

TIME DOMAIN REFLECTOMETRY - AN OPTOELECTRONIC APPROACH

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Introduction

Rapid advances in the fields of telecommunications, computing and optoelectronic technology are driving increased demand for high-bandwidth instrumentation, systems and circuits, with the consequent increase in calibration and traceability requirements. An important area in the dissemination of traceability is the calibration of fast sampling oscilloscopes with risetimes of 7 ps (50 GHz bandwidth) and pulse generators down to 11 ps [Ref 1].

Much of the research to provide such high-speed traceability is based on propagating short electrical pulses along planar transmission lines and across coaxial-planar transitions. Automatic network analysers (ANAs) are widely used to determine the scattering parameters of microwave components and circuits. For measuring frequency domain effects ANAs have no equal; however ANAs are not widely used for examining time domain effects. A powerful technique to analyse such transmission lines - required to improve the speed and uncertainty associated with our systems - is time domain reflectometry (TDR) [2]. Electrical steps or pulses are fed down transmission lines and the resulting delay and amplitude of the scattered signal, for example reflected by a discontinuity, provides information about the position and impedance of the discontinuity.

Two approaches are used to provide commercial oscilloscope sampling heads with TDR capability. The first uses an external step generator (15 ps risetime) and a feed-through connector into a 20 GHz sampling head. The second solution builds a slower step generator (30 ps) into the sampling head itself. To improve the time resolution the response is measured at a calibration plane with known standard artefacts - e.g. shorts and loads similar to conventional network analysis - and filtering and deconvolution techniques applied. The effective risetime can be decreased to 10 ps, though a practical limit of 20 ps is typical as filtering the response more can introduce significant ringing.

This paper discusses recent advances in the optoelectronic generation and measurement of picosecond pulses and describes how these techniques can be applied to build an all-optoelectronic planar TDR system with an overall time resolution better than 3 ps. Examples of analysing planar circuits are discussed using this technique and compared to conventional electrical TDR and ANA techniques.

The optoelectronic approach

Optoelectronic techniques can be used in several ways to improve on the limitations of conventional TDR measurements. Three improvements are described here.

One improvement is to replace the step generator with faster commercially-available optoelectronic pulse generators such as a 50 GHz photodiode. A laser system producing short optical pulses is required. The exact configuration of the system depends on the device to be measured; for example an oscilloscope can be used in transmission, with the device under test between the photodiode and oscilloscope, or a matched power splitter can be used for reflection. If a feed-through oscilloscope head is not required then 50 GHz samplers can be used.

A second stage is to replace the oscilloscope with a faster optoelectronic system to reduce the TDR system time resolution to that of the pulse generator alone. The system used at NPL is an electro-optic sampling (EOS) system with sub-picosecond time resolution [3]. The EOS system uses an external probe consisting of an active 20 μm thick LiTaO_3 tip cemented to a quartz prism. The probe is moved around the plane of the electrical circuit being measured, but must be positioned a few microns above

the circuit to measure with adequate sensitivity changes in the electric field due to the propagating electrical pulses. Optical pulses from a laser are focused into the probe. We use a modelocked Ti:sapphire laser producing 200 fs duration optical pulses with a repetition rate of 76 MHz. The polarisation of the reflected laser beam is rotated by the electric field across the electro-optic tip and converted to an intensity change that is detected by a photodiode and phase sensitive detection system. An optical delay line in the probing beam enables a sampled representation of the electrical pulse to be recorded.

The temporal resolution of the EOS system is limited by the optical pulse width and the thickness of the electro-optic tip and has been calculated to be less than 500 fs, equivalent to an electrical 3 dB bandwidth of over 800 GHz. A further advantage of the EOS system is that, combined with optoelectronic pulse generation, the inherent jitter of the measurement system is zero, since the same optical pulse train is used both to generate and sample the electrical pulse. The EOS system with a photodiode, including connectors, achieves a best risetime of around 8 ps.

The final improvement is to replace the commercial photodiode with a faster optoelectronic pulse generator such as a photoconductive switch. This is discussed later.

Beatty line experiments

To demonstrate the optoelectronic system, alumina coplanar waveguide (CPW) test devices were mounted in a Universal Test Fixture (UTF) with "V" coax connectors. Different length 50 Ω through lines and a 18 mm-long "Beatty" line were used, the latter containing a 10 mm section of 30 Ω line. All lines were measured with conventional TDR, a 40 GHz ANA and with our optoelectronic TDR (OE-TDR) system. Results with other lines will be presented at the conference but here only the Beatty results are shown - the finite discontinuity of known impedance provides a good test for TDR.

