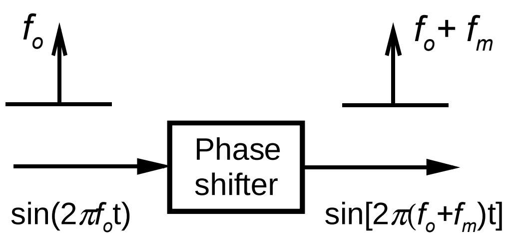
DUT = Device Under Test

Linear modulation of phase with time results in translation of frequency



Linear phase function

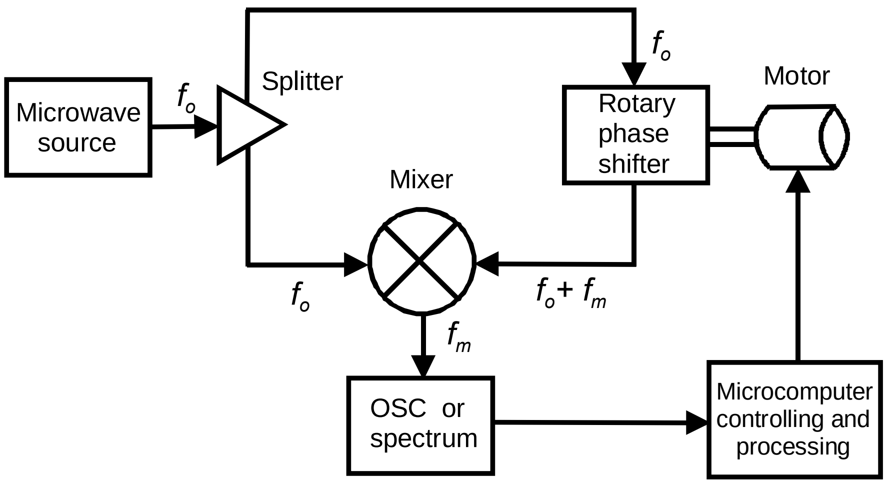


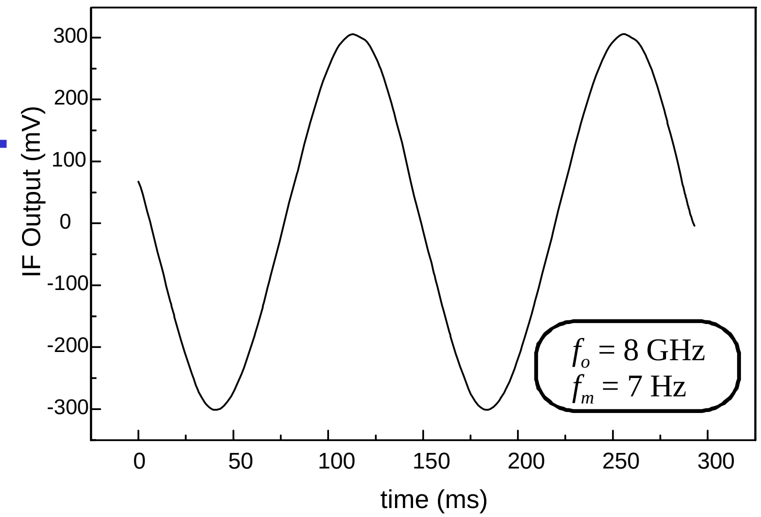


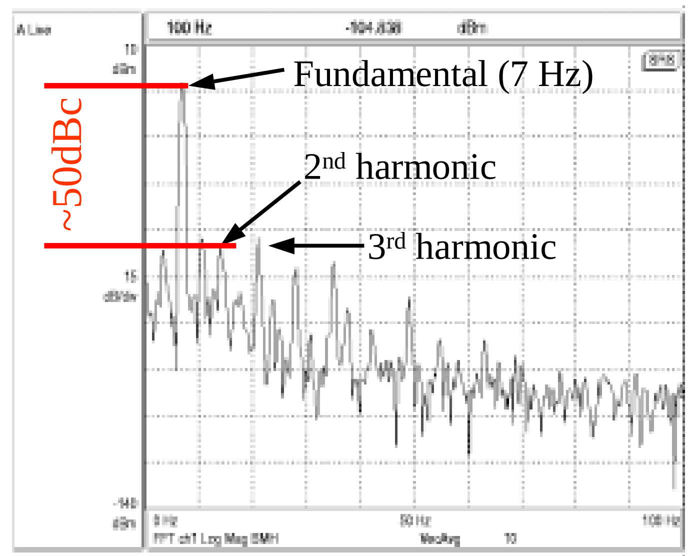
Translated frequency:

$$f = \frac{d\theta}{dt}$$

Frequency translators can be rotary phase shifters





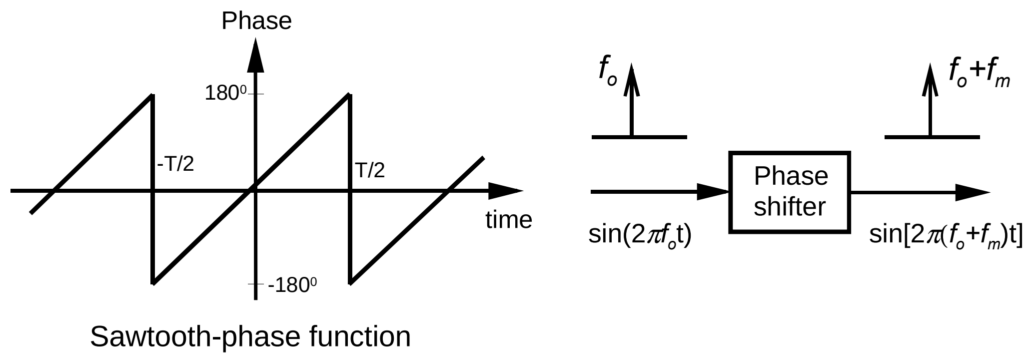


Rotary phase shifter: HP J885 A

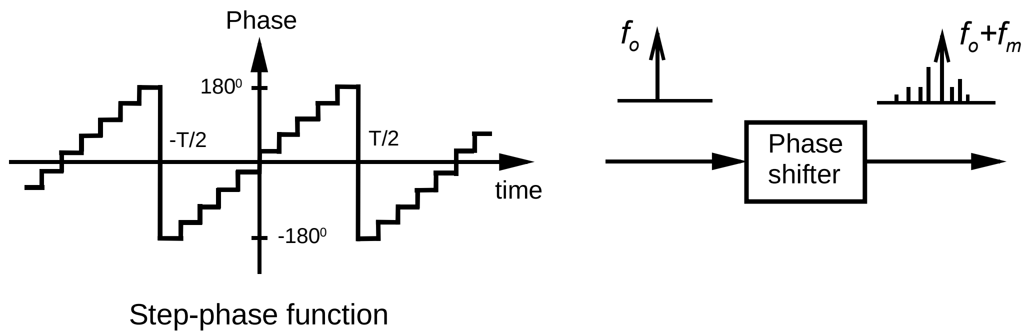
ADVANTAGES: simple, low losses, and very rugged

LIMITATIONS: only circular hollow-waveguide, bulky, inertia, and low speed (f_m)

Frequency translators can also be realized with serrodyne modulation of delay

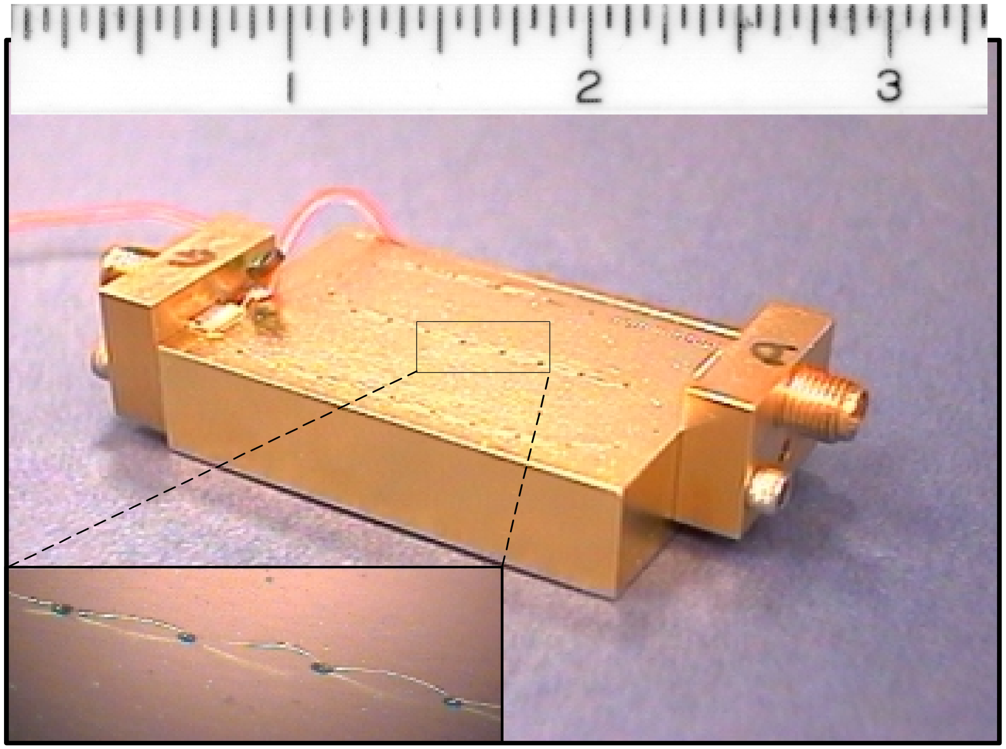


(a)



(b)

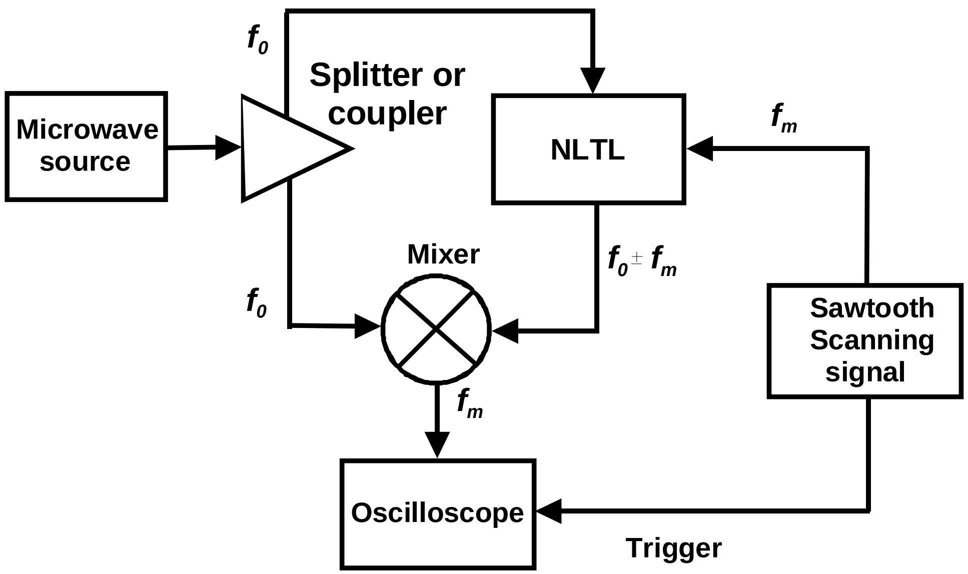
We have built large scale NLTLs as delay lines for serrodyne frequency translation



