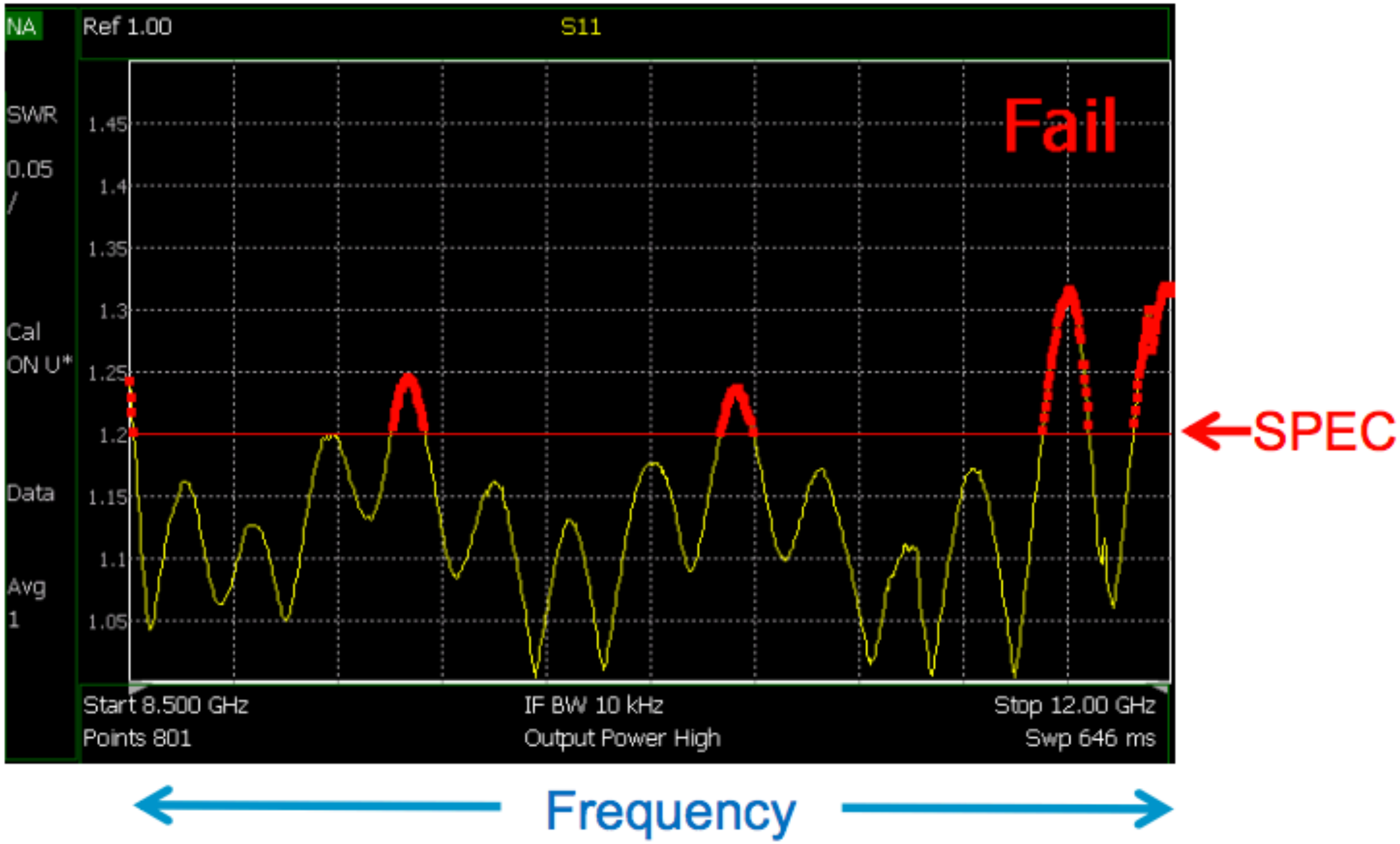
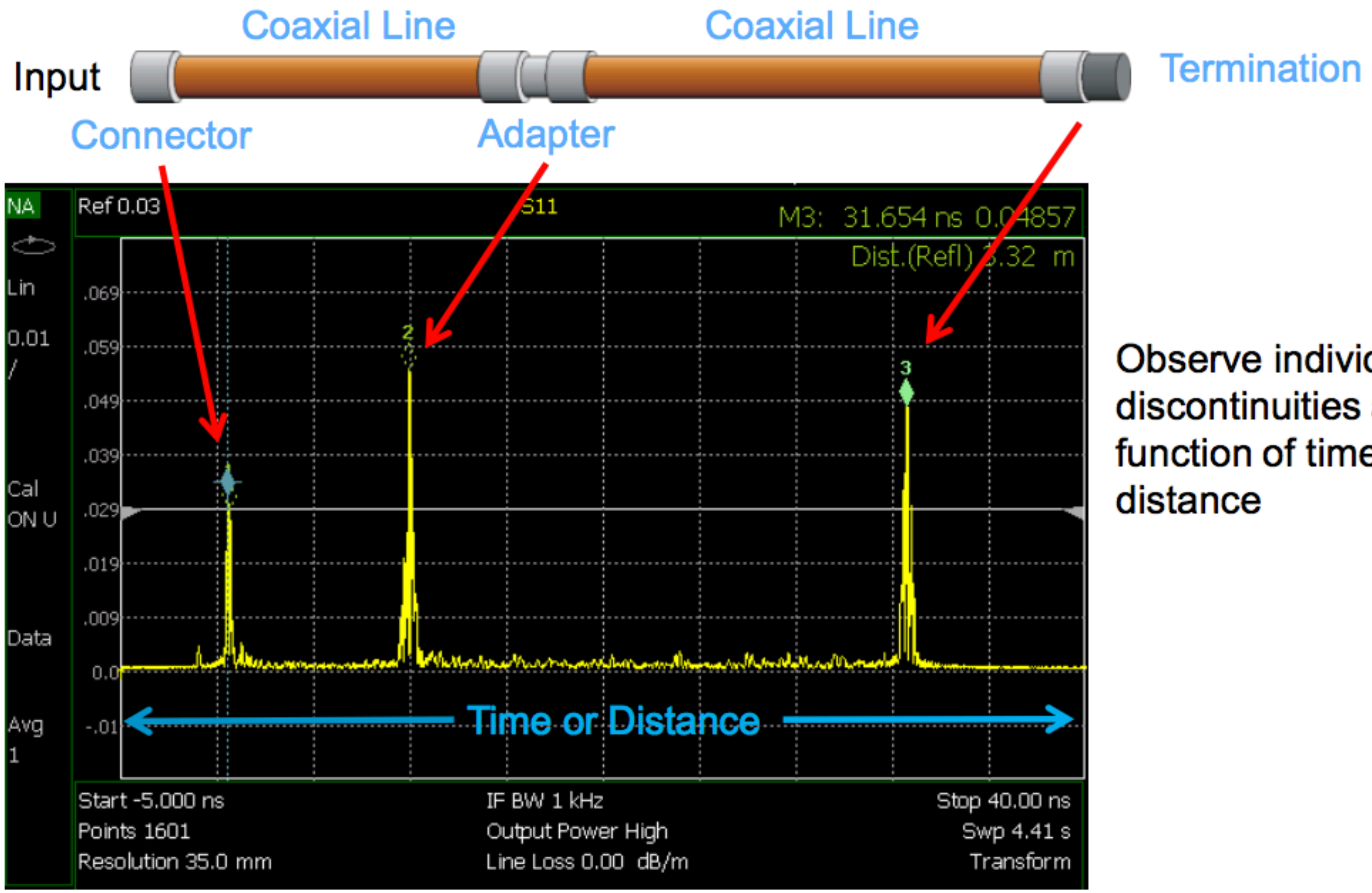
Measured VSWR of complete system



Which component is causing the problem ?

Where is the fault located ?

Time Domain Response



Observe individual discontinuities as a function of time or distance

Fault locations

Identify impedance variation of connectors

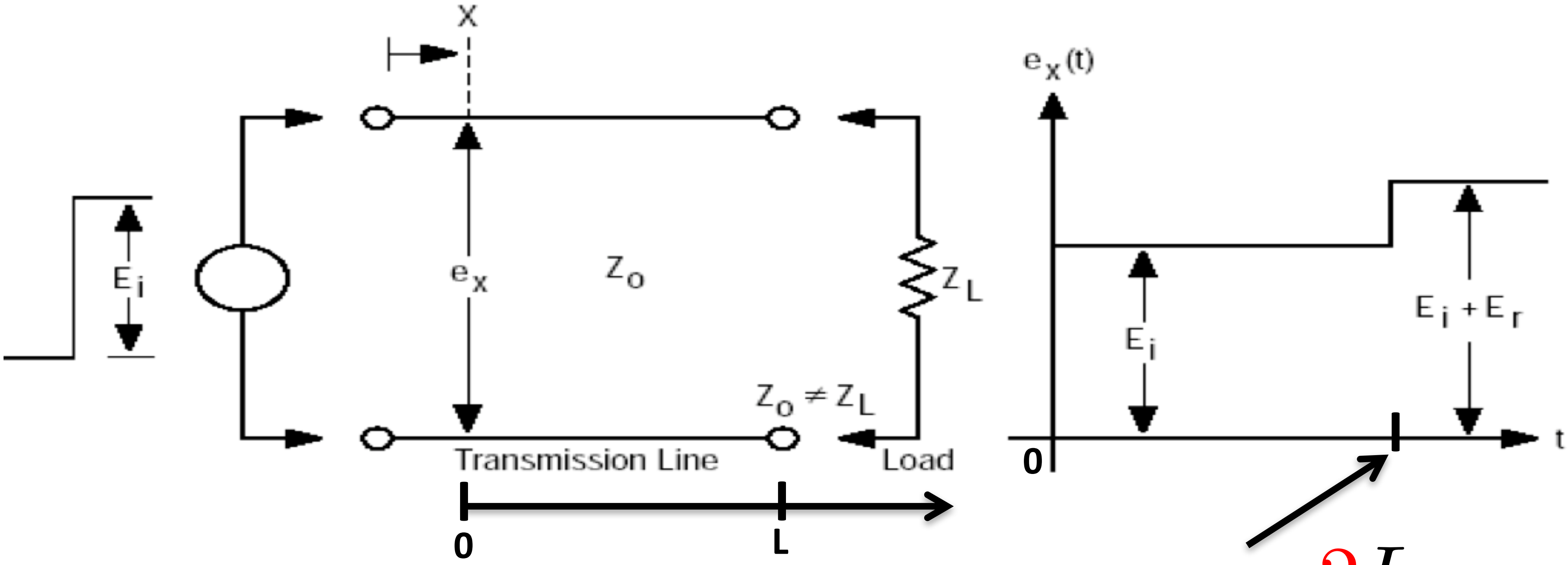
Remove unwanted discontinuities

Simplify filter tuning

Time domain reflectometry

Echo measurement (similar to a radar)

Time domain measurement → Different times correspond to different positions



$$\frac{E_r}{E_i} = \Gamma = \frac{Z_L - Z_0}{Z_L + Z_0}$$

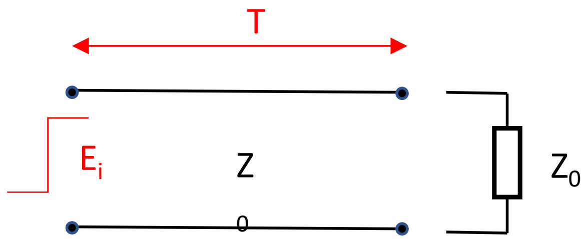
$$T = \frac{2L}{v}$$

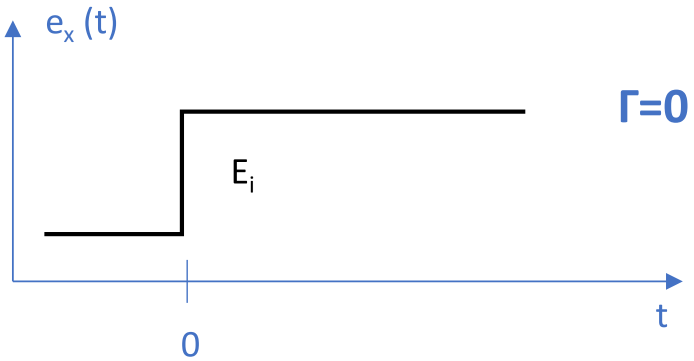
Nature and amplitude of the mismatch

Localization of the mismatch

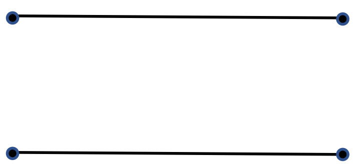
Examples of DUTs

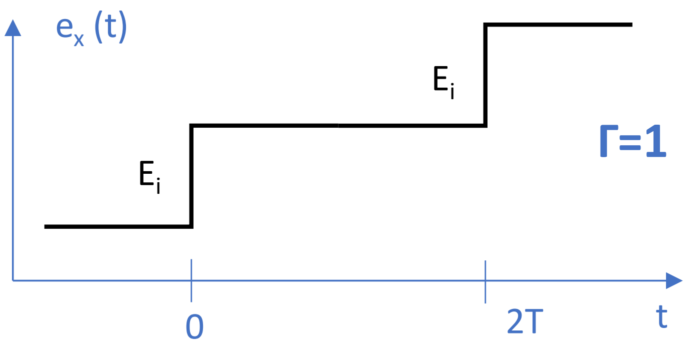
Matched Termination (Z_L=Z_0)





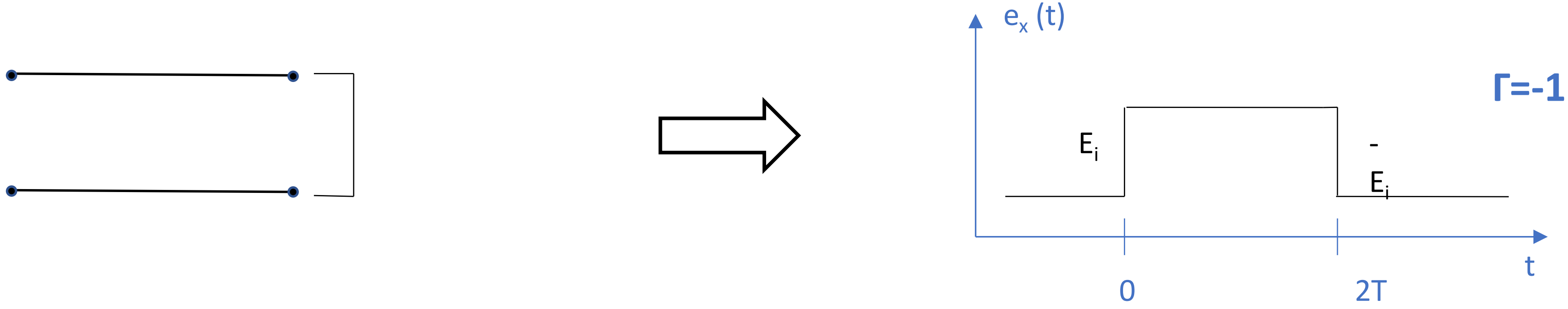
Open Circuit Termination (Z_L=∞)



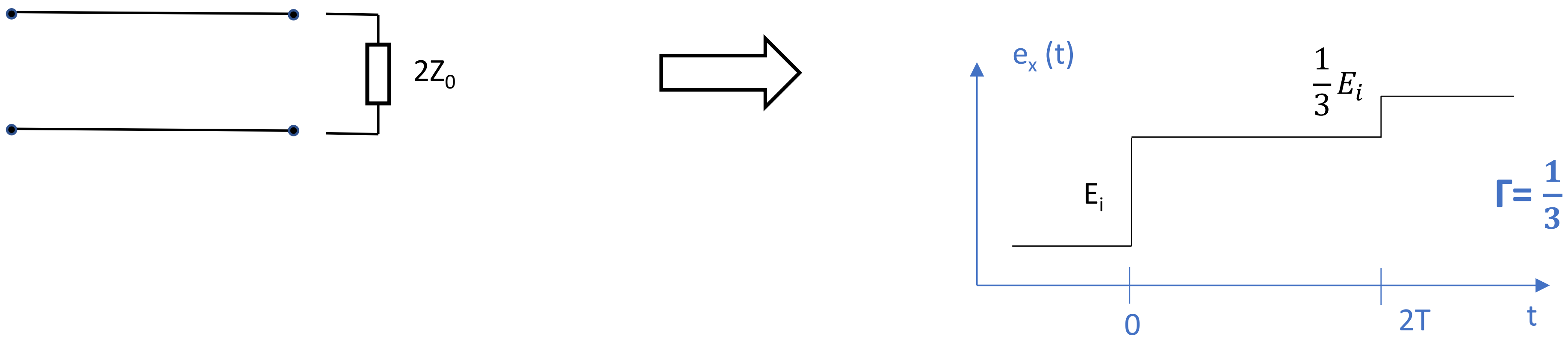


Examples of DUTs

Short Circuit Termination ($Z_L = 0$)

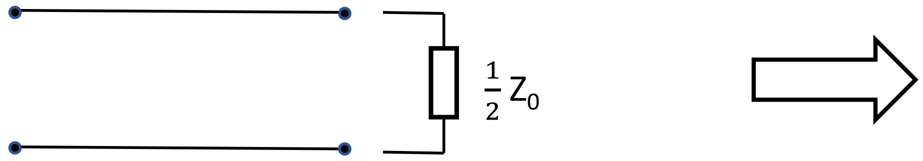


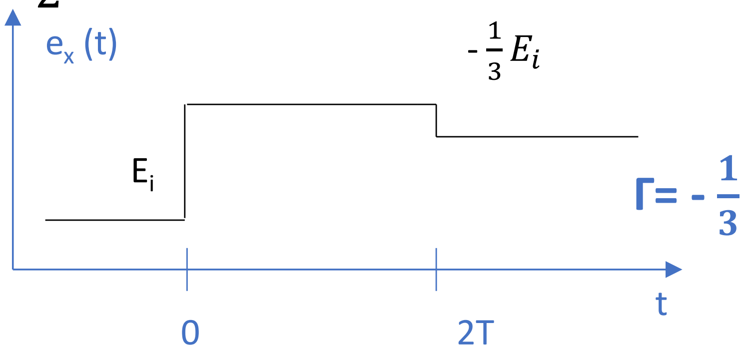
Line Terminated in $Z_L = 2Z_0$



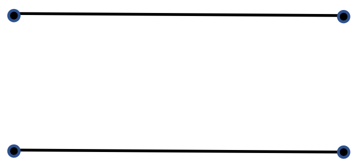
Examples of DUTs

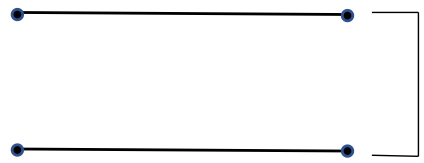
Line Terminated in $Z_L = \frac{1}{2} Z_0$



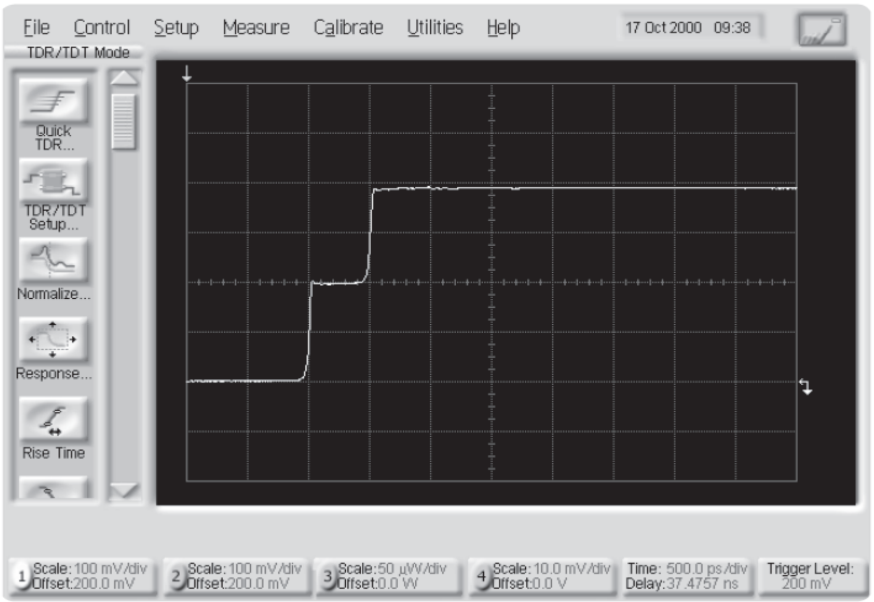


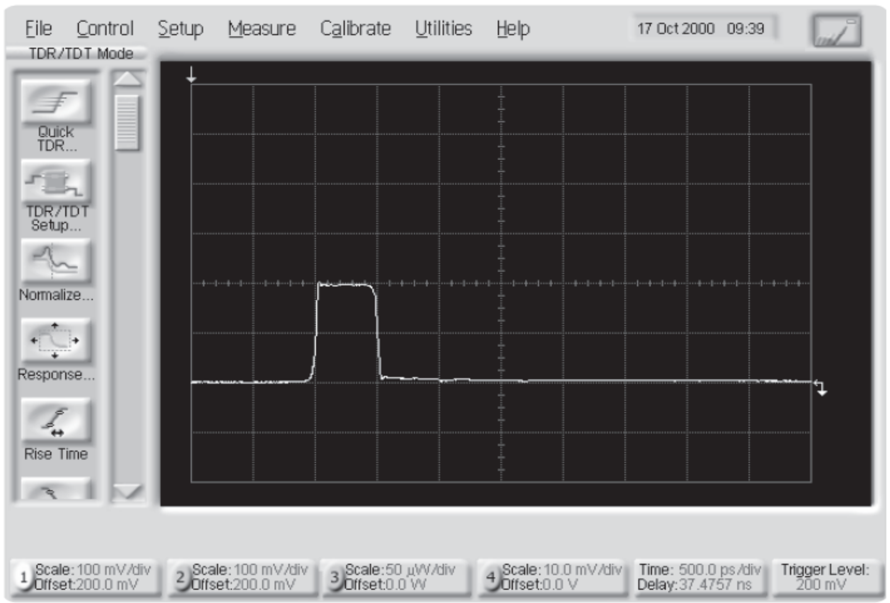
Measurements





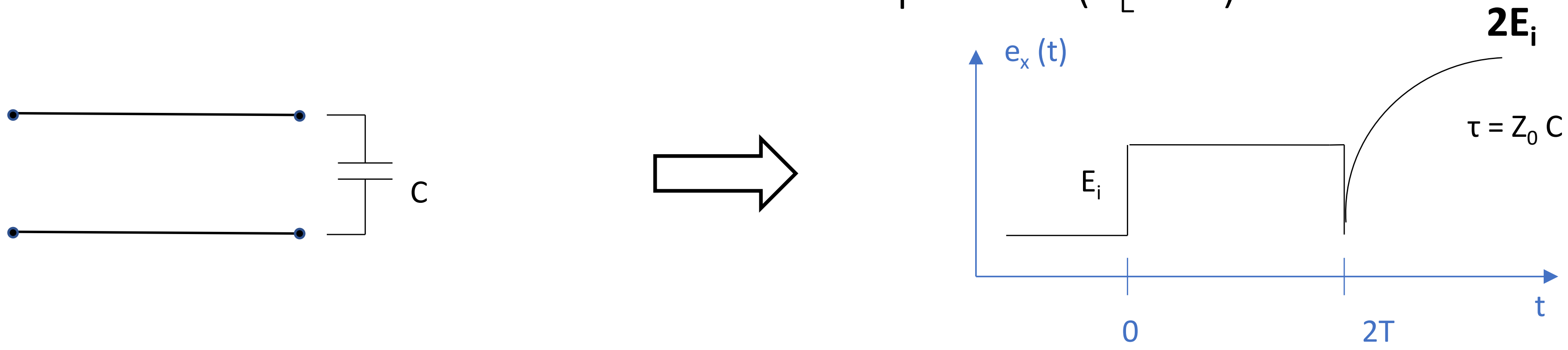
Examples of open and short circuit terminations (Screen captures from the 86100B)



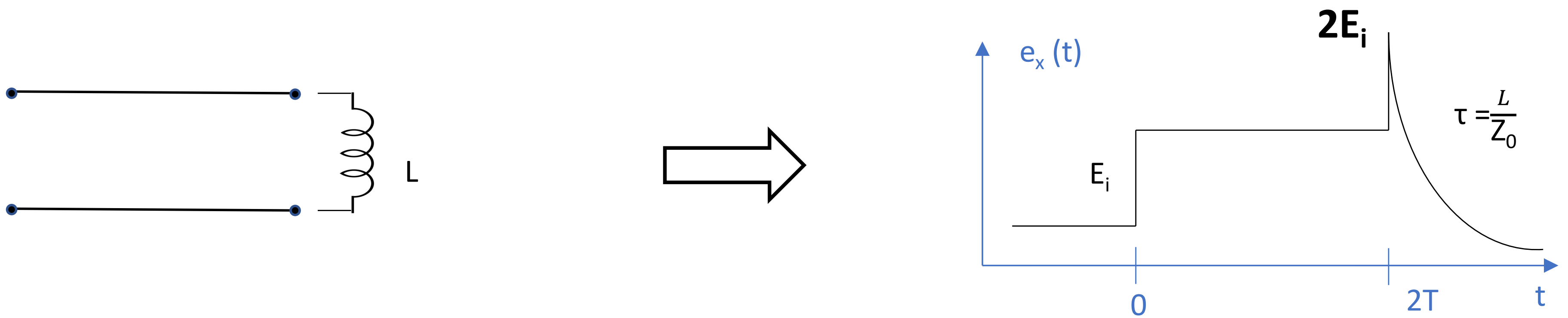


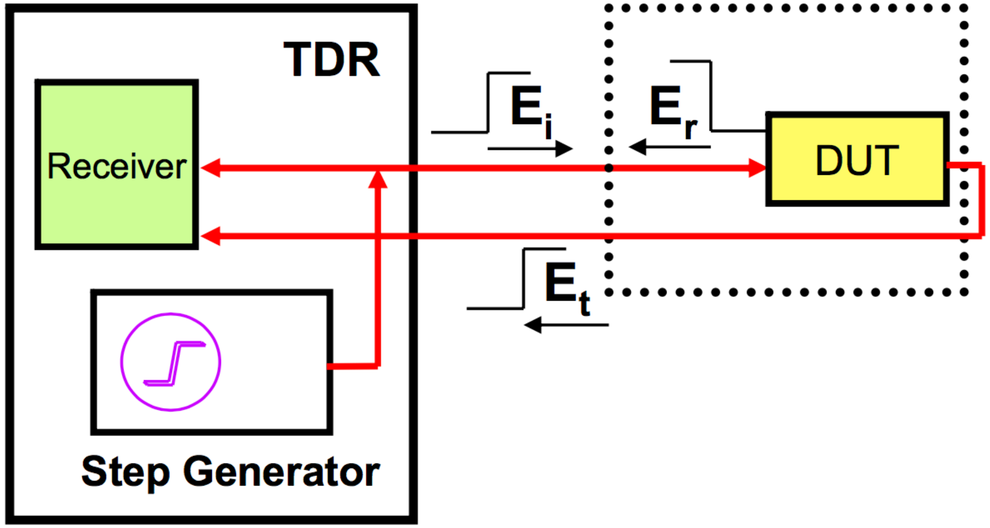
Examples of DUTs

Line Terminated with a Capacitor (Z_L = C)

