Beyond 40 GHz:
Chips to be tested,
Instruments to measure them

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>40 GHz Measurements: Why now ?

Very high frequency instruments have existed for some time.

Emerging applications → increased need for instruments
40 Gb/s (40-50 Gb line rate) optical fiber transmission
60 GHz wireless LANs
rates and bandwidths will get still higher

Typical circuit / signal parameters
~40-60 GHz circuit bandwidths
40-50 GHz digital clock rates
~5-8 ps pulse rise times
~150 GHz transistor cutoff frequencies in medium-scale (2000-transistor) ICs

Instruments needed
sampling oscilloscopes (waveform measurements)
network analyzer (circuit response, transistor characterization)

Problems faced
sampling oscilloscope: timebase stability, connectors, cable loss calibration
network analyzer: cost-effective hardware, precise on-wafer calibration

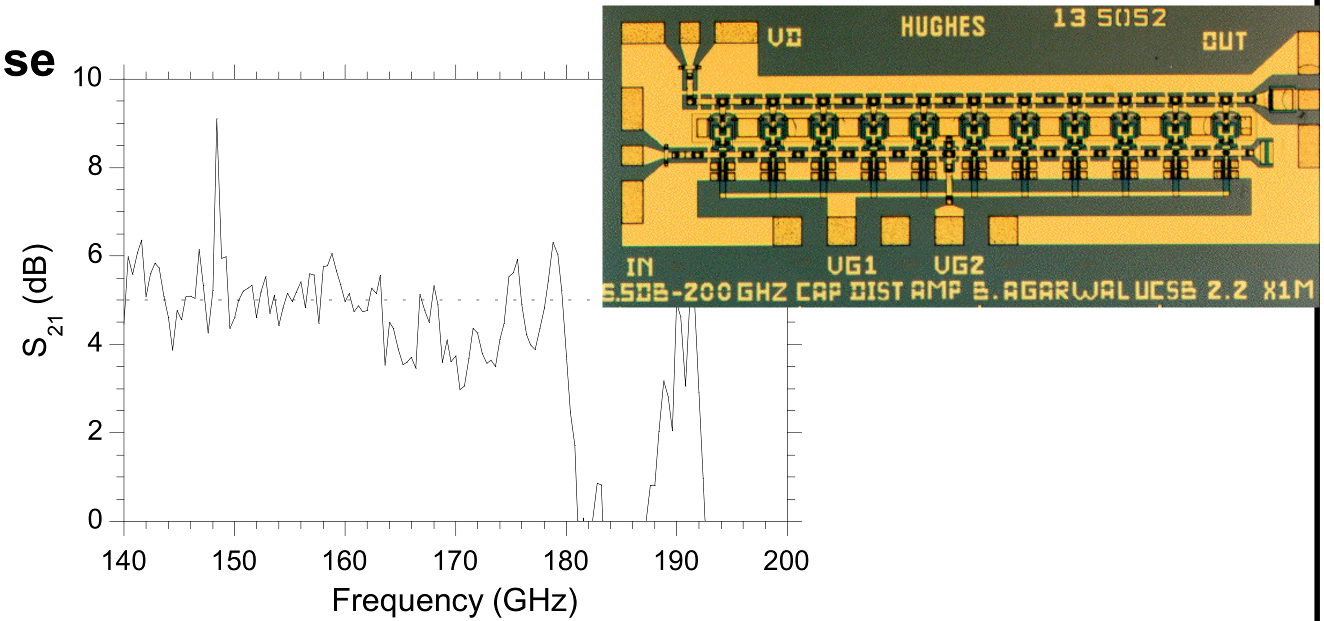
types of measurements and problems

High-Frequency Measurements: Network Analysis

Circuit frequency response

No extrapolation

Acceptable errors (roughly)
~ 0.25 dB in S21
30 dB directivity

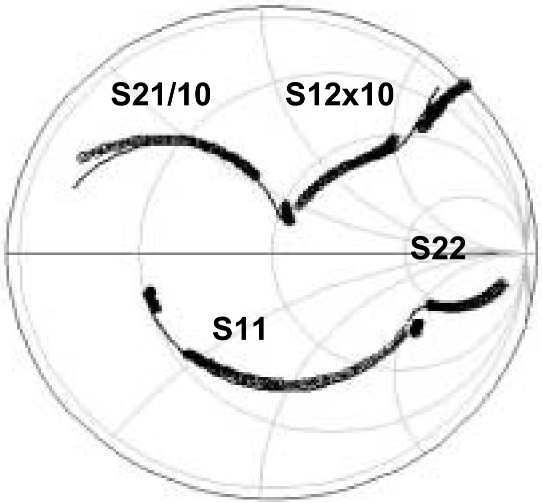


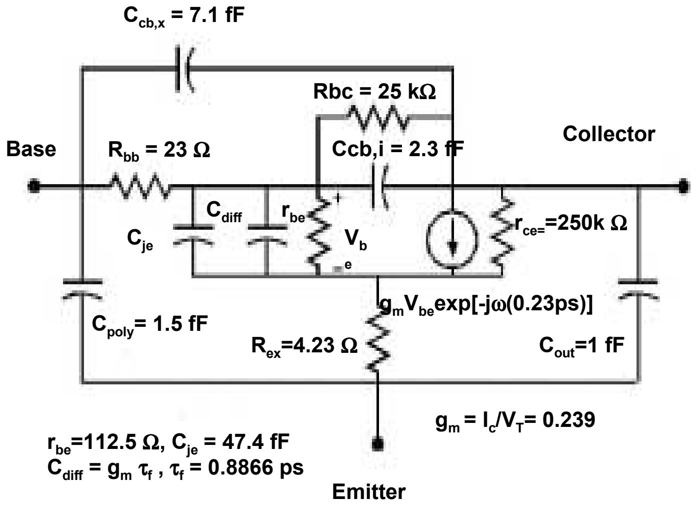
Device characterization

S-parameters converted to Y_{ij} and Z_{ij}

Frequency variation allows device parameter extraction.

Calibration must be **very** precise



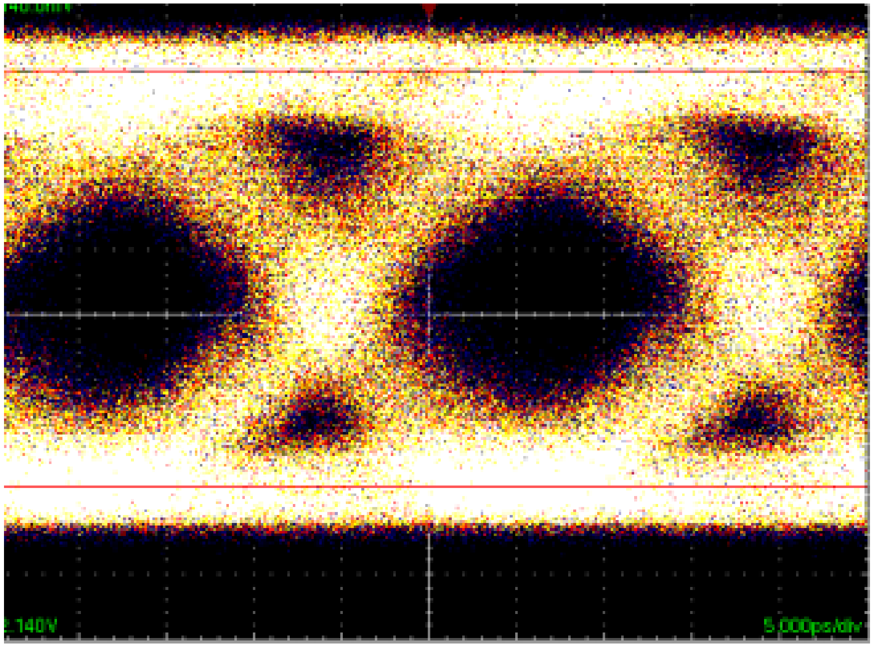


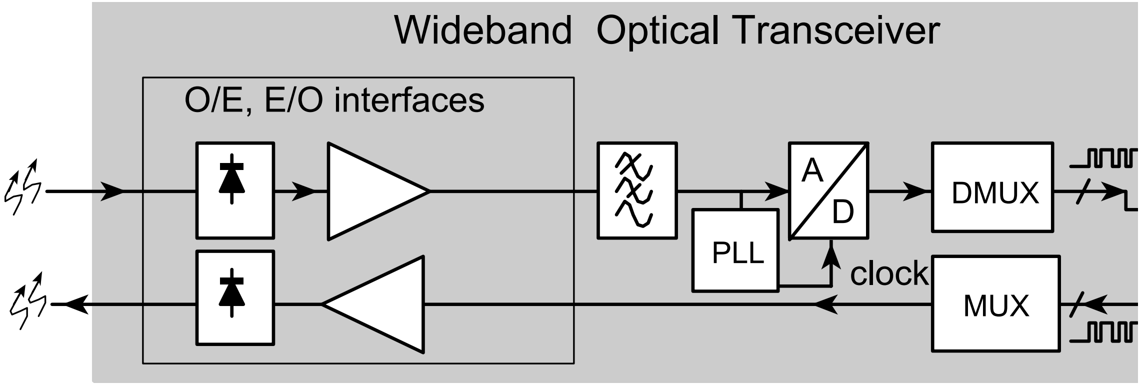
High-Frequency Measurements: Waveform Measurements

Circuit pulse response
Circuit or system modulation response
Functioning system

Measurements in 50 Ohm system
(Internal node testing not feasible)

Waveforms may be
repetitive / periodic
transient single-shot
random data (eyes)

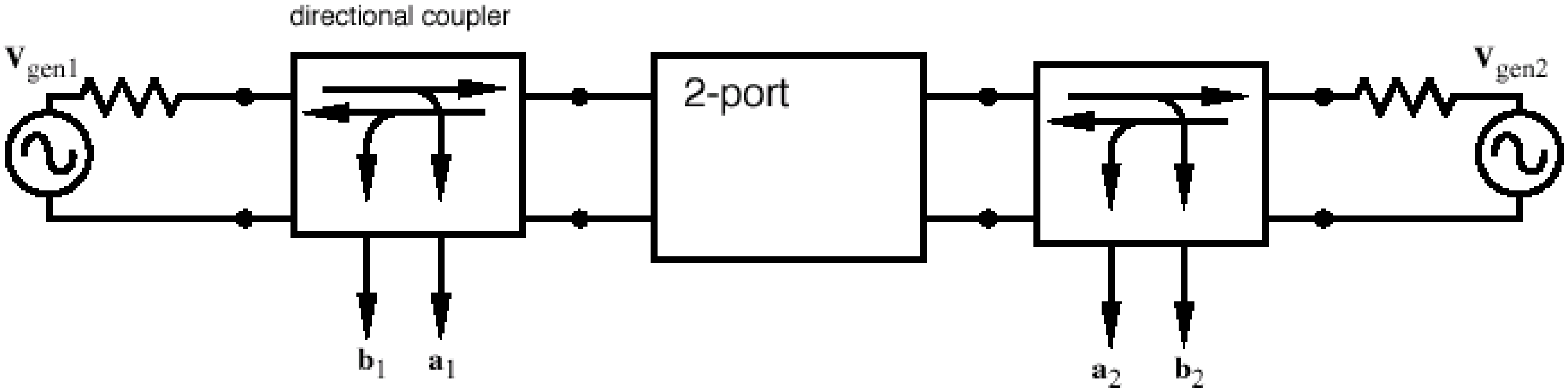




Network Analysis: system-level

microwave network analysis

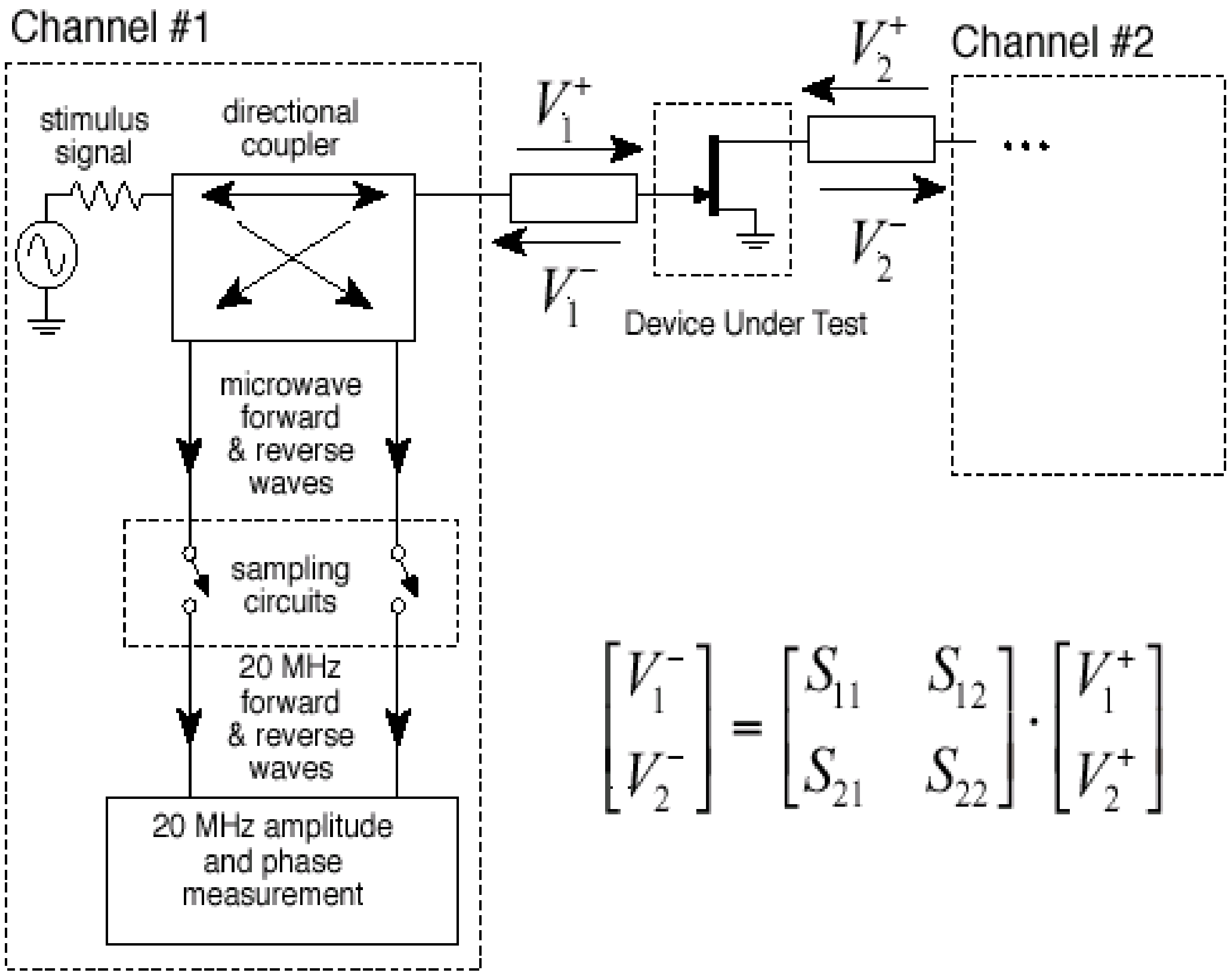
Measurement of (linear / small signal) 2-port network parameters in the frequency domain.



Swept-frequency sources (V_{gen1} and V_{gen2}) are alternately applied to the 2-port input and output, and the incident and emanating waves measured with directional couplers.

Calibration: amplitude/phase contributions of cabling (etc.) between the instrument and the d.u.t. are corrected for by first measuring a series of devices of known characteristics in place of the d.u.t. , either 50Ω load, open, short, and through line, or a series of through lines of differing lengths ("LRL")

Block Diagram: microwave network analysis



$$\begin{bmatrix} V_1^- \\ V_2^- \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \cdot \begin{bmatrix} V_1^+ \\ V_2^+ \end{bmatrix}$$

Bandwidth limits include

available connectors and cables,

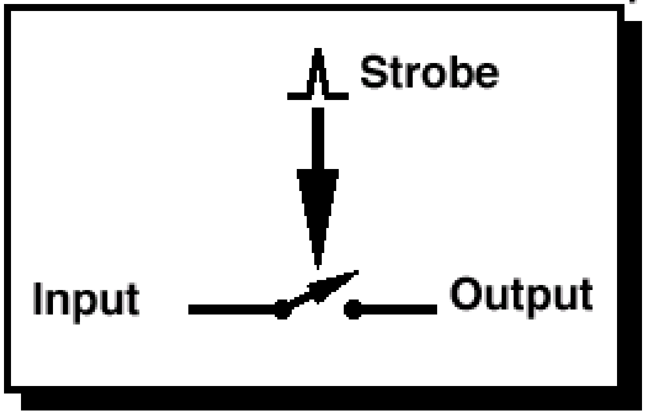
sampling circuits,

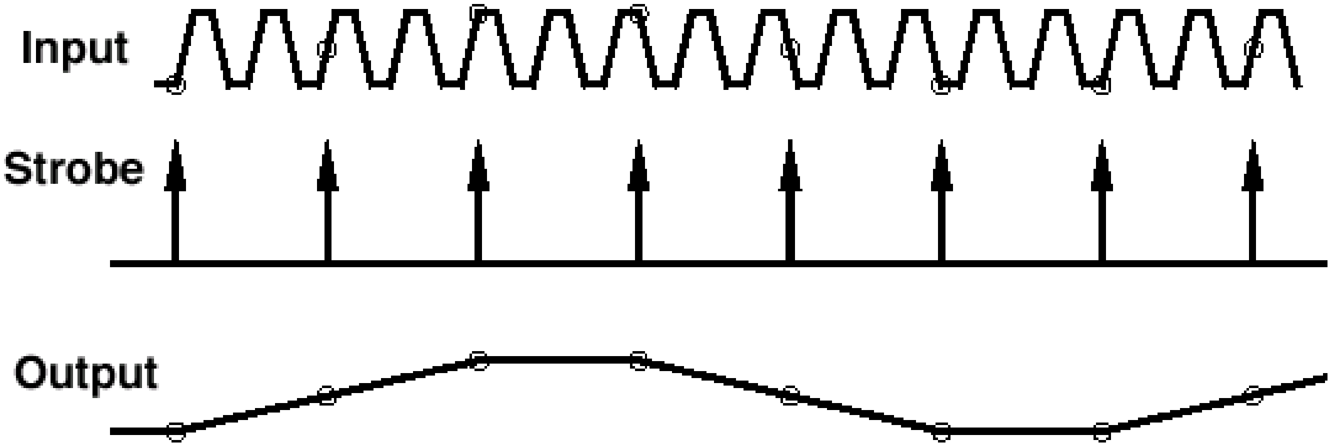
signal source frequency range

sampling oscilloscopes

Sampling

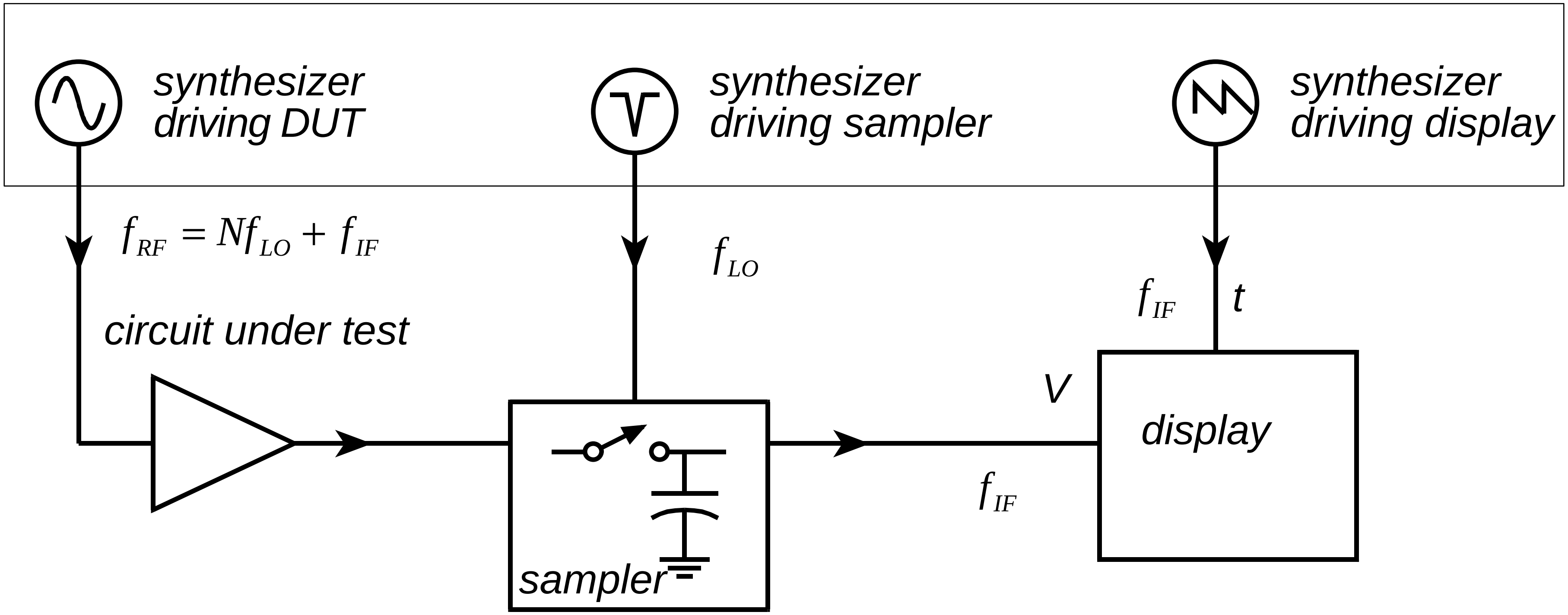
Reducing the repetition frequency (bandwidth) of a signal so that it can be measured with low-frequency instruments





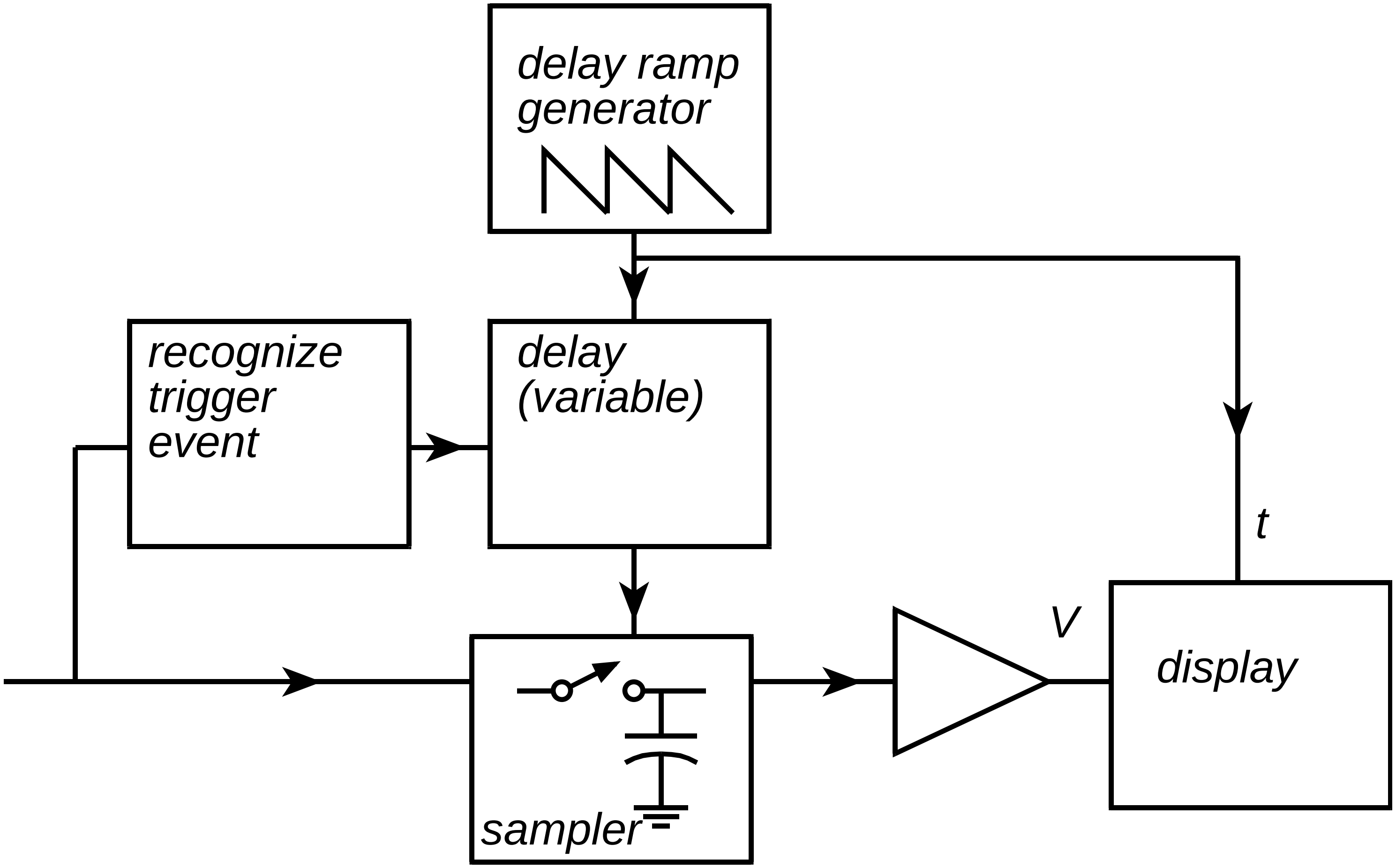
If the strobe signal has repetition frequency f_0 and the input signal has repetition frequency $nf_0+\Delta f$, the sampled output will be at frequency Δf.

