All-Optical Wavelength Conversion of 80 Gb/s Signal in Highly Nonlinear Serpentine Chalcogenide Planar Waveguides

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Abstract: Newly developed 22 cm long, serpentine shaped As_2S_3 waveguide exhibiting record low loss of 0.05 dB/cm and ultra-high nonlinearity of 1700 $W^{-1}km^{-1}$ enables all-optical wavelength conversion of an 80 Gb/s return-to-zero signal via cross-phase modulation.

OCIS codes: (060.4510) Optical communications; (070.4340) Nonlinear optical signal processing; (190.2620) Frequency conversion; (230.4320) Nonlinear optical devices

1. Introduction

All-optical devices enable native processing of communication signals at data rates beyond what is capable by current electronic processing. Wavelength conversion, in particular, is of significant interest for wavelength agile optical networks, however challenges remain to reduce device footprint size, required optical power levels and overall device performance for practical applications. In this regard, chalcogenide glasses have attracted significant attention due to their large Kerr (n_2) nonlinearity [1] (100's × silica glass) and low to moderate two-photon absorption. Whilst all-optical wavelength conversion has been demonstrated in Bi_2O_3 [2] and As_2Se_3 [3] fiber, enhanced performance can be achieved using chalcogenide waveguides [4] as the combined high nonlinearity and intrinsic response time of < 100 fs enables the realization of the multi-functional, monolithically integrated photonic chips capable of processing of high bandwidth signals. In this paper, we achieve broadband 80 Gb/s wavelength conversion (×8 increase compared to earlier work [4]) in a long, ultra low-loss (0.05 dB/cm) serpentine shaped, chalcogenide glass rib waveguide using cross-phase modulation (XPM) side-band filtering.

2. Waveguide fabrication and characterization

Figure 1(a) shows the cross-section of a typical chalcogenide rib waveguide fabricated from As_2S_3 films thermally evaporated onto an oxidized silicon wafer, with the waveguide defined through photolithography and dry-etching. The height and width of the rib was 2.6 µm and ≈4 µm respectively, while the surrounding film was 1.7 µm thick. The waveguide was clad with UV cured inorganic polymer glass and end facets were cleaved resulting in a ≈7 cm long chip. Fig. 1(b) shows that the 22.5 cm waveguide schematic consisting of 3 straight sections connected with two 180° bends of radii ≈3 mm. The mode-field area of the TE mode was calculated to be 7.1 μm^2 at 1550 nm while the dispersion parameter D = −341 ps/nm/km (normal). The nonlinear refractive index of As_2S_3 ($n_2 = 2.92^{-18}$ m^2/W [5]) yields a nonlinear coefficient approaching 1700 $W^{-1}km^{-1}$ at 1550 nm. The propagation loss at 1550 nm was measured to be 0.05 ± 0.005 dB/cm for the TE mode. The low propagation loss (5× lower than previous waveguides [5]) despite the additional complexity of the 3 mm bends, ensures nonlinear interaction over the full waveguide length. Butt-coupling with higher numerical aperture fiber and index matching fluid resulted in ≈6 dB insertion loss.

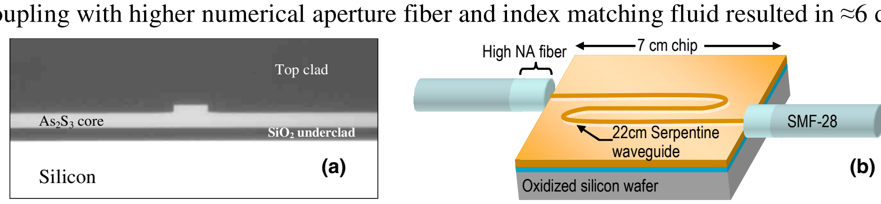

Fig 1. (a) Optical micrograph of waveguide cross-section. (b) Serpentine waveguide geometry yields a compact device.

