Terabaud Optical Sampling on a Chalcogenide Optical Chip

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Abstract: We demonstrate terabaud optical sampling by combining four-wave mixing in a chalcogenide chip with a long wavelength carbon nanotube modelocked fiber laser. System resolution is 320 fs, 150 fs lower than previous systems.

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Optical sampling using optical switching allows for high baudrate signal monitoring beyond the limit of electronics. This can be accomplished using parametric mixing processes between the signal and a low repetition rate probe, for instance using sum-frequency generation (SFG) in periodically-poled lithium-niobate (PPLN) [1]. To avoid the temperature dependent phase-matching of such SFG media, we can instead use four-wave mixing (FWM) in amorphous materials. Picosecond resolution can be achieved in highly nonlinear optical fibers (HNLF) [2], limited by the FWM bandwidth. This can be overcome with integrated highly nonlinear waveguides. Optical sampling of TBd signals was demonstrated in a silicon nanowire [3]. Highly nonlinear chalcogenide glasses can be used to avoid multiphoton and free-carrier losses in silicon, but so far only 640 GBd sampling has been demonstrated in a chalcogenide chip [4].

Here we report on the first terabaud optical sampling in an on-chip chalcogenide waveguide. The full FWM bandwidth of the highly non-linear waveguide is made accessible by a turnkey fiber laser system modelocked around 1600 nm using carbon-nanotube (CNT) saturable absorber technology. Signals up to 1.28 TBd are sampled with 320 fs resolution, an improvement of 150 fs compared to previous HNLF and chalcogenide systems. Numerical simulations reveal that FWM saturation can limit resolution if excessive powers are used.

The non-linear sampling gate is a 2x0.85 μm^2 chalcogenide rib waveguide as shown in Fig. 1(a) [5]. The non-linearity $\gamma = 9.9$ (W m)$^{-1}$ at 1550 nm enables a short length of 7 cm. Dispersion engineering yields low anomalous dispersion for the TM mode around 1550 nm ($\beta_2 = -42$ ps^2/km, $\beta_3 = 1.2$ ps^3/km and $\beta_4 = 8.8 \cdot 10^{-4}$ ps^4/km) [6]. The propagation loss is 0.6 dB/cm and coupling is accomplished using lensed fibers, leading to ∼4 dB loss per facet.

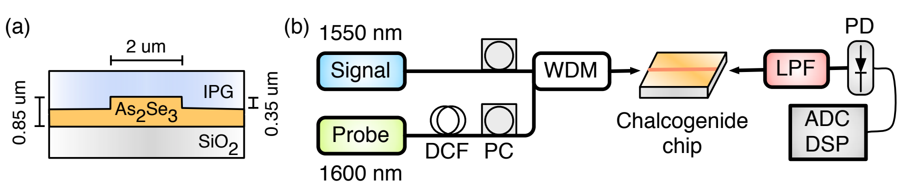

Fig. 1. (a) Cross-section of chalcogenide waveguide, IPG: inorganic polymer glass. (b) Setup for optical sampling using chalcogenide optical chip: DCF: dispersion compensating fiber, PC: polarisation controller, WDM: wavelength division multiplexer, LPF: long-pass filter, PD: photodiode, ADC/DSP: analog-digital converter and digital signal processor.

The sampling setup is shown in Fig. 1(b) and is based on a modified commercial optical sampling oscilloscope (OSO, Alnair Labs EYE-Checker). By replacing its HNLF optical gate with our chalcogenide chip, we can push the resolution into the TBd regime. The probe laser is a fiber laser based on CNT saturable absorber mode locking, capable of turnkey operation at 1600 nm with 30 MHz repetition rate and 5.7 nm FWHM bandwidth [7]. This greatly expands the bandwidth available for signal and probe pulses compared to previous work [4]. The signal under test is from an OTDM system based on a fiber laser and pulse compressor described in details in Ref. [8]. The 1550 nm signal is combined with the probe laser and coupled into the chalcogenide chip. Polarization controllers align the polarizations to the TM mode of the waveguide. At the output, a long-pass filter (3 dB cutoff around 1635 nm) isolates the sampled FWM idler. The sampled signal is detected using a photodiode and processed using the OSO's digitizing electronics.

The autocorrelation of the signal and probe at the chip input are shown in Fig. 2(a). We imparted a slight negative chirp to the probe, controlled by dispersion compensating fiber, yielding a FWHM of 725 fs while its bandwidth supports about 500 fs. This mitigates spectral broadening from self-phase modulation (SPM) in the optical gate, avoiding contamination of the sampled channel.

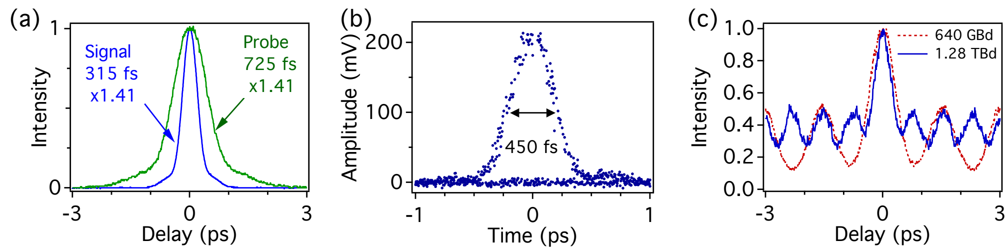

Fig. 2. (a) Autocorrelation of the probe and TBd pulses before OTDM MUX. (b) Optical sampling trace of the pre-MUX 40 GBd pulses showing system resolution. (c) Autocorrelation of the multiplexed 640 GBd (dashed) and 1.28 TBd (solid) data streams.