Synthesizers as sampling scope timebase



Simple to implement (we use this at UCSB)
Demands that instruments can control signal stimulus
Extremely good timebase stability
Acceptable for eye patterns, hard for data patterns.

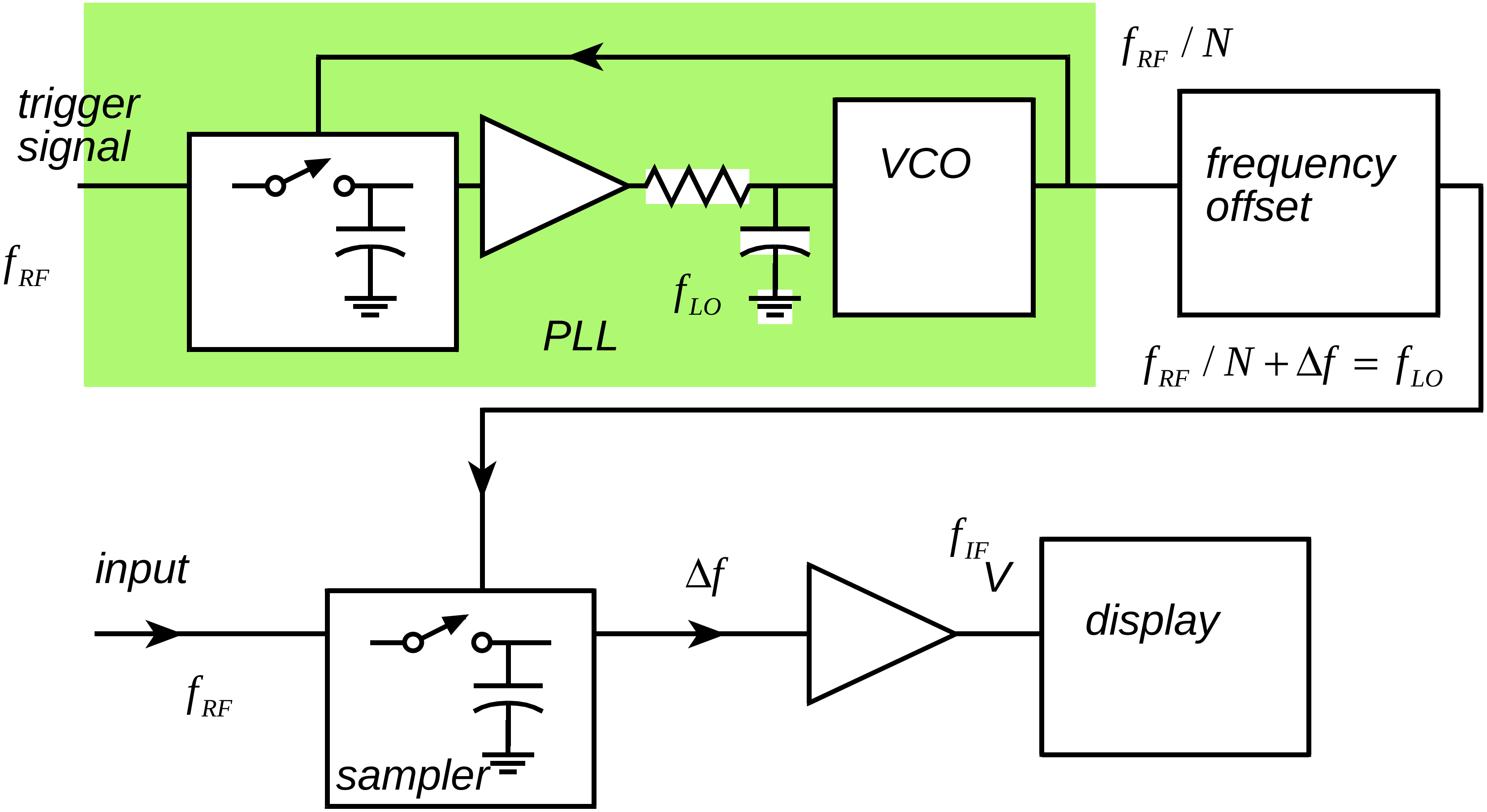
Common triggered-timebase sampling scope



Good: trigger on ***aperiodic*** repetitive signal

Bad: no band limiting in triggering → trigger jitter

PLL as sampling scope timebase ?



PLL is narrowband filter: noise suppression of trigger signal→ less jitter

Challenge: maintaining LO frequency within acceptable design range

Alternatives:

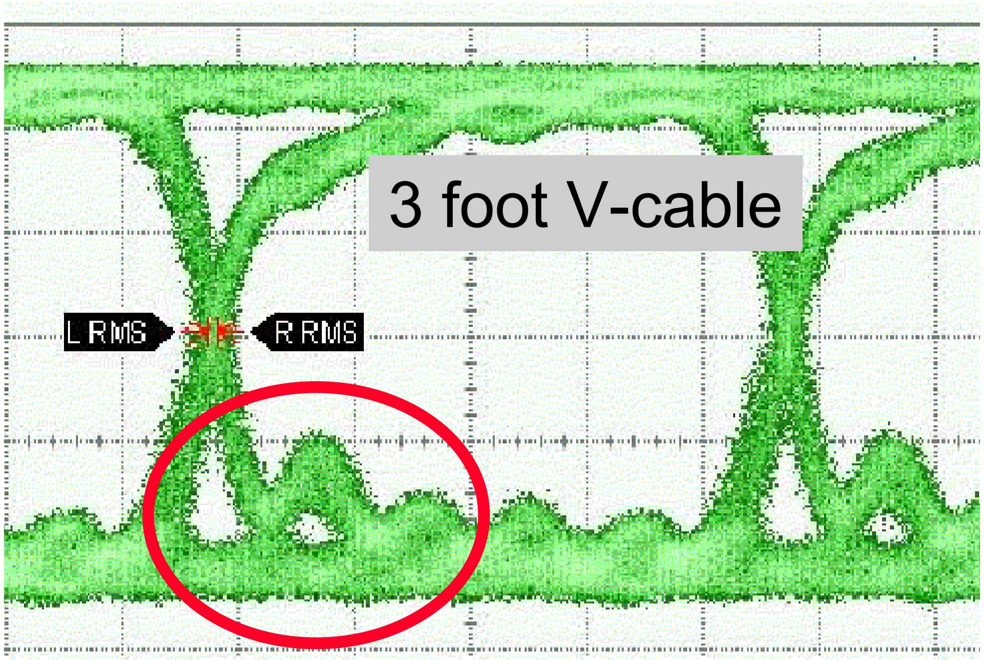
- Δ–Σ frequency synthesis for frequency offset
- Direct digital frequency synthesis timebase control

Cable losses with sampling scopes

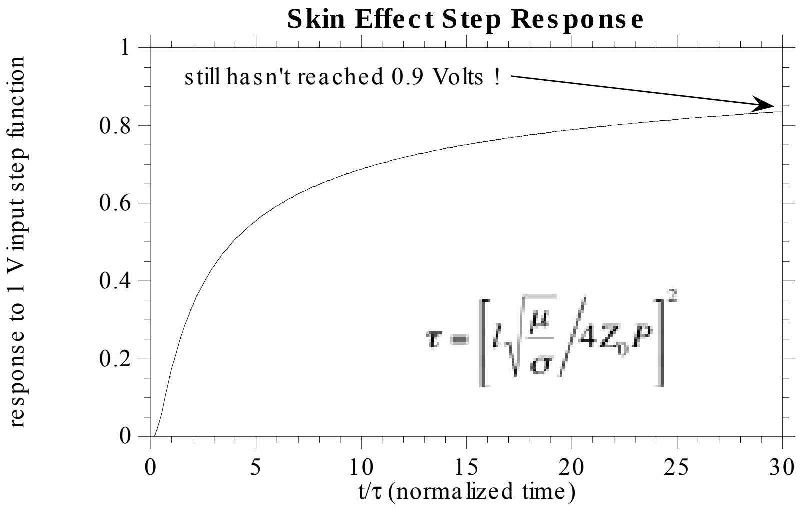
Present sampling oscilloscopes do not provide calibration correction of cable + connector losses

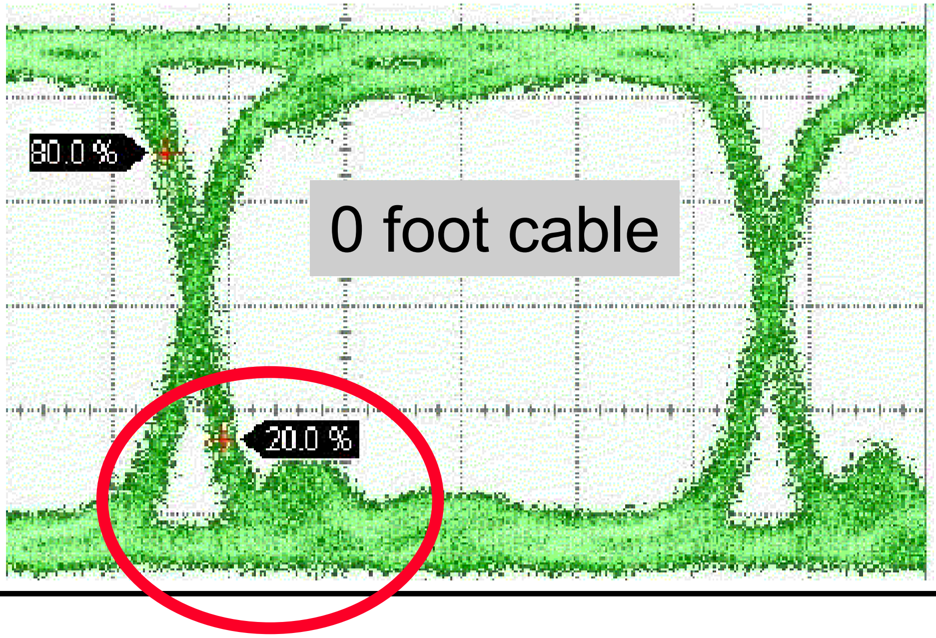
significant ambiguity in waveform measurement, particularly for on-wafer measurements*

*skin losses of wafer probes are high



3 foot V-cable





0 foot cable

Calibration in sampling oscilloscopes ?

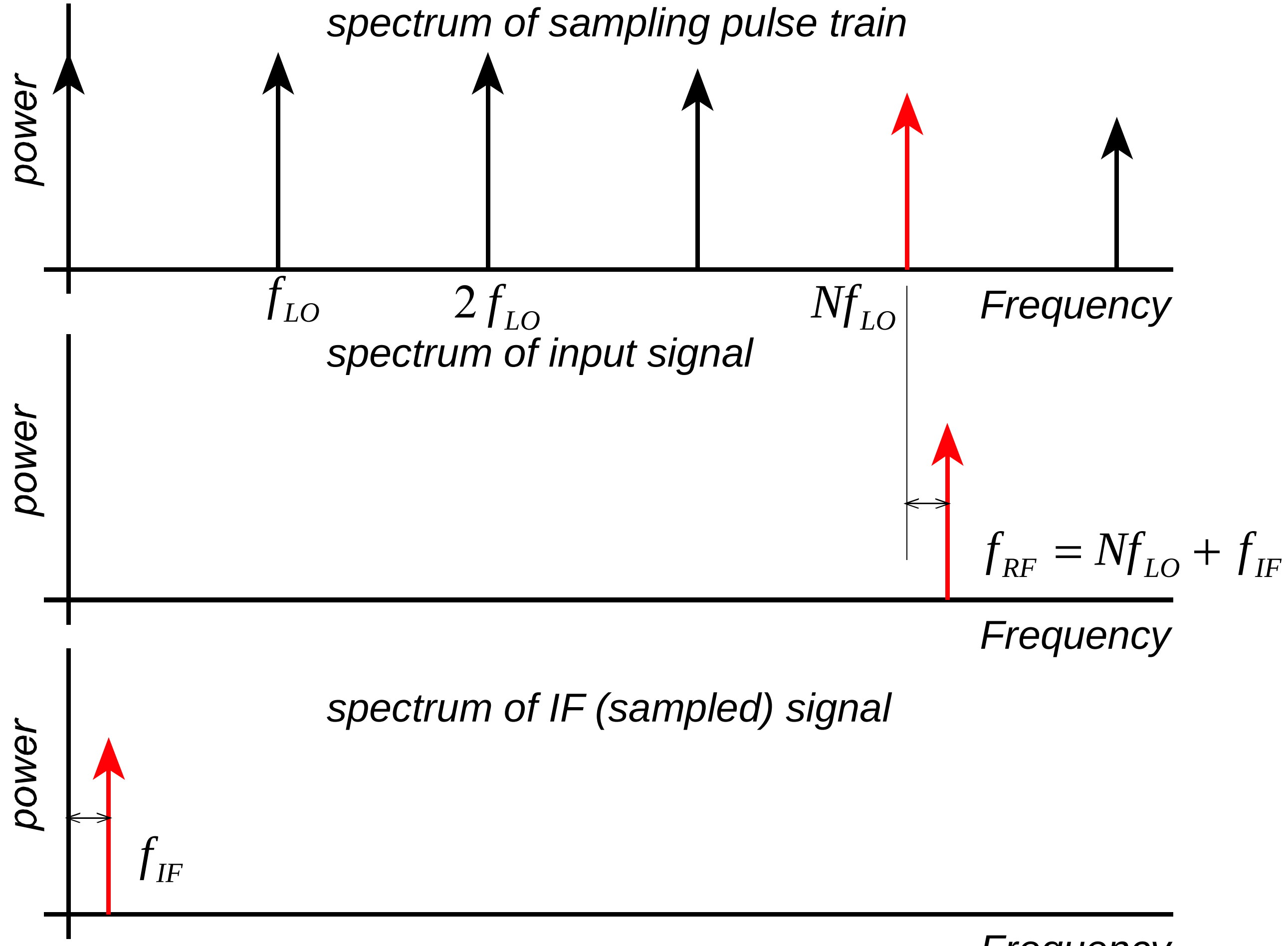
Pulse response distortion due to cable loss is becoming major measurement limit.

Network analysis removes such artifacts by calibration

Can NWA calibration be extended to sampling oscilloscopes ?

sampling bridges and harmonic mixers

Equivalence of sampling and harmonic mixing



Sampling circuits are one type of high-order harmonic mixer.

Sampling circuits used in oscilloscopes and network analyzers

Harmonic-mixing order in network analysis

Noise figure of Sampling Circuit

$F \geq$ harmonic order of conversion (frequency domain description)

$F \geq$ (time off / time on) (time domain description)

Sampling circuits with low high harmonic orders :

inexpensive hardware : LO at low frequency, low LO tuning

degraded dynamic range due to high noise figure

Network analysis with low harmonic orders

moderately expensive hardware : higher LO, more LO tuning

better noise figure

harmonic mixer may be diode pair or sampling bridge

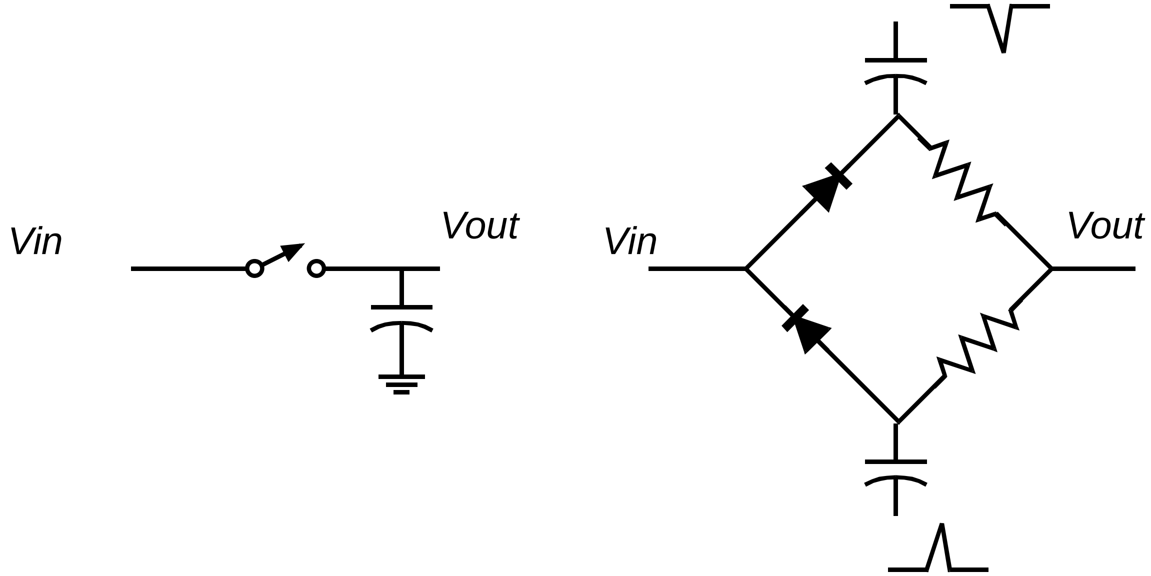
Network analysis with fundamental mixing

expensive hardware

best dynamic range

Diode Sampling Bridges

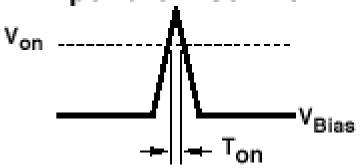
Used in sampling oscilloscopes and network analyzers



RC risetime at input

$$T_{RC} = 2.2\frac{Z_o}{2}(2C_{diode})$$

Aperture Risetime



Total Effective Risetime

$$T_{EFF} = \sqrt{T_{ON}^2 + T_{RC}^2}$$

Schottky diodes are readily made with << 5 fF junction capacitance and » 2 THz R-C cutoff frequencies.

The primary bandwidth limitation of sampling circuits: duration of the strobe pulse used to gate the diodes.

Strobe pulses generated using either Silicon step-recovery diodes, NLTLs, or transistor limiting amplifiers

The Step Recovery Diode

Under bias, carriers are stored in the intrinsic region

Charge control model:

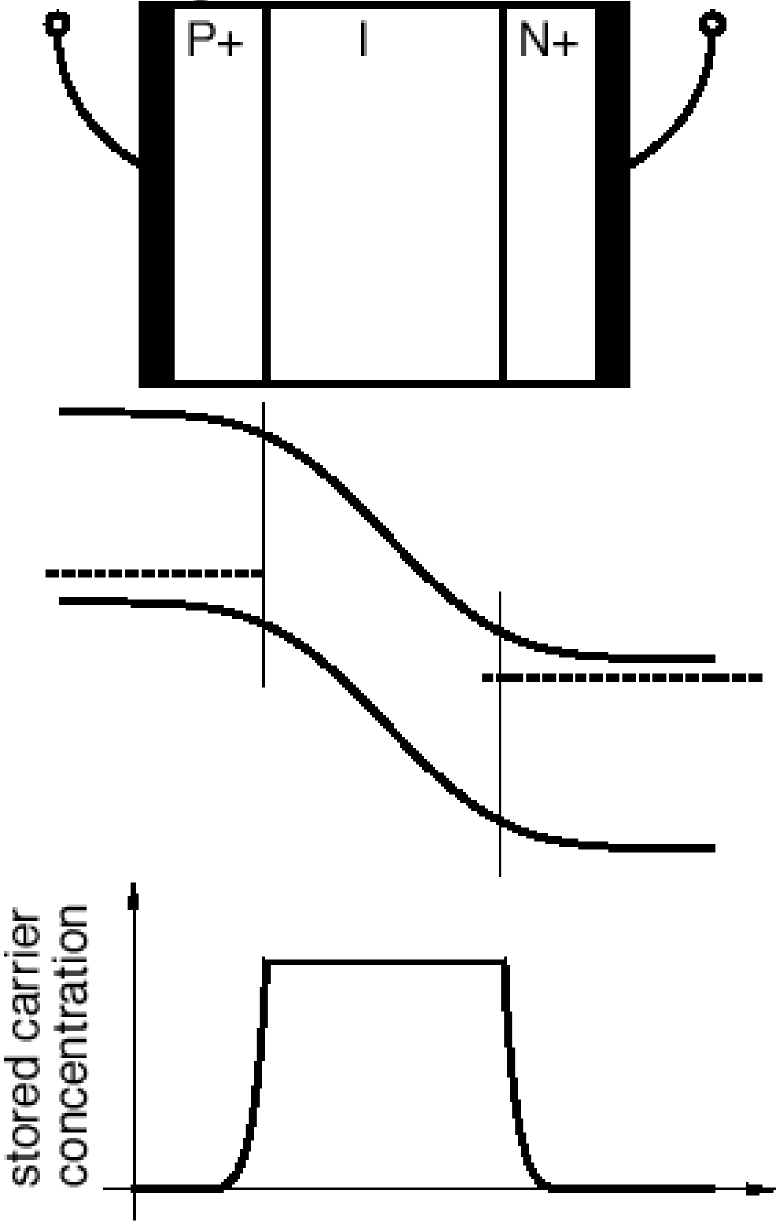
- Stored charge

$$Q_s = Q_0\left(\exp(qV / kT) - 1\right)$$

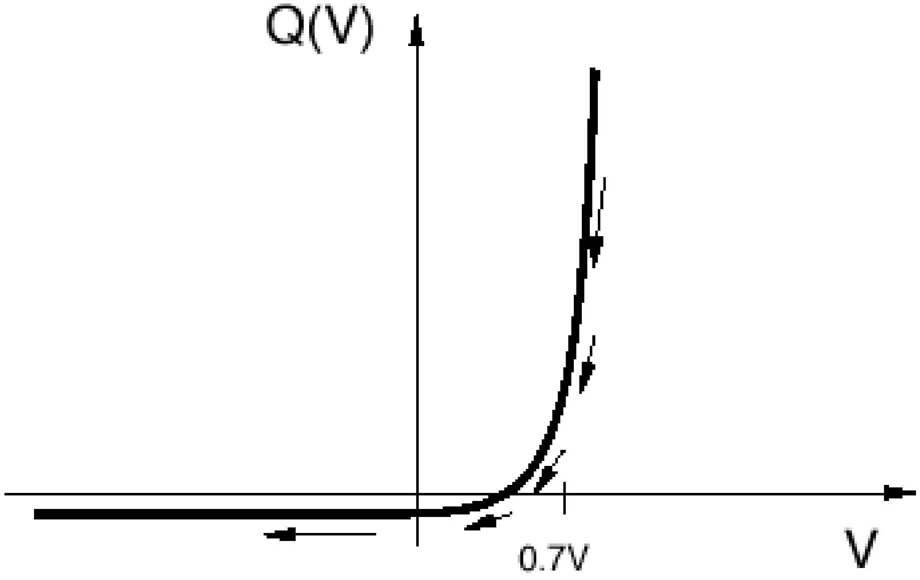
- Diode current

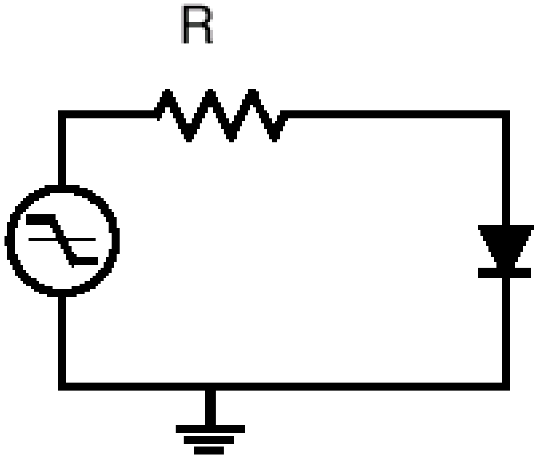
$$I = \frac{dQ_s}{dt} + \frac{Q_s}{\tau}$$

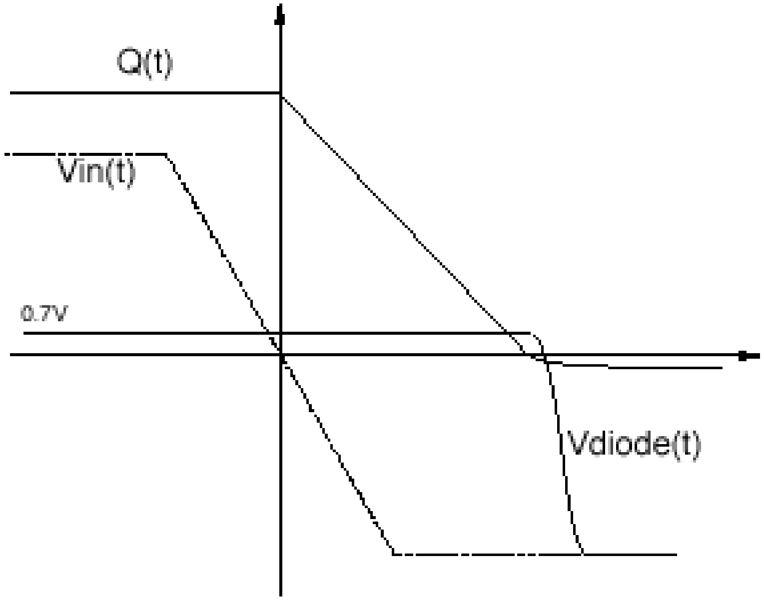
- Widely used as a pulse generator in microwave instruments



Electrical Falltime Compression with SRD's







$$I = \left(V_{diode} - V_{in}\right) / R$$
$$dQ / dt \cong -I$$

For a fast-changing input signal, the SRD acts as a nonlinear capacitor.

