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Application of Chalcogenide Glasses for Optical Fibre Amplifiers at 1.3 microns

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The majority of optical fibre now installed in Europe and North America operates in the second telecommunications window, centred at 1.32 microns. In this region, fibre loss reaches one of its minima and chromatic dispersion is negligible. Unlike trans-oceanic cables which operate at 1.55 microns, no optical fibre amplifier exists at this lower wavelength, thus necessitating a conversion of optical signals to electrical signals in order to amplify and re-transmit over long distances. It is clear that to upgrade currently installed fibre and to remove barriers that limit the full exploitation of land-based fibre, an optical fibre amplifier operating at 1.3 microns will play a critical role.

Intense interest in fluoride glass optical fibres doped with praseodymium, the PDFA, was generated three years ago with the announcement of a 1.3 micron amplifier operating with a gain of over 10 dB. This host was extremely inefficient however, with a gain of less than 0.1 dB/mW of pump power, compared to the gain coefficient of 11 dB/mw achieved with an erbium-doped amplifier operating at 1.55 microns.

Sulphide glasses based on Ga_2S_3 and La_2S_3 have recently attracted attention as a promising alternate host for the rare-earth praseodymium. When doped in a suitable glass, two energy levels of this ion are separated by an energy equivalent to 1.3 microns. In fibre form, such a glass provides the potential for highly efficient amplification. In addition to the basic Ga:La:S composition, we have developed and characterized a number of related glasses with an aim to improving quantum efficiency and also the thermal properties which are critical for fibre drawing. The goal is to approach the present 1.550 micron power amplifier performance of a 20 dB gain using only a few tens of milliwatts of pump power. In this paper, we present details of the properties of these glasses, progress towards the realization of a single-mode optical fibre and the overall suitability of sulphide glasses for an optical-fibre-based amplifier operating at this important telecommunications wavelength.

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Introduction

There are some 20 million kilometres of installed fibre transmission links throughout the world, the great majority of which operate at a wavelength of 1.3 microns. These links are limited in capacity by a combination of fibre loss and the bandwidth of their electronic repeaters, both of which limitations can be removed by the use of optical amplifiers. It is therefore highly attractive to consider uprating the world's installed fibre base by the simple installation of optical amplifiers.

The concept of an optical fibre amplifier as a practical component for telecommunications was demonstrated in 1987 by Mears et al[1], who showed that efficient amplification at a wavelength of 1.55 microns could be obtained by adding the trivalent erbium ions (Er^{3+}) to the core of a standard telecommunications fibre. Unfortunately, nature has not been so kind as to provide a direct equivalent with a 1.3 micron operating wavelength. The rare earth neodymium (Nd^{3+}) is known to provide amplification at 1.35 microns, a wavelength slightly longer than desired, however this transition suffers from excited state absorption which robs the amplifier of pump power and amplified spontaneous emission which competes with signal gain. In 1991, praseodymium in a fluoride glass host was shown to provide useful gain. Extensive development of Pr^{3+}-doped fluoride-glass fibre amplifiers in Japan has resulted in 20 dB gain from approximately 100 mW of pump power at 1.02 microns, and diode-pumped modules have been demonstrated[2]. However, the quantum microns, and diode-pumped modules have been demonstrated[2]. However, the quantum efficiency of the Pr^{3+}-doped ZBLAN fibre amplifier is low (typically 3-4%) as a result of non-radiative multiphonon decay in which pump energy is lost as heat in the glass matrix. Although this performance is perhaps adequate for a power (ie. post) amplifier, significant further improvements are unlikely without development of alternative hosts with lower phonon-energy.

Sulphide glasses based on Ga_2S_3 and La_2S_3 have recently attracted attention as promising alternative hosts for the rare-earth praseodymium. Because of their low phonon, or vibrational energy, the probability of non-radiative decay is greatly reduced. In fibre form, such a glass would provide the potential for highly efficient amplification[4-5]. The Link GOAL project has set itself the task of developing this sulphide family of low-phonon-energy glasses. In addition to the basic Ga:La:S composition, the authors have developed and characterized a number of related glasses with an aim to improving both the quantum efficiency and the thermal properties which are critical for fibre drawing. The goal is to approach the present 1.55 micron power amplifier performance of a 20 dB gain using only a few tens of milliwatts of pump power. In this paper, we present details of the properties of these glasses, progress towards the realization of a single-mode optical fibre and the overall suitability of sulphide glasses for an optical-fibre-based amplifier operating at this important telecommunications wavelength.