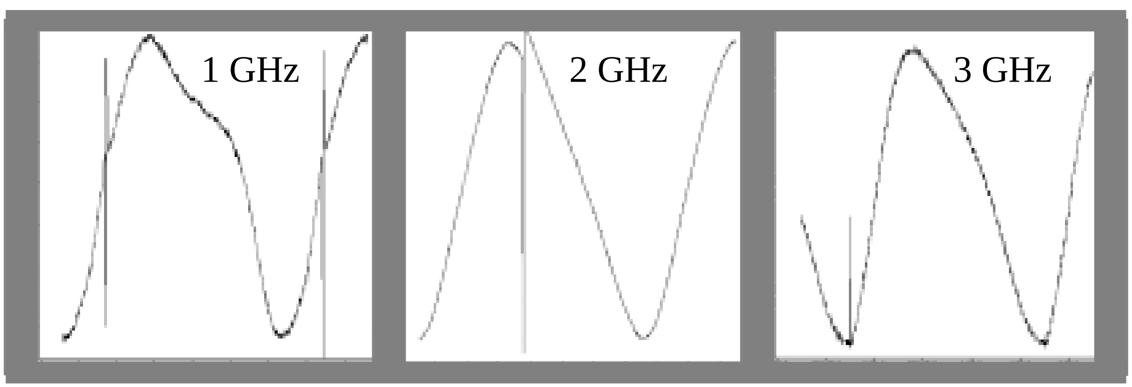
Section1: 30 diodes (Cjo=2pF) with 4.6 mm interval spacing

Section2: 20 diodes (Cjo=0.8pF) with 0.6 mm interval spacing

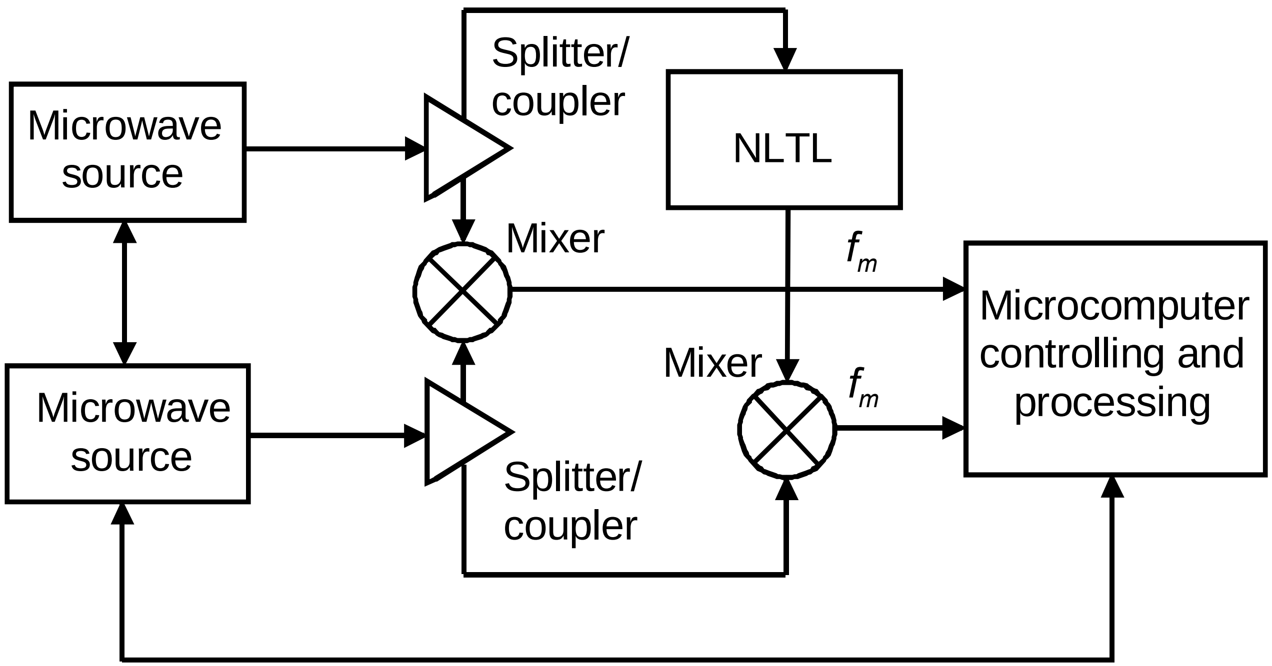
The raw output shows potential, but needs correction as well



500 Hz

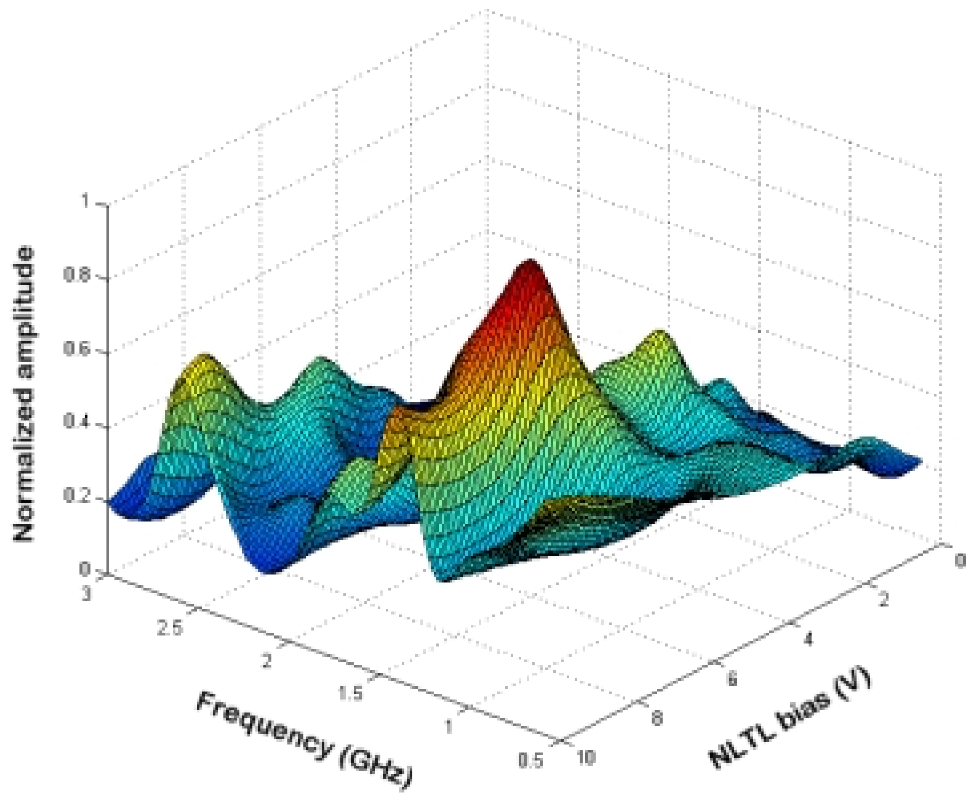


We measured the amplitude and phase distortion over frequency to correct it

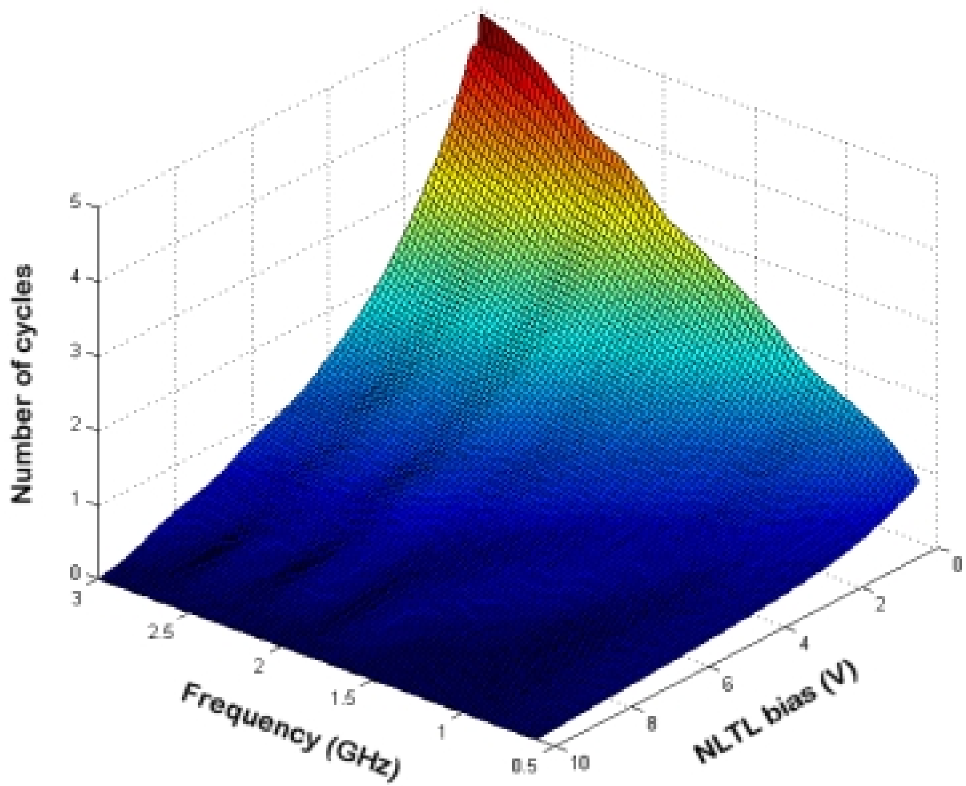


P. Akkaraekthalin, S. Kee and D.W. van der Weide, "Distributed broadband frequency translator and its use in a 1-3 GHz coherent reflectometer," IEEE Transactions on Microwave Theory and Techniques, vol. 46, pp. 2244-2250, December 1998.