Risetime / pulse width limits to SRDs

Depletion Capacitance

$$\tau = Z_o C_{SRD}$$

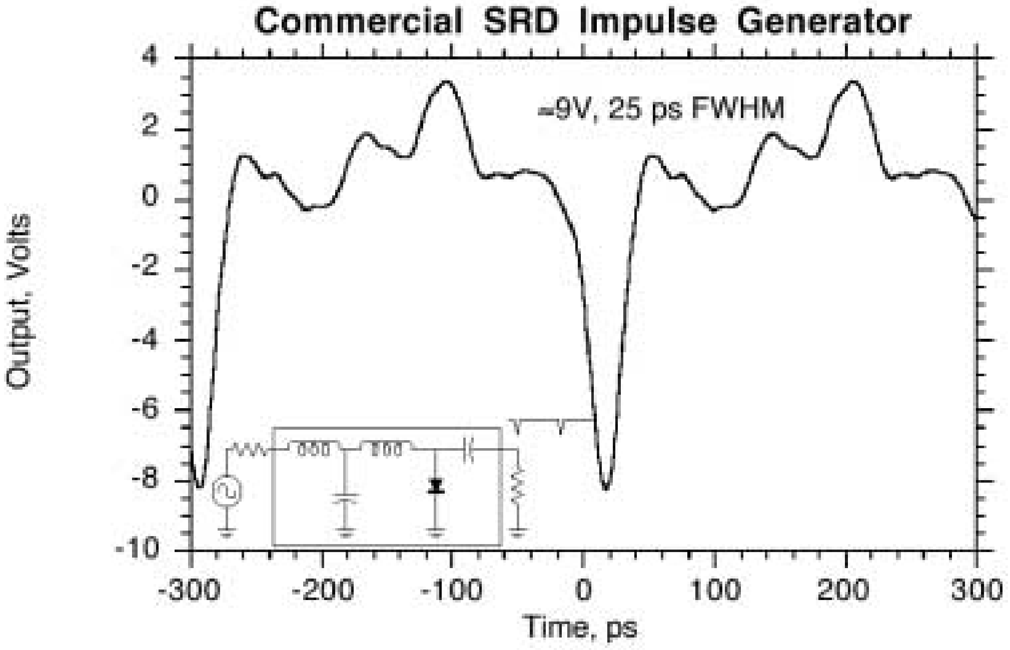
Carrier Diffision Time

Time in which final carrier collapse arises in depletion region

Moll (1969) estimates this as 10 ps/micron of depletion width

Typical Performance

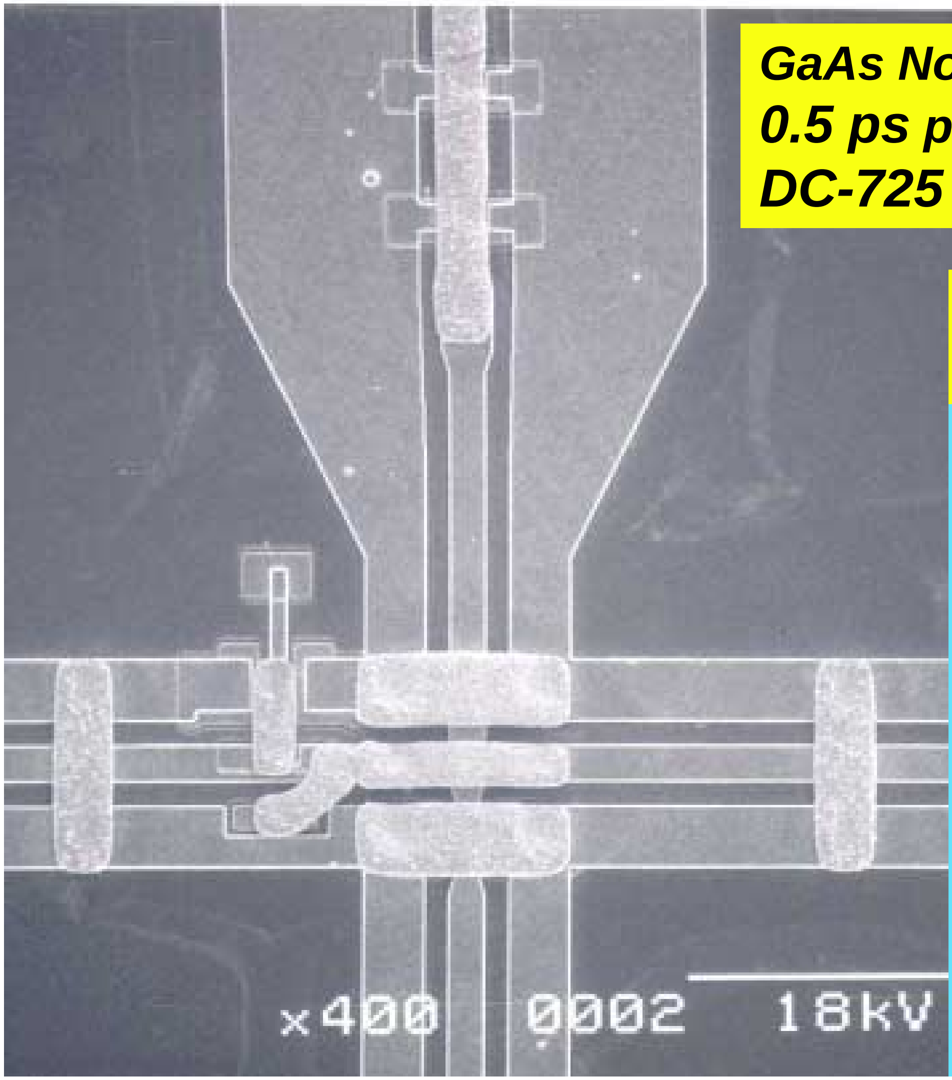
Best commonly - available devices are 20 - 30 ps



NLTL technology

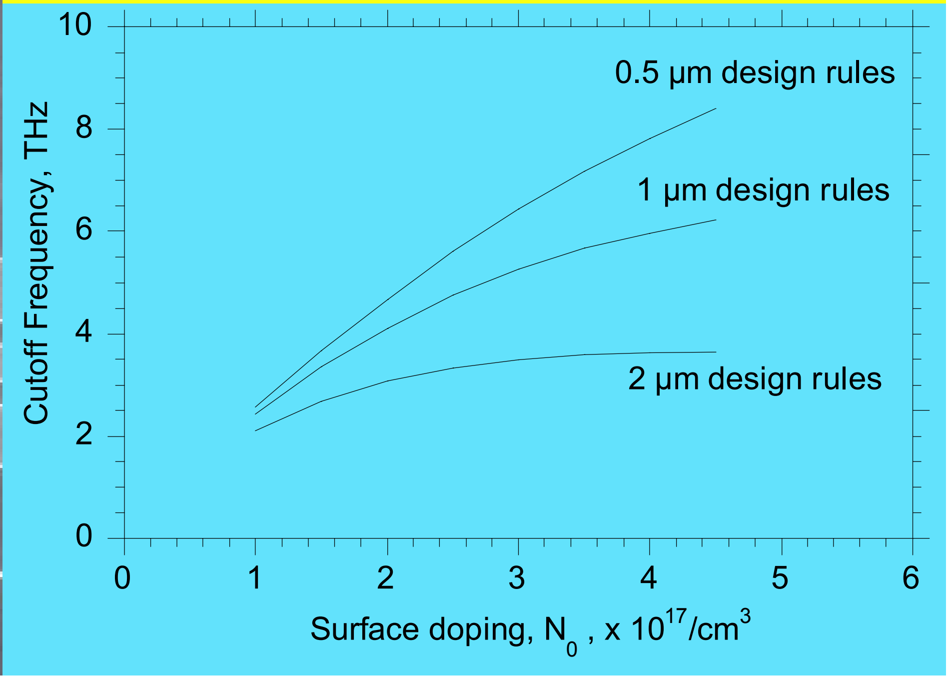
GaAs Schottky diode ICs for mm-wave Instruments

UCSB, Stanford, Hewlett-Packard 1985-1995



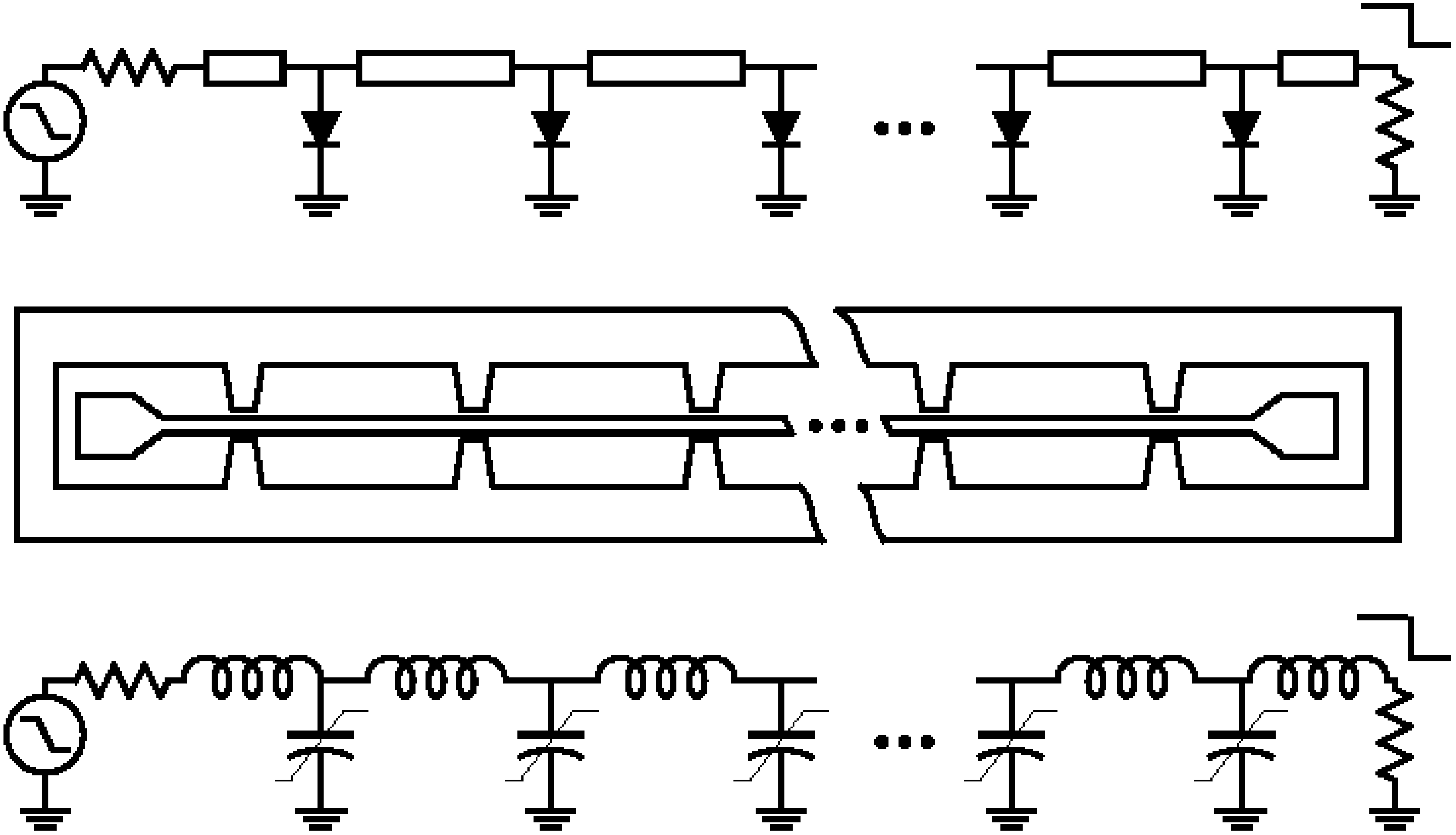
GaAs Nonlinear Transmission Line ICs:
0.5 ps pulse generators &
DC-725 GHz sampling circuits

Semiconductor Technology:
scaled THz Schottky varactor diodes

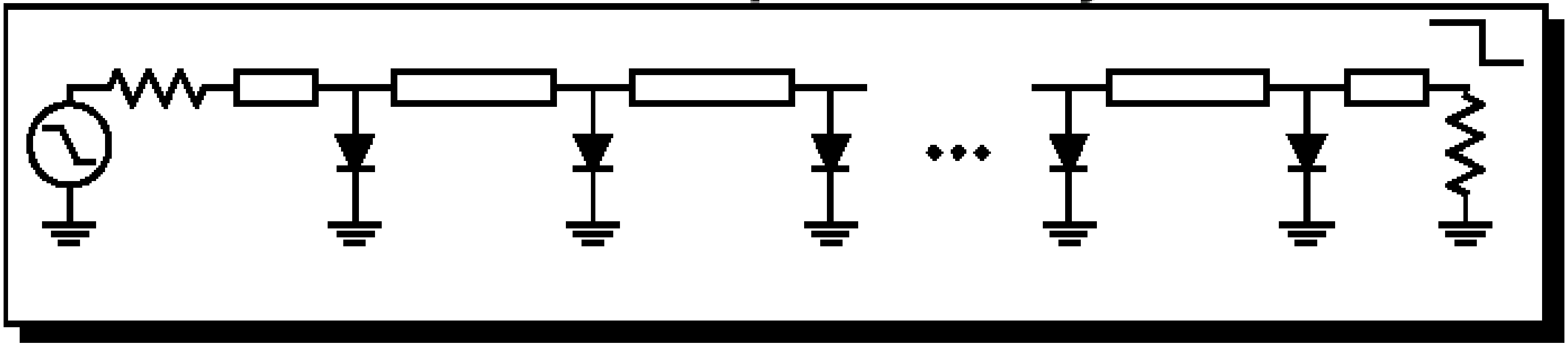


NLTL technologies can cheaply address emerging needs for 100 GHz instruments.
Connector and timebase difficulties will dominate cost and accuracy

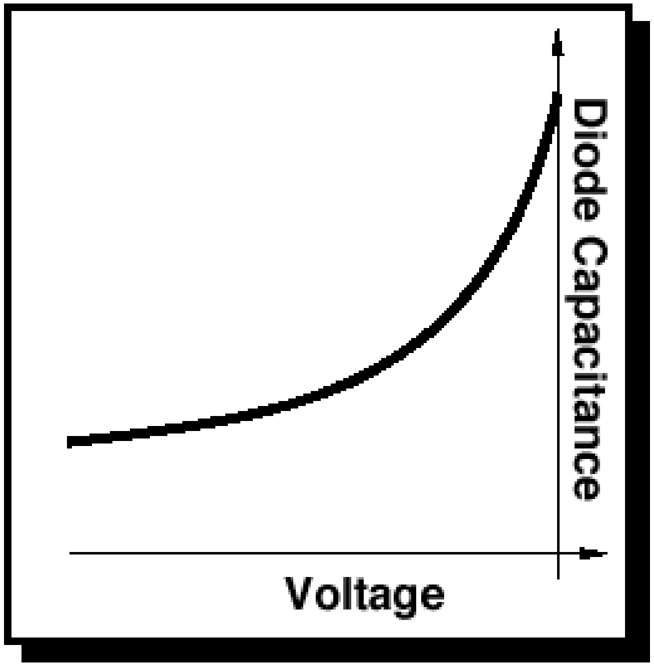
NLTL Structure and Equivalent Circuit

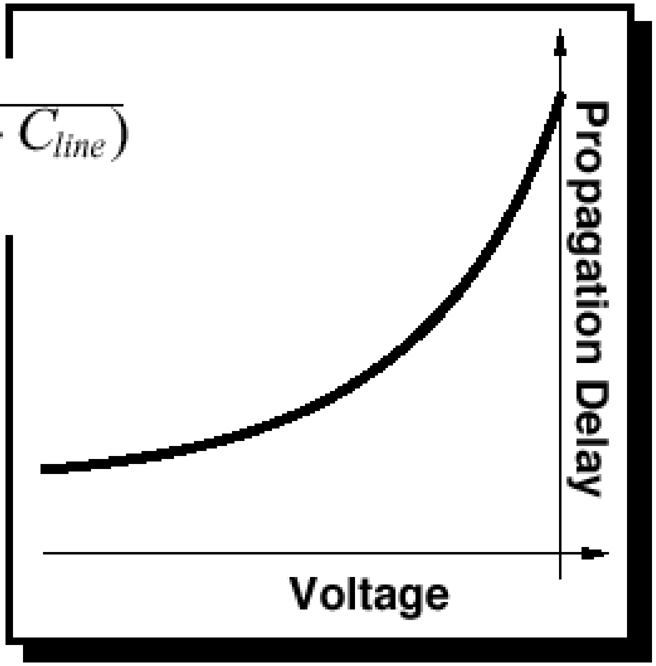


Wavefront Compression by NLTL

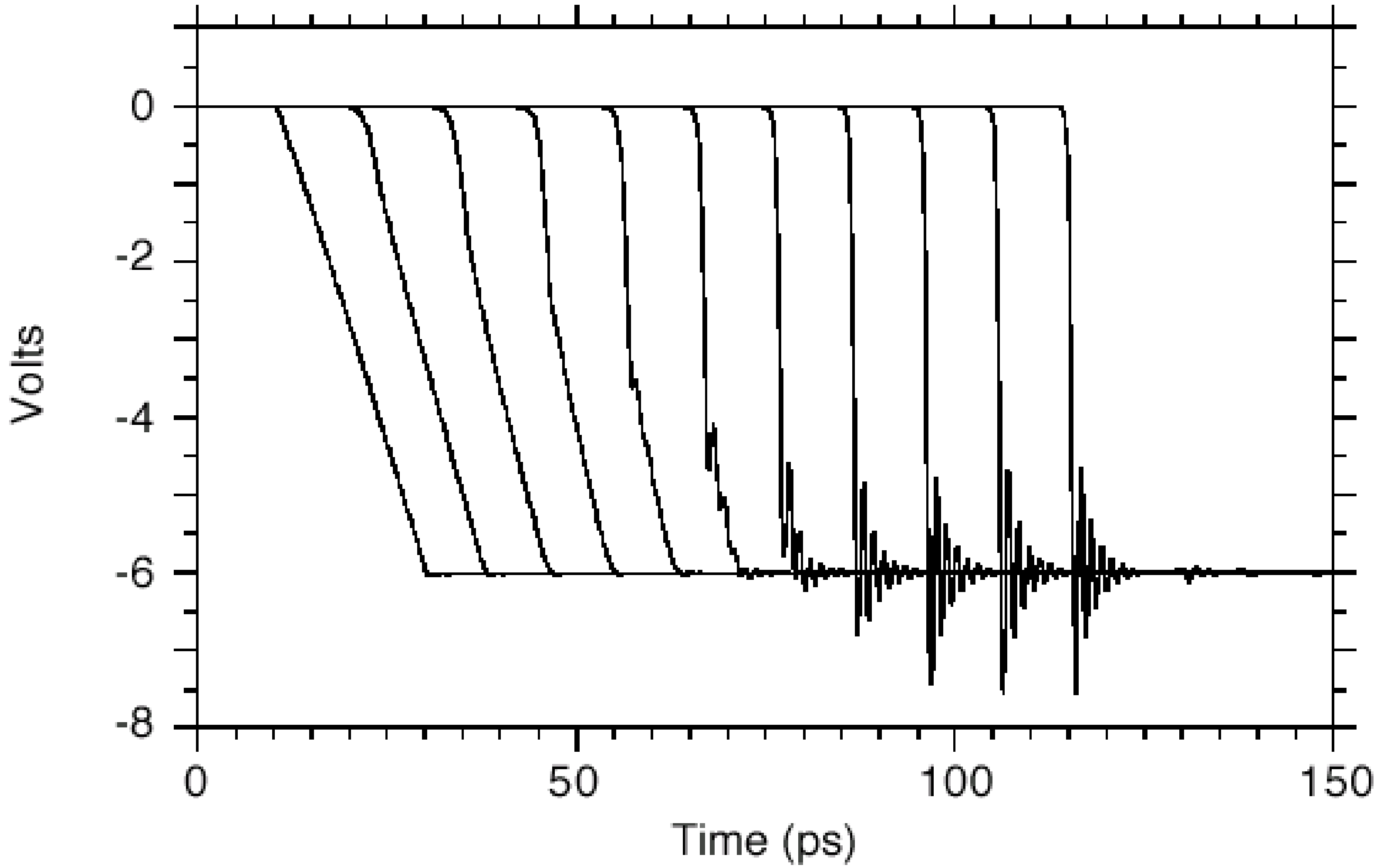


$$T_{delay} = \sqrt{L(C_{diode} + C_{line})}$$





SPICE Simulation of Shock Formation



Limits to NLTL Shock-Wave Transition Time

Periodic-Network (Bragg) Frequency
The periodic structure results in a sharp filter cutoff inversely proportional to the diode spacing. Within lithographic limits, this can easily be 1-2 THz.

