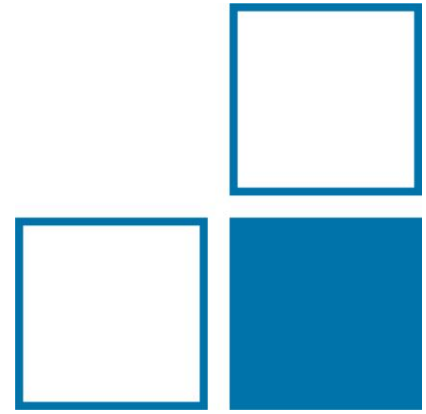
Physikalisch-Technische Bundesanstalt
Braunschweig and Berlin
National Metrology Institute

Elektrooptische Abtastung ultraschneller Photodioden

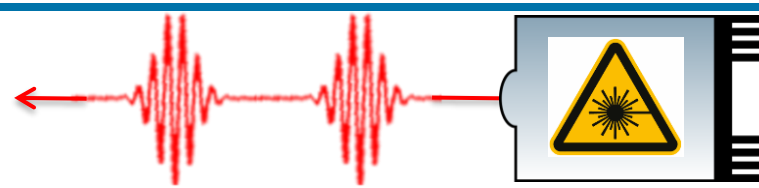
Grundlagen und internationaler Vergleich

AG 2.54 Femtosekundenmesstechnik

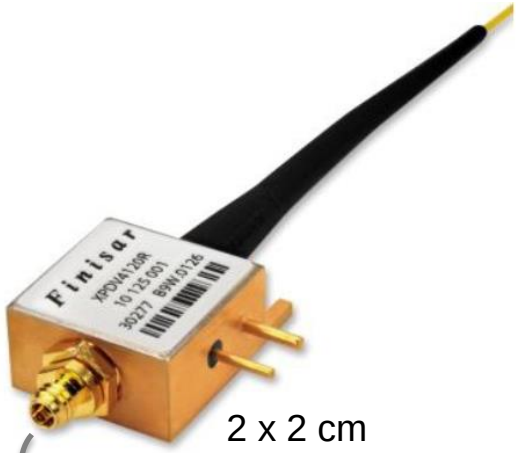
Heiko Füser, Paul Struszewski, Mark Bieler



Ultrafast Photodiodes

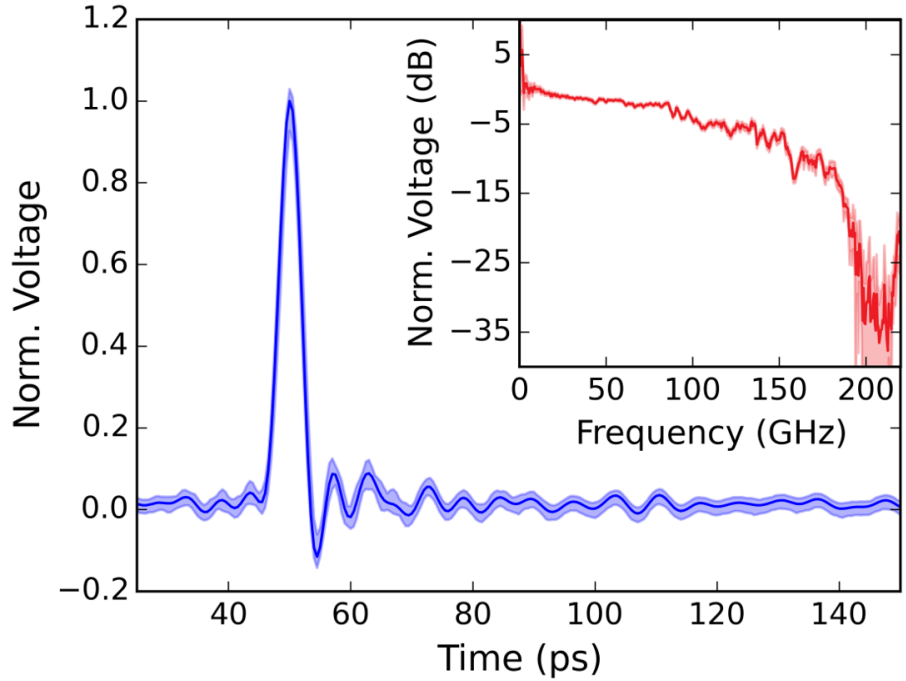


Optical excitation



2 x 2 cm

Electrical signal @ coaxial line (1.0 mm or 1.85 mm)



100 GHz PD:

- FWHM 5 ps
- Frequency components up to 180 GHz

Applications of High-Speed Photodiodes

Optical links in modern communication schemes

- High-bandwidth receiver
- Key technology of 6G networks

Ultrashort voltage pulse standards

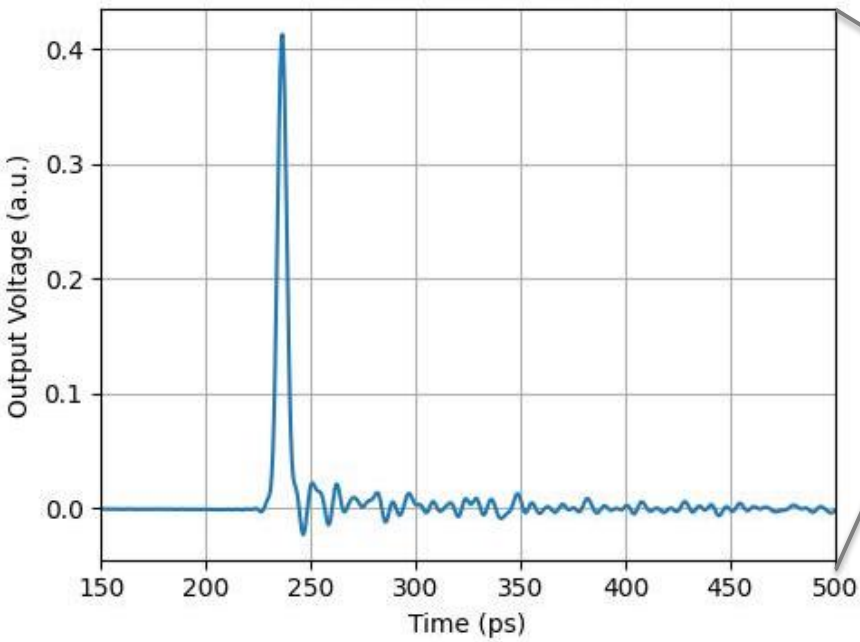
- Metrology: characterization of high-speed electronic devices (e.g., oscilloscopes)
- Transfer standard for industrial usage

Broadband phase reference standard

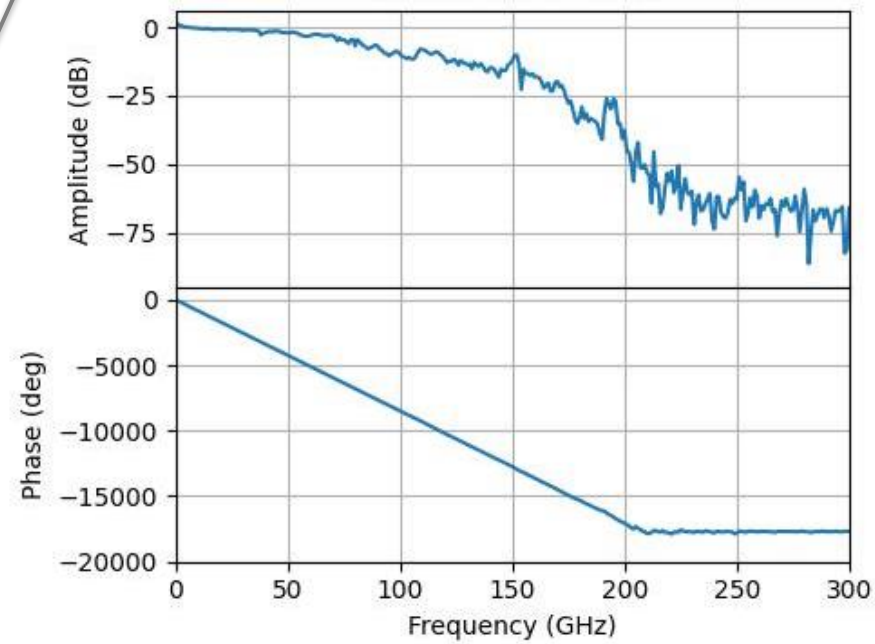
- System design
- System tests

Required:
Detailed knowledge of the impulse response
+
Uncertainty budged
=
Full waveform metrology

