Charge Recovery Measurements with TLP

High Power Pulse Instruments (HPPI)

https://www.hppi.de/

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Outline

Definition of Terms

Generic Measurement Setup

Transformer-Based Current Sensor

Bias Tee Pitfalls

Conclusions

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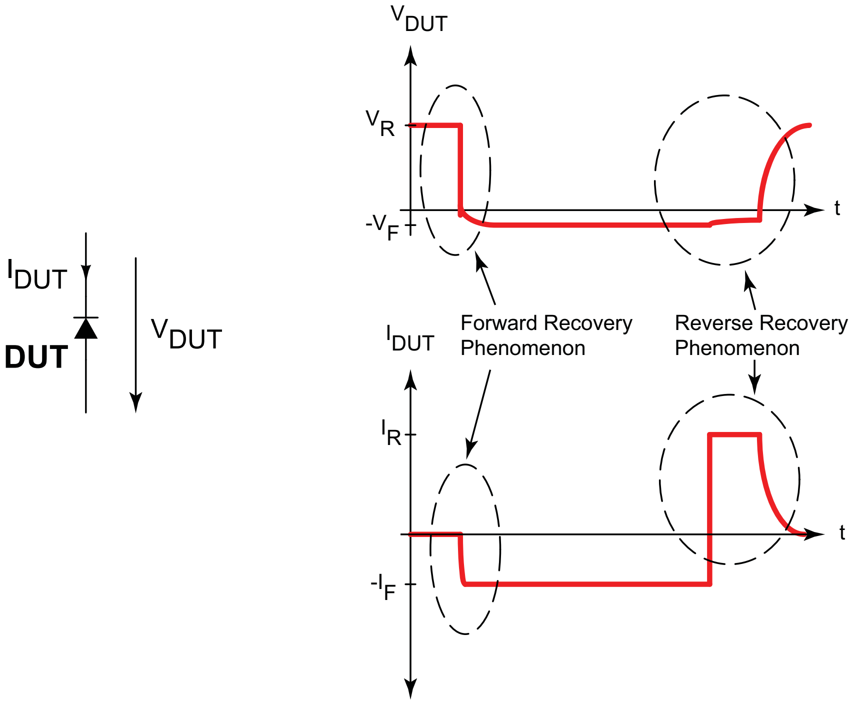
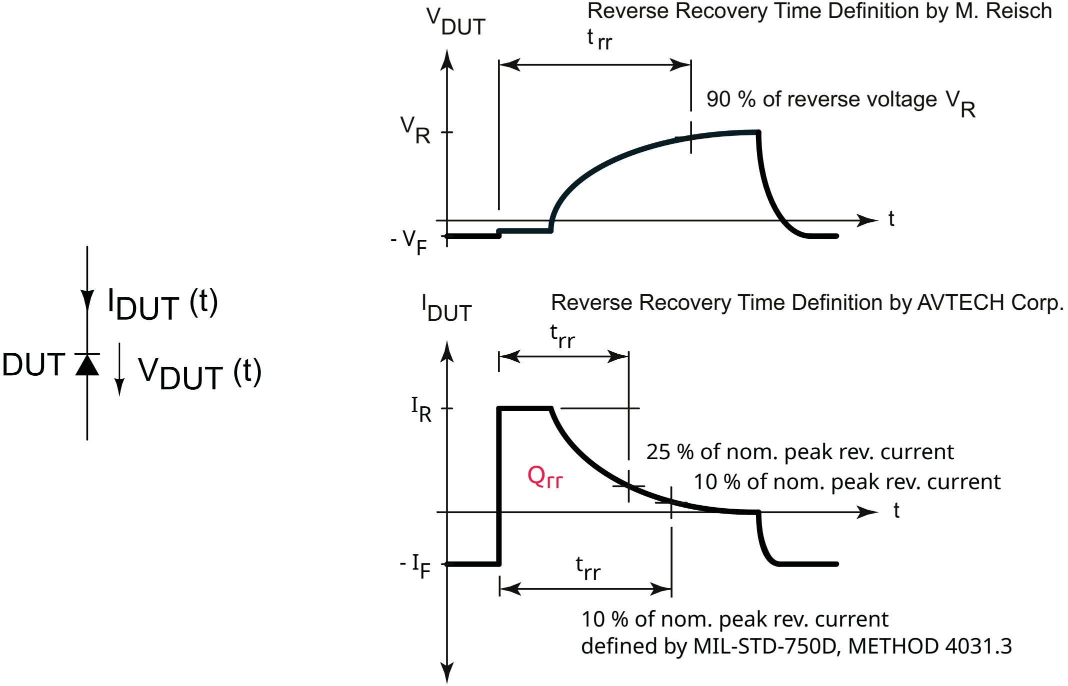
Charge Recovery Phenomenon of Diodes



Reverse Recovery Time of Diodes

Various Definitions



Reverse Recovery Time Definition by M. Reisch

90 % of reverse voltage V_R

Reverse Recovery Time Definition by AVTECH Corp.

25 % of nom. peak rev. current

10 % of nom. peak rev. current

10 % of nom. peak rev. current
defined by MIL-STD-750D, METHOD 4031.3

Reverse Recovery Time of Diodes

Various Definitions

Reverse Recovery Setup:

50 Ω and 100 Ω

Reverse Recovery Definition - I:

25 % of nominal peak reverse current [1]

Reverse Recovery Definition - II:

10 % of nominal peak reverse current [2]
MIL-STD-750D, method 4031.3

Reverse Recovery Definition - III:

90 % of reverse voltage [3]

Reverse Recovery Definition - IV:

Reverse recovered charge [4]

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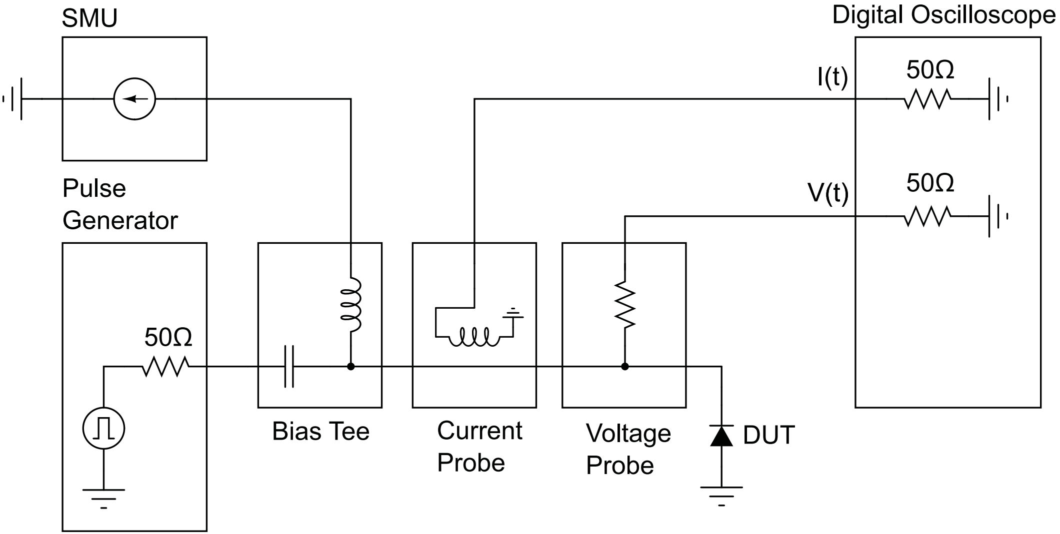
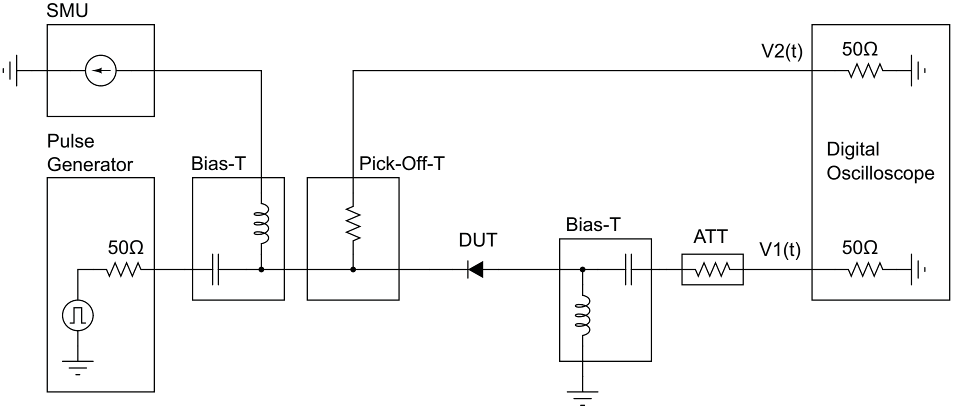
50 Ω


