Chalcogenide Glasses for All-optical Processing

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Abstract: Chalcogenide glasses, which contain S, Se or Te atoms combined with network forming elements such as Ge, As, Sb have the largest third order optical nonlinearity of any inorganic glass. As a result they are attractive candidates for fibre and waveguide devices for all-optical signal processing in the telecommunications bands. In this talk I will review our recent progress in all-optical devices such as regenerators, wavelength converters and other devices in chalcogenide glasses.

Keywords: All-optical processing; chalcogenide glasses, devices

1. Introduction

Chalcogenide glasses containing the chalcogens S, Se and Te combined with network forming elements such as As, Ge, Si are an important group of high index ($n \approx 2$-3) infra-red transmitting glasses. According to Miller's rule [1], high linear index implies large ultra-fast optical nonlinearity making these glasses interesting for all-optical signal processing in high bit rate communications systems. Particularly important is the fact that these glasses have a combination of high refractive nonlinearity ($n_2 \approx 1000$x silica) and low absorptive nonlinearity (β) which leads to favourable nonlinear figure of merit (FOM), $T=n_2/\beta\lambda>>1$. Thus these glasses should be suitable for fabricating all-optical switching devices operating above 100Gb/s.

As well as their favourable nonlinear properties, chalcogenides are attractive for other reasons. They form glasses for a wide range of compositions and thus their refractive index to be tuned sensitively to obtain arbitrary core-cladding index contrast. Their high index allows the fabrication of single mode waveguides with sub-micron dimensions. This leads to strong field confinement that enhances the nonlinear response of devices. Additionally they have relatively high Verdet constants making magneto-optic structures feasible; they have shown potential to be poled leading to moderate second order nonlinearity [2]; they are photosensitive allowing inscription of gratings as well as direct writing of waveguides; and they display large Raman gain; etc.

The first demonstration of the use of chalcogenides for all-optical switching was in fact made by in the early 1990s by Asboe *et al.*[3]. Switching of a 40GHz pulse train using pulse powers as low as 0.4W was reported using an As_2S_3 glass fiber 4m long.

Whilst this early result was encouraging many challenges remain before chalcogenides can be accepted for all-optical processing. Furthermore whilst most demonstrations so far have been performed in fiber geometry, the ultimate goal will be to demonstrate fast low power switching in integrated devices based on chalcogenide glass films. In this talk I summarise some of our recent results in all-optical processing using chalcogenides and outline our approach to low power switching in integrated devices.

2.1 Fiber based all-optical regenerator

To demonstrate the efficacy of chalcogenide glasses for all-optical processing we have recently reported [4] an all-optical regenerator based on the use single mode As_2Se_3 fiber. As_2Se_3 has significantly higher optical nonlinearity (≈400x silica) compared with the As_2S_3 glass (≈100x silica) used by Asobe *et al.*[3] although its nonlinear absorption is higher yielding a nonlinear figure of merit, $T \approx 2.3$. However as will be shown below, it appears that this is an almost optimal value of the FOM for this particular application and leads to an near ideal optical transfer function for the regenerator.

The regenerator is based on the design suggested by Mamyshev in 1998 (figure 1) [5]. A noisy return to zero input signal is passed through a dispersive and nonlinear medium (As_2Se_3 fiber with D=-504ps/nm/km; n_2=0.9 10^{-13}cm^2/W; and β=2.5 10^{-12} m/W) producing self phase modulation (SPM) induced spectral broadening. Low power noise experiences minimal SPM spectral broadening and so is filtered out the band-pass filter offset from the input centre wavelength. On the other hand high power pulses experience sufficient spectral broadening to be partially transmitted through the bandpass filter. This results in a step-like power transfer function that suppresses noise in both the "zeros" and "ones" in the data stream.

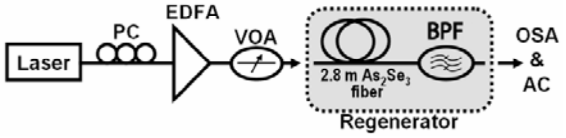

Figure 1: Experimental configuration for demonstrating optical regeneration. PC – polarization controller, EDFA – erbium doped fiber amplifier, VOA – variable optical

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attenuator, BPF - bandpass filter, OSA – optical spectrum analyzer and AC – pulse autocorrelator.