Figure 1 shows a comparison between the three TDR methods. Conventional TDR measurements were performed with different oscilloscopes and different settings. It was found that the oscilloscope containing a 35 ps pulse generator and 18 GHz feed-through sampling head with optimal filtering (25 ps) provided the best results. We used a 40 GHz ANA to measure full scattering parameters with a OSLT "K" calibration and used the instrument's internal software to transform S_{11} to the time domain to obtain the ANA equivalent to TDR. The results show the modulus response only; other information can be obtained by plotting the impedance directly against time.

The OE-TDR measurements were made with a 50 GHz photodiode connected to the UTF and the EOS probe positioned at various locations along the planar line. For the comparison the probe was positioned just before the first impedance change on the Beatty line. Both the ANA and the oscilloscope TDR produce similar results. The optoelectronic TDR plot was derived by subtracting the Beatty waveform from a measurement on a through-line performed with the probe at the same position; this was

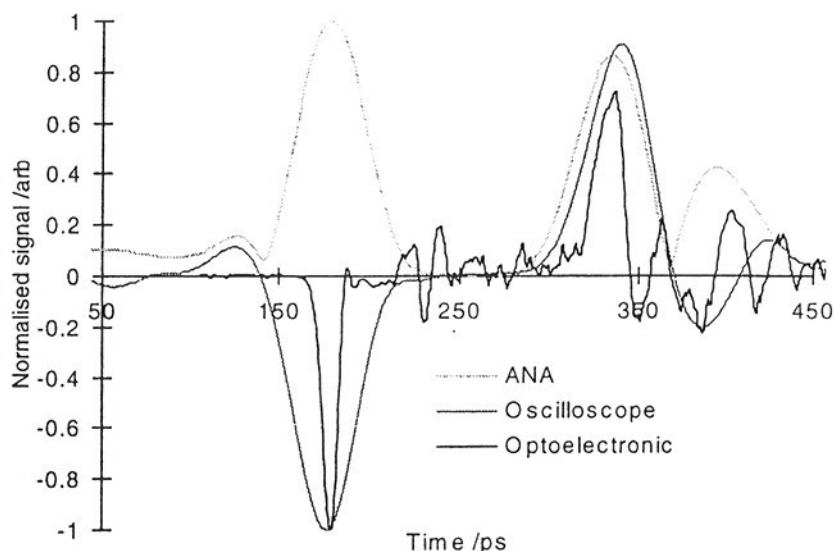


Figure 1. TDR measurements of Beatty line with different systems, normalised for comparison.

required to remove the input waveform from the signal under investigation. The time resolution is better, even after dispersion of the line broadens the pulses, but the subtraction process results in more noise. Noise, dispersion and spurious reflections are areas we are now working on to improve the response further.

Ultrafast pulse generation

One method of improving the pulse generation is to replace the 50 GHz photodiode with a faster photoconductive switch. An epitaxial GaAs layer was grown on a bulk GaAs wafer using an MBE process at low temperature [4]. The resulting layer, known as low-temperature-grown GaAs (LT-GaAs), has excellent properties for ultrafast pulse generation [5], specifically a high mobility, sub-picosecond carrier recombination time and high resistivity. Fast photoconductive switches were fabricated on the LT-GaAs with microwave transmission lines such as CPW or coplanar stripline (CPS) using standard photolithography techniques. The shortest electrical pulse we have measured, for a LT-GaAs switch in a CPS arrangement, has a FWHM of 650 fs [6].

A LT-GaAs photoconductive device was connected in the test-fixture. Fast electrical pulses were produced by illuminating a biased series-gap in a CPW central line with the laser pulses. The EOS probe was initially positioned as close to the generation point as possible and then measurements were made at increasing propagation distances along the CPW.

Two example waveforms are plotted in Figure 2. The pulse broadens from an initial FWHM of 1.3 ps to 1.5 ps. There is good agreement between the measured reflection (labelled "A") and the theoretical delay of the initial pulse reflected from the transition (i.e. circuit end) back to the EOS probe. Other reflections, e.g. from the UTF back to the series gap and back again to the probe, have been identified but are not shown here. The superior time resolution of the LT-GaAs system is apparent - changes in the reflections from moving the probe position by just 150 μm can easily be resolved. In effect both the generation and measurement are carried out without the limitation of the coax-CPW transition used with the previous OE-TDR.