Impulse Response

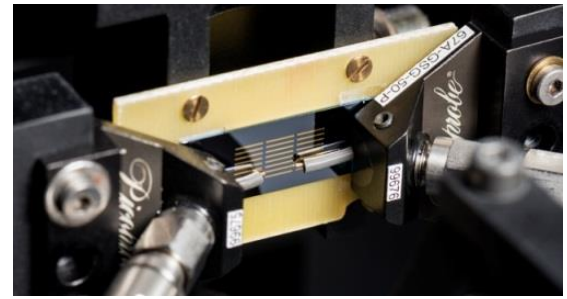


Fourier Transformation



Outline

- Motivation
- General measurement procedure
- International comparison
- Summary & outlook

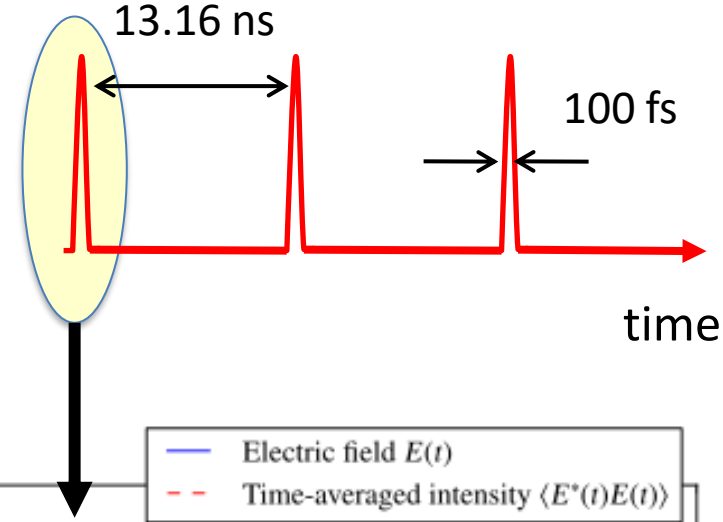


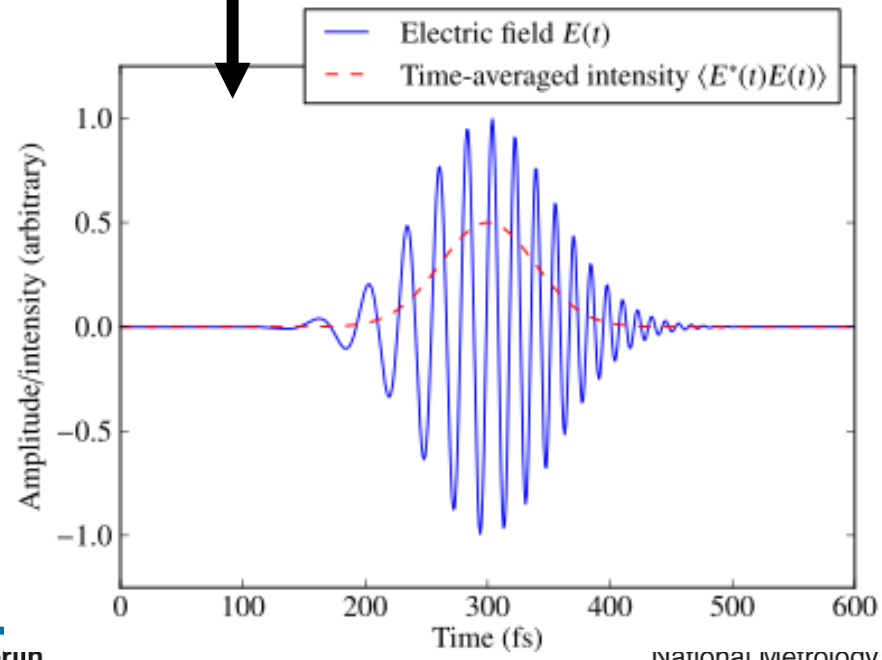
The Femtosecond Laser

Optical pulse train

- Repetition rate ≈ 76 MHz ≈ 13.16 ns
- Pulse length ≈ 15-100 fs
- Wavelength ≈ 800 nm / 1600 nm
  (≈ 380 THz / 190 THz carrier frequency)

http://www.menlosystems.com





The Femtosecond Laser

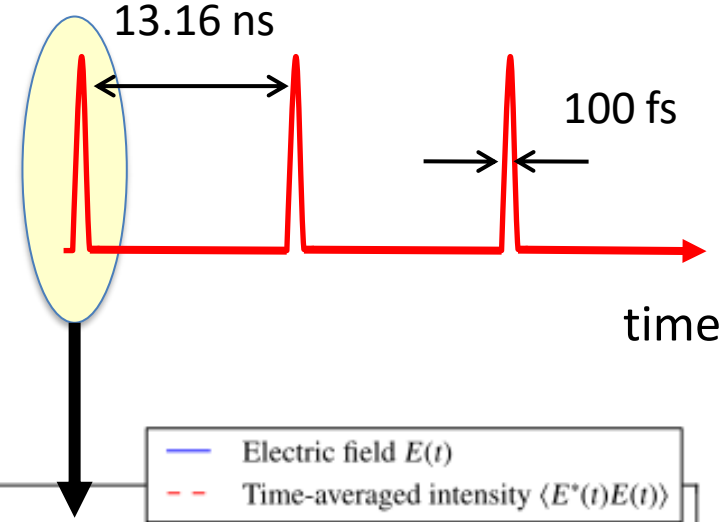
Optical pulse train

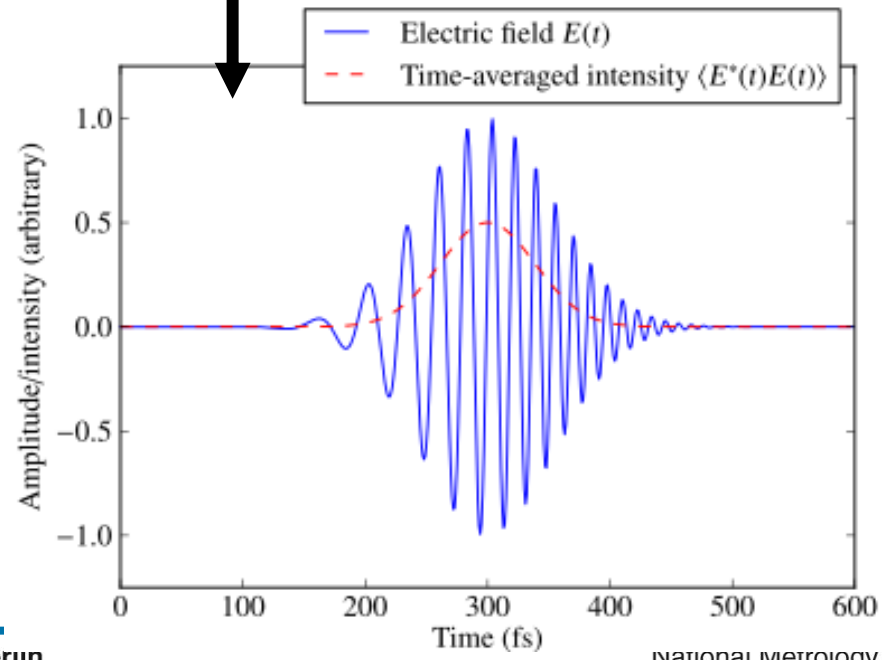
- Repetition rate ≈ 76 MHz ≈ 13.16 ns
- Pulse length ≈ 15-100 fs
- Wavelength ≈ 800 nm / 1600 nm
  (≈ 380 THz / 190 THz carrier frequency)

Smaller than a shoe box!