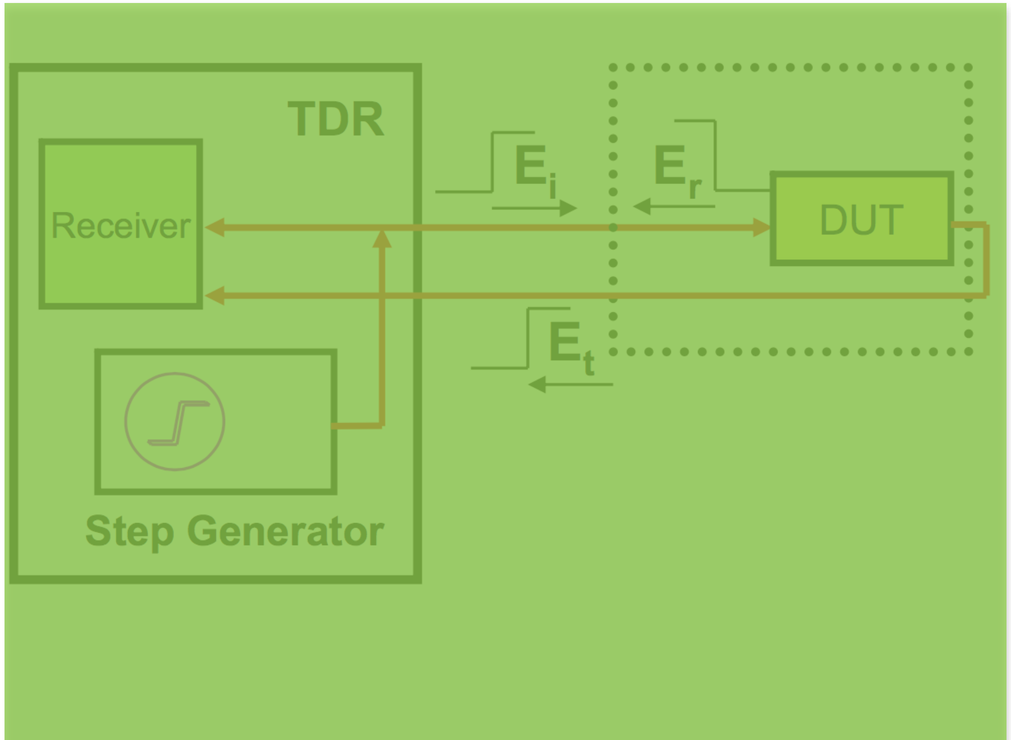


Line Terminated with a Inductor (Z_L = L)

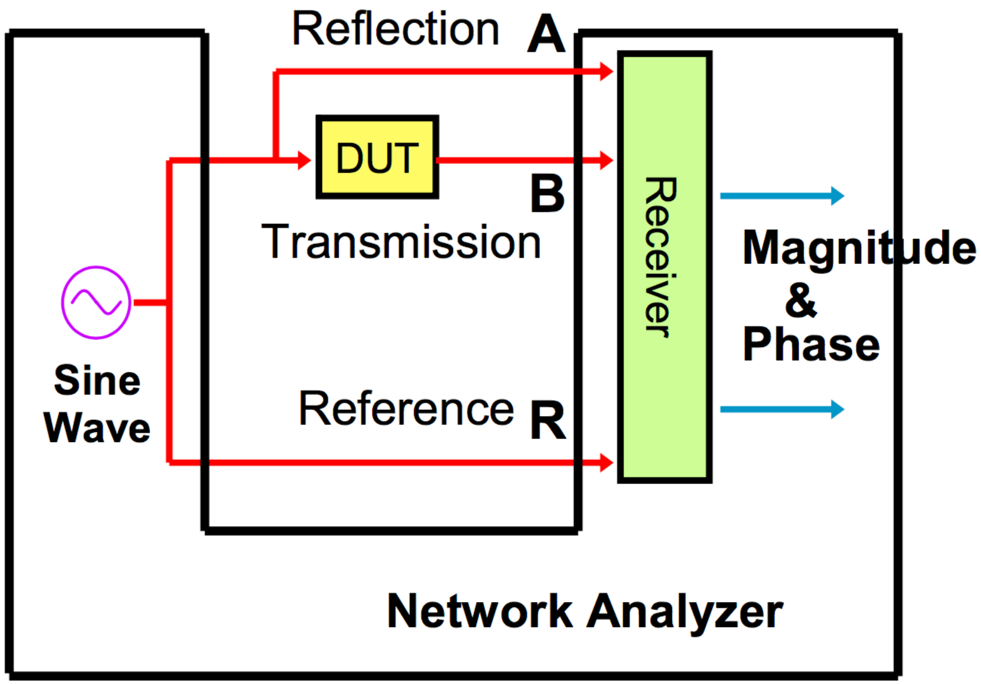




Time Domain Reflectometer (TDR)



Time Domain Reflectometer (TDR)



Vector Network Analyzer (VNA)

Synthetic pulse with VNA

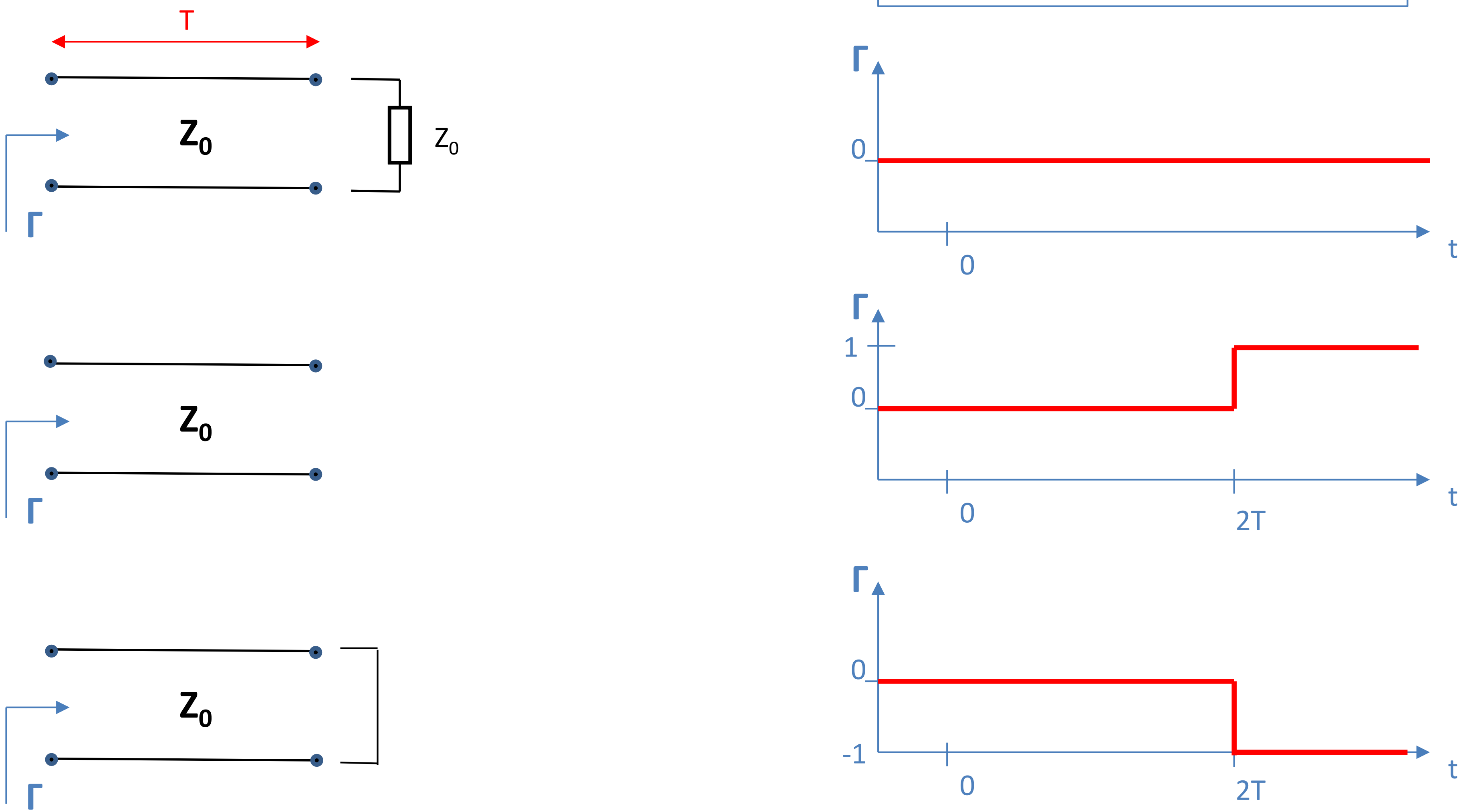
(Time Domain Option)

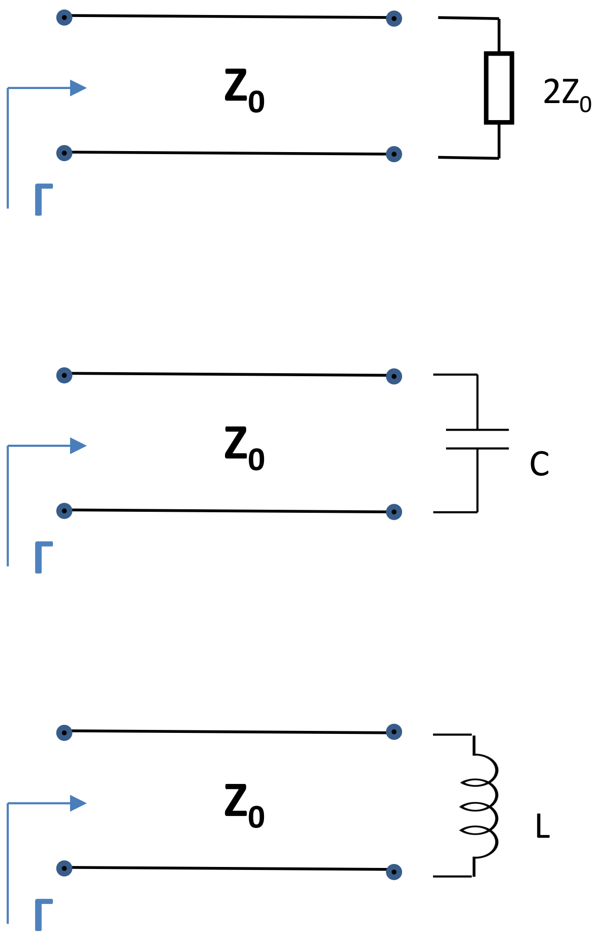
Convenience: VNA’s outstanding dynamic range compared to the traditional TDR.

Time Response ⟺ **FOURIER** ⟺ Transfer Function

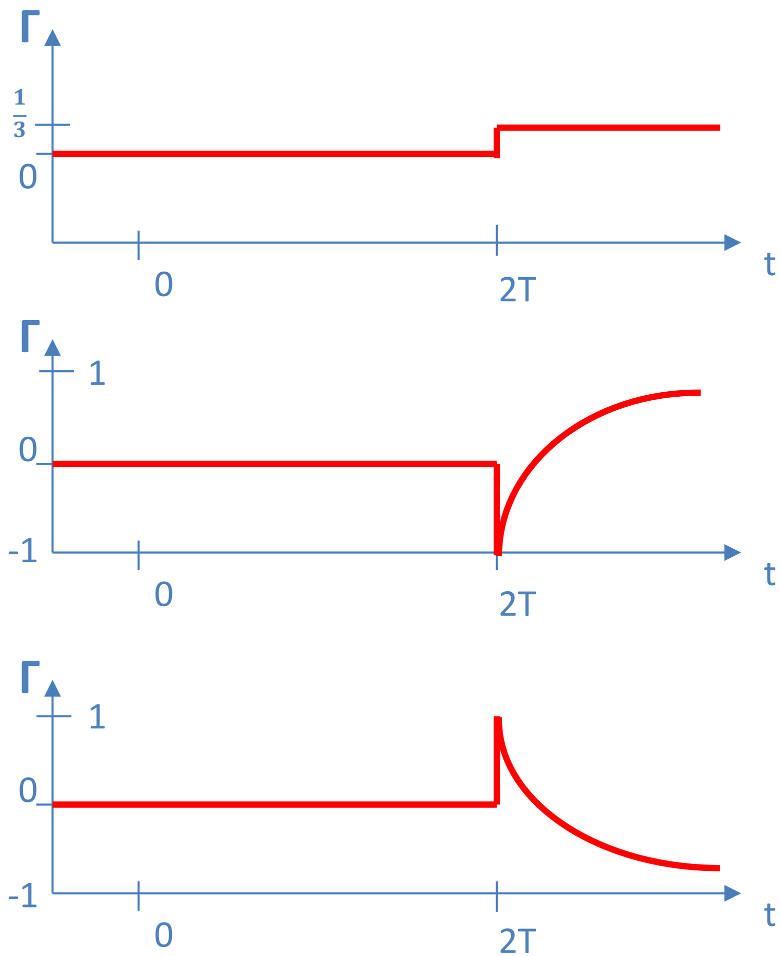
The VNA operates the FFT of the Transfer Function, to obtain the Time Response.

