Oscilloscopes
Keysight HD3
Oscilloscope Probes

Introduction

- oscilloscopes are essential instruments for general power measurements and power component characterisation
  - voltage, current → power (two channels needed for a single „power channel“); calculation of other parameters like efficiency
    - 8 channel oscilloscope might be needed for three phase DUTs
  - low bandwidth for „general“ power measurements
    - 50/60 Hz + harmonics; power on/off transitions
  - higher bandwidth needed for characterization of switching components (transistors, ...)
    - rise times in the order of ns → tens to hundreds of MHz

Oscilloscopes – parameters

- number of channels – 2 (handheld), 4, 6, 8 (benchtop)
  - can be important for example for power measurements (V, I)
- bandwidth – maximum frequency which can be reasonably measured and displayed (typically a -3 dB point)
  - bandwidth is inversely proportional to the rise time and defines the ability to display rapid amplitude changes in the measured signal

$$t_r = \frac{0{,}35}{f_{-3\,dB}} \quad \longleftrightarrow \quad f_{-3\,dB} = \frac{0{,}35}{t_r}$$

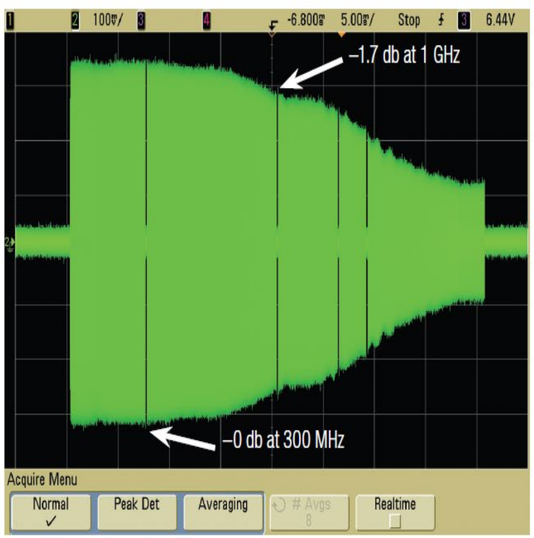
rise time	bandwidth
1 ns	350 MHz
10 ns	35 MHz
100 ns	3.5 MHz
1 µs	350 kHz
10 µs	35 kHz

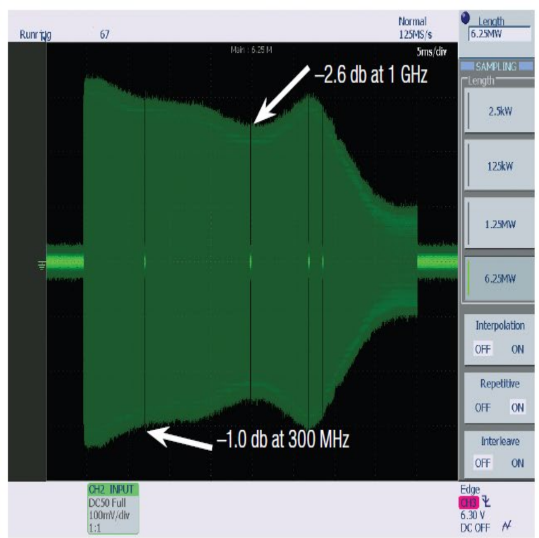
Oscilloscopes – parameters

- total rise time of a series of elements can be calculated as a square root of a sum of individual squared rise times

$$t_{r\_total} = \sqrt{t_{r1}^2 + t_{r2}^2 + \ldots + t_{rN}^2}$$

- very important is the flatness of the oscilloscope's frequency response within it's bandwidth





Oscilloscopes – parameters

- sample rate – should be ideally at least 3x the bandwidth
  - in some oscilloscopes, the full sample rate is available only when half the channels are enabled at the same time
- resolution of the oscilloscope's ADC – "number of bits"
  - "traditional" digital oscilloscopes use 8-bit ADCs → 256 leves
  - modern oscilloscopes can have 10, 12 and now also 14-bit ADCs
  - however, even more important is the quality of the analog frontend „delivering" signal to the ADC – **low intrinsic noise**, low distortion
  - "ENOB" – effective number of bits – how well the scope interprets an ideal sinusoidal signal at it's input

Keysight HD3 oscilloscopes

Keysight HD3 oscilloscope

- new (released on September 4th) and industry-leading low-to-mid range oscillosope
- 2 or 4 analog channels + 16 digital channels
- 14-bit ADCs (real hw resolution)
- very „clean“ low noise analog frontend
  - under 50 µV rms intrinsic noise in full 1 GHz bandwidth
- 200 / 350 / 500 / 1000 MHz bandwidth
  - fully upgradeable with license
- 3.2 GSa/s sample rate for all channels (not shared)