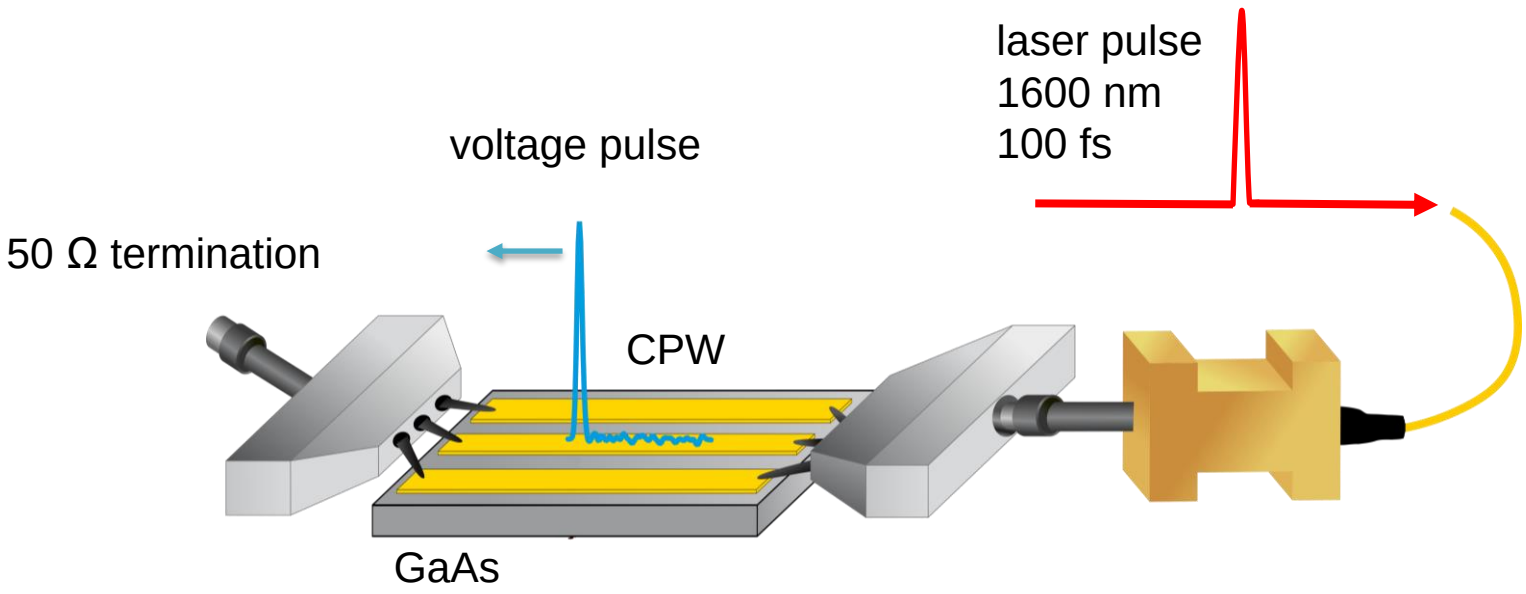
27 x 11 x 8 cm³

http://www.menlosystems.com

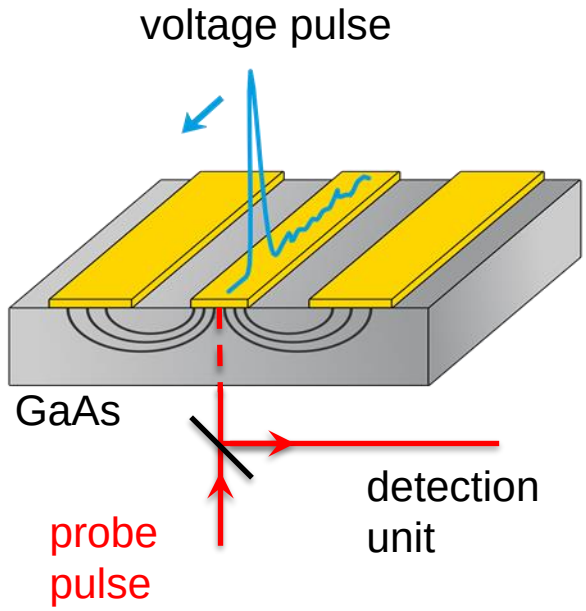




Electro-Optic Sampling



Electro-Optic Sampling



Electrical field changes the refractive index (electro-optical effect)

↓

Polarization change of the probe beam

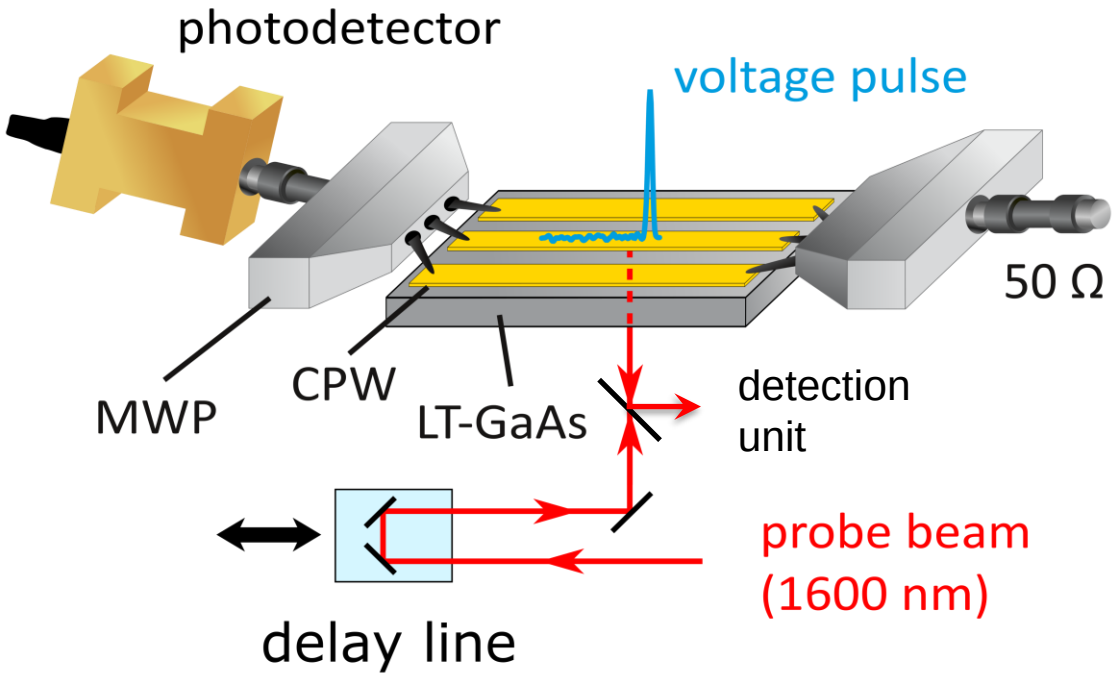
↓

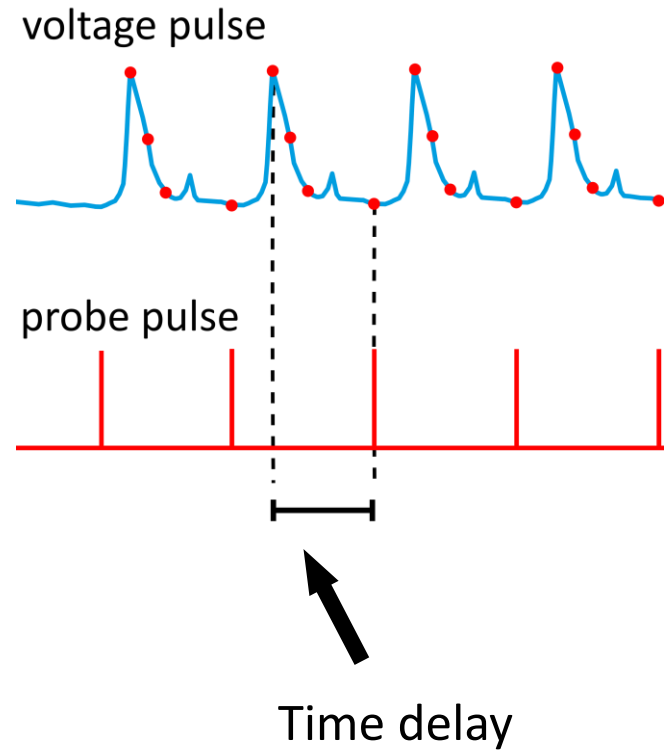
Relative polarization change (∝F) is detected by ellipsometric techniques

$$V_{\mathrm{det}} = G_{\mathrm{det}} E_{\mathrm{laser}}^2 \frac{\omega \Delta l}{c} n_0^3 r_{41} F_z$$

