Dual-Comb Asynchronous Electro-Optic Sampling Technique for High-speed Optoelectronic Devices

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Abstract: A dual-comb asynchronous electro-optic sampling (DC-AEOS) system is built for characterizing the response of high-speed optoelectronic devices. Utilizing DC-AEOS, a 40 GHz photodiode is characterized with short acquisition time, and high signal-to-noise ratio.

Electro-optic sampling (EOS) techniques are widely utilized to determine the impulse response of high-speed optical-to-electrical devices [1–6]. Such high-speed devices act as transfer standards for electrical phase in nonlinear network analyzer measurements [6] and are used to characterize the impulse response of high-speed oscilloscopes [1]. Despite being widely used, conventional EOS suffers from long measurement times, very strict trade-offs between signal-to-ratio (SNR) and acquisition time, and poor frequency resolution due long delay scans. To overcome these drawbacks, we have built a DC-AEOS system. By adopting asynchronous data acquisition methods from dual-comb spectroscopy (DCS) [8-10] in our DC-AEOS system, we measured the response of a 40 GHz photodiode with an acquisition time of 50 seconds with a signal-to-noise ratio (SNR) of 65 dB.

In dual-comb systems (DCS), two stabilized pulses trains of repetition frequencies f_r and $f_r + \Delta f_r$ scan each other with an effective time shift of $\delta t = \Delta f_r / f_r^2$. Given $f_r = 100$ MHz and $\Delta f_r = 1$ kHz our experiment can asynchronously sample a fast electrical signal with a resolution of $\delta t = 100$ fs. The asynchronous sampling effectively maps GHz electrical signals to slower signals by a factor of $(f_r/\Delta f_r) = 10^5$ which can be recorded with a slower digitizer. As in conventional EOS, the fast electrical signal is mapped to the optical signal via electric field-induced birefringence in a uniaxial electro-optic crystal. However, the main difference of DC-AEOS is that the delay scanning is done by the offset in the combs' repetition frequencies rather than a mechanical delay line.

The experimental schematic is depicted in Fig. 1(a). The output of the 100 MHz Optical Frequency Comb 1 (OFC1) with pulse duration of ~100 fs and average power of 50 mW is tapped (100 µW tap) to pump the 40 GHz photodetector (PD). The fast electrical output of the PD is coupled to the coplanar waveguide (CPW) fabricated on a $LiTaO_3$ EO substrate via a 110 GHz microwave probe (MPW). The 400 µm long CPW consists of a 6 µm wide center conductor and 36 µm gap between the ground planes (50-ohm characteristic impedance on dielectric constant 43.4 LiTaO3) and is terminated with a 50 Ω PdAu resistor. The output of OFC2, which is used to sample the fast electrical signal, is focused through the CPW gap. The polarization state of the light of OFC2 is set to 45 degrees with respect to the polarization ellipse of the EO substrate by using half and quarter waveplates. The light transmitted through the $LiTaO_3$ is collimated and polarization-resolved using a polarizing beam splitter (PBS). The orthogonal polarization states are then fed to a balanced photodetector (BPD) for differential detection. The output of BPD is conditioned for acquisition using signal conditioning and acquisition block.

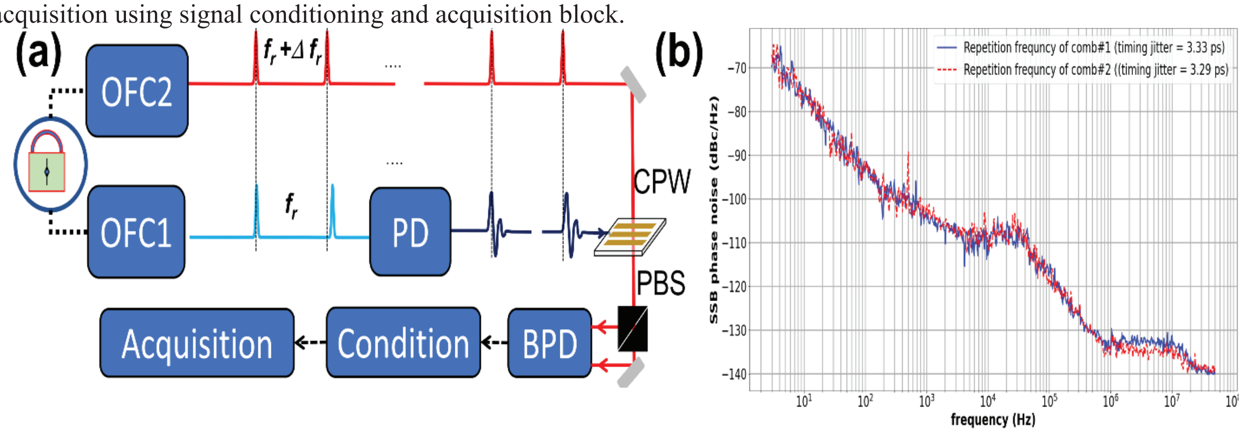

Fig. 1. (a) Block diagram for dual frequency comb EOS system to characterize a 40 GHz photodiode (PD). One optical frequency comb (OFC1) incident on a fast photodetector (PD) generates an electrical signal. A second comb (OFC2) with a different repetition rate f_r asynchronously samples this PD signal via electro-optic sampling in a $LiTaO_3$ co-planar waveguide (CPW). The resulting signal is detected by balanced photodetector (BPD). PBS: polarizing beam splitter; BPD: balanced photodetector. Solid (dashed) line represents optical (electrical) path and comparison of (b) SSB phase noises of repetition frequencies of two combs.