SMU
Digital Oscilloscope
I(t)
50Ω
V(t)
50Ω
Pulse Generator
50Ω
Bias Tee
Current Probe
Voltage Probe
DUT

100 Ω

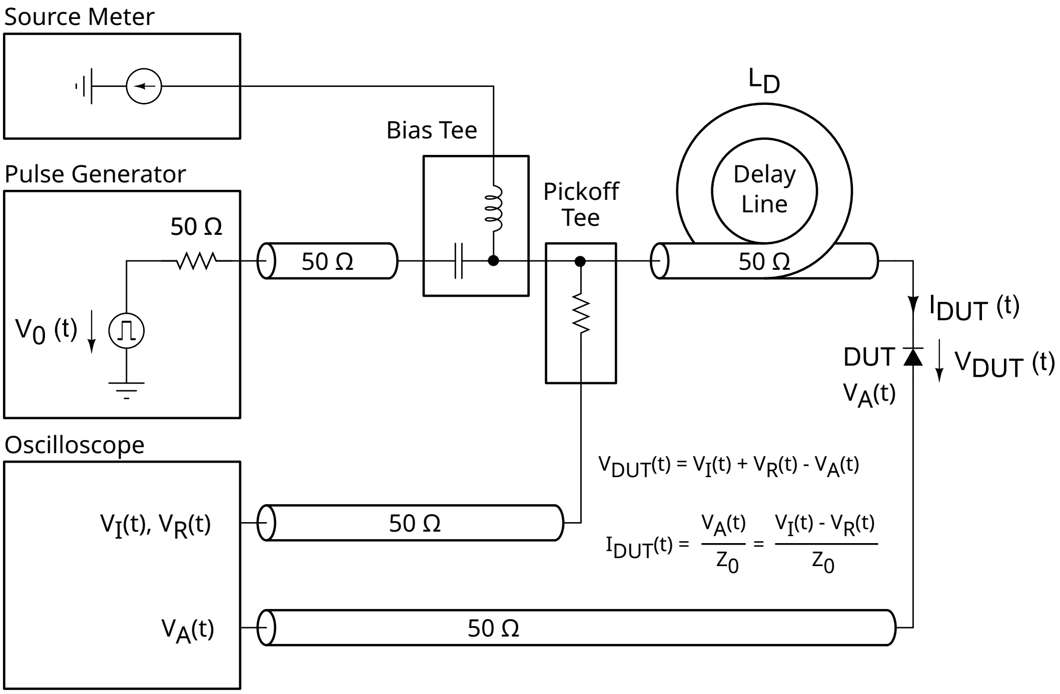


$$V_{DUT} = V2(t) \cdot k_{PT} - V1(t) \cdot k_{ATT}$$

$$I_{DUT} = \frac{V1(t) \cdot k_{ATT}}{50\,\Omega}$$

100 Ω TDR

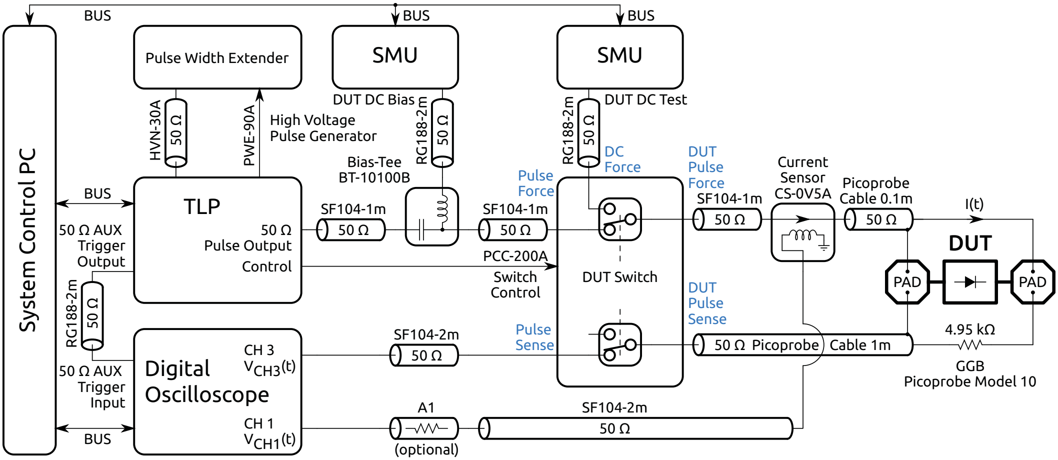
Sub-ns Recovery Time Measurement



$$V_{DUT}(t) = V_I(t) + V_R(t) - V_A(t)$$

$$I_{DUT}(t) = \frac{V_A(t)}{Z_0} = \frac{V_I(t) - V_R(t)}{Z_0}$$

50 Ω Standard TLP



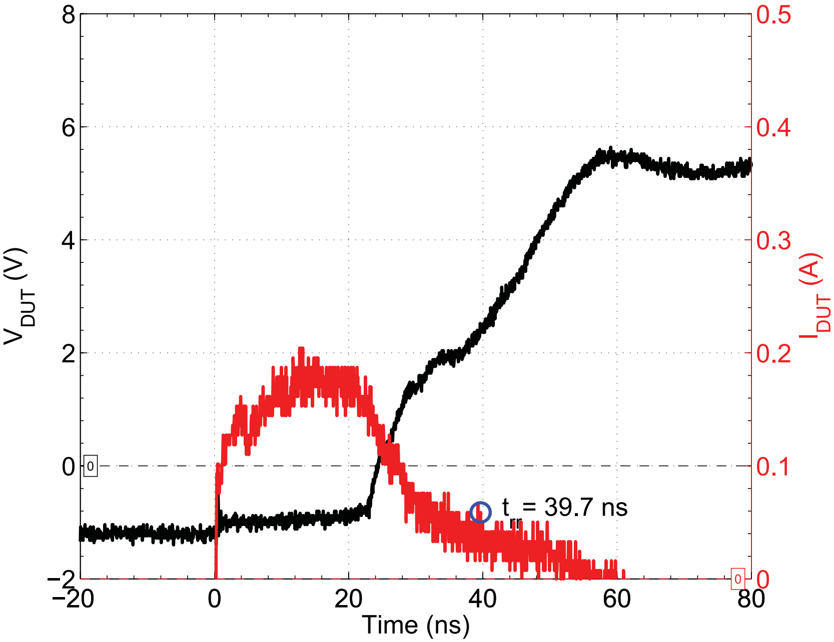
Reverse Recovery Time Measurement

t_{rr} Extraction Procedure (Example)

- Set the pulse parameters to minimum available rise time of 100 ps and a pulse width which is approximately two to three times the expected reverse recovery time.
- Operate diode in forward mode with a defined forward bias current $\mathrm{I_F}$.
- Apply a reverse mode TLP pulse with a defined reverse voltage $\mathrm{V_R = V_{TLP} - |V_F|}$. The pulse width of the TLP has to be increased until the voltage $\mathrm{V_R}$ remains steady state.
- Measurement of the nominal peak reverse current.
- Extract 25 % (or 10 % according MIL-STD) of the nominal peak reverse current.
- The time where the current $\mathrm{I_{DUT}}$ decreases down to 25 % (or 10 % according MIL-STD) of the nominal peak reverse current, is the reverse recovery time.