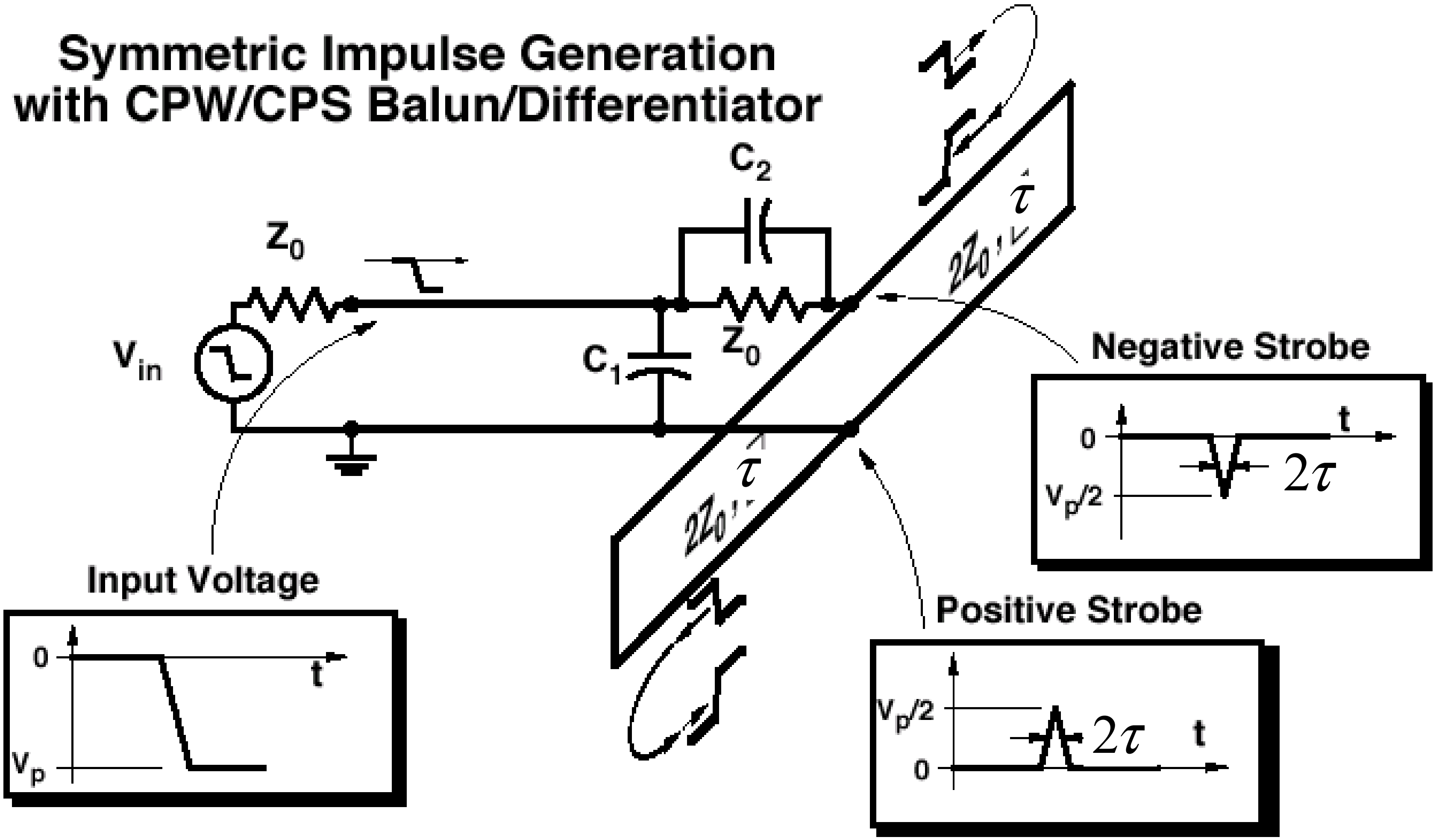
Diode Cutoff Frequency
The fundamental limit of the technology.
Falltime limited to

$$T_{fall}\, f_{c,diode} = 0.14\,\mathrm{ps} \bullet \mathrm{THz}$$

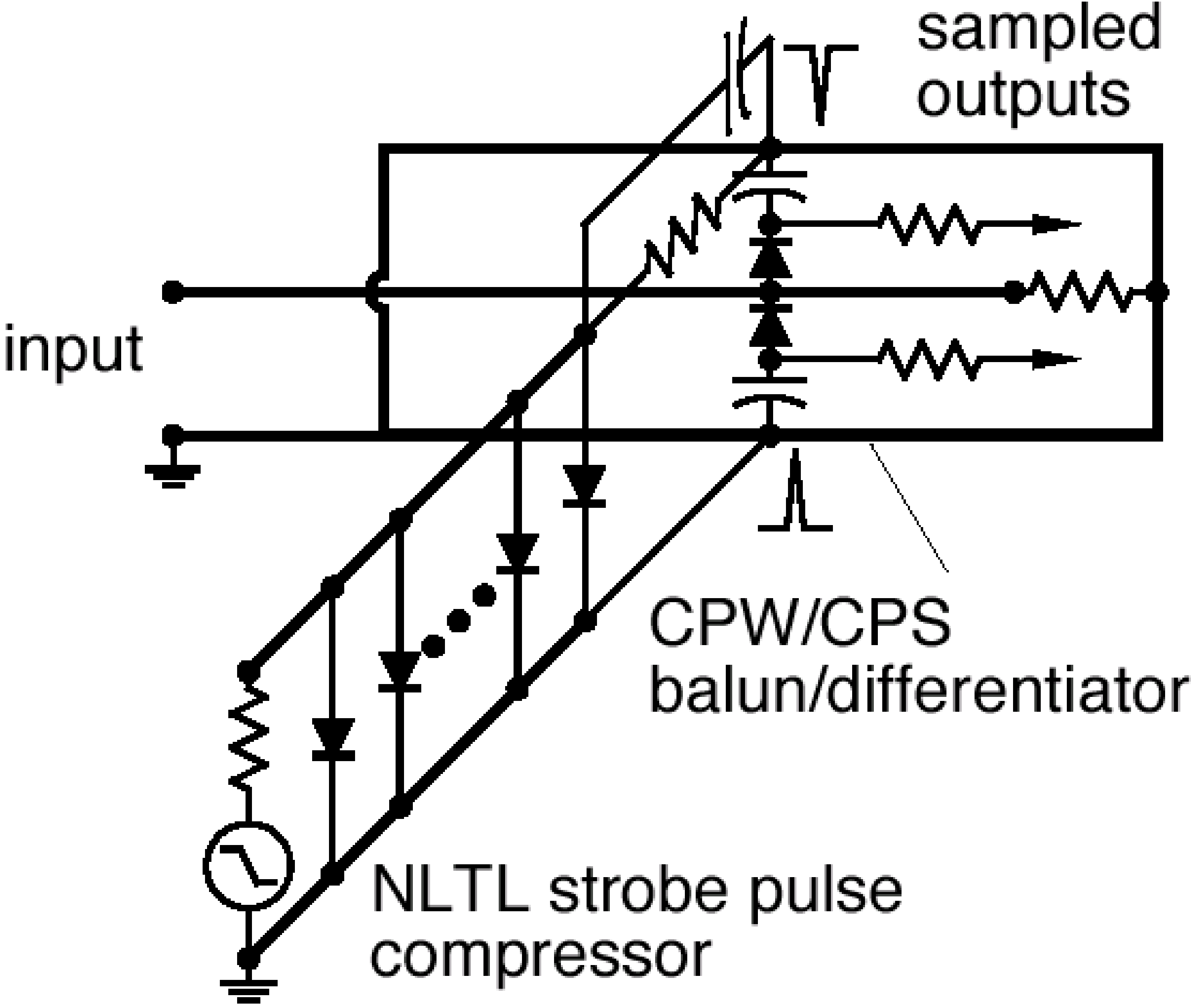
5 THz diode cutoff frequency: 0.28 ps Shock wave

Shorted-Line Differentiator for Impulse Generation

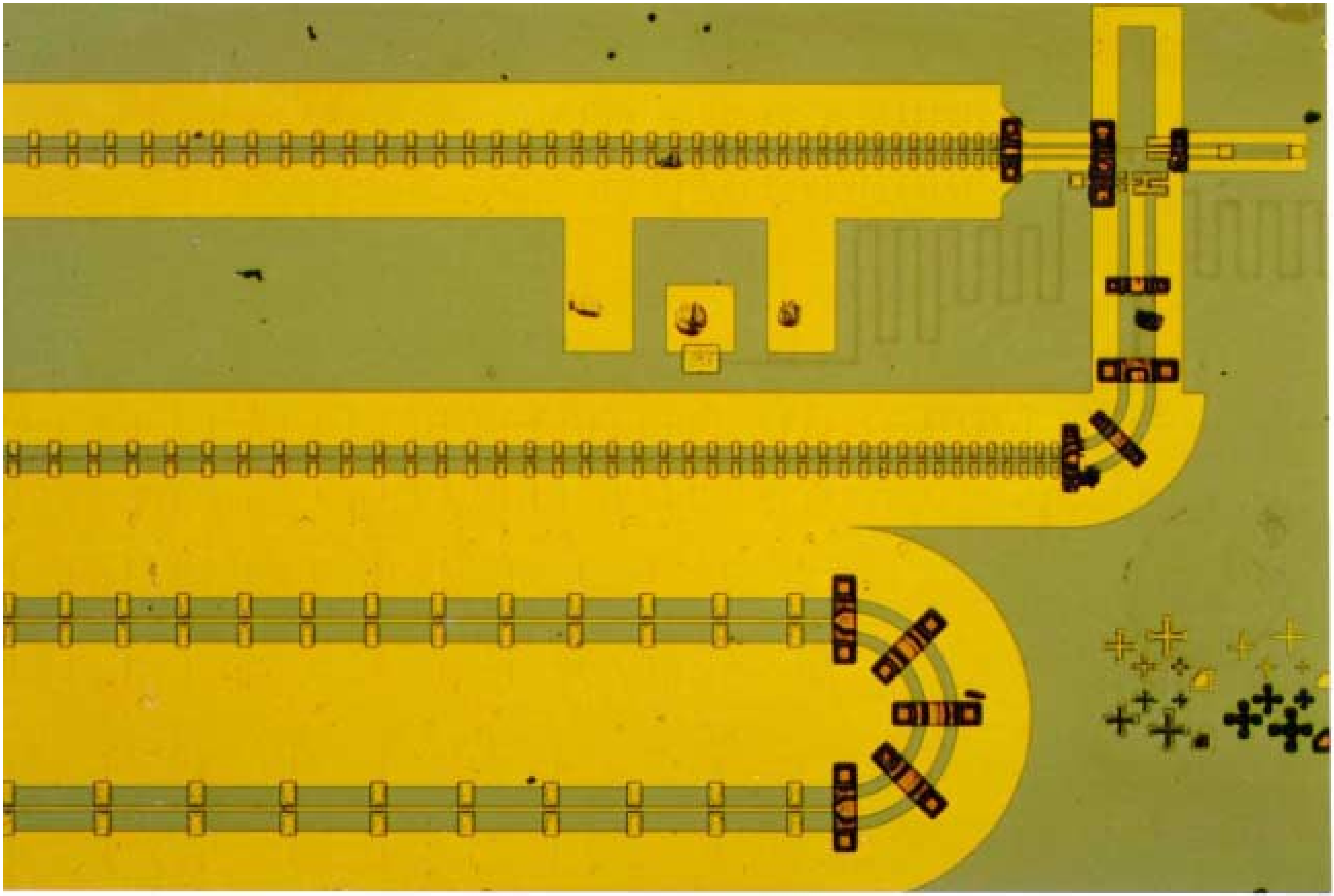
Symmetric Impulse Generation with CPW/CPS Balun/Differentiator

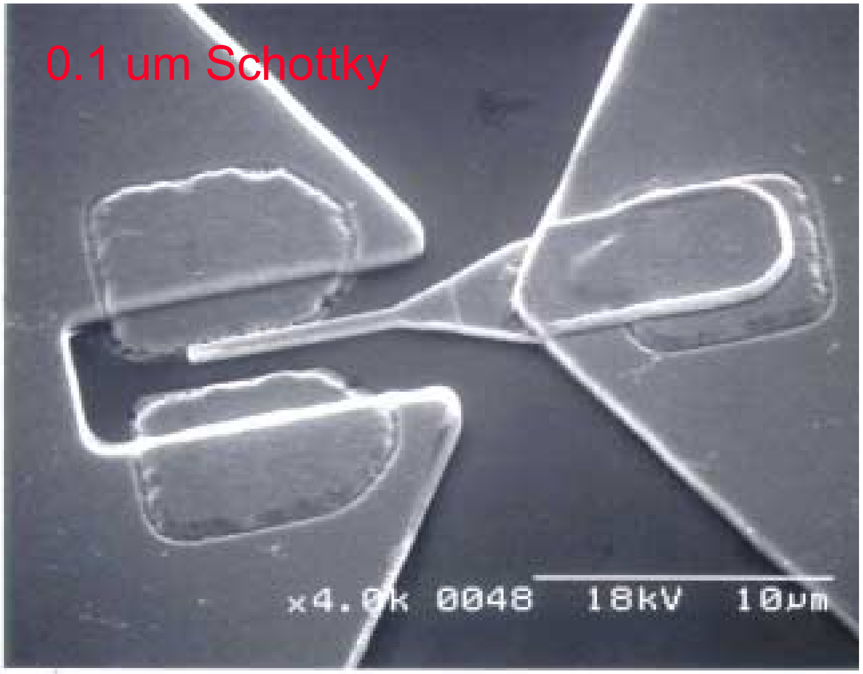


NLTL-strobed sampling circuit

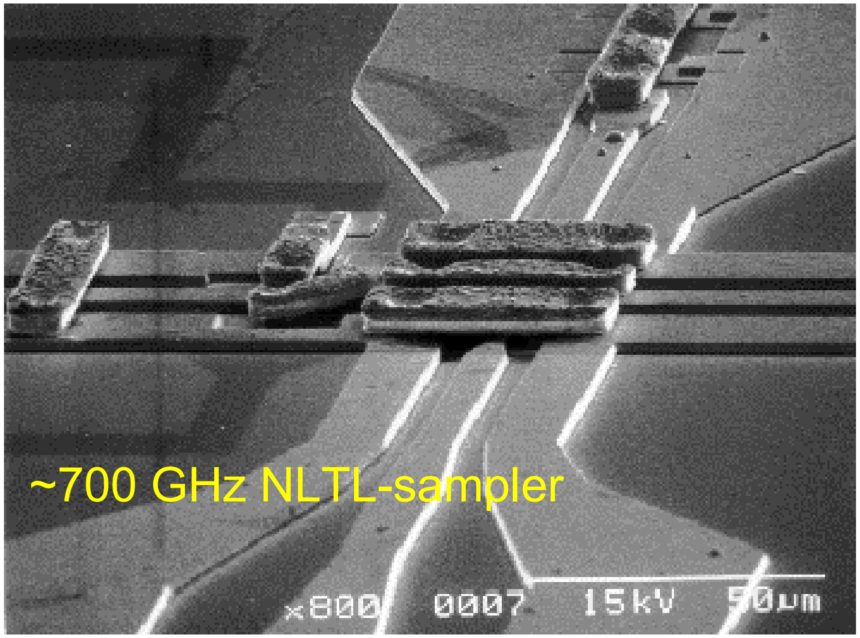


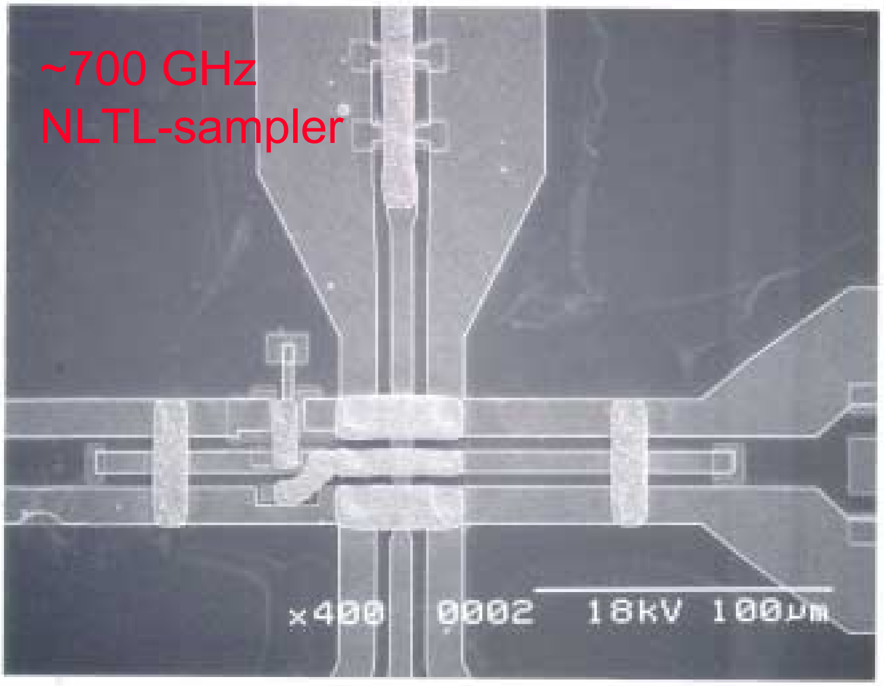
NLTL & Sampling Bridge, M. Case ~1992



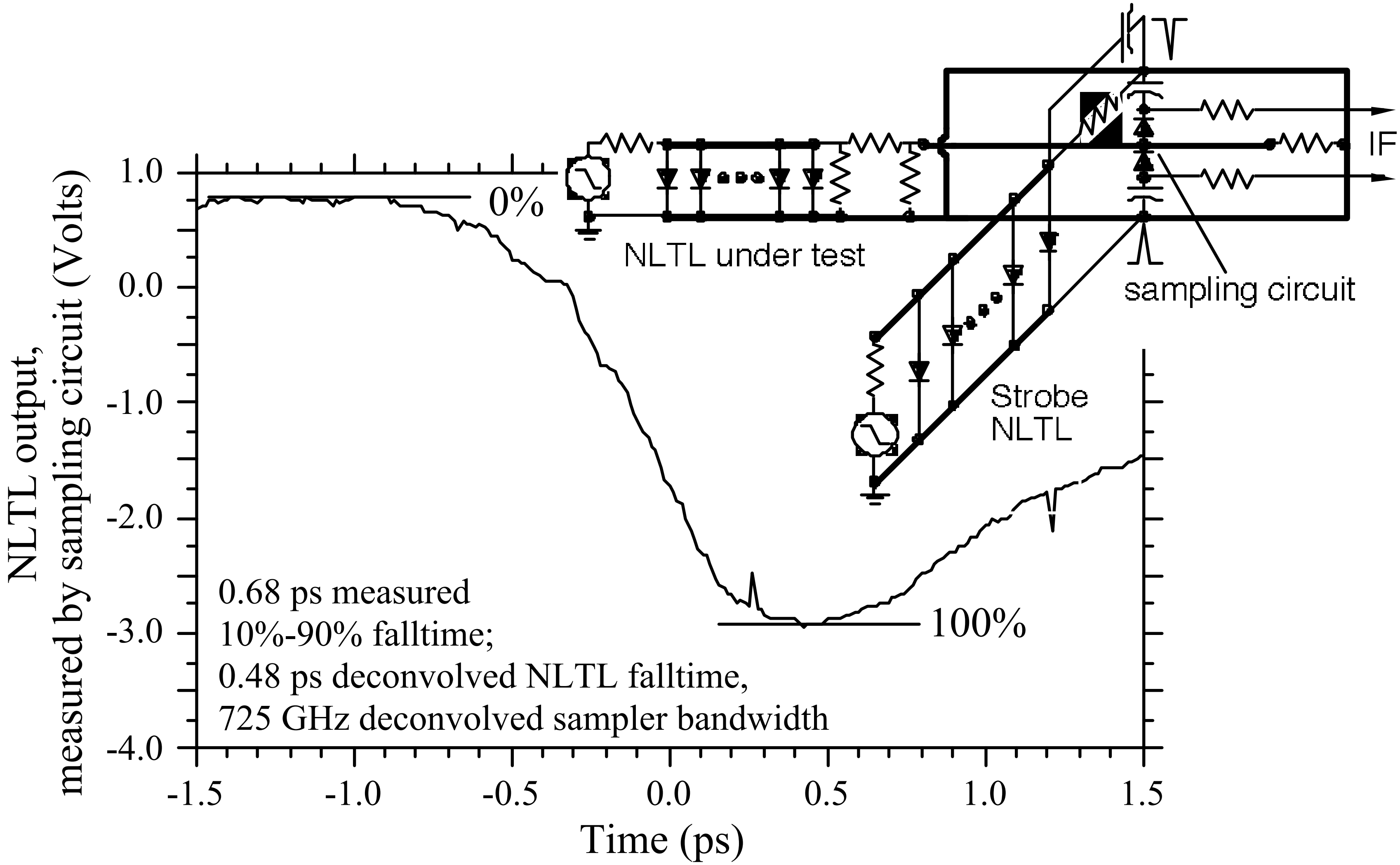

0.1 um Schottky


NLTL using low-loss "air CPW"


~700 GHz NLTL-sampler

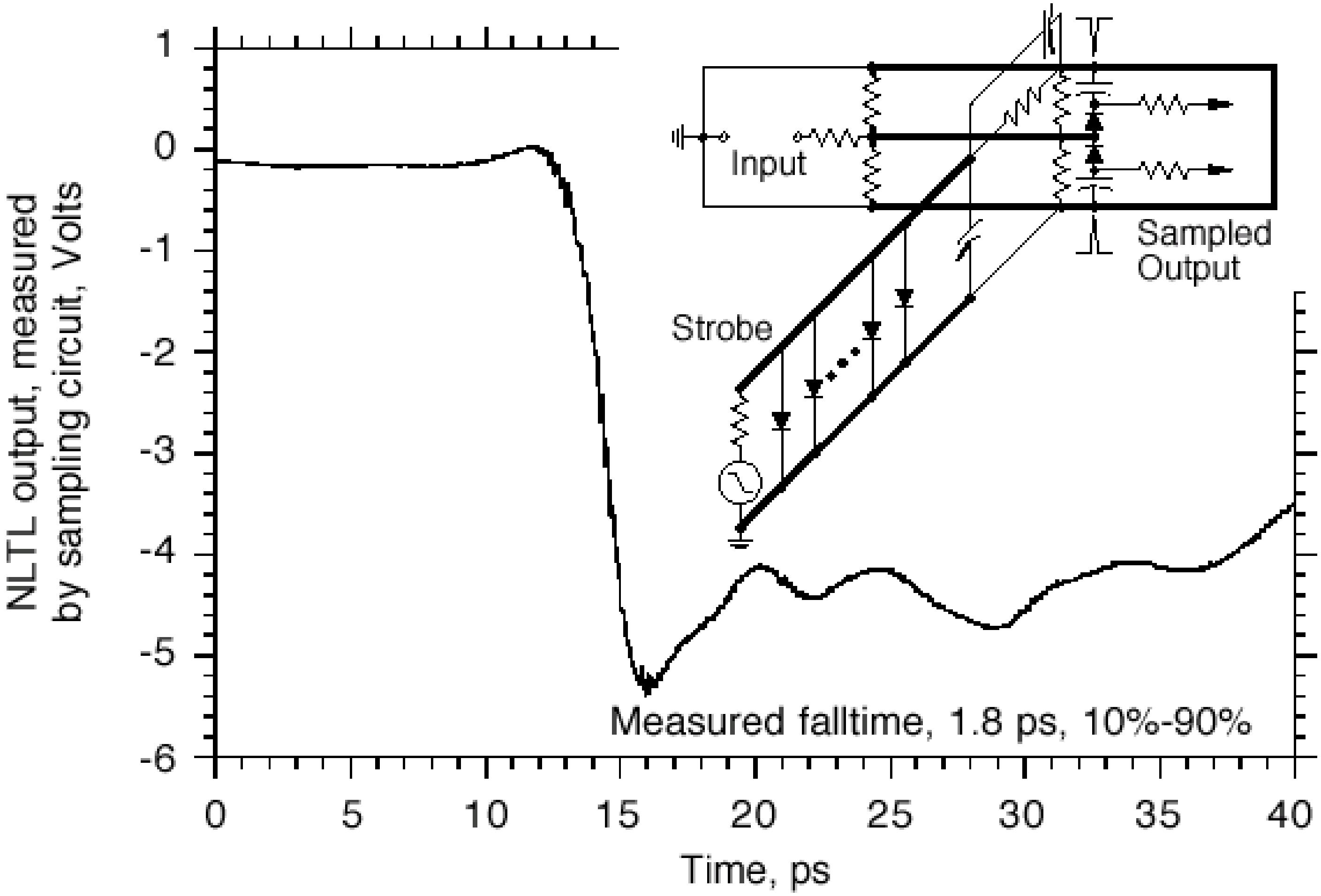

~700 GHz
NLTL-sampler

measurement of NLTL with NLTL-gated sampling IC



Aggressive sampling IC design with
1 um diode geometries
low-loss elevated coplanar waveguide in the NLTLs

measurement of NLTL with NLTL-gated sampling IC



Very simple sampling IC design using 2-3 um process minimum feature size
Sampling bridge bandwidth is approximately 275 GHz
DC-110 GHz instruments can be realized using simple, low-cost ICs

Prospective for use of NLTLs in Instruments

NLTLs have been used commercially since early 1990's

HP/Agilent 50 GHz sampling oscilloscopes

Microwave transition analyzer

45 MHz -- 50 GHz 8510 network analyzer ?

Recent emergence of higher-frequency markets now driving instruments

Less Expensive 45 MHz -110 GHz network analysis

Present systems frequency-combine waveguide-banded systems.
  These are accurate but expensive.

