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Highly Nonlinear Chalcogenide Glass Waveguides for All-optical Signal Processing

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Abstract: I describe the development of highly nonlinear chalcogenide glass waveguides for photonics and their application as nonlinear optical devices for high speed processing and monitoring of telecommunications signals.

OCIS codes: (130.3120) Integrated Optics Devices; (130.4310) Nonlinear

1. Introduction

Chalcogenide glasses (ChGs) contain one or more of the chalcogen elements (S, Se, Te) covalently bonded to network formers such as As, Ge, Sb, etc. Research into ChGs started about sixty years ago [1] motivated particularly by their exceptional optical transmission in the infra-red. Being composed of heavy elements means that the vibrational absorption bands of ChGs occur around 8μm for sulphides; at ≈14μm for selenides; and beyond 20μm for tellurides. Because the bonding between atoms is weak relative to oxides, the optical gap lies in the visible or near infra-red. Weak bonding implies rather low glass transition temperatures (a few hundred C) and this is attractive for glass molding to produce optical elements such as lenses as well as optical waveguides [2]. Glass densities are high and combined with the strong polarizability of the bonds, leads to a large index of refraction (2-3). A large linear refractive index implies, according to Miller's rule [3], a large nonlinear index and this has been confirmed by measurements that report third order optical nonlinearities 100-1000 times that of silica [4].

These basic properties suggest that compact nonlinear optical waveguides fabricated from chalcogenide glass films can achieve a large nonlinear parameter, $\gamma=\omega n_2/cA_{eff}$, where A_{eff} is the area of the propagating mode; n_2 the real part of the ultrafast third order nonlinearity; and ω the angular frequency of the light. To date the highest values for γ in nanowire waveguides have been reported to be around $150W^{-1}m^{-1}$ – a value that is comparable to that achieved in silicon nanowires. These nonlinear waveguides can be used for all-optical processing of high-speed telecommunications signals. Most importantly for this application, nonlinear absorption in these glasses at telecommunication wavelengths is usually negligible and free carrier effects are also absent. This means that losses due to two-photon or free carrier absorption can be neglected and the nonlinear response is purely refractive which is an advantage when processing phase-encoded signals.

Whilst these basic properties are favourable for all-optical processing, chalcogenides also possess characteristics that are distinctly less attractive for optical devices that will be subjected to very high light intensities. In particular a striking characteristic is their photosensitivity that reflects the tendency of the chemical bonds to change under illumination by light near their band edge [5]. The mechanism behind bond switching is the production of electron-hole pairs which change the valency of neighboring atoms and thereby the chemical bonds. Related to this is a wide range of intriguing phenomena such as photo-darkening [6]; photo-crystallization [7] and photo-diffusion [8]. Whilst observable in bulk glasses these effects generally become more pronounced in thin films which contain a larger number of defective bonds compared with bulk glasses and as a result bond switching creates the pathway by which the films can relax towards an equilibrium state. This is quite undesirable for waveguides used for optical processing. It is worth noting that whilst photo-sensitivity is most pronounced for band edge light it has also been reported in films irradiated in the infra-red well away from the absorption edge.

Generally chalcogenides form glasses over a very wide range of compositions, and hence it is important to ask how the properties of the glasses are affected by composition and can optimum compositions be identified for optical applications that achieve low optical losses combined with high nonlinearity and good stability.

In this presentation I will review our research on the development of nonlinear waveguides from chalcogenide glass and will also outline some of our latest achievements where we have used dispersion engineered As_2S_3 waveguides for all-optical processing.

2. Chalcogenide nonlinear waveguides

Dispersion engineering is essential in chalcogenide waveguides in order to overcome the large normal material dispersion that would compromise the bandwidth of an all-optical processor even if the waveguide were only a few cm-long. We have implemented two dispersion-engineered designs for our research. These are an As_2S_3 rib waveguide formed in an 850nm thick glass film etched ≈350nm deep with the rib width being between 2 and 4µm; and a 500nm x 500nm fully etched nanowire made from $Ge_{11.5}As_{24}Se_{64.5}$ glass. Both structures are clad with a polysiloxane film with index ≈1.53. These waveguides achieve a nonlinear parameter of $10W^{-1}m^{-1}$and $150W^{-1}m^{-1}$ with losses of 0.3dB/cm and 1.5dB/cm respectively [9]. In the case of the rib waveguide, zero (or anomalous) dispersion is achieved only for the TM mode whilst in the case of the nanowire, both TE and TM modes fall in the anomalous regime. The use of a silica top cladding would make the dispersion of the nanowire polarization independent.