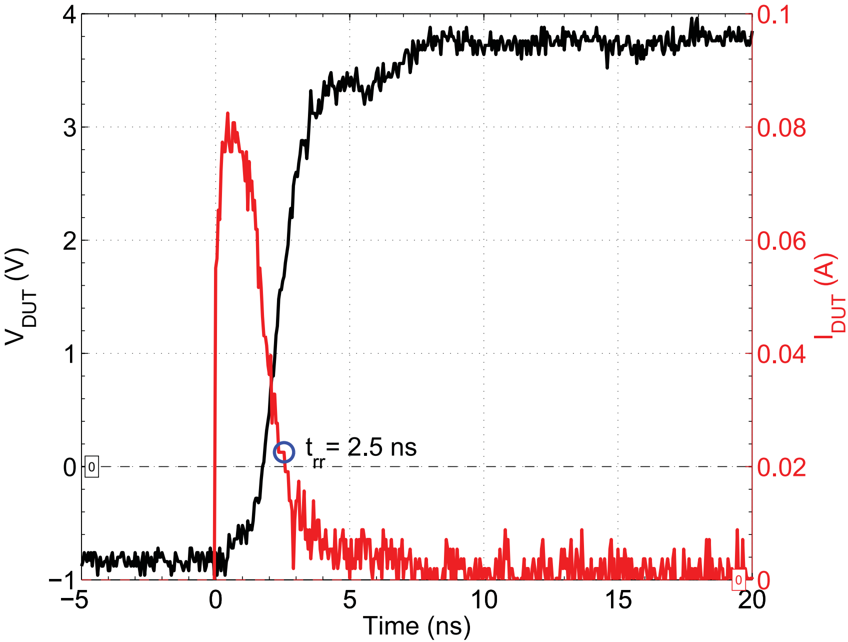
Reverse Recovery Transient Waveforms

Example: 39.7 ns



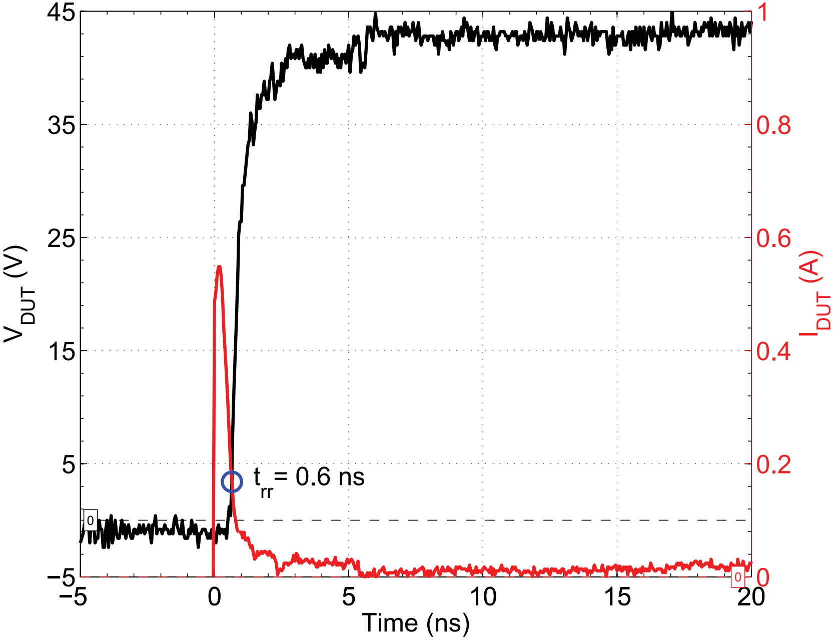
Reverse Recovery Transient Waveforms

Example: 2.5 ns



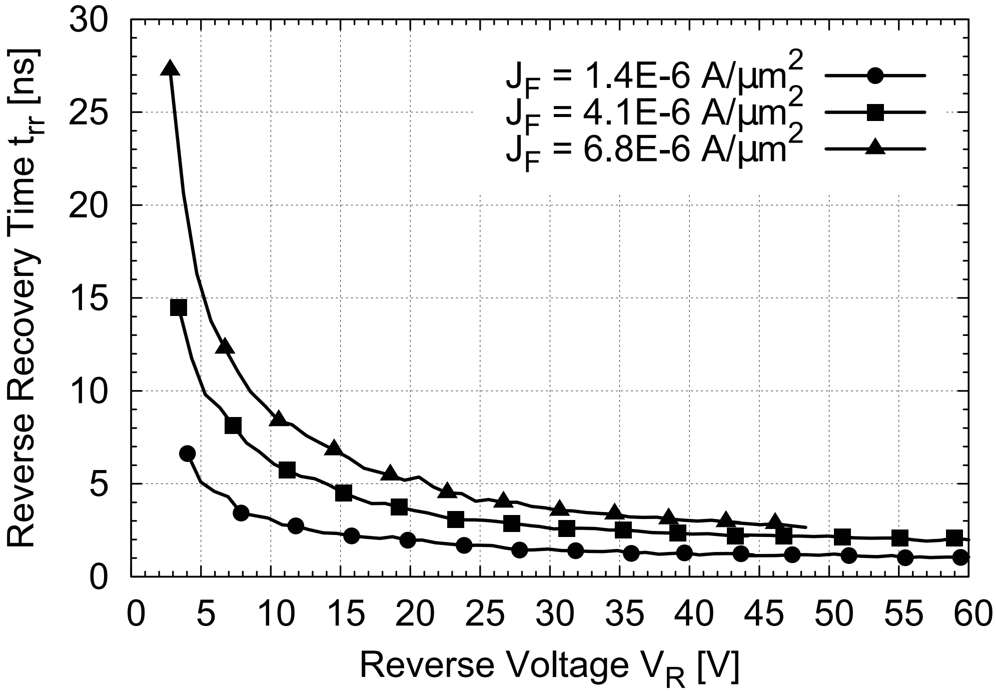
Reverse Recovery Transient Waveforms

Example: 0.6 ns



50 Ω Reverse Recovery Measurement Setup

Example: Reverse Recovery Measurement Result of a Silicon Diode



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Transformer-Based Current Sensor