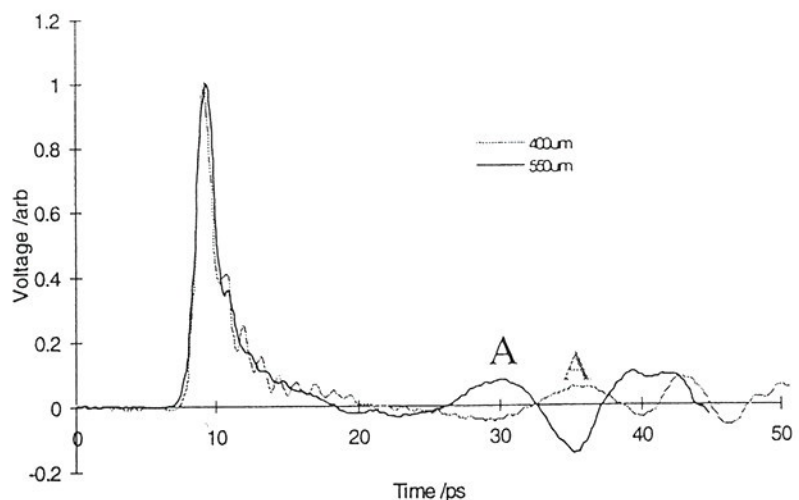


Figure 2. EOS of LT-GaAs photoconductor. Waveforms are shifted in time and normalised for comparison. The distances are the separation between sample point and generation point.

Improved test-fixture

We are replacing the UTF with air-coaxial microwave probes for a more flexible system with less physical constraints as well as providing the potential to investigate higher frequency coax connectors. We have made initial measurements using the same photodiode and EOS system and will report on the final goal - to combine LT-GaAs measurements with these new probes - at the conference. We tested the microwave probe system with smaller GaAs CPW connected to coax using 50 GHz (2.4 mm) "Picoprobes".

Figure 3 shows examples of results from two measurement configurations. On one (A) the photodiode is connected to a 5 mm GaAs CPW with a Picoprobe, with no connection on the other end of the CPW, which defines a good open. The optical probe was positioned on the circuit within 0.2 mm of

the microwave probe. The FWHM of the initial pulse was 8.1 ps and a clear reflection from the circuit open is evident, with a FWHM of 11.9 ps.

The second measurement in Figure 3 (B) shows the same system with a second probe connected at the far end of the circuit to provide 50 Ω termination. In addition, the first Picoprobe was moved 0.5 mm away from the circuit end to deliberately introduce a reflection. The optical probe was again positioned on the circuit within 0.2 mm of the first Picoprobe. The observed "twin peak" provides a good indication of the time resolution of the system. In double-pass 0.5 mm of GaAs is equivalent to 8.7 ps.

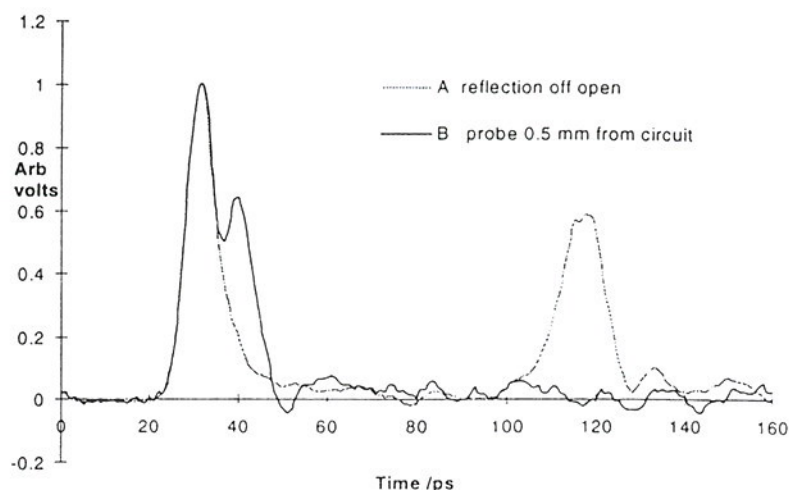


Figure 3. OE-TDR of a 5 mm GaAs CPW with photodiode and EOS.

Conclusions and further work

We have demonstrated optoelectronic time domain reflectometry using two optoelectronic pulse generator systems. The first system, with a photodiode and EOS, demonstrates the feasibility of such an approach and compares favourably with conventional TDR; more work is however required to determine and reduce the uncertainties. The use of a LT-GaAs pulse generator and EOS promises significantly better time resolution. We have designed a mask containing over 40 separate reflection artefacts, with series gaps to allow for photoconductive pulse generation when fabricated on LT-GaAs. Figure 4 shows an example of one device with graded impedance changes to test the limitations of the OE-TDR technique and further compare with conventional techniques.



Figure 4. Example test artefact for TDR.

Acknowledgement

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