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Prospects for New Glass-Based Optical Waveguide Devices

W.A. Gambling and D.W. Hewak

Optoelectronics Research Centre
University of Southampton, Southampton, ENGLAND SO17 1BJ
Tel.: +44 01703 594522, Fax.: +44 01703 593142
E-mail: WAG@orc.soton.ac.uk

Introduction

Why not silica? Over the past three decades, optical fibres based on high-purity silica, have established themselves as perhaps the ultimate communications material. These global cobwebs of glass have revolutionized telecommunications, reaching virtually every populated region on earth and providing enormous bandwidth, the full extent of which has yet to be exploited. Passive waveguides are today being spliced together with lengths of fibre doped with the rare-earth ion erbium, providing optical fibre amplifiers which can boost a fading signal by three orders of magnitude. This combination of active and passive waveguides, has made possible all optical networks, with no electrical/optical interfaces except at the signal source and receiver, and paved the way for global optical fibre telecommunications.

Why then new glasses? Through a series of case studies based on current research topics in Southampton, we describe optoelectronic devices whose realization is entirely dependent on new materials. The first is a practical optical fibre amplifier for the second telecommunications window at 1.3 μm. Such a device based on rare-earth-doped fibres simply does not work in a silica host, where all useful emission is dissipated as heat in the glass. The second is a planar waveguide device, the lossless splitter. In this important component for fibre to the home, fibres with lengths of several metres would normally be required. New glasses allow greater concentrations of the active rare-earth dopant to be incorporated, thereby shrinking the size of the device to dimensions of a few centimetres. Thirdly, new glasses and fibres for fibre-based acousto-optic modulators will be described. These devices have the potential to allow direct modulation of the light within the fibre.

Through these three case studies, we highlight the potential role of new materials in three key waveguide devices for telecommunications; amplifiers, splitters and modulators. The paper will conclude by reviewing overall efforts in Southampton in new glasses for optoelectronics, identifying key materials, their properties and applications in a global telecommunications network.

Case 1. A Practical 1.3 μm Optical Fibre Amplifier

There are millions of kilometres of land-based fibre installed in the world today, the great majority of which operate at a wavelength of 1.3 μm. These links are limited in capacity by a combination of fibre loss and the bandwidth of their electronic repeaters, whose bottleneck effect 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 operating at 1.3 μm.

While nature has been kind in providing efficient amplification at 1.55 μm through the addition of erbium ions to the core of a standard telecommunications fibre, there is no direct equivalent for the 1.3 μm telecommunications window. Devices based on the rare-earth element neodymium are known to provide peak amplification at 1.4 μm, a wavelength outside the telecommunications window which extends from 1285 to 1130 nm. In 1991, praseodymium in a fluoride glass host was shown to supply usable gain and extensive development has resulted in 20 dB gain from approximately 100 mW of pump power [1]. However the efficiency of Pr^{3+}-doped ZBLAN glass is low, with over 96% of the pump power lost as heat in the glass, through the process of multiphonon decay.

The key to an efficient and practical 1.3 μm optical fibre amplifier, using either neodymium or praseodymium, is a new host material. Generally, more ionic glasses tend to shift the emission spectrum of neodymium towards shorter wavelengths, as shown in Table 1. Clearly the strong covalent bonds of silica result in an emission wavelength longer than desired. However, neodymium suffers also from problems with excited state absorption (ESA) which further shifts the peak gain. From the table, low-index glasses such as the fluorophosphates and the fluoroberyllates hold the most promise for a Nd^{3+}-doped device.

Table 1. New Host Materials for Nd^{3+}-doped 1.3 micron Amplifiers

Glass	Peak Emission (nm)	Peak Gain (nm)
Silica	1360	1400
Phosphate	1325	1360
Fluorophosphate	1323	1323
ZBLAN	1317	1340
Fluorberyllate	1312	1312

Praseodymium on the other hand suffers no ESA, but a low efficiency results from loss of pump power to non-radiative mechanisms, such as phonon vibrations, and prevents the emergence of a suitable commercial device. World-wide effort is therefore aimed at a series of new low-phonon-energy glasses for application at 1.3 μm. The search for a suitable host has targeted glasses such as the halides and sulphides, all of which offer good transmission in the infrared, a low glass transition temperature and high atomic weights, features which indicate a low-phonon-energy[2]. Through measurements on bulk samples, the total radiative efficiency of the doped glasses can be estimated from the ratio of rate of radiative decay to non-radiative decay. As shown in Figure 1, the fluoride glasses based on indium and gallium show only a slight improvement over the fluorozirconate glasses which offer efficiencies around 4%. These glasses, however, show the most promise for realization in low-loss fibre form[3]. By substitution of the heavier chlorine for fluorine, the mixed cadmium halide glasses show efficiencies over 10%. Unfortunately, these materials are highly unstable, rapidly attacked by moisture, and are characterized by very low melting temperatures. These undesirable properties are indicated by the large uncertainty even in the measured quantum efficiency.