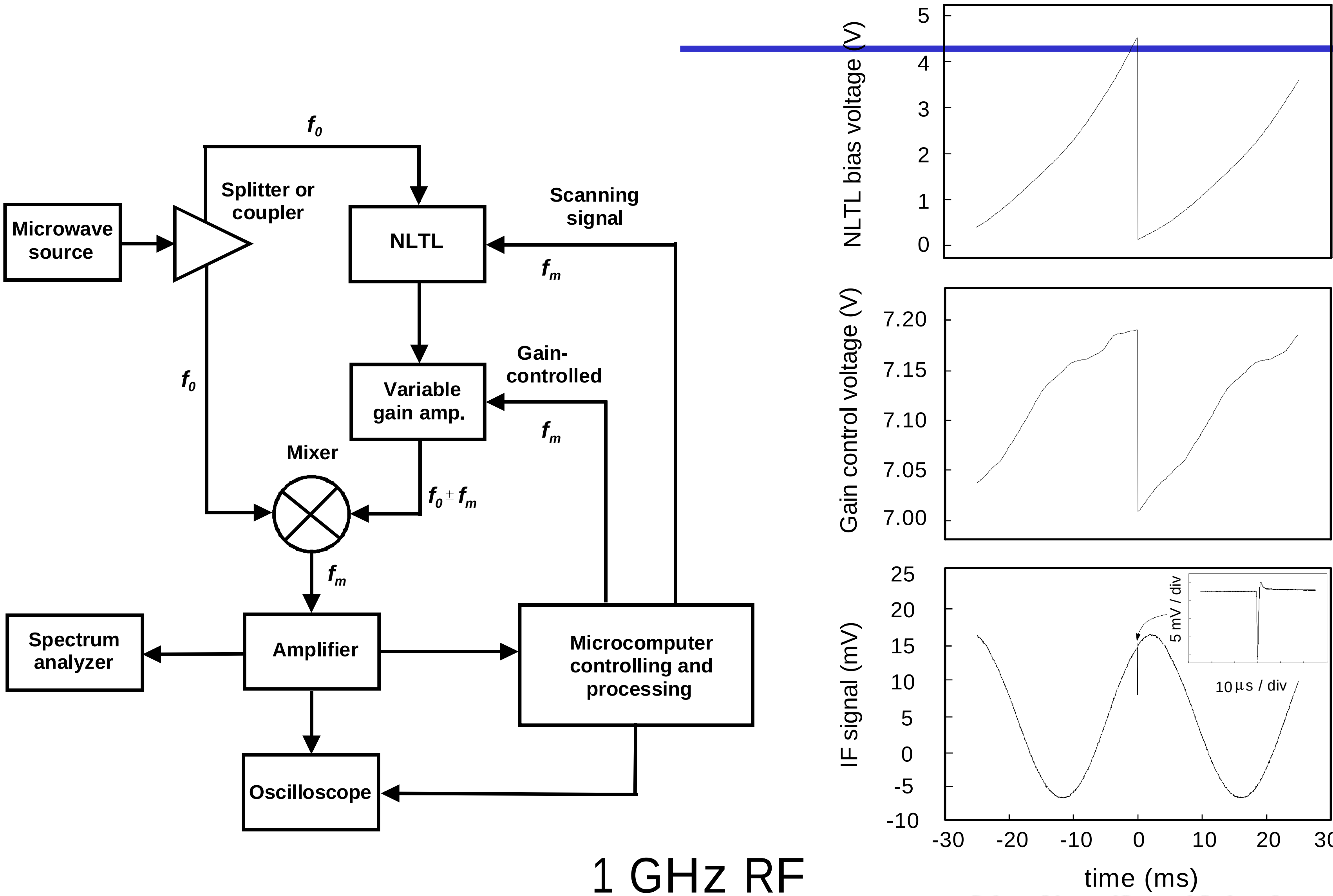
Amplitude distortion surface



Phase (or delay) distortion surface



We compensated for these distortions with look-up tables



1 GHz RF

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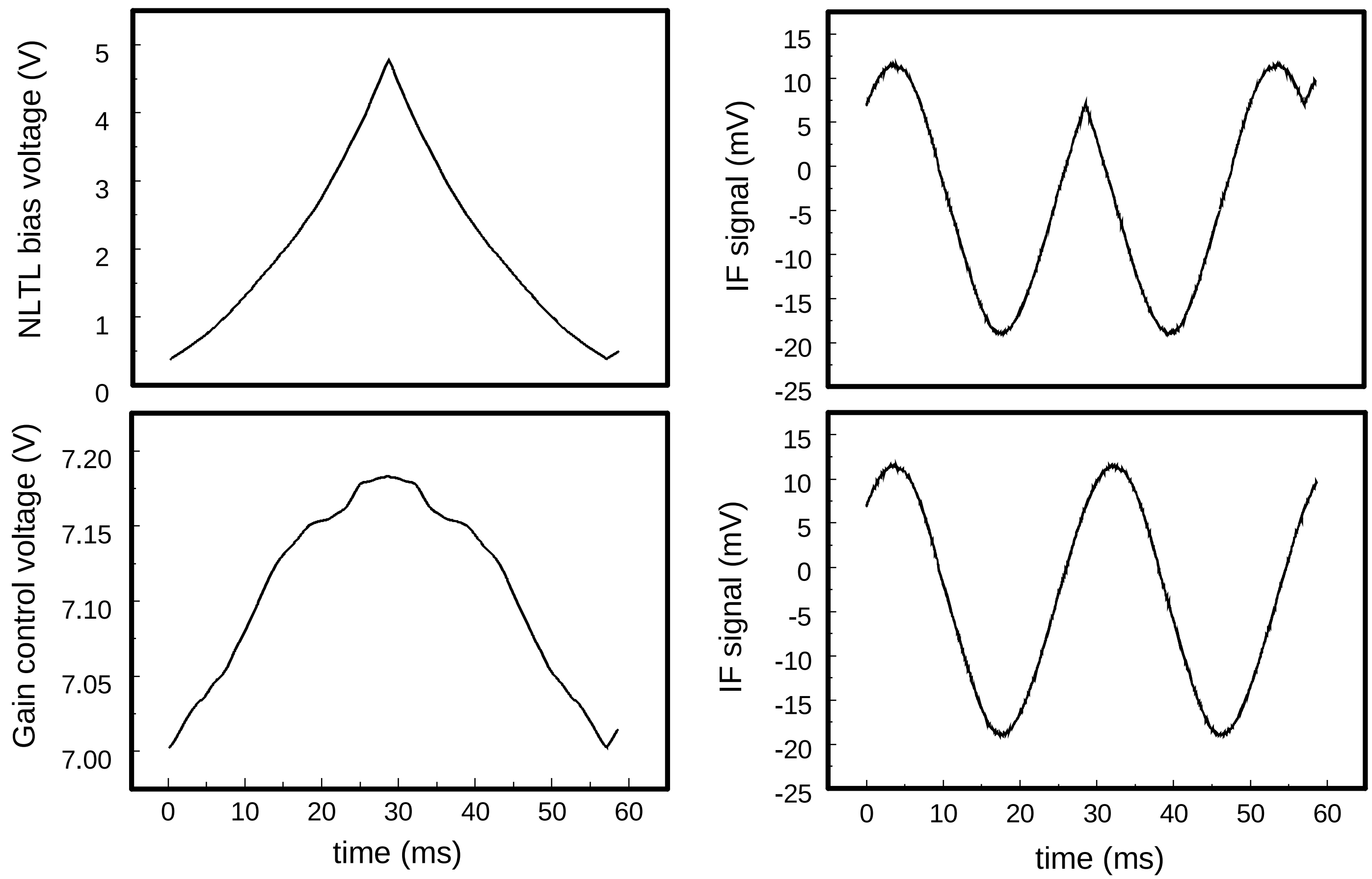
Using triangle modulation with time reversal eliminates the small spikes



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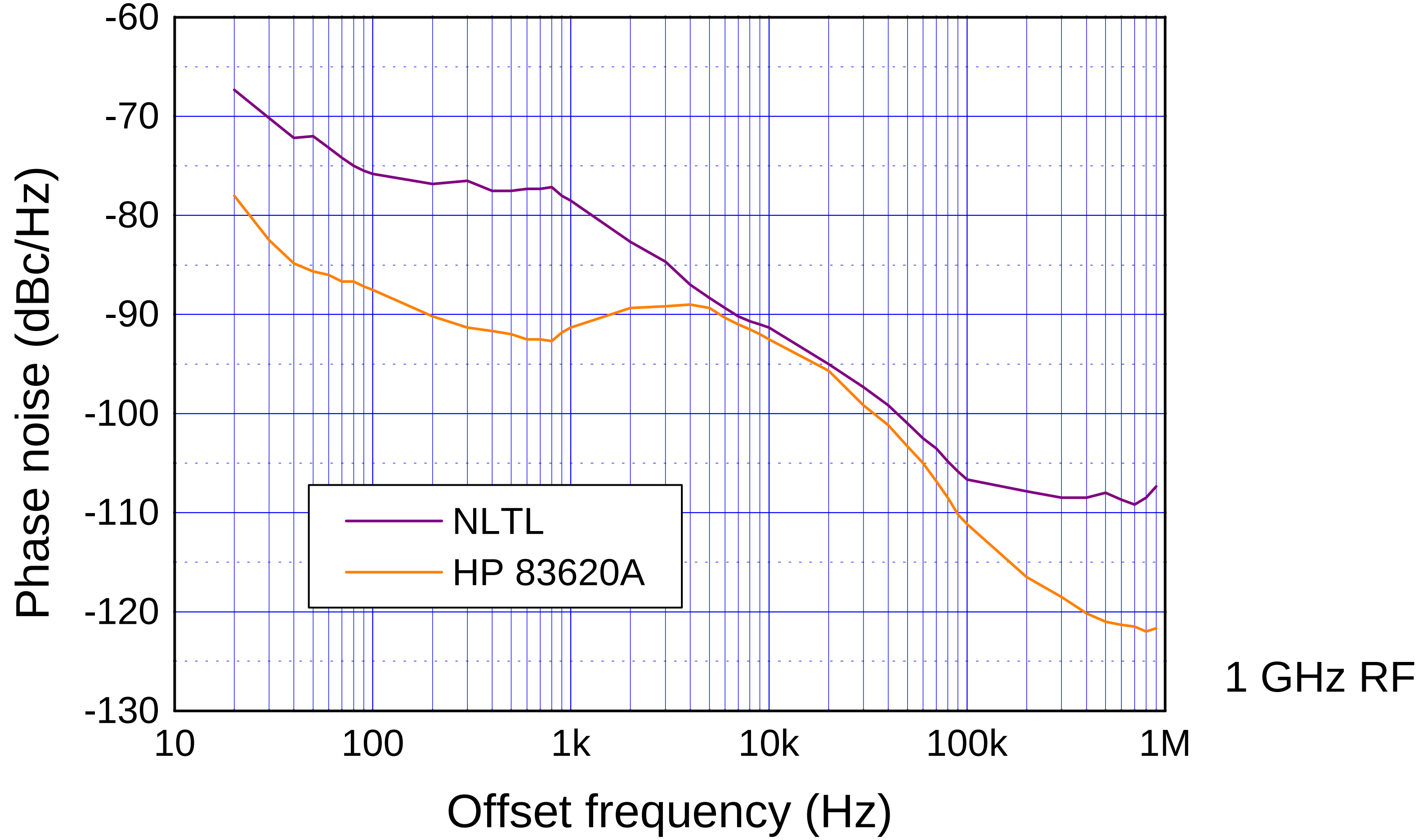
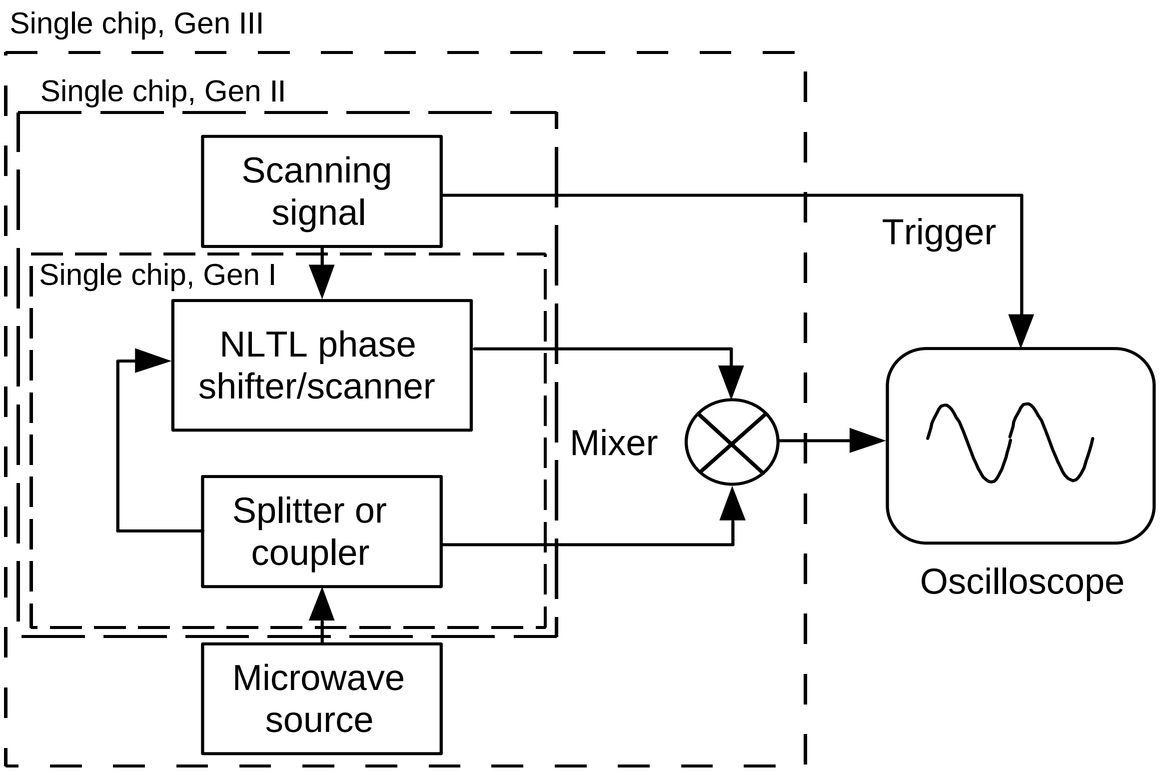
The stability of this technique is comparable to the frequency synthesizer