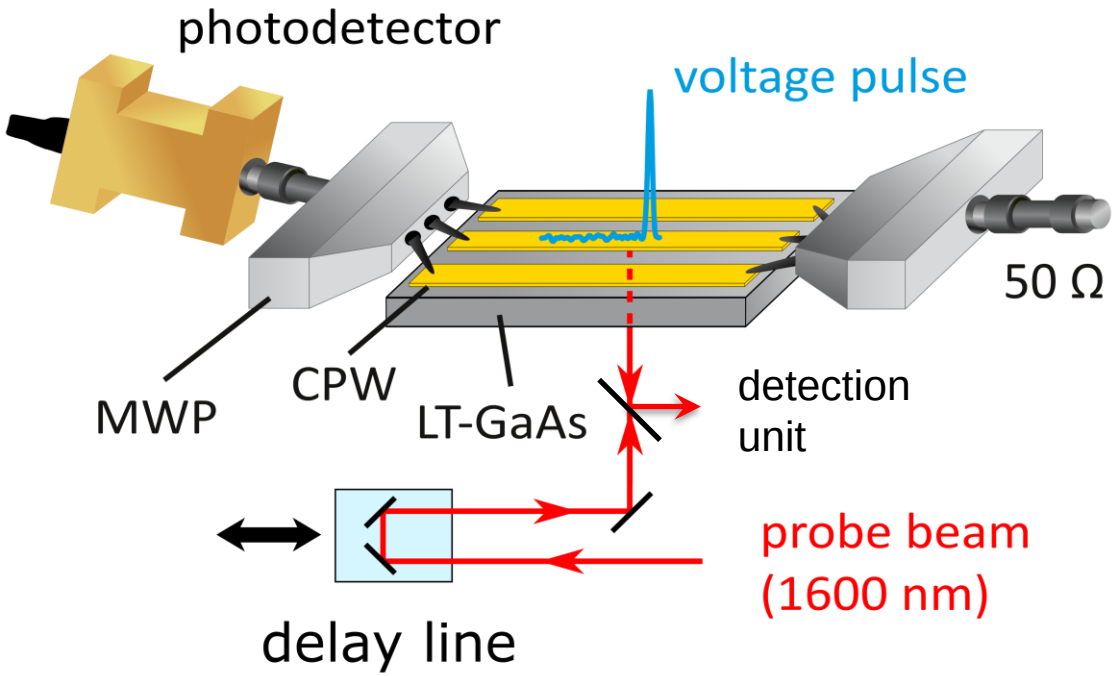
V_{det} : measured detector signal
G_{det} : detector gain
E_{laser} : probe laser field strength
ω : probe laser frequency
Δl : interaction length
c : speed of light in vacuum
n_0 : refractive index of GaAs
r_{41} : electro-optic coefficient
F_z : electric field of the voltage pulse

Detection of ultrashort voltage pulses





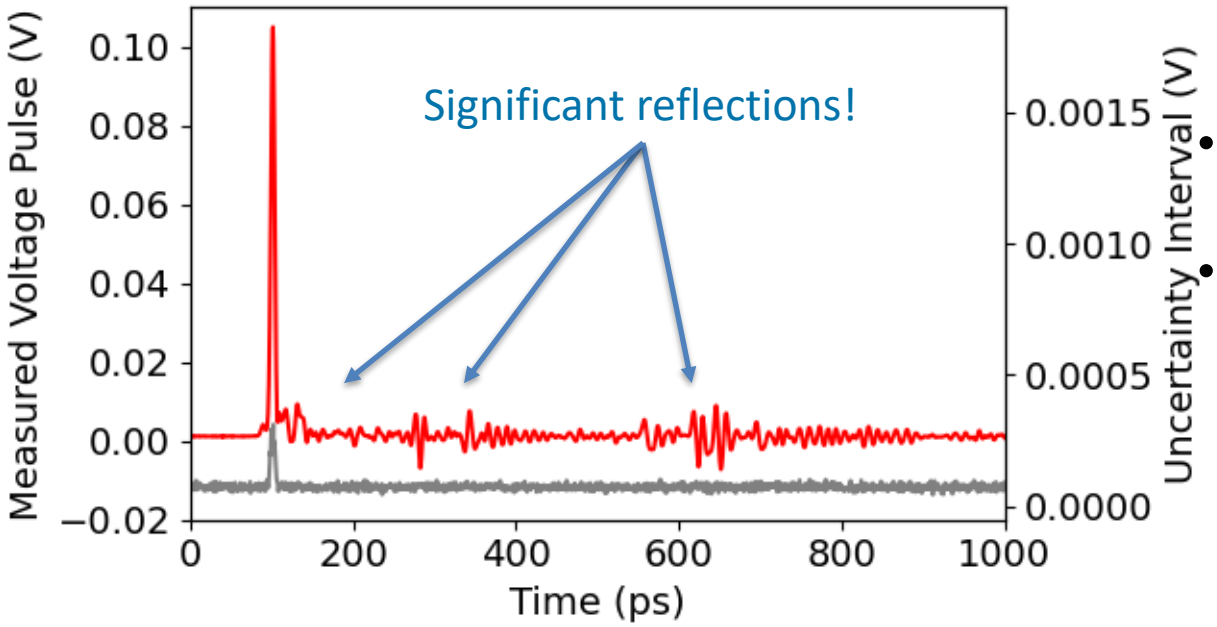
Detection of ultrashort voltage pulses



Properties:

- bandwidth of ~500 GHz
- frequency spacing of 500 MHz
- dynamic range of > 50 dB
- directly traceable to the unit of length (time)

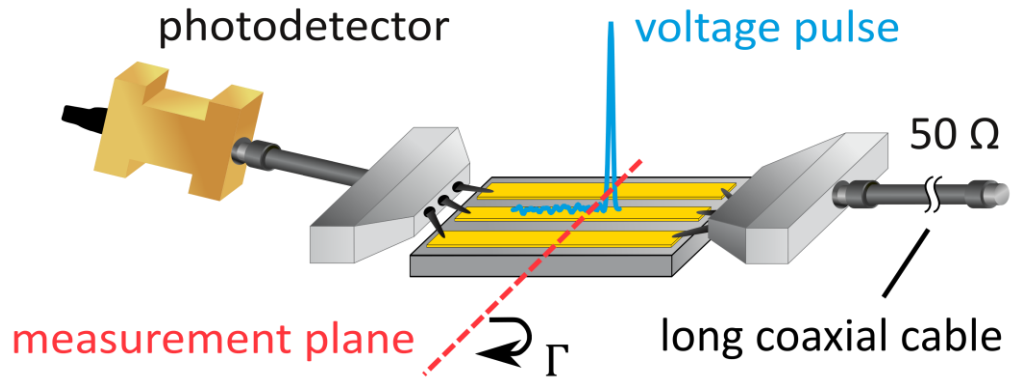
Ultrashort voltage pulses



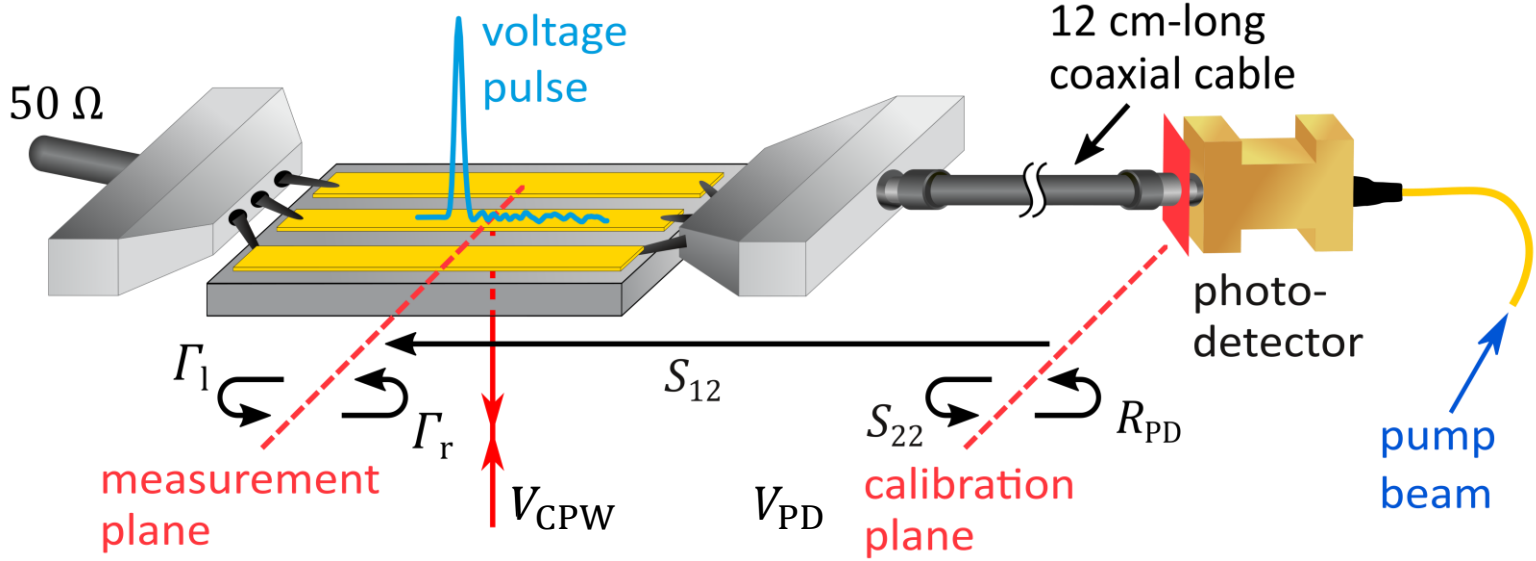
- Signal distortions by MWP and CPW
- Reflections: forward and backward propagating signals overlap

All devices have

50 Ω impedance!