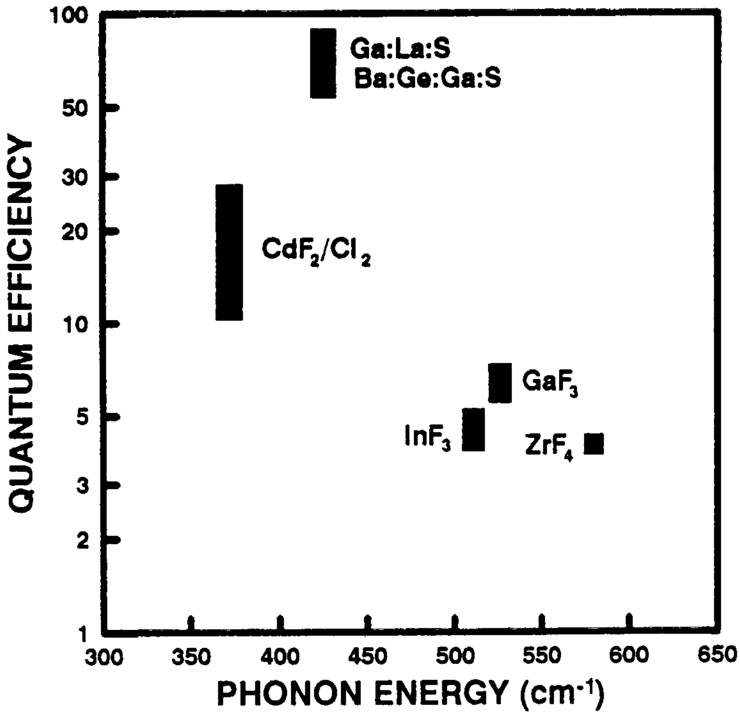

Figure 1. Total Radiative Quantum Efficiencies for Pr^{3+}-doped Glasses.

Considering, on the other hand, the chalcogenide glasses, and in particular sulphides based on gallium in combination with lanthanum or germanium, efficiencies well over 50% are indicated. These glasses benefit not only from a low phonon energy, which, as in the halides, lowers the rate of non-radiative decay, but also are characterized by a high refractive index, typically on the order of 2.4, compared to the 1.5 of fluorozirconate glass. The high refractive index raises the rate of radiative decay and this, in combination with the low non-radiative rates, boosts the efficiency to the highest levels yet measured[4]. Efforts are underway to achieve these glasses in fibre form, a task made difficult by their high viscosity at temperatures below the onset of crystallization.

Efforts towards a practical 1.3 μm optical fibre amplifier continue, with both neodymium and praseodymium remaining as contenders. Although each of these rare-earth ions provides their own advantages and disadvantages, they share the requirement of a new glass host in order for their potential to be fully realized.

Case 2. Planar Lossless Splitter

The erbium-doped fibre amplifier is now firmly established as a commercial product with an important role in global telecommunications. However, for the end-user of future telecommunications networks, the local loop requires low-cost, mass-produced components to deal with the complex, multichannel signals entering the home. One such device is the planar lossless splitter, which provides the function of signal distribution and, through the incorporation of gain, offsets insertion and splitting losses. The key to this component is the planar erbium-doped amplifier.

In comparison to the Er^{3+}-doped fibre amplifier, the equivalent planar device requires much higher dopant concentrations to compensate for the shorter optical path lengths. High erbium levels in silica lead to problems of clustering which degrades the performance. As a result, research has turned to new materials for erbium-doped planar amplifiers, as summarized in Table 2. While work is underway around the world on this problem, no commercial device is yet imminent, partly due to the complex technology required to realize these active waveguides[5].

A lossless splitter takes an incoming signal from an optical fibre and divides it between multiple output fibres, but maintains signal strength with an integrated optical amplifier. In the device now under-development at the ORC and illustrated in Figure 2, one part of the substrate is doped with erbium to provide the optical amplification medium and the other carries out the passive splitting function.

Table 2. Experimental Er^{3+}-doped planar waveguide devices.

Host Material	Waveguide Fabrication
Bulk-doped Phosphate glass	Ion-exchange
Flame Hydrolysis SiO_2-on-Si	Reactive ion etching
Erbium-diffused $LiNbO_3$	Ti-diffusion/Proton Exchange
Bulk-doped Silicate glass	Ion-Exchange
Sputtered Silicate glass	Reactive ion etching
PECVD SiO_2-on-Si	Reactive ion etching
Sputtered Y_2O_3 films	Ion beam etching
Ion-Implanted sputtered Al_2O_3	Reactive ion etching

Recent results on borosilicate glass, bulk doped with 0.5 % by weight erbium, and with waveguides formed by ion-exchange have provided internal gains of 10 dB over a waveguide of length 23 cm. High pump powers, however, are required to achieve this result and efforts are underway to reduce the power required through higher doping levels, again made possible by new materials.