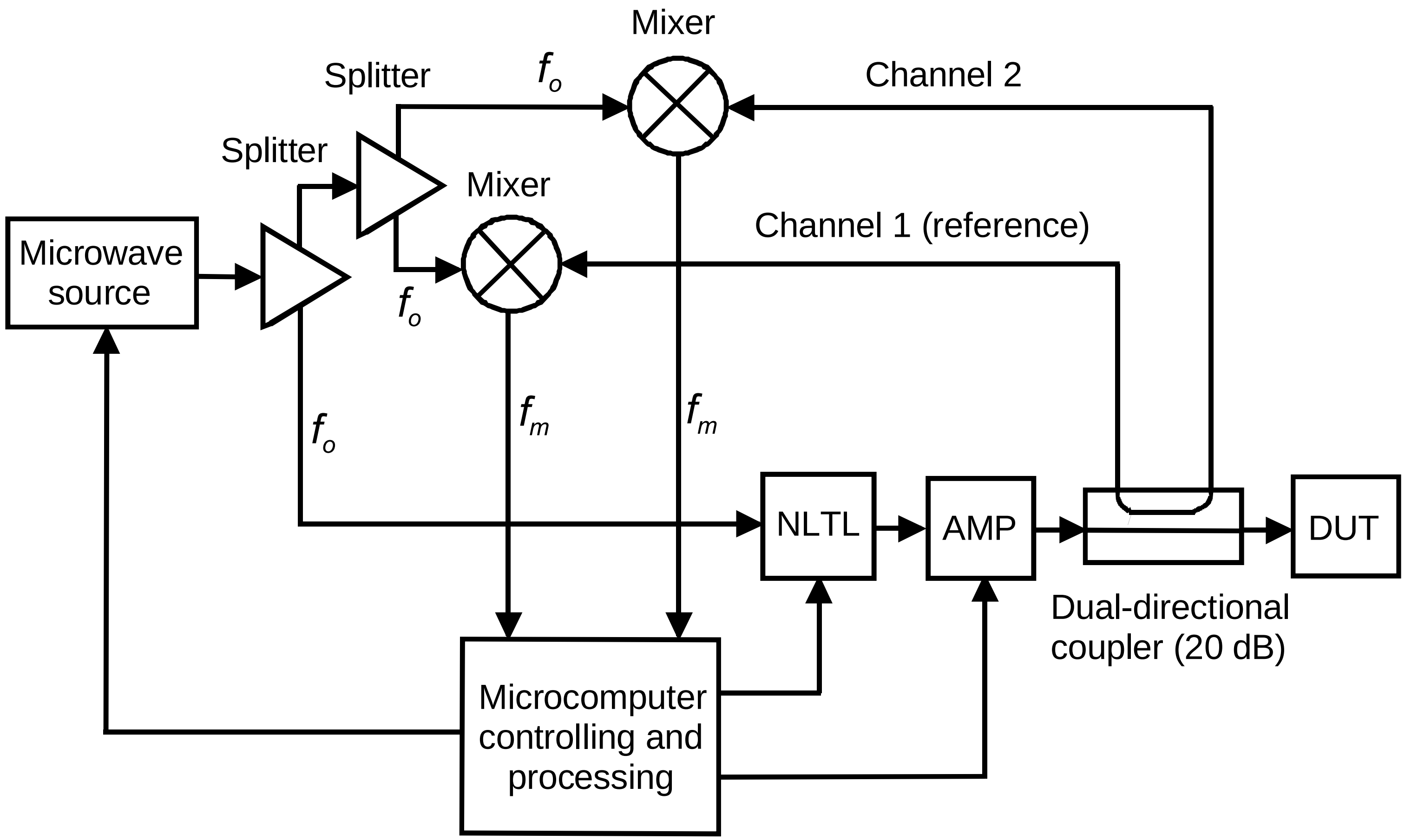


Phase noise doesn't vary significantly over RF

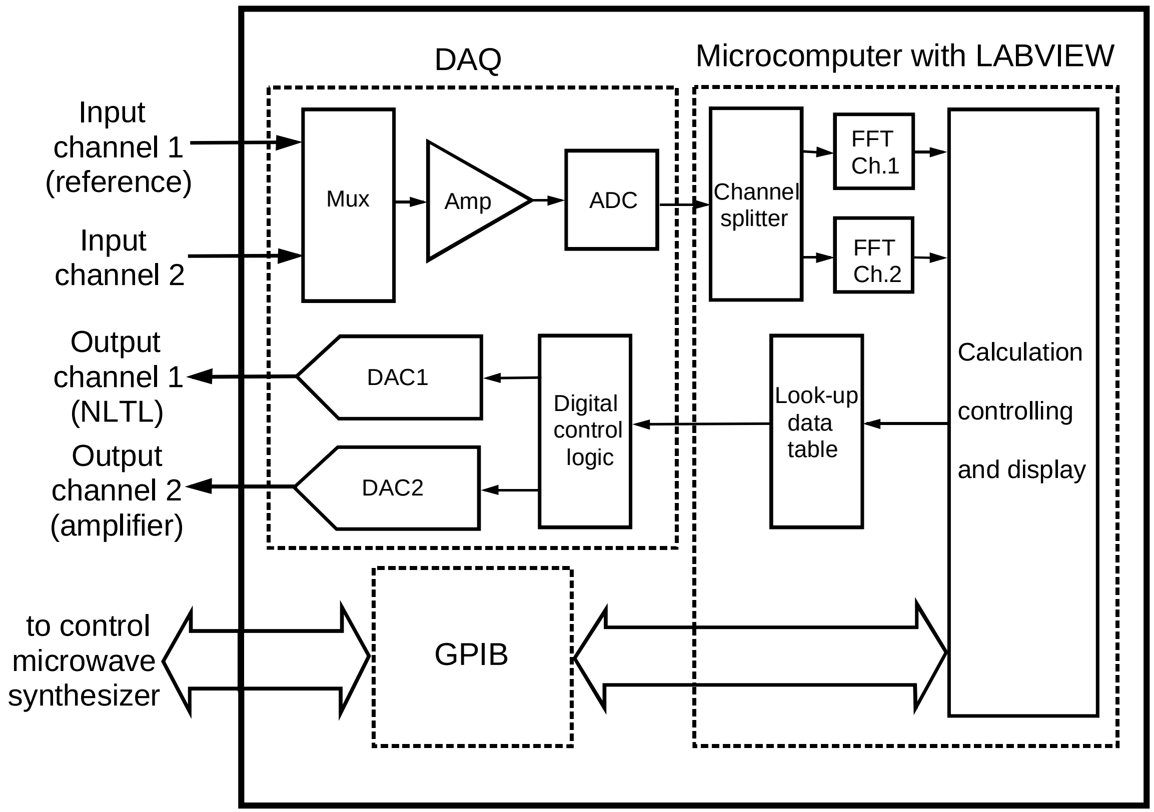
Our goal is to realize complete picosecond coherent generation/system on a single chip



