Optoelectronic techniques for improved high speed electrical risetime

Andrew J A Smith, Alan G Roddie and Peter D Woolliams

Centre for Electromagnetic and Time Metrology, National Physical Laboratory, Teddington, Middlesex, TW11 0LW, UK

Abstract — **The NPL optoelectronic system for calibrating high-bandwidth sampling oscilloscopes is described, with emphasis on the importance of accurately defining the impulse response to enable the calibration of fast electrical pulse generators (risetime <15 ps). The problems encountered in determining the waveforms of such pulse generators, particularly aberrations close to the transition and long-term settling, are discussed and a proposal for the application of electro-optic sampling to the measurement of electrical pulse generators is presented.**

I. INTRODUCTION

The National Physical Laboratory in the UK has been at the forefront of developing traceable standards for fast electrical and optical pulse measurements for over 15 years. During this period we have developed a range of electrical and optoelectronic measurements systems for generating and measuring picosecond and sub-picosecond electrical pulses. These systems have been applied to a number of areas including the calibration of sampling oscilloscopes [1], calibration of pulse generators, calibration of photodiodes, electro-optic measurement of MMICs [2] and on-wafer probing. The ultrafast laser and electro-optic sampling system enables us to calibrate the transition duration (risetime) of high bandwidth electrical sampling oscilloscopes, now pushing beyond 50 GHz bandwidth.

In addition to calibrating oscilloscopes, NPL, and other national standards laboratories such as NIST, calibrate the transition duration (risetime) of the step output of electrical pulse/step generators and calibrators, now being developed with risetimes significantly shorter than 15 ps. Such electrical pulse generators are frequently used as both stand-alone instruments and portable calibration transfer standards. The pulse generator is calibrated against a calibrated sampling oscilloscope and therefore the accuracy of the pulse generator calibration is largely determined by that of the oscilloscope. While acceptable uncertainties in the risetime are obtained, problems in determining the oscilloscope impulse response shape, which generally exhibits varying degrees of ringing, may affect the determination of the 100% level of the pulse generator and its aberrations, particularly close to the transition. For longer intervals beyond the transition, sufficiently well-characterised flat-topped electrical pulse generators can be used to improve the knowledge of the oscilloscope response. As customers demand improved knowledge and quantification of the aberrations and their associated uncertainties, of increasing importance when measuring digital signals, then better techniques for measuring these are required. This paper summarises the work at NPL in two areas. Firstly, the latest work on the calibration of fast sampling oscilloscopes is described. Secondly, a novel electro-optic method for measuring electrical pulse generators is proposed.

II. CALIBRATION OF SAMPLING OSCILLOSCOPES

There are essentially four techniques used to calibrate high-bandwidth sampling oscilloscopes, one in the frequency domain and three in the time domain.

The swept frequency technique determines the magnitude response of the oscilloscope to sinusoidal stimuli. A synthesiser sweeps across a range of frequencies from near dc to beyond the bandwidth of the oscilloscope. The synthesiser power is calibrated at the oscilloscope reference plane with a calibrated power sensor. Using this method the 3 dB electrical bandwidth of the oscilloscope can be easily determined but no phase information is available. Both NPL and NIST have successfully used this method and shown good agreement of the frequency domain magnitude with other methods [3,4]. However, without phase the time domain response cannot be determined directly, although in principle it can be modelled by making assumptions about the sampling head.

An electrical pulse generator can be used to calibrate an oscilloscope in the time domain. However, the step output must have sufficiently short risetime for the application (currently available 15 ps risetime generators are only marginally capable of calibrating oscilloscopes with bandwidths up to 20 GHz), and the generator must be calibrated.

Another method is the so-called nose-to-nose technique. Here the kick-out pulse of one sampler is used as a test pulse and measured on a second sampling head [5,3]. By making several assumptions the oscilloscope time and frequency domain responses can be derived. To determine the response of a single sampler, three independent sets of measurements of pairs of samplers are required. The technique is relatively straightforward; however it is worth noting that it is only applicable for one particular sampling architecture, it has many inherent assumptions [4] and by definition uses an input (test) pulse no shorter that the sought oscilloscope response.

NPL favours an optoelectronic technique which is described in more detail here. The method requires a test pulse, shorter than the response of the oscilloscope to be calibrated, and an independent, traceable method of measuring the test pulse with better time resolution (i.e. higher measurement bandwidth).

The short test pulses are generated using a low-temperature–grown GaAs (LT-GaAs) [6] photoconductive switch illuminated by a modelocked femtosecond laser (Ti:sapphire). Electrical pulses of approximately 1.5 ps pulse duration (FWHM) are generated on 50 Ω coplanar waveguide and propagate via a planar-coax transition to the oscilloscope reference plane.

