Accepted as invited paper 136 2996-14, to appear in SPIE Proceedings vol. 2996. "Rare-Earth-Doped Devices" in OE '97 (Optoelectronics: Integrated Devices & Applications) San Jose, California Feb. 8-14 1997

Ion-exchanged glass waveguide lasers and amplifiers

Martin Hempstead*

Optoelectronics Research Centre, University of Southampton, Southampton SO17 1BJ, UK

ABSTRACT

In this paper I will survey the field of ion-exchanged glass waveguide lasers and amplifiers. Ion-exchanged waveguide devices have significant virtues, such as low propagation losses and suitability for mass production. The progress in realising lasers and amplifiers has been impressive, but more work is needed to produce commercially viable devices.

Keywords: ion-exchange, waveguide, laser, optical amplifier, neodymium, erbium

1. INTRODUCTION

This paper is an overview of the field of waveguide lasers and amplifiers fabricated by ion-exchange in glasses. Other types of host - insulating crystals and semiconductors - and methods of waveguide fabrication will be considered only insofar as they represent competing technologies for the fabrication of waveguide lasers and amplifiers. I will also largely restrict the discussion to lasers operating in a single transverse mode.

Lasers are of interest in a number of applications; as signalling sources for telecommunications, in materials processing and in analytical applications such as spectroscopy and environmental sensing. Their desirable properties include high brightness and high coherence, which make them more than just intense light sources. By far the most numerous and lowest cost type of laser is the laser diode (LD), which has relatively poor output beam geometry. Waveguide lasers based on rare-earths are well-suited as means for converting LD power into a guided mode at a desirable wavelength, while in principle maintaining compactness, robustness and relatively low cost. Applications of immediate interest include multiline sources in the 1500nm telecommunications window for wavelength-division-multiplexed (WDM) networks, blue sources for high-density data storage and visible sources for display. Each of these applications demands high quality output with good wall-plug efficiency and low cost; equally important, each application could represent a mass market where economies of scale and integration may be realised. As an integrated optics technology, ion-exchanged waveguide fabrication lends itself to such economies of scale.

Optical amplifiers are also a very attractive technology, with the erbium-doped fibre amplifier (EDFA) standing out as a particular success story. There are still unfilled requirements for an optical amplifier operating in the 1300nm telecomms window, a window used by most installed fibre. Erbium-doped planar amplifiers (EDPAs) also appear an attractive proposition, especially if they can be realised in an integrated form incorporating other functions useful in an optical network, such as passive splitters and WDM devices. As will be seen below, this initial attraction is dimmed by the consideration that EDPAs must be quite inexpensive in order to be viable, since their cost in an optical network is typically shared by only a few consumers. While this proximity to the customer implies large markets and economies of scale, the cost of an erbium-doped amplifier is dominated by the pump laser diode, and is thus insensitive to improvements in EDPA technology.

Driven by these considerations, the bulk of work in waveguide lasers and amplifiers has focussed on neodymium- or erbium-doped systems. Nd^{3+} has an efficient 4-level system emitting around 1060nm; while there is little demand for this specific wavelength range, the system is often used for applications demanding high power lasers. Er^{3+} is important because it has an emission band covering the wavelength range of the third telecomms window.

---

* Further author information -

Email: mh2@orc.soton.ac.uk; Telephone: +44 1703 592809; Fax: +44 1703 593149

In considering the status of work in ion-exchanged devices, comparison should be made not only with other waveguide technologies, but also with equivalent fibre-based devices. Fibres have a number of advantages, including extremely low propagation losses, ease of fabrication both of the basic fibre and of Fabry-Perot cavities, and ease of splicing to other fibre components to build up complex devices. Fibre structures are not necessarily less compact than integrated devices, unless waveguides of very high NA are used. Thus in considering the virtues of an EDPA, for example, one must always ask whether a better solution may not be to splice a piece of erbium-doped fibre onto a planar structure. The ultimate advantages of waveguide devices may lie in the possibility of using material with valuable properties that cannot conveniently be reproduced in silica fibre, or in levels of integration so complex that the device cannot reliably be realised with high yield in a bulk fibre-based form. This is a challenging prospect; for example, fibre-based splitters based on concatenated 1x2 couplers remain competitive up to high splitting ratios.