Full Mismatch Analysis



$$V_\mathrm{PD}(\omega) = \frac{V_\mathrm{CPW}}{S_{12}\, Z_\mathrm{R}\, H_\mathrm{EOS}} \frac{(1-\Gamma_\mathrm{r}\Gamma_\mathrm{l})(1-S_{22}R_\mathrm{PD})}{1+\Gamma_\mathrm{l}}$$

$\Gamma_r, \Gamma_\mathrm{l}$: Reflection coefficients

S_{12}, S_{22} : Scattering parameter

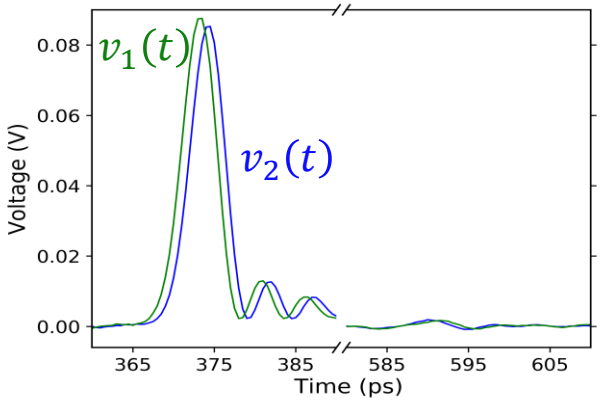
H_EOS : EOS transfer function

Z_R : Impedance ratio (CPW, coax)

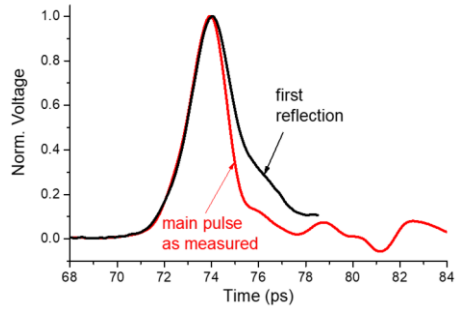
https://doi.org/10.1109/TMTT.2015.2481426
https://doi.org/10.1007/s10762-017-0433-7

Full Mismatch Analysis

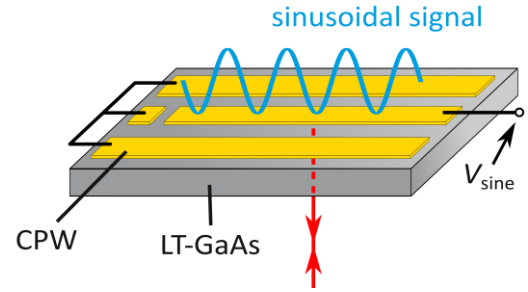
Γ_r, Γ_l: spatial shift of measurement position



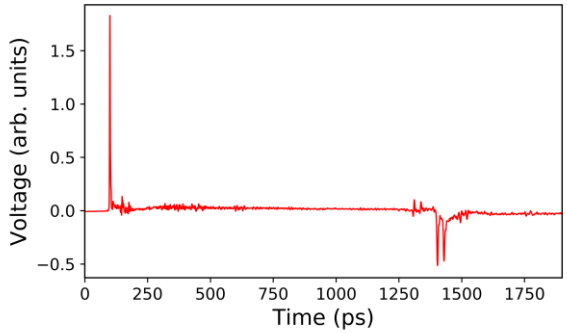
H_{EOS} via optical reflex



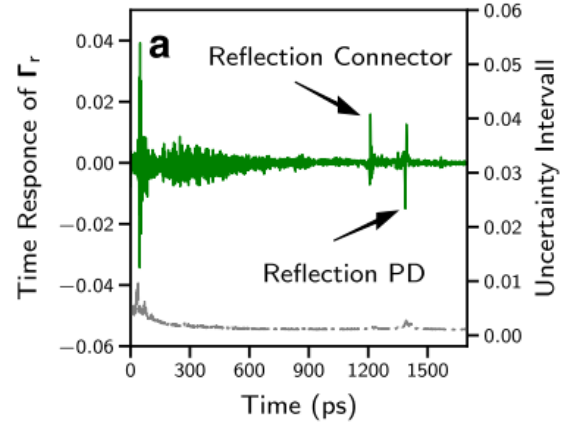
Amplitude: normalization via reference signal



