Traceability of High-Speed Electrical Waveforms at NIST, NPL, and PTB

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Abstract — **Instruments for measuring high-speed waveforms typically require calibration to obtain accurate results. The national metrology institutes of the United States of America, the United Kingdom, and Germany offer measurement services based on electro-optic sampling that can be used to establish a traceable calibration chain between high-speed waveform measurements and the SI. These services are increasingly switching to a *full waveform metrology* paradigm, obtaining an estimate of the central value and associated uncertainty of the entire waveform as a function of time.**

Index Terms — **Electro-optic sampling, metrology, oscilloscope, photodetector, pulse, ultrafast, uncertainty, waveform.**

I. Full Waveform Metrology and Traceability

Accurate electrical waveform measurements are required to assess modern data-intensive communications. Traditionally, a small collection of waveform parameters [1], such as transition duration and amplitude, have been used to specify a waveform. This leads to a loss of information since, for example, infinitely many different pulses may have the same transition duration but differ in other significant details. As increasingly complex waveforms are required to carry greater amounts of information this information loss becomes unacceptable and a new measurement paradigm is required.

Our respective metrology institutes are developing such a paradigm, which we refer to as *full waveform metrology*. Its goal is an estimate of the central value and associated uncertainty at each time point. Because the corrections for systematic effects are conducted in the frequency domain, and our goal is also to characterize signals and devices in both the time- and frequency-domains, we must account for correlations between uncertainties at different times and/or frequencies as in, *e.g.*, [2, 3]. In the context of electrical measurements, this necessitates the additional characterization of impedance. From the full waveform measurement, uncertainties on any waveform parameter may be derived [2-4]. Using this paradigm, waveform measurement instruments and, in turn, signal sources can be made traceable to the SI.

NIST, NPL, and PTB use electro-optic sampling (EOS) techniques, in conjunction with ultrafast lasers (duration ~100 fs), as primary standards for high-speed electrical measurements. Such techniques are capable of measurement bandwidths on the order of 1 THz and the dominant contributors to the measurement can be characterized traceably to the SI through physics-based measurement models.

II. Traceability at NIST

NIST's primary EOS system [2,5] splits the linearly polarized output of a 1550 nm Erbium-doped fiber laser into pump and sampling beams to calibrate a 1.00 mm coaxially connectorized photodiode, which is then used in turn to calibrate lightwave component analyzers and a large class of waveform measurement instruments. When illuminated by the pump, the photodiode creates a series of electrical impulses at its coaxial output which propagate through a microwave probe to a coplanar waveguide (CPW) that is fabricated on an electro-optic (EO) $LiTaO_3$ wafer.

The sampling beam passes through a variable optical delay and is then focused through the gap between the center and outer conductors in the CPW and through the $LiTaO_3$. The electric field in the crystal changes the polarization of the sampling beam via the (EO) effect, and this change is detected with a polarization compensator, polarizer, and balanced detector. The pump beam is modulated to enable lock-in detection and improve sensitivity. By using the optical delay to vary the time at which the pulse reaches the electro-optic crystal relative to the photodiode output, the electrical waveform on the CPW is sampled as it evolves with time. Calibrating the variable optical delay provides traceability of the time axis of the measurement to the unit of length, and thus to the unit of time.

The probe, CPW, and termination distort the measured waveform. This distortion is characterized and traceably compensated for as described in [5]. First, the scattering parameters of the photodiode, probe, and termination are measured by use of a vector network analyzer in conjunction with coaxial standards and a multi-line thru-reflect-line calibration set fabricated on the $LiTaO_3$. These scattering parameters are then used to determine the impedance levels in the measurement system and determine the frequency-domain voltage the photodiode would generate across a 50 Ω load. These frequency-domain results can then be Fourier transformed to traceably characterize temporal- and frequency-domain instruments up to 110 GHz.

III. TRACEABILITY AT NPL

The NPL primary standard EOS system differs from the NIST system in its use of a 850 nm mode-locked Ti:Sapphire laser, an external $LiTaO_3$ EOS probe and a CPW fabricated on GaAs epitaxially grown at low temperature (LT-GaAs) with a semi-insulating GaAs substrate. The $LiTaO_3$ probe is placed in close proximity to the CPW and the sampling pulses focused and returned from the $LiTaO_3$ probe via a total-internal-reflection geometry [6]. The inclusion of a photoconductive switch in the CPW enables the generation of electrical pulses of 1-2 ps duration by focusing the pump beam onto the biased switch. Alternatively, photodiodes can be measured, as above. The sampling pulses can be linked to a 1480-1550 nm ultrafast laser, for photodiodes operating within this range, or to a microwave signal, to enable EOS of purely electrical sources.

Calibration of the CPW-to-coaxial transition is achieved by connection of impedance standards to the microwave probe and measuring over an epoch of suitable range to include the input pulse waveform from the photoconductive switch and the reflections from the standards as well as the other parts of the system [7]. A reflection model under development determines the reflection coefficients and match corrections for connected devices under test. Deconvolution techniques are used to determine the waveform response or output at the coaxial connector (1.85 mm or 1.0 mm) [8], with the final aim being the determination of the individual point uncertainties for the derived waveforms.

IV. TRACEABILITY AT PTB

The PTB primary standard EOS system uses a femtosecond laser operating at 900 nm with a CPW fabricated on LT-GaAs incorporating photoconductive switches similar to the NPL system. However, because a significant portion of the 900 nm laser power is transmitted through the GaAs substrate, and GaAs exhibits the EO effect, sampling is achieved by transmitting the focused sampling beam through a point between the center and outer conductors. This technique allows quasi-noninvasive sampling influenced only by propagation effects [9]. Detection of the change in polarization of the sampling beam is achieved as in the other two systems.

The PTB system has been shown to be capable to generate and detect voltage pulses with a frequency spectrum extending up to 1 THz [9] and has been applied to the characterization of the time response of 70 GHz [10] and 100 GHz [3] sampling oscilloscopes. The measurement uncertainty is propagated using Monte-Carlo simulations, allowing for determination of correlations in the uncertainty estimate [3] and traceability of the full waveform measurement to the SI.

V. PROPOSED INTERCOMPARISON

There have been previous comparisons between our institutions in the context of waveform parameters, such as on pulse generator aberrations between NIST and NPL [11], and on oscilloscope transition duration between NPL and PTB [12]. Further comparisons are planned as all three institutions push towards the goal of full waveform metrology.

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