2. WAVEGUIDE FABRICATION BY ION-EXCHANGE

Ion exchange involves a local change in composition, which is brought about by mass transport driven by thermal or electric field gradients or some combination of the two, constrained in general by a mask which defines the regions altered. The change in composition leads to a change in index, and thus to waveguiding in a region of suitable geometry. Ion exchange assumes a host structure in which there is some form of network, rigid and covalently bonded, through which mobile ions can move. The technique is thus particularly appropriate for silicate and phosphate glasses, which have this structure. A similar process can be carried out on crystals such as lithium niobate and potassium titanyl phosphate (KTP). Ion exchange thus stands in contrast to fabrication techniques which "sculpt" the index distribution, generally through some kind of etching of a deposited film; it is more similar to ion-implantation, but involves processes which are much less energetic and thus less damaging to the host.

As a diffusive process which does not damage the host network, ion exchange tends to produce smooth, well-graded structures, with fairly low propagation losses. Since ion exchanged waveguides are usually produced by alteration of the glass surface through contact with a molten salt bath or metal film, the propagation losses can be reduced further by burial of the waveguide, in which an electric field is applied to drag the altered zone into the glass host, the surface composition being reconstituted by simultaneous immersion in a bath of the appropriate salt mixture. By moving the optical field away from the relatively rough surface, and by allowing further smoothing of the profile, burial leads to waveguides with extremely low losses, claimed to be around 0.01 dB/cm. While not approaching the losses of optical fibres, these are the best values claimed for integrated optics. It should be noted that very similar values have been obtained for waveguides made by entirely different methods, involving flame-hydrolysis deposition followed by etching to define the confined waveguide.[1] For all techniques, propagation losses in rare-earth-doped glasses turn out to be substantially higher than in undoped glasses.

Another consequence of the smoothing effect of diffusion is that it is not possible to make short-range structures; in particular, it is difficult in surface waveguides to make gratings with large K-vectors, such as 500nm-period Bragg reflectors for 1500nm applications, and impossible in buried waveguides. Moreover, while burying waveguides reduces their losses, it also renders their evanescent fields inaccessible. On the other hand, the diffusive smoothing assists the realisation of adiabatic transitions between integrated components.

One of the advantages of ion exchange is that it appears suitable for a wide range of glasses. However, it is necessary that the ions in the raw glass and in its ion-exchanged composition be immobile at normal temperatures, so that devices will last up to the 20 years demanded by the telecomms industry, while becoming sufficiently mobile at elevated temperatures for acceptable processing times. In practice, only the monovalent ions, especially the alkaline cations, meet these criteria; bivalent and trivalent ions will not diffuse appreciably under concentration gradients at whatever temperature, and the electric fields required to move them can alter the glass network structure. Exceptionally, exchange of monovalent anions has been used in fabricating waveguides in fluoride glass substrates.[2] The limited choice of exchangeable mobile ion pairs leads to a similarly limited maximum index change (Δn). Thallium and silver ions lead to the largest Δn when exchanged with Na^+ or K^+. Thallium is highly toxic, and demands great care in handling; despite this, it has been the basis of a successful industrial process developed by Corning Europe for the fabrication of passive splitters. Silver ions have a tendency to reduce to metallic silver, leading to high propagation losses. Nevertheless silver exchange also forms the basis of an industrial process, being used by IOT of Germany to make passive splitters.

Thus a successful ion exchange process, which leads to reproducible, stable, low-loss waveguides demands control of host glass composition and much effort to determine the ideal processing conditions of temperature and salt-bath composition, as well as the development of compatible masking procedures.[3] For example, the fabrication of silver-exchanged waveguides in Nd^{3+}-doped glass, leading to the demonstration of lasing at three wavelengths, required a special host glass with reduced levels of fining agent.[4] A major drawback arising from the compositional constraints is that ion-exchanged waveguides cannot be directly bonded to silica-based fibres, whereas it is conceivable that silica-based waveguides - produced for example by flame-hydrolysis deposition[5] or PECVD[6] - may in principle be fusion-bonded.

