CW pumped wavelength conversion of 40 Gb/s DPSK and 160 Gb/s OOK signals in a Chalcogenide glass chip

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Abstract
We demonstrate broadband wavelength conversion of amplitude and phase-shift keyed signals at 40-160 Gb/s using the optical Kerr-effect in a photonic chip for the first time. This is enabled by a dispersion-shifted, highly nonlinear As_2S_3 waveguide.

Introduction
All-optical wavelength conversion will play an important role in future high capacity optical communication networks requiring wavelength flexibility. Transparency to both data rate and modulation format will ensure compatibility with both conventional on-off keying (OOK) and emerging alternatives such as differential phase-shift keying (DPSK), amongst others.

A wavelength conversion scheme enabling these features has been demonstrated by optically mixing the signal with a continuous wave (CW) pump in a nonlinear waveguide [1-4]. Variants include using cascaded sum-difference frequency generation in periodically poled Lithium Niobate (PPLN) [1] or four-wave mixing (FWM) by either the optical Kerr-effect in highly nonlinear fiber (HNF) [2], or nonlinear gain effects in a semiconductor optical amplifier (SOA) [3]. While HNF has its practical advantages including being a passive solution, its relatively long length makes both integration and broadband FWM phase matching difficult. Recent progress in both silicon [4] and chalcogenide (ChG) waveguides [5], [6] has enabled large $\chi^{(3)}$ nonlinearity on chip-scale devices with much shorter (centimeter length) circuits that can be integrated. ChG's in particular, unlike silicon and SOAs, do not suffer from free carrier effects, making them excellent candidates for ultra-fast signal processing. However, neither ChG or silicon have demonstrated AOWC of phase-shift keyed signals so far.

In this paper, we demonstrate the wavelength conversion of DPSK signals via the optical Kerr effect in a photonic chip for the first time. This is enabled by exploiting CW pumped FWM in a 7 cm length, highly nonlinear, dispersion-shifted As_2S_3 planar rib waveguide. We show penalty-free wavelength conversion of a 40 Gb/s return-to-zero (RZ) DPSK signal over 30 nm, and conversion of a 160 Gb/s RZ-OOK signal over 15 nm. The results are a first demonstration of signal processing by CW pumped FWM in a ChG waveguide. It is also distinguished from previously reported wavelength conversion of 40 Gb/s [6] and 80 Gb/s signals [5] that used a different signal pumping scheme which is incompatible with DPSK.

Waveguide features
The key feature of the ChG chip is its design for high nonlinearity and broadband low dispersion. This stems from using As_2S_3 glass, whose nonlinear index, n_2, is over 100 times greater than silica. By depositing a 0.85 µm thick film of As_2S_3 on a silica-on-silicon substrate, 2 µm wide ribs formed by standard photolithography and dry etching, produce waveguides with a smaller effective area approaching 1 μm^2 [7]. This both raises the nonlinearity to ~10,000 /W/km at the 1550 nm wavelength, and enhances the waveguide dispersion for the TM mode, countering the large normal material dispersion of As_2S_3 (−364 ps/nm/km). The net dispersion is shifted to a small value in the anomalous regime of 28 ps/nm.km. After hand-cleaving the end facets, an anti-reflection coating based on SiO_2/TiO_2 is deposited to minimize Fabry Perot reflections. A typical device schematic is shown in Fig. 1.

Experimental Results
A 7 cm length waveguide was applied to wavelength conversion using the set-up in Fig. 1. The 40 Gb/s RZ-DPSK signal was generated from a CW laser using two single drive, 40 GHz Mach-Zehnder (MZ) modulators – one for 40 Gb/s DPSK encoding (with a 2^{31}-1 PRBS), the other for carving 40 GHz pulses of 33% duty cycle.

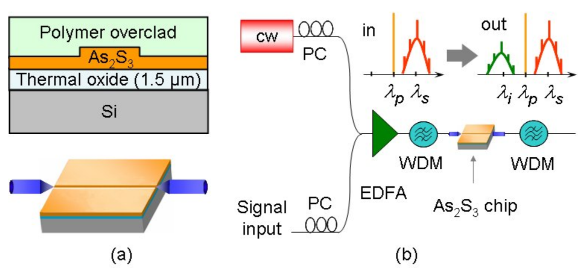

Fig. 1. (a) Structure and device schematics of dispersion-shifted, planar As_2S_3 waveguide. (b) Experimental set-up for broadband wavelength conversion using a 7 cm length circuit.

The signal was combined with a more intense CW laser whose wavelength was at 1547 nm. Both were amplified in the same EDFA, and coupled into the waveguide via lensed fibers. A WDM coupler was inserted before the waveguide to reject amplifier noise. Another was inserted after to isolate the FWM idler generated at the wavelength $1/\lambda_i = 2/\lambda_p - 1/\lambda_s$, where λ_p and λ_s are the CW and signal wavelengths respectively.