Reduced-cost instrument could use NLTL-driven sampler for down conversion
- NLTL-based sampler can easily down convert DC-200 GHz
- Use DC-10 GHz synthesized source for LO
- Mixing harmonic order <11 in DC-110 GHz bandwidth: good dynamic range
- main design challenge: LO drive interface to NLTL input

Wider-bandwidth sampling oscilloscopes

Present instruments are DC-65 GHz, some are NLTL-based.

It is easy to build NLTL-gated samplers far faster than this.

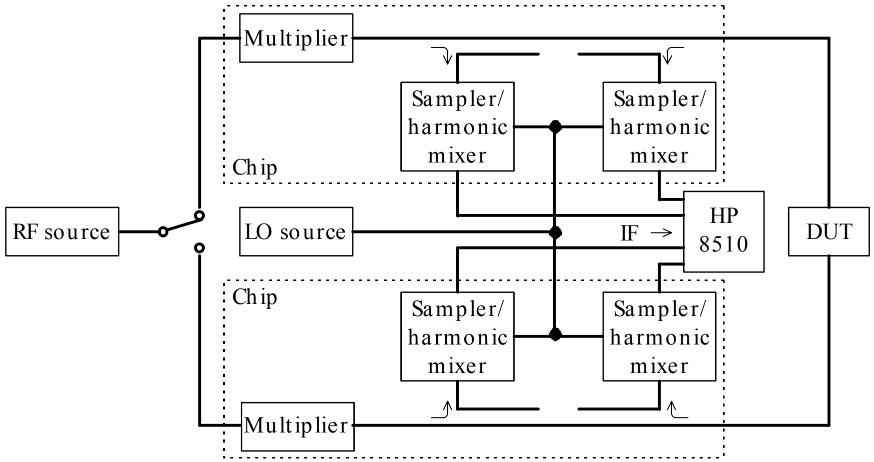
Practical limits to DC-110 GHz oscilloscope development are:
- timebase stability (eliminating trigger jitter)
- connector bandwidth limit (110 GHz connectors are fragile)
- correction of connection (cable, wafer probe) frequency response by calibration.

High Frequency Network Analysis

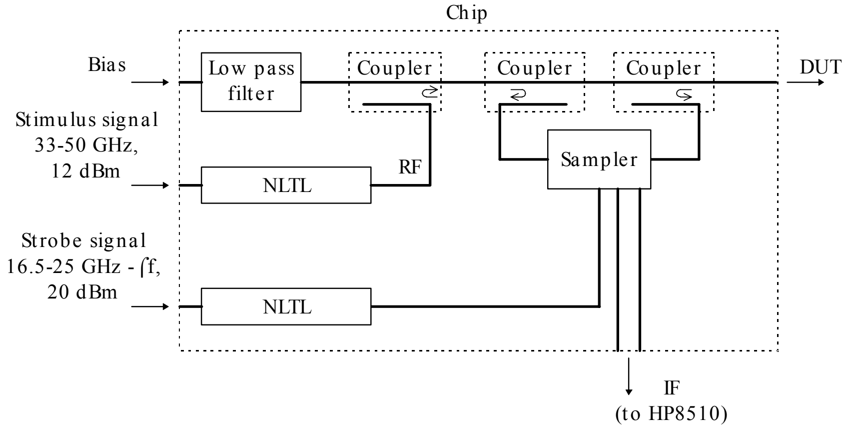
O Wohlegemuth
R. Yu

Active Probes for On-wafer mm-wave network analysis

system



mm-wave interface IC



IC implementation of samplers, multipliers, & couplers allowed for easy system demonstration

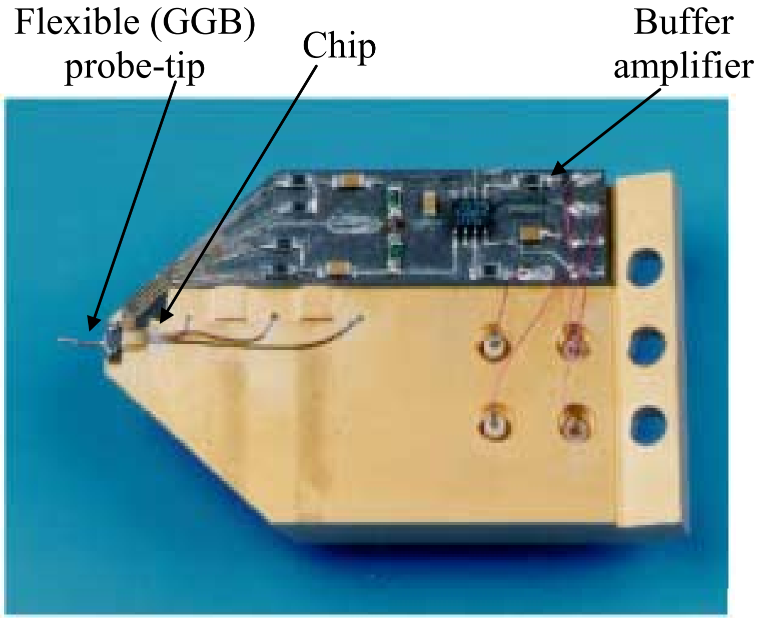
→ proof-of-principle demonstration

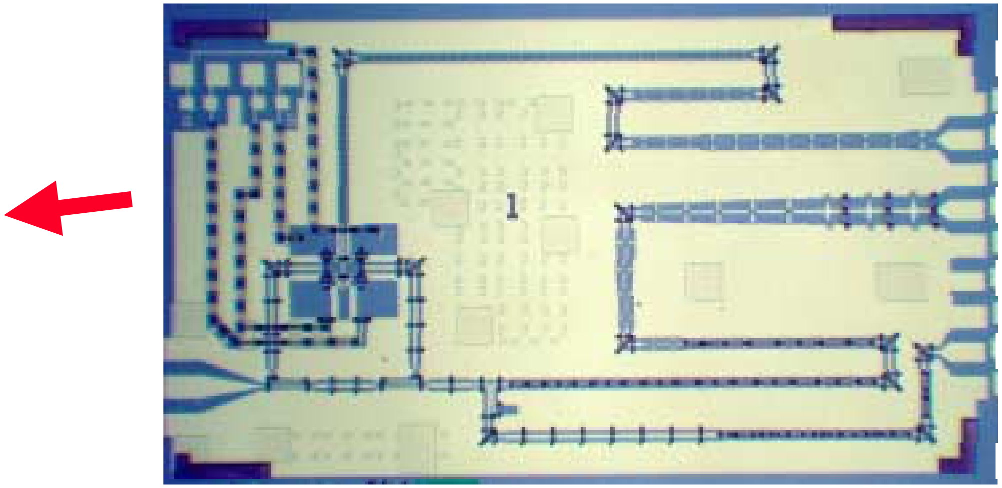
Close proximity of all components on IC lead to crosstalk, degraded dynamic range.

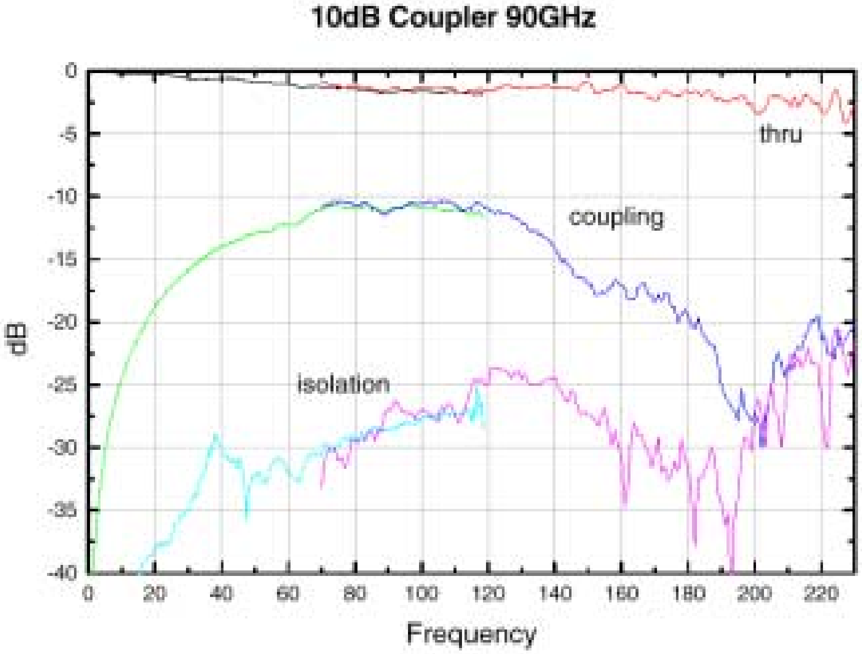
→ less accurate than needed for real instrument

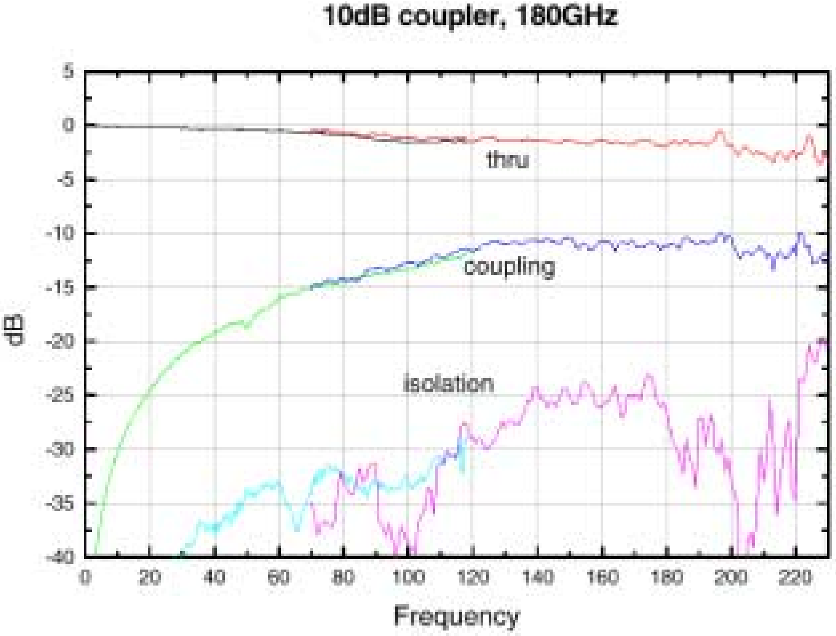
O Wohlegemuth
R. Yu

Fraunhofer / UCSB 70-220 GHz Network Analyzer






10dB Coupler 90GHz


10dB coupler, 180GHz

O. Wohlgemuth et al *IEEE Transactions on Microwave Theory and Techniques*, Vol. 47, No. 12, December.1999

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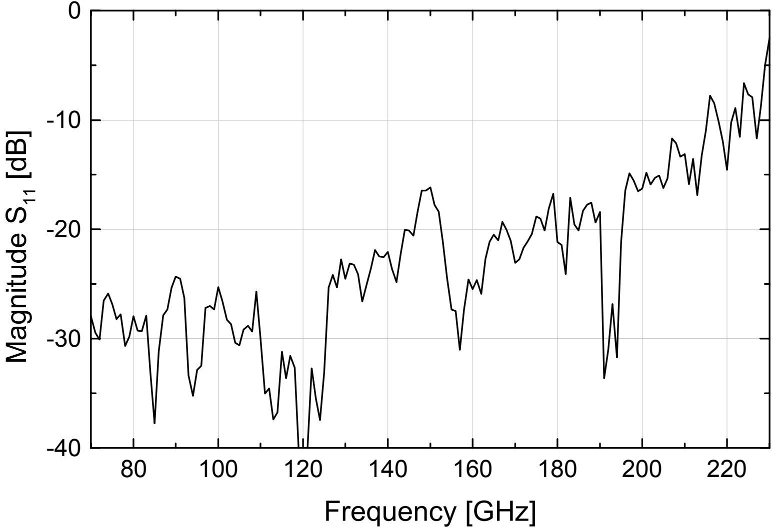
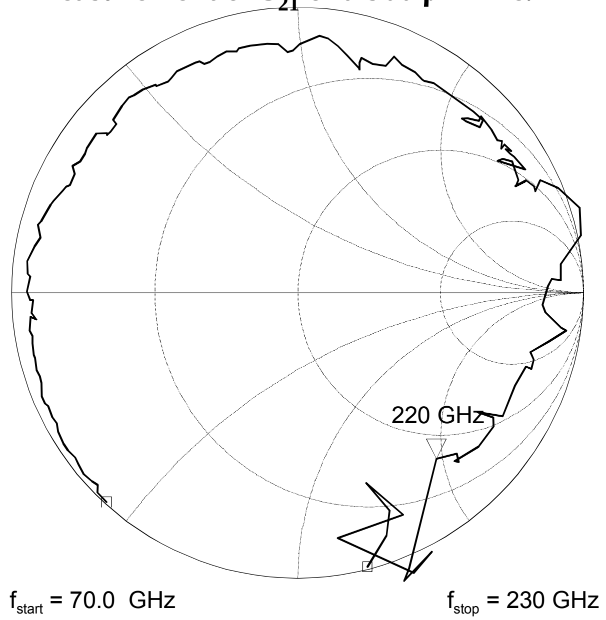
Fraunhofer / UCSB 70-220 GHz Network Analyzer

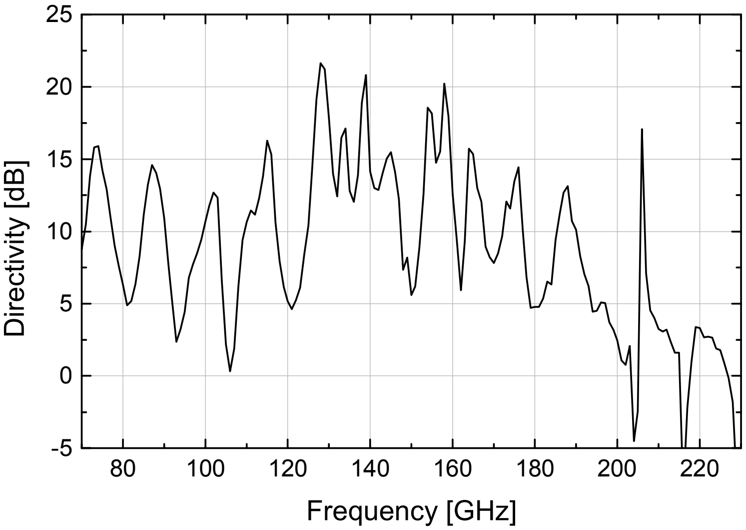
Measurement of S_{11} of a 900 µm line.



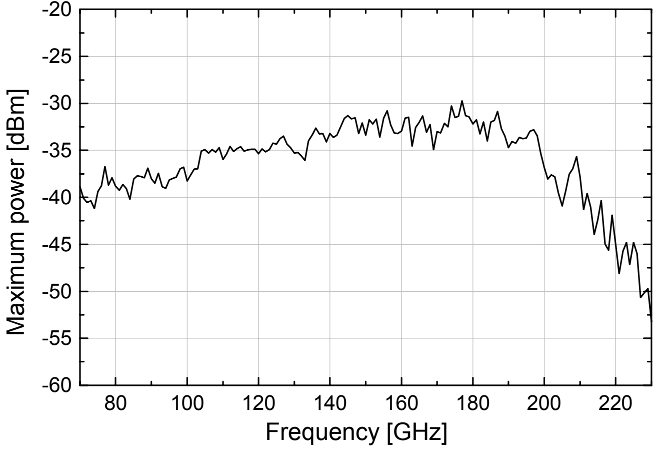
Measurement of S_{21} of a 900 µm line.



Measured raw directivity of the ac-tive probe



Measured maximum power at the IF-ports.



O. Wohlgemuth et al *IEEE Transactions on Microwave Theory and Techniques*, Vol. 47, No. 12, December.1999

Precision
on-wafer
> 40 GHz
network analysis

Network analysis above 40 GHz: commercial tools

Instruments

Agilent, Wiltron:
- RF→ 50 (65) GHz in coax, sampler-based
- higher bands using waveguide and harmonic mixers
- multiplexed together for single-sweep measurements

Oleson Microwave Labs.
- frequency extenders for Agilent, Wiltron
- 140-220 GHz and 220-330 GHz

credits also to the JPL group (T. Gaier et al)

Probes

Probes with coaxial connectors
DC-110 GHz, GGB and Cascade

Waveguide coupled probes
to 110 GHz (Cascade)
to 220 GHz (GGB)
to 330 GHz (from GGB soon ?)

Picoprobe Model 220 Microwave Probe

Durable

140 to 220 GHz

Insertion loss 2.0 db typ.

Return loss 15 db typ.

Individually spring loaded contacts

Patented Coaxial Design

Individually Spring-loaded Contacts

Bias-T Option Available

GGB INDUSTRIES, INC. • P.O. BOX 10958 • NAPLES, FL 33941

On-wafer mm-wave Network Analysis at UCSB

Applications:
Measurements of transistor amplifiers to 220 GHz
Precise characterization of transistors (power gains, parameter extraction)

45 MHz-50 (40) GHz:
Agilent 8510 NWA, coaxial cables and probes

75-110 GHz:
Agilent 8510 NWA, waveguide, GGB waveguide-coupled probes

140-220 GHz:
Oleson frequency extenders, waveguide, GGB waveguide-coupled probes

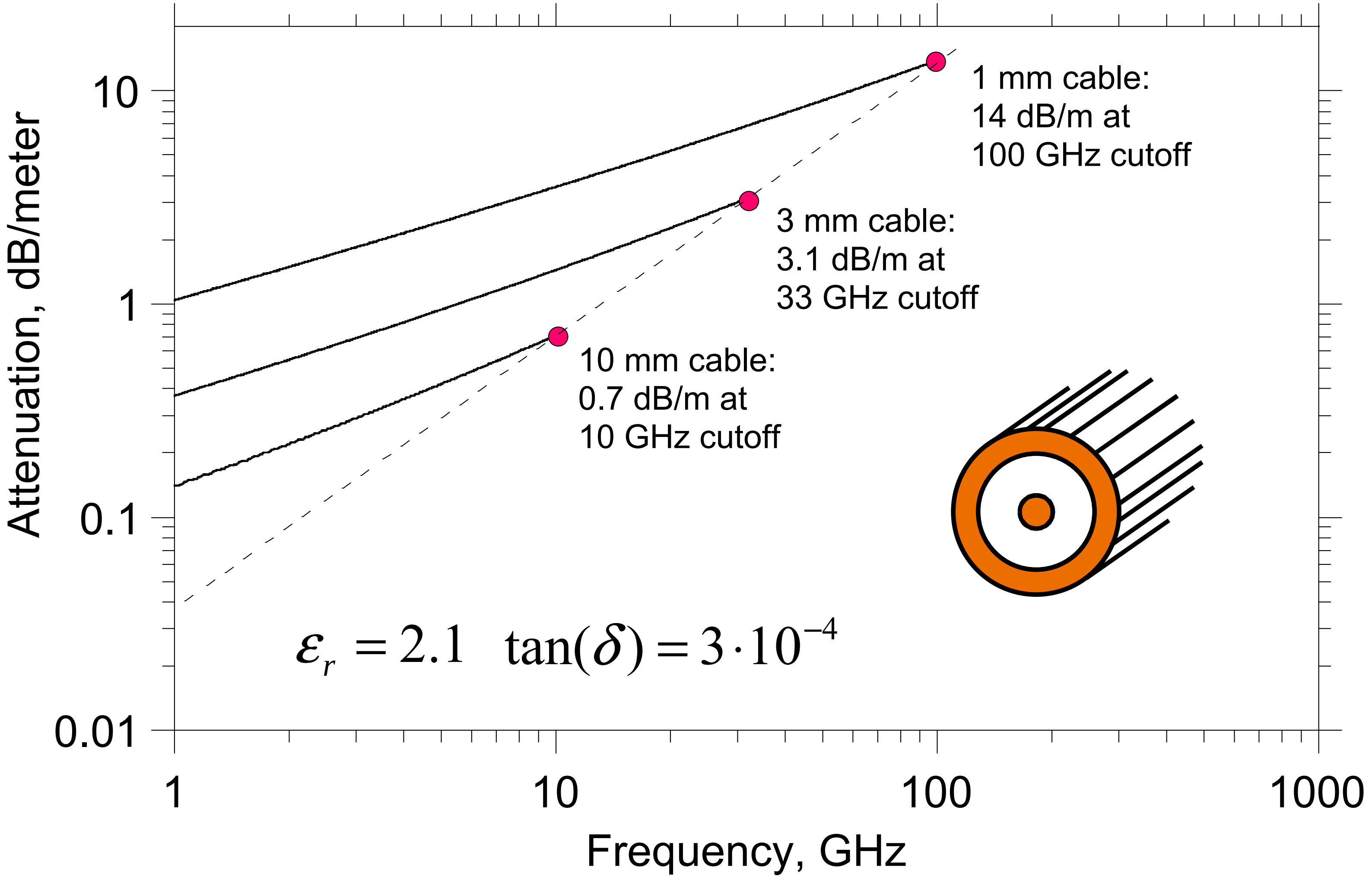
Key features for good measurements

on-wafer LRL microstrip calibration standards with offset reference planes

waveguide instrument-probe connections: less loss, less phase drift.

higher band instruments use low-order mixers → better dynamic range

Loss of Coaxial Cable



Single - mode propagation requires $f \le c\cdot(2/\pi)\varepsilon_r^{-1/2}\left(D_{inner}+D_{outer}\right)^{-1}$

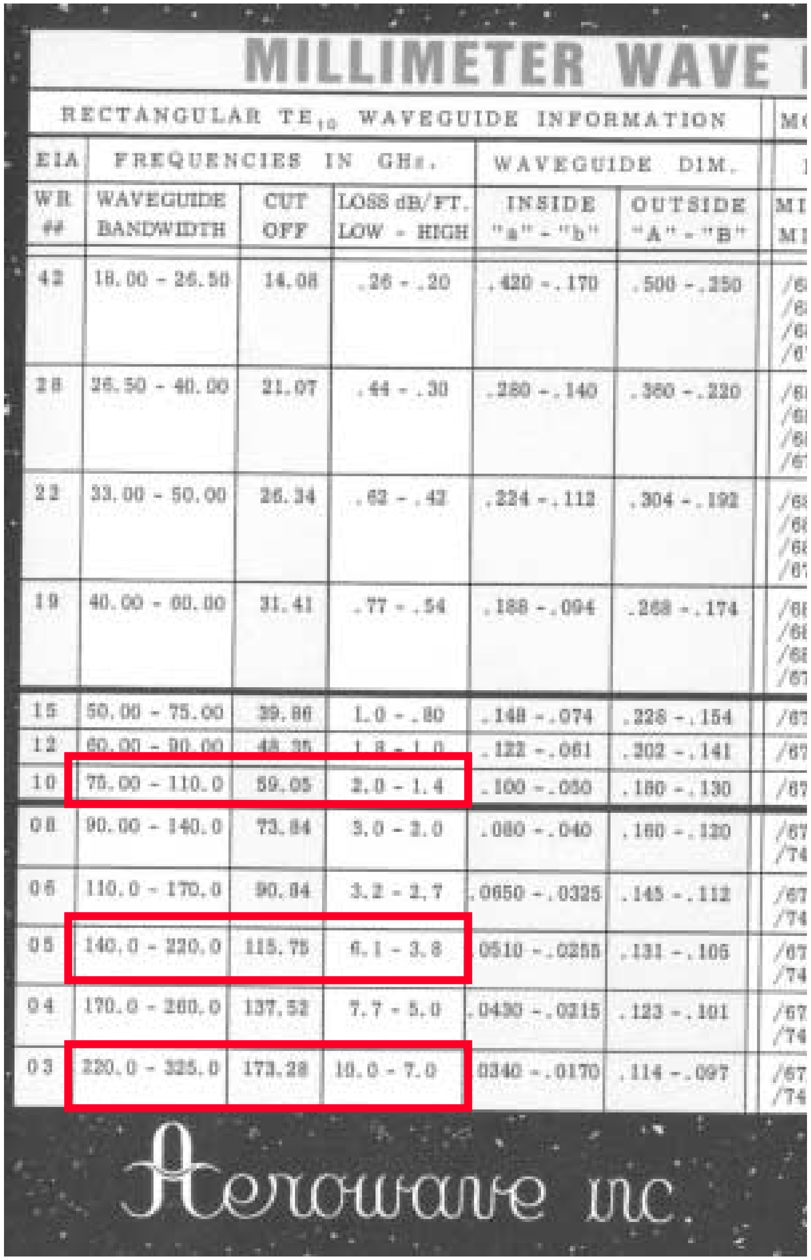
Skin loss $\alpha_{skin} \propto f^{1/2}/D_{inner} \longrightarrow$ Loss $\alpha_{skin} \propto f^{3/2}$

Why waveguide ?

