High quality pulse and device characterisation using EAM-based frequency resolved optical gating
Michael A.F. Roelens\textsuperscript{1}, Marco Forzati\textsuperscript{2}, Anders Djupsjöbacka\textsuperscript{1}, Periklis Petropoulos\textsuperscript{1}, Anders Berntson\textsuperscript{2}, David J. Richardson\textsuperscript{1}
\textsuperscript{1}: Optoelectronics Research Centre, University of Southampton, Southampton, SO17 1BJ, United Kingdom
Phone: +44(0)2380594527, Fax: +44(0)2380593142, Email: maf@orc.soton.ac.uk
\textsuperscript{2}: Optical System and Networks Laboratory, Acreo AB, SE 16440 Kista, Sweden, marco.forzati@acreo.se

Abstract We report on the versatility of frequency resolved optical gating using an electro-absorption modulator to accurately characterise the pulse shape and phase of high speed telecommunication pulses, as well as properties of optical components.

Introduction
The development of new data modulation formats has become an area of acute interest for communications research since it provides a route to extend the total capacity and bit-rate-distance product of optical systems [1]. Many different modulation formats are under active consideration and studies of their relative performance, for example, in terms of resilience to the effects of chromatic dispersion, polarization mode dispersion, fibre nonlinearity and amplifier noise, are of great importance. Implementing these more advanced formats generally dictates the need for additional active and/or passive optical components within the transmitter, and it is becoming ever more critical to be able to fully characterise the transmitter performance, and indeed the performance of its constituent parts, in order to better interpret the results of system experiments.

In this paper, we report the results of a detailed set of measurements on the performance of an APRZ transmitter using the linear spectrogram technique first demonstrated by Dorner [2,3]. We compare the retrieved pulse intensity profiles with the results of independent direct optical sampling measurements of the pulse intensity profile, and confirm that the retrieved phase response is in good agreement with expectations from the component specifications. Our results highlight the quality of the spectrogram technique and show that it provides a simple technique to characterise the properties of active optical components. We also show for the first time that the technique can give accurate results even in the instance that the pulses under test are modulated with a pseudo random bit sequence (PRBS).

Measurement technique
The pulses under test are split into two parts, one of which is converted to the electrical domain with a clock recovery unit after passing through a variable delay stage. The electrical signal is then used to drive the EAM, which samples the rest of the optical signal. This cross-correlation between the EAM sampling window and the pulses under test is then spectrally resolved with an optical spectrum analyser (OSA) as a function of the delay, to create the spectrogram. There is no use of optical nonlinearities here, and the EAM is polarisation insensitive meaning that the technique is particularly suitable for pulse characterisation in high speed telecommunication systems where pulses generally have low peak powers. Complete phase and intensity information about the pulse and gate can be retrieved from the spectrogram using numerical processing [4]. Note however that useful information can be obtained from a simple visual inspection of the spectrogram. For example a slight skew on the intensity features indicate that the sampling window or the pulses are chirped. This meaning that the spectrogram alone can already be used directly for coarse pulse monitoring.

Experiments
To experimentally assess the accuracy of this characterisation tool, we perform a series of characterisations of different pulses, including alternate-phase return-to-zero (APRZ) modulated pulses [5]. The APRZ pulse generation and data modulation setup used in the experiment is shown in Fig. 2. The driving signal on the phase modulator is tuneable in amplitude (\(\Delta f\)) and temporal offset (\(\Delta t\)) with regards to the maximum intensity of the pulses. Simulated intensity and phase profiles pulses are
shown in Fig. 3, top and bottom respectively. In the measurements discussed below, the pulses are data modulated with a $2^{21}-1$ PRBS data signal, as this is required for the clock recovery unit we used.

Typical measured and reconstructed spectrograms for EAM carved APRZ pulses are shown in Fig. 4. The retrieved intensity is compared with a directly measured intensity trace (without data modulation) using an optical sampling oscilloscope (HP Terascope) in Fig. 5a. The agreement is remarkable, and shows that the technique can readily be used to characterise the average intensity of the marks in a data modulated pulse stream with a good extinction ratio between the marks and the spaces opening up further signal monitoring possibilities.

The phase profile of the pulses is shown in Fig. 5b. Due to the fact that the original EAM carved pulses already have a distinct phase profile (slightly chirped), the phase of the APRZ modulated pulses is not exactly sinusoidal. However, when we account for this by subtracting the phase profile of the unmodulated pulses from the phase profile of the APRZ pulses, the sinusoidal phase change between the pulses becomes clear, as shown in Fig. 5b. This characterises the phase modulator properties in a direct way, as opposed to inferring these properties indirectly from interferometric measurements.

The same setup was used to characterise pulses with durations down to 1.3ps by replacing the EAM carved pulse source with a 40 GHz mode locked ring laser (Calmar PSL-40). Equally good agreement between the optical sampling oscilloscope traces and the

Fig. 4. Measured and retrieved spectrogram of APRZ modulated EAM carved pulses (rms error: 0.003 on a 64x64 grid). The fourth root of the intensity is shown to highlight the dynamic range.

Fig. 5. a) Intensity of APRZ modulated EAM pulses (with $\Delta t=0$ and $\Delta \phi_{C}=\Delta \phi_d$), retrieved from the spectrogram technique (x) compared with the intensity measured with an HP Terascope (solid line). b) Crosses: retrieved phase of the pulses, solid line: the phase corrected by subtracting the inherent phase of the unmodulated pulses from the APRZ pulse phase.

retrieved intensity profiles was obtained for these short pulses highlighting the high resolution of the approach. However, the phase of the waveform is undefined where there is no pulse intensity, making it impossible to derive the same sinusoidal phase modulator profile from the retrieved pulses in this instance. The retrieved and directly measured intensity is shown in Fig. 6.

Fig. 6. Intensity of the 1.3ps ring laser pulses retrieved from the spectrogram technique (x) compared with the intensity measured with a fast sampling oscilloscope (gray line).

Conclusion
We have demonstrated the accuracy of the linear spectrogram technique by comparing the retrieved profiles with direct optical sampling measurements. We simultaneously characterised the sinusoidal phase modulation of a fast phase modulator. Our results highlight the value of the technique for high resolution signal and component characterisation.

References
1 S. Bigo et al., ECOC '04, paper Th2.5.1
2 C. Dorier and I. Kang, IEEE PTL 16 p672, 2002
3 X. Wei et al., OFC'05, paper JWA42
4 K. W. Delong et al., Opt Lett. 19, p2152, 1994
5 M. Forzati et al., IEEE PTL 14, p1285, 2002