The pulses are measured with an electro-optic sampling (EOS) system [7]. A lithium tantalate probe (20 μm thick, 50 μm wide) is positioned near the planar line along which the electrical pulses propagate (see Figure 1). The electric field induces changes in the birefringence of the crystal which are measured by probing the crystal with polarised light and detecting the induced polarisation rotation. An optical delay line is used to vary the arrival time of the probing pulses relative to the generating pulses. By performing measurements at points over the delay line range, a sampled representation of the generated pulses is built up.

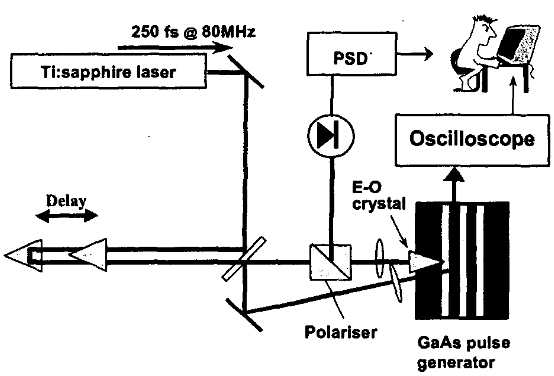

Fig 1. Electro-optic sampling system for oscilloscope calibration.

To determine the oscilloscope response and derive the uncertainties we also measure several other contributions including the timebase linearity, vertical gain linearity, jitter, and reproducibility. The oscilloscope impulse response is derived by deconvolving the jitter and EOS measurement of the photoconductor from the oscilloscope record of the photoconductor, using regularisation filter techniques in the frequency domain [8]. Figure 2 shows the deconvolved impulse responses of two oscilloscopes from different manufacturers. Although the bandwidths of both oscilloscopes are nominally 50 GHz, the difference in the time domain responses shows the importance of such characterisation. The oscilloscope step response is determined by integration of the impulse response.

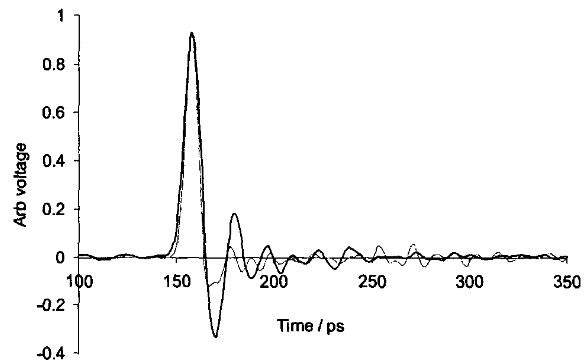

Fig 2. Deconvolved responses of two oscilloscopes.

The inherent advantages of this optoelectronic method are the picosecond time resolution, the jitter-free performance of the EOS system and the fact that no assumptions are required to calibrate the oscilloscope in the time domain.

The method does have certain drawbacks. One problem is determining the effect of the planar to coaxial transition between the optoelectronic pulse generator and the input port of the oscilloscope. Techniques have been developed to de-embed the transition response [9] but errors in this, while having only a small effect on the oscilloscope impulse response duration, can translate to larger uncertainties in the derived step response. The use of ultrashort pulses (1.5 ps) measured over relatively short time windows leads to loss of low frequency information in the calibration process - the typical epoch of the electro-optic measurement is 1 ns or less. Small offsets or drifts in the sampled signal translate to large uncertainties in the integrated step response.

While the impulse response of the oscilloscope is in principle the best method of defining its response, the issues raised above suggest an additional method should be investigated for measuring steps. An electrical step waveform with a well-defined or characterised flat top can provide additional information, particularly on lower frequency components in the response, but requires measurement using a method independent of an oscilloscope. In practice, it is not possible to produce a well-defined step using optical pulse generation. One approach is to use the electro-optic method of measuring electrical signals to characterise an electrical step generator.

III. Optoelectronic Measurement of Pulse Generator

The above explains the reason we are investigating the electro-optic measurement of an all-electrical pulse generator independent of the sampling oscilloscope, to our knowledge not attempted before.

The main issues to consider in implementing such a system include the difference in the repetition rates of the pulse generator and laser, achieving low-jitter synchronisation of the pulse generator with the probing laser pulses, and overcoming the inherent low sensitivity of the electro-optic method.

The laser operates at a repetition frequency of around 80 MHz, set by the cavity length, which is considerably higher than the maximum 1 MHz frequency of most electrical pulse generators. We use an optical "pulse picker" to select laser pulses at a sub-multiple of the repetition frequency.

Providing that the pulse generator under test can be externally triggered it can be synchronised with the laser. The Ti:sapphire laser is passively mode-locked but active stabilisation of the laser cavity length can be used to lock to an external synthesised source. We use a chopper stabilised phase-locked loop system [10] to provide low jitter synchronisation.