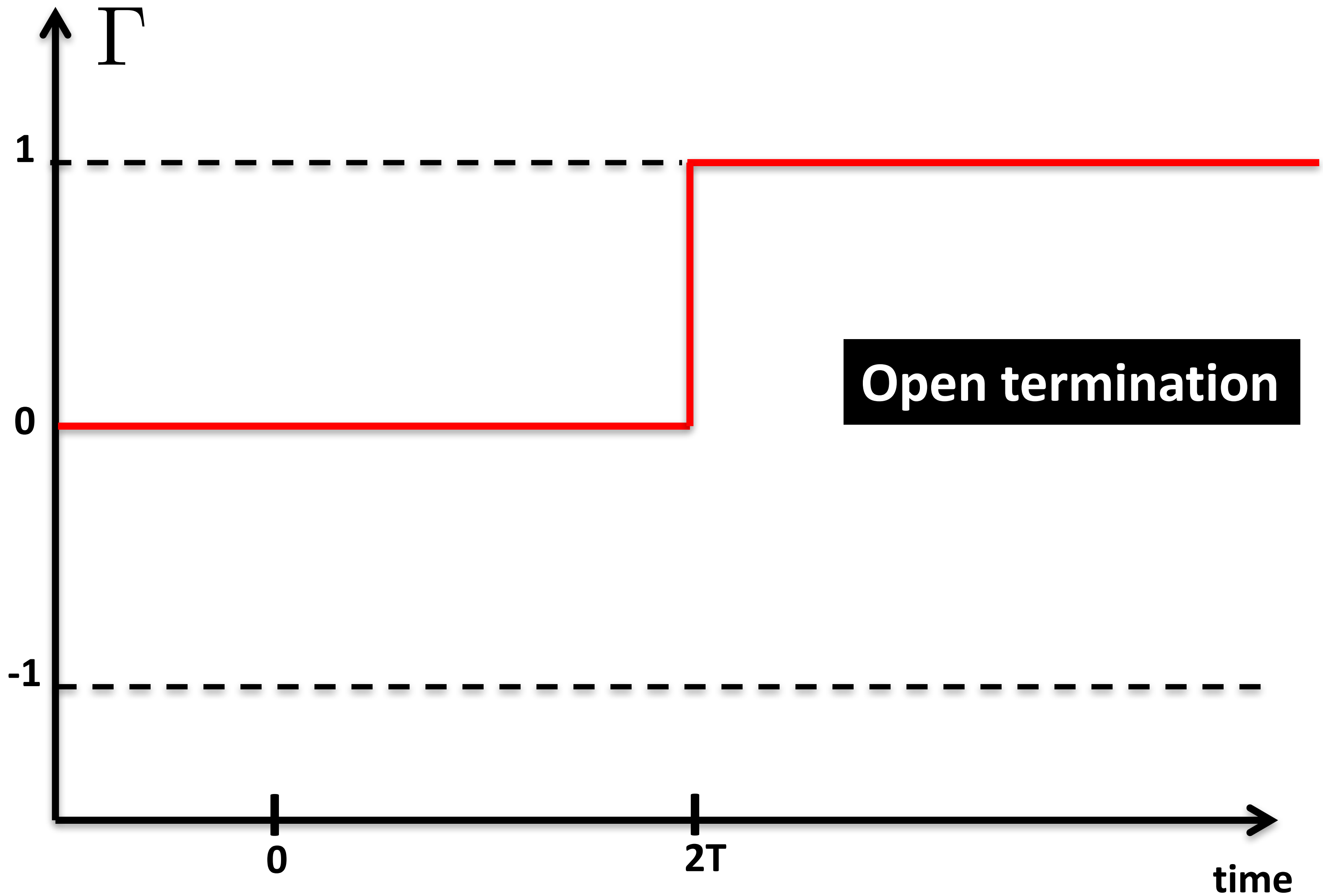
Step Response

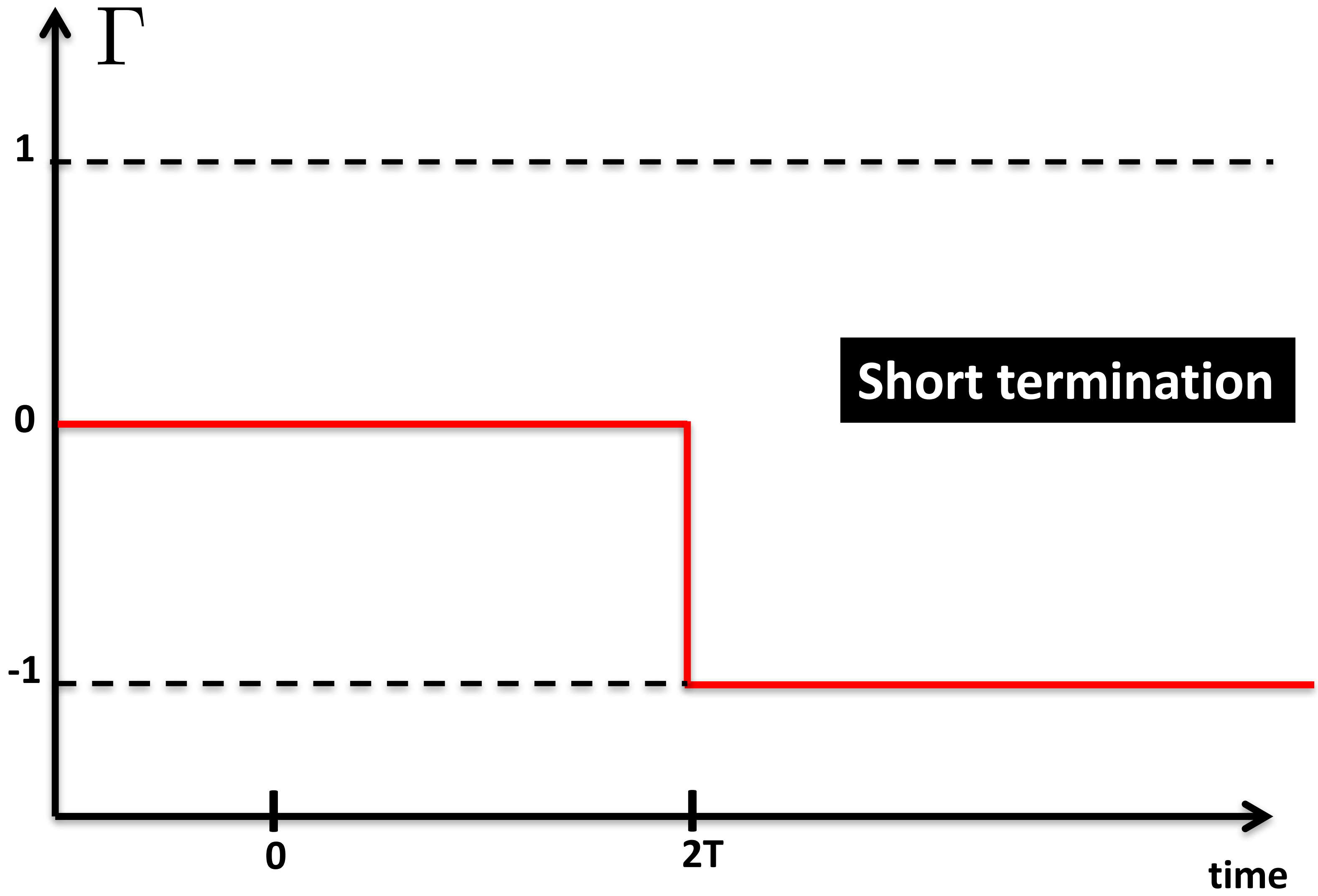


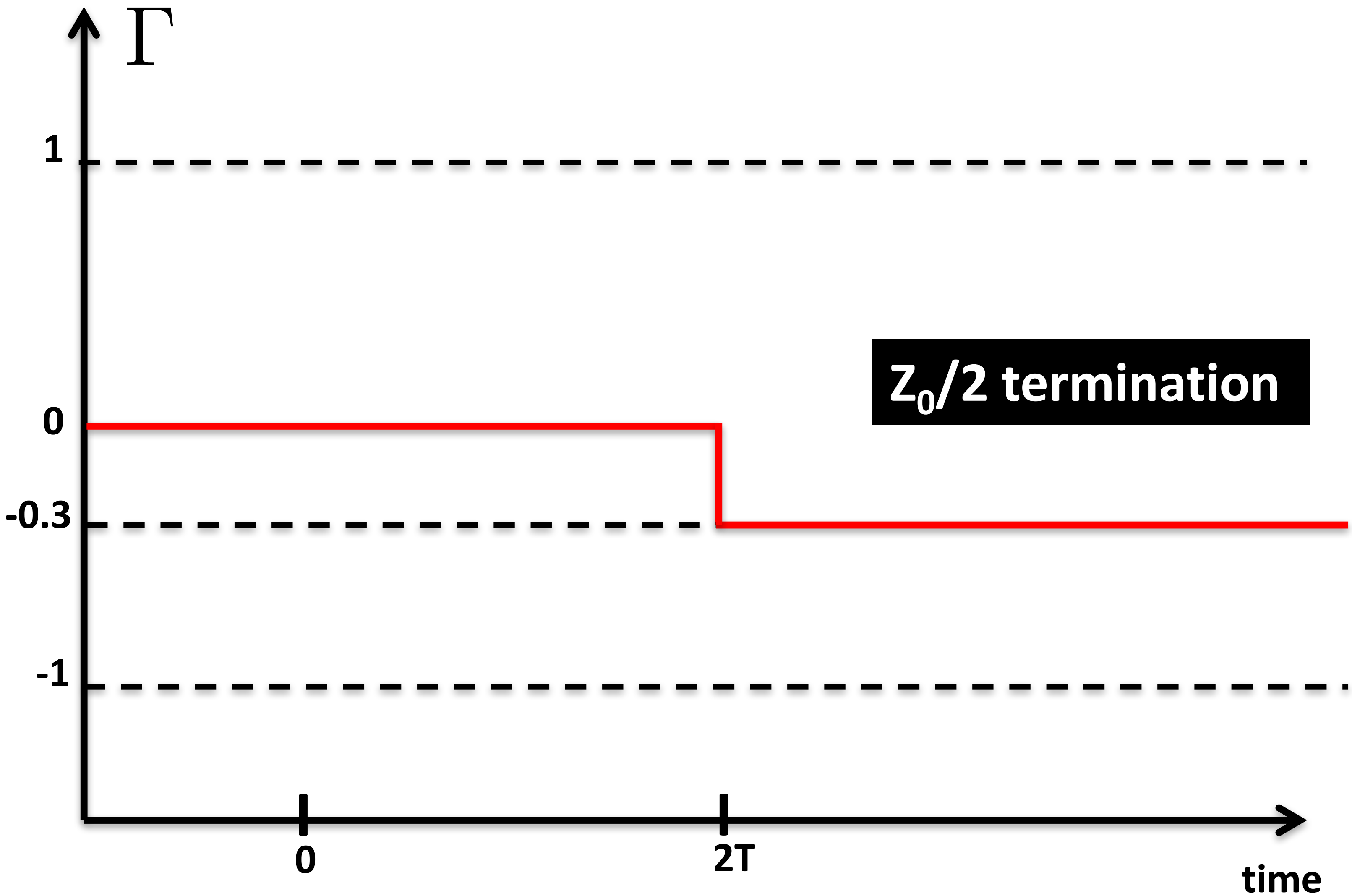


Step Response



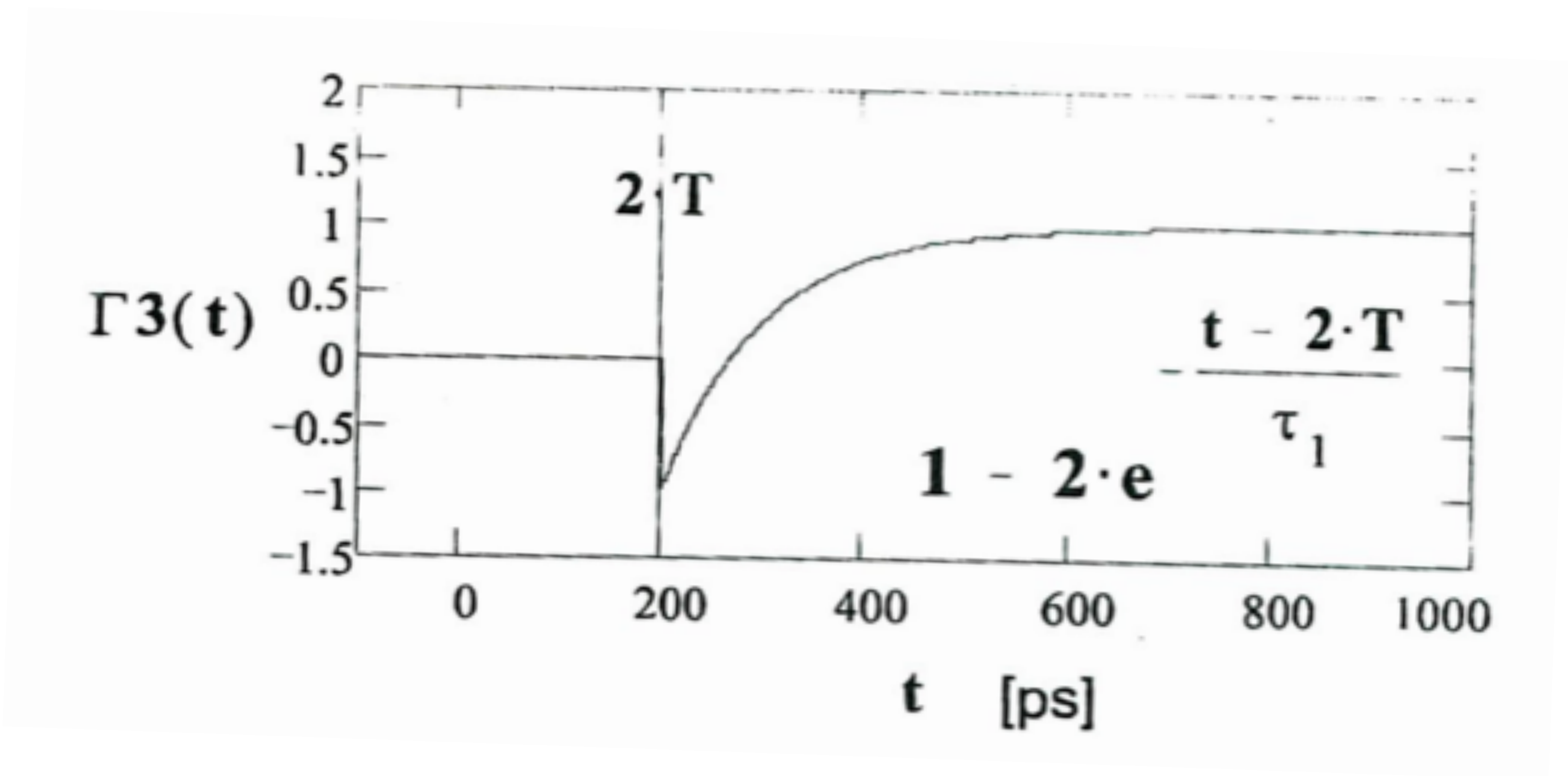

Γ
1
0
-1
Open termination
0
2T
time


Γ
1
0
-1
Short termination
0
2T
time



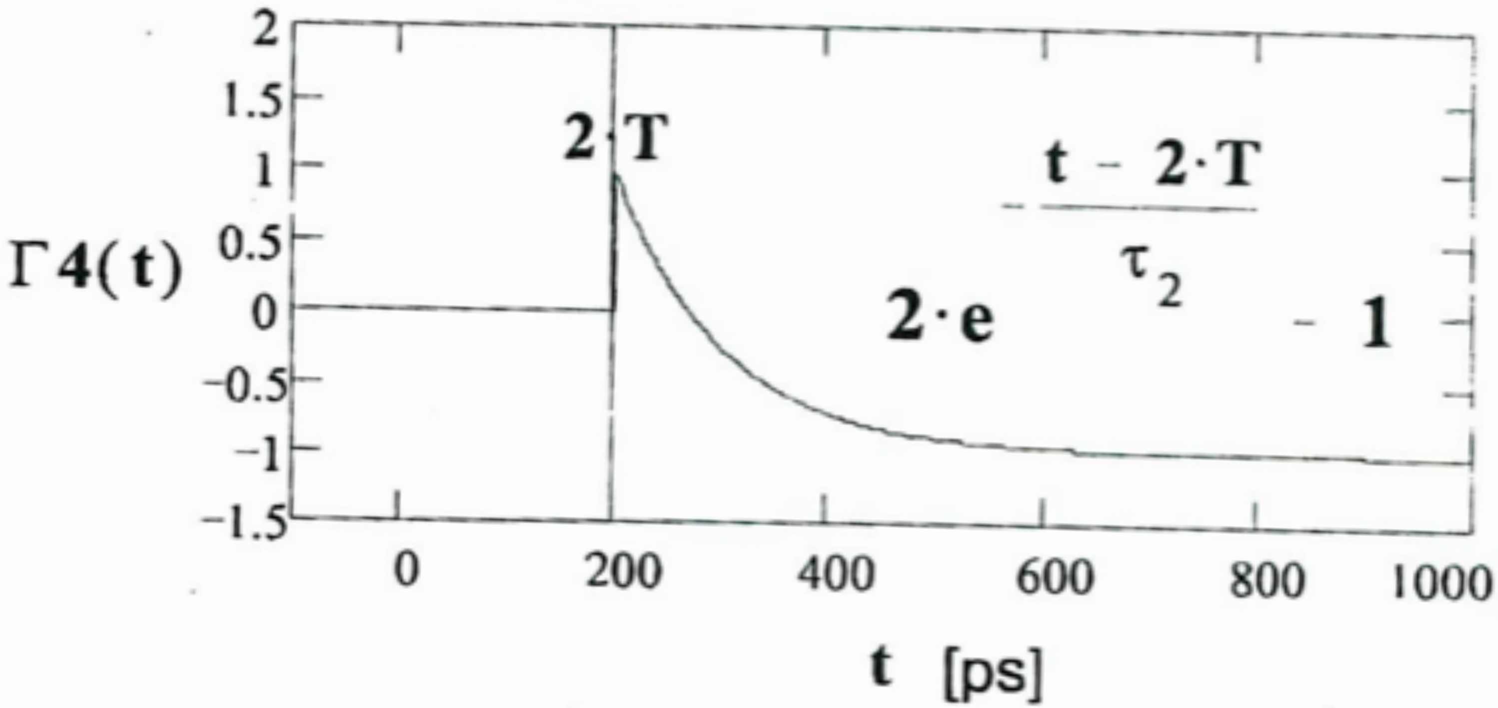
Γ
1
0
-0.3
-1
Z0/2 termination
0
2T
time

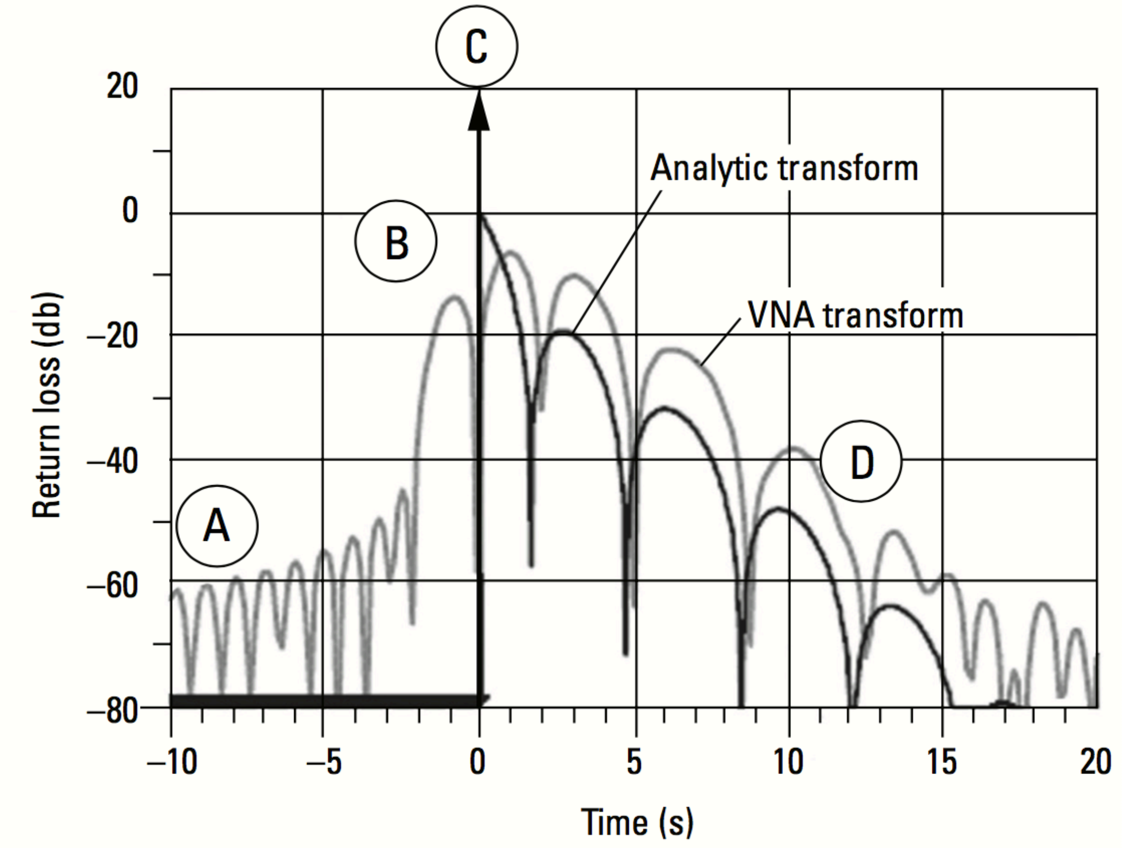
Capacitor



2
1.5
1
0.5
0
−0.5
−1
−1.5
Γ3(t)
2·T
$1 - 2 \cdot e^{-\frac{t - 2 \cdot T}{\tau_1}}$
0
200
400
600
800
1000
t [ps]

Inductor





A The ringing is caused by the frequency truncation

B The differences in the width are caused by windowing (between the gray and black traces)

C The finite impulse is determined by the frequency range of the VNA

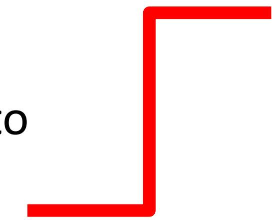
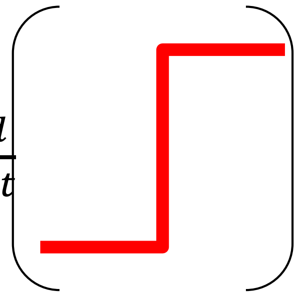
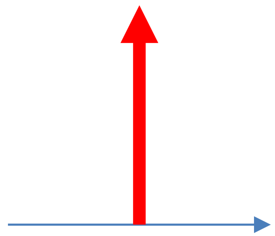
D The difference in magnitude is caused by renormalization (between the gray and black traces)

Figure 2. Comparing IFT calculated (analytic transform) and VNA time domain transform of the same function.

Figure 2 shows the analytically derived transform of the return loss of a 3-pole Butterworth filter along with the VNA time domain transform of the same function. In the analytic transform, the frequency response is calculated using standard network theory, and the Inverse Fourier Transform (IFT) is performed to get the time response. The differences between the analytic transform (IFT calculated) and the VNA transform are caused by the effects of discrete data sampling, frequency truncation, windowing, and renormalization.

The **Time Domain Reflectometry** in the **VNA** is a **mathematical operation**
(Chirp Z Transform)

1)

response to  ⇨ response to $\frac{d}{dt}$  = 

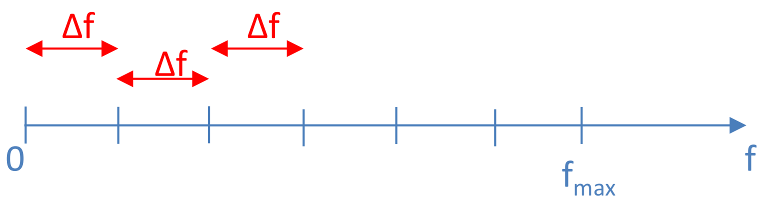
Step Response

Pulse Response

2) FFT algorithm requires **symmetric frequency samples** (with respect to the zero).

$f_{min} \neq 0$ zero frequency sample MUST be extrapolated.

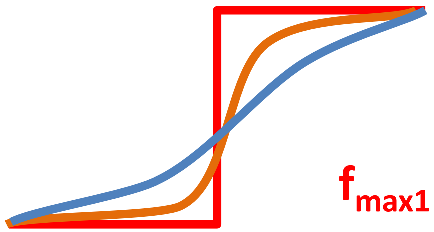
$\mathbf{f_{min} = \Delta f}$



$\Rightarrow$ **f_{min} depends by f_{max} and by the number of samples (number of points).**

SET LOW FREQUENCY PASS before calibration!

3) The slope of the simulated signal depends by f_{max} :



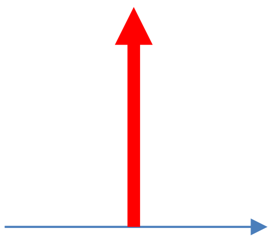
f_{max1} > f_{max2} > f_{max3}

$$\text{RISE TIME} \propto \frac{1}{f_{max}}$$

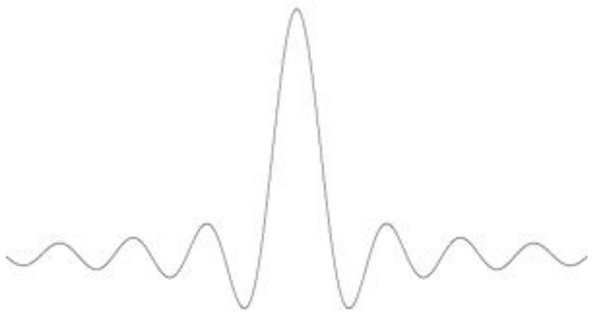
The spatial resolution is related to f_{max} .

The f_{max} is finite.

The Pulse Response isn't



but **sinc(t) :**



4) Discrete sampling of frequency:

$T_{max}=1/2\Delta f$

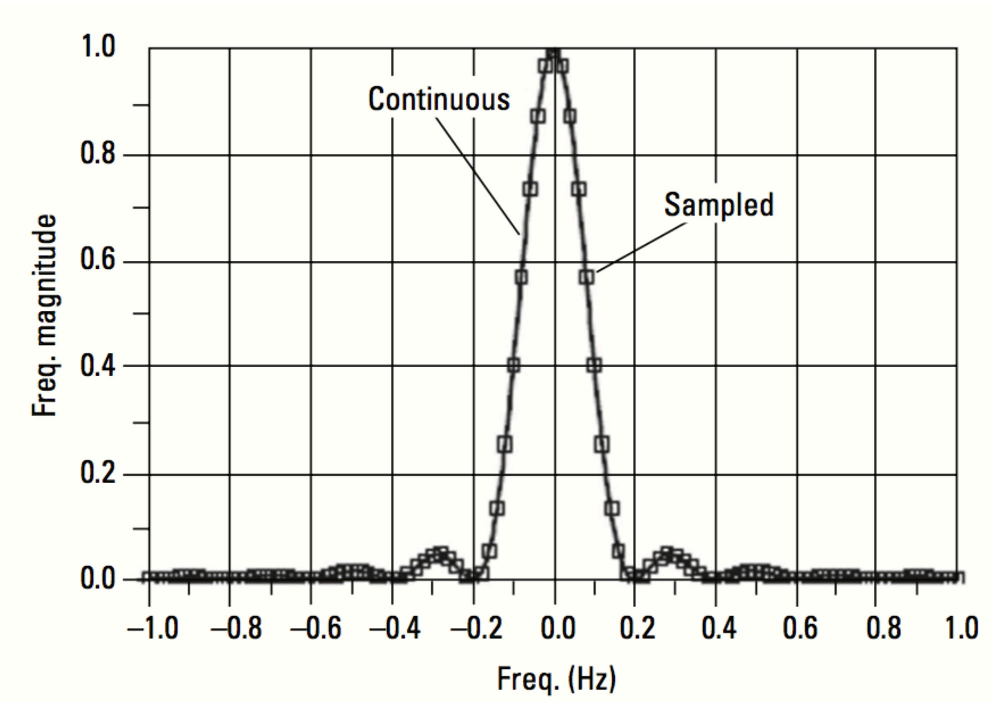


Figure 3a. Continuous function and discrete (sampled) function.

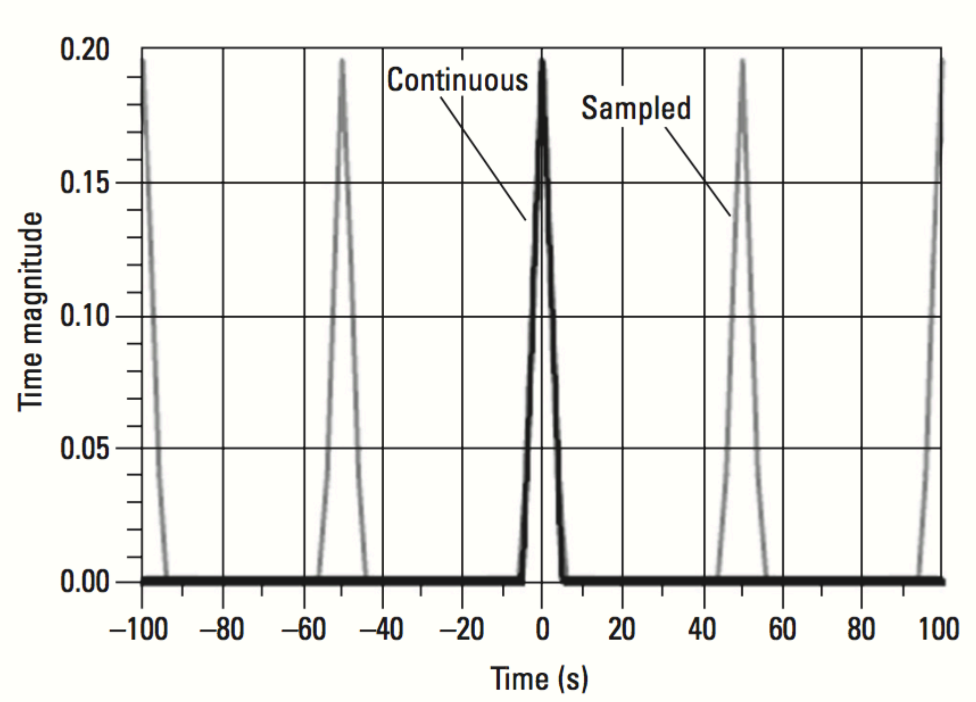


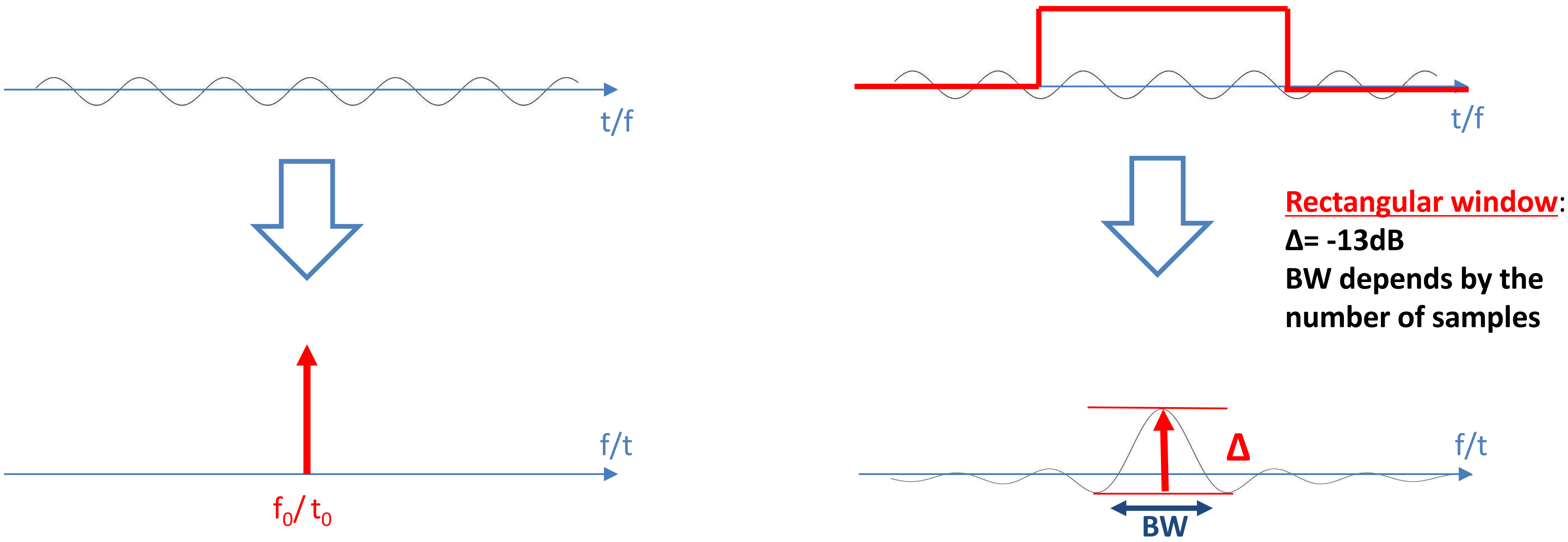
Figure 3b. Alias responses due to discrete sampling.

The Fourier Transform operates on continuous functions, while the VNA time domain transform must operate on discrete data. One way to look at this is to assume the measured data is a sampled version of a continuous response. The frequency sampling can be visualized as data points evenly distributed over the frequency range of the measurement as shown in Figure 3a. This also creates images of the original function called aliases which occur at repetitive intervals of 1/(frequency step size). Figure 3b illustrates both the discrete data sampling and the alias responses.

5) **TIME DOMAIN** ⟵ FFT ⟵ **FREQUENCY DOMAIN**

(SYNTHETIC) *(MEASUREMENT)*

The FFT is influenced by the limited number of samples.



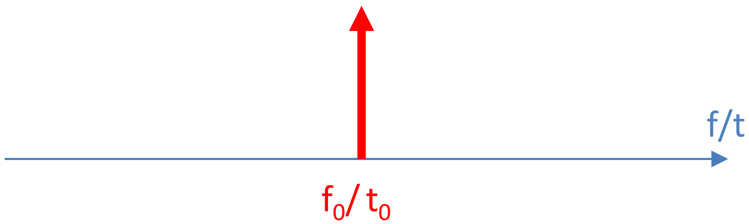
5) TIME DOMAIN  FREQUENCY DOMAIN

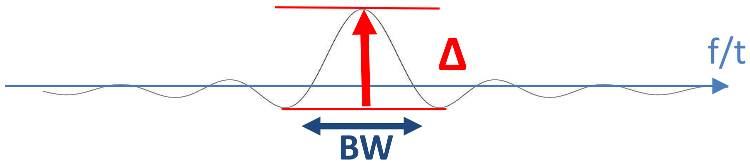
(SYNTHETIC) *(MEASUREMENT)*

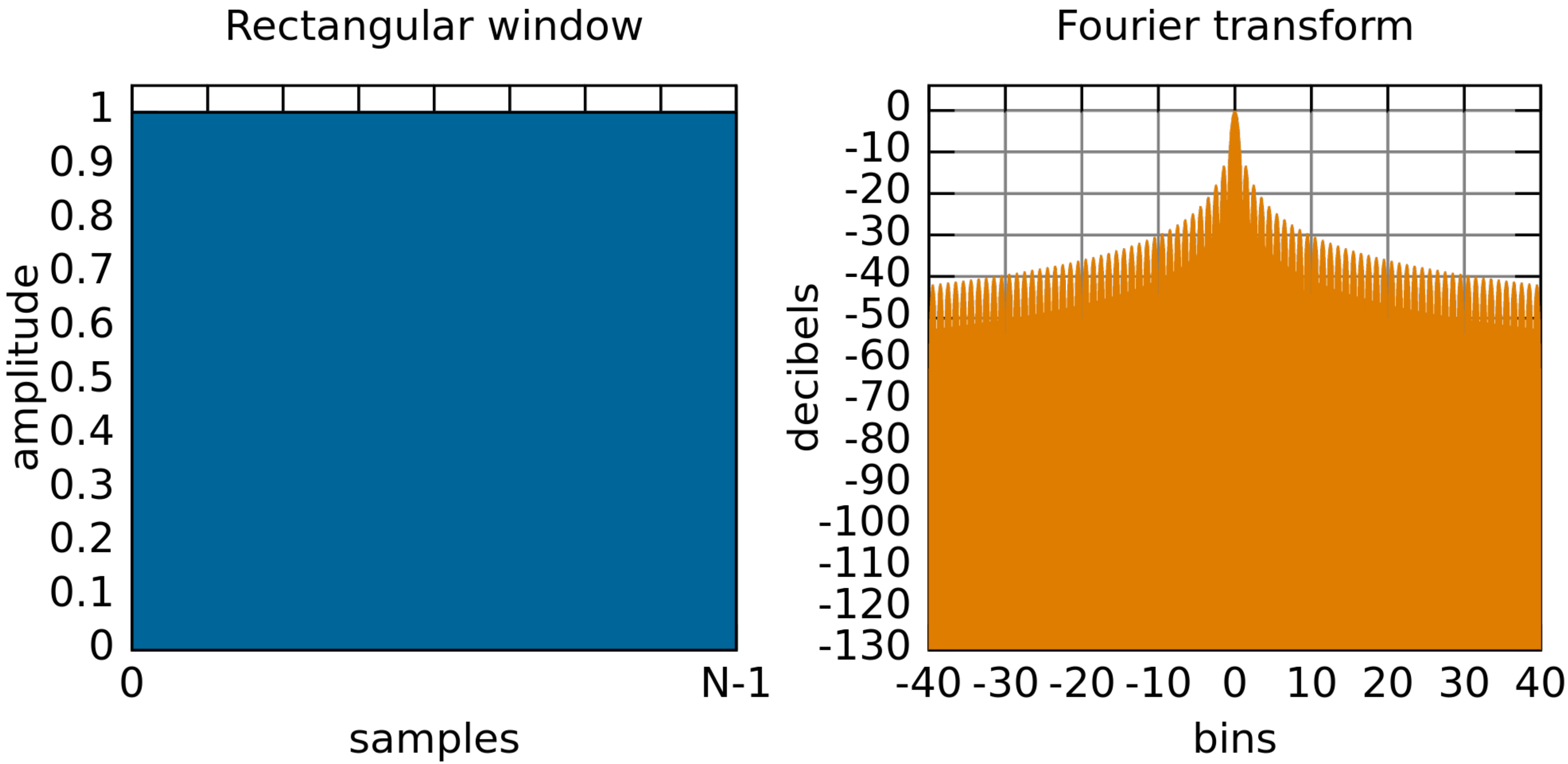
The rectangular window isn’t the only possible choice.