The measured transfer function for our device is shown in figure 2 along with model predictions including dispersion and illustrating the effect of the finite level of two photon absorption. Clearly an almost ideal step like transfer function can be obtained using this glass at least using fibers a few meters long. Frequency Resolved Optical Gating (FROG) confirmed that the output pulses were near transform limited with pulse durations close to those of the incoming pulse train.

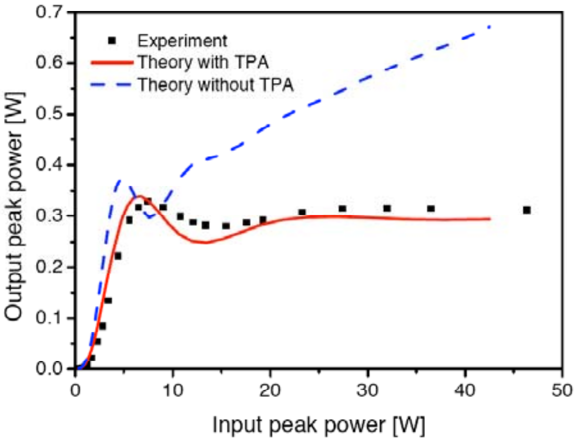

Figure 2: Regenerator transfer function for a filter offset of 1.35 nm. Experiment compared to theory, with and without two photon absorption.

2.2 Towards an Integrated Regenerator

Whilst this demonstration using fiber indicated the feasibility of using the chalcogenides for all-optical processing, integrated devices are far preferable and would allow fabrication of compact devices for regenerating multiple WDM channels on a single wafer. To this end we are developing methods for processing low loss chalcogenide glass films to create compact high index contrast planar waveguides for all-optical processing.

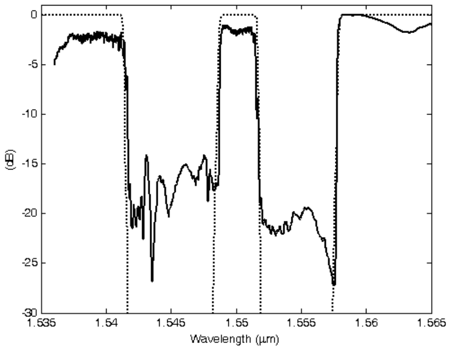

Figure 3: Experimental (solid) and theoretical (dotted) transmission spectra for the pass-band filter, consisting of two Bragg gratings. The longer wavelength grating was written closest to the output facet of the waveguide. Pass and rejection bands are respectively 2.8 nm and 16.3 nm wide

We have shown that a combination of ultra-fast pulsed laser deposition combined with conventional dry etching can be used to produce relatively low loss (≈0.2dB/cm) chalcogenide glass rib waveguides [6]. Furthermore the inherent photosensitivity of chalcogenides to near-band-gap light has allowed us to write strong Bragg gratings required for the regenerators directly into these waveguides [7]. A sample filter response used in a prototype waveguide all-optical regenerator is shown in figure 3.

In a waveguide device 5cm long we have shown a nonlinear transfer function could be obtained [8] although the operating power of this prototype was around 50W – well above the level required for telecommunications applications. Considerable potential exists however to reduce the required power by increasing the device length (from 5-50cm); reduce the mode area (by around a factor of 5) and increase the nonlinearity by choosing a different glass (by a factor of 4-5). Thus operating powers of <1W appear possible.

2.3 Wavelength conversion in a chalcogenide rib waveguide

A Mamyshev regenerator inevitably causes a wavelength shift at the output relative to the input and hence integrated devices should be capable of wavelength conversion to restore the original signal wavelength (or alternatively shift the output to a new WDM channel). We have recently demonstrated all-optical wavelength conversion in an As_2S_3 rib waveguide using cross phase modulation. The principle of operation is shown in figure 4.

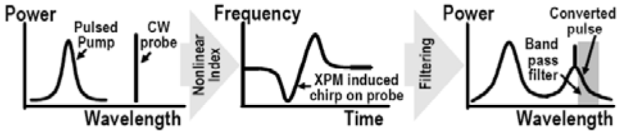

Figure 4 Principle of operation of wavelength conversion via cross-phase modulation (XPM) followed by filtering.

A pulsed pump source, potentially containing digital data, is directed though the nonlinear medium along with a CW probe beam near the desired output wavelength. The pump beam induces a transient chirp on the probe beam via cross phase modulation through the Kerr nonlinearity. This broadens the probe spectra generating sidebands, and when a single sideband is selected using an optical filter, the output signal is modulated in time similarly to the pump pulse.

