Continuous Wave Four Wave Mixing in Highly Nonlinear As_2S_3 Waveguides

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Abstract
We report experiments on CW four-wave mixing in an As_2S_3 nonlinear waveguide. Using total launch powers ≈360mW we obtained FWM efficiencies of 1-2% over the C-band in a single device and an idler powers at the output > −10dBm.

Keywords: nonlinear optics; four-wave mixing; parametric effects; planar waveguides

Introduction
The development of photonic integrated circuits capable of processing optical data streams entirely in the optical domain is an important and challenging goal of current research. Many of the first experimental demonstration of all-optical processing were made using the Kerr nonlinearity of an optical fiber or the free carrier nonlinearity of a semiconductor optical amplifier. In the fiber case, the inherently low Kerr nonlinearity can be compensated by using long path lengths to achieve all-optical processing at powers compatible with an optical communications system. In the case of the SOA the path lengths are inherently small because the optical nonlinearity is very large, but the finite carrier lifetime makes it difficult to use SOAs at very high bit rates.

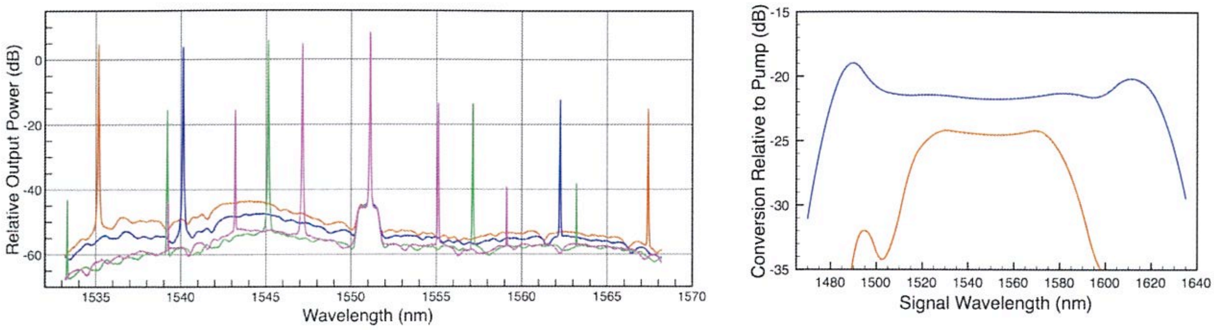
To achieve bit rate and format independent all-optical processing, chip sized devices are preferable utilizing only ultra-fast Kerr nonlinearities. We have, therefore, focused our efforts onto producing all-optical devices from chalcogenide glasses that have favourable nonlinear properties and negligible nonlinear absorption. Using waveguides fabricated from As_2S_3 we have successfully demonstrated a wide range of all-optical processing functions [see e.g. Pelusi *et al.* (2008), Galali *et al* (2009)]. We have also fabricated As_2S_3 waveguides with a nonlinear parameter of $10W^{-1}m^{-1}$ and losses ≈0.5dB/cm with low dispersion at telecommunications wavelengths [Lamont *et al.* (2008)]. These waveguides offer the first opportunity to demonstrate nonlinear effects using CW beams in chalcogenide photonic chips. We report here the first CW FWM experiments covering the telecommunications C-band using powers of only a few hundred mW.

Experimental Approach
The waveguides were fabricated from 800nm thick films of As_2S_3 that had been thermally evaporated onto an oxidized silicon wafer from a baffled boat. Waveguide patterns were transferred to a photoresist by contact printing and after development, 350nm high rib waveguides were formed by etching using CHF_3 plasma in an Oxford ICP-100 etcher [Choi *et al*, (2008)]. A top cladding with an index of 1.53 was spin-coated onto the patterned wafers. End faces were prepared by hand cleaving after which TiO_2/SiO_2 anti-reflection coatings was thermally evaporated onto the end faces. Both 4μm and 2μm wide waveguides were used in these experiments with nonlinear parameters of 6.2 $W^{-1}m^{-1}$ and 10.8 $W^{-1}m^{-1}$ respectively. Optical losses were measured using the cut-back method at 0.2dB/cm for the 4μm waveguides and ≈0.5dB/cm for the 2μm wide waveguides (TM mode). 14cm long waveguides were used in these experiments. The group velocity dispersion of the waveguides was calculated Rsoft FemSIM for TM modes. At 1550nm the TM_0 mode dispersion was 6.4ps/nm/km and 26.9ps/nm/km for the 4μm and 2μm wide waveguides respectively but around -270ps/nm/km for the TE_0 mode. The small dispersion values for TM_0 mode leads to larger FWM bandwidth and hence was used for all these experiments.