Loss is much lower than for coax
(4.5-6 dB / meter in W-band)

> 110 GHz connectors available

No phase drift from Teflon mechanical creep.



MILLIMETER WAVE

RECTANGULAR TE_{10} WAVEGUIDE INFORMATION

EIA	FREQUENCIES IN GHz.			WAVEGUIDE DIM.	
WR ##	WAVEGUIDE BANDWIDTH	CUT OFF	LOSS dB/FT. LOW - HIGH	INSIDE "a" - "b"	OUTSIDE "A" - "B"
42	18.00 - 26.50	14.08	.26 - .20	.420 - .170	.500 - .250
28	26.50 - 40.00	21.07	.44 - .30	.280 - .140	.360 - .220
22	33.00 - 50.00	26.34	.62 - .42	.224 - .112	.304 - .192
19	40.00 - 60.00	31.41	.77 - .54	.188 - .094	.268 - .174
15	50.00 - 75.00	39.86	1.0 - .80	.148 - .074	.228 - .154
12	60.00 - 90.00	48.35	1.8 - 1.0	.122 - .061	.202 - .141
10	75.00 - 110.0	59.05	2.0 - 1.4	.100 - .050	.180 - .130
08	90.00 - 140.0	73.84	3.0 - 2.0	.080 - .040	.160 - .120
06	110.0 - 170.0	90.84	3.2 - 2.7	.0650 - .0325	.145 - .112
05	140.0 - 220.0	115.75	6.1 - 3.8	.0510 - .0255	.131 - .105
04	170.0 - 260.0	137.52	7.7 - 5.0	.0430 - .0215	.123 - .101
03	220.0 - 325.0	173.28	10.0 - 7.0	.0340 - .0170	.114 - .097

Aerowave inc.

140-220 GHz On-Wafer Network Analysis

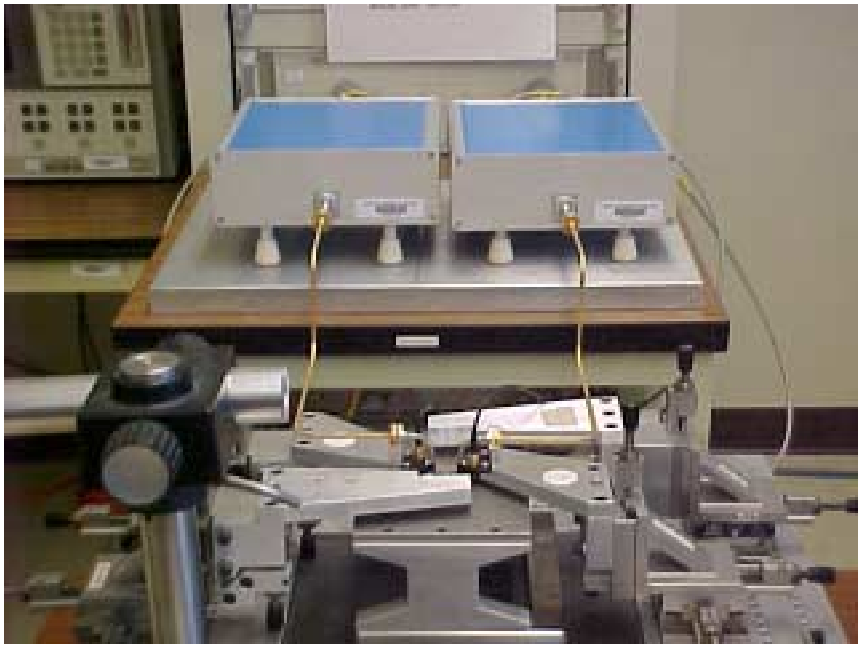
- HP8510C VNA,
Oleson Microwave Lab mm-wave Extenders

- *GGB Industries* coplanar wafer probes

- connection via short length of WR-5 waveguide

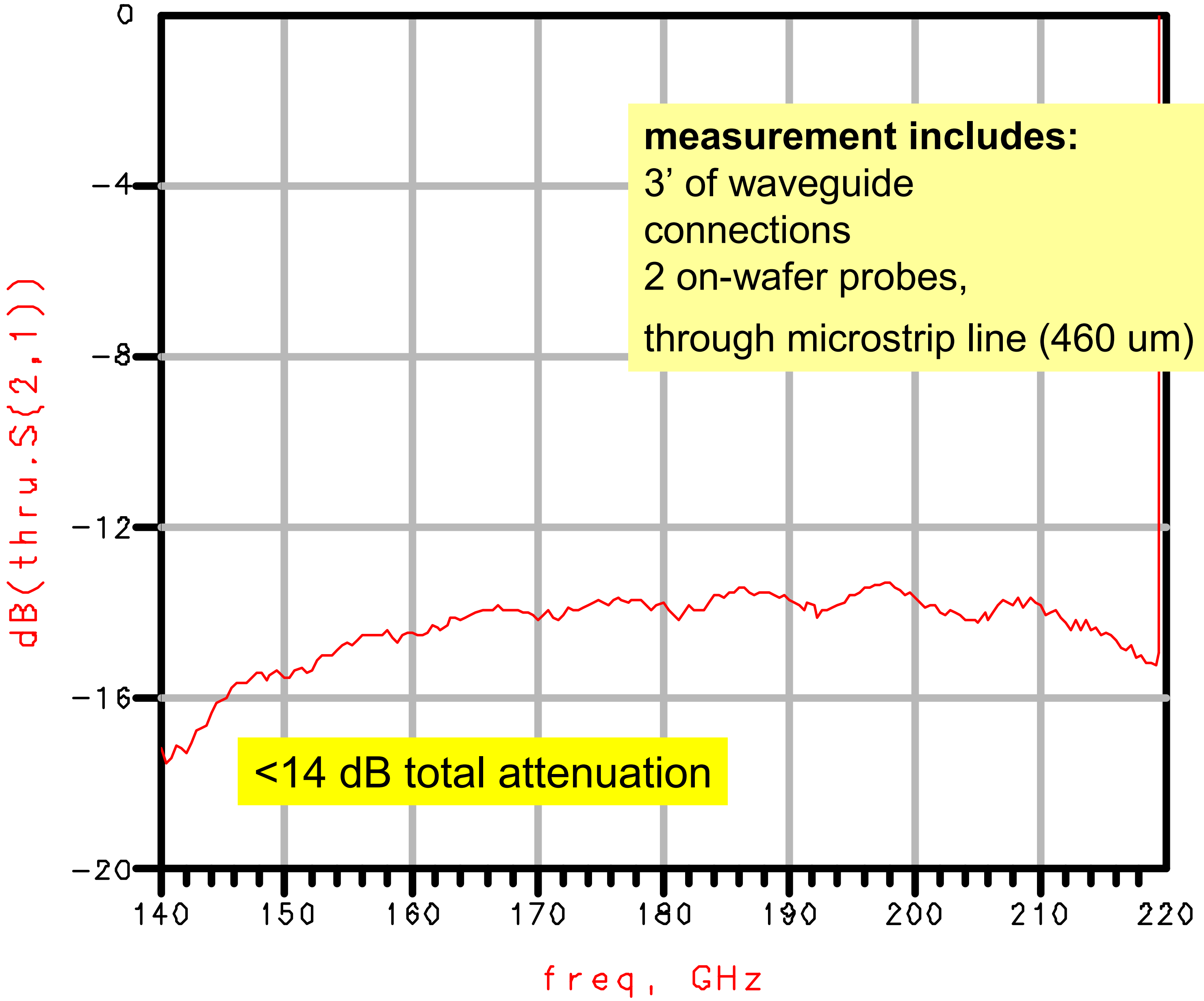
- Internal bias Tee's in probes for biasing active devices

- 75-110 GHz set-up is similar



UCSB 140-220 GHz VNA Measurement Set-up

Insertion Loss of Measurement Set-up



measurement includes:
3’ of waveguide
connections
2 on-wafer probes,
through microstrip line (460 um)

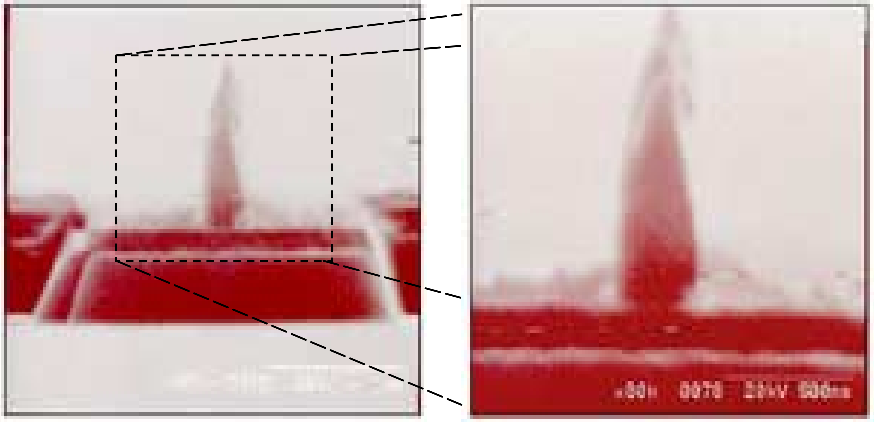
<14 dB total attenuation

Miguel Urteaga

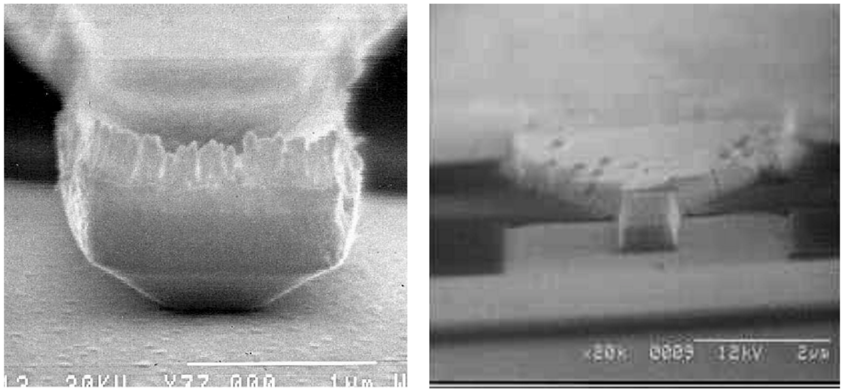
Application: Characterizing mm-wave bipolar transistors (HBTs)

- Electron beam lithography used to define submicron emitters and collectors
- Minimum feature sizes
  - ⇒ 0.2 µm emitter stripe widths
  - ⇒ 0.3 µm collector stripe widths
- Improved collector-to-emitter alignment using local alignment marks
- Aggressive scaling of transistor dimensions predicts progressive improvement of f_{max}

As we scale HBT to <0.4 um,
f_{max} keeps increasing,
measurements become ***very*** difficult



0.3 µm Emitter before polyimide planarization



Submicron Collector Stripes
(typical: 0.7 um collector)

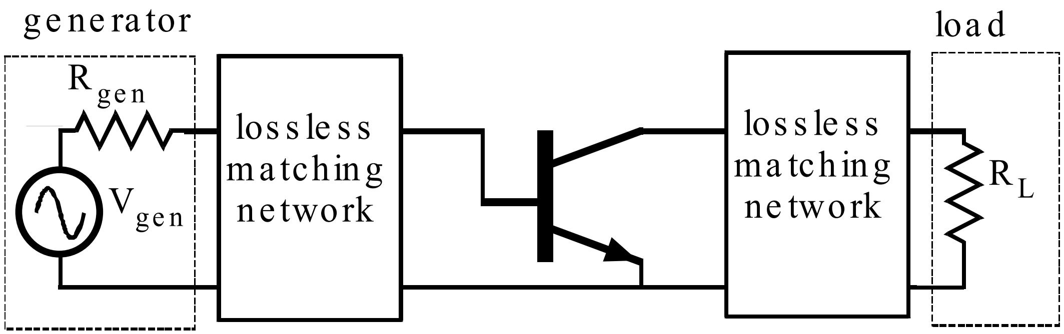
How do we measure f_{max}?

Maximum Available Gain

Simultaneously match input and output of device

$$\mathbf{MAG} = \frac{|S_{21}|}{|S_{12}|}\left(K - \sqrt{K^2 - 1}\right)$$

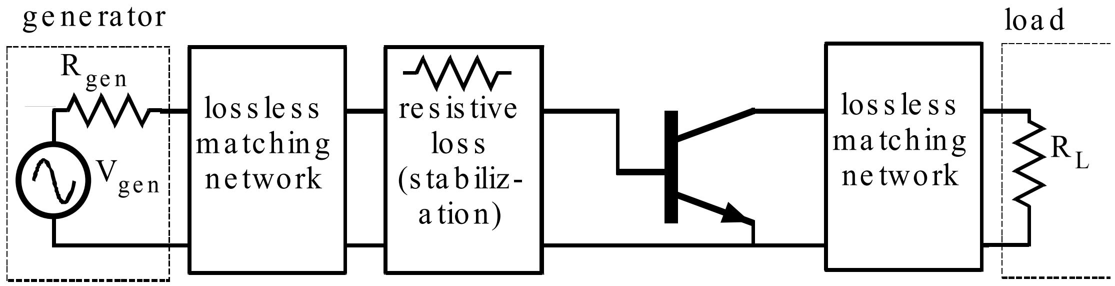
K = Rollet stability factor



Transistor must be unconditionally stable or MAG does not exist

Maximum Stable Gain

Stabilize transistor and simultaneously match input and output of device



$$\mathbf{MSG} = \frac{|S_{21}|}{|S_{12}|} = \frac{|Y_{21}|}{|Y_{12}|} \approx \frac{1}{\omega C_{cb}\left(R_{ex} + {kT}/{qI_c}\right)}$$

Approximate value for hybrid-π model

To first order MSG does not depend on f_τ or R_{bb}

For Hybrid- π model, MSG rolls off at 10 dB/decade, MAG has no fixed slope CANNOT be used to accurately extrapolate f_{max}

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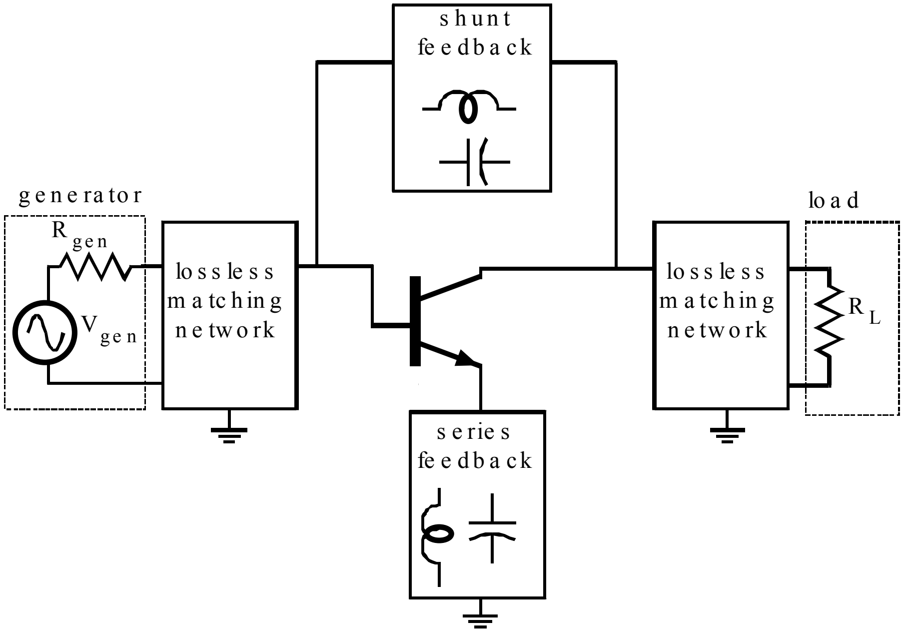
Unilateral Power Gain

Mason's Unilateral Power Gain

Use lossless reactive feedback to cancel device feedback and stabilize the device, then match input/output.

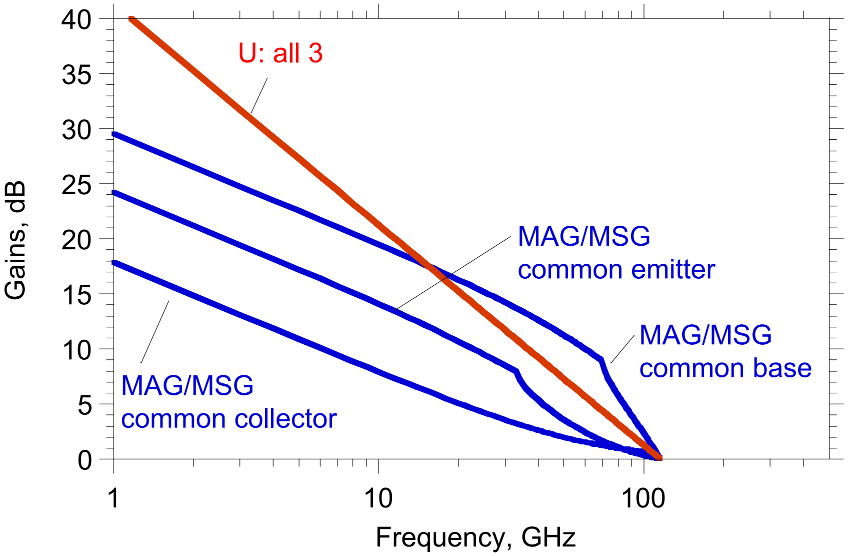
$$\mathbf{U} = \frac{\left|Y_{21} - Y_{12}\right|^2}{4\left(G_{11}G_{22} - G_{21}G_{12}\right)}$$

U is not changed by pad reactances



For Hybrid- π model,
U rolls off at 20 dB/decade

ALL Power Gains must be unity at *f*$_{max}$



On-wafer NWA:

calibration problems

Accurate Transistor Measurements ***Are Not Easy***

- Submicron HBTs have **very low** C_{cb} (< 3 fF)
- Characterization requires accurate measure of very small S12
- Standard 12-term VNA calibrations do not correct S12 background error due to probe-to-probe coupling

Solution

Embed transistors in sufficient length of transmission line to reduce coupling

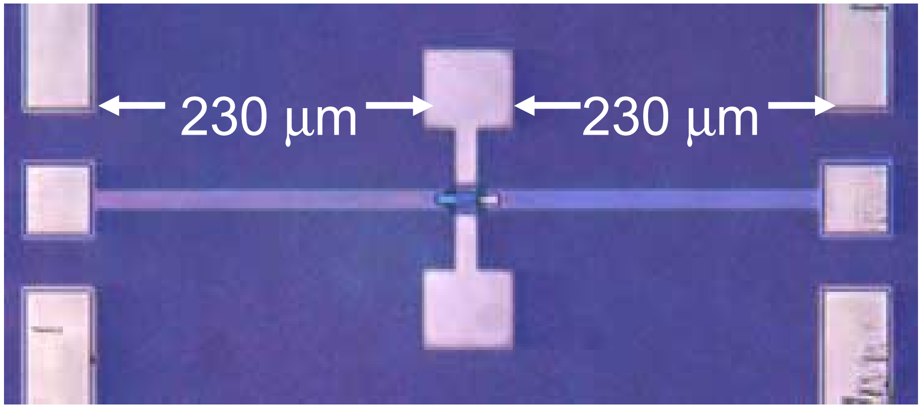
Place calibration reference planes at transistor terminals

Line-Reflect-Line Calibration

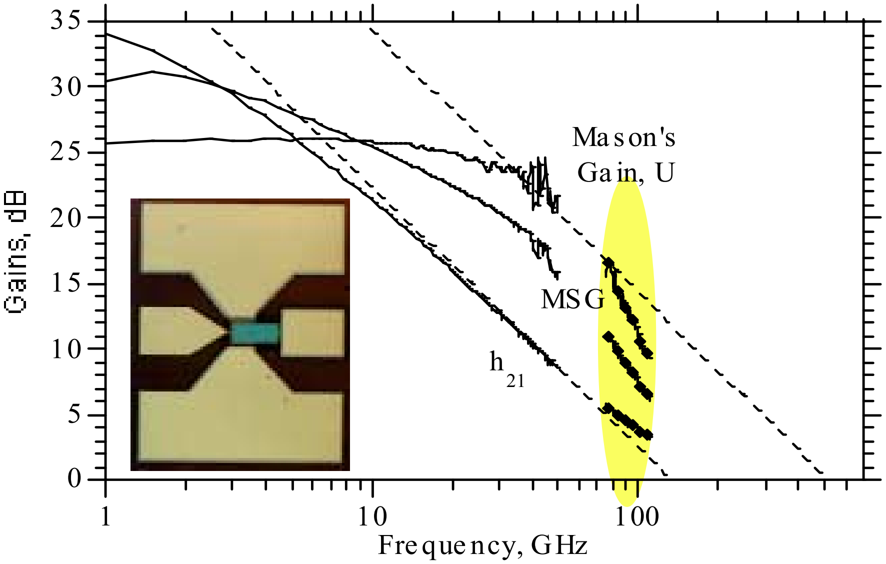
Standards easily realized on-wafer

Does not require accurate characterization of reflect standards

Characteristics of Line Standards are well controlled in transferred-substrate microstrip wiring environment