Name	Δ	Window
Rectangular	-13 dB	Minimum
Hamming’s	-44 dB	Normal
Tchebiceff’s	-75 dB	Maximum

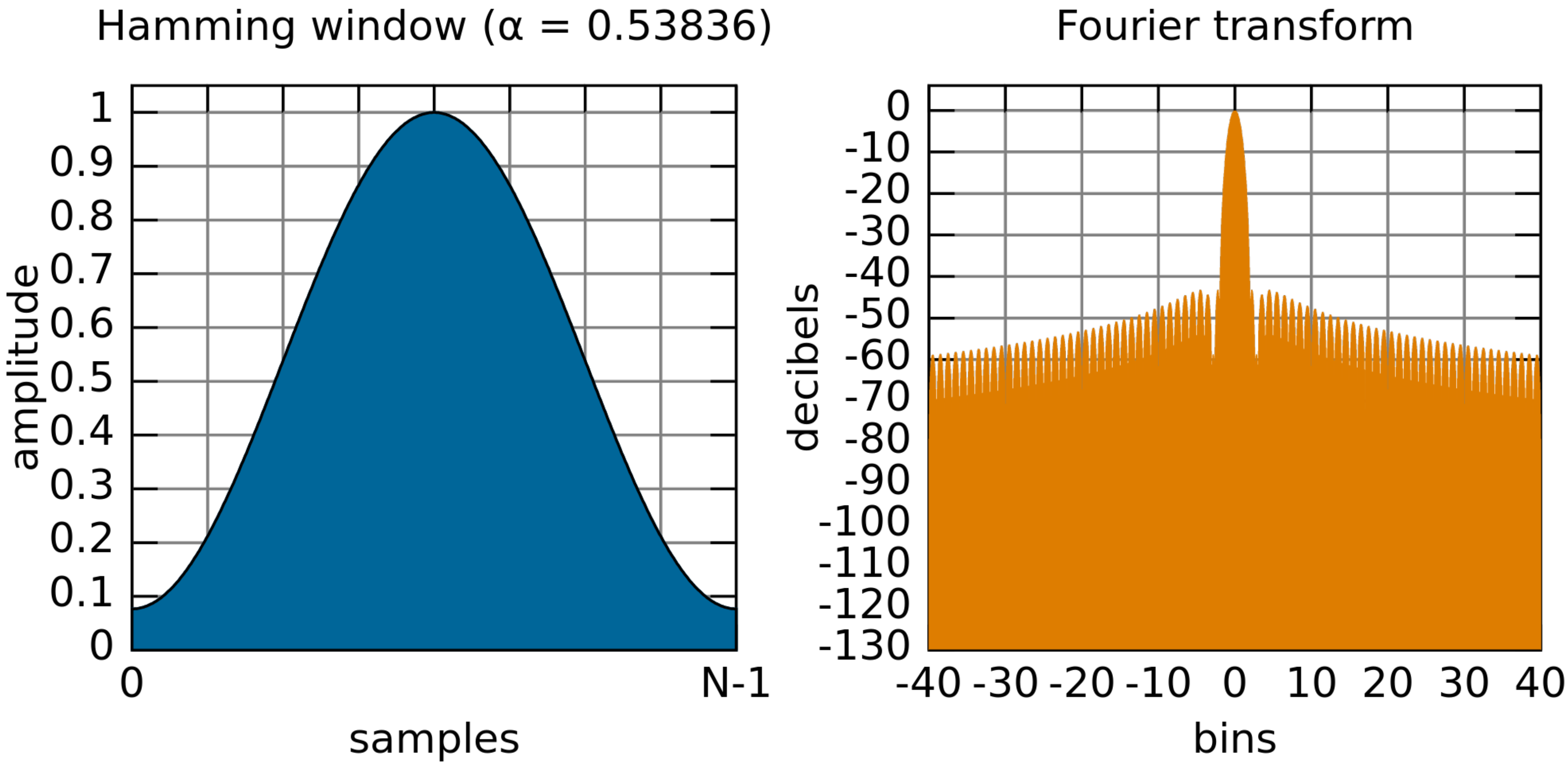
Different windows have different Δ related to better/worse BW



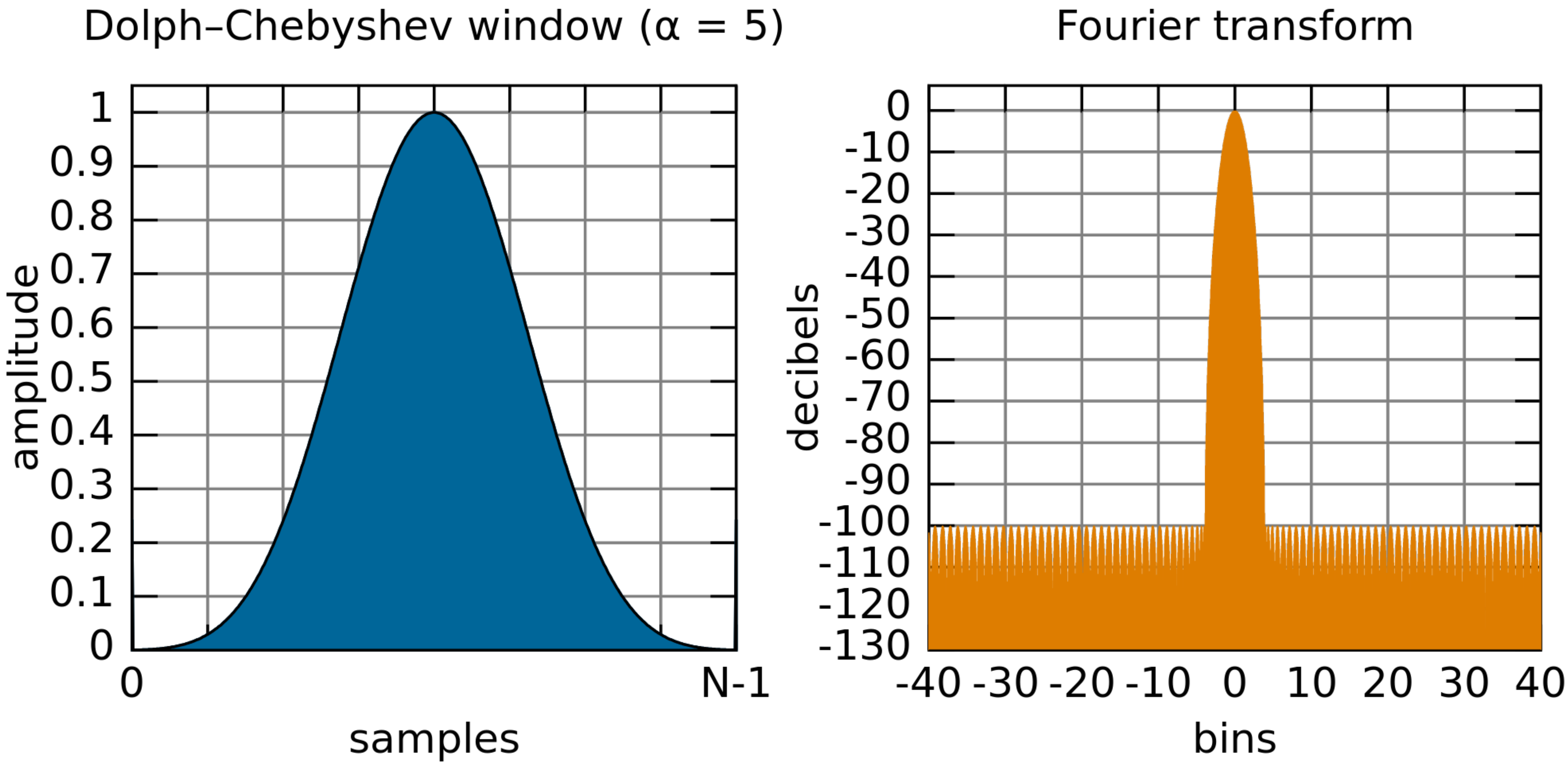




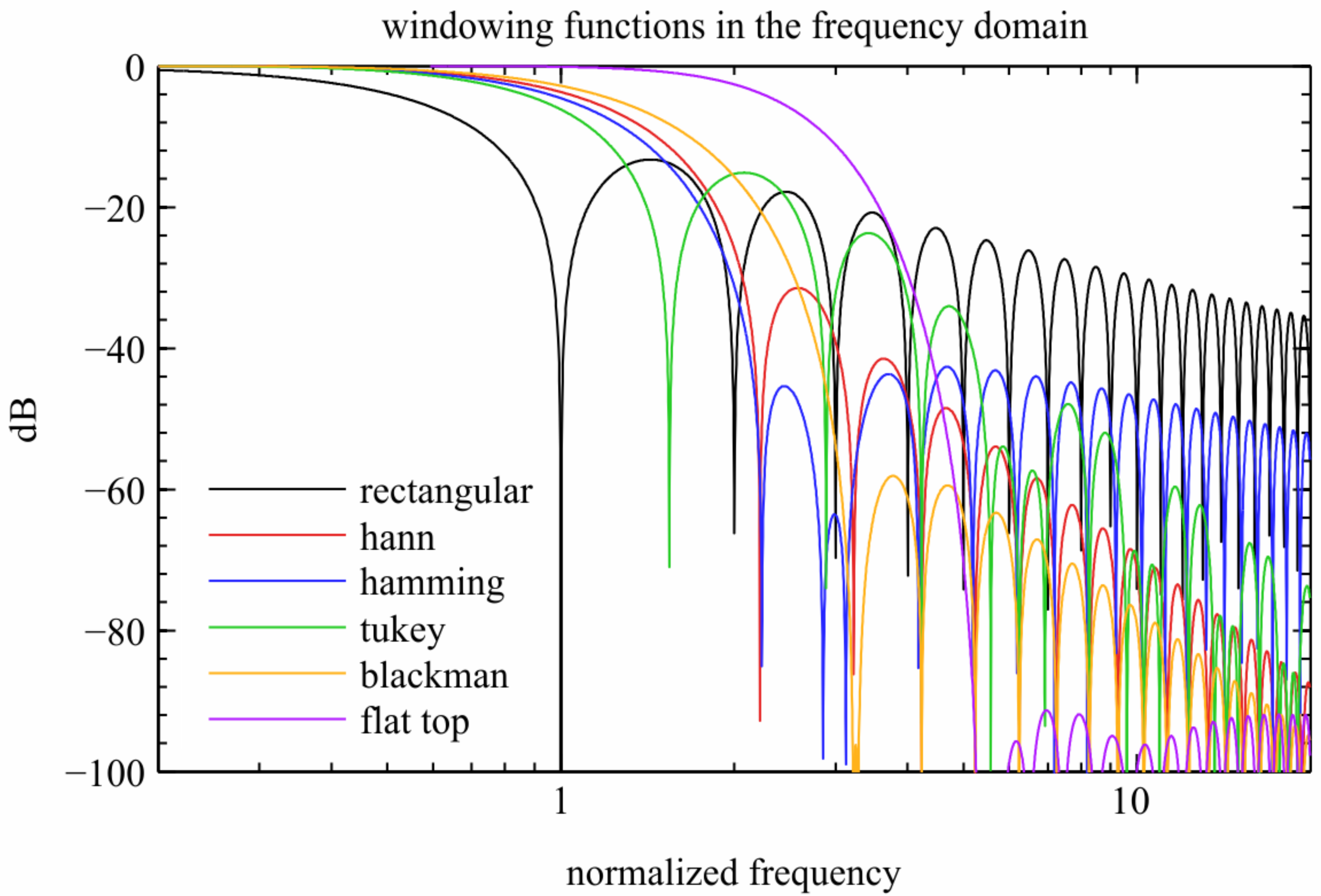
Rectangular window
amplitude
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
N-1
samples
Fourier transform
decibels
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
-110
-120
-130
-40 -30 -20 -10 0 10 20 30 40
bins



Hamming window (α = 0.53836)
amplitude
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
N-1
samples
Fourier transform
decibels
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
-110
-120
-130
-40
-30
-20
-10
0
10
20
30
40
bins



Dolph–Chebyshev window (α = 5)
amplitude
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
N-1
samples
Fourier transform
decibels
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
-110
-120
-130
-40 -30 -20 -10 0 10 20 30 40
bins



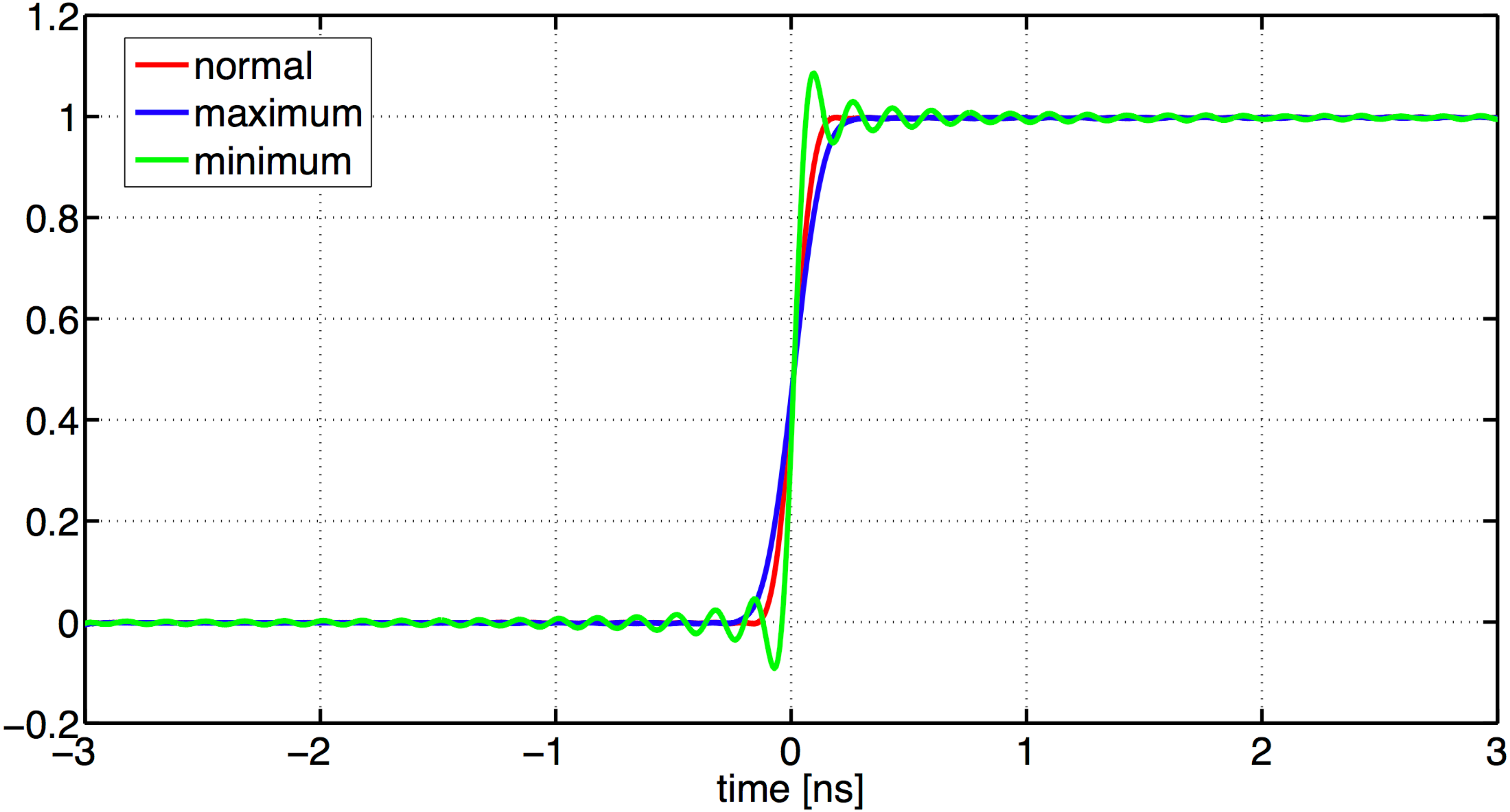
windowing functions in the frequency domain
0
−20
−40
−60
−80
−100
dB
1
10
normalized frequency
rectangular
hann
hamming
tukey
blackman
flat top

To select a window, press (System) TRANSFORM MENU WINDOW. A menu is presented that allows the selection of three window types (see Table 6-12).

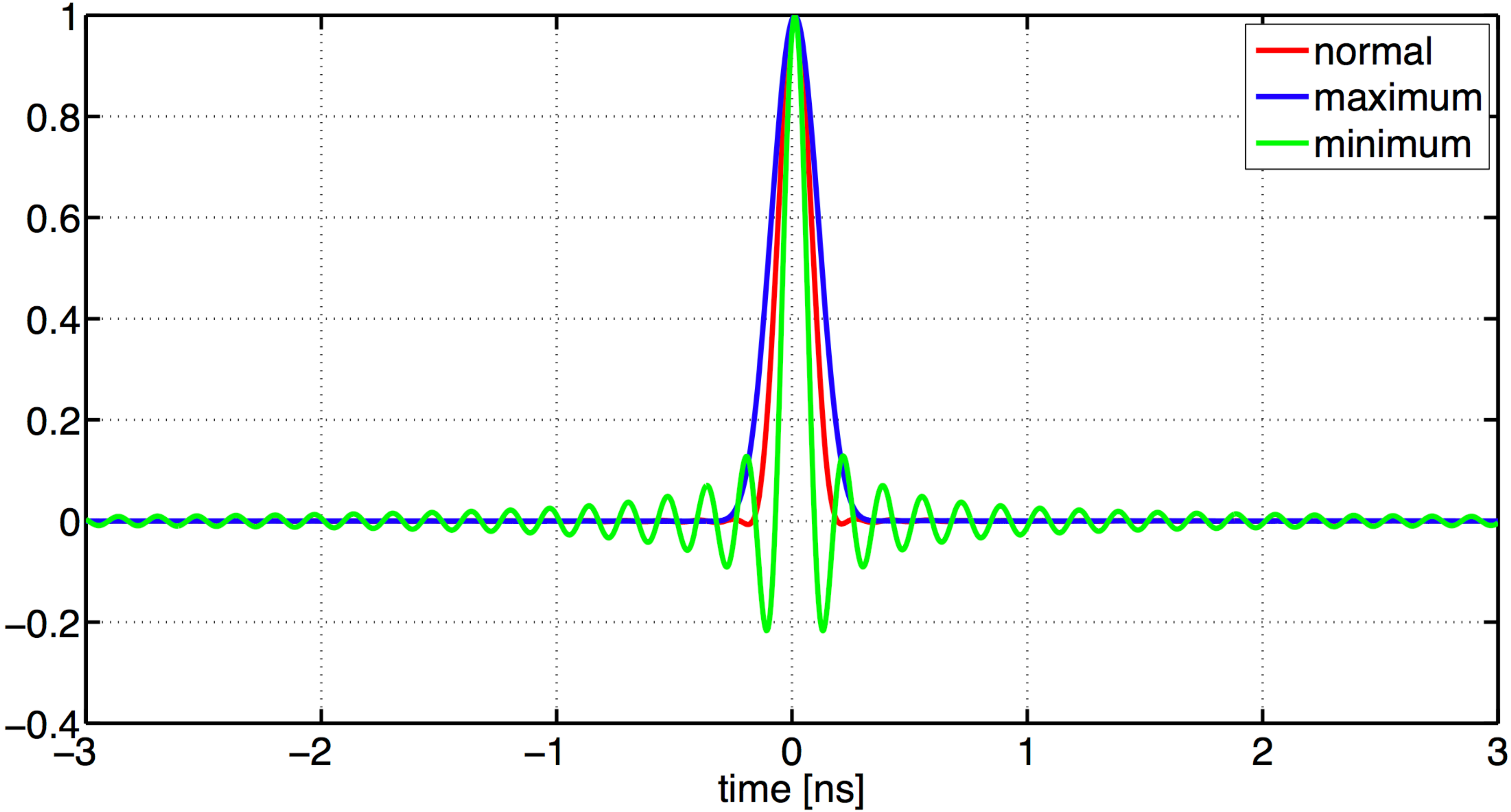
Table 6-12. Impulse Width, Sidelobe Level, and Windowing Values

Window **Type**	**Impulse Sidelobe** Level	**Low Pass Impulse** Width (50%)	**Step Sidelobe** Level	**Step Rise Time** (10 - 90%)
Minimum	**−13 dB**	**0.60/Freq** Span	-21 **dB**	**0.45/Freq** Span
Normal	**−44 dB**	**0.98/Freq** Span	-60 **dB**	**0.99/Freq** Span
Maximum	-75 **dB**	**1.39/Freq** Span	-70 **dB**	**1.48/Freq** Span

NOTE: The **bandpass** mode simulates an impulse **stimulus. Bandpass** impulse width is twice that of low pass impulse width. The **bandpass** impulse **sidelobe** levels are the same as low pass impulse **sidelobe** levels.



normal
maximum
minimum
1.2
1
0.8
0.6
0.4
0.2
0
−0.2
−3
−2
−1
0
1
2
3
time [ns]


1
0.8
0.6
0.4
0.2
0
−0.2
−0.4
−3
−2
−1
0
1
2
3
time [ns]
normal
maximum
minimum

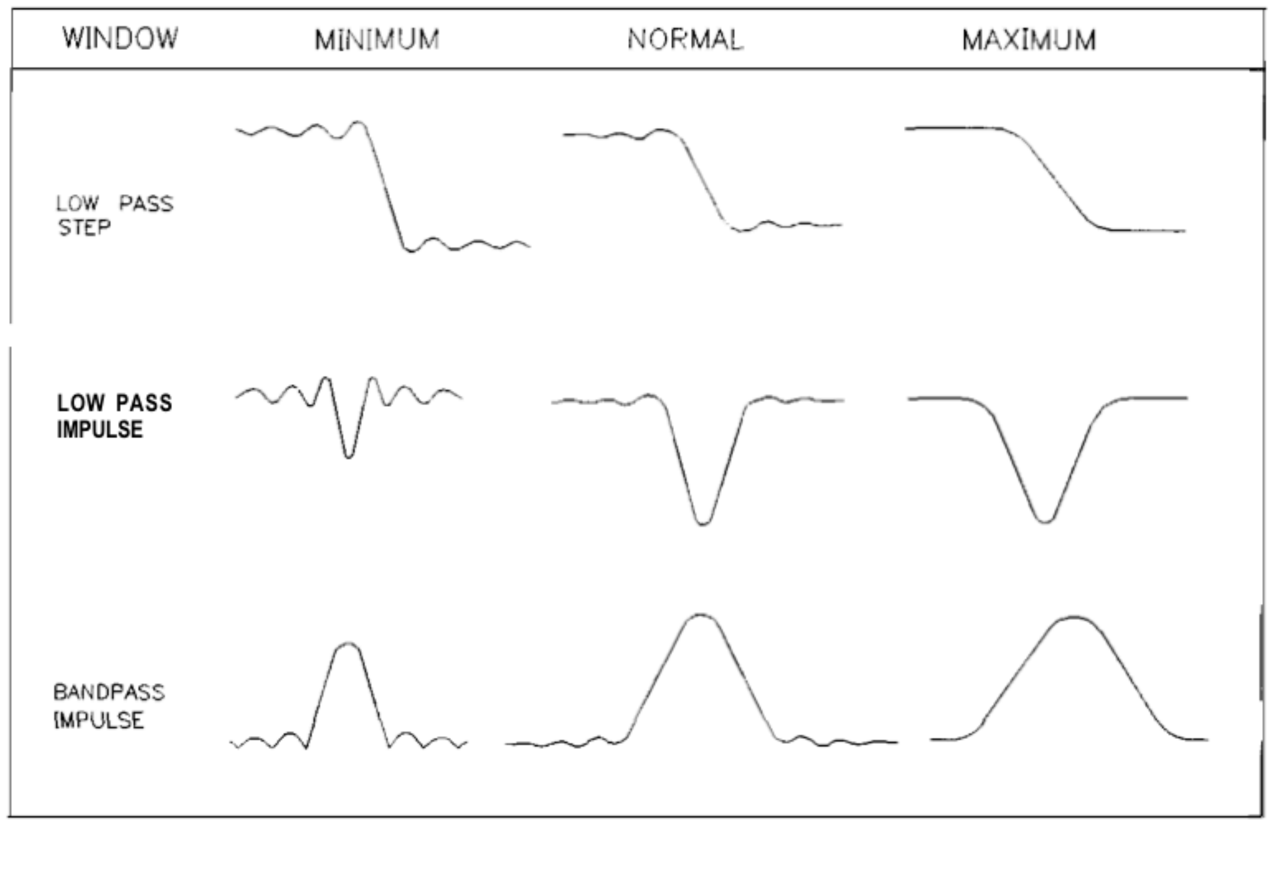


Figure 6-72. The Effects of Windowing on the Time Domain Responses of a Short Circuit

Can we measure the window used?

The pulse response to open or short loads is the FFT of the window being used

Summary

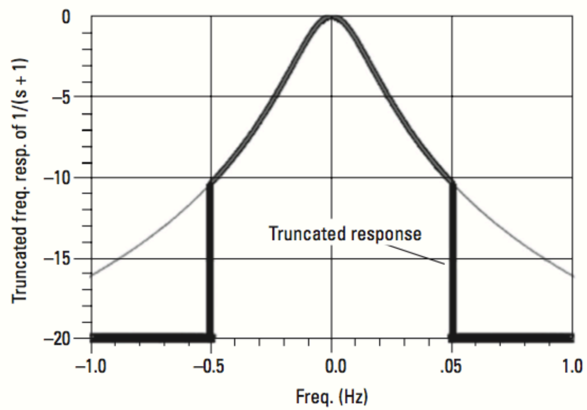


Figure 4a. Sample of truncated response in frequency domain.

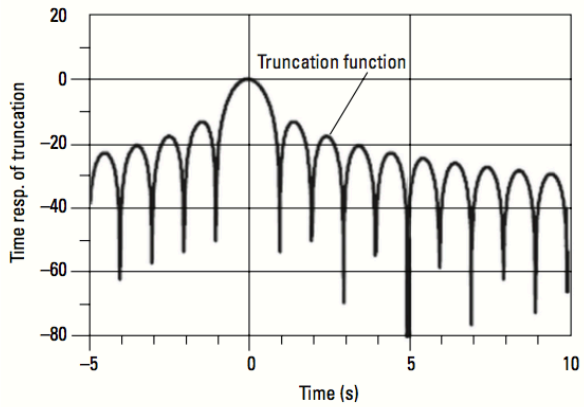


Figure 4b. Truncation causes ringing in time domain.

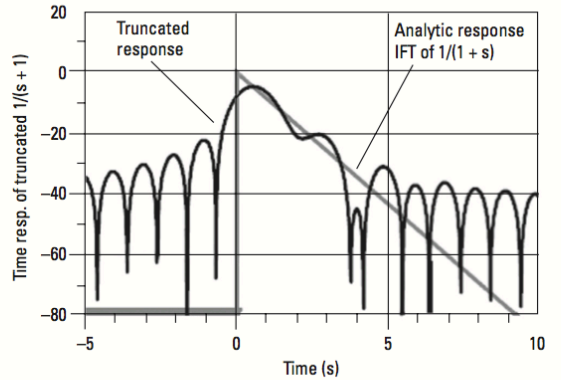


Figure 4c. Comparing truncated time response to the unit step function.

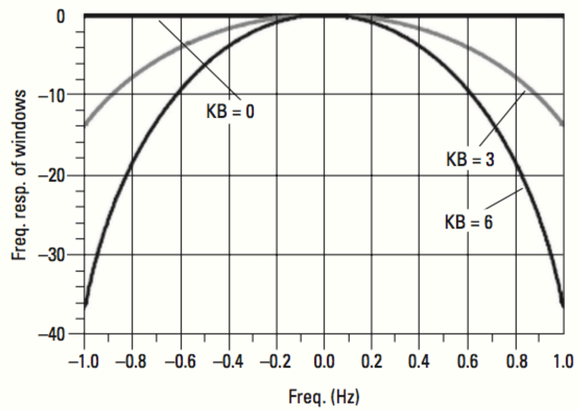


Figure 5a. Applying windowing functions with different β values. Higher values of β reduce the height of the sidelobes. (KB stands for Kaiser-Bessel and is a commonly used window function.)