3. Device principle and setup

XPM can be used as a simple technique for achieving wavelength conversion of a return-to-zero signal [6]. Pump pulses carrying data were launched into the waveguide along with a continuous wave (CW) probe tuned to the

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desired output wavelength. The pump pulses induce a transient chirp on the CW probe via XPM which broadens the probe spectra, generating sidebands. A single sideband is extracted using an optical filter so that the output wave at the converted wavelength is modulated in time similar to the pump pulse. Fig. 2 shows the experimental implementation. The signal (pump) was generated from an optically filtered 40 GHz active mode-locked fiber laser (MLFL) natively producing ≈1 ps pulses. An external electro-optic Mach-Zehnder modulator (MZ) encoded data on the pulses at 40 Gb/s with a $2^{31}-1$ pseudorandom bit pattern (PRBS), and a single stage fiber interferometer circuit of $2^{7}-1$ bit delay-length optically multiplexed (MUX) the pulses up to 80 Gb/s bit-rate. This amplified signal pump was combined, through a 70/30 coupler, with a CW probe, generated from an amplified external-cavity diode-laser. Polarization of both pump and probe were aligned to the lower loss TE-mode of the waveguide. A 2 nm band pass filter (BPF) offset from the CW probe, selected a single XPM sideband while a fiber Bragg grating (FBG) notch filter removed residual CW probe.

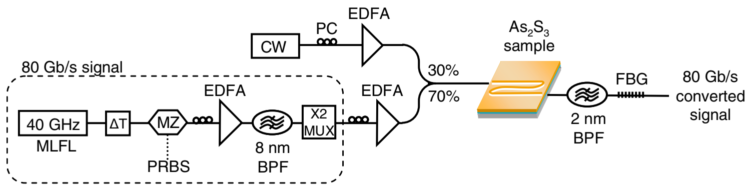

Fig 2. Experimental setup for XPM wavelength conversion.

4. Experimental results and discussion

In our initial experiments we characterized the suitability of the As_2S_3 serpentine waveguides for wavelength conversion using 40 Gb/s signals which is generated and received natively by the bit-error test bed equipment. The 40 Gb/s signal was generated by replacing the MUX in Fig. 2 with a BPF to broaden the signal pulses to 4.3 ps. At the waveguide output the notch FBG filter was replaced with a tunable sharp 0.56 nm BPF for XPM sideband filtering. Using power for pump and probe of 23.8 dBm and 19.7 dBm (326 mW combined), eye diagrams shown in Fig. 3 were obtained at wavelengths of 1545, 1555 and 1565 nm by tuning the CW probe and BPF. The clean, open data eye shows only a small amount of additional noise present while the BER measurements show a power penalty of only ~1.2 dB at a BER = 10^{-9} for the three converted signals with respect to the 40 Gb/s back-to-back (B2B) signal centered at 1539 nm.

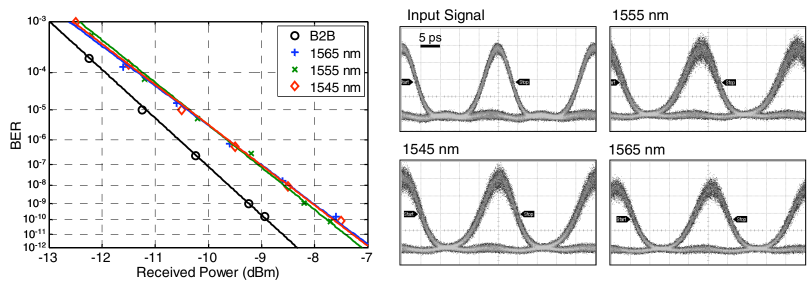

Fig 3. Left: BER vs. received power for back-to-back (B2B) and converted 40 Gb/s signal. Right: eye diagrams (65 GHz optical bandwidth).

The 40 Gb/s results suggest that good conversion can be achieved for an 80 Gb/s signal, provided duty-cycle is preserved for the same average powers. The XPM broadening is reduced both for increased duty-cycle, due to the adverse effect on the peak-to-average power ratio, as well as for decreasing duty-cycle, due to the effects of group-velocity walk-off between the pump pulse and the phase modulation CW probe. For the 80 Gb/s experiment, the pulse width at the waveguide input was 1.8 ps, yielding a similar duty-cycle as the 40 Gb/s experiment. The average signal power was 24.4 dBm, while the CW probe power (at 1545 nm) was 21.8 dBm, resulting in a combined optical power of 406 mW, at the input facet of the As_2S_3 waveguide.

Fig. 4 shows the optical spectra taken directly after the waveguide for an 80 Gb/s input signal and the CW probe varied over the C-band. The broad pedestals located at the base of the CW probe are the XPM induced sidebands, while the additional spectral components symmetric around the pump and probe are due to four-wave mixing (FWM). FWM in these waveguides is inefficient and wavelength dependent due to strong normal dispersion. For this experimental setup, the walk-off length ($L_W = T_0/D\Delta\lambda$) is significant for wavelength offset $\Delta\lambda$>15 nm. Consequently, the XPM spectral sidebands are relatively independent of the CW probe wavelength.