The mobility properties of the ions make localised post-annealing possible, because the ions will move appreciably only where the temperature is high enough. This has been exploited several times very successfully to make tapers, permitting good coupling to single-mode fibres at the waveguide input while retaining the desirable features of a high NA guide away from the input.[7-9] Such processing may have further possibilities, permitting perhaps the trimming of couplers and other structures under the influence of localised heating, for example from a CO_2 laser.

Despite reports to the contrary,[10] the trivalent rare-earth ions are effectively immobile, and it is not possible to use ion exchange to localize rare-earth doping. In ion-exchanged rare-earth-doped glass waveguide devices, the host is almost invariably bulk-doped with the rare-earth, the only exception being the use of ion-implantation of erbium.[11] Where the rare-earth ion is used as a 3-level system, as is the case with Er^{3+}, this leads to problems of signal reabsorption in the modal tails, as will be discussed in more detail below. This inevitably hampers the performance of Er^{3+}-doped ion-exchanged devices, but with a 4-level system such as Nd^{3+} lasing around 1060nm, this is not an issue.

3. ION-EXCHANGED WAVEGUIDE LASERS AND AMPLIFIERS

Laser and amplifier waveguide devices are likely to be technologically attractive only to the extent that they can be integrated with other components to make integrated optical circuits with high added value. I thus preface the discussion of the work in this field with a brief overview of the kinds of passive waveguide component that have been demonstrated, even when they have not been combined with an active section. I continue by considering the basic systems that have been made to lase or amplify in ion-exchanged waveguides. Finally, I summarize the work that has been done to combine active components with passive structures to realise more specific functions, and in some cases to test the resulting devices as part of an optical system.

3.1 Ion-exchanged passive devices

A number of passive components in ion-exchanged format have been reported, most of them several times using various ion/host systems. One of the simplest is the y-junction which acts as a 1x2 power splitter;[12] cascades of y-junctions have been used to realise a $1x2^n$ power splitter, with n up to 5. Two y-junctions arranged head-to-tail produce a basic Mach-Zehnder interferometer.[13,14] Directional or proximity couplers rely on exchange of power between two modes in adjacent waveguides to permit wavelength-multiplexing or demultiplexing.[15] Geometrical and stress-induced birefringence have been exploited to realise polarisation filters.[16] Other useful structures include heating elements for thermooptic tuning,[17] which have some applications despite millisecond response times, and etched[18] and photoinduced Bragg gratings.[19] Light sources[20] and photodetectors[21] have also been mounted to ion-exchanged waveguides.

The basic elements listed above have been used to fabricate some sophisticated devices, such as ring resonators,[22] a Michelson interferometer,[23] and wavelength-division multi/demultiplexers, for use, for example, with EDFAs.[24] In many cases,insertion losses have been reduced with extra features, such as staggered waveguide transitions,[24] to allow for modal shifts in bends, and thermal mode-expanding tapers, to match integrated optical elements to fiber pigtails.[7-9]

Complex integrated circuits require the kind of components listed above, but the insertion losses must be low if a number of them is to be combined. Moreover, the components must fit into the limited real estate available on glass substrates; while bent waveguides can be used to keep the length within limit, the area occupied by a complete circuit must be small, so that the cost advantages of fabricating a large number of devices on a single substrate can be realised. This makes it desirable that the size of each component be minimized.

3.2 Basic ion-exchanged lasers and amplifiers

Various ion-exchanged lasers and amplifiers have been developed over the past seven years. The first results were obtained with Nd^{3+} operating as a 4-level system. Er^{3+} -doped devices took longer to develop, and face competition from Er^{3+} /Yb^{3+} co-doped systems which have a number of advantages. All ion-exchanged lasers have employed rare-earth ions as their active elements; an introduction to the main aspects of the spectroscopy of rare-earth-doped materials can be found in Yen and Selzer[25]. Note that glasses are not only the natural substrates for ion-exchanged waveguides, they are also good hosts for rare-earth dopants, since their disordered structure leads to spectral smoothing through inhomogeneous broadening, and intrinsic polarisation independence. There is one drawback which glass-based fibres and integrated optics share - the lack of second order non-linearity, which implies lack of electrooptic device control.