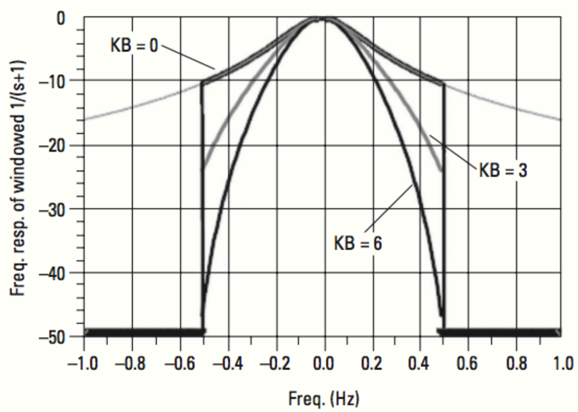


Figure 5b. Windowing functions applied to a 1-pole filter response.

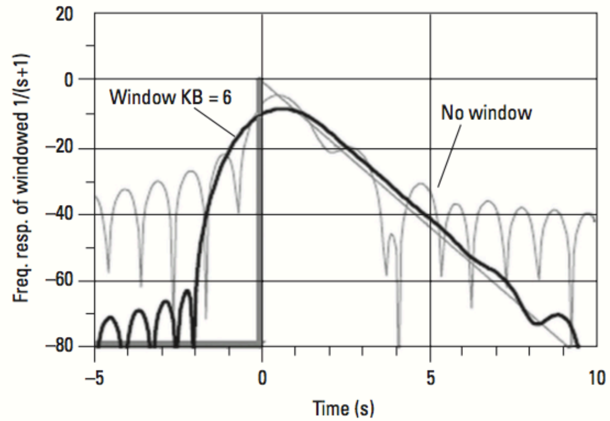
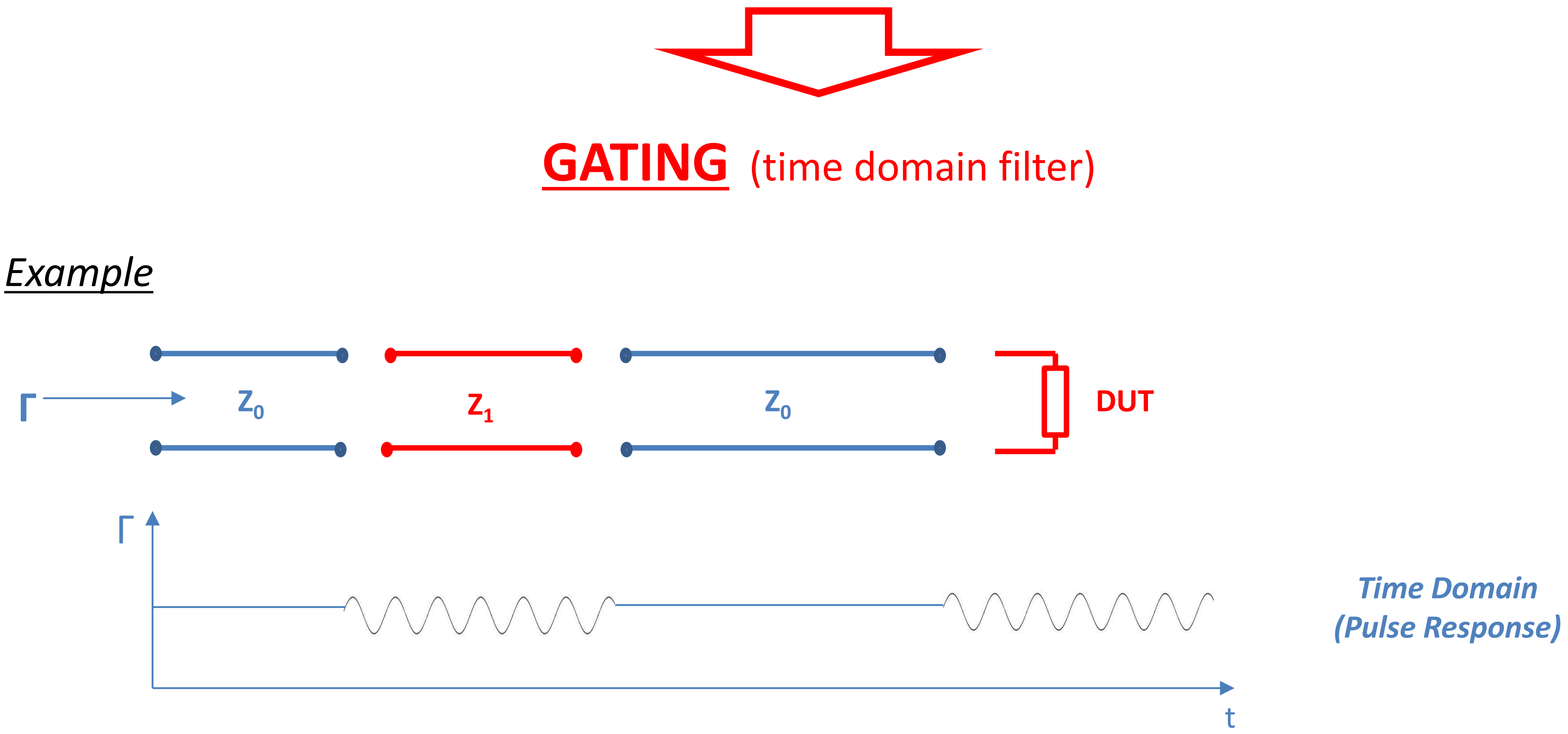


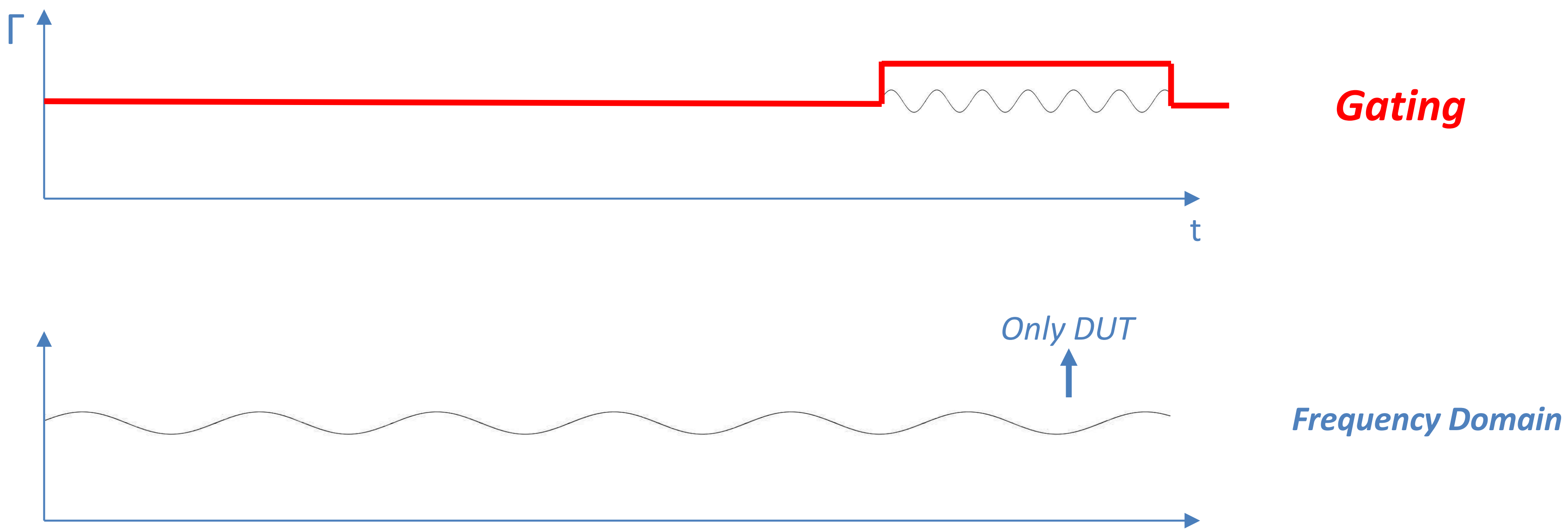
Figure 5c. Time response of windowed functions and the unit step function.

6) it's possible to identify, in time domain, the part of response I'm iterested in.

GATING (time domain filter)

Example





Inconvenience:

Gating decreases signal's power ⇒ **Lower SNR**

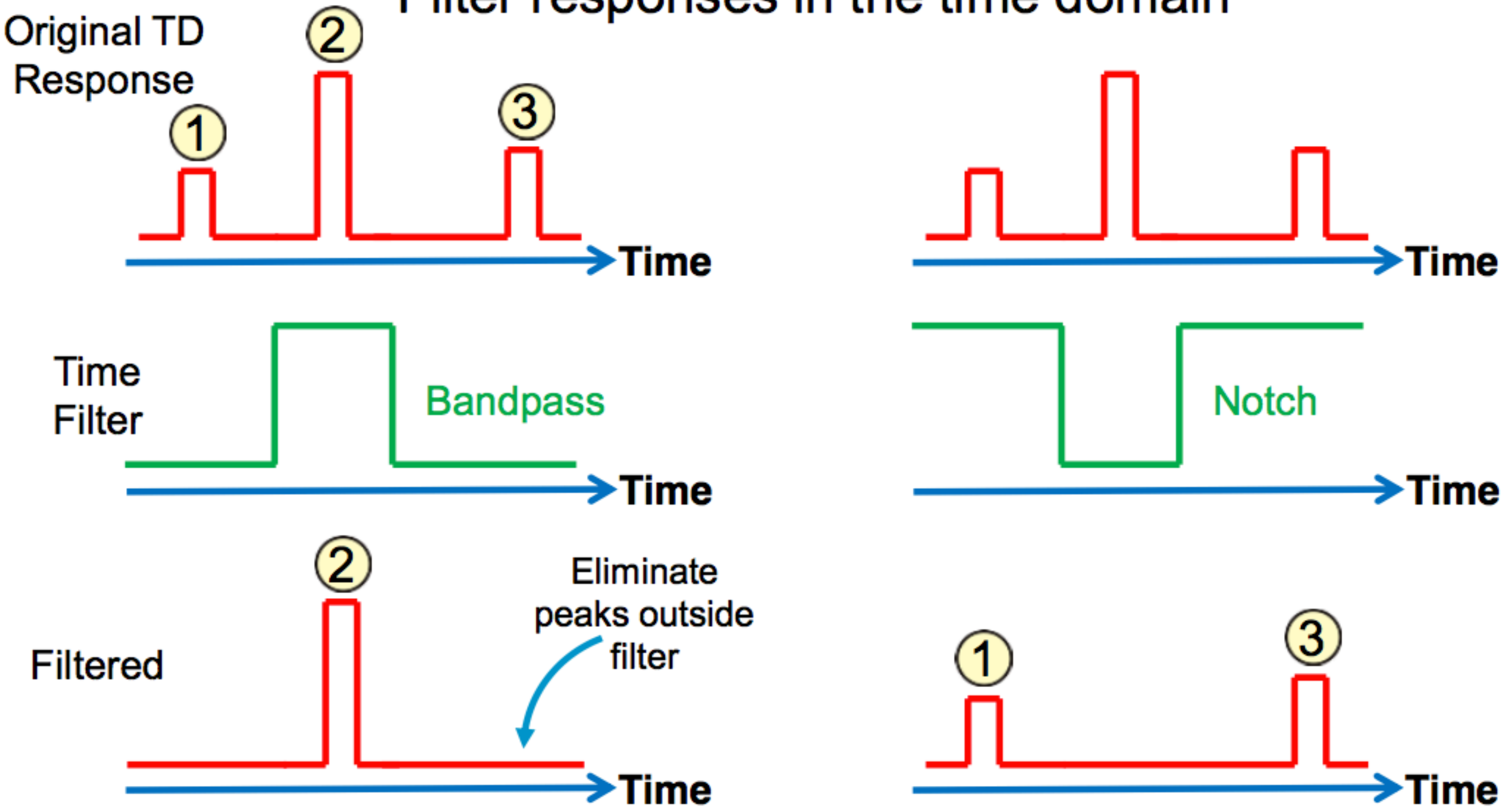
General example: an attenuator will attenuate more than expected

Table 6-13. Gate Characteristics

Gate Shape	Passband Ripple	Sidelobe Levels	Cutoff Time	Minimum Gate span
Gate Span Minimum	±0.10 dB	−48 dB	1.4/Freq Span	2.8/Freq Span
Normal	● 0.01 dB	-68 dB	2.8/Freq Span	5.6/Freq Span
Wide	±0.01 dB	-57 dB	4.4/Freq Span	8.8/Freq Span
Maximum	±0.01 dB	-70 dB	12.7/Freq Span	25.4/Freq Span

Time Gating

Filter responses in the time domain

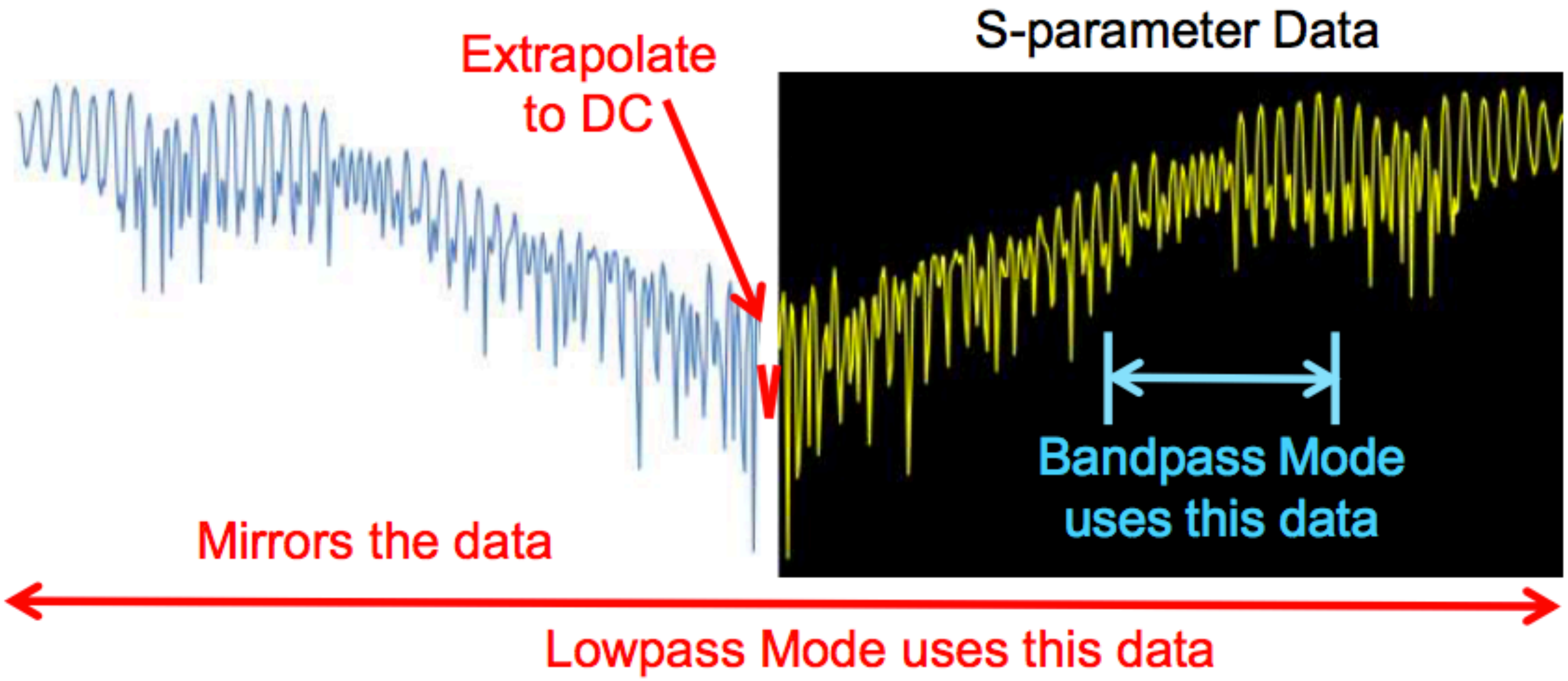


Lowpass Mode

- Coaxial Cables
- Coaxial Adapters

Bandpass Mode

- Waveguide Components
- Couplers
- Filters
- Antennas



LOW PASS STEP

LOW PASS PULSE

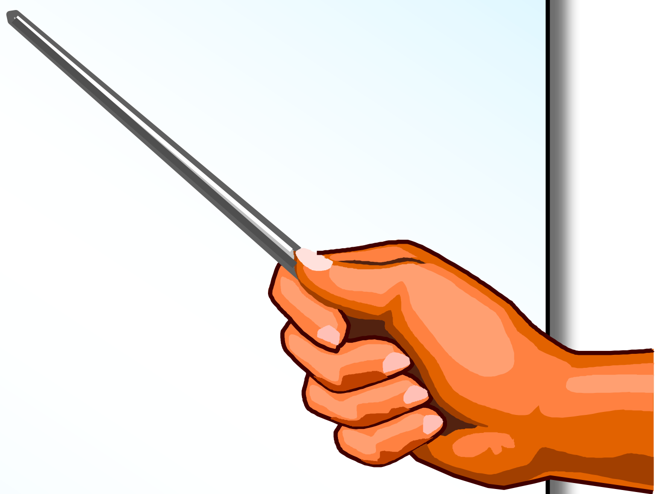
BAND PASS

- Used for band pass devices
- Sign and amplitude of ρ isn’t always easy to understand
- Used for **gating**

	LOW-PASS	BANDPASS
	Simula la TDR tradizionale	Analisi nel dominio del tempo per dispositivi a banda stretta
	Frequenza di inizio dipende dalla freq. massima e dal numero dei punti di misura	Scopi più generali
	Risoluzione doppia rispetto alla modalità BAND PASS	
Eccitazione a gradino (*step response*)	Ideale per identificare discontinuità (distanza e tipo) in dispositivi che supportano la componente DC	
Eccitazione ad impulso (*impulse response*)	Ideale per osservare piccole risposte in dispositivi che supportano la componente DC	Ideale per misurare dispositivi con banda limitata come filtri. Utile anche per localizzare guasti (non la tipologia), specialmente in sistemi che non supportano la frequenza nulla

Ten Steps for Performing TDR (Low Pass Step)

1. Set up desired frequency range (need wide span for good spatial resolution)
2. Under SYSTEM, transform menu, press "set freq low pass“
3. Perform one- or two-port calibration
4. Select S11 measurement *
5. Turn on transform (low pass step) *
6. Set format to real *
7. Adjust transform window to trade off rise time with ringing and overshoot *
8. Adjust start and stop times if desired
9. For gating:
   - set start and stop frequencies for gate
   - turn gating on *
   - adjust gate shape to trade off resolution with ripple *
10. To display gated response in frequency domain
    - turn transform off (leave gating on) *
    - change format to log-magnitude *

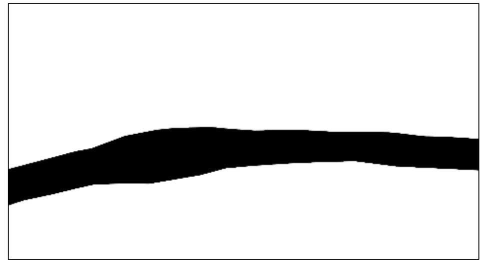


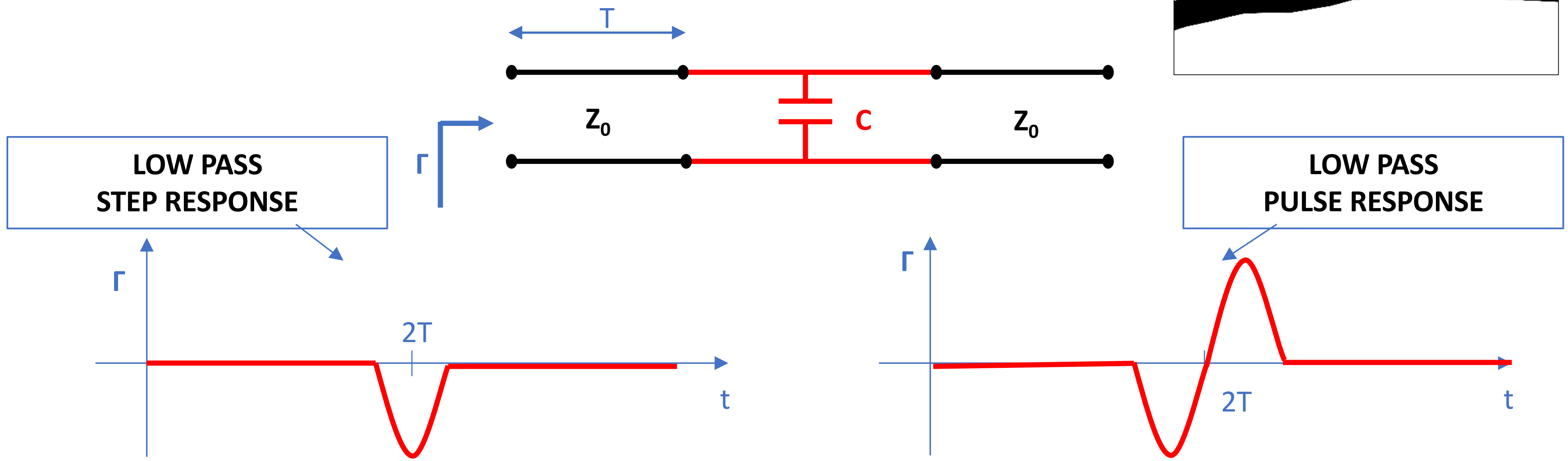
* *If using two channels (even if coupled), these parameters must be set independently for second channel*

EXERCISES

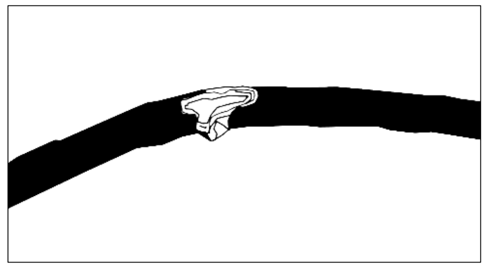
Fault location

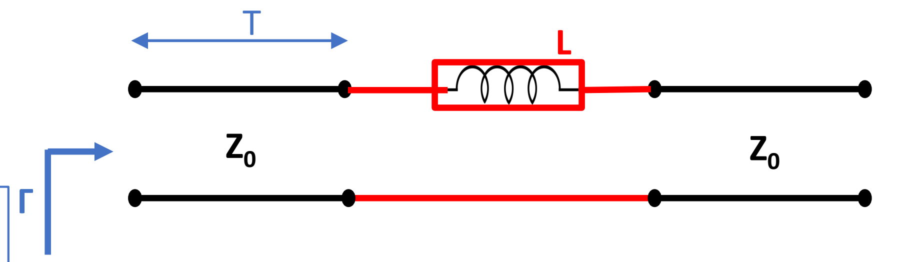
Capacity variation (Folded cable)

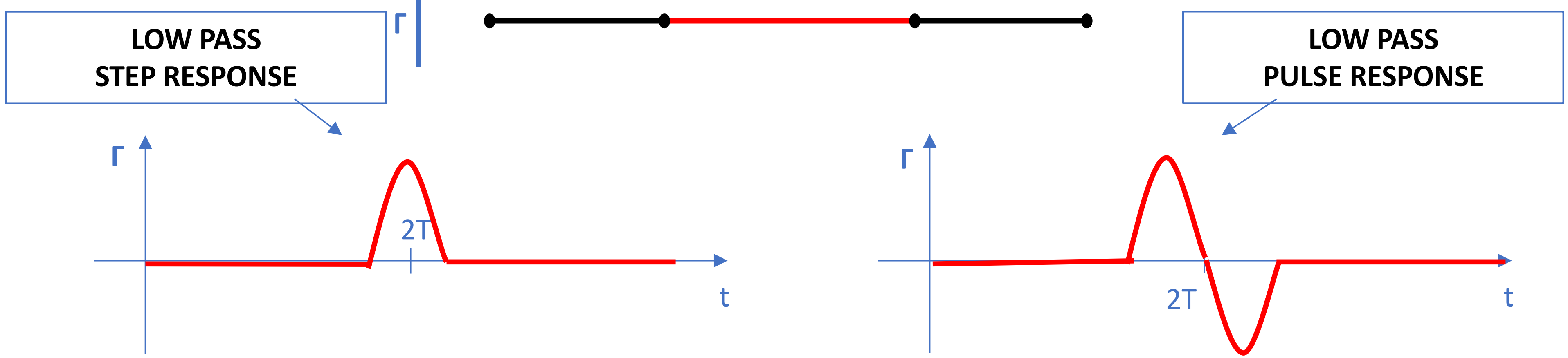




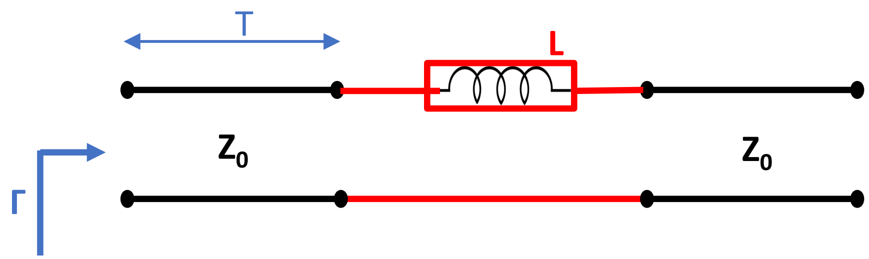
Inductance variation (Frayed cable)



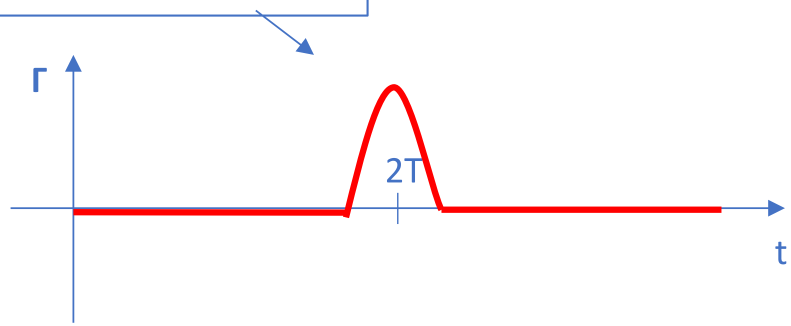




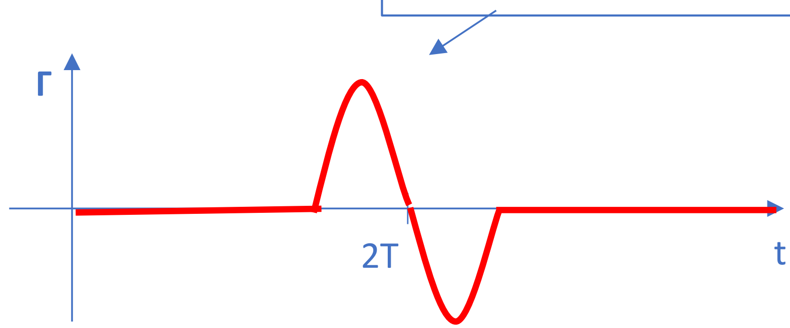
Inductance variation (Frayed cable)