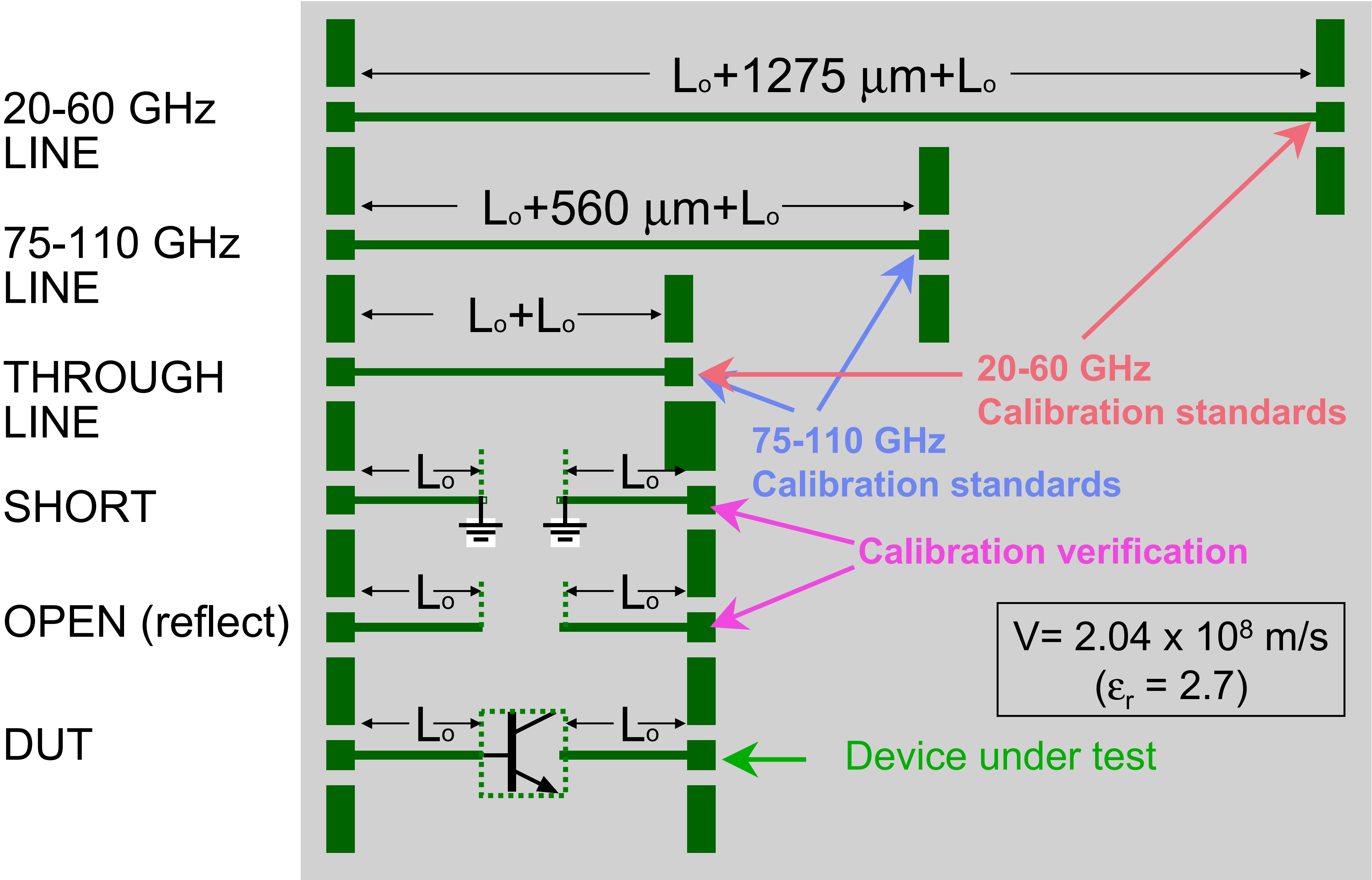


Transistor in Embedded in LRL Test Structure



Corrupted 75-110 GHz measurements due to excessive probe-to-probe coupling

Line-reflect-line on-wafer cal. standards



20-60 GHz
LINE

75-110 GHz
LINE

THROUGH
LINE

SHORT

OPEN (reflect)

DUT

**20-60 GHz
Calibration standards**

**75-110 GHz
Calibration standards**

Calibration verification

Device under test

V= 2.04 x 10^8 m/s
(ε_r = 2.7)

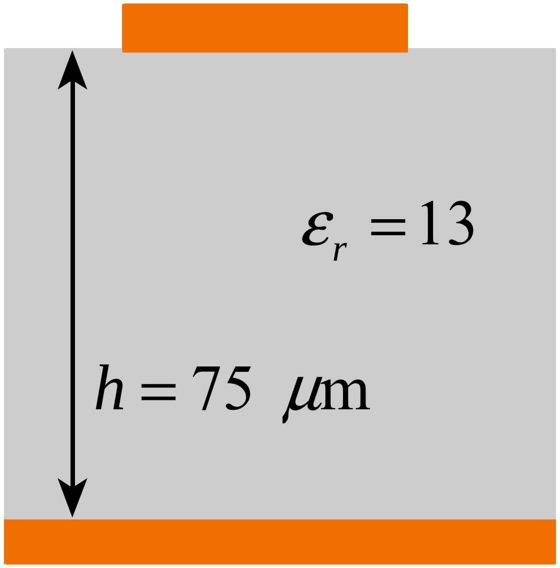
Note that calibration is to line Zo : line Zo is complex at lower frequencies, and must be determined

On-wafer transmission-line wiring environment: impact on LRL calibration

Thin-film microstrip

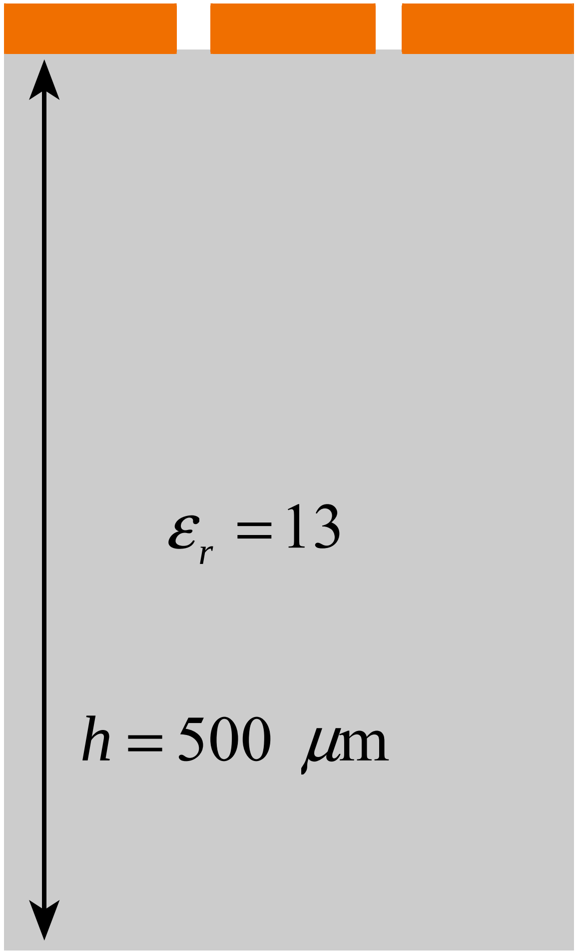
precise LRL calibration

microstrip



might be OK: watch for substrate modes

CPW



problem with substrate modes
thin wafer ? absorber ?

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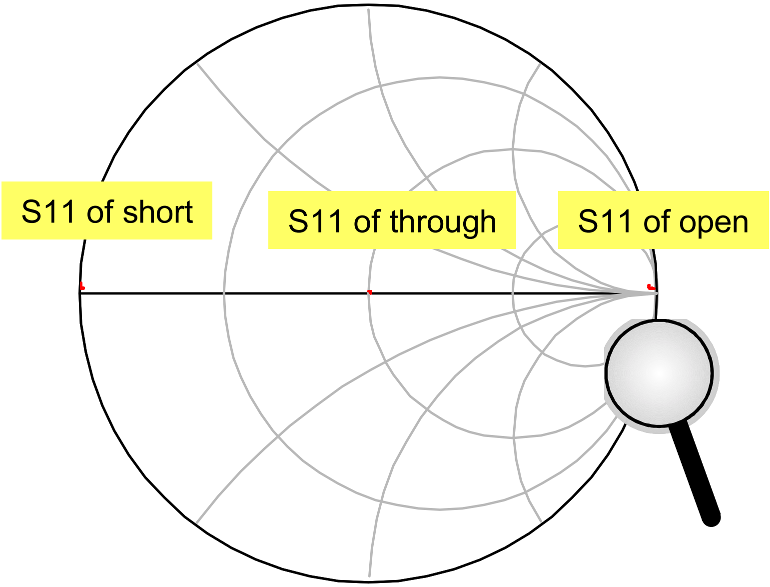
How good is the calibration ?

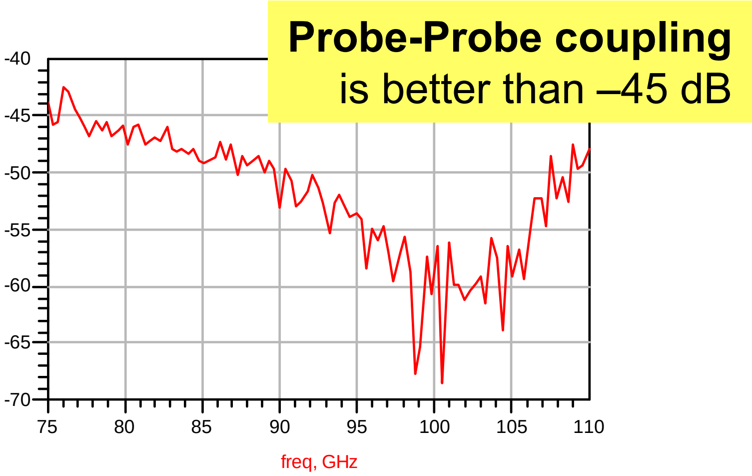
75-110 GHz calibration looks ***Great***


S11 of short

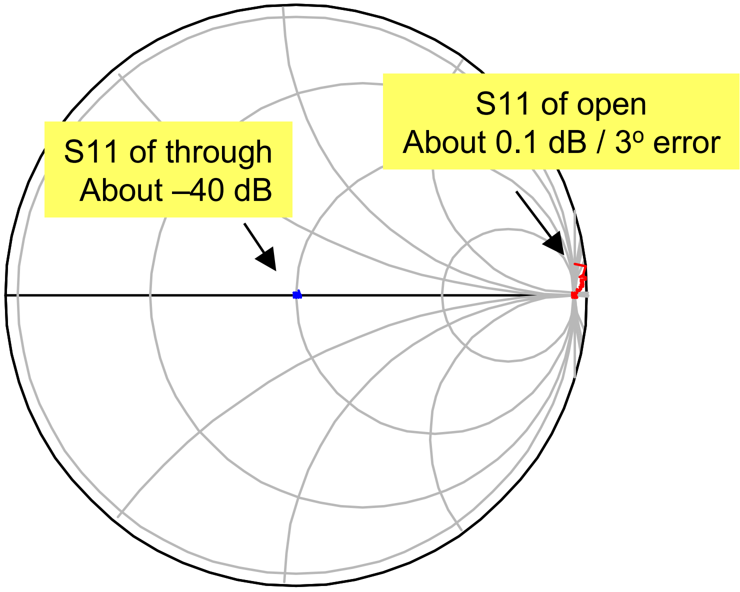
S11 of through

S11 of open

freq (75.00GHz to 110.0GHz)

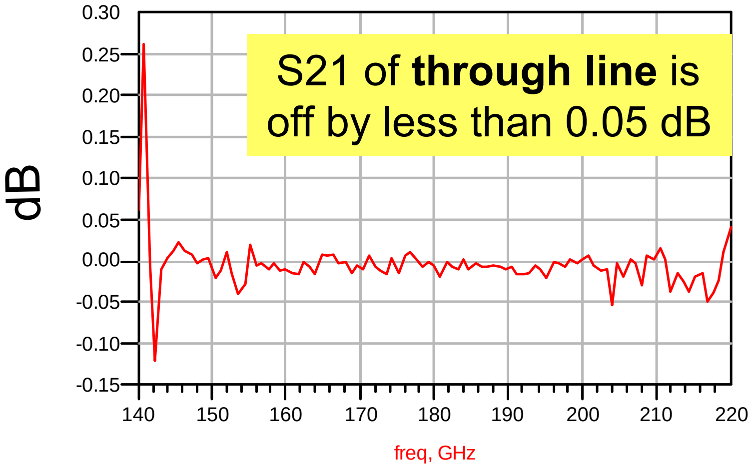

Probe-Probe coupling is better than –45 dB

140-220 GHz calibration looks OK


S11 of through
About –40 dB

S11 of open
About 0.1 dB / 3° error

freq (140.0GHz to 220.0GHz)


S21 of **through line** is off by less than 0.05 dB

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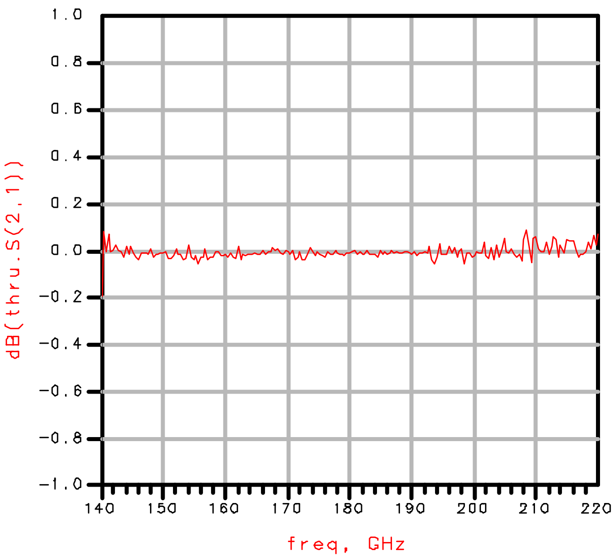
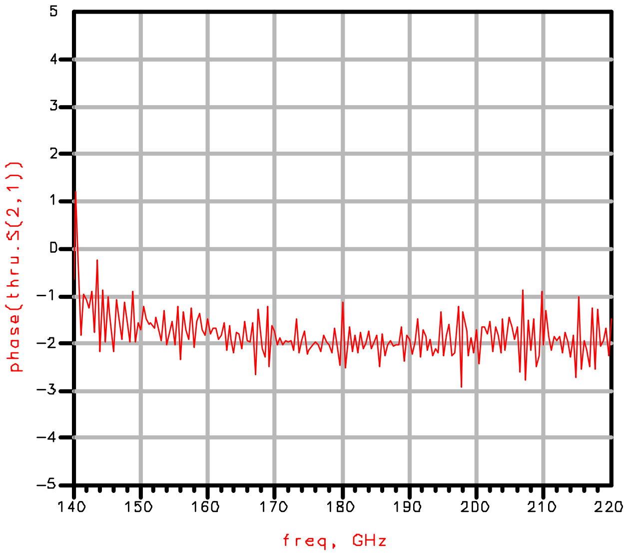
Measurement of Thru Line after Calibration

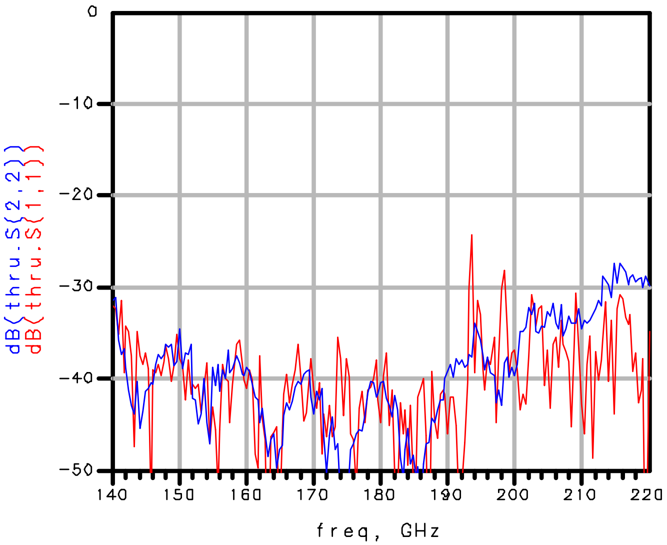
Magnitude S21 (dB)



Phase S21 (degrees)



S11, S22 (dB)



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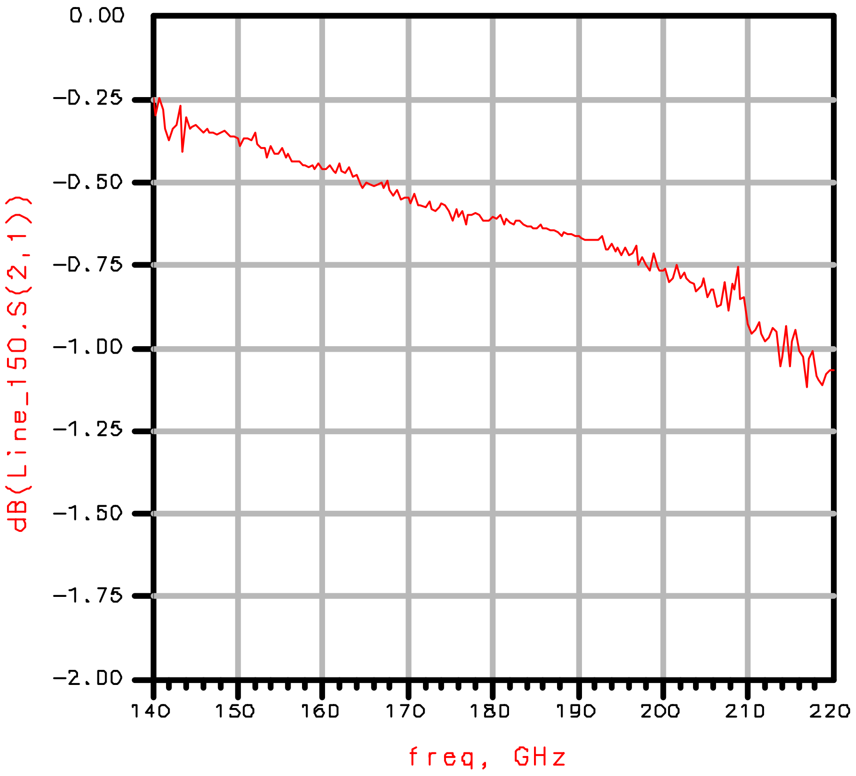
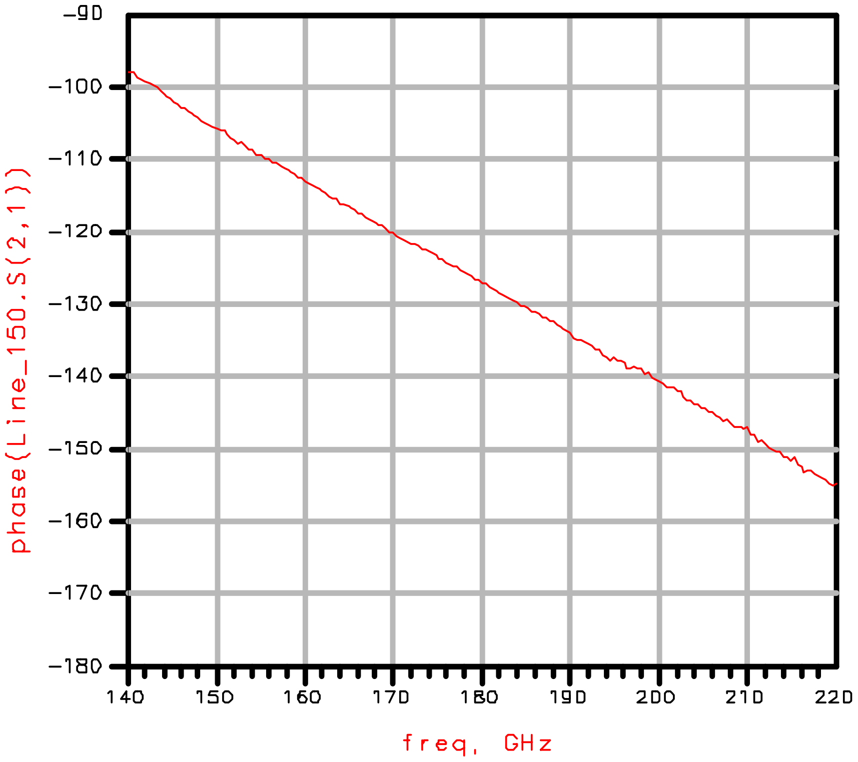
Measurement of Line Standard after Calibration


Magnitude S21 (dB)


Phase S21 (degrees)

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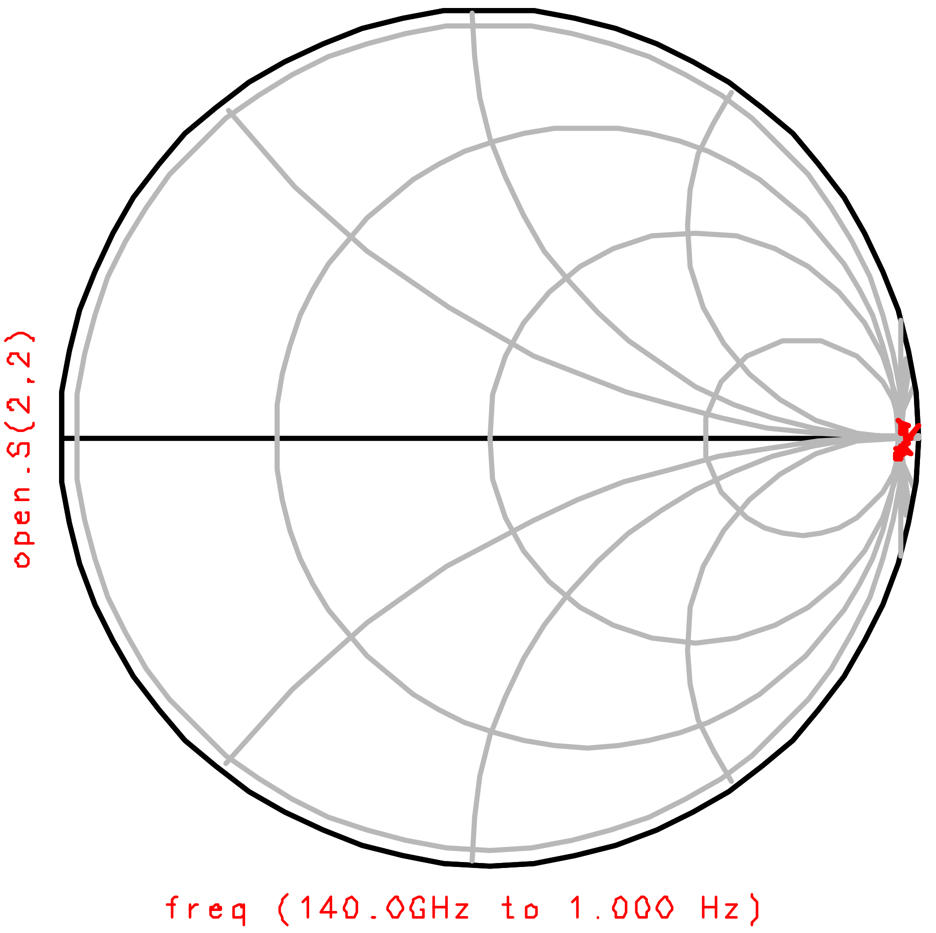
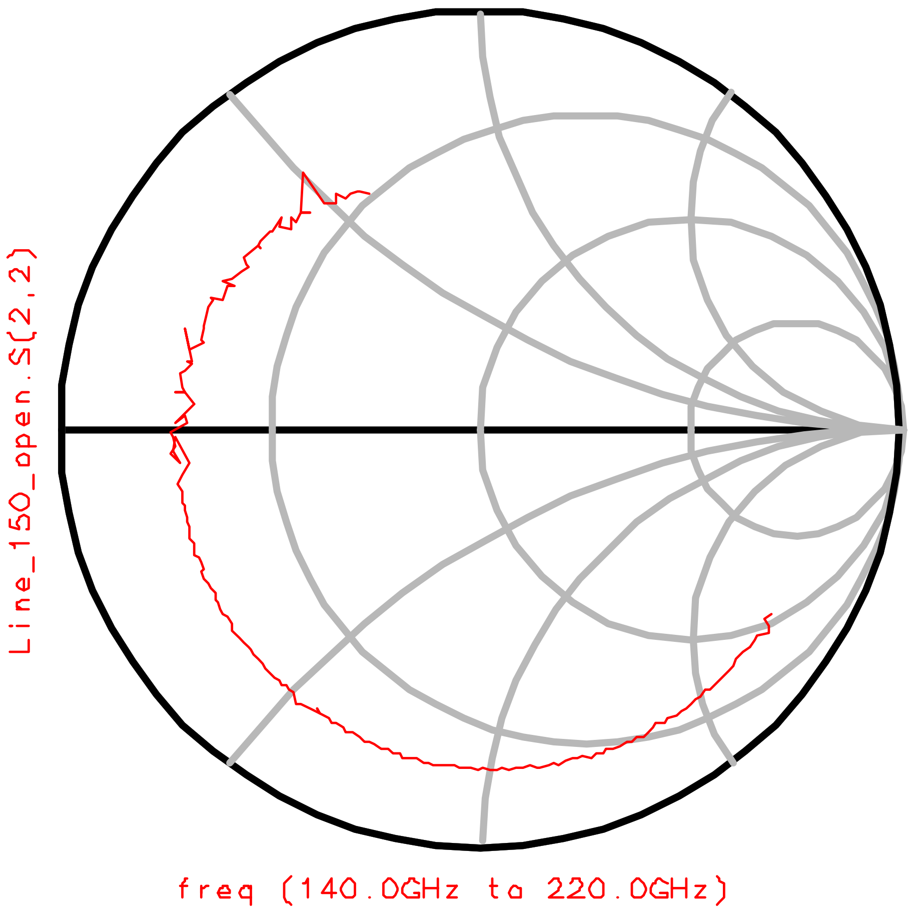
Measurement after Calibration