The output of two amplified CW sources were combined via polarization controllers in a WDM and coupled into the waveguides using fiber lenses with a mode field diameter of 2.5μm. Taking the fiber lens transmission losses into account the total coupling losses (both facets) were -6.5dB and -8.7dB respectively. In most experiments the signal power used was about half that of the pump the total coupled power was ≈ +25.5dBm (360mW) or +26.6dBm (460mW) for the 2μm and 4μm wide waveguides respectively. No damage occurred in these waveguides up to the maximum power available from the lasers of ≈600mW.

Results
The pump wavelength was fixed at ≈1550.92nm whilst the probe wavelength could be tuned over the range 1533-1565nm limited by the use of a C-band EDFA. We performed a series of experiments to determine the output power, bandwidth, and power scaling of the FWM process in the waveguide. The power transfer characteristics

were measured at a signal wavelength of 1549.3nm by measuring the output power in the idler on an ANDO AQ6317 optical spectrum analyser using a 0.01nm resolution bandwidth. In the absence of saturation caused by processes such as two-photon or free carrier absorption the idler power would be expected to scale as $P_s P_p^2$ and these relationships were evident from the measurements confirming the absence of nonlinear absorption in As_2S_3.



LHS: Fig1a. Measured FWM spectra for different pump wavelengths. The waveguide was 2µm wide, 14cm long and pump and signal powers in the waveguide 190mW and 92mW respectively. RHS: Fig 1b. Calculated FWM mixing conversion vs signal wavelength using 250mW pump at 1550nm and 125mW signal. Red: 2µm wide waveguide; blue: 4µm wide waveguide.

We examined the bandwidth over which the idler power remained approximately constant by tuning the signal from 1535-1565nm. Sample results again for a 14cm long 2µm wide waveguide sample are shown in Fig. 1a. The FWM efficiency remained constant over the full tuning range available from the EDFA. Fig. 1b shows the conversion efficiency (relative to the pump) calculated using the split-step Fourier method using the calculated dispersion parameters and measured losses. For the 2µm waveguide the -3dB bandwidth is 68nm, which is consistent with the experimental data and indicates the waveguide operates over the entire C-band. Using the lower dispersion 4µm wide waveguides the bandwidth extended over the complete S-, C- and L-bands.

Conclusions

We have demonstrated for the first time that the nonlinearity of a dispersion engineered As_2S_3 waveguide is sufficient to allow significant nonlinear effects using CW powers of a few hundred mW. Using a total power (signal plus pump) of ≈400mW, the idler reached ≈1% of the signal power at the output of the waveguide across the whole telecommunications C-band. An even wider bandwidth would be obtained by moving the zero dispersion point closer to the centre of the C-band. In these experiments this could be achieved using the 4µm wide waveguides which had 150nm of bandwidth, although a more effective solution would be to increase the thickness of the waveguide from 800nm to 960nm and use 2µm wide structures which maintains the nonlinear parameter at $>9.8W^{-1}m^{-1}$ with zero dispersion to 1548nm yielding a FWM bandwidth of >150nm. Finally, these current devices offer the opportunity for efficient nonlinear optical processing at almost arbitrary bit rates at realistic powers. Their low net dispersion will allow operation at any bit rate used in current optical communications systems as well as extending to the extreme bit rates and advanced formats being considered for future systems.

Acknowledgements

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