Keysight HD3 oscilloscope

- 20 / 50 / 100 Mpoints capture memory for each channel
- fast update rate > 1 300 000 waveforms/s
  - doesn’t slow down with math, measurements, ...
- pre-defined fine bandwidth limits
  - bandwidth filters + limited sample rate + “hi-res” averaging
  - 5, 10, 20, 50, 100, 200, 350 MHz limits
  - significant noise reduction for capturing „slow“ signals
- larger and configurable display
  - individual waveforms can be arranged in separate grids with different vertical settings; user can define custom display layout

Keysight HD3 oscilloscope

- HD3 series uses custom hybrid ASICs which enable fast hw accelerated signal processing
  - fast update rate, hw mask test, hw serial decoding, hw zone trigger
- HD3 oscilloscopes are almost completely software upgradeable (except for the number of channels)
- included standard functions
  - frequency response analysis (FRA), Fault Hunter, Zone trigger, Segmented memory, Mask test, Histograms, FFT, DVM, Counter
  - MSO – the 16 digital channels are always present and licensed; only the cabling needs to be purchased

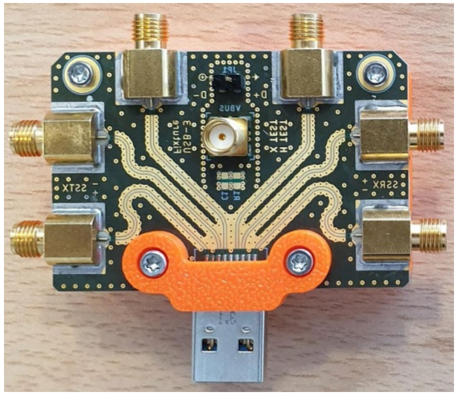
Oscilloscope probing

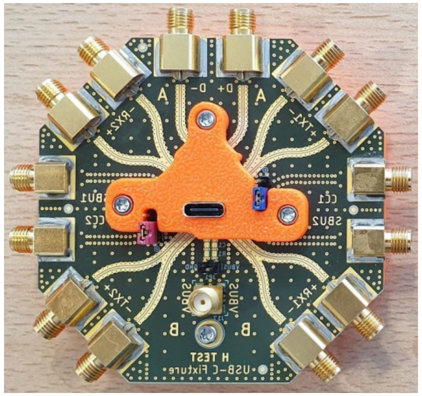
- three ways how to connect an oscilloscope to a signal source:
  1) direct connection to the coaxial input
     - typically used in 50 Ω signal paths with 50 Ω termination selected
     - preferred method (high signal quality; works well to high frequencies)
     - limited to **5 Vrms into 50 Ω** and to **tens to hundreds of V** into 1 MΩ
     - channel **grounds are connected together** and with the power cord ground – users need to be careful when using single-ended probes

Oscilloscope probing

2) fixtures

- adapter between some specific connector/interface and one or more coaxial connectors - USB, LAN, HDMI, PCIe .....