Bias Tee Pitfalls

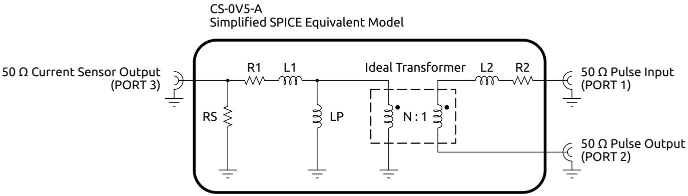
Conclusions

Transformer-Based Current Sensor

- Transformer-based current sensors are widely used for TLP measurement because of its very low parasitic load impedance and high frequency bandwidth
- Drawback are zero DC current readout and potential magnetic core saturation
- Therefore the readout of the current sensor need to be corrected to obtain right results
- Magnetic core saturation must be avoided
- A SPICE equivalent model (no magnetic core saturation effects included) of a transformer-based current sensor (next slide) may help to review and analyze the situation

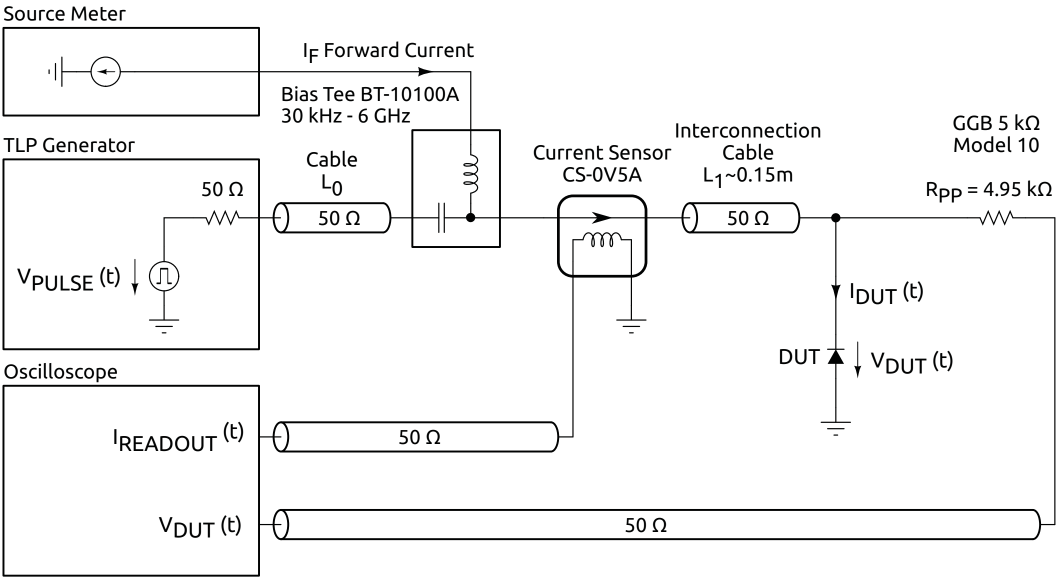
100 A, 3 GHz, 50 Ω, 0.5 V/A Current Sensor CS-0V5-A

SPICE Equivalent Model



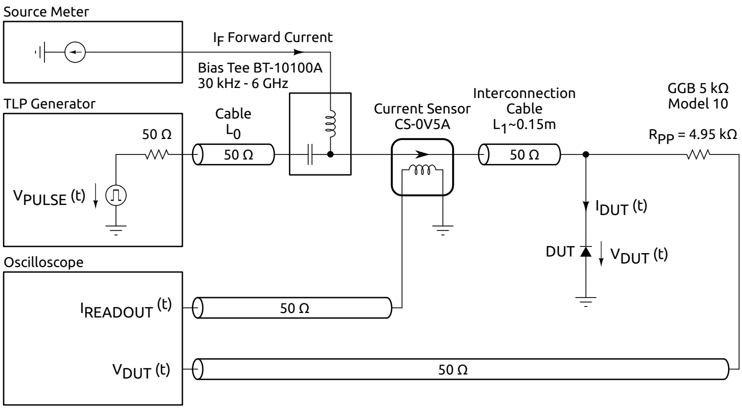
$$
\begin{aligned}
N &= 18 \\
k &= 0.9999 \\
RS &= 11\,\Omega \\
R1 &= 0.1\,\Omega \\
LP &= 1.324\,\text{mH} \\
L1 &= LP \cdot \left(\frac{1}{k} - 1\right) = 132.4\,\text{nH} \\
L2 &= \frac{L1}{N^2} = 0.408\,\text{nH} \\
R2 &= 0.01\,\Omega
\end{aligned}
$$

Typical TLP Measurement Setup



- The transformer-based current sensor does not readout the DC bias current

Setup and Polarity Definition



- Voltage and current polarities are defined as shown in this schematic
- Therefore the diode forward current is considered as a negative value, e.g. $IF = -45\,\text{mA}$
- $I_{DUT,CALC} = I_{READOUT} + I_F$

Measurement Setup with Discrete Current Sensor

Transformer-based Current Sensor

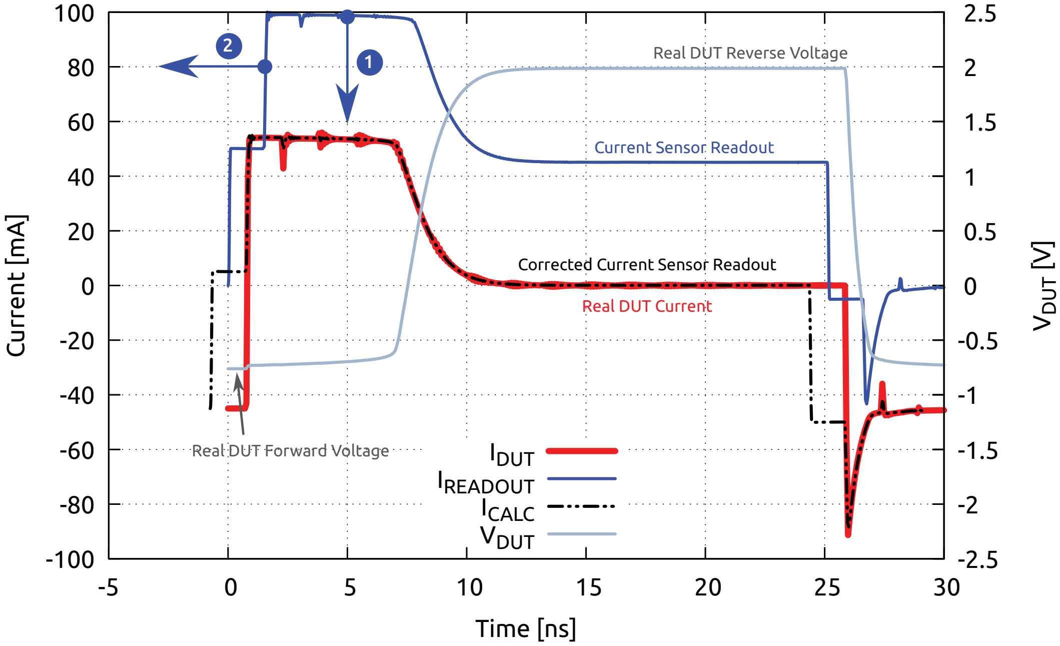
- Because of the transformer, the current sensor will not read out the DC forward bias current IF
- The sensor will read out the difference in the time domain:

  Read Out Current = IDUT - IF

- This means we need to correct the result by post processing to get the correct IDUT value:

  IDUT = Read Out Current + IF
- In addition the readout signals shows a delay and a plateau due to the cable L_1

How to Correct the Current Sensor Readout Signal?



How to Correct the Current Sensor Readout Signal?