3.2.1 Nd^{3+}-doped lasers and amplifiers

The first report of any planar waveguide in an active medium was published in 1985,[26] and described the behaviour of Ag+-K+ ion-exchanged multimode planar waveguides in Nd^{3+}-doped silicate glass. A small gain was seen, and further work was done on a similar system.[27] However, the honour of forming the first waveguide laser went four years later not to an ion-exchanged device but to a flame-hydrolysis-deposited Nd^{3+}-doped silica-on-silicon waveguide,[5] lasing at 1064nm. This was closely followed by a report of lasing in a Ti-diffused waveguide on lithium niobate.[28] In the next year, ion-exchanged Nd^{3+} lasers were demonstrated in phosphate,[29] borosilicate[30] and silicate[31] glass hosts. All these devices operated in the single-mode regime. With the basic principle thus well-established, the various groups developed more advanced devices. Pumping by GaAs laser diodes was shown to be possible, thanks to low lasing thresholds.[32] The 1300nm transition was made to lase, despite the problems of excited state absorption,[4,33] and lasing was also achieved at the difficult 3-level transition at 906nm.[4]

Work on Nd^{3+}-doped waveguide lasers has moved beyond proof-of-principle to the development of more highly functional integrated sources, as will be discussed in 3.3. There are as yet no commercial applications for simple Nd^{3+}-doped waveguide sources; in the interim, however, bulk laser diode-pumped microchip lasers have become strikingly successful as commercial products.[34] They are relatively easy to fabricate and extremely robust; they produce high output powers in high quality beams. In contrast, waveguide lasers do not readily produce the same power levels, being limited to less than about 100mW. Moreover, there is no specific demand for high-quality fibre-coupled light in the 1060nm region.

There have been some reports of optical amplifiers at 1060nm based on Nd^{3+}-doped ion-exchanged waveguides.[35-38] The 4-level Nd^{3+} system with its high cross-sections and high maximum doping levels lends itself to the easy fabrication of high-gain amplifiers, and power at the pump wavelength of 810nm is inexpensively available from GaAs laser diodes. Nevertheless, the lack of telecommunications applications in this wavelength region reduces the drive to explore this area; perhaps such amplifiers can find application as components in LIDAR systems using pulsed Nd:YAG sources. Nd^{3+} also has emission in the 1300nm region, which is suitable for the second telecommunications window. Unfortunately, there is an excited-state absorption which makes it difficult to obtain significant net gain, and the strong emission around 1060nm also needs to be suppressed. No Nd^{3+}-doped waveguide amplifiers have been reported in this wavelength region.

3.2.2 Er^{3+}-doped lasers and amplifiers

Er^{3+}-doped lasers and amplifiers have an obvious application in telecommunications systems operating in the third window around 1530nm. There is a need for stable, high-power, low-noise sources in an inexpensive technology, with narrow linewidth and frequency stability highly desirable for use in WDM-based networks. Similarly, the performance of optical networks can usually be improved through the use of optical amplifiers to enhance the effective receiver sensitivity; with the increasing use of WDM, flat gain over the wavelength range used is an important consideration.

Despite these attractions, Er^{3+}-doped waveguide devices were not demonstrated until two years after Nd^{3+}-doped lasers. There are several reasons for this. Unlike Nd^{3+}, the Er^{3+} system is strongly 3-level, which means that it must be approximately 50% inverted to show net gain. The absorption and emission cross-sections in Er^{3+} are substantially lower than those of Nd^{3+} . The maximum concentration of Er^{3+} in glass tends to be quite limited; at even moderate concentrations, the Er^{3+} ions tend to cluster, an effect which exacerbates parasitic ion-ion interactions which shorten the fluorescence lifetime at high inversion levels. Finally, the 980nm pump wavelength