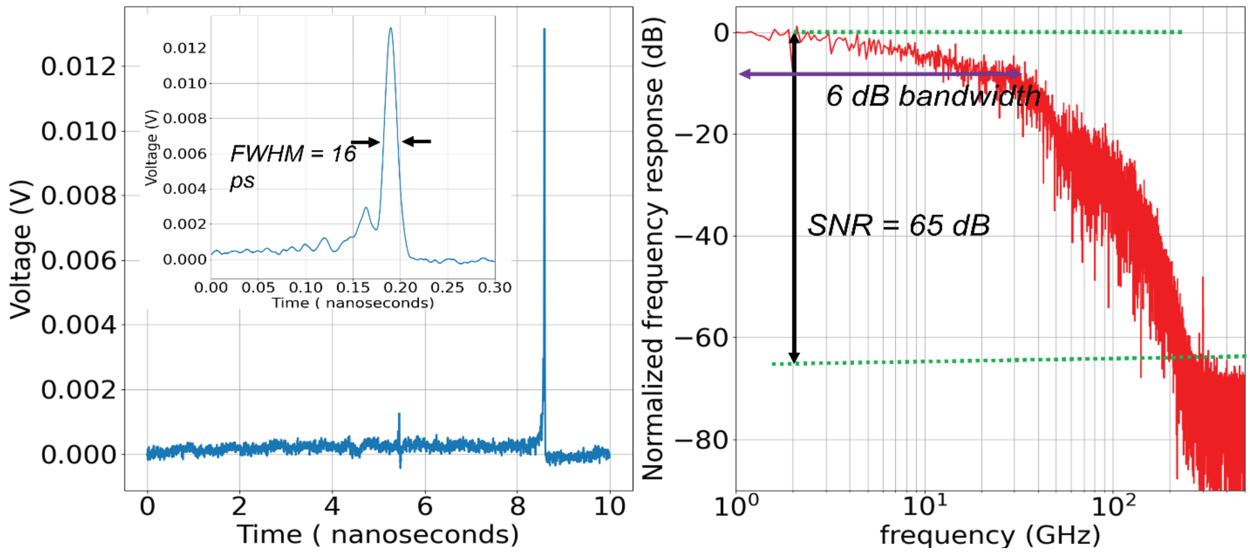

Fig. 2. (a) Impulse response of 40 GHz photodiode (Inset: zoomed response peak), (b) FFT of impulse response

The signal conditioning and acquisition blocks are crucial for acquiring the response of the PD. The output of the BPD is conditioned using a 300 Hz high pass filter (HPF), 1 MHz low-pass filter (LPF), and a low noise DC amplifier before processing with the DAQ. Due to the 1 kHz offset in repetition frequencies of the lasers, the 10 ns delay is being scanned in just 1 ms with delay-steps of 100 fs giving 100000 sampled points at a rate of 100 MHz. To properly sample, digitize, process and store such response, we adopted the acquisition methods utilized in DCS. Our DAQ uses a 250 MHz, 14-bit digitizer clocked externally by 100 MHz of OFC1. Due to the very small birefriengence change in the EO substrate, 100000 sample points representing a single trace of PD response does not offer good SNR. To improve the SNR, this signal is aquired 50 times to generate a hardware averaged signal using a field-programmable gate array (FPGA). Finally, 1000 hardware-averaged signals are phase-corrected and summed in software to produce the final temporal resonse. The total data aquistion time is 1 ms×50×1000 = 50 s.

The performance of the DC-AEOS system depends crically on the synchronization between the pulse trains emitted by the two lasers. To synchronize our lasers, we stabilized the 10^{th} harmonic of the repetition frequencies of each laser to radio-frequency (RF) references which were phase-locked with each other. The phase noises of repetition frequencies of two lasers after stabilization is shown in Fig. 1(b) yielding the rms timing jitter, from 3 Hz to 10 MHz, of 3.3 ± 0.1 ps and 3.2 ± 0.1 ps, resectively. Further, 1 kHz beats between the repetition frequencies of stabilized lasers yielded fractional frequency error of $<10^{-4}$ for 0.5 s gate time.

Figure 2(a) shows the impulse response of a 40 GHz PD measured using our DC-AEOS system. The response is measured in an equivalent time manner by scanning the probe beam path length from 0 to 10 ns with a delay step of 100 fs in just 1 ms. The full width at half maximum (FWHM) of the response is 16 ps (inset). The inset shows the zoomed trace of the response with timing resolution of 0.1 ps and SNR of 65 dB. The frequency response of the PD is shown in Fig. 2(b). The frequency response ripple is due impedance mismatches in the measurement circuit [1] that we have not corrected for. Next, we will model and perform the uncertainity analysis of our measurement system in order to investigate the drop in the bandwidth of measured response as well as the long tail of the resonse [11].

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