Step 1: Shift down the current sensor readout signal by *IF*

Step 2: Shift left the current sensor readout signal by the delay time t_{L1} due to the cable length $L1$:

$$t_{L1} = \frac{L_1}{v} \approx \frac{L_1 \cdot \sqrt{\epsilon_r}}{c}$$

Example:

$$\begin{aligned} L_1 &= 0.15\,\mathrm{m} \\ v &= 0.2\,\mathrm{m\,ns^{-1}} \\ t_{L1} &= 0.75\,\mathrm{ns} \end{aligned}$$

Probe Parasitics and Cable De-Embedding

Required to avoid wrong readouts

- Voltage scale factor of the 5k Picoprobe model 10:

$$\frac{4950\,\Omega + 50\,\Omega}{50\,\Omega} = 100$$

- Probe Parasitic Shunt Resistance:

$$4950\,\Omega + 50\,\Omega = 5000\,\Omega$$

- Activate correct cable de-embedding
- **Disable** oscilloscope offset correction

Cable De-embedding

	Current	Voltage	Wfm 3	Wfm 4
cable:	RG-188	Sucoflex 104	-	-
Length (m):	2	3	0	0

Probe De-embedding

	Current	Voltage	Wfm 3	Wfm 4
Type:	-	Picoprobe 5k(0502)	-	-

Oscilloscope Correction

☐ Offset Correction % of waveform 1 Enable for: ☑ Ch 1 ☑ Ch 2 ☑ Ch 3 ☑ Ch 4

Probe Parasitics

Shunt Resistance (Ω) 5000

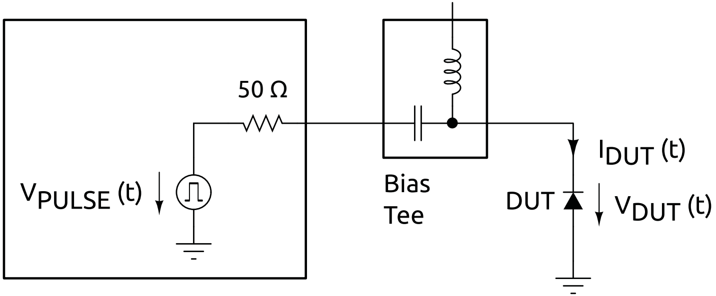
Series Resistance (Ω) 0

Result Calculations:

V = Ch3 * 100

I = Ch1 * 4.2 - Ch3 * 100 / 5000

Maximum Peak Reverse Current



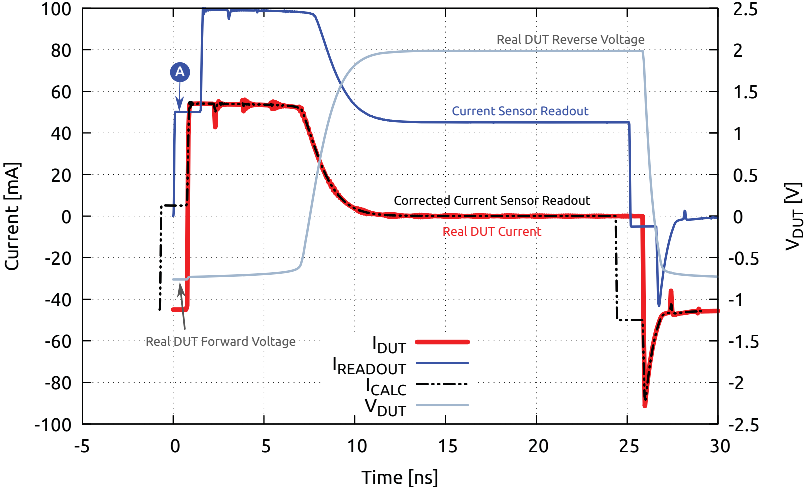
- The maximum peak reverse current is **limited** by the pulse voltage:

$$I_{DUT,max} = \frac{V_{PULSE}}{50\,\Omega} + I_F$$

- Example:
  $V_{PULSE} = 5\,\mathrm{V}$, $I_F = -45\,\mathrm{mA}$
  Maximum possible peak reverse current: $I_{DUT,max} = 55\,\mathrm{mA}$

Readout Detail A

$V_{PULSE} = 5\,\mathrm{V}, I_F = -45\,\mathrm{mA}$

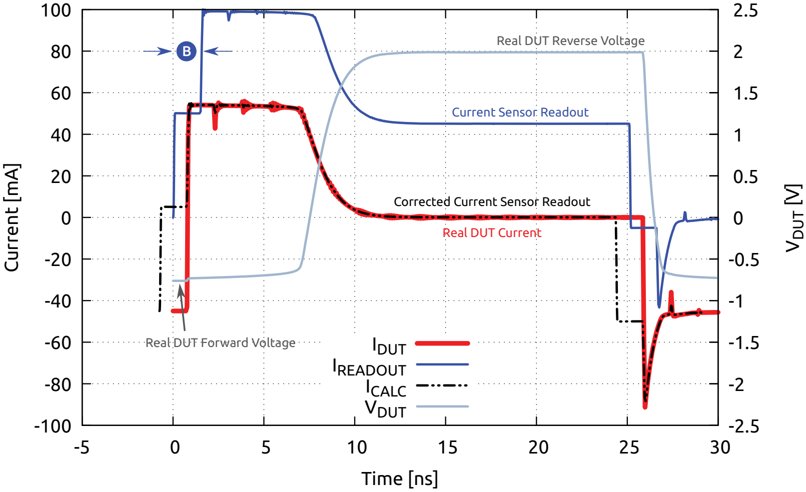


- The amplitude of the plateau **A** results from:

$$I_A = \frac{V_{PULSE}}{2} \cdot \frac{1}{50\,\Omega} = 50\,\mathrm{mA}$$

Readout Detail B

$V_{PULSE} = 5\,\text{V}, I_F = -45\,\text{mA}$

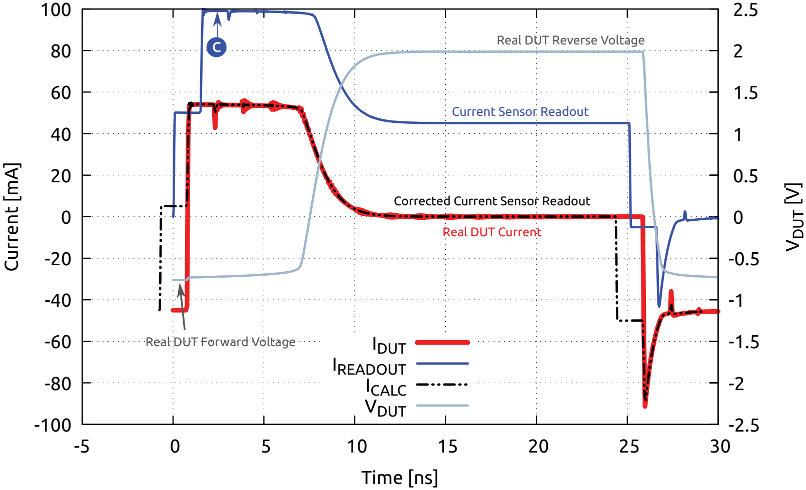


- The pulse width **B** of plateau **A** (page 27) results from:

$$t_B = 2 \cdot t_{L1} = \frac{2 \cdot L_1}{v} \approx \frac{2 \cdot L_1 \cdot \sqrt{\epsilon_r}}{c}$$