We have already built a microwave reflectometer on this concept

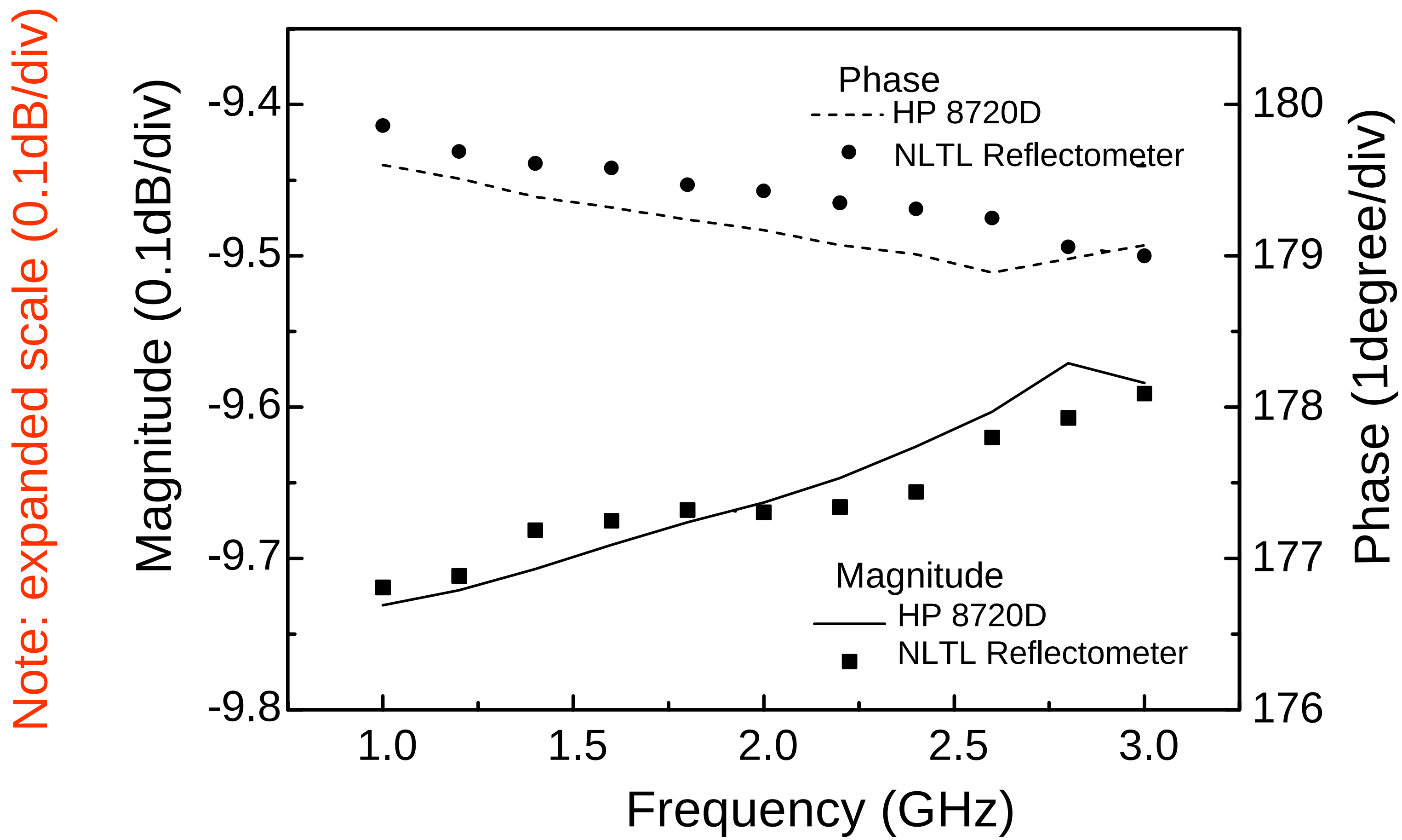


The system is controlled by PROM correction and LabVIEW

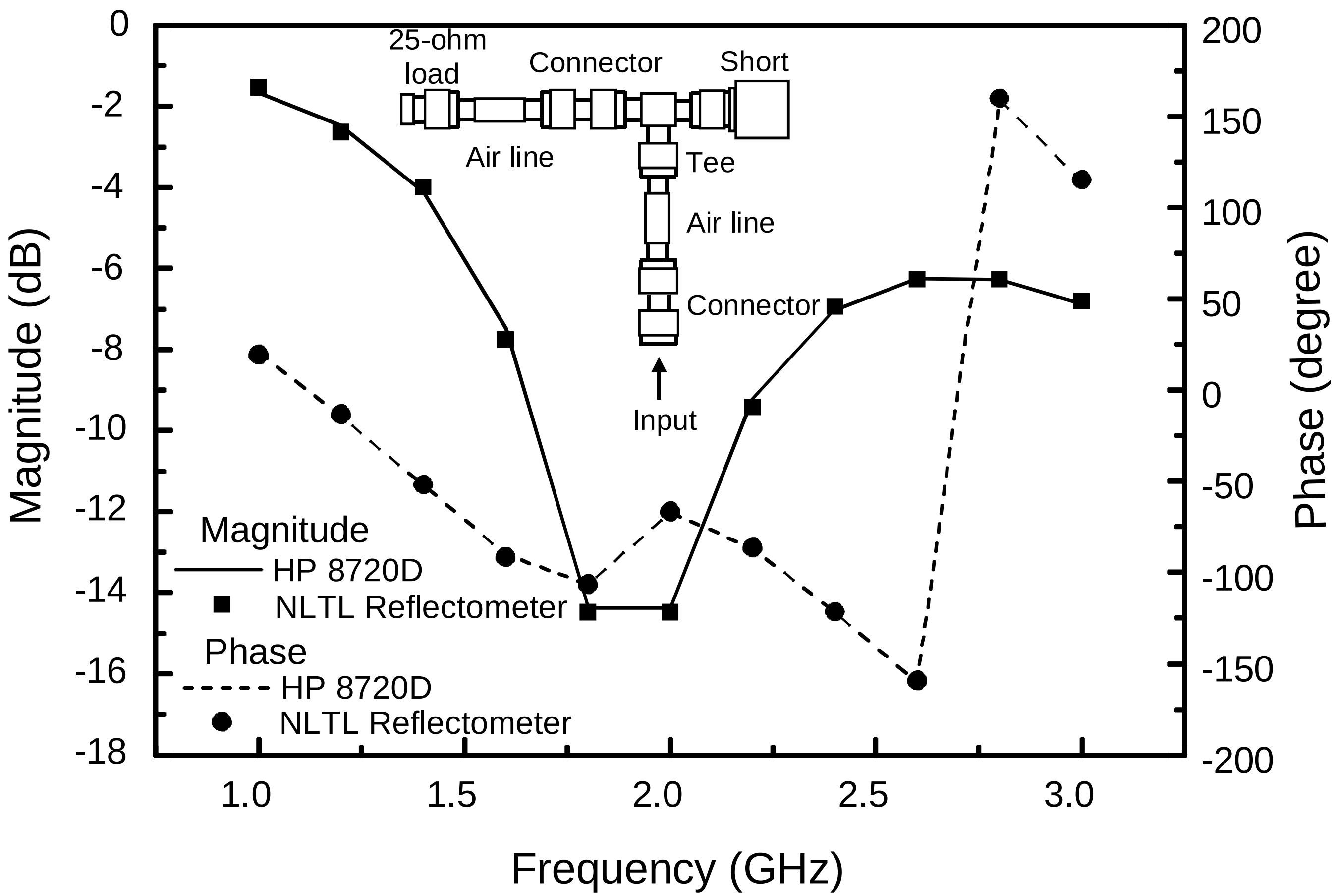


The result from a 25Ω load almost exactly corresponds to a commercial instrument

Reflection coefficient compared to HP 8720D network analyzer



An arbitrary load also shows excellent correspondence

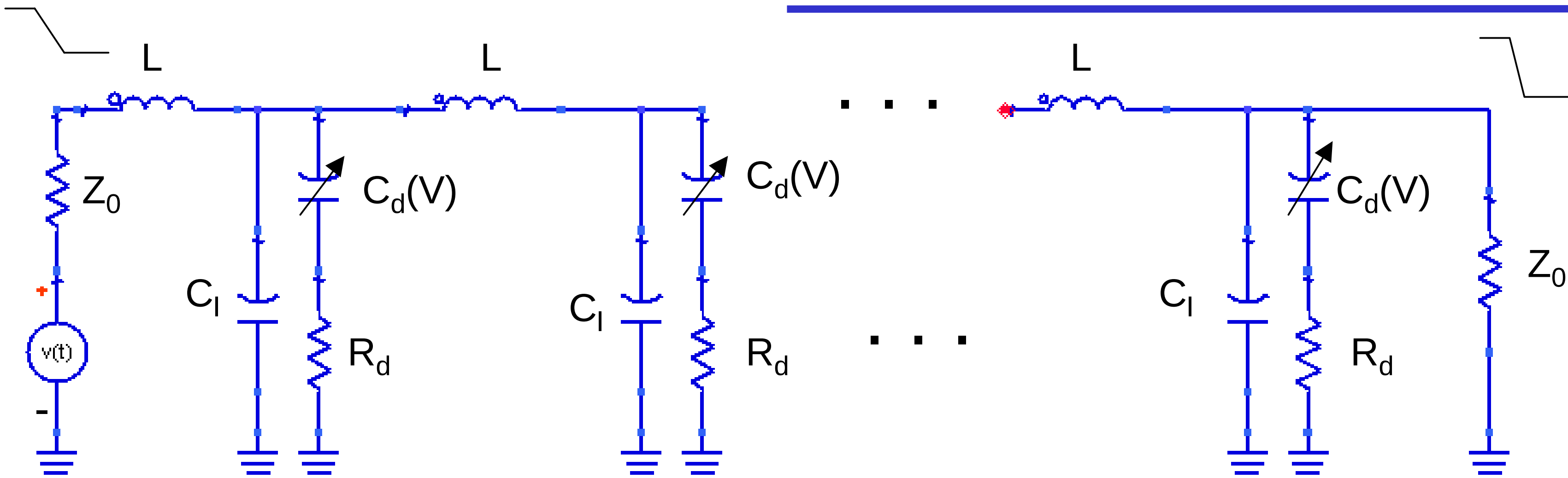


Akkaraekthalin, Kee, and van der Weide, *IEEE Trans MTT* December 1998

The frequency translator performed well in its first system application

- *We proposed a new reflectometer using a heterodyne technique with the distributed frequency translator*
- *We analyzed the error correction for the reflectometer*
- *We designed and built an* inexpensive *automatic reflectometer controlled by a PC*
- *Excellent correspondence with a commercial network analyzer (HP 8720D)*

NLTL and delay line improvement through device development



Z_0 : Characteristic Impedance
L : Line Section Inductance
C_l : Line Section Capacitance
$C_d(V)$: Variable Diode Capacitance
R_d : Diode Series Resistance

Critical factors for NLTL design

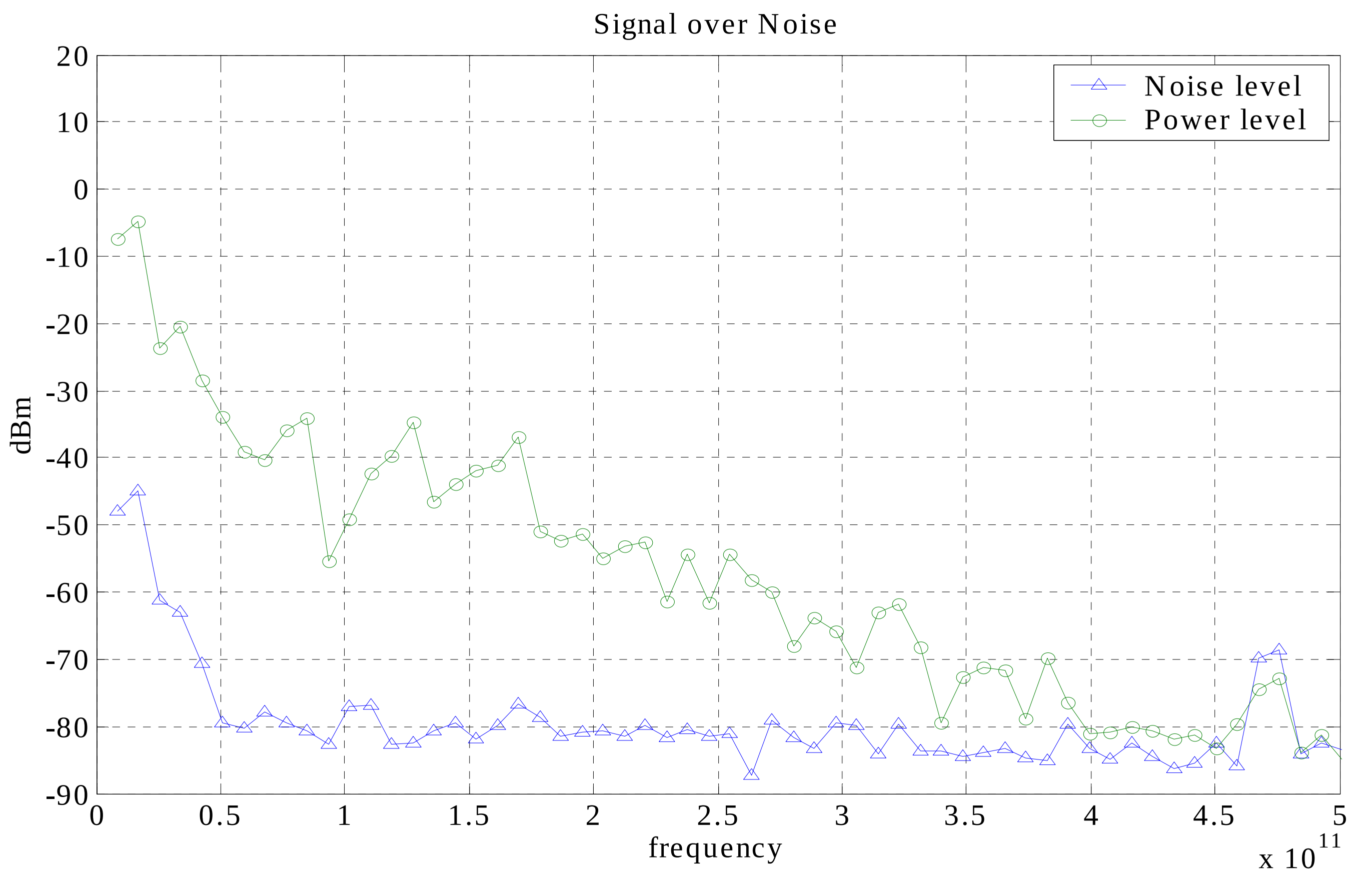
- 1. Need large difference in diode capacitance and low-loss capacitors

  - Higher signal compression and fewer sections → lower loss

- 2. Bragg Cut-off Frequency
- - $$f_{Bragg} = \frac{1}{\pi \bullet \sqrt{L[C_l + C_d(V)]}}$$
- 3. Diode Cut-off Frequency
- - $$f_c = \frac{1}{2\pi \bullet R_d \bullet C_d(V)}$$
- 4. Characteristic Impedance, Attenuation, etc