The total average power at the input connector of the waveguide was 400 mW with a signal to CW power ratio of -6.2 dB. The polarization state of both the signal and CW pump were aligned using polarization controllers (PC) and oriented for coupling to the waveguide TM mode to take advantage of its lowest dispersion. The total insertion loss of the device was 12.8 dB, which is 1 dB greater than for TE. This is mostly attributed to coupling losses of ~4.5 dB per facet. Fig. 2 shows the output spectra from the waveguide in case of tuning the signal wavelength from 1554 nm to 1560 and 1564 nm, to convert in the range 1531-1540 nm. The power ratio of signal to idler at the waveguide output is ~25 dB.

The filtered output from the WDM coupler was transmitted through an EDFA, then a 0.55 nm bandwidth bandpass optical filter (BPF), and DPSK demodulator, before detection with a 40 Gb/s receiver. Comparing the received eye diagram in Fig. 2 with the "back to back" (B2B) case of bypassing the AOWC, highlights the low distortion achieved. Bit-error rate (BER) measurements indicate a negligible power penalty at a BER of 10^{-9} even for the widest 33 nm tuning range (limited by the WDM couplers and EDFA gain bandwidth).

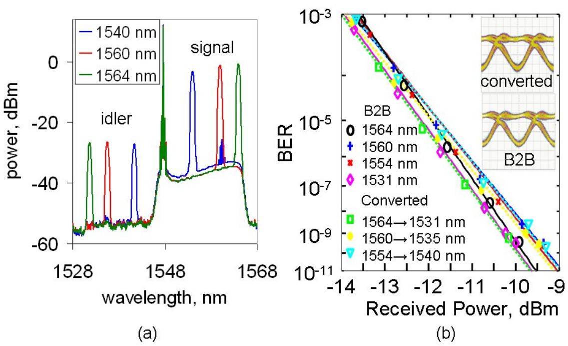

Fig. 2. Wavelength conversion of 40 Gb/s RZ DPSK signal a) Overlaid output spectra from 7 cm length waveguide for input signal wavelength tuned from 1554 to 1564 nm. b) Bit error rate of converted signal with B2B and corresponding received eye diagrams for signal conversion from 1564 nm to 1531 nm.

We also investigated AOWC of a higher bit rate 160 Gb/s signal using the same set-up in Fig. 1(b). In this case, the signal was generated from a modelocked fiber laser emitting a 40 GHz pulse train at 1550 nm wavelength. This was amplitude modulated with a 2^{31}-1 PRBS to produce a 40 Gb/s RZ-OOK signal which was then optically time-division multiplexed to 160 Gb/s in a fiber interferometer circuit of 2^7-1 bit-delay.

In this example, the AOWC used a 400 mW total launch power and -6.3 dB power ratio between signal and CW. Conversion from 1535 to 1551 nm was achieved by tuning the CW pump to 1543 nm. Fig. 3 compares both the original and converted waveforms, measured on a high resolution optical sampling scope, highlighting the small pulse distortion achieved.

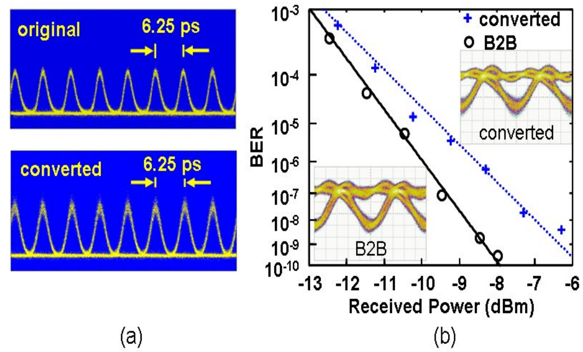

Fig. 3. Wavelength conversion of a 160 Gb/s RZ signal from 1535 to 1551 nm. a) Optical sampling oscilloscope traces of (top) input and (lower) converted signals. b) Received eye diagrams for converted and B2B signals after demultiplexing, and their measured BER.

The performance was measured by first time-division demutiplexing the 160 Gb/s signal using a MZ modulator [8], to enable detection and BER measurement with the same 40 Gb/s receiver. Comparing the received signal eye diagrams measured on a sampling oscilloscope showed slight degradation after the AOWC. The curves in Fig. 3 indicated a BER power penalty of at least 1.5 dB when compared to the B2B with AOWC bypassed. This is partly attributed to the degraded OSNR at the higher bit-rate. There are several routes to improve the device performance for enhanced FWM conversion efficiency. These include increasing the circuit length, or using higher n_2 ChG glasses [9] or incorporating on-chip tapers for more efficient coupling to SMF, which has been shown to be capable of < 1dB per facet for silicon nanowires [10].

Conclusions

Broadband all-optical wavelength conversion of high-speed DPSK and OOK signals has been demonstrated at 40-160 Gb/s bit rate using the optical Kerr-effect in a photonic chip for the first time. The high performance achieved by CW pumping of FWM in a Chalcogenide waveguide, highlights its capability for signal processing with transparency to bit-rate and modulation format.

References

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