Readout Detail C

$V_{PULSE} = 5\,\text{V}, I_F = -45\,\text{mA}$



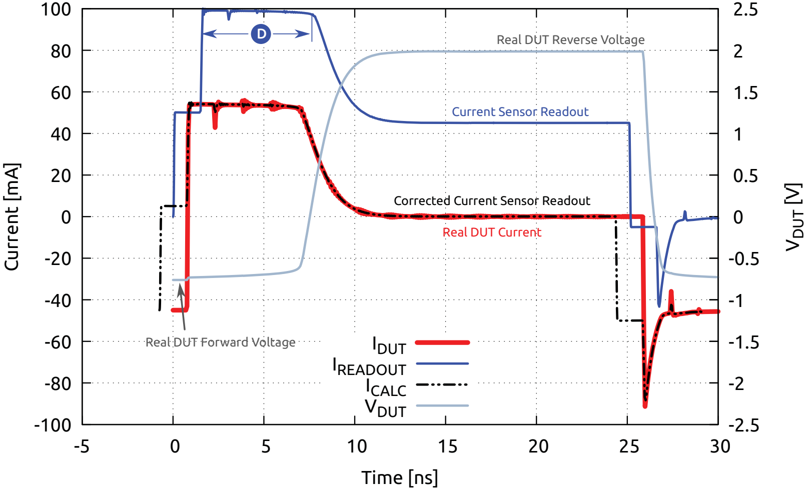
- The amplitude of the plateau **C** results from:

$$I_{C,max} = V_{PULSE} \cdot \frac{1}{50\,\Omega} = 100\,\text{mA}$$

- The peak value can be less in case Q_{rr} is small, but never $> I_{C,max}$

Readout Detail D

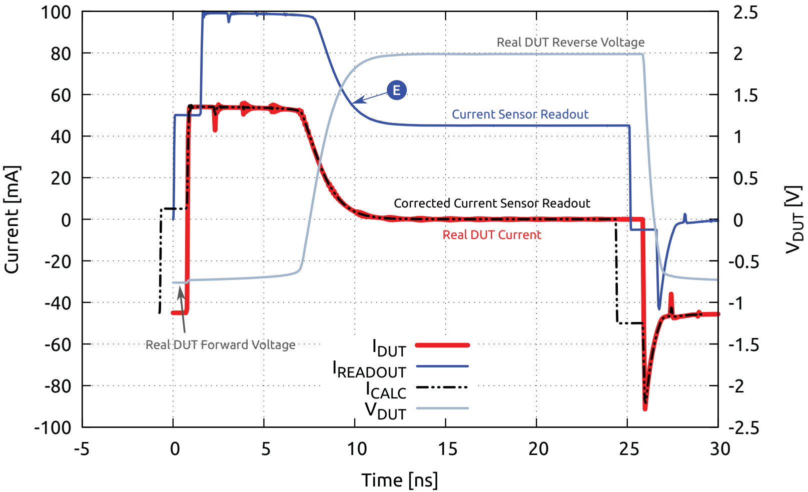
$V_{PULSE} = 5\,\mathrm{V}, I_F = -45\,\mathrm{mA}$



- The time **D** is depending on Q_{rr}

Readout Detail E

$V_{PULSE} = 5\,\mathrm{V}, I_F = -45\,\mathrm{mA}$



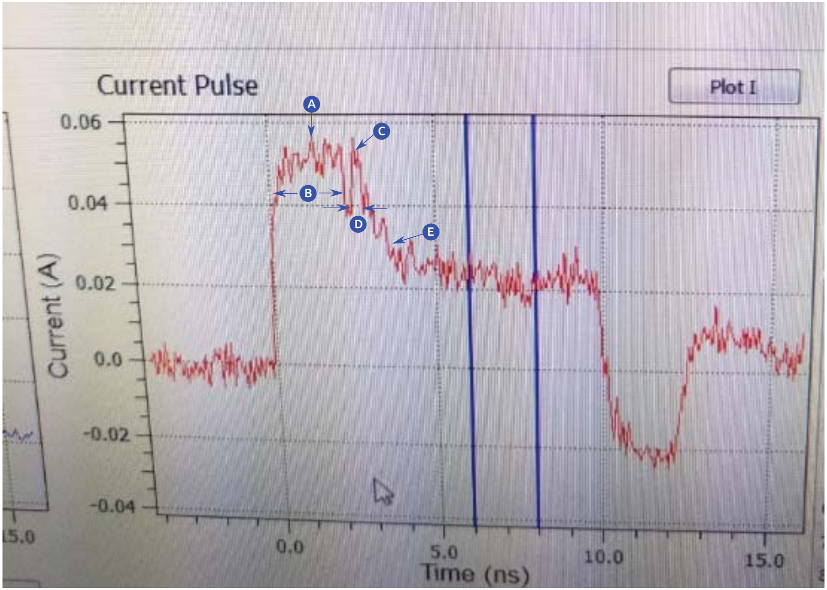
- The decay **E** is depending on C_{jo}

Calculation of the DUT Current

Using Transformer-based Current Sensors

- Post-processing procedure:
  1. Shift left $I_{READOUT}$ by $t_B/2$ on the time axis
  2. Add DC bias current: $I_{DUT,CALC} = I_{READOUT} + I_F$
- $I_{DUT,CALC}$ is valid after t_B, this means that the time t_B needs to be blanked (set $I_{DUT,CALC} = I_F$) in order to get the right peak reverse current of the diode.
- Precise evaluation of t_B is necessary for this purpose
- In all cases for I_F and V_{PULSE} the calculated peak reverse current and decay give the right result, despite the current sensor delay

Example With Very Low Q_{rr}



- All details **A-E** as described before

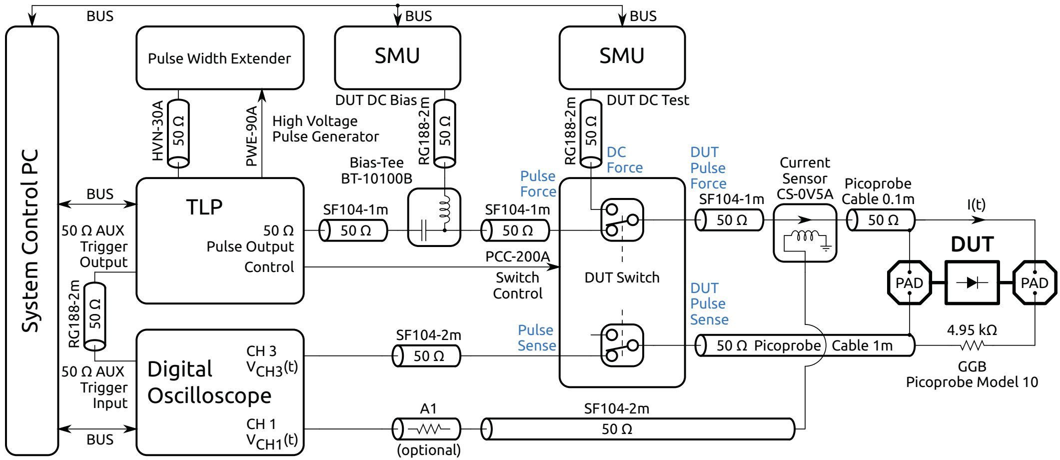
Outline

Bias Tee Pitfalls

- Bias tee's are widely used for TLP and charge recovery measurements
- Despite of the advantages of using bias tee's, there are two major drawbacks:
  1. Potential SMU control loop instabilities and oscillations
  2. Potential DUT voltage and current transient distortions
- There are two options:
  1. Don't use bias tee's (= separate topic for presentation)
  2. Use bias tee's and review/analyze the risk of malfunction