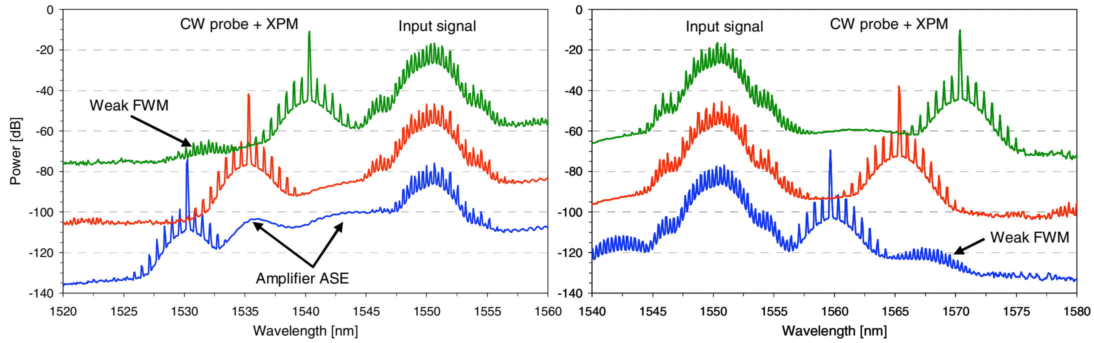

Fig 4. Waveguide output spectra for varying probe wavelength (left: probe on short wavelength side; right: probe on long wavelength side) with 70 pm resolution bandwidth.

Fig. 5 examines the converted signal for the CW probe at 1559.35 nm. The effect of the FBG is clearly evident in the converted spectra, as are the 80 GHz modes. Comparing the open eye diagrams for the converted 80 Gb/s signals to that of the 40 Gb/s converted signals (Fig. 3), we expect a marginal increase in the BER power penalty. Given the ultrafast nonlinear response of the chalcogenide glass, these experiments were noise limited and the reduced 80 Gb/s eye opening can be attributed to sub-optimal filtering.

In our earlier report [4] of XPM based wavelength conversion in As_2S_3 waveguides, device performance was limited by the short propagation length (5 cm) and conservative estimates on the damage threshold, resulting in the use of low duty cycle signals (2.1 ps pulses at 10 Gb/s) to obtain the necessary peak optical power. In this paper, the combination of longer, lower-loss waveguides and greater average power have enabled an eight-fold increase in the data rate. Although much longer waveguides were used, the group velocity difference between the pump and phase modulated CW probe was small allowing broadband wavelength conversion. Reducing the waveguide transverse dimensions can potentially reduce group velocity dispersion effects, improving the wavelength conversion range [7].

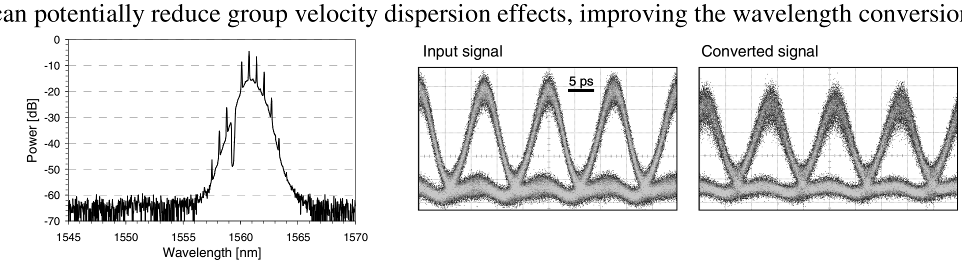

Fig 5. Left: Converted signal spectra (70 pm resolution bandwidth). Right: eye diagrams (65 GHz photodetector) for 80 Gb/s signals.

5. Conclusion

We demonstrate broadband wavelength conversion of an 80 Gb/s return-to-zero signal by cross-phase modulation within a 22.5 cm long, As_2S_3 rib waveguide with nonlinearity = 1700 $W^{-1}km^{-1}$. Low waveguide loss ensures the full propagation length contributes to the nonlinear process while the ultrafast Kerr nonlinearity allows the data rate to be scaled eight-fold compared to earlier work.

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