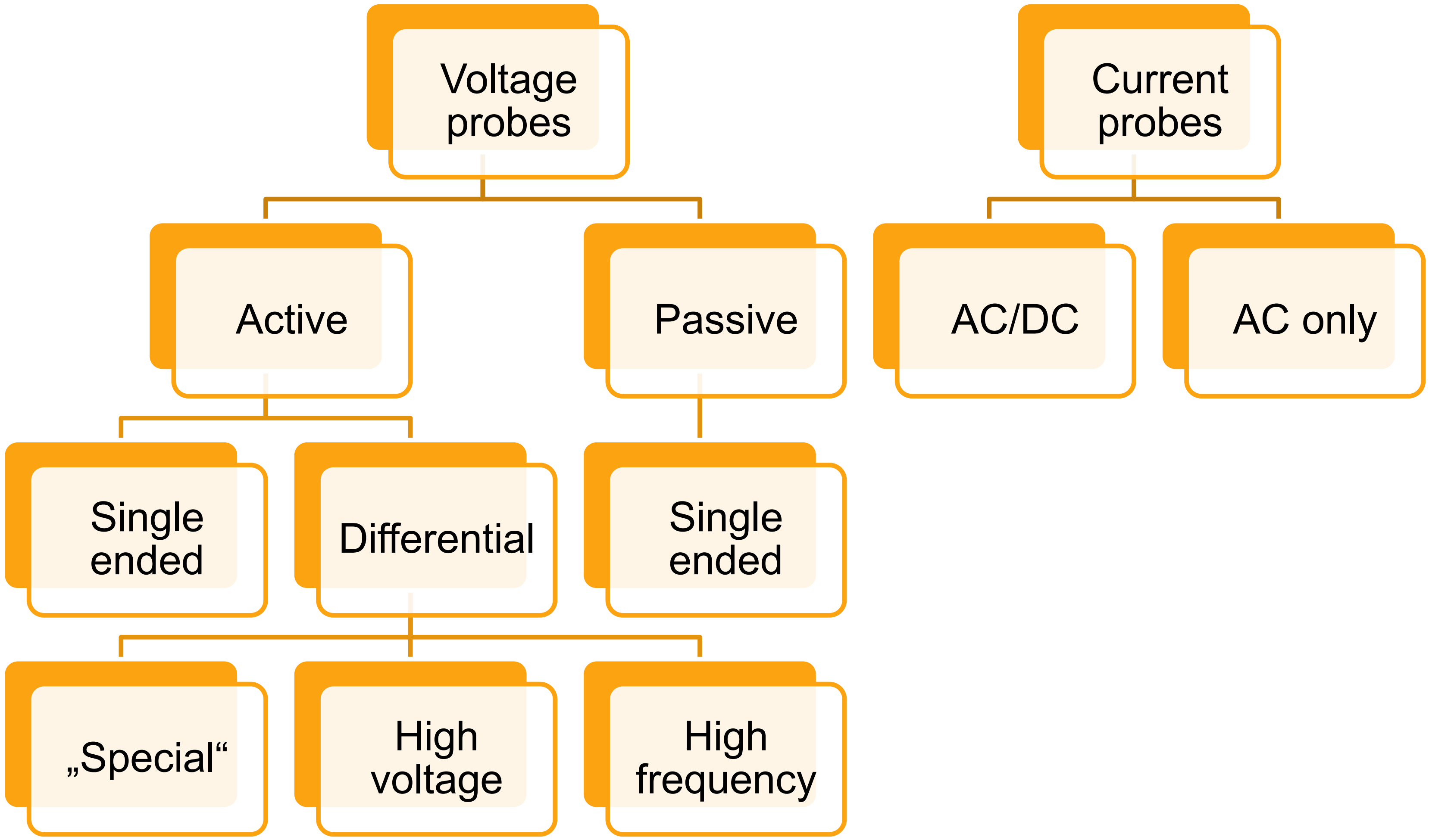
3) probes

- probes facilitate the connection between the measured circuit and the oscilloscope; many kinds of probes for different measurement needs
- power measurements are generally not possible without special voltage and current probes

Oscilloscope probing

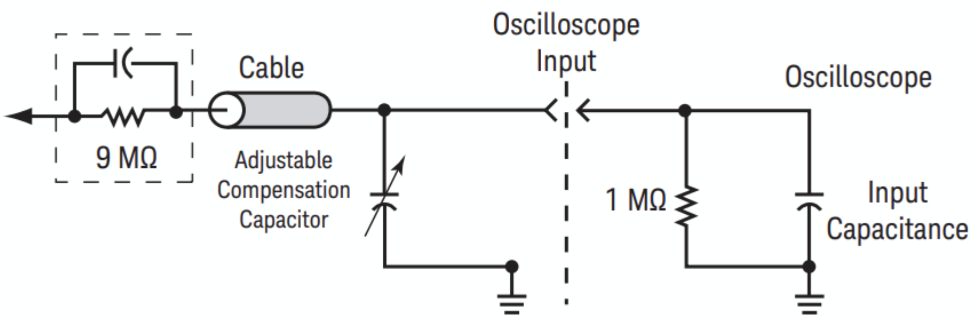
- an ideal probe would:
  - be able to reach any point of the DUT
  - present a perfect replica of the measured signal
  - have an infinite range and would not add any noise
  - would not affect the probed circuit
- unfortunately, ideal probes do not exist:
  - probes influence the measured circuit and change the signal shape
  - at the same time, they are not able to reproduce the measured signal 100 % correctly – non ideal frequency response; noise, ...
  - it can be difficult to reach and contact the measurement point