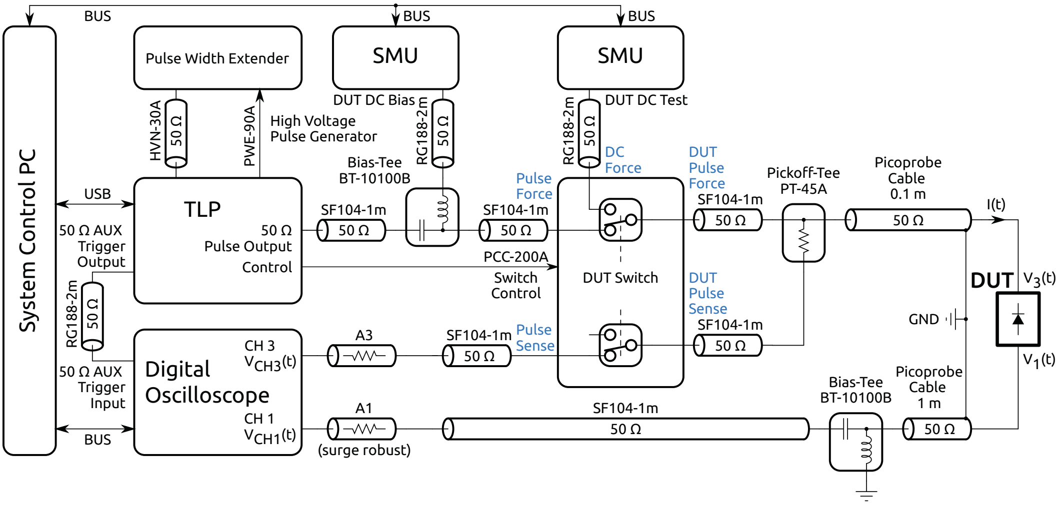
Example: 50 Ω Measurement Setup

Single Bias Tee



Example: 100 Ω Measurement Setup

Dual Bias Tee



Bias Tee Choices and Trade-Off

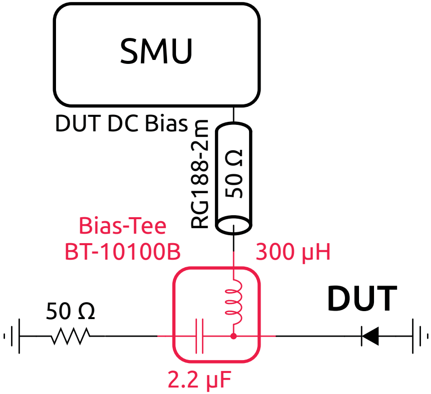
There are a lot of RF bias tees on the market, but it is probably very hard to find the unique combination of features required for TLP:

- High voltage capability
- Low cut-off frequency 30 kHz (for large µs pulse width)
- High cut-off frequency >7 GHz (for VF-TLP)
- Low insertion loss (for low pulse distortion)
- Low reflection coefficients (for low pulse distortion)

Therefore HPPI did develop bias tees suitable for TLP to combine all features mentioned above.

Bias Tee Pitfall #1: SMU Control Loop Instabilities

Can Cause High Voltage SMU Oscillation and SMU/DUT Damage



- For typical TLP measurements the 50 Ω bias tee must have a low cut-off frequency of around 30 kHz for large pulse width and an upper cut-off frequency in the range of 7 GHz to ensure a fast pulse rise time. This results in quite large L and C values inside the bias tee.

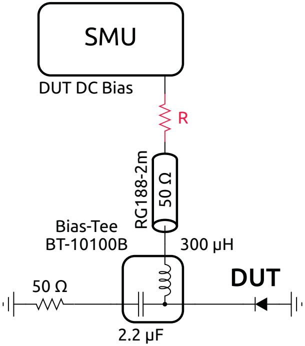
Bias Tee Pitfall #1: SMU Control Loop Instabilities

Can Cause High Voltage SMU Oscillation and SMU/DUT Damage

- This extreme load impedance at the SMU output may have strong impact on the control loop of the SMU. Depending on the phase margin of the SMU open-loop gain, the SMU output may become unstable. Unexpected damage of the DUT may happen because of a sudden SMU output runaway or high voltage oscillations. If the DUT impedance is changing in a wide range from short circuit to high impedance or representing a nonlinear characteristic, the SMU stability will be dependent on the DUT impedance in the measurement setup. Note: the situation may change significantly in case of a 4-wire (Kelvin) setup.
- Investigate the stability of the SMU with a separate test setup, check the SMU manual and/or contact the SMU vendor

Bias Tee Pitfall #1: SMU Control Loop Instabilities

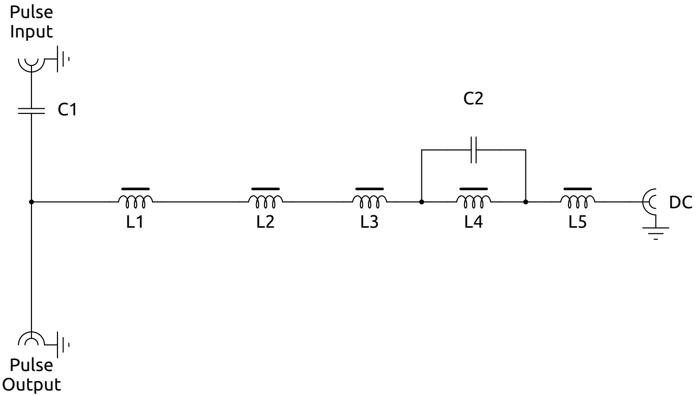
Countermeasure



- A simple but very effective countermeasure to increase the SMU control loop stability is to connect a resistor *R* directly at the output of the SMU.
- The value of the resistor should be as large as possible. Several hundred Ω to kΩ may be sufficient.

Bias Tee Pitfall #2: Dynamic Transient Distortions

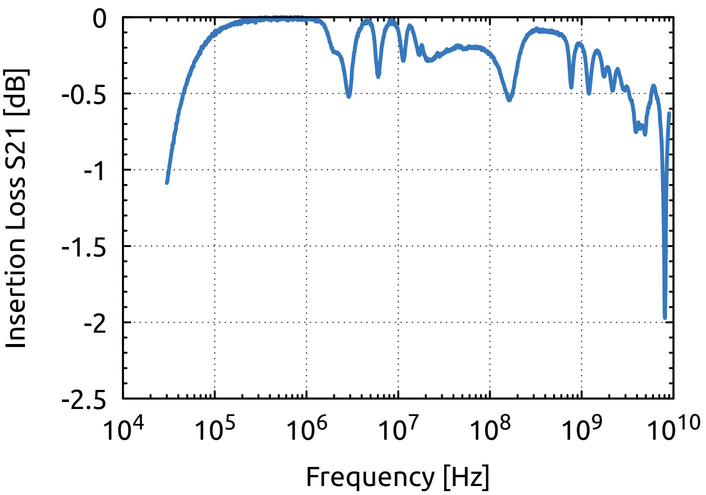
Root Cause



- By its nature, a bias-tee represents a multi-resonant wide-band circuit

Bias Tee Pitfall #2: Dynamic Transient Distortions

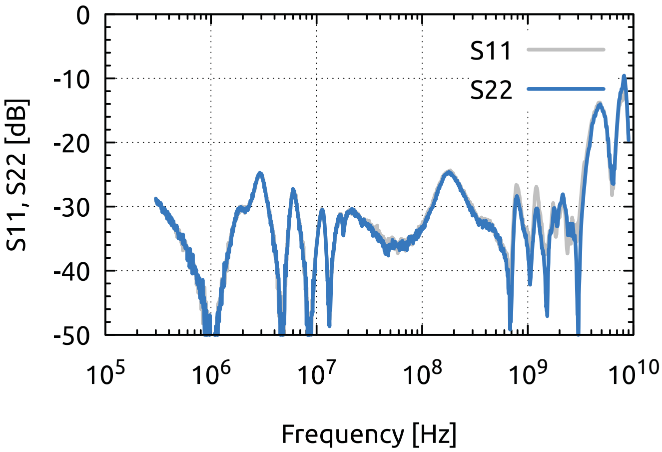
Bias Tee Typical Characteristics



- BT-10100B (https://www.hppi.de/files/BT10100B.pdf) pulse input to output transfer characteristic