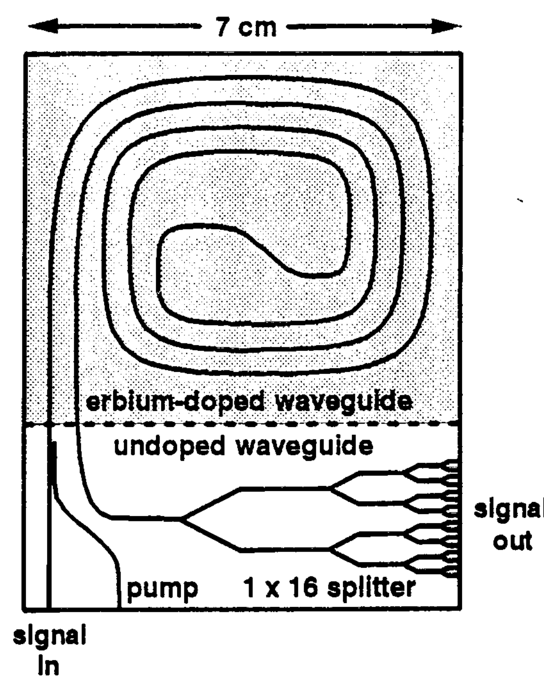

Figure 2. Schematic of the lossless splitter fabricated in Er^{3+}-doped glass.

Case 3. Acousto-Optic Modulator

One crucial advantage of optical fibre devices is their inherently-low loss, which allows for efficient fibre amplifiers, soliton and short-pulse generators, and high finesse fibre resonators. Unfortunately, much of this advantage is lost when a high-speed modulator is required, such as for signal modulation or for signal processing, because existing modulators based on lithium-niobate or optoelectronic integrated-circuits have high coupling and insertion losses, typically 4-10 dB. In an attempt to overcome this problem, research is underway to examine acousto-optic interactions directly in fibres with the objective of modulation at gigahertz frequencies with negligible losses. Unfortunately, the very inertness that makes silica an ideal long-distance transmission medium results in its having both a low Verdet constant and poor acousto-optic performance. As a result, acousto-optic components simply do not work in silica.

Response of a material to acoustic intensity can be assessed through evaluation of the second acousto-optic figure of merit,

$$M_2 = \frac{n^6 p^2}{\rho V^3}$$

where n is the refractive index, ρ is the density, p is the Pockels coefficient and V the acoustic velocity. From this equation, high-index materials made from large heavy ions through which acoustic velocities would be low, result in a higher figure of merit and are thus the optimum device material.

We have evaluated both heavy metal oxides and chalcogenide glasses for this application, and experimentally measured their diffraction efficiency. For the former, a new chlorotellurite glass based on tellurium oxide and zinc chloride has proved to be a promising acousto-optic material [6]. Measurements on bulk samples provide a 65% diffraction efficiency at the wavelength of 633 nm using an 80 MHz piezoelectric transducer with 1.5 W of RF power. Device dimensions were 15 x 1 mm. Alternatively, the sulphide glasses, the figure of merit indicated the promise of even higher diffraction efficiencies. With acousto-optic efficiencies 3-4 orders of magnitude higher than that of silica, there is little doubt that when these new materials are demonstrated in low-loss fibre form, in-fibre acousto-optics will be the method of choice for manipulating the radiation they carry.

Table 3. Figures of Merit (M_2) for various fibre materials.

Glass	M_2 ($\times 10^{-15}$ m^2/W)
Silica	0.002
Tellurite	4.1
Sulphide	20.4

Summary

What then is the ideal new glass for new device applications? Recent trends, as summarized in Table 4, indicate high refractive index, high acousto-optic merit, low-phonon-energy and good solubility of the rare earth are all essential characteristics of new materials for optical waveguide devices of the future. At the ORC, research on advanced materials for multifunction waveguides is driven by device requirements. A more efficient optical fibre amplifier for 1.3 μm, requires new glasses of lower vibrational energies to minimize non-radiative decay. A planar lossless splitters relies on a new waveguide material which allows a high incorporation of erbium. Modulators need bulk or fibre optics which interact with acousto-optic power. Other new devices, under study at the ORC include photorefractive gratings, which provide in-fibre filters and reflectors[7], and switches which exploit the non-linear properties of the host material[8]. Both of these devices again require departures away from traditional fibre and waveguide materials.

Table 4. Summary of Material Requirements for New Optoelectronic Devices

Device	Glass Property	Target Material
Fibre Amplifiers and Lasers	High Refractive Index Low-Phonon-Energy	Chalcogenides Fluorides
Planar Amplifiers and Lasers	High Rare Earth Solubility	New Oxide Glasses
Modulators	High Acousto-optic Merit	Heavy Metal Oxides Chalcogenides
Fibre Switches	High $\chi^{(2)}$	Poled Silica Doped Silica
Bragg Gratings	Photorefractivity	Doped Silica Doped Fluorides

In conclusion, while the ultimate material, silica, for long-distance optical fibre telecommunications has now been available for decades, devices to allow full exploitation of the bandwidth of a fibre link remain to be developed. As we show in this paper, whether for the function of amplification, splitting, modulation, switching or filtering, the key to these devices is new materials.

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