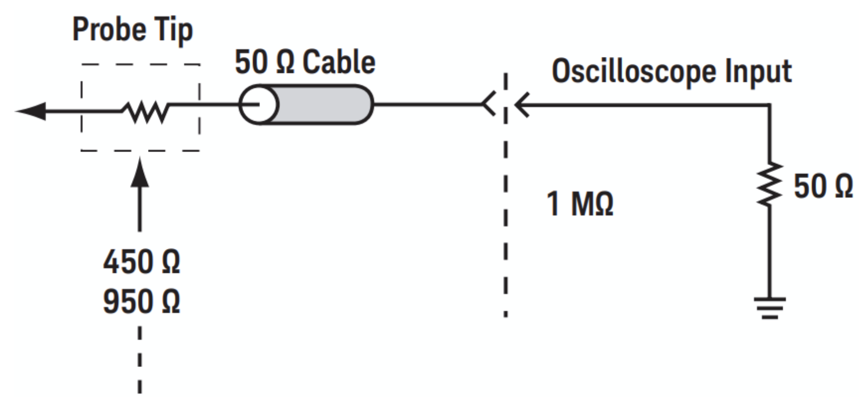
Types of probes



Passive voltage probes

- rugged, inexpensive, wide dynamic range; only single-ended
- high impedance
  - relatively high bandwidth – 500 MHz ~ 1 GHz
  - 10:1 – most common; ~ 400 V
  - 100:1 – ~ 2 to 3 kV rms
  - high capacitive loading
- low impedance
  - requires 50Ω scope input
  - low C/high R loading
  - up to 1,5 GHz





Active voltage probes

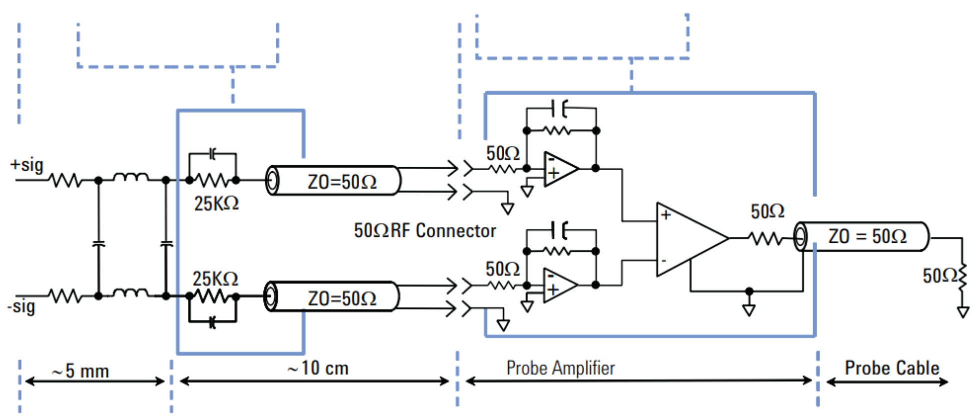
- better signal integrity (less parasitics), lower circuit loading
- differential or single-ended
- more expensive

„high speed“

- higher bandwidth (52 GHz)
- low input voltage (diff/common)
- in circuit testing on digital transmission lines

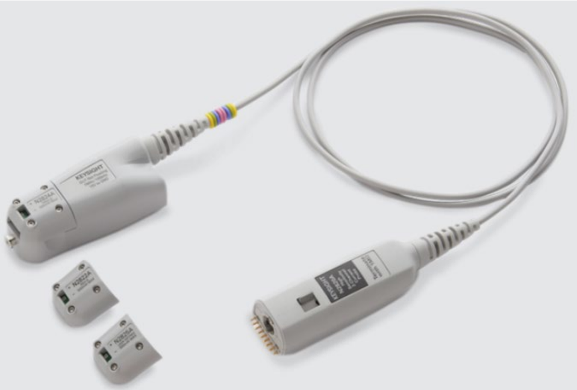
„high voltage“

- lower bandwidth (hundreds of MHz)
- higher input voltage
- general purpose or special high voltage measurements



Current probes

- current → voltage converters
- AC/DC probes:
  - Hall-Effect clamp-on probes
    - bandwidth up to 150 MHz
    - currents of up to 700 A
    - can be easily connected to the measured conductor
  - probes with resistive shunt
    - Keysight N2820A / N2821A special high-sensitivity probes
    - measurement on internal or external shunt resistors



Current probes

- AC only probes:
  1) current transformers with magnetic core
     - higher sensitivity, electrical isolation
     - prone to DC saturation, lower bandwidth, bulky, not easy to connect to the circuit, higher insertion inductance, worse linearity
     - from low to very high currents (tens of kA peak)
     - bandwidth of up to 60 MHz (for lower current versions)

