High-resolution optical sampling by means of dispersion-shifted highly nonlinear chalcogenide waveguides

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Abstract

We demonstrate a photonic-chip-based optical sampling system with temporal resolution <500-fs, making use of a 7-cm short chalcogenide planar waveguide. Its high nonlinearity and dispersion-shifted design enables broadband operation without compromising the achieved resolution.

Introduction

Driven by the ever-increasing bit rates in optical networks, the quest for accurate monitoring of optical waveforms has been ongoing for decades and is likely to continue well into the future. In recent years, optical sampling has emerged as a technique to perform time-resolved measurements of optical data signals at high data rates with a bandwidth that cannot be reached by conventional photodetectors and oscilloscopes [1]. In an optical sampling system, the optical signal is sampled in the optical domain by a nonlinear optical sampling gate before the resulting samples are converted to an electrical signal. This avoids the need for high bandwidth electronics if the optical sampling gate is operated with a modest repetition frequency.

One class of nonlinear optical gates, forming the central part of the optical sampling system, makes use of the second-order susceptibility $\chi^{(2)}$ in nonlinear crystals, such as periodically poled $LiNbO_3$ (PPLN) [2]. A second class makes use of the third-order susceptibility $\chi^{(3)}$ in optical fibers [3]. The latter provide unrivalled speed capability since the $\chi^{(3)}$ nonlinearity is near-instantaneous. However, while PPLN crystal-based optical gates have device lengths on the order of centimeters, much longer propagation lengths are required for optical fiber to provide sufficient nonlinearity with moderate launch powers. This longer length leads to detrimental effects owing to dispersion, limiting the temporal resolution and broadband operation. In the quest for alternative, compact, high nonlinearity waveguides, chalcogenide (As_2S_3) rib waveguides can be fabricated to exploit the material's ultra-high nonlinear index n_2 (up to two orders of magnitude greater than for silica), and low two-photon absorption for obtaining sufficient $\chi^{(3)}$ nonlinearity in compact, ultrafast photonic circuits suited to all-optical processing at high bitrates [4,5].

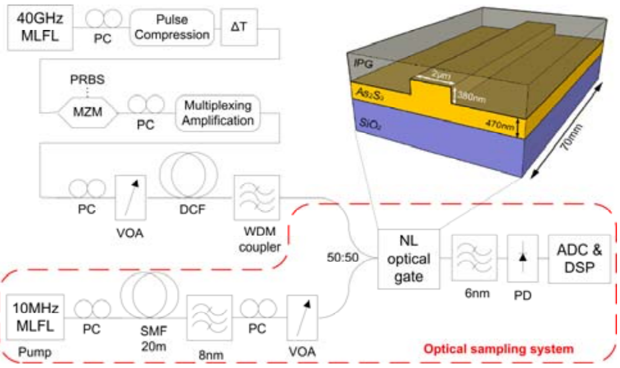

Fig. 1. Experimental setup of the chalcogenide photonic-chip-based optical sampling system, and the setup for the generation of the 640-Gb/s signal

In this paper we present the use of four-wave mixing (FWM) in As_2S_3 planar waveguides as an ultrafast nonlinear optical gate, with the aim of achieving high resolution photonic-chip-based optical sampling. We demonstrate the optical sampling of a 640-Gb/s optical time domain multiplexing (OTDM) signal, with a temporal resolution <500-fs. The ultrahigh nonlinearity and low dispersion of the As_2S_3 waveguides enables the measurement of high-speed signals without chromatic dispersion effects impacting both pump and signal distortion as well as their phase velocity matching (which in turn degrades the FWM efficiency and the senstivity of the measurement). Furthermore, our system provides the unique capability for parallel optical sampling of multiple signal channels simultaneously on a single chip using a single optical pump source.

Experimental setup

Figure 1 shows a schematic of the experimental setup of our optical sampling system. A 640-Gb/s OTDM signal was generated from an active mode-locked fiber laser (MLFL) emitting 1.4-ps pulses at a 40-GHz repetition rate and centered at 1535-nm. An external electro-optic Mach-Zehnder modulator encoded data on the pulses at 40-Gb/s with a $2^{31} - 1$ pseudo-random bit sequence (PRBS). After amplification the pulses were optically multiplexed to 640-Gb/s. The polarization of the signal was aligned to the As_2S_3 waveguide's TM mode using a polarization controller. Finally, the signal was filtered using a WDM coupler with 1530–1542-nm pass band.