Glass Fundamentals

In many cases, the search for a low-phonon-energy glass begins through some qualitative knowledge of the physical and optical properties of the potential host. Good transmission in the infrared, a low glass transition temperature and high atomic weights among the glass constituents all suggest the possibility of a low-phonon-energy. Principle considerations for a practical device are phonon-energies less than that of ZBLAN (580 cm^{-1}), transparency in the visible and near infra-red, and thermal properties which give fibre drawing a reasonable chance of success.

Starting materials for the Ga:La:S glasses consist of lanthanum, gallium and praseodymium sulphides, (Ga_2S_3, La_2S_3 and Pr_2S_3) prepared by Merck Ltd. These compounds provide the high atomic weights and weak bonds which result in low-phonon-energies. These sulphides are prepared by the reaction of a precursor (metal or oxide) with hydrogen sulphide.

Bulk-glass samples were prepared by melting the starting materials in a vitreous carbon crucible sealed within an evacuated silica ampoule in an electric furnace. Melting is undertaken for several hours at 1150°C and then the ampoule is rapidly quenched[6]. Small 10 gram samples were prepared for spectroscopic and thermal analysis and larger, up to 50 gram melts were performed to provide glass for fibre drawing trials.

Glass Properties

Fundamental understanding of the radiative and non-radiative properties of the halide and sulphide glasses is obtained through a series of spectroscopic measurements. Absorption spectroscopy of samples heavily doped with Pr^{3+} reveals the position and the integrated absorption cross-section for each energy level of the Pr^{3+} ion. Transmission from the ultraviolet edge to the infrared cut-off follows from absorption and FTIR measurements. Emission spectroscopy completes the analysis, providing fluorescence spectra and lifetimes.

Figure 1 shows the results of transmission measurements through a bulk glass sample which are extrapolated to yield the minimum or intrinsic loss. An absorption of less than 0.1 dB/m is considered necessary for a useful device, thus Ga:La:S glass provides a transmission range from the visible to about 6 microns with a loss minimum at about 5 microns. We note the intrinsic loss at the pump wavelength of 1.0 microns to be about 0.01 dB/m. In practice, loss is higher than the intrinsic minimum due to absorption caused by impurities and scattering from inhomogenities and crystals. Figure 2 shows the actual transmission in an undoped glass sample from 1 to 8 microns. We note that in this sample, absorption due to OH^- and SO_4^{2-} dominates the spectrum. Efforts are now underway to minimize these impurities by processing in a dry argon environment.

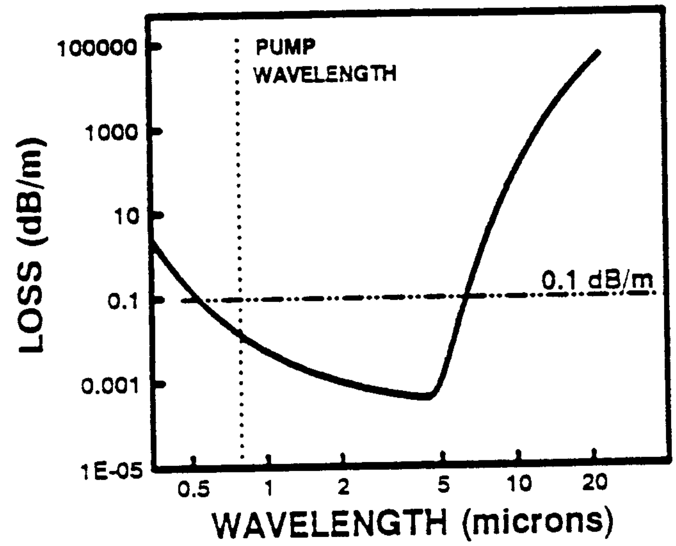

Figure 1. Intrinsic absorption and scattering loss of Ga:La:S glass extrapolated from transmission measurements.