We measured the resolution of the OSO by probing the 40 GBd signal pulses before the OTDM x32 multiplexing (MUX). The average powers in the waveguide were estimated to be −2 dBm for the signal and −3.1 dBm for the probe. As shown in Fig. 2(b), the signal pulses broadened from 315 fs to 450 fs after sampling. This corresponds to an ultimate resolution of about $\sqrt{450^2 - 315^2} = 320$ fs. For comparison, we repeated the measurement with an HNLF gate replacing the chalcogenide chip and found a resolution of 470 fs (not shown).

We used the chalcogenide optical gate to sample 640 GBd and 1.28 TBd on-off keying (OOK) signals whose autocorrelations are shown in Fig. 2(c). The input average powers inside the waveguide were estimated to be up to 11.5 dBm for the signal and −3.1 dBm for the probe. The spectra at the chip output are shown in Fig. 3(a), where the sampled idler channel is clearly seen around 1650 nm. The sampled eye diagram at 640 GBd in Fig. 3(b) shows well resolved individual pulses. The eye opening and temporal jitter of about 200 fs are an improvement compared to our previous results [4]. The eye diagram at 1.28 TBd signal is shown in Fig. 3(c). Individual pulses can be resolved, but the timing jitter limits visibility. However, given the good performance obtained for isolated pulses in Fig. 2(b), we suspect the jitter may be mostly due to the intrinsic jitter of the fiber laser as well as the OTDM MUX, rather than being limited by the sampling system itself.

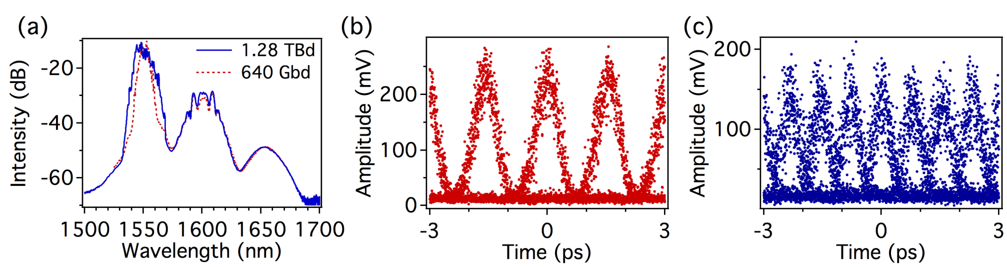

Fig. 3. (a) Spectra at the chalcogenide chip output (1 nm resolution). (b) Optical sampling trace of the 640 GBd and (c) 1.28 TBd data streams.

To better understand the resolution limits of the system, we performed numerical modelling using the non-linear Schrödinger equation (NLSE) [9]. The simulated eye diagrams are shown in Fig. 4. The lower powers used in simulation could be due to experimental factors reducing FWM efficiency such as dispersion fluctuations and polarisation imperfections. At low probe powers, optimal resolution close to experiments is obtained. At higher power, saturation of the sampling process is visible and increases the sampled pulse width. At even higher powers, pulse distortion is visible. This could be due to a combination of FWM saturation, SPM contamination from the probe and cross-phase modulation on the idler from the probe.

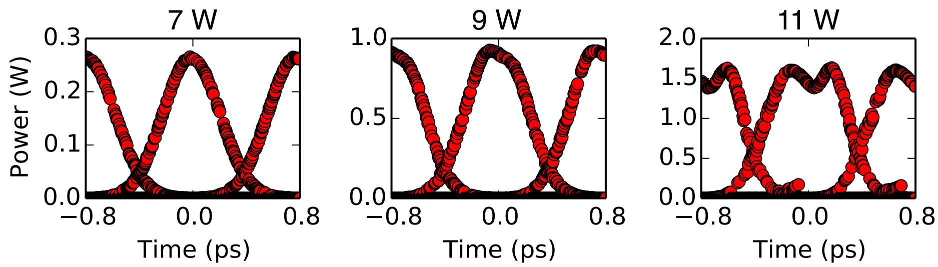

Fig. 4. Simulated sampled eye diagrams for increasing probe input peak powers, corresponding to average powers of −7.8 dBm,−6.8 dBm and −5.8 dBm respectively.

In conclusion, we have demonstrated an optical sampling oscilloscope combining an on-chip chalcogenide optical gate with a long-wavelength CNT modelocked fiber laser. Data streams up to 1.28 TBd were sampled, with resolutions down to 320 fs, an improvement of 150 fs compared to previous results in HNLF and chalcogenide. Timing jitter is currently the main limit to sampled signal quality, although the timing jitter of the OTDM system seems to dominate. Simulations indicate nonlinear saturation and distortions limit the amount of probe power that can be used without loss of resolution. Better resolution and sensitivity could be achieved by minimizing chip coupling losses.

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