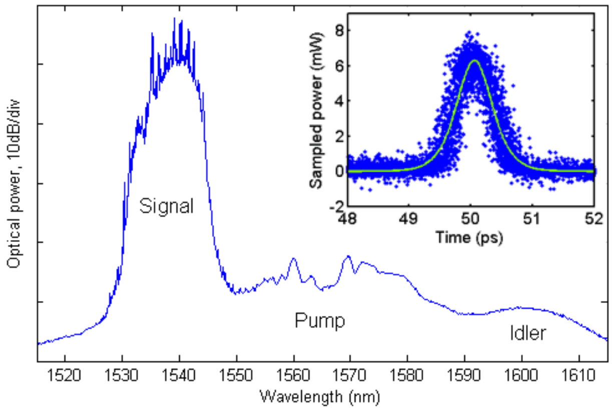

Fig. 2 FWM spectrum at the output of the As$_2$S$_3$ waveguide. Inset: Sampled compressed 10-GHz pulse.

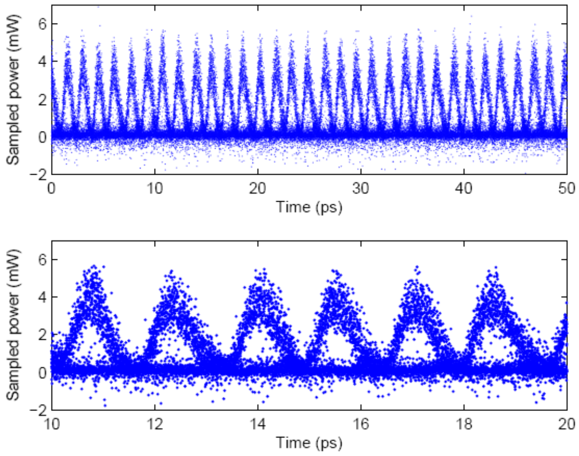

Fig. 3. Sampled 640-Gb/s OTDM signal, with 50-ps span (top) and 10-ps span (bottom).

The sampling pulses (pump) were generated from a passive MLFL at 1550-nm with a repetition rate of 10-MHz. To avoid spectral overlap between the signal and the pump, we shifted the wavelength of the pump to 1568-nm through Raman self-frequency shifting [6] by means of 20-m of SMF, followed by an 8-nm BPF centered around 1568-nm.

A 50/50 coupler was used to combine the signal and the pump. Lensed fibers with mode field diameter of 2.5-µm were used to couple the light to and from the waveguides. An AND gate product is generated, through the generation of an FWM idler at frequency $f_{idler} = 2f_{pump} - f_{signal}$ [6] (see Figure 2). A 6-nm bandwidth tunable BPF, centered around 1603-nm, was used to filter out the generated idler. It is subsequently detected by a low bandwidth photodetector and processed for visualization of the eye diagram. This was done by making use of the software-based clock recovery of a commercial PSO-101 optical sampling oscilloscope [7].

Results and discussion

Figure 3 shows the optical eye diagram measured using our optical sampling system, with an SNR of 27.6-dB. The average signal power launched into the waveguide was 23.4-mW (13.7-dB), corresponding to a peak power in the waveguide of about 15-mW. The total insertion loss was 13.1-dB for the signal with polarization aligned to the TM mode of the waveguide. The average pump power launched was 0.12-mW (–9.3-dB), or about 6.6-W peak power in the waveguide. Comparing the observed sampled pulsewidth of a compressed 10GHz pulse (see inset of Figure 2) with the input signal pulsewidth (measured with an autocorrelator) yields a temporal resolution of 446-fs. In the current setup of our optical sampling system, the achieved temporal resolution is mainly limited by the sampling pulse source and the available filters.

The waveguide's low anomalous dispersion accross the C-band and its very short length of only 7-cm, enables broadband FWM [8] without compromising the sampling system's high temporal resolution for an increasing wavelength separation between signal and sampling pulse, and it avoids dispersion of the signal (compromising the integrity of the measurement) and dispersion of the pump (impacting temporal resolution and sensitivity due to reduced FWM efficiency).

With respect to sensitivity, the limiting factor is mainly the insertion loss of the As$_2$S$_3$ waveguides due to the reduced cross-sectional dimensions associated with engineering their dispersion. Further improvements in the fabrication process of the waveguides will enable a reduction of the insertion loss and hence strongly lower the power requirements, i.e. increase the sensitivity of the system.

Nonetheless, we believe that the possibility of integrating high-resolution monitoring of ultra-high bitrate signals on a single, compact photonic device together with other nonlinear signal processing functions, has a very strong potential for application in future high-speed optical communication networks.

Conclusions

We have shown that chalcogenide glass planar waveguides integrated on a photonic chip can be used for optical sampling of signals at ultrahigh bitrates with temporal resolution <500-fs, limited by the available band-pass filters and sampling pulse source. The dispersion-shifted design and ultrahigh nonlinearity of the waveguides, in combination with their short length, strongly limits the impact of chromatic dispersion on the temporal distortion of the signal and pump pulses, and their phase mismatch, hence allowing for broadband high-resolution optical sampling.

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