S_{12}: Reflection analysis with short

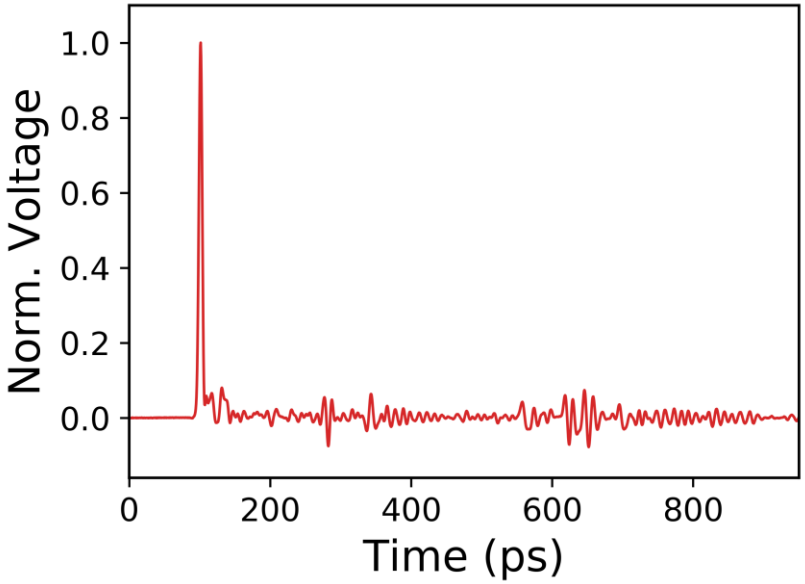


$S_{22}R_{PD}$: reflection analysis

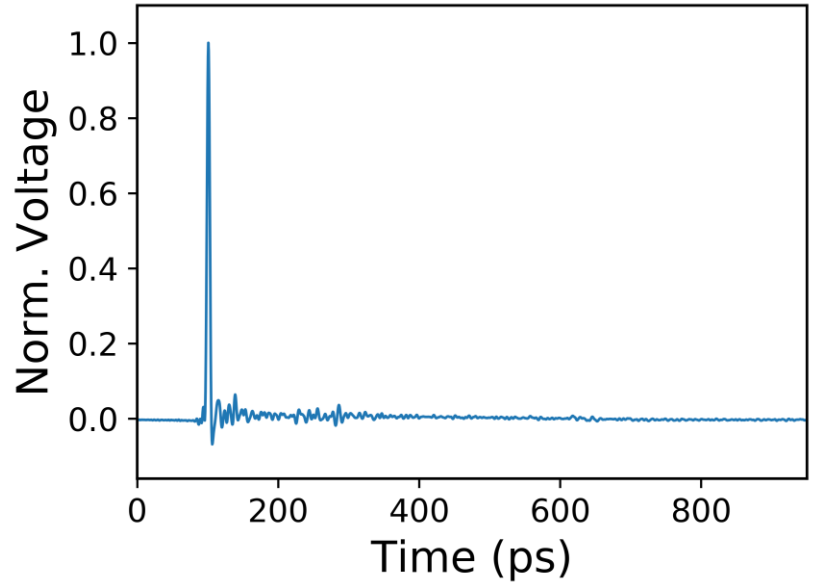


Full Mismatch Analysis

Measured voltage V_{CPW}

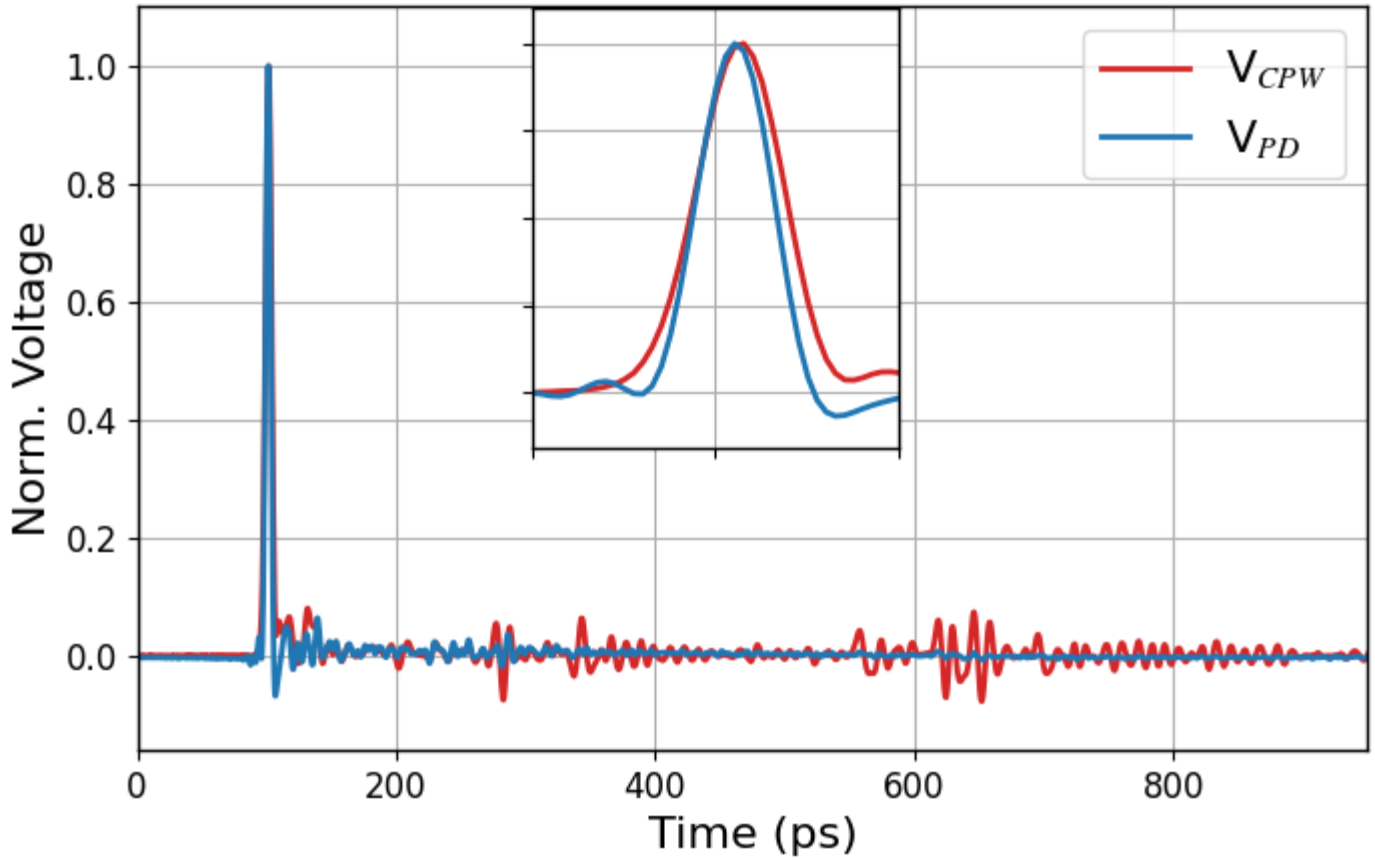


Photodetector response V_{PD}



https://doi.org/10.1007/s10762-017-0433-7

Full Mismatch Analysis



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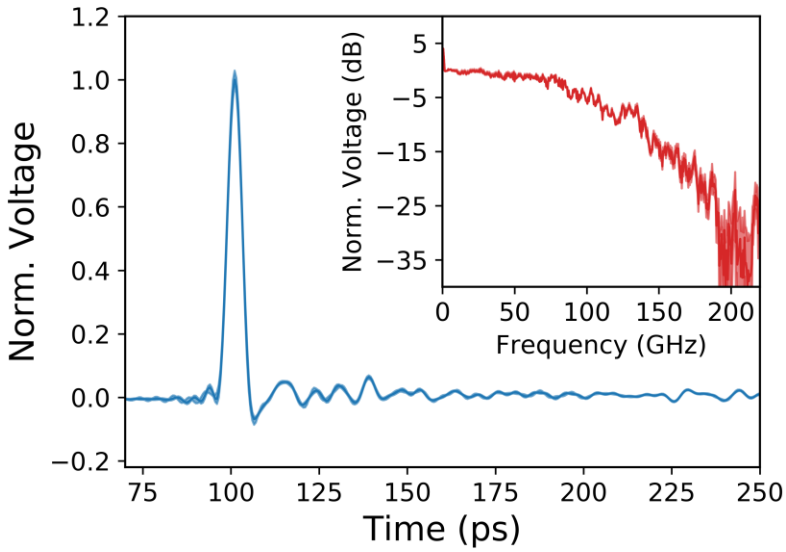
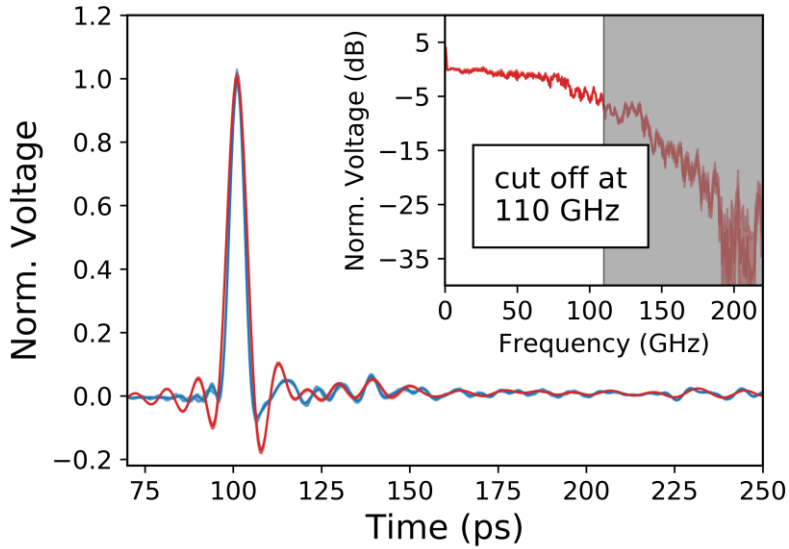
Full Mismatch Analysis



- pulse width: 4.6 ps
- flat spectrum up to 130 GHz
- frequency components up to ~180 GHz



- cut-off at 110 GHz leads to significant changes in the time-domain response (pulse width: 5.9 ps)

Calibration and Measurement Capability

Zusatzleistungen

Quantity	Instrument or Artifact	Method of Measurement	Minimum value	Maximum value	Units	Parameter	Specifications	Value	Units	Coverage Factor	Level of Confidence	Is the expanded uncertainty a relative one?
Signal and pulse characteristics: step response	Ultrafast photodiode	Optoelectronic time-domain measurements based on femtosecond lasers	-0.1 (multivariate quantity)	1.5 (multivariate quantity)		Nominal bandwidth, type of coaxial connector, excitation wavelength	70 GHz or 100 GHz, 1.85 mm or 1.0 mm, 1550 nm	Typically between 0.005 - 0.3 (multivariate quantity, depends on MC simulations)		2	95%	No

https://www.ptb.de/cms/fileadmin/internet/fachabteilungen/abteilung_2/QMH_A2_KAP_31_V17_2020_web.pdf

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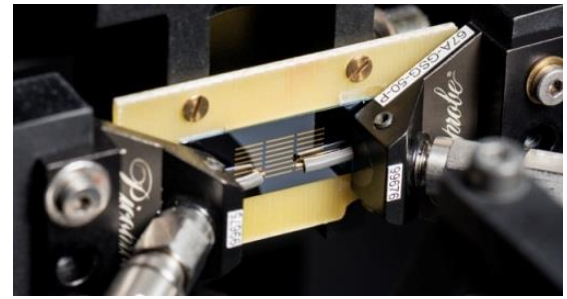

International Comparison

- First international comparison on ultrafast waveform metrology between 4 NMIs:
  - BIRMM & NIM (China)
  - PTB (Germany)
  - NIST (USA)

- Comparison of the frequency- and time-domain response of a high-speed photodiode

- Measurements started in spring 2018 and ended in summer 2019

- Publication
  10.1109/CPEM49742.2020.9191926

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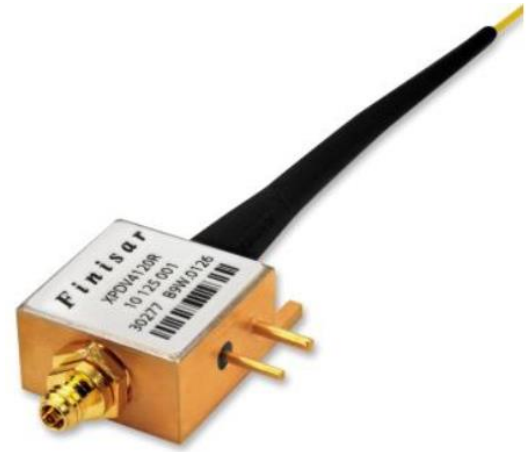
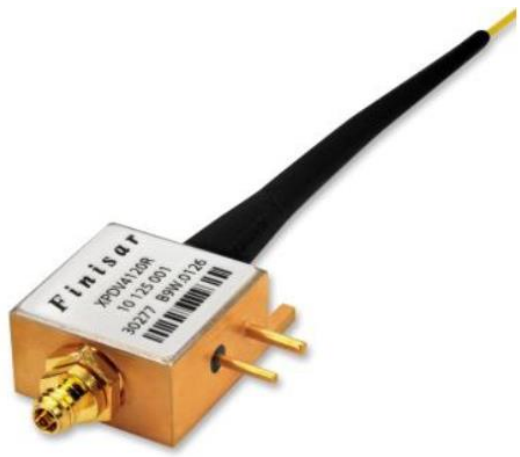
National Institute of Standards and Technology
U.S. Department of Commerce