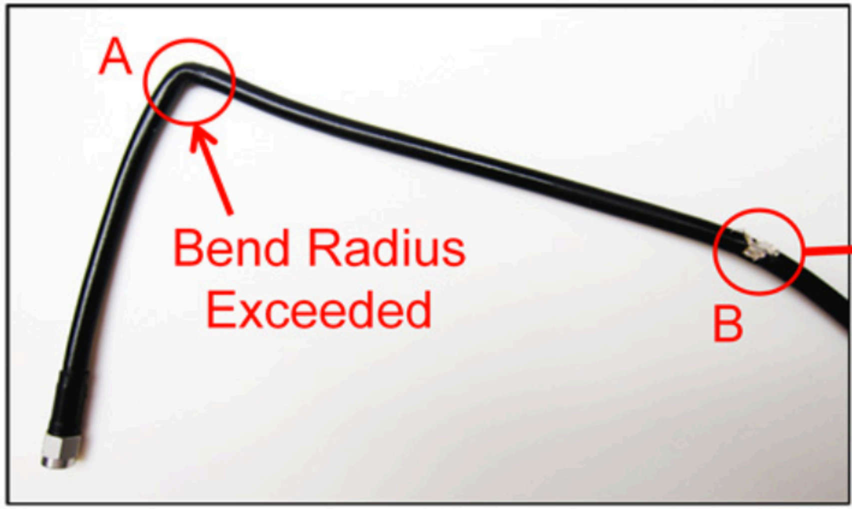
LOW PASS
STEP RESPONSE

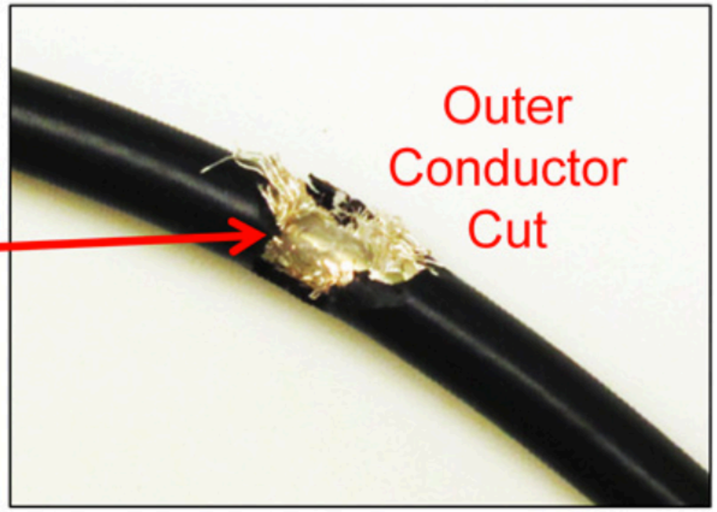


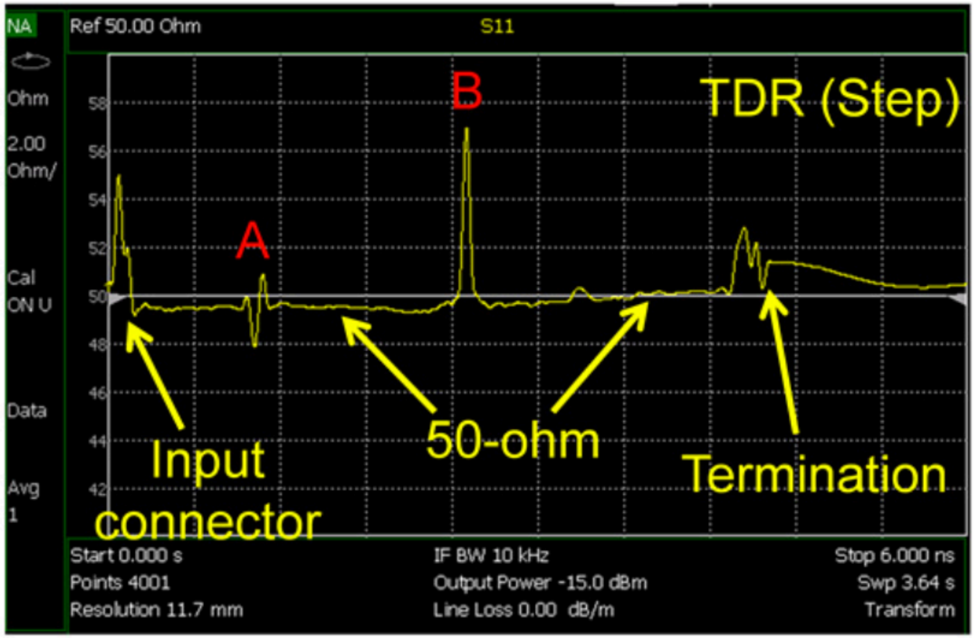
LOW PASS
PULSE RESPONSE

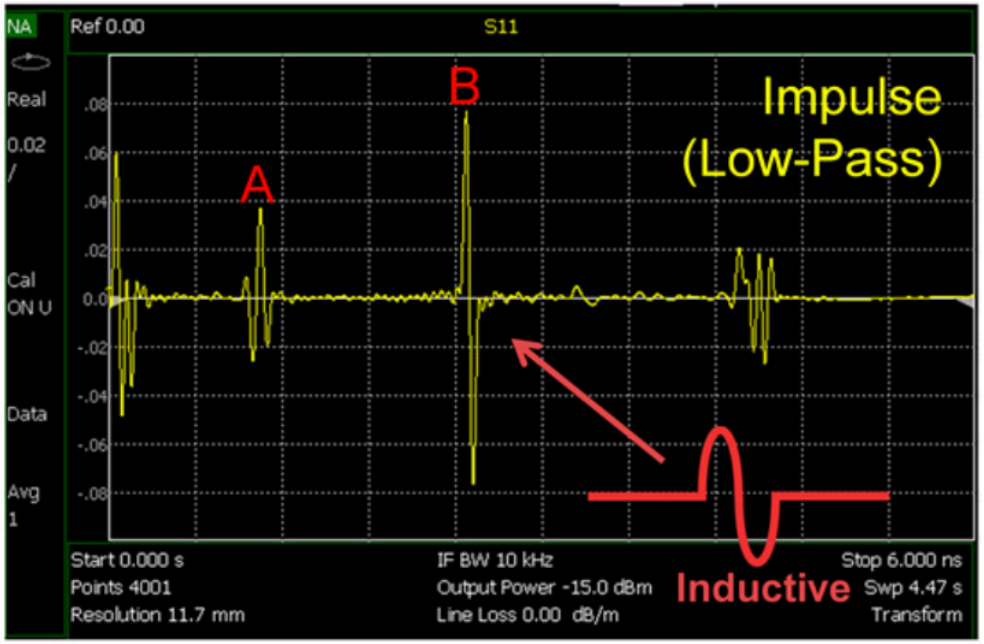


TDR and Impulse Response

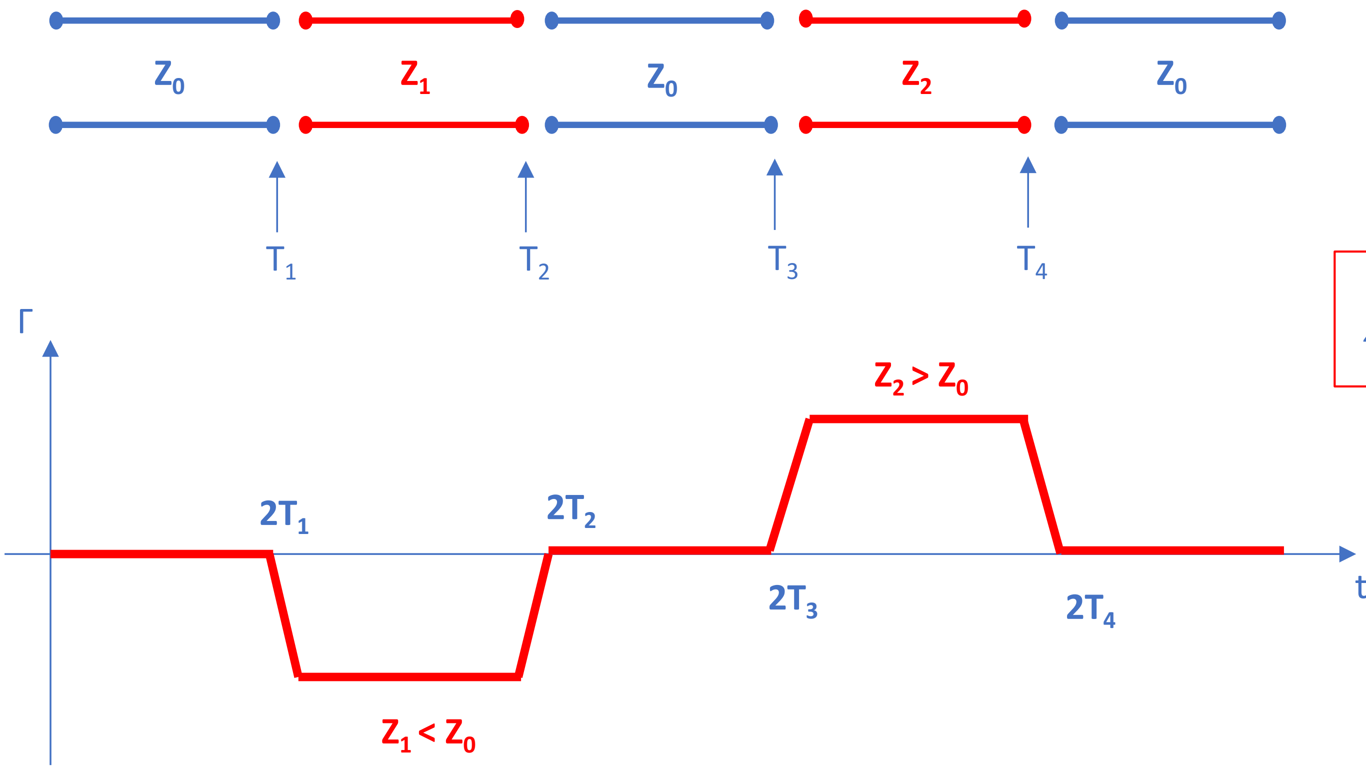






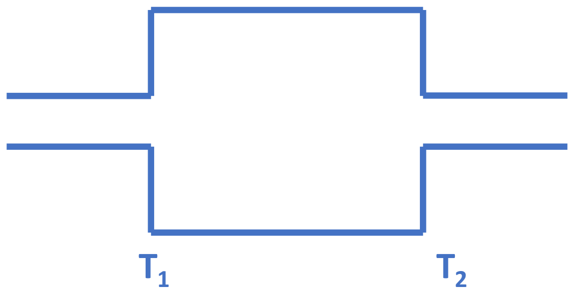


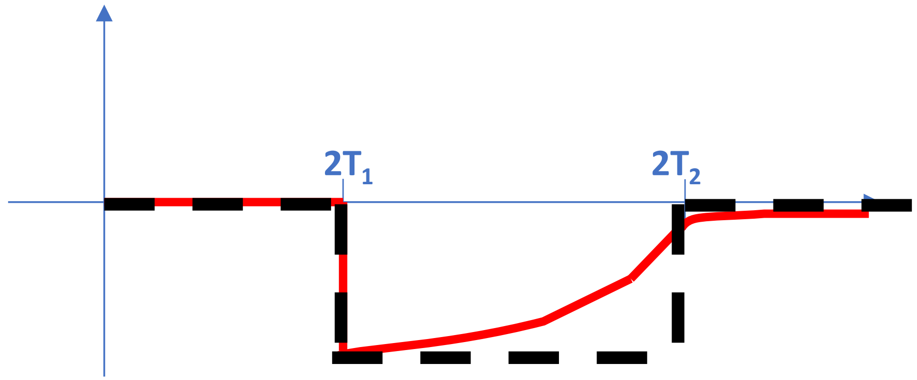
Impedance measurement as a function of Z



$$Z(t) = Z(x) = Z_0 \frac{1 + \Gamma}{1 - \Gamma}$$

Example: Microstripes





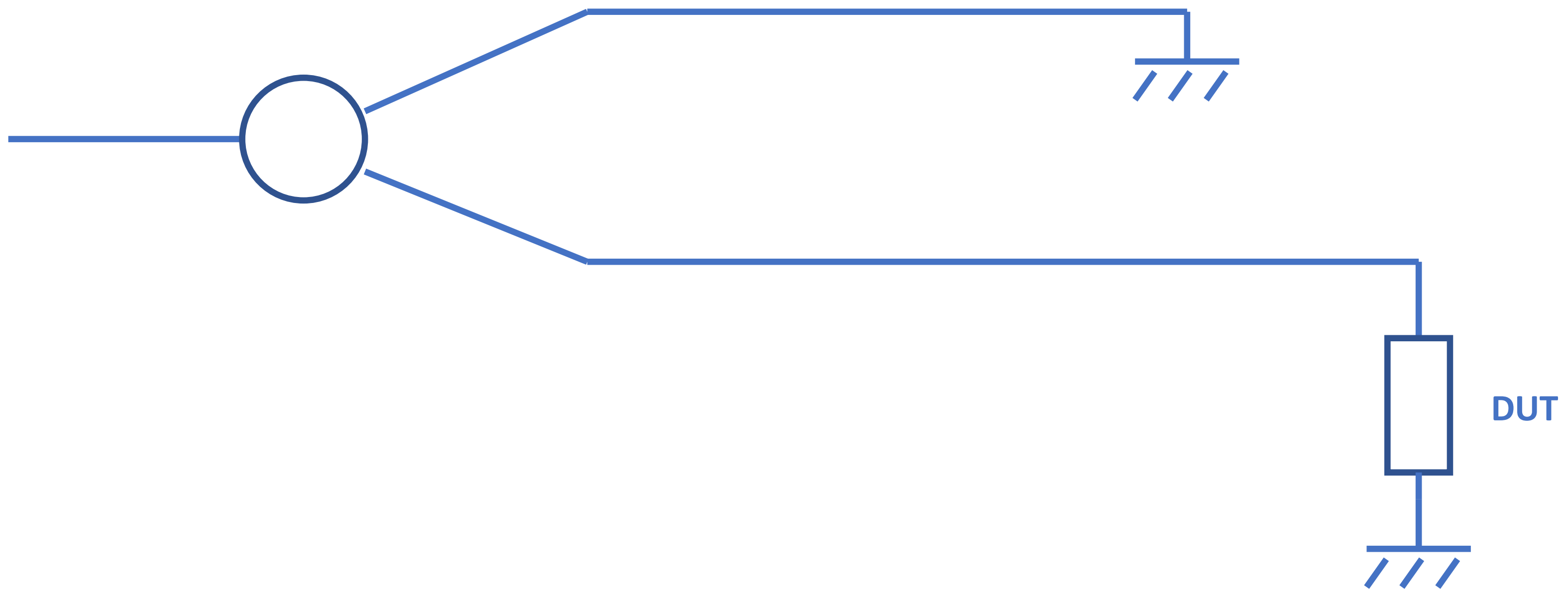
Nonideality:

1) The function doesn't end at zero (attenuation, energy loss, reflections)

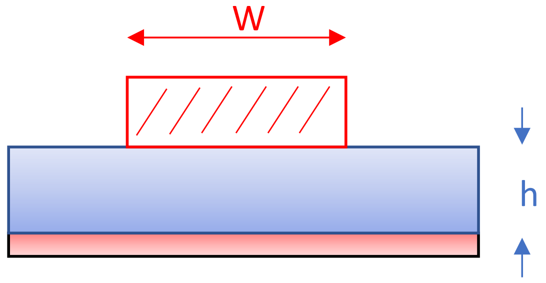
2) Second rise time is slower (dispersion, sharp corner are capacitive and cut high frequencies)