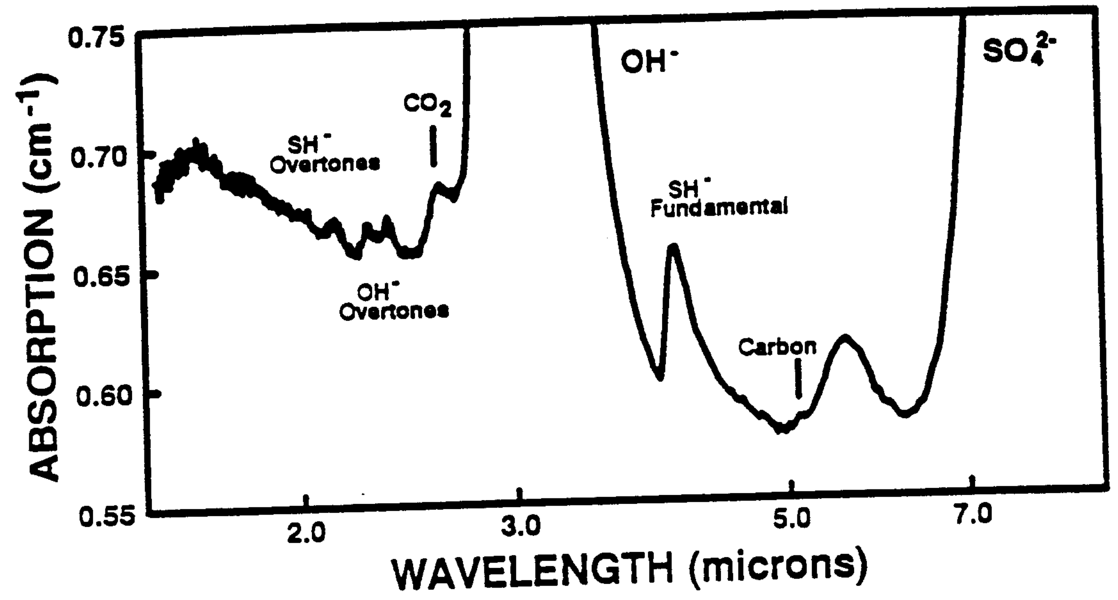

Figure 2. Impurity Analysis by FTIR spectroscopy.

Thermal properties for the sulphide glasses were measured by differential thermal analysis (DTA), which provided characteristic temperatures and by thermal mechanical analysis (TMA), which yielded the coefficient of thermal expansion and softening temperature. Table 1 provides the thermal analysis results for a typical sample. Fibre drawing must take place at a temperature which avoids crystallization, yet at which the glass is sufficiently softened to flow into fibre form. Typically, the fibre drawing temperature lies between T_g and T_x. In addition, the coefficient of thermal expansion of the core and cladding material must be matched in order to avoid stress and mechanical failure of the glass.

Table 1. Basic glass optical and thermal properties for the halide and sulphide glasses.

Index of Refraction (n_d)	2.38
Density (g/cm^3)	4.01
Glass Transition T_g (°C)	552
Crystallization onset T_x (°C)	681
Crystallization peak T_p (°C)	687
Melting onset T_m (°C)	861
Expansion Coef. (°C^{-1}x10^{-7})	90

The fluorescence spectrum of a Pr^{3+}-doped glass sample was obtained by pumping with a Ti:Sapphire laser tuned to the peak of the $^1G_4$ ground state absorption, at about 1.0 micron, and then analyzing the emission on an optical spectrum analyzer. By chopping the signal with an acousto-optic modulator and directly detecting the decay of the fluorescence intensity, the lifetime of this level could be determined. Figure 3 provides the fluorescence spectrum obtained from excitation at 1.02 microns. We note that for the bulk sample, the peak of the emission is at about 1.34 microns, slightly outside the telecommunications range of 1.28 to 1.32 microns.