NLTL designed for 8.5 GHz fundamental frequency

Signal and noise measurement



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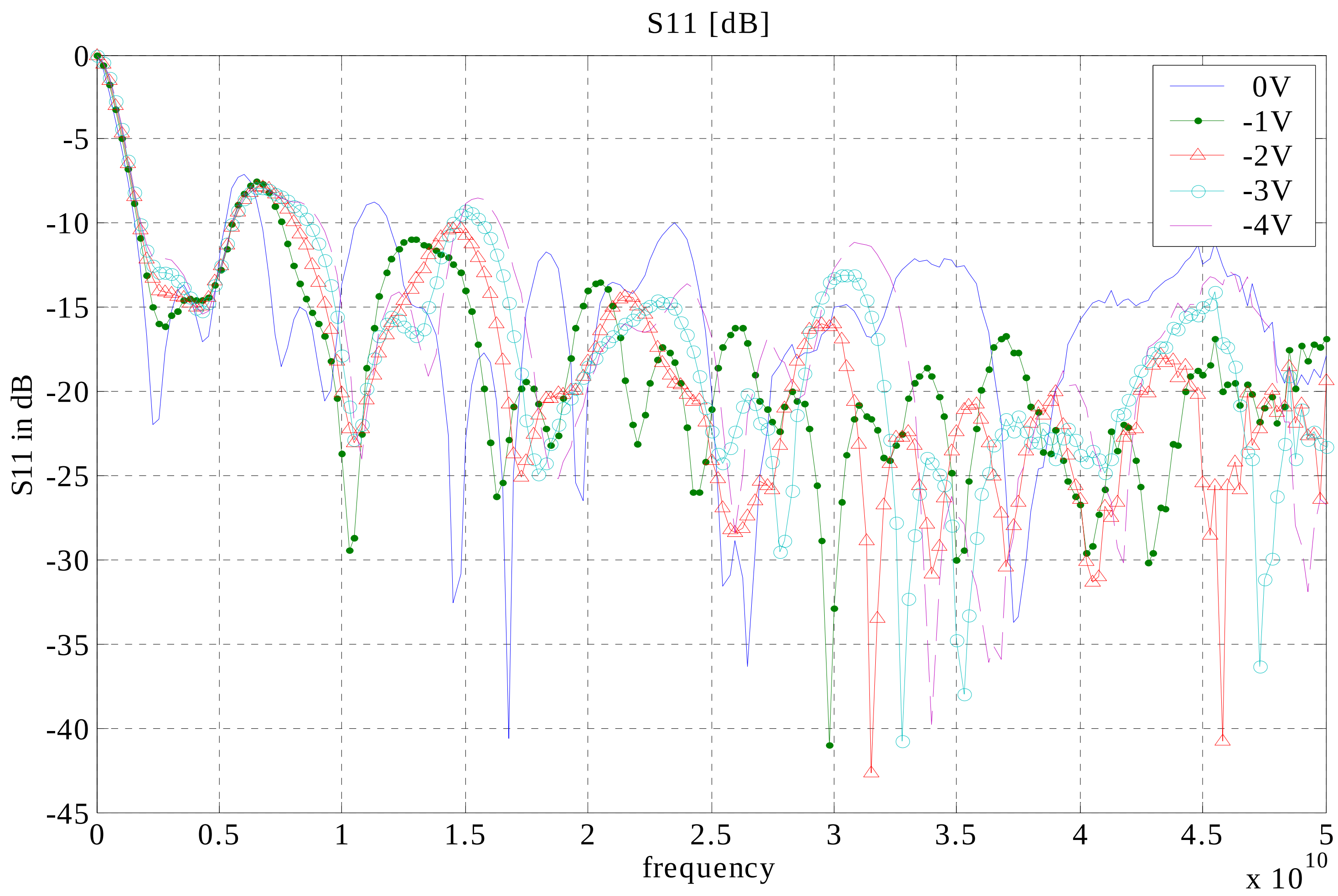
NLTL designed for 8.5 GHz fundamental frequency measured return losses with different bias vs frequency



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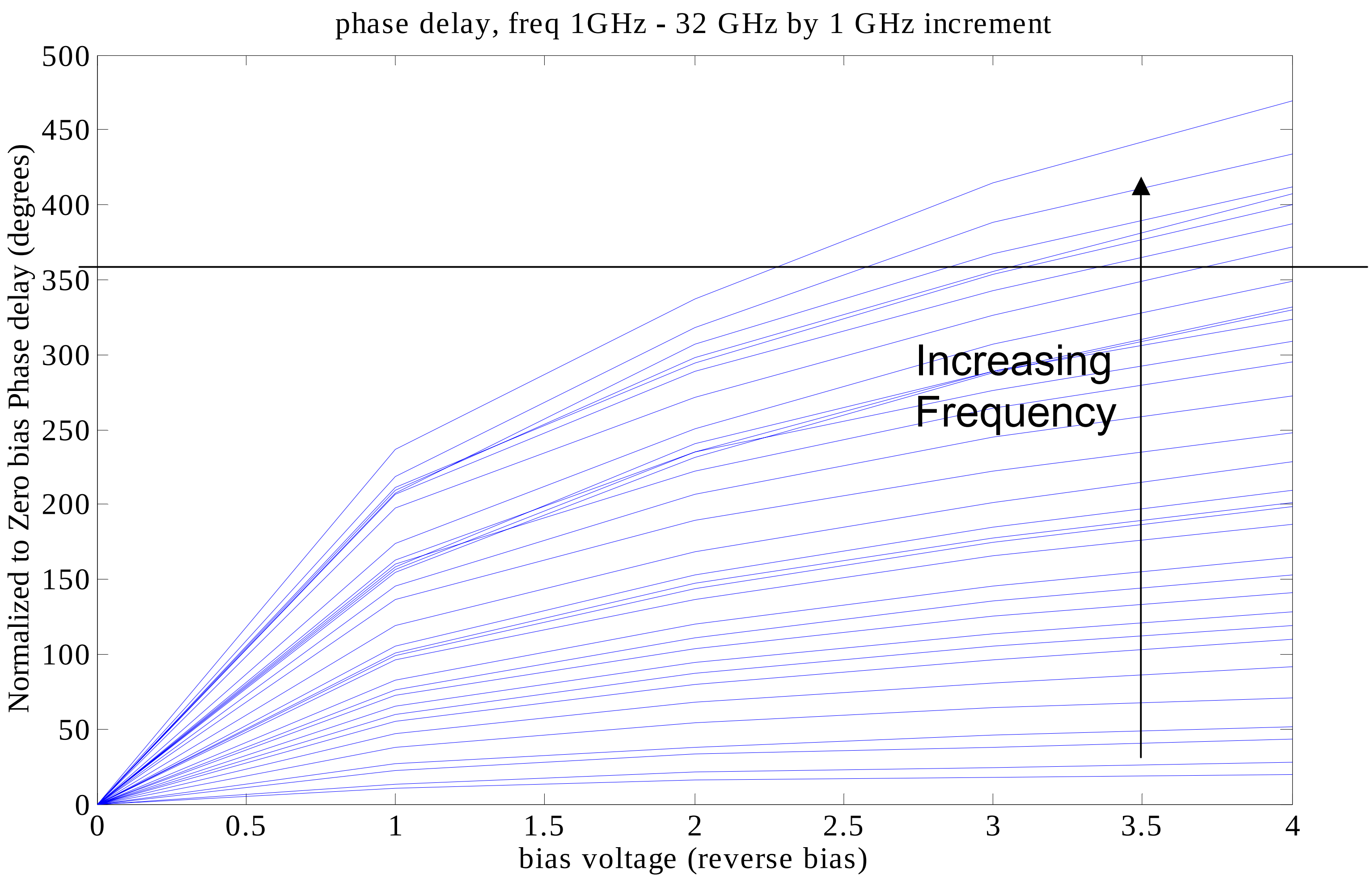
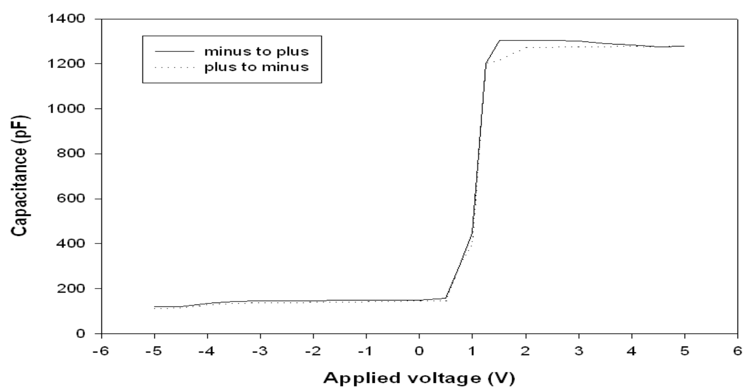
NLTL designed for 8.5 GHz fundamental frequency phase shifting function
Phase shift (degrees) vs Bias (Voltage) (1GHz – 32 GHz by 1 GHz increment)



NLTL phase shifter improvements through new device design

- *True delay time can be determined by the capacitance of the transmission line*
- *Compared to the usual NLTL MESFET diode which has Cmax/Cmin = 4, the MOS diode has Cmax/Cmin = 10. Therefore, it can reduce the NLTL length, which means less loss while the signal goes through the phase shifter.*
- *MOS diode can change the most capacitance variation within the bias voltage of 2 V, so it gives us faster operation.*



< GaAs MOS CV characteristic measurement by Dong Hwan Kim>

MES and MOS diodes in NLTLs

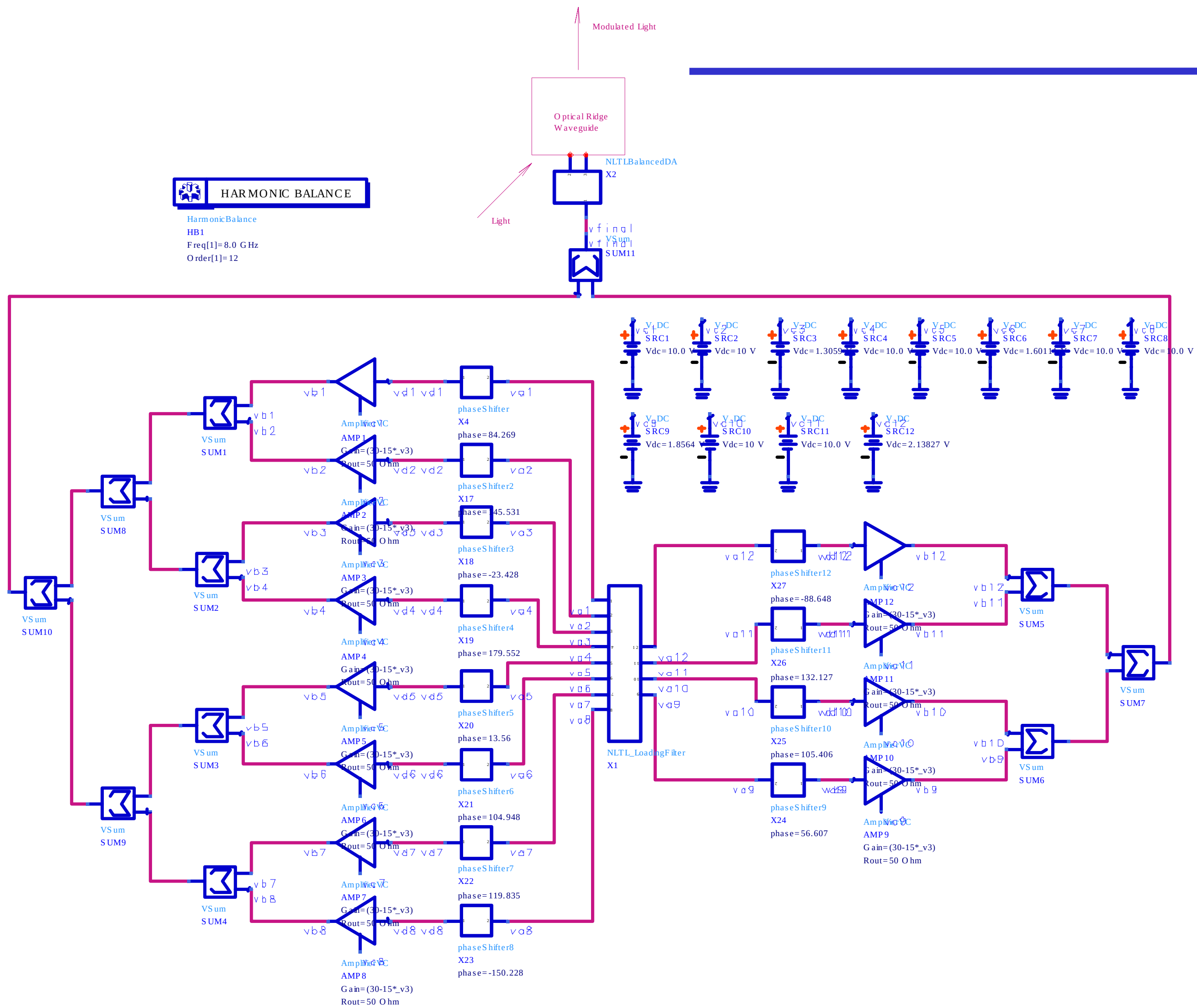
Advantages of MOS diode instead of MES diode