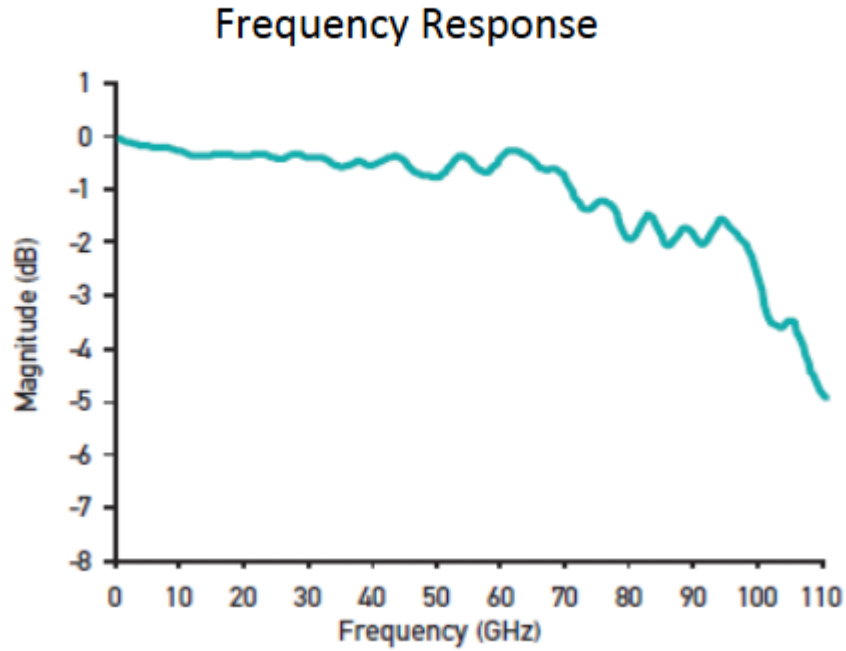
Device under Test

100 GHz Photodetector

- Optical input 1550 nm
- 1.0 mm coaxial output
- 3dB bandwidth 100 GHz



Typical Performance



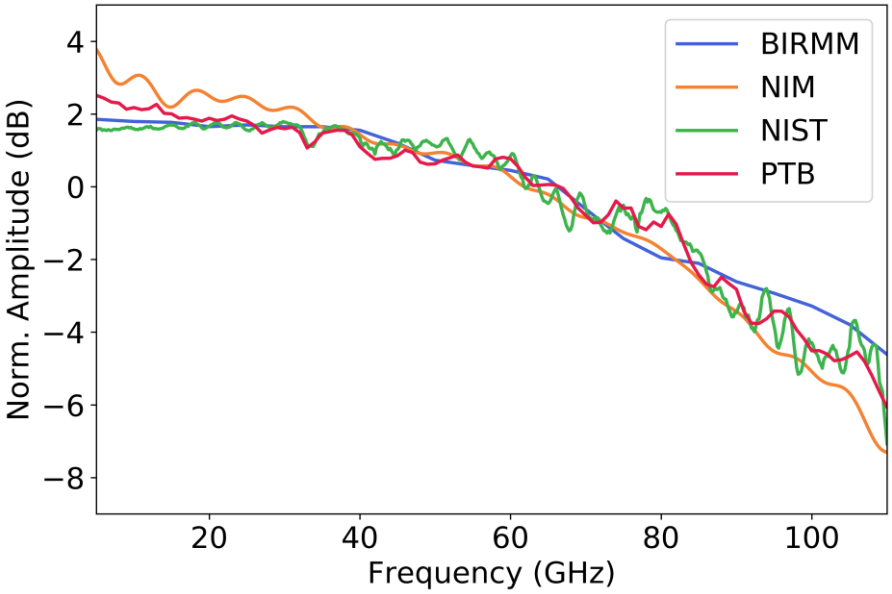
https://ii-vi.com/product/100-ghz-single-high-speed-photodetector

Partner Details

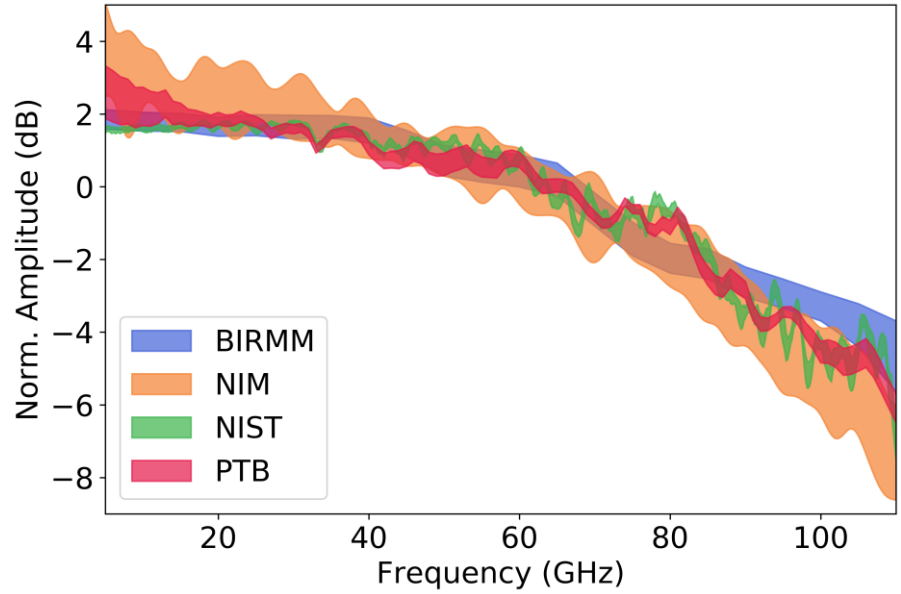
	PTB	BIRMM	NIM	NIST
Laser	76 MHz 100 fs	250 MHz 100 fs	80 MHz 80 fs	10 MHz 100 fs
Substrate	(001) GaAs reflection	(001) GaAs reflection	y-cut $LiTaO_3$ transmission	y-cut $LiTaO_3$ transmission
S-Parameter, Reflection Coefficients	Laser-based VNA	Laser-based VNA	VNA	VNA
Uncertainty Contributions	EOS, impedance, scattering parameters, measurement repeatability	delay line, reflections, de-embedding, measurement repeatability	EOS, impedance, scattering parameters, measurement repeatability	impedance, reflections, field penetration, radius/width of the beams, measurement repeatability
Uncertainty correlation / propagation	Monte-Carlo simulations	Monte-Carlo simulations	Monte-Carlo simulations	NIST Microwave Uncertainty Framework