Current probes

2) Rogowski coil probes (with air core)

- low insertion impedance, higher bandwidth, good linearity, no magnetic saturation, electrical isolation
- very flexible to use – coil is easy to wrap around a conductor
- affected by external magnatic fields, worse sensitivity
- 100 MHz BW; up to 120 kA peak

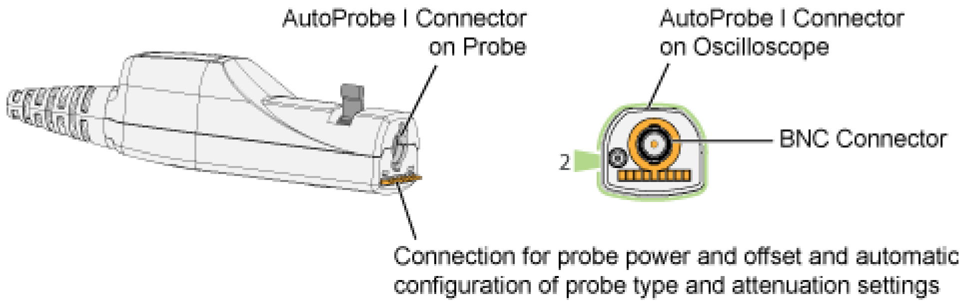
Probe interfaces

- oscilloscope probes can have a universal BNC interface
  - expects a 1 MΩ or a 50 Ω input on the oscilloscope

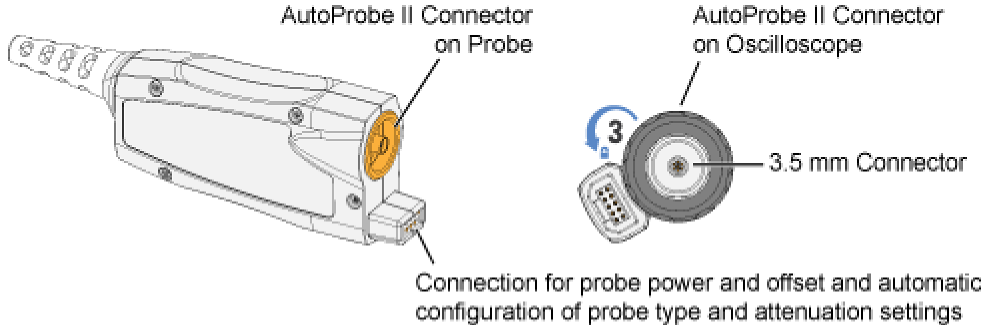
    - in case that 50 Ω is required on a 1 MΩ only scope; a 50 Ω feed-thru load can be used
  - active probes need to be powered and in this case, the power can be supplied from a battery or an external power adapter
  - probe parameters need to be configured manually in the scope
- some active probes use special interfaces proprietary to a specific oscilloscope manufacturer
  - probe interface supplies power to the probe and provides communication; probe setup is done automaticaly

Keysight probe interfaces

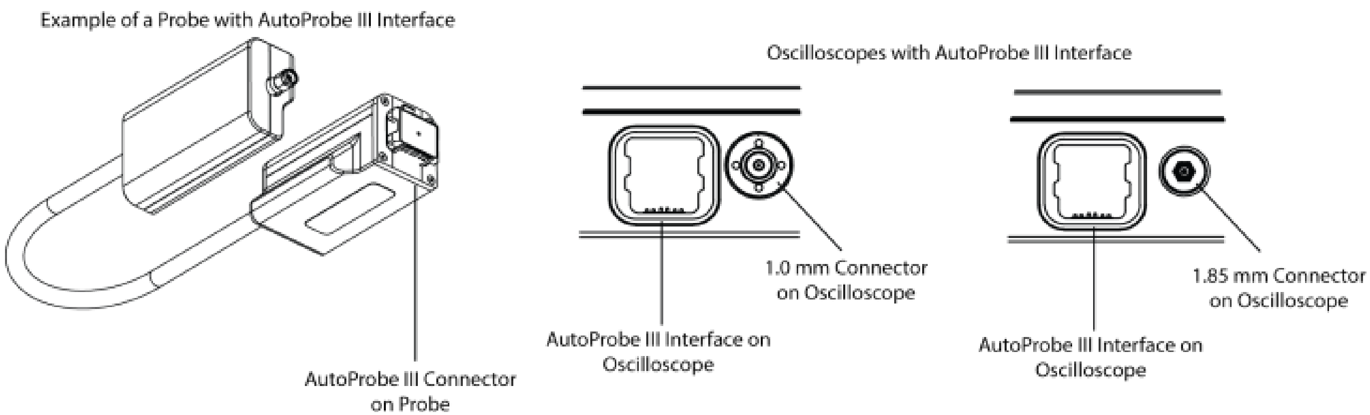
- AutoProbe I:



- AutoProbe II:



- AutoProbe III:

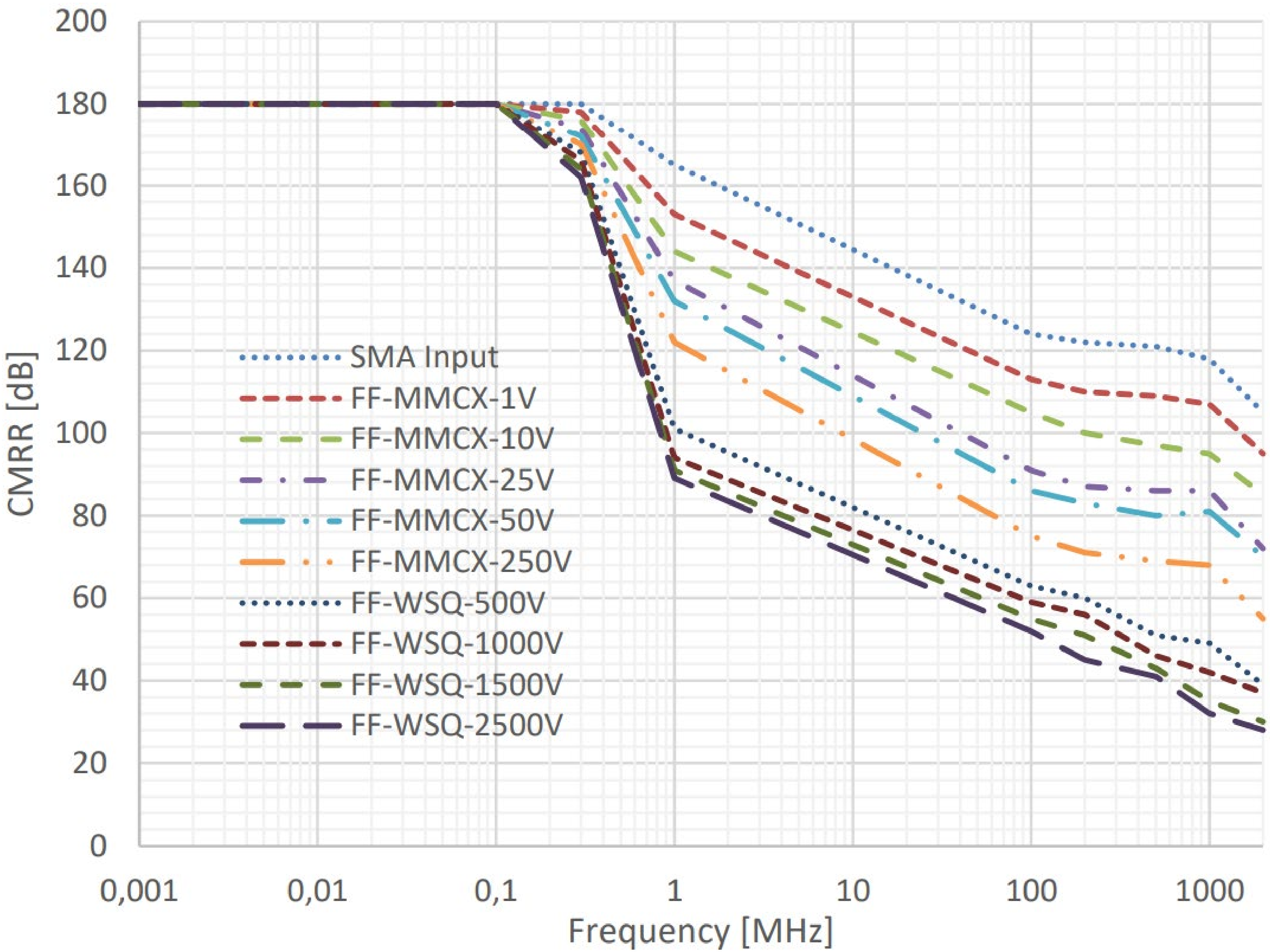


PMK FireFly probe

- special differential high voltage optically isolated probe
- 1.5 GHz BW; ± 60 kV common mode and 2.5 kV differential input
- unmatched CMMR (> 180 dB up to 500 kHz; 80 dB at 1 GHz)
  - the probe is able to resolve high bandwidth and small amplitude differential signals in presence of large common mode voltages
- ideal for GaN / SiC high side V_{GS} measurements
- wide range of input tips and other connection accessories
- universal BNC interface – can be used with any oscilloscope
- probe head is battery powered
  - there will be a „power over fibre“ option soon