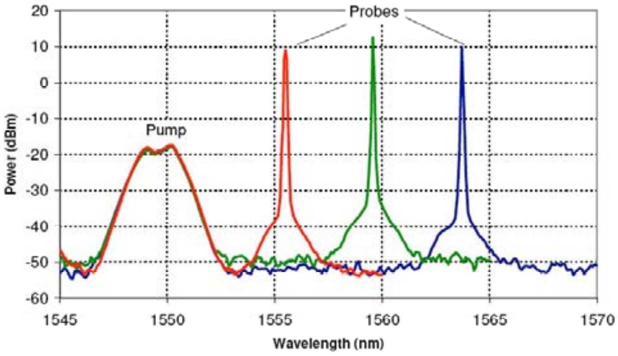

Figure 5 Unfiltered output spectra showing 2nm wide pump spectra (left) and CW probe spectra (right) with optical sidebands imposed by XPM.

Figure 5 shows the spectra of the unfiltered output signal containing both the pump (2nm wide signal at 1550nm) and CW probes set to three different wavelengths (1555nm, 1560nm and 1565nm). The sidebands on each probe are clearly visible. Note that the strength of the sidebands are low in this demonstration because of the low duty cycle (5ps pulses at 9MHz) used in these experiments. For a full 33% RZ signal the relative strength of the sidebands would be increased by about 40dB. After filtering to isolate the upper sideband in figure 5 the pulses were analysed using FROG that showed that the phase and amplitude integrity of the pulse in both the time and frequency domains was maintained by the wavelength converter. Because of the short waveguide length, pump/probe walk-off as well as pulse dispersion were not a limiting factor in device performance.

2.4 Towards lower operating power

The waveguide based devices described above generally required powers in excess of those available in optical communications system. As indicated in section 2,2, however, a clear route exists to reducing the operating powers to sub-W levels by scaling the physical dimensions of the devices. However, further reduction, can only be achieved by a radical change in device design.

A common theme in research to produce low power photonic switching structures is to employ high-Q resonators to reduce the external switching power. A popular route to achieving this involves the fabrication of compact optical resonators in photonic crystal lattices. Unlike low index glasses, chalcogenides are suitable for fabricating 2-D photonic crystal lattices because of their high index and hence this route can also be used to reduce operating power albeit at the expense of increased switching times.

We have demonstrated the fabrication of high quality 2-D photonic crystal lattices in $Ge_{33}As_{12}Se_{55}$ glass films [9]. Defect mode waveguides and resonators in these lattices have been probed via evanescent coupling from a tapered optical fiber (figure 6) [10].

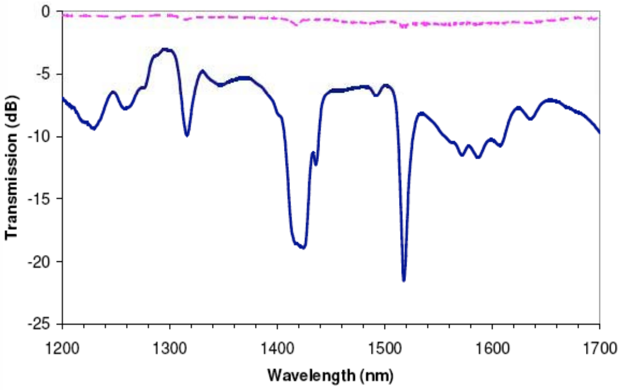

Figure 6: Transmission spectrum of tapered nanowire for TE polarized light, in close proximity to chalcogenide glass photonic crystal waveguide, showing resonant coupling. Dashed curve is for large (>2μm) fibre-waveguide separation. Solid curve is for close coupling (< 1 μm separation).

More than 98% coupling can be achieved in this geometry opening up the way for the demonstration of all-optical switching in micro-resonators based on photonic crystal structures in chalcogenides.

3. Conclusion

We have shown that chalcogenide glasses have considerable potential for all-optical signal processing. Their excellent nonlinear properties suggest that ultra-fast all-optical switching should be possible at pulse powers of a few hundred mW in chalcogenide nanowire waveguides. Lower operating powers should be possible using resonators embedded in photonc crystal waveguides.

6. Acknowledgment

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