Measured lifetimes of the excited state were found to be 280 μsec. Long lifetimes indicate a greater probability of radiative decay and we have shown that maximum lifetimes are critically dependent on the elimination of all hydroxyl impurities from the glass. Through a Judd-Ofelt analysis, the total radiative decay rates can be calculated. We have performed this calculation and obtained a total radiative lifetime of 520 μsec.

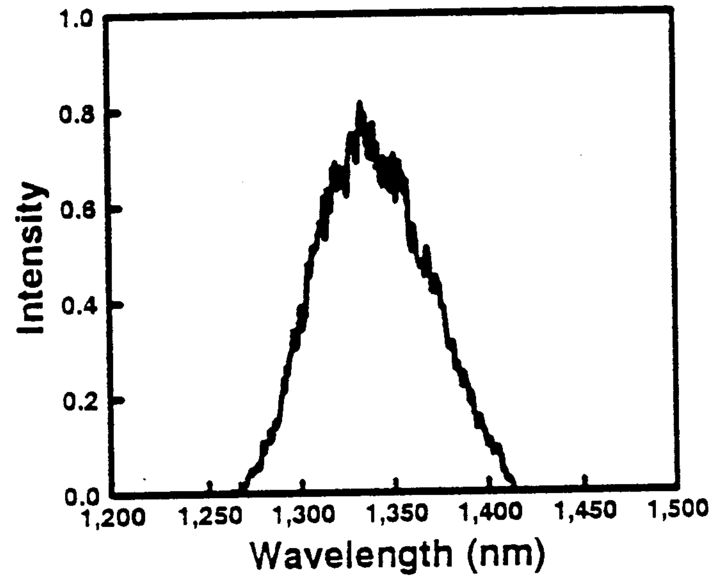

Figure 3. Fluorescence spectrum of Pr^{3+}-doped Ga:La:S glass pumped at 1.02 microns.

Device Modelling

The measured and calculated lifetimes for the $^1G_4$ level allow prediction of the quantum efficiency of an amplifier, defined by the number of photons emitted at 1.3 μm over the number of pump photons absorbed. The calculated quantum efficiency assumes only radiative and multiphonon non-radiative processes occur and thus places an upper limit on the efficiency for small signal gain. From the ratio of the calculated total and radiative decay rates, given by the reciprocal of the corresponding lifetime, we predict a radiative quantum efficiency for the gallium sulphide glass of 80%, while a value of 53% is presently measured.

These values represent over an order of magnitude increase in the performance over that of current 1.3 micron devices.

A numerical model has been developed which describes the principle performance features of a 1.3 μm optical fibre amplifier, including the effects of ground state absorption (GSA), excited state absorption (ESA) and amplified spontaneous emission (ASE). The rate equations for the relevant Pr^{3+} energy levels are solved alongside the equations describing the propagation of the pump, signal and ASE (both forward and backward propagating) using routines developed for the erbium doped fibre amplifier. Figure 4 shows the calculated gain spectrum for a single-mode Ga:La:S fibre of length 13 m and numerical aperture 0.4. When pumped at a wavelength of 1.02 microns, this fibre will provide a small-signal gain of approximately 30 dB, ie. a factor of 1000 increase in signal strength for a pump energy of 50 to 75 mW. This performance far exceeds that of current Pr^{3+}-doped fluoride fibres.