To have Z(x) you need to calculate the velocity

Gating

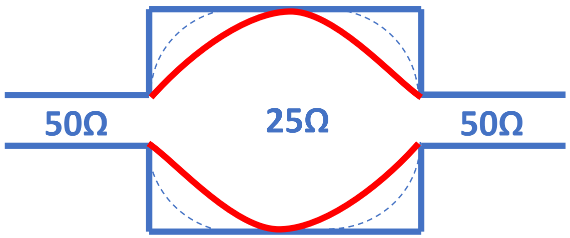


Microstipes

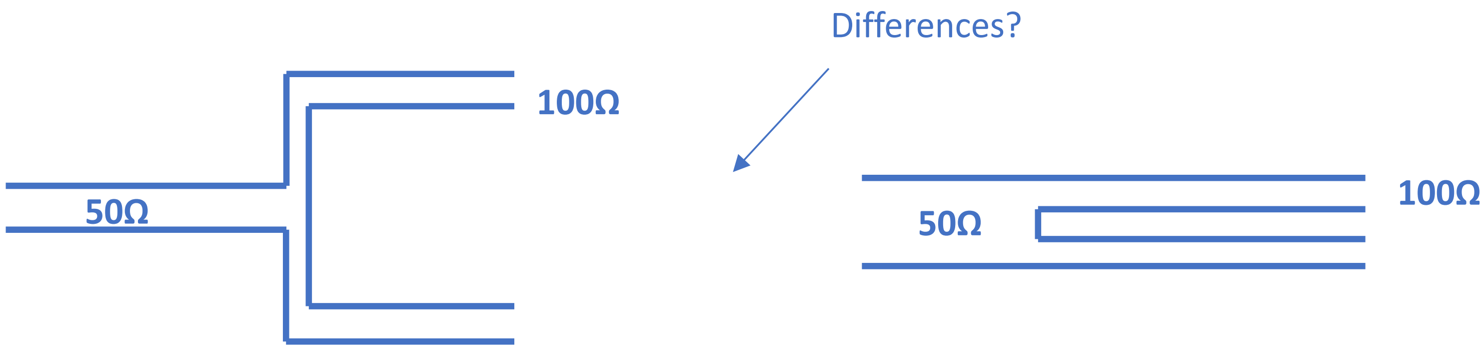


Impedances Various $\frac{W}{h}$

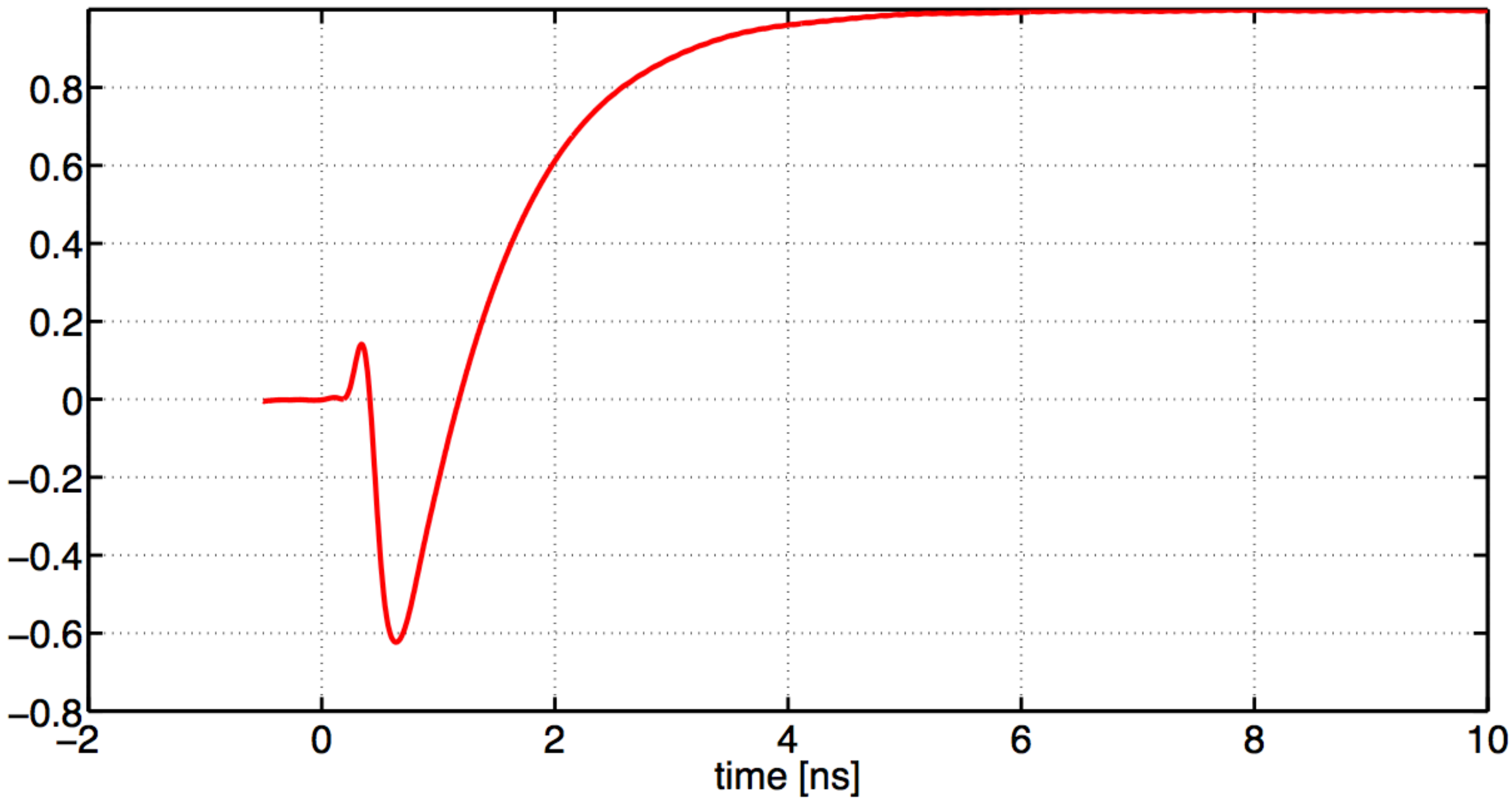
Taper



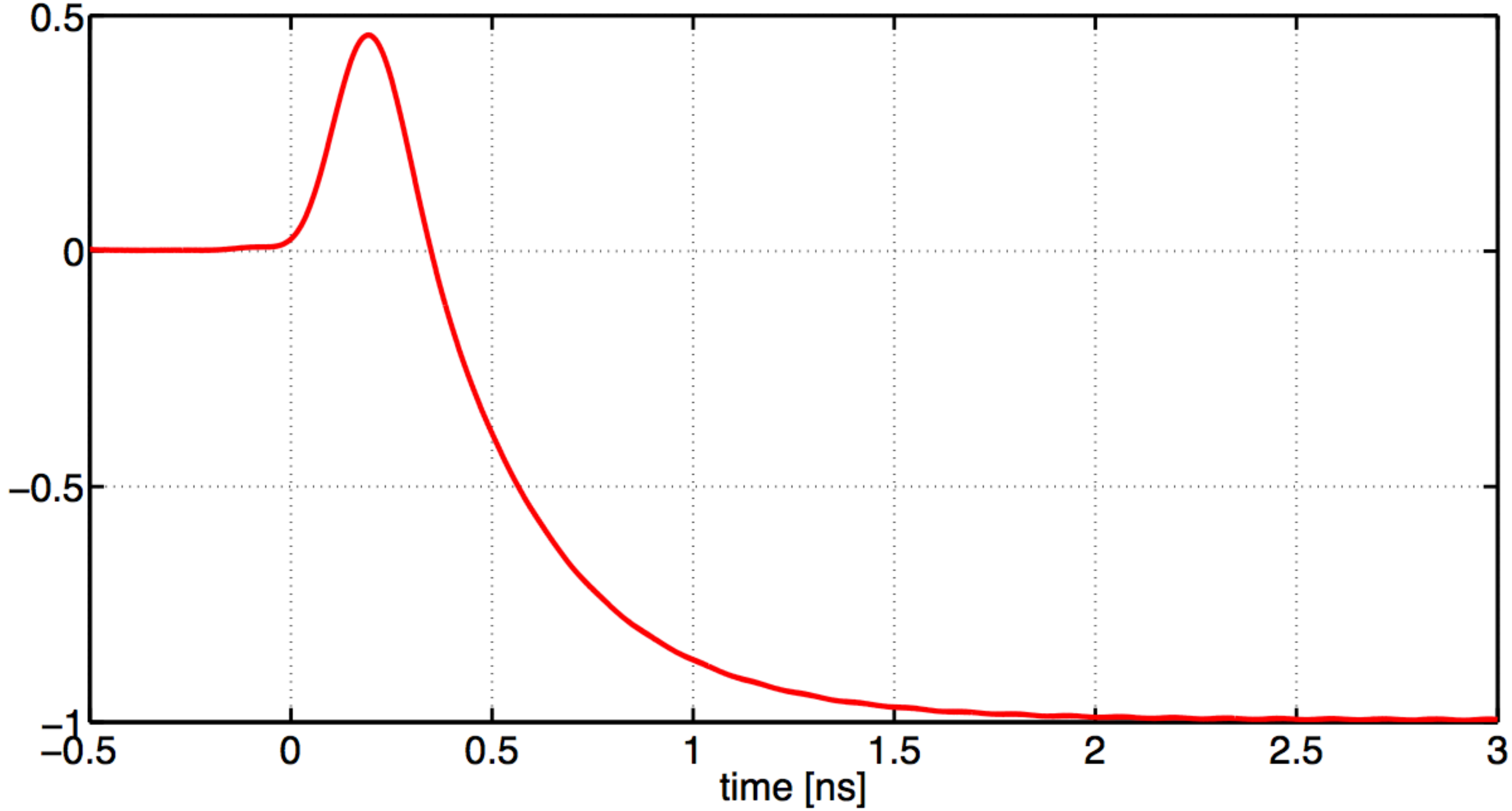
Cross-Talk

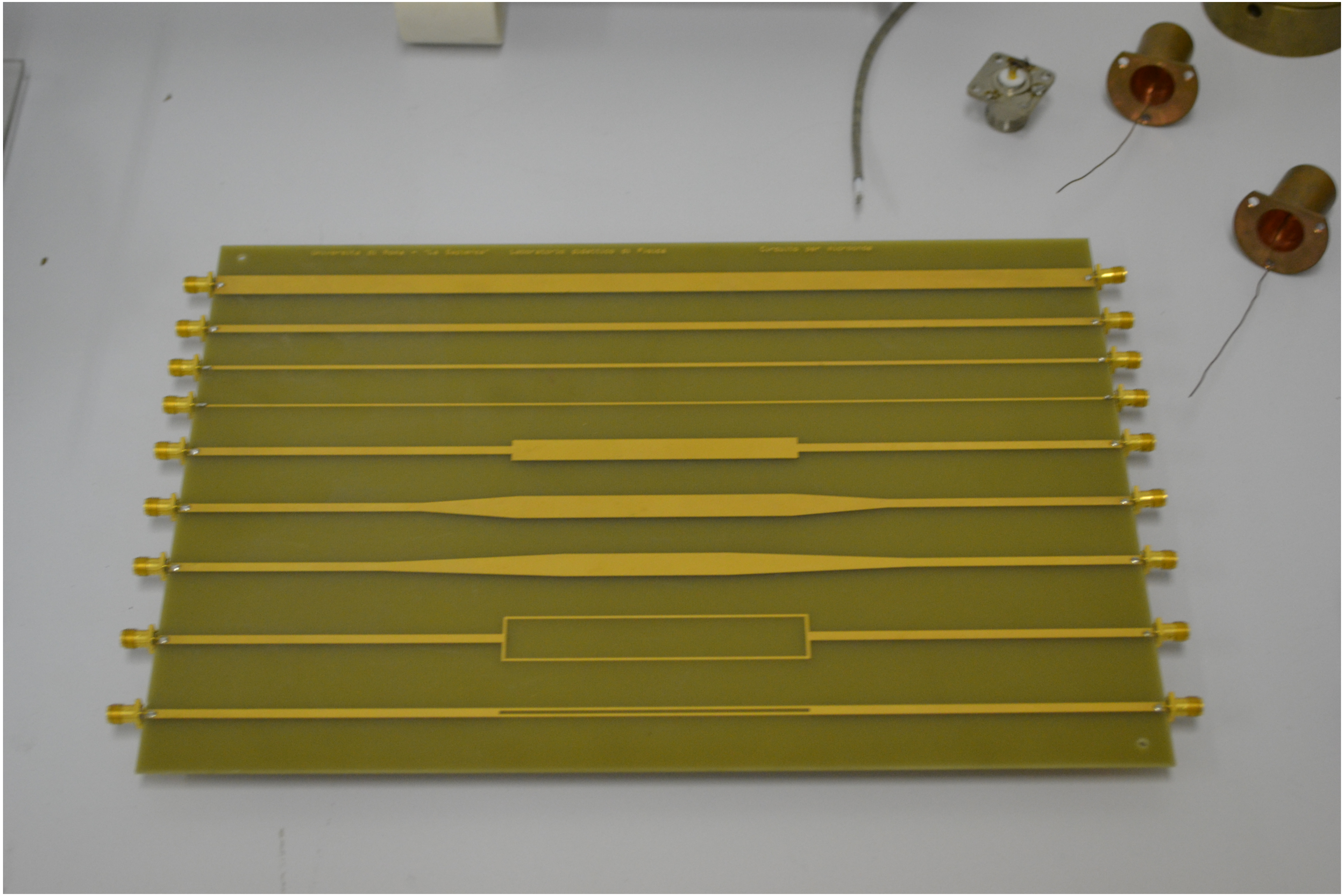


20 pF CAPACITOR

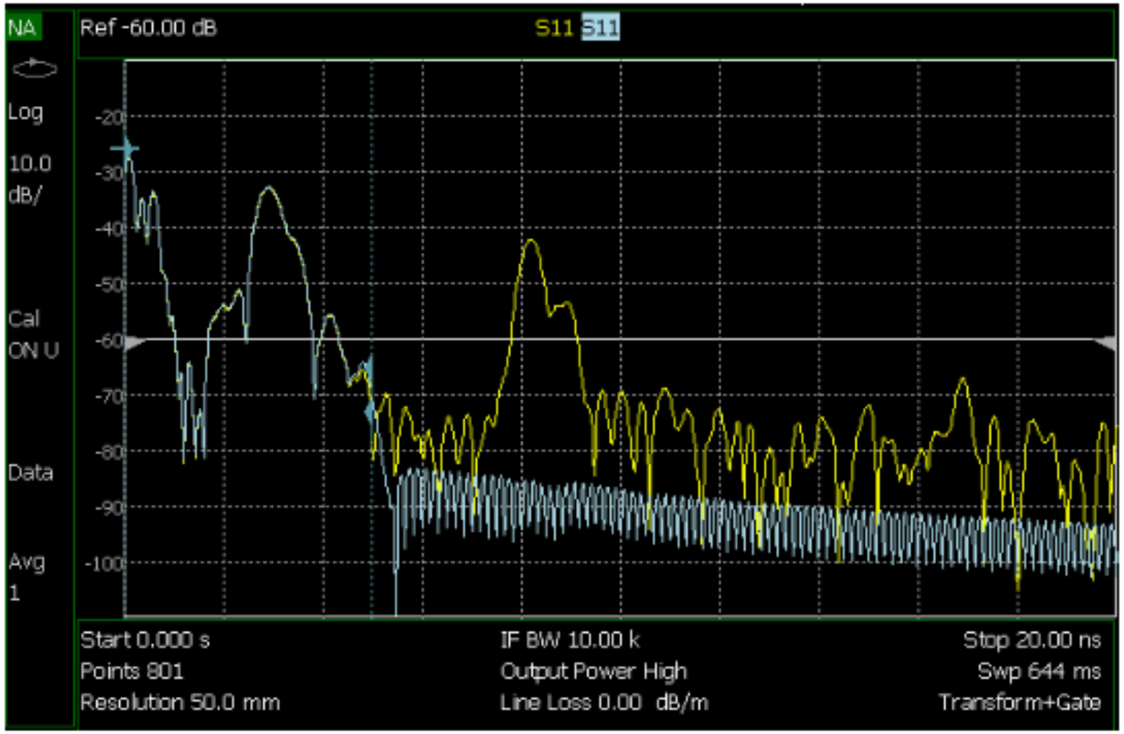


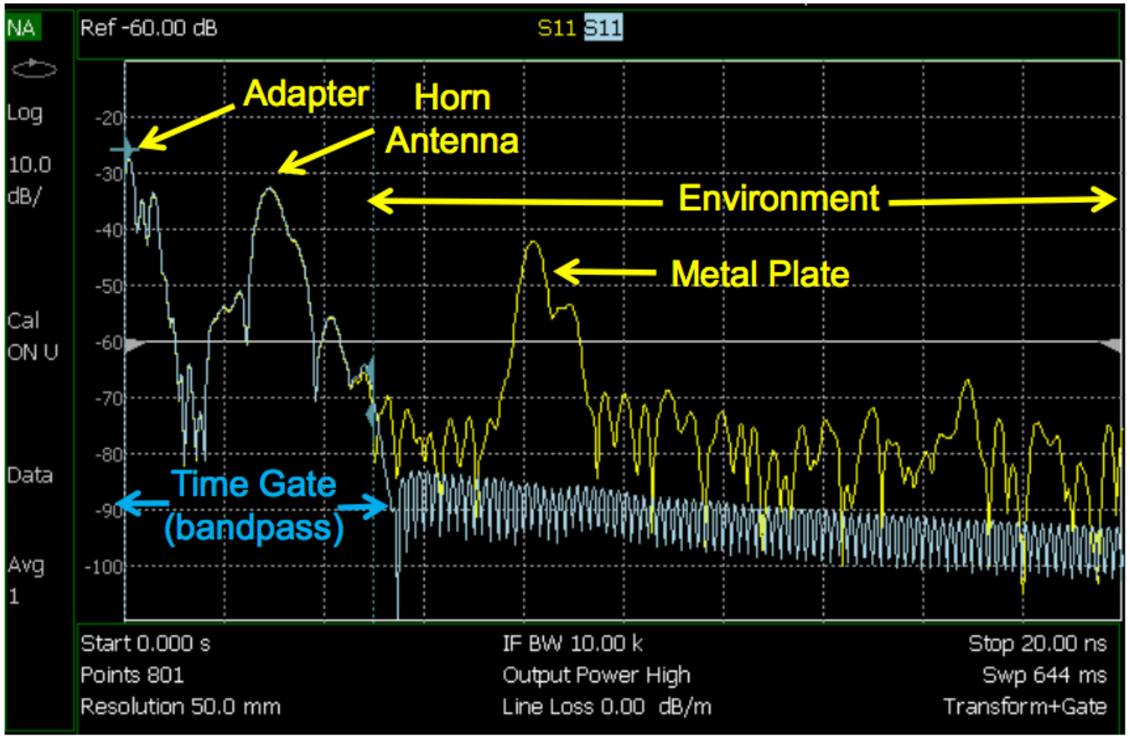
19 nH INDUCTANCE

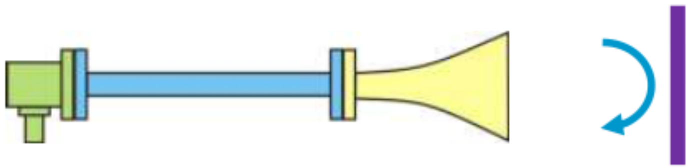




APPLICATIONS

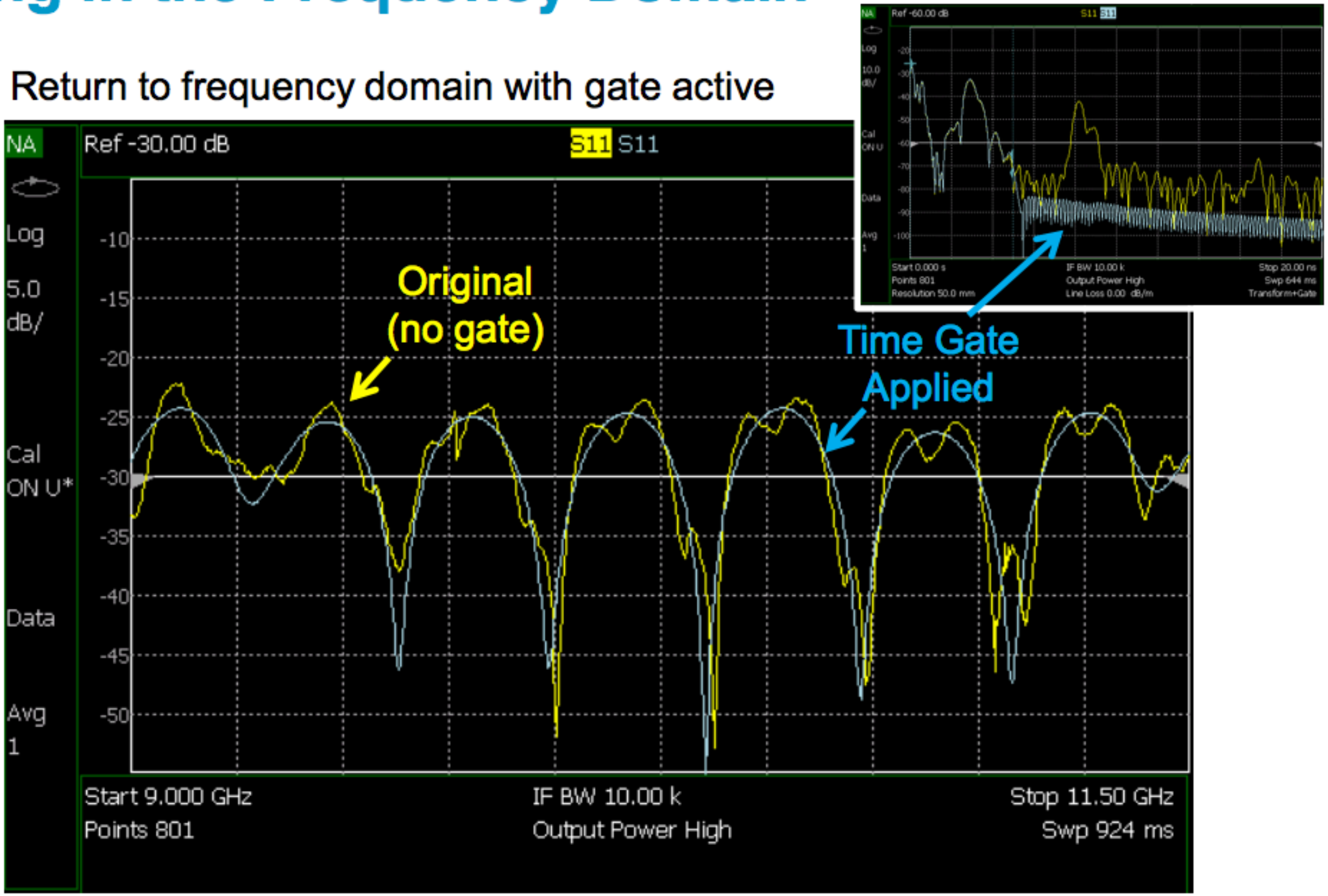

NA
Ref -60.00 dB
S11 S11
Log
10.0
dB/
Cal
ON U
Data
Avg
1
-20
-30
-40
-50
-60
-70
-80
-90
-100
Start 0.000 s
Points 801
Resolution 50.0 mm
IF BW 10.00 k
Output Power High
Line Loss 0.00 dB/m
Stop 20.00 ns
Swp 644 ms
Transform+Gate

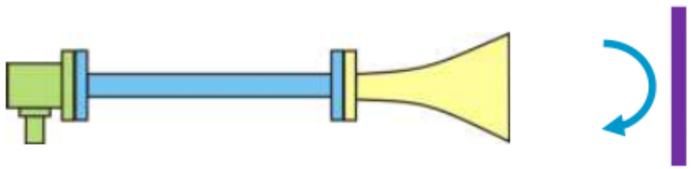

NA
Ref -60.00 dB
S11 S11
Log
10.0
dB/
Cal
ON U
Data
Avg
1
-20
-30
-40
-50
-60
-70
-80
-90
-100
Adapter
Horn
Antenna
Environment
Metal Plate
Time Gate
(bandpass)
Start 0.000 s
Points 801
Resolution 50.0 mm
IF BW 10.00 k
Output Power High
Line Loss 0.00 dB/m
Stop 20.00 ns
Swp 644 ms
Transform+Gate



Gating in the Frequency Domain

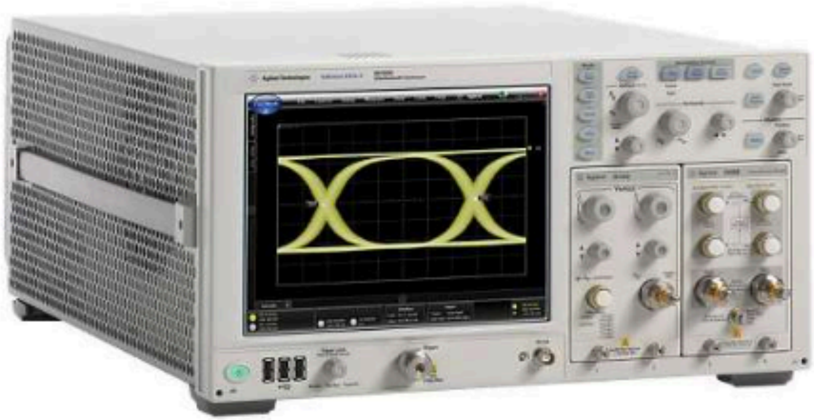
Return to frequency domain with gate active





Equipment Types with Time Domain Capability

Time Domain Reflectometer (TDR)



86100D DCA with 54754A TDR Module

- True time-sampled measurements
- Step Generator with fast rise time
- Oscilloscope-based

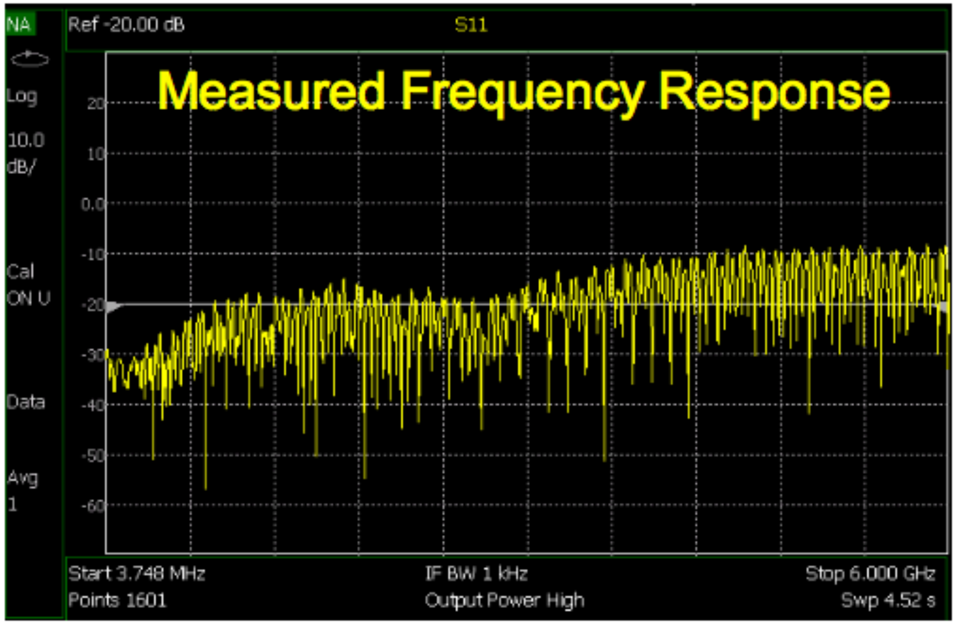
Vector Network Analyzer (VNA)

Cable and Antenna Test (CAT) Analyzer

N9918A FieldFox
30 kHz to 26.5 GHz

- Swept frequency measurements
- Transform to time domain
- High dynamic range receiver
- Measure band-limited devices

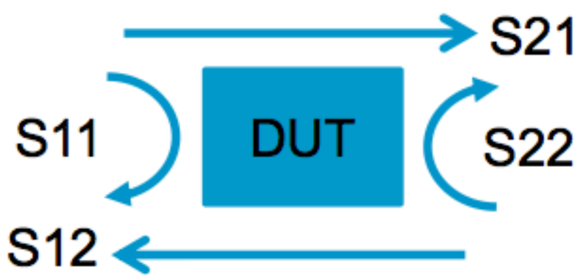
Measured Frequency to Time Transformation

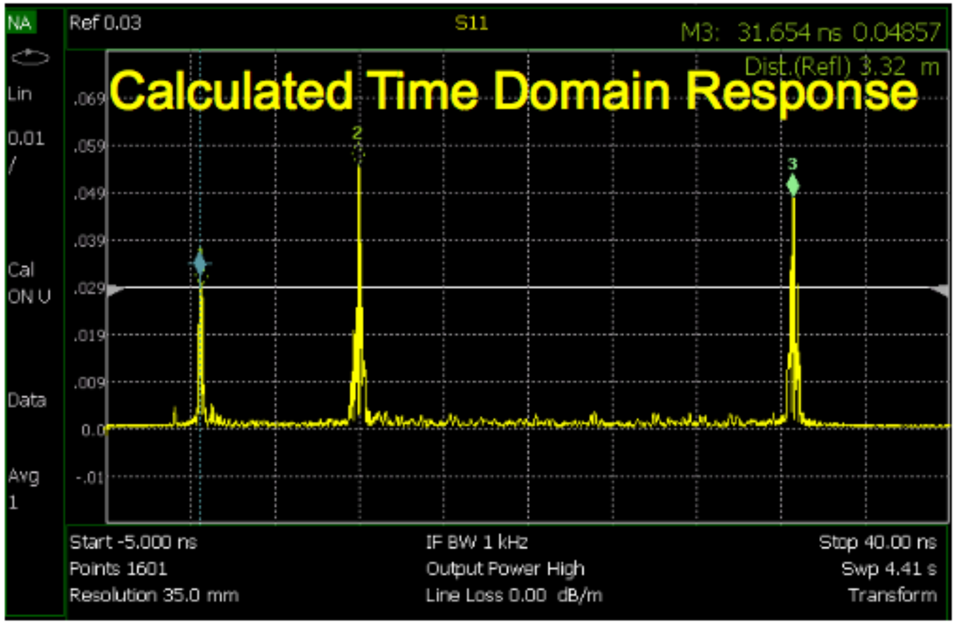


Measure S-parameter (e.g. S11 shown here)