- Oxide gives us fixed high capacitance

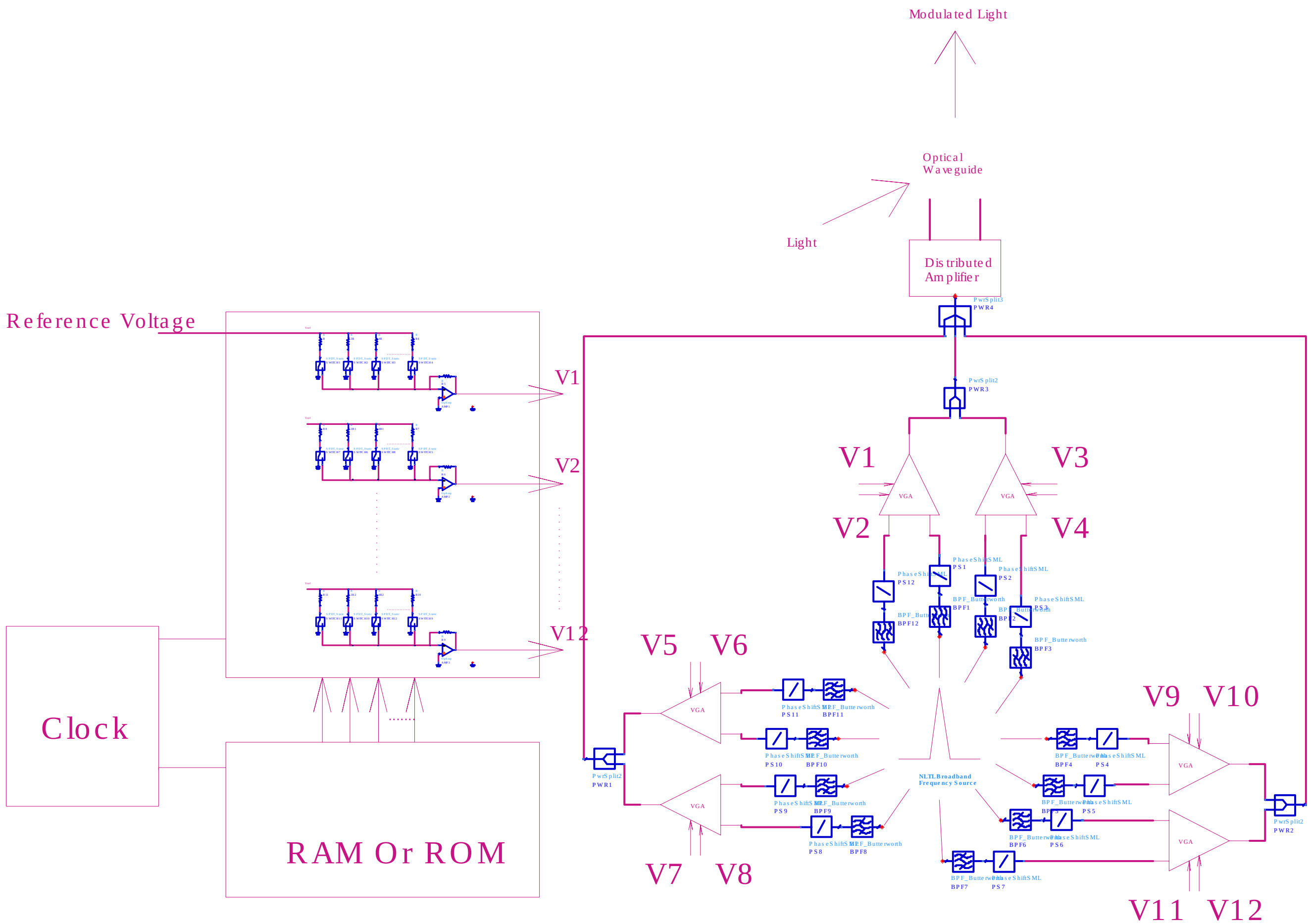
- Higher capacitance difference between forward and reverse biases due to oxide

- Low current leakage due to oxide → low noise, low power consumption

One element of a multiplexed OPTIARB



Behavioral model of OPTIARB element in ADS



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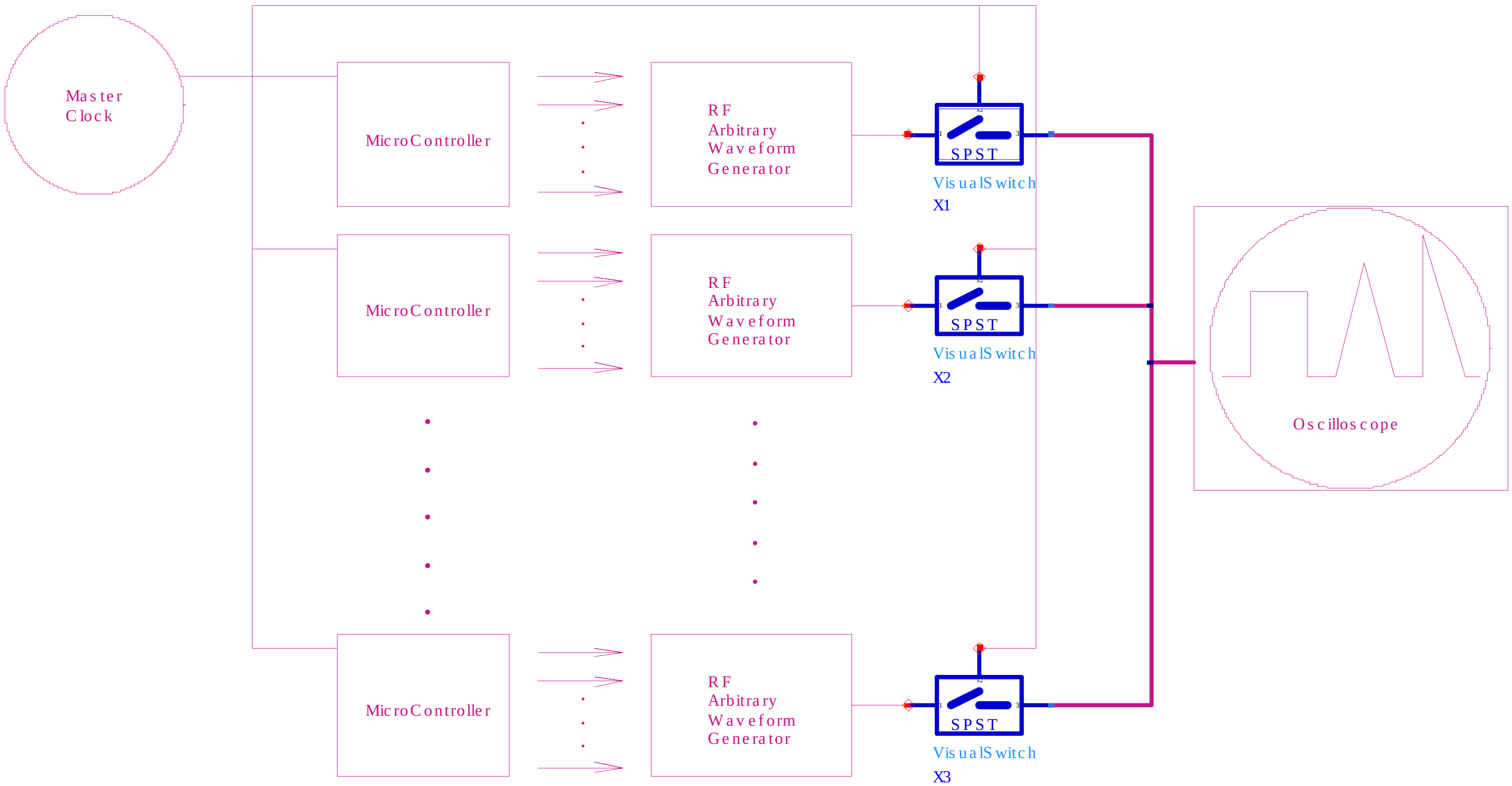
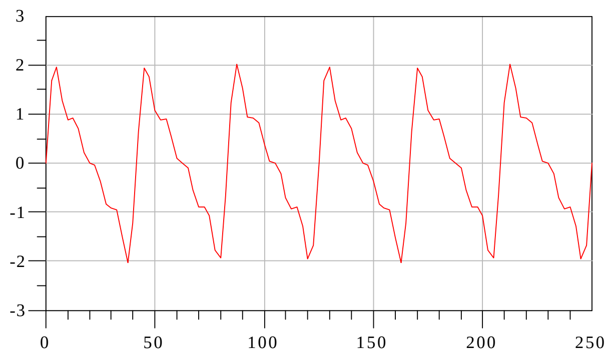
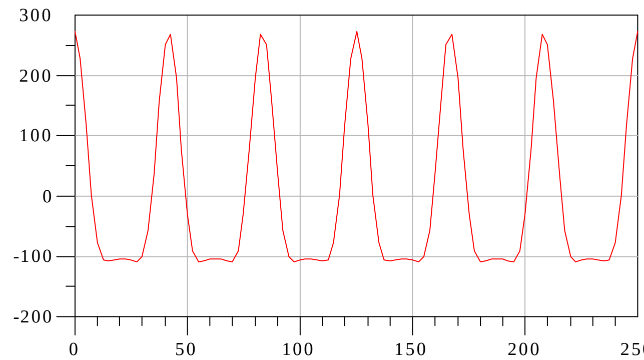
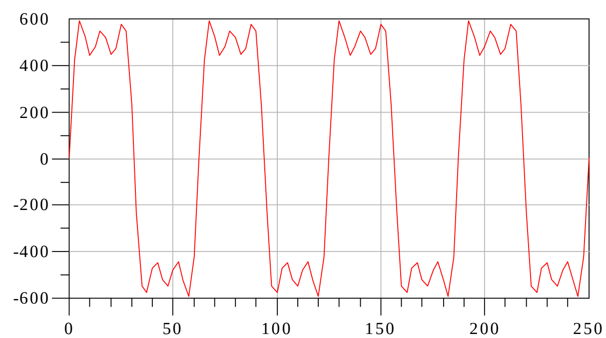
System block diagram