PMK FireFly probe

PMK FireFly probe



PMK BumbeBee and HORNET

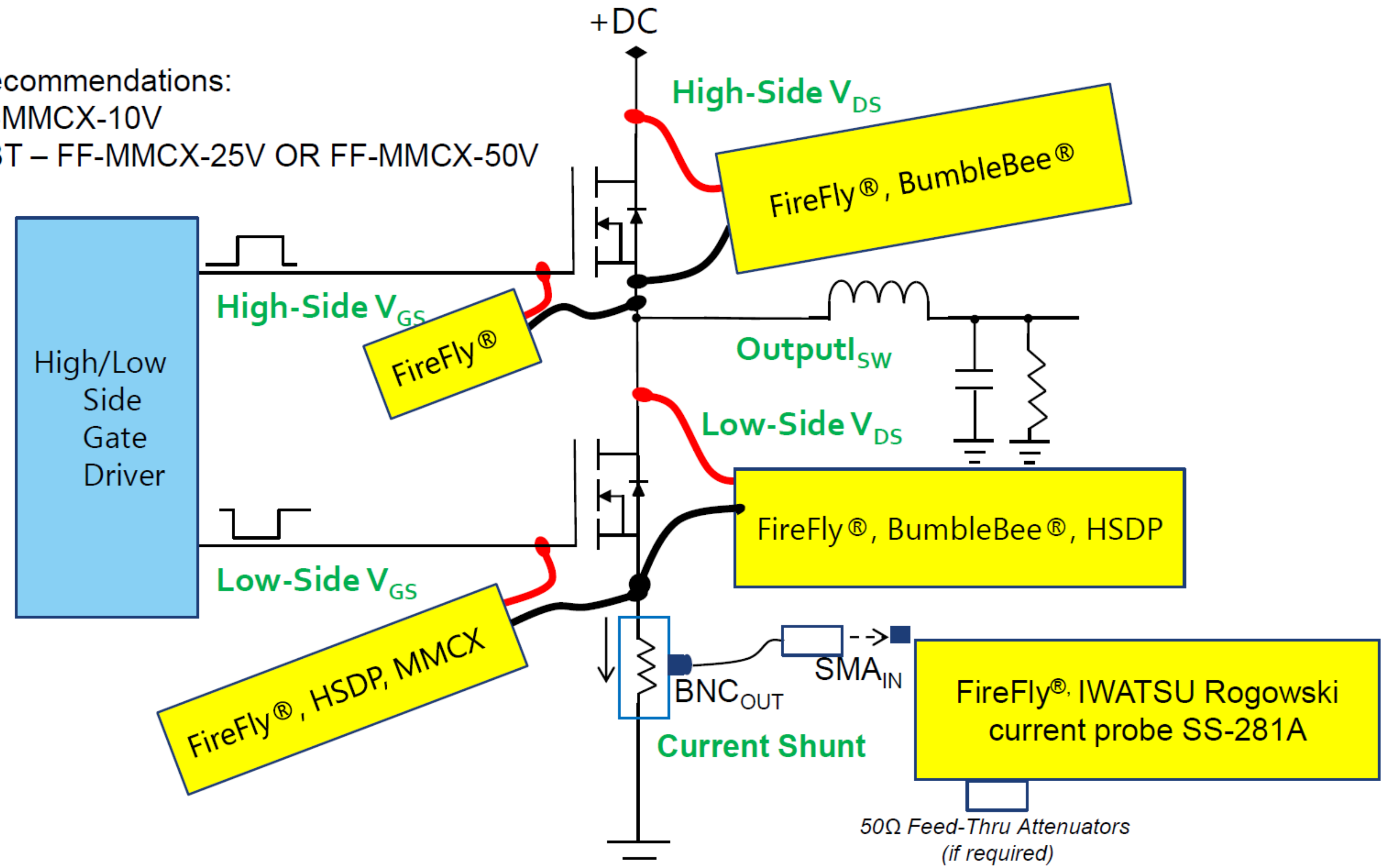
- industry leading high voltage differential probes
  - for less demanding applications than the FireFly, but still very good
- up to 500 MHz BW (depending on the model and selected range)
- five models; up to 200 / 400 / 1000 / 2000 / 4000 V
  - each model has four selectable ranges with different division factor
- high CMMR – 80 dB (DC) to 35 dB (400 MHz) to 80 dB (DC)
- up to 7 m cable length
- universal BNC interface; usable with any oscilloscope
- very wide selection of connection accessories (standard)