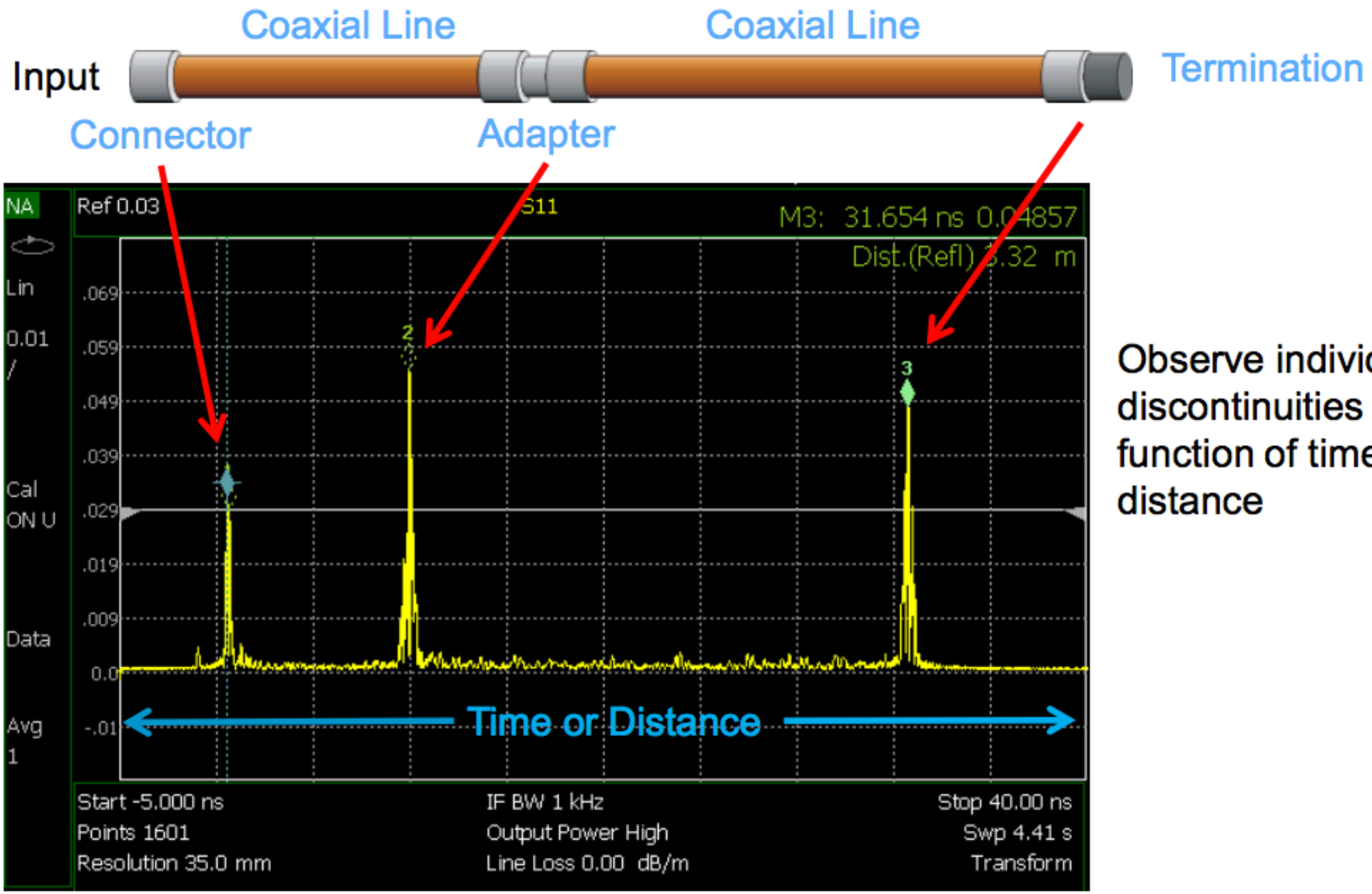
Activate Time Transform on VNA

Perform Time Transform on any S-parameter



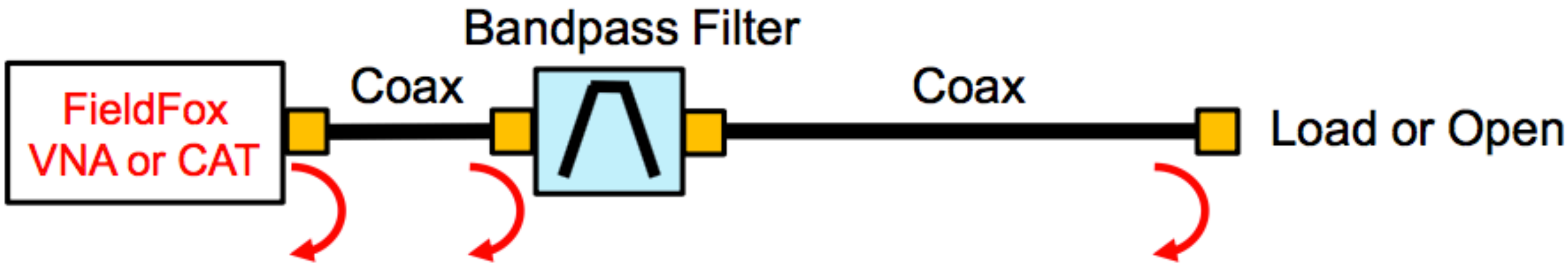


Measured Frequency to Time Transformation

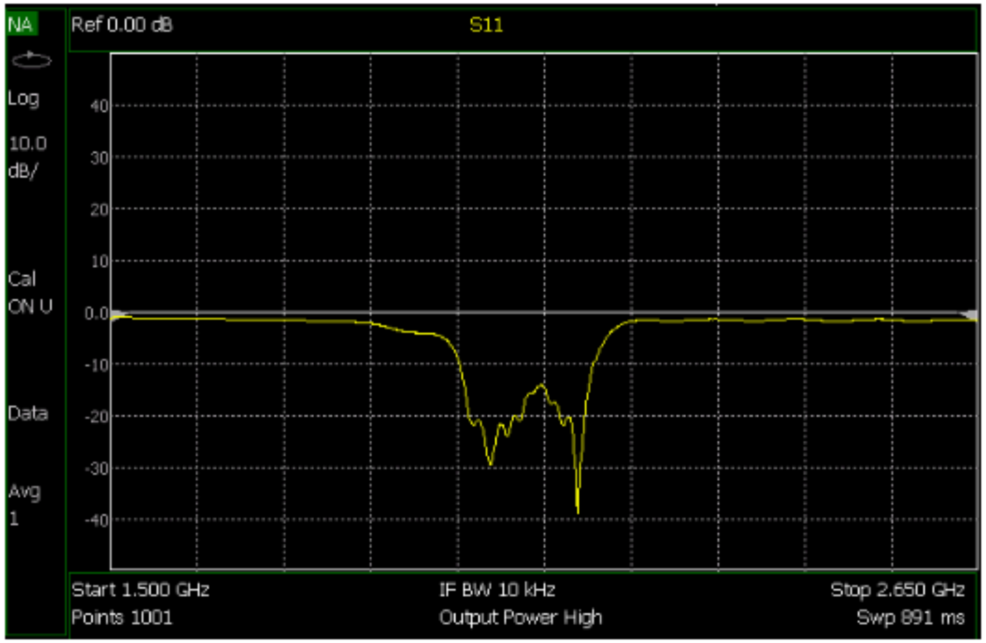


Observe individual discontinuities as a function of time or distance

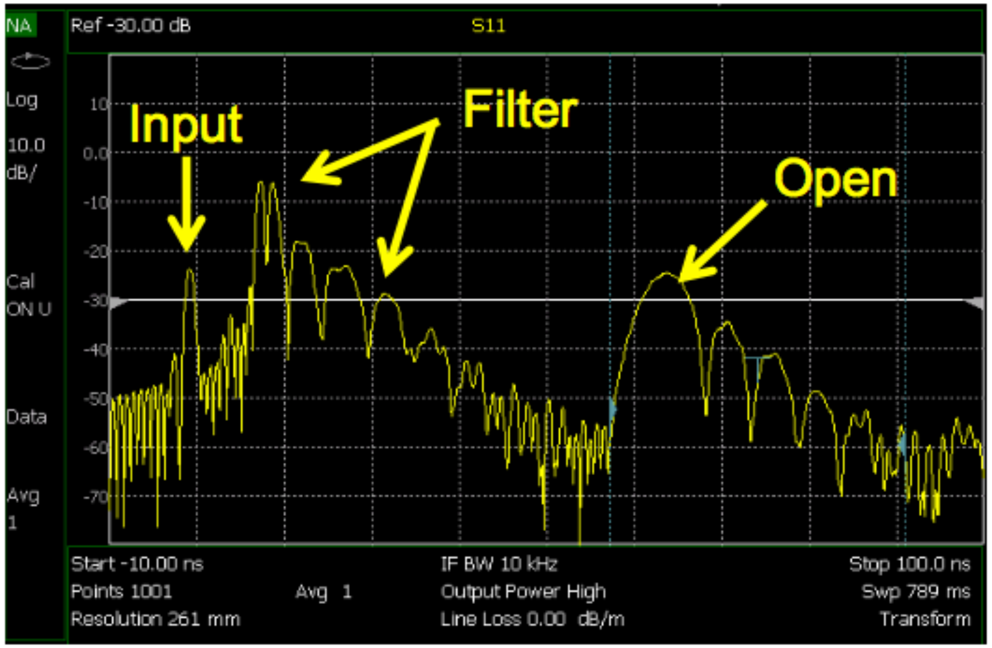
Time Domain with Filter



Frequency Domain: S11 → Time Domain: S11

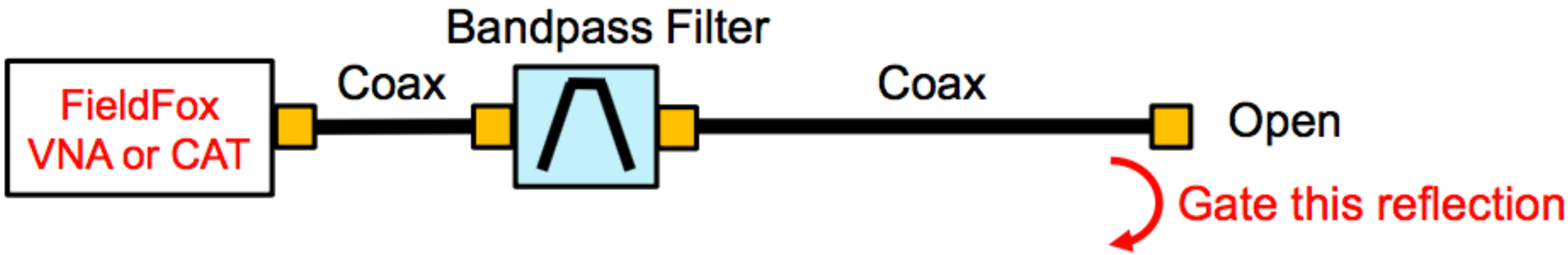


Terminated with 50-ohm load

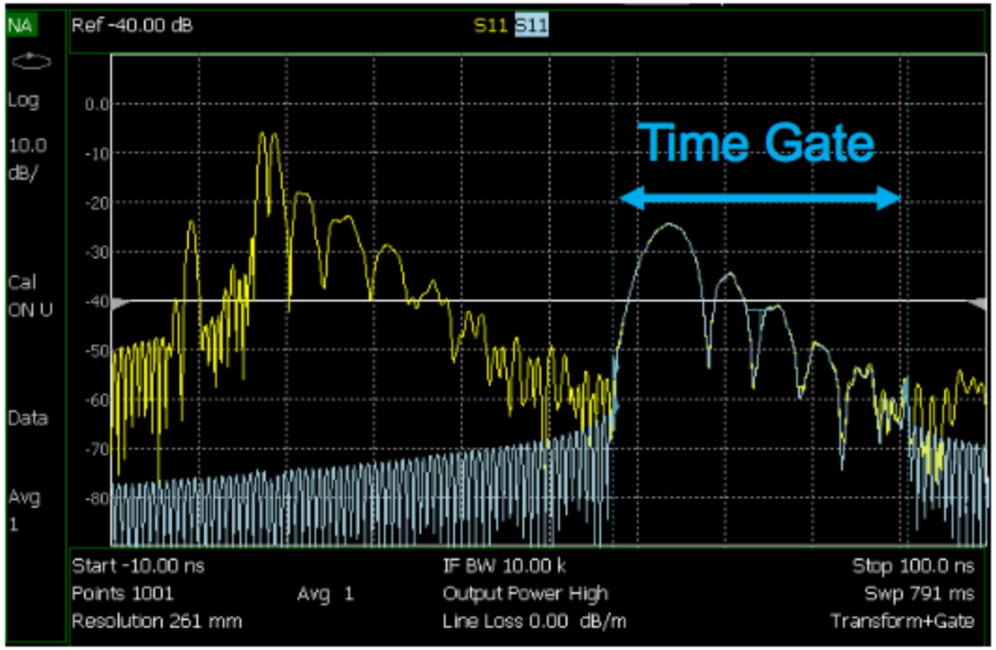


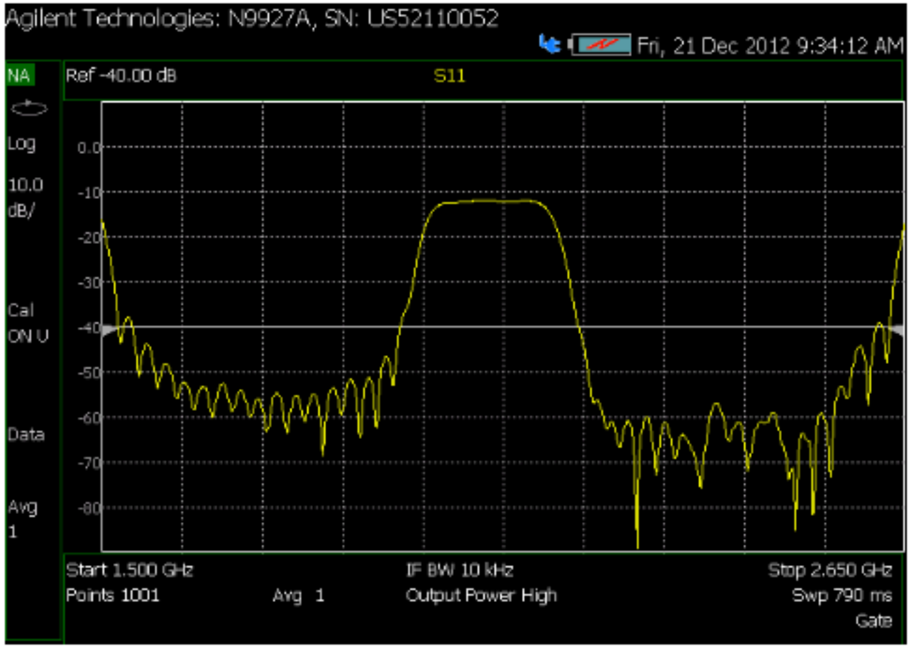
Terminated with open

Masking Effects with Filter



Time Domain Gating → Frequency Domain with Gating



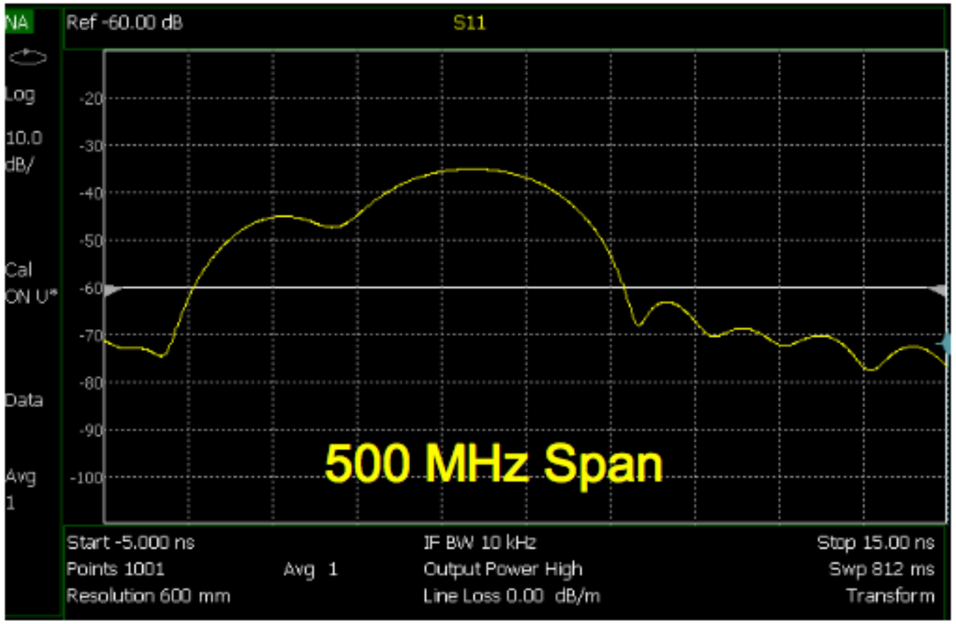


- Reflection from open includes *masking* effects of BPF
- Cable loss entry will not compensate for filter masking

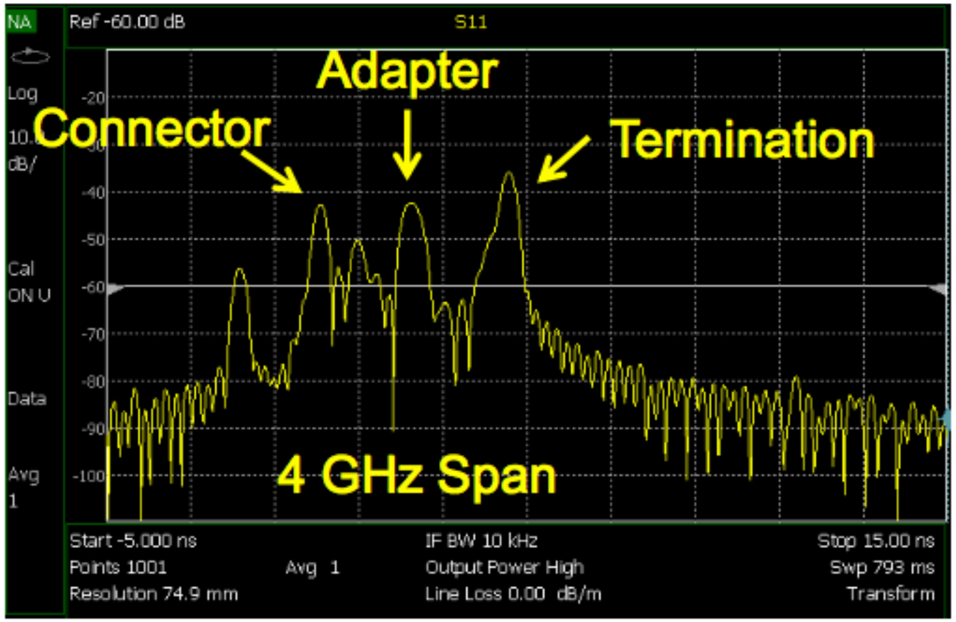
Frequency Span and Pulse Width

Pulse Width ~ 1/(Freq. Span)

Time Domain using 500 MHz Span



Time Domain using 4 GHz Span



Frequency Span and Time Span

$$\text{Max. Time Span} \sim 1/(2\Delta f) = \frac{(\text{Points}-1)}{2(\text{Freq. Span})}$$

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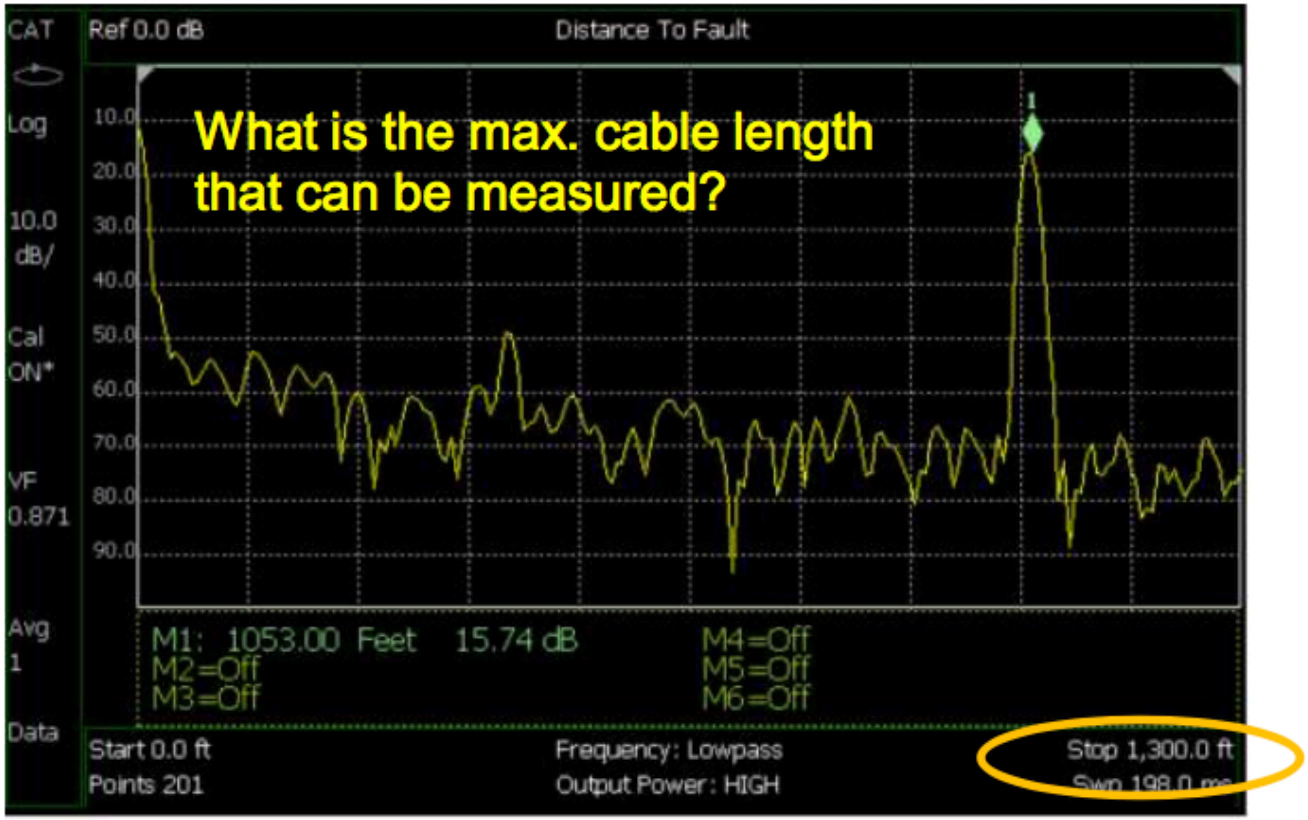
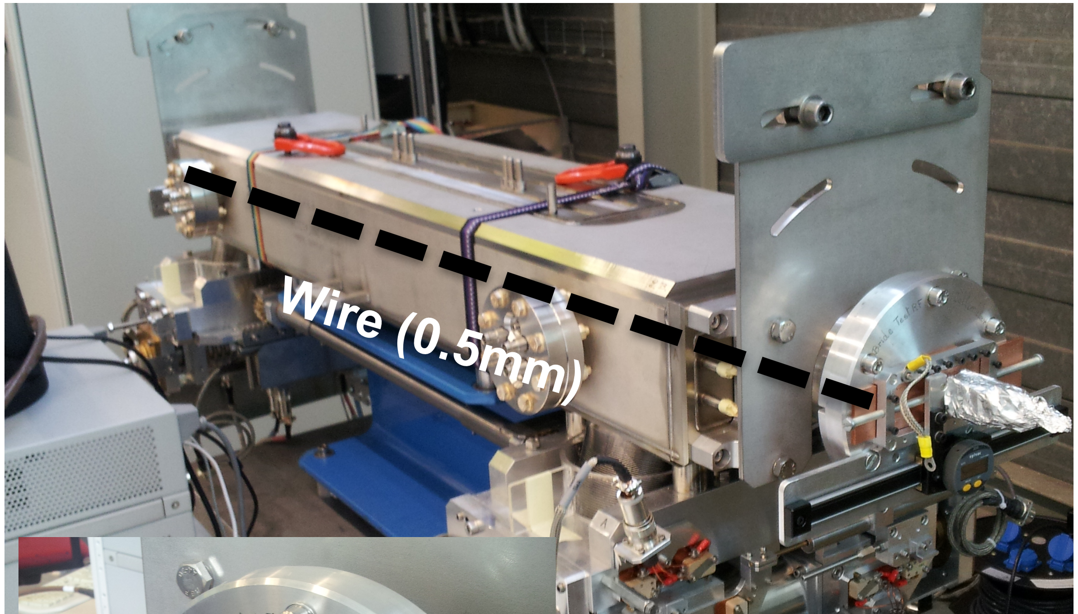
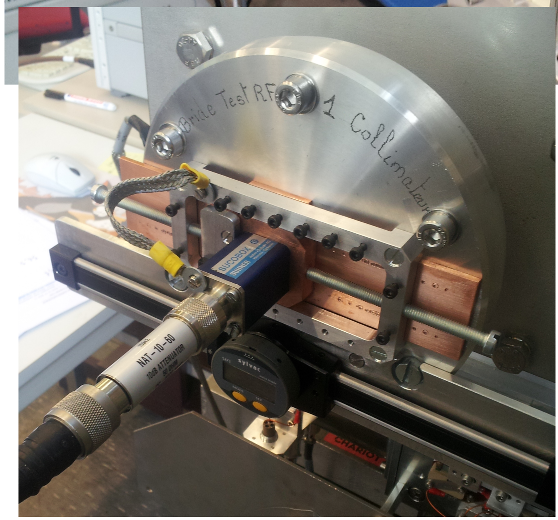


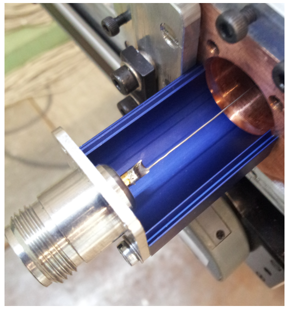
VF=0.66
10,001 points

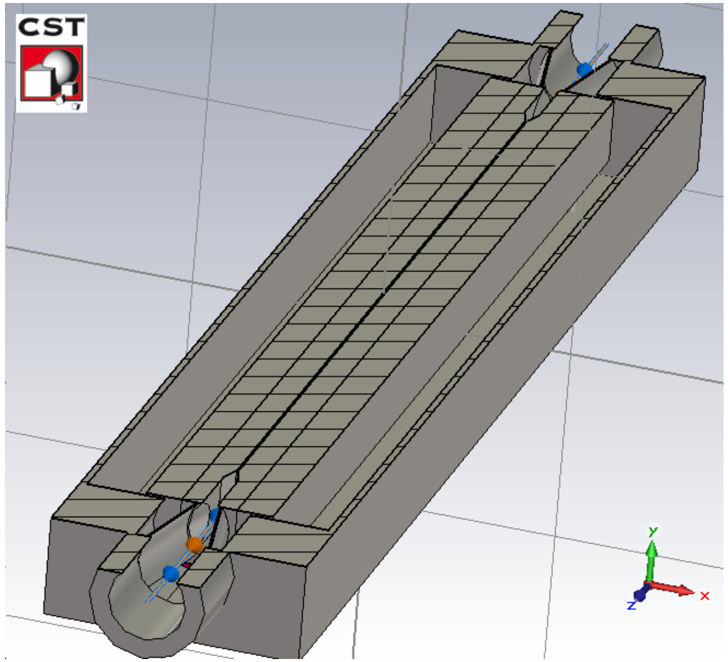
Span (GHz)	Max Time (μs)	Range (m)
2.5	2	395
5.0	1	198

LHC TCTP COLLIMATOR WIRE MEASUREMENT

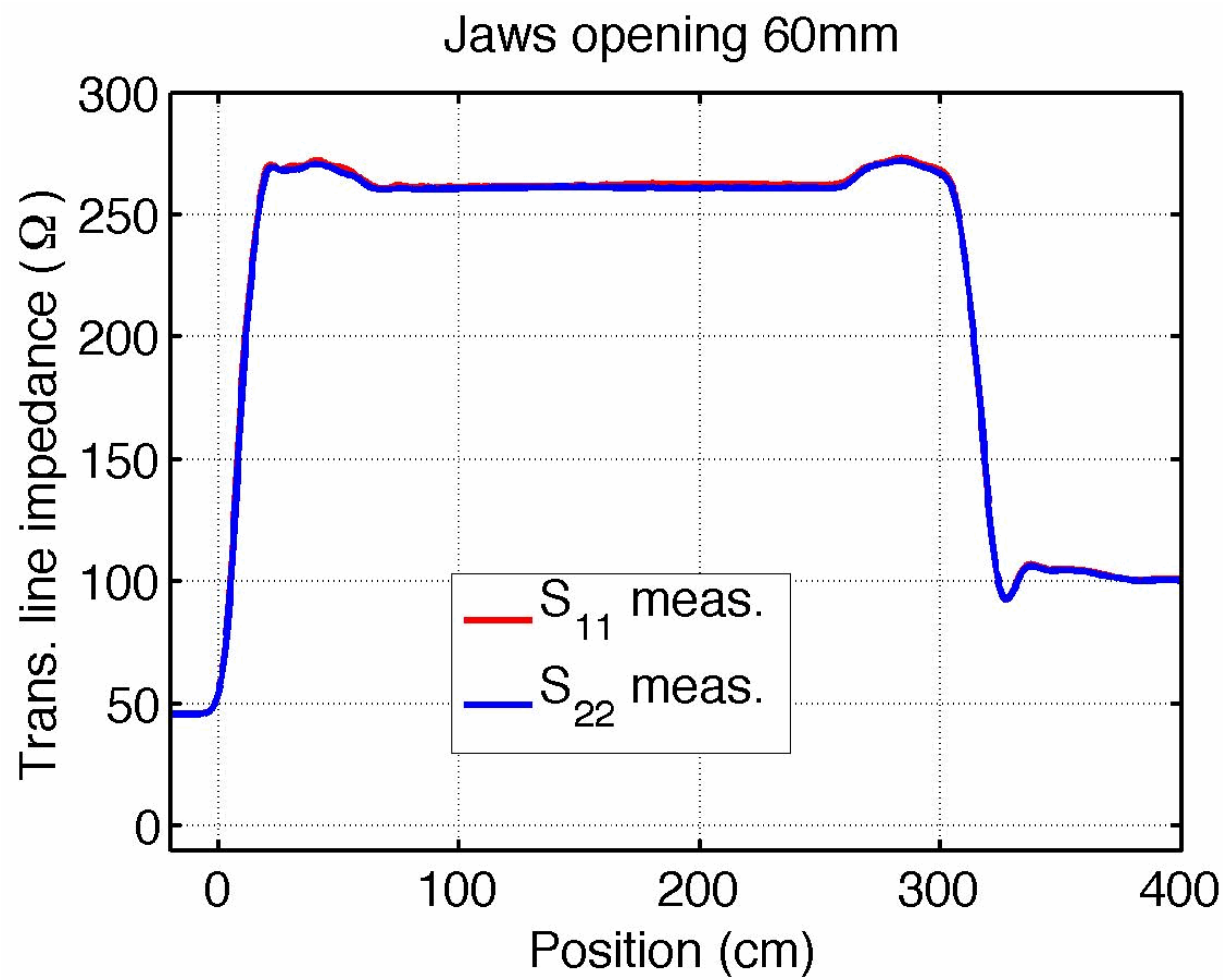


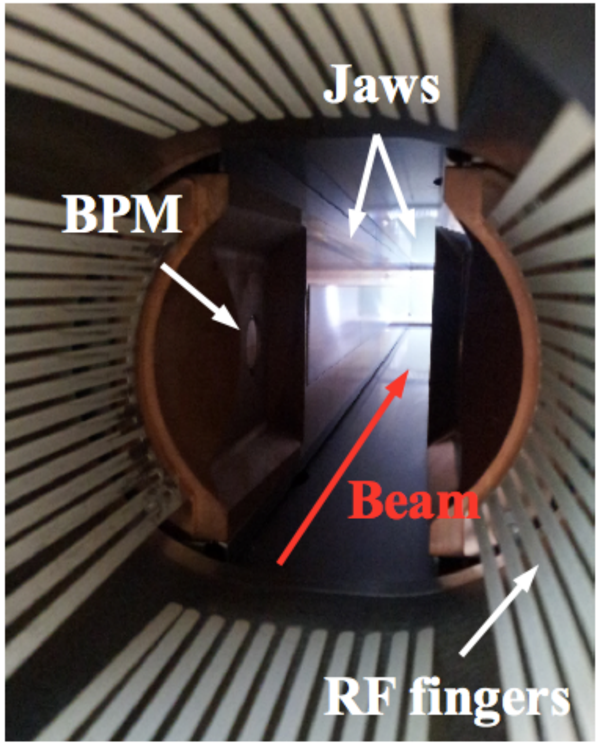


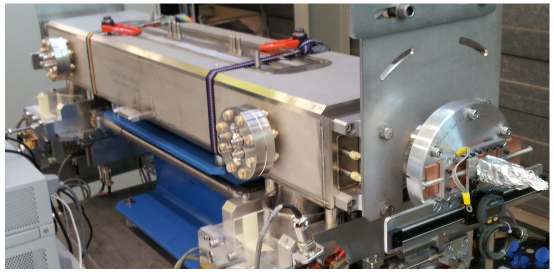




COAXIAL TRANSMISSION LINE PROPERTIES







Matching in impedance measurement is critical.

N. Biancacci et al., TCTP collimator meas., 2014