When fabricating the waveguides, great care has to be taken to achieve the best stability and the highest power handling capabilities in the waveguides. For example, as-deposited As_2S_3 films have a refractive index very different from the bulk glass, 2.29 c.f. 2.43. These films differ from the bulk and are unstable because they contain large numbers of defective bonds and molecular clusters which must be eliminated before the films can be used in all-optical processing. This is achieved by a combination of thermal and/or optical annealing. These annealing steps relax the chemical bonds towards those characteristic of the bulk glass. For example, thermal annealing at 130C for 24hours causes the index to increase from ≈2.29 to ≈2.39, still somewhat less than the bulk value. Annealing at higher temperatures whilst leading to a higher index is accompanied by a roughening of the film surface which increases scattering losses in the waveguides [10]. Optical annealing with broadband green light can successfully push the index to higher values where it saturates at the bulk level. In the case of the $Ge_{11.5}As_{24}Se_{64.5}$ glass, this composition is chosen because of an unusual property that makes it unique amongst chalcogenides from the Ge-As-Se system because it self-assembles during deposition from the vapour phase to form a film with chemical bonds indistinguishable from bulk. As a result, the film properties are stable even when annealed up to or slightly above the glass transition temperature.

To achieve high power handling we have found that it is important to passivate the surface of the waveguides after etching. We apply a thin (few nm) coating of Al_2O_3 by atomic layer deposition for this purpose. After alumina deposition the waveguides can successfully handle continuous average powers in the range 20-30MW/cm^2. If failure occurs it is by the "fiber fuse" mechanism seen in silica fibers where damage originates at a defect well in to the waveguide and propagates as a "damage" wave back to the input destroying the waveguide. An example of such a damage track in an uncoated waveguide is shown in Fig. 1.

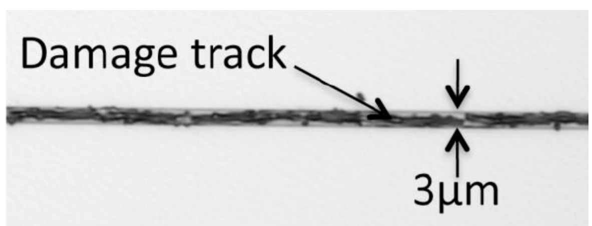

Fig 1. "fiber fuse" damage in a 3µm wide $Ge_{11.5}As_{24}Se_{64.5}$ rib waveguide without Al_2O_3 coating exposed to CW power around 40mW. The track extends over a distance of about 1cm in this case and appears to originate at a defect in the waveguide. The molten damage snakes along the waveguide back to the entrance surface

3. All-optical processing

We have reported many demonstrations of on all-optical signal processing high-speed telecommunications signals using in general the As_2S_3 rib waveguide. We have demonstrated error-free demultiplexing at data rates of up to 1.28Tb/s [11], emphasizing the broad bandwidth capabilities of our devices. Recently we reported the use of a similar waveguide for mid-span spectral inversion of 3x40Gb/s phase encoded signals over a 225km span [12]. The chips have also been used for impairment monitoring [13]; and for RF spectral analysis of data [14] and for the measurement of fsec optical pulses [15]. I will highlight their capabilities by some recent experimental results.

4. Conclusions

Highly nonlinear chalcogenide glass waveguides have proven to be effective as nonlinear optical devices for all-optical signal processing in the most demanding conditions. The other interesting properties of chalcogenides such as excellent transparency in the mid-IR which are just beginning to be exploited for IR nonlinear topics and for sensing [16]. Thus the future for this intriguing materials platform indeed looks bright.

5. Acknowledgements

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6. References

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