PMK FireFly probe

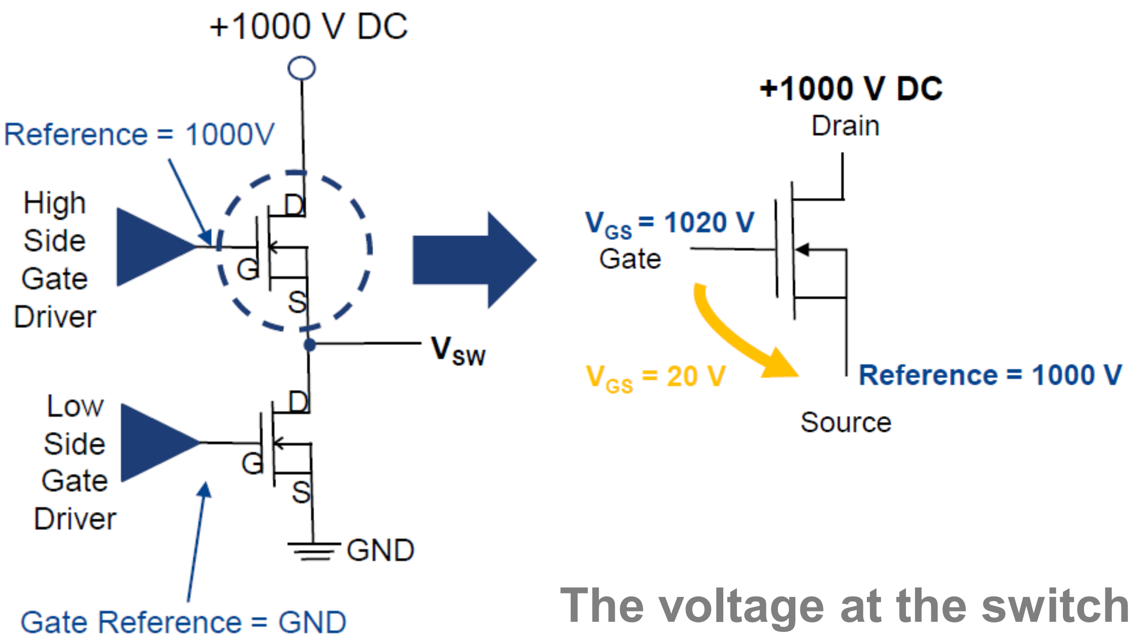
+

Typical measurement setup

V_{GS} Tip Recommendations:
GaN – FF-MMCX-10V
SiC/Si/IGBT – FF-MMCX-25V OR FF-MMCX-50V



High-side measurement



The voltage at the switch node (V_{SW}) swings between the supply voltage (1000V) and the low-side reference voltage (GND).

Common Mode Voltage = 1000 V
Diff. Voltage (HS V_{GS}) = 1020 - 1000 = 20 V

High-side V_{GS} measurement

- resulting common mode error - FireFly with the 25V Input Tip vs. the BumbleBee 1000 V differential probe:

Frequency	CMMR FireFly		CM Error FireFly	CMMR BumbleBee		CM Error Bumblebee
	(dB)	linear		(dB)	linear	
DC	180	1,000,000,000	1 µV	80	10,000	100 mV
1 MHz	137	7,079,458	141 µV	70	3,162	316 mV
100 MHz	91	35,481	28 mV	40	100	10 V
200 MHz	87	22,387	44 mV	40	100	10 V
500 MHz	86	19,952	50 mV	35	56	18 V
1 GHz	86	19,952	50 mV	---	---	---

Keysight N7020A / N7024A

- special single-ended active “power rail” probes
- used for high-sensitivity power integrity measurements on low voltage power rails - ripple, noise, transients
- 1:1 ratio – adds only ~ 10 % to the scope noise baseline
- large offset range of ± 24 V; active signal range of ± 850 mV
  - because of the large offset in the probe, the whole dynamic range of the oscilloscope can be used on the signal of interrest
- low circuit loading – 50 kΩ DC input impedance
- high bandwidth – 2 GHz (N7020A) or 6 GHz (N7024A)

Keysight N7020A / N7024A