Results: Frequency Domain Amplitude

Best estimates



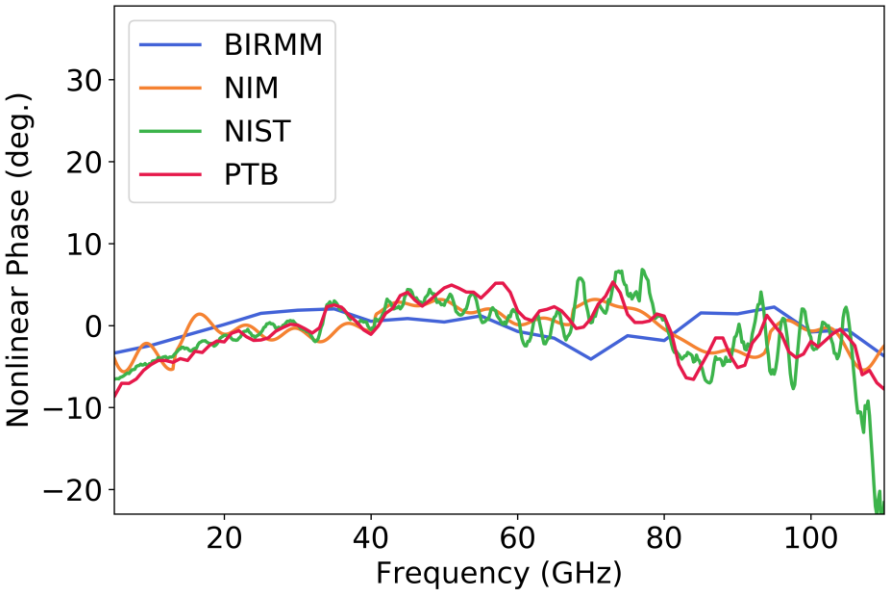
95% coverage intervals



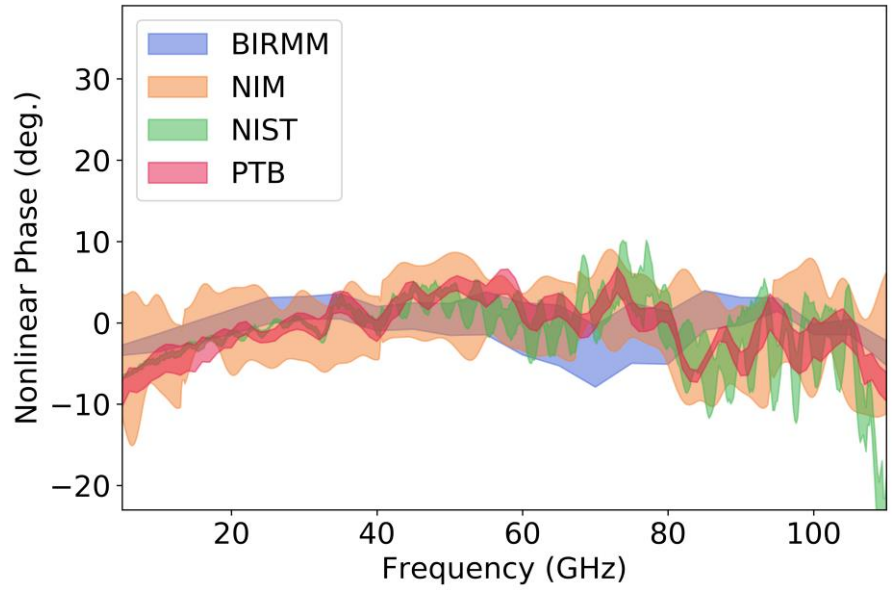
- Normalized to mean value obtained from frequency range [10 GHz, 100 GHz]
- Very good agreement in frequency range 30 GHz → 70 GHz
- Larger deviations (2 dB) at very small (<10 GHz) and very large (>100 GHz) frequencies

Results: Frequency Domain Phase

Best estimates

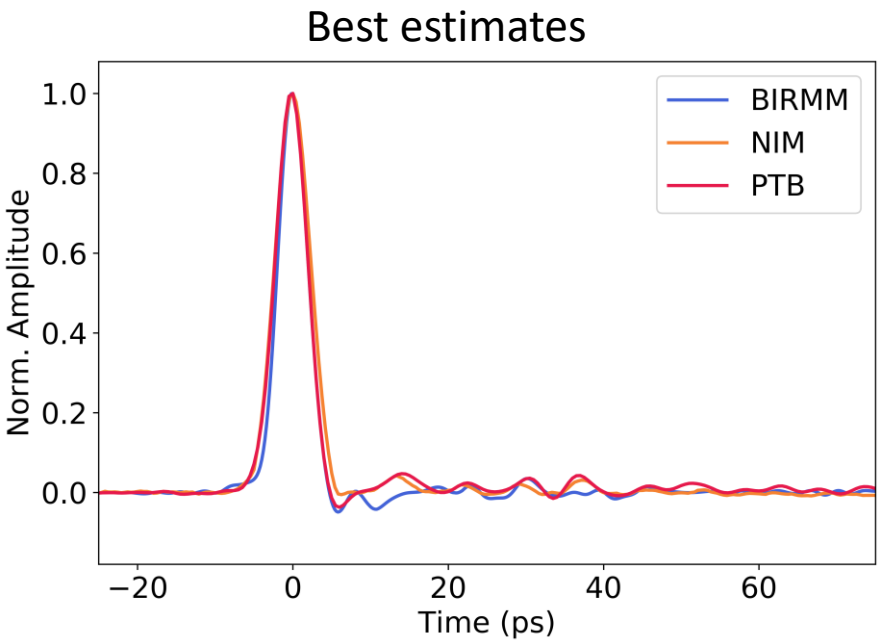


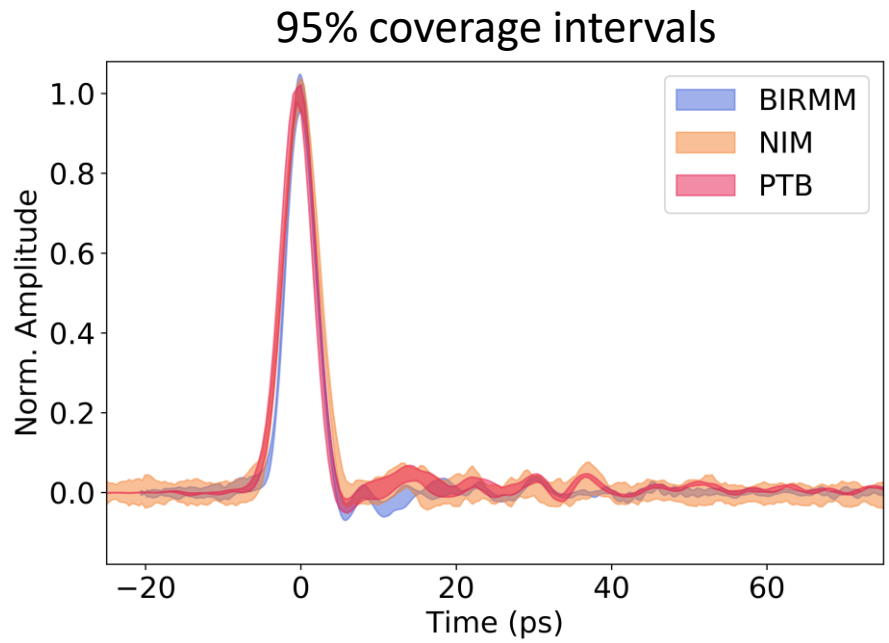
95% coverage intervals



- Linear phase obtained from frequency range [10 GHz, 100 GHz] was subtracted
- Good overall agreement, some features observed by several partners
- Size of coverage intervals vary, not all intervals overlap

Results: Time Domain

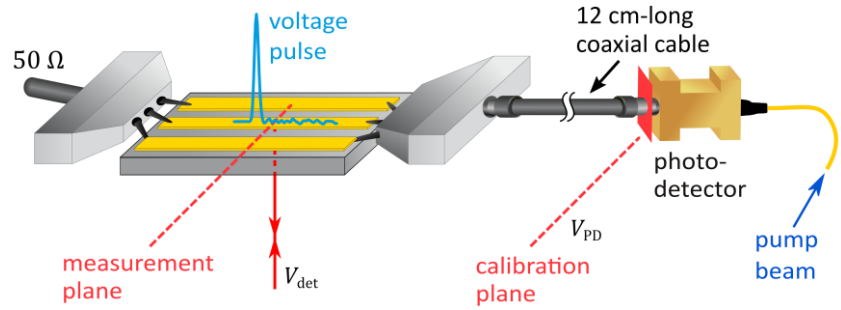




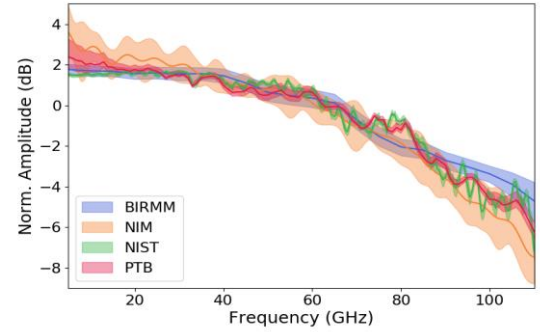
- NIST's limitation to 110 GHz does not allow one to plot time-domain response
- Maximum normalized to one and shifted to 0 ps
- Some oscillations after the main peak nicely reproduced

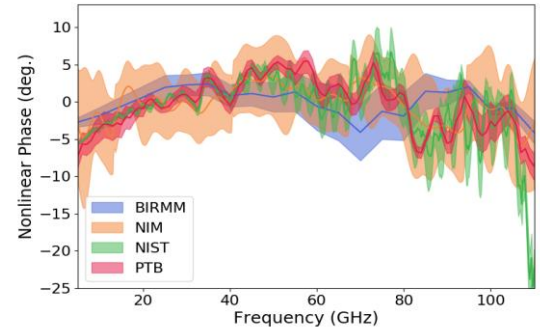
Summary & Outlook

- Ultrafast waveform metrology: Characterization of photodiodes



- First international comparison
  - Overall good agreement despite different measurement techniques
  - Not all coverage intervals overlap
  - Not all features were reproduced by all NMIs





Further work:

- IEC standard on sample-by-sample uncertertainty
- Improve low-frequency uncertainty
- Quantitative electro-optic sampling

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Thank you for your attention

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