The electro-optic sampling process is relatively inefficient, producing signals at the microvolt level. A modulation scheme is required with a lock-in amplifier to reduce the noise contribution of the laser pulses. The lock-in reference frequency must also be lower than that of the pulse generator. In the oscilloscope calibration system, the optical pulses incident on the photoconductive switch were intensity modulated at 1.5 MHz. However, in this case the pulse generator output cannot be directly modulated by applying an arbitrary reference frequency to the trigger and the addition of an eternal modulator after the pulse generator output would severely degrade the signal under test.

We have therefore designed a novel triggering and modulation scheme. The 80 MHz femtosecond Ti:sapphire laser is both phase-locked to a microwave source and pulse-picked to provide optical pulses at an effective repetition rate of 2 MHz. A 2 MHz trigger signal, synchronous with the laser, is derived from a second microwave synthesizer (referenced to the 10 MHz output

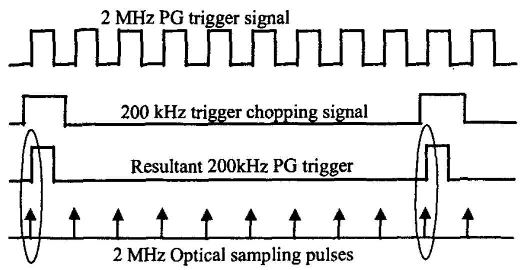

Fig 3. Schematic of triggering pulses for effective modulation.

of the laser stabilisation synthesizer). The slew rate of the sinusoid is increased using an overdriven amplifier to significantly decrease the associated jitter.

This sharpened signal is synchronously chopped with a microwave switch at a sub-multiple of 2 MHz - in this case 200 kHz - using a third source (also referenced to the common 10 MHz) and further electronics to attain a 1:9 mark-to-space ratio. The chopping must be synchronous to prevent the switch introducing spurious edges. The signal (2 MHz signal gated at 200 kHz) is applied to the pulse generator, outputting a clean 200 kHz electrical pulse train. Figure 3 shows a schematic of the triggering pulses.

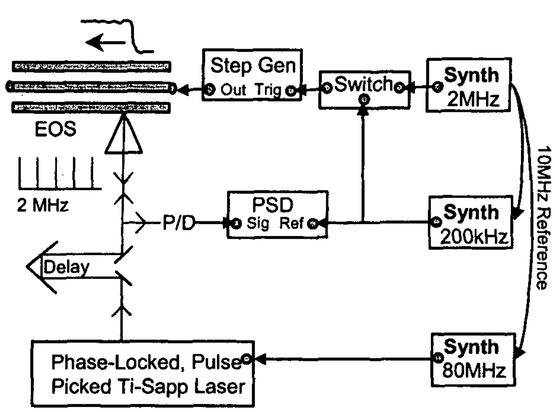

Fig 4. Electro-optic sampling system for pulse generator measurement.

The lock-in amplifier is referenced to the 200 kHz signal. The laser pulses, at 2 MHz, are used to electro-optically sample the pulse generator waveform. Therefore, only every tenth optical pulse provides signal information, the other nine contributing to noise. Figure 4 shows a schematic of the overall system.

One important requirement for the system is to achieve low jitter and wander between the probing laser pulses and triggered pulse generator. Table I summarises some of the relevant jitter contributions measured in the system. Whilst a smaller jitter would provide better information for risetime comparison, the overall jitter of 4 ps is adequate for the application - measuring the pulse generator to characterise the flatness and lower frequency components in its waveform to enable its use for characterising an oscilloscope.

We have demonstrated proof of concept with this system and will report the full results at the conference.

TABLE I
SUMMARY OF JITTER

Contribution	Jitter (rms) ps
Laser - 80 MHz synth (PLL)	2.5
Common reference between synths	1.5
2 MHz synth - pulse generator	<1
Overall (laser - pulse generator)	**4**

IV. CONCLUSIONS

We have described some of the obstacles encountered in calibrating fast sampling oscilloscopes and electrical pulse generators, in particular, the problem of using an imperfectly known oscilloscope impulse response for calibrating a pulse generator with broadly comparable bandwidth. While the electro-optic sampling technique is not perfect – it is difficult to match the planar geometry of the EOS system to the coaxial geometry of the pulse generator and the sensitivity is low – the technique provides an independent measurement with good temporal resolution.

Both the pulse generator and the oscilloscope, when used with the electro-optic system, present the same measurement problem – they have coaxial connectors and require planar sampling geometry. Although the bandwidths of these instruments are different it may be possible to make use of such commonality to extract further information on the planar-coaxial transition with a view to improving the measurements of both pulse generators and oscilloscopes.

In addition to the work described we are examining techniques to calibrate the next generation of both electrical and optical oscilloscopes.

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