Bias Tee Pitfall #2: Dynamic Transient Distortions

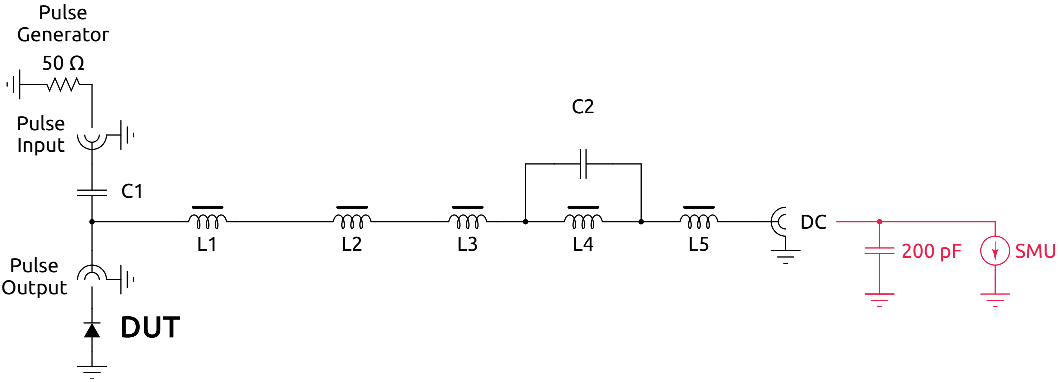
Bias Tee Typical Characteristics



- BT-10100B (https://www.hppi.de/files/BT10100B.pdf) pulse input/output return loss

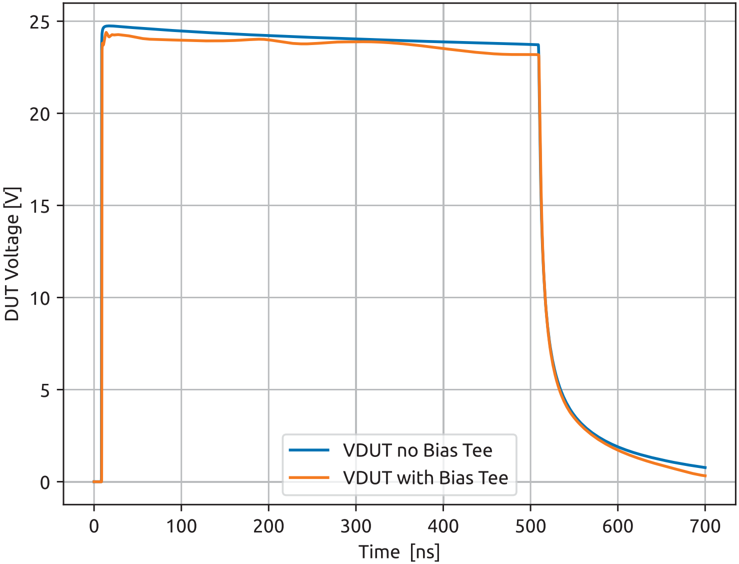
Bias Tee Pitfall #2: Dynamic Transient Distortions

Root Cause



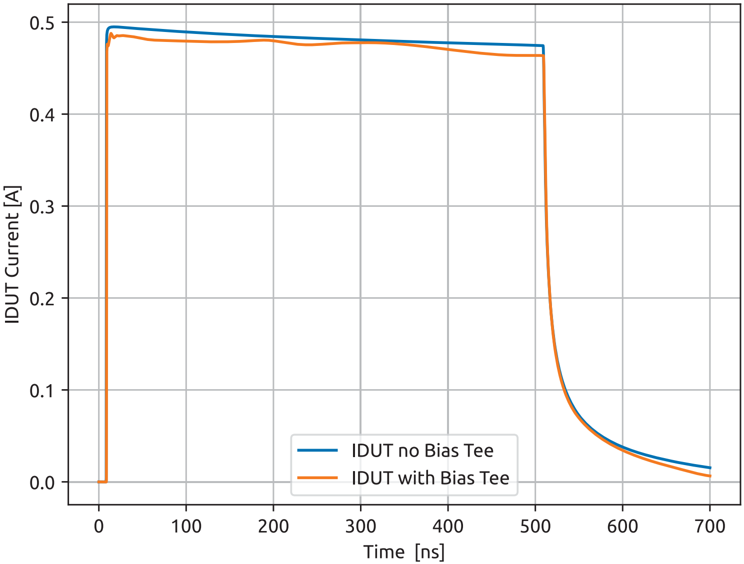
- 200 pF is the equivalent capacitance of 2 m long 50 Ω cable
- Root cause: pulse excitation of a multi-resonant circuit at very low resonant frequency

Bias Tee Pitfall #2: Dynamic Transient Distortions



- VDUT distortion

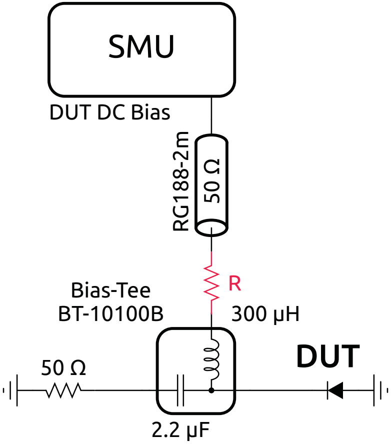
Bias Tee Pitfall #2: Dynamic Transient Distortions



- IDUT distortion

Bias Tee Pitfall #2: Dynamic Transient Distortions

Countermeasure



- Connect series resistor to isolate the parasitic cable capacitance
- Required for SMU in current force mode
- Not required for SMU in voltage force mode

Outline

Conclusions

- Charge recovery measurements require exact specification and documentation of test method, measurement setup and extraction procedure. Otherwise the measured numbers are useless.
- Transformer-based current sensors require special readout data processing
- The impact of bias tee's in the setup need to be investigated in detail
- Extraction of Q_{rr} can be easily done by post processing (not covered in this presentation)
- HPPI support with Python code snippets for effective data processing

References

[1] AVTECH Electrosystems LTD, “A comparison of reverse recovery measurement systems,” Nov. 2006.

[2] *MIL-STD-750D, method 4031.3, reverse recovery characteristics*,

[3] M. Reisch, *Elektronische Baulemente*, 2nd ed. Springer, 2007, ISBN: 3-540-34014-9.

[4] N. Shammas, D. Chamund, and P. Taylor, “Forward and reverse recovery behaviour of diodes in power converter applications,” in *Microelectronics, 2004. 24th International Conference on*, vol. 1, May 2004, pp. 3–10.