Example waveforms at 16-24 GHz repetition rate simulated in ADS

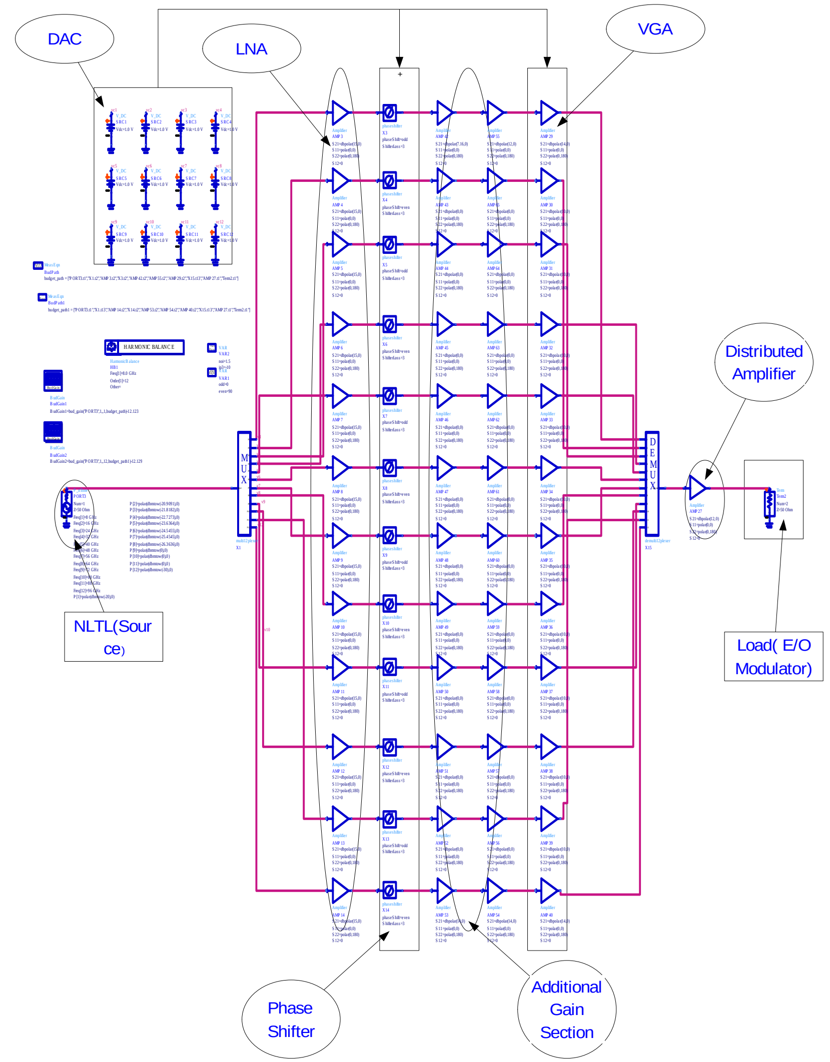




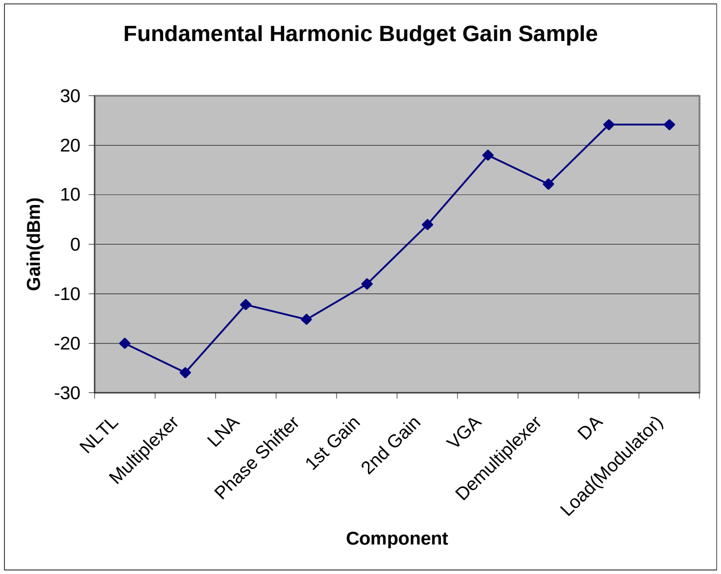


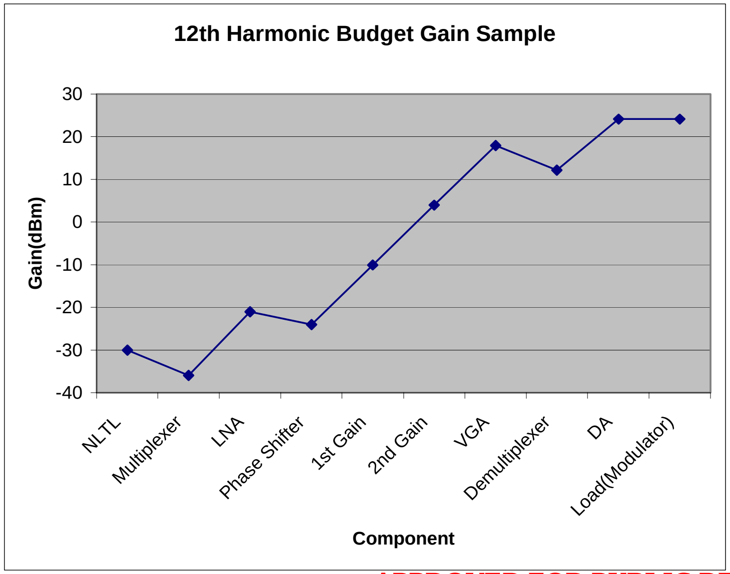
Gain budget simulation setup

- *Worst case (single ended distributed amplifier is used instead of balanced distributed amplifier)*
- *2 stage gain block after phase shifter when used with single output DA*



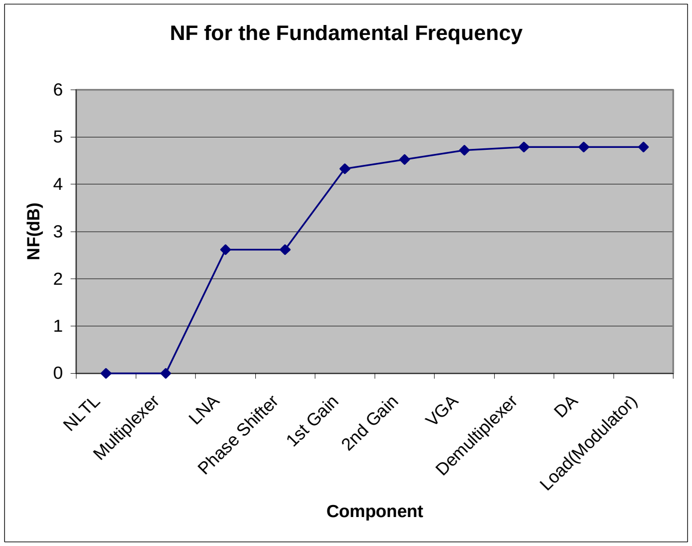
Harmonic gain budget example

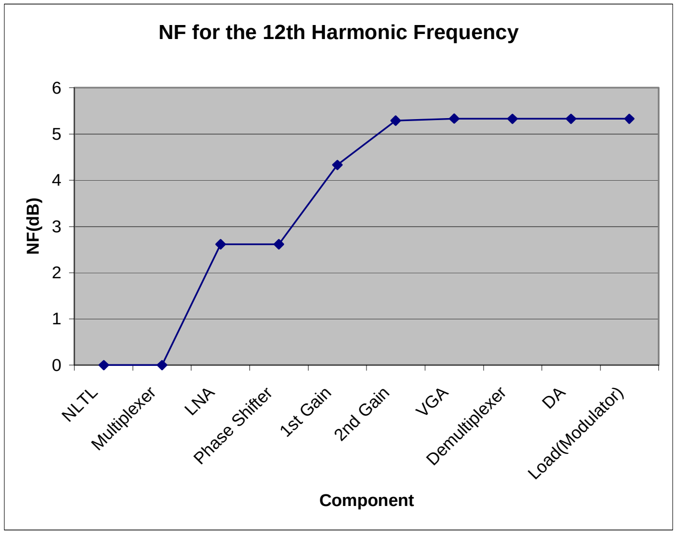




- *ADS budget gain simulation shown for the 1st and 12th harmonics*
- *Every harmonic was level within 4 dB*
- *Worst case when used with single ended DA*
- *$V_\pi \approx 5$ V assumed (+24 dBm into 50 Ω)*

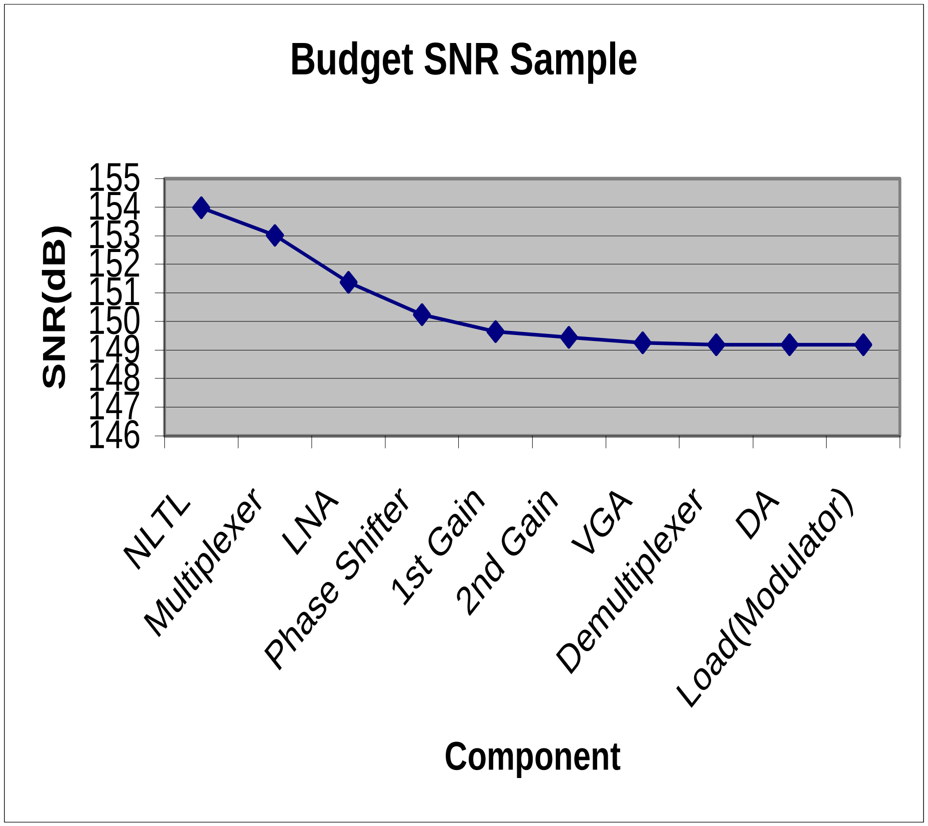
Noise figure budget example

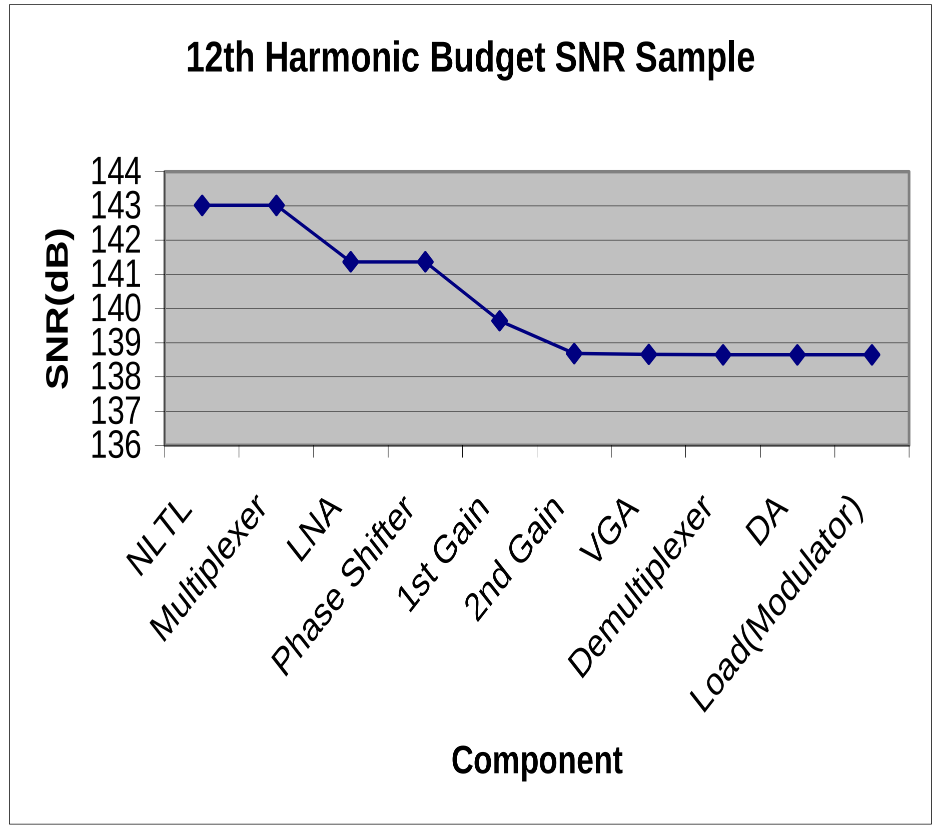




- *Noise figure starting from the NLTL pulse generator*
- *Assumed NF of each component:*
  - *LNA ≈ 1.5 dB*
  - *VGA ≈ 15 dB*
  - *Gain Block ≈ 8 dB*
  - *DA ≈ 5 dB*

SNR budget example





Same components as NF simulation were used in this simulation

Conclusion: Signal generation and processing for complex waveforms demands an arbitrary waveform generator

- *Radar front ends, jamming*
  - *"Noise" UWB radar*
  - *Can be coupled to our UWB antenna arrays*
- *Secure communications on fiber*
- *Security measures*
  - *Sensing explosives and weapons*