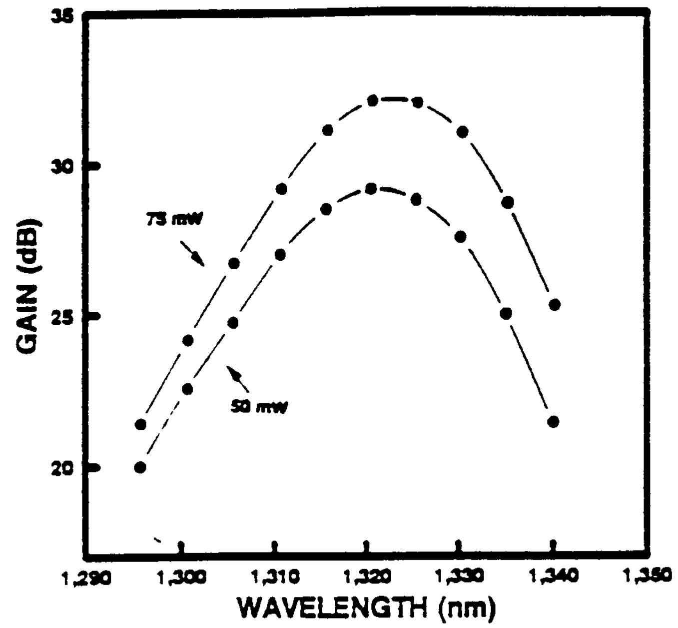

Figure 4. Calculated gain spectrum for a practical Ga:La:S fibre device.

Fibre Drawing

Fibre drawing has concentrated on the technical effort required to design, build and test a radically new furnace capable of meeting the challenges of chalcogenide glass drawing. A highly controllable, stable hot zone can be produced in a furnace by radio frequency (RF) heating of a graphite ring. To this end, a novel RF furnace has been designed and constructed. Temperature control has been facilitated by the addition of an optical temperature probe which will read the temperature directly without interference from the RF field. Crystallization has been minimized by the addition of water-cooling above and below the hot zone.

Preliminary tests on the fibre drawing furnace have been performed using a phosphate glass with a softening temperature slightly higher than that of Ga:La:S, in order to verify drawing temperature, and with fluoride glasses to verify the temperature control and preventative measures against crystallization. Multimode fibre from both materials has been successfully achieved, coated and drawn to several metres in length. Figure 5 shows the first results of the pulling of a Ga:La:S fibre, in this case a Pr^{3+}-doped sulphide glass core surrounded by a lower index cladding. Efforts are now underway to minimize loss and expand the technique to single-mode fibre geometries.

Current Status

The LINK project GOAL (Glasses for Optical Amplifiers and Lasers) has identified and exploited a new family of glasses for application as a 1.3 micron optical fibre amplifier. Merck Ltd has developed novel methods of synthesizing high purity sulphide starting materials and glasses, in cooperation with the Optoelectronics Research Centre of the University of Southampton, who melt and characterize the sulphide glasses. Characterization and fibre drawing has been coordinated between Pirelli Cables Ltd and the University. Promising results have been obtained leading the way towards a practical and efficient device capable of outperforming the current technology.

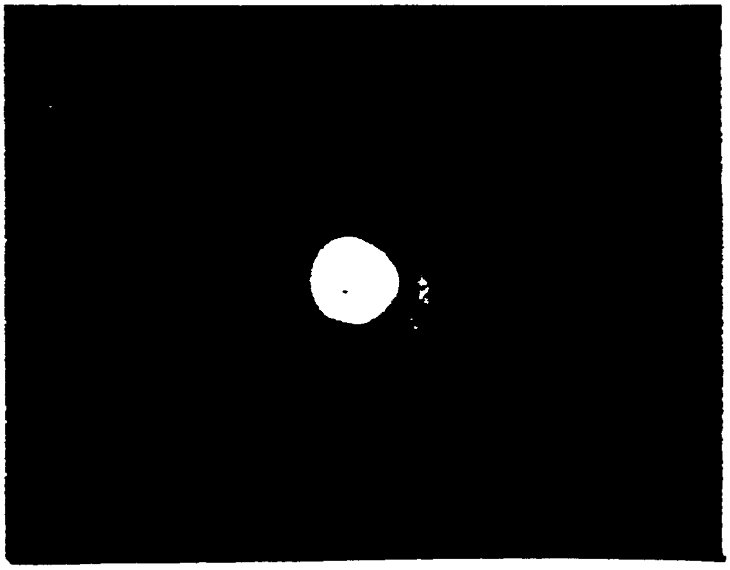

Figure 5. Cross-section of a multimode Ga:La:S fibre.

Acknowledgements

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