Open Standard

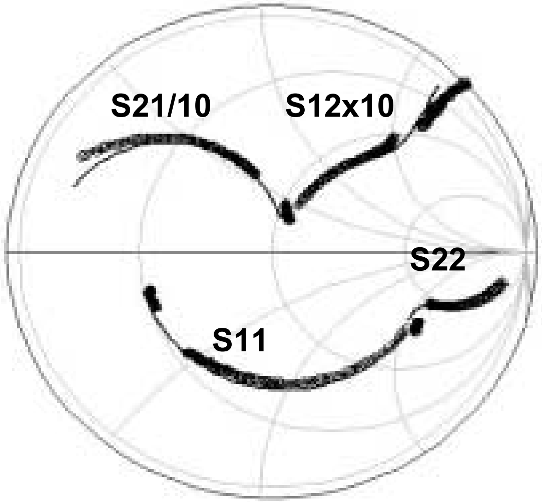


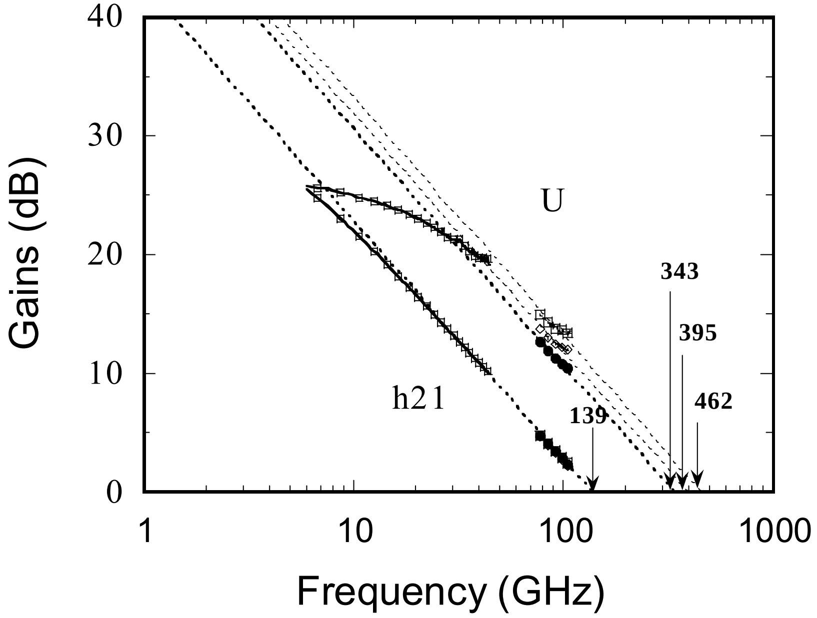
Line Standard with
Open Termination at Second Port

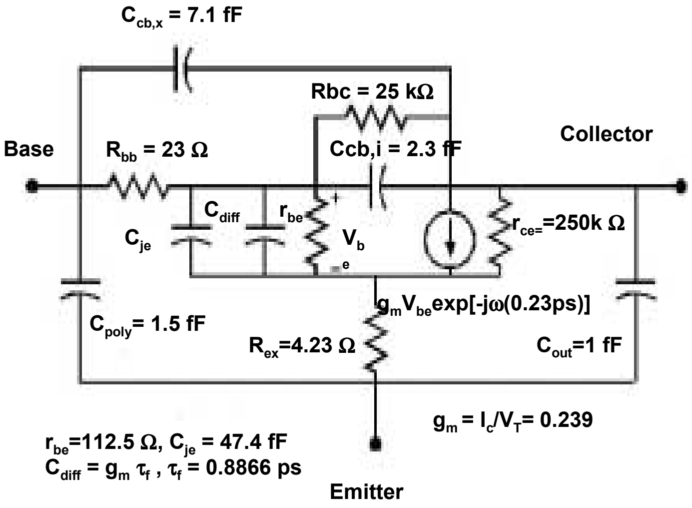
On-wafer NWA:

results with good LRL calibration

characterization results, DC-40 and W-band







Measurements are

smooth

resonance-free

consistent across bands

consistent with known R's and C's

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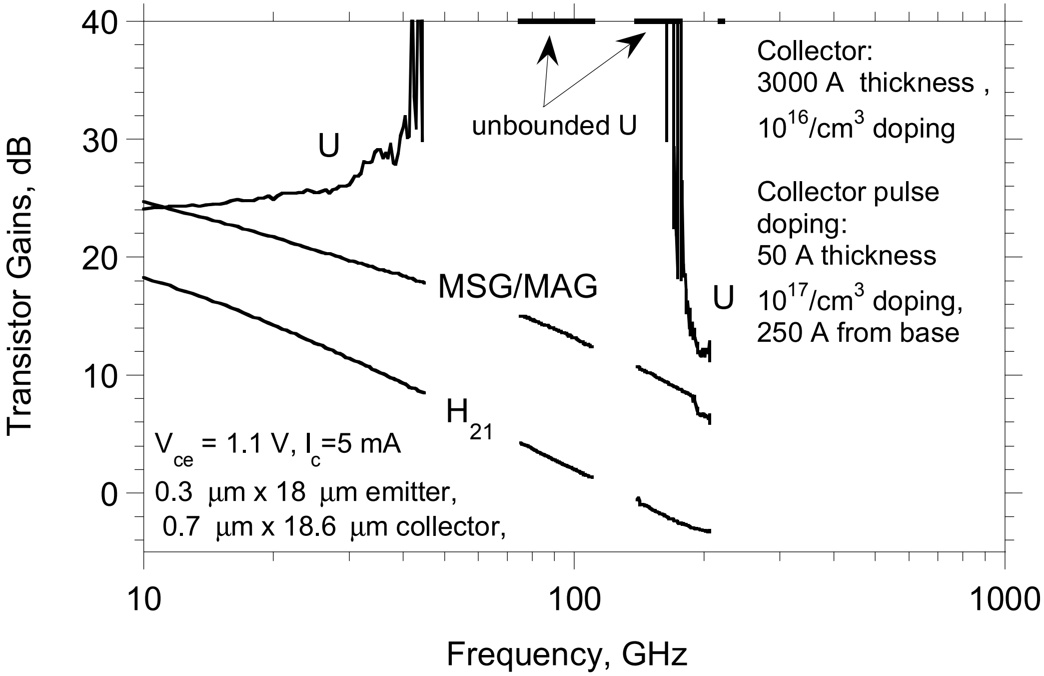
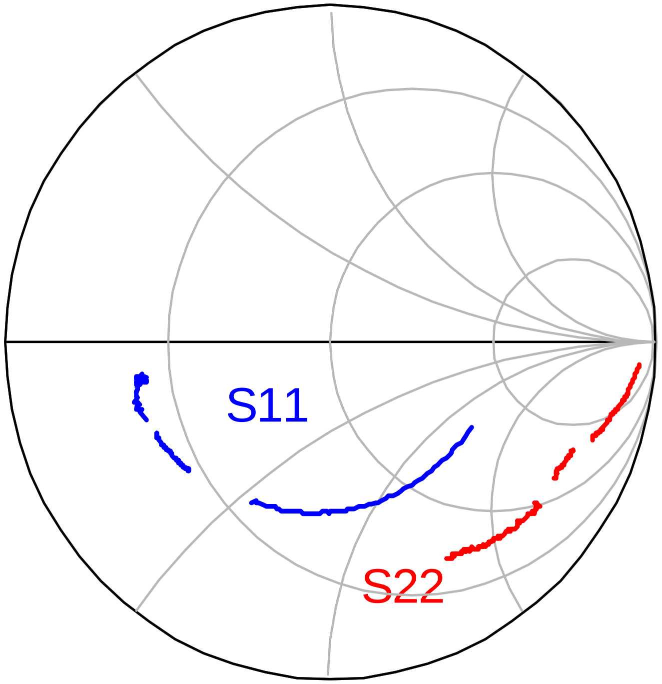
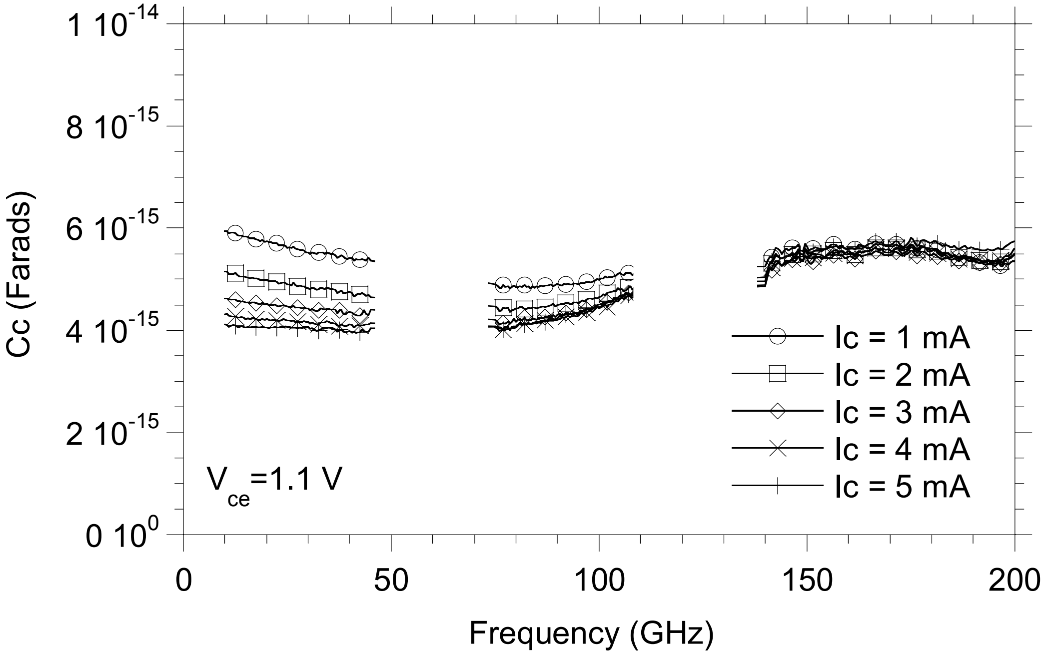
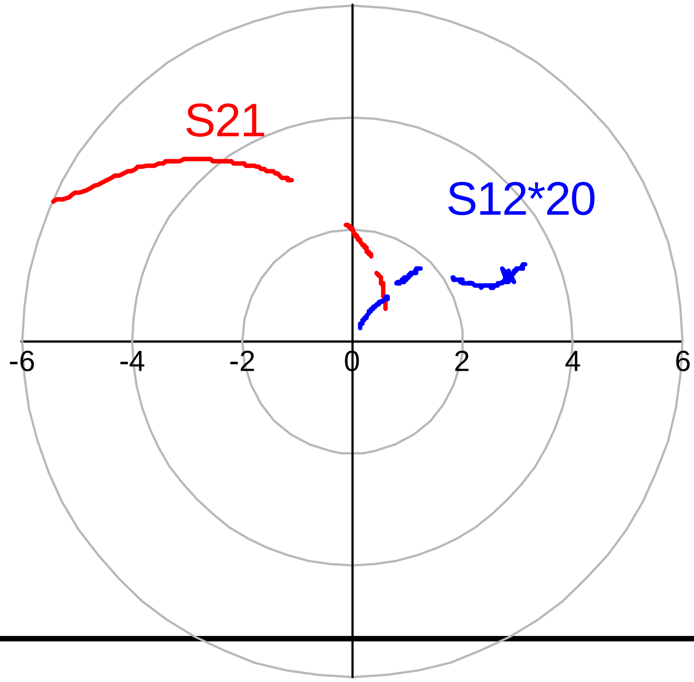
Measurements of Wideband HBTs to 220 GHz







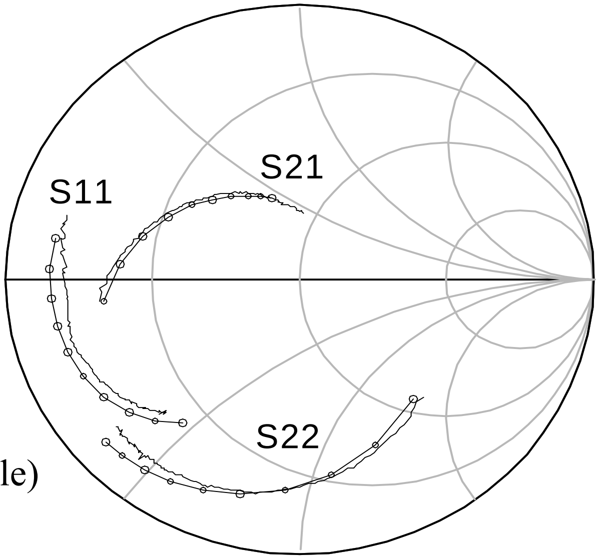


Urteaga et al, 2001 Device Research Conference, June, Notre Dame, Illinois

Miguel Urteaga

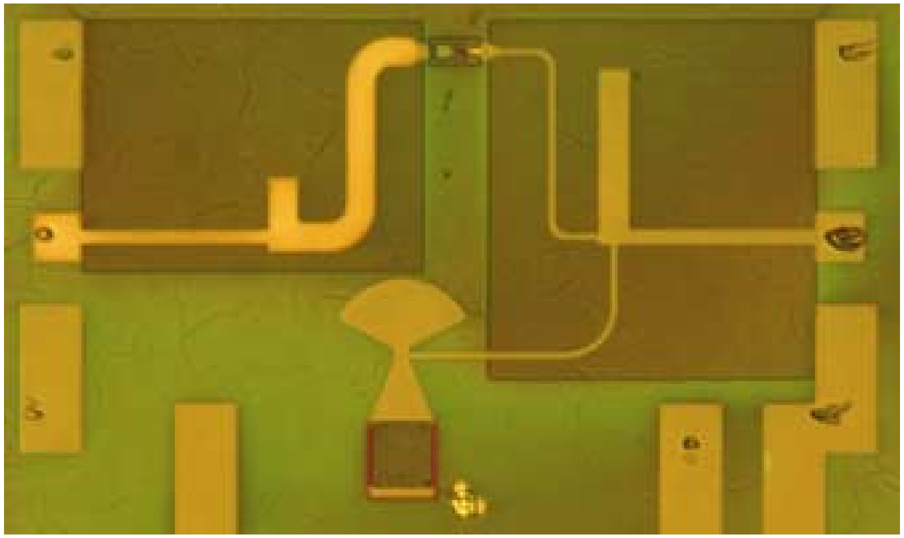
174 GHz Single-HBT Amplifier

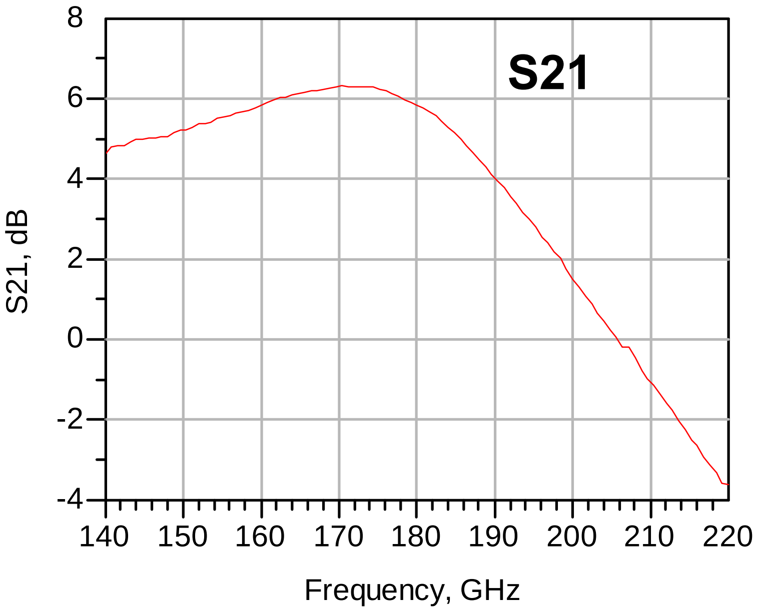
UCSB

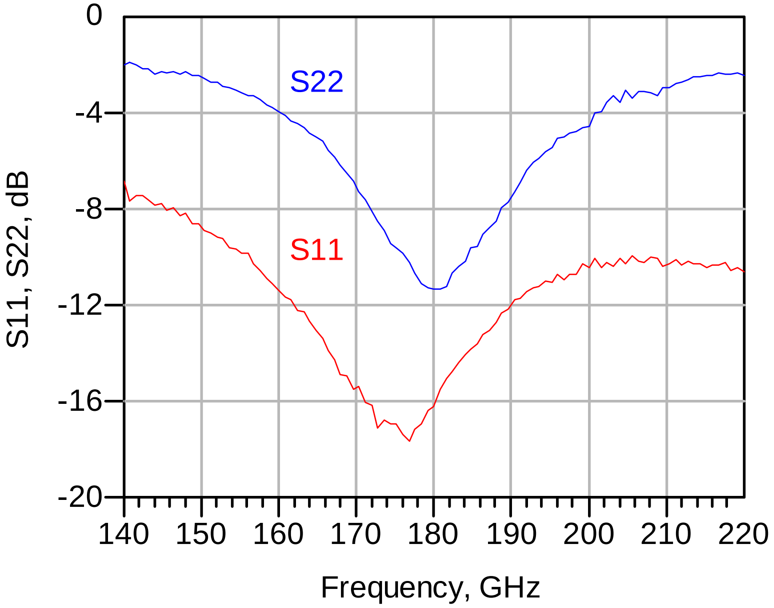


freq (140.0GHz to 220.0GHz)

Measured (solid)
and modeled (circle)
S-parameters of
matching network
test structure

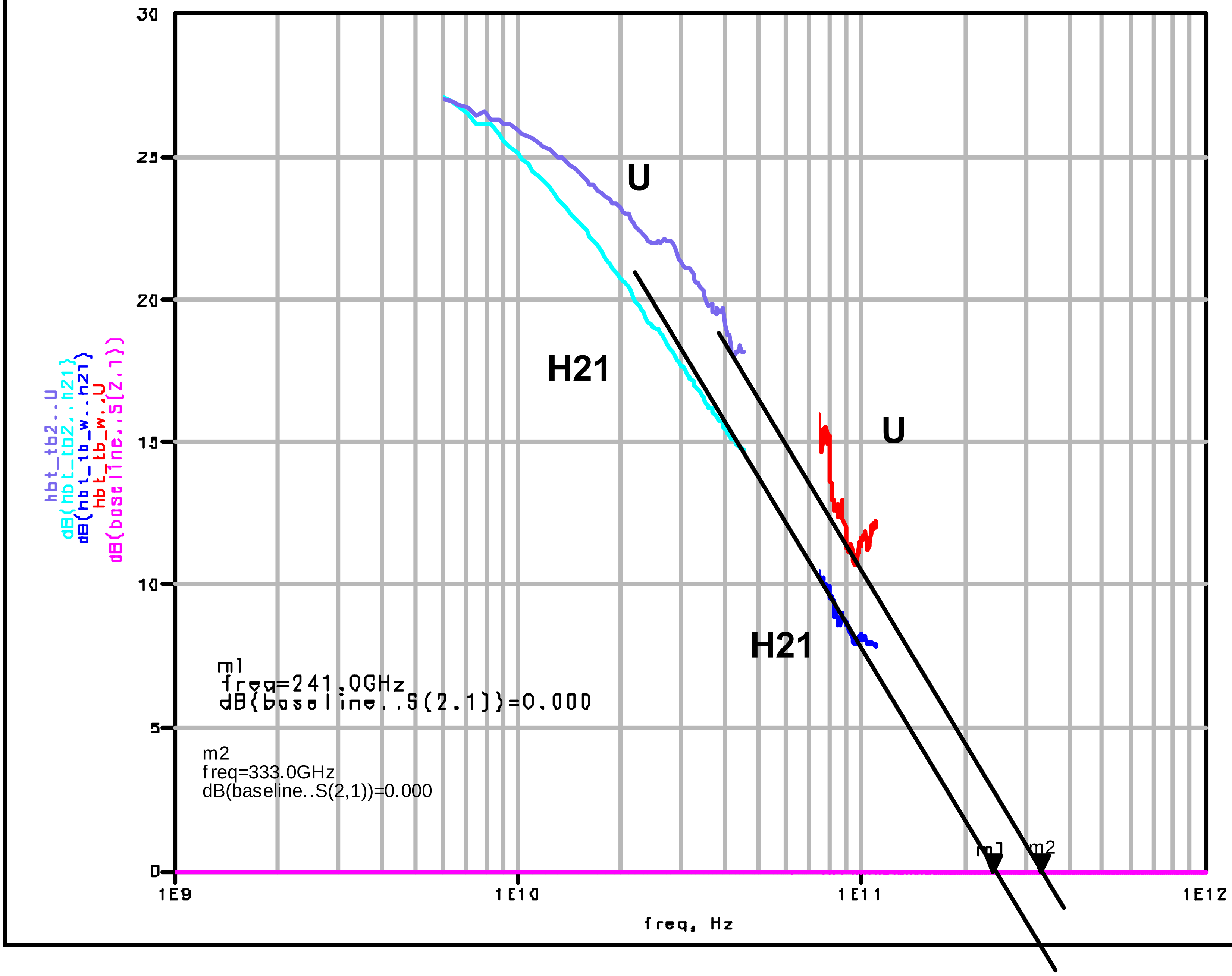






Mattias Dahlstrom

Poorer quality of an on-wafer LRL calibration using CPW



High Frequency Instruments

Needs:
100 GHz sampling oscilloscopes for 40 Gb fiber transmission, …
Accurate and affordable 60 GHz (100 GHz ?) network analyzers

Easy to Address:
sampling (harmonic down conversion) is easy and cheap over DC-200+ GHz
other problems are relevant

Sampling Oscilloscopes
timebase stability and flexibility in triggering: conflicting requirements !
better time bases: 3-synthesizer, PLL, or DDFS
choose timebase appropriate for application
cable losses are major source of error
network-analyzer-like calibration procedures should be developed

Network Analysis
combined accuracy, frequency coverage, and cost
good solution (?): moderate-order harmonic conversion with sampler for 40-110 GHz
better calibration methods needed for testing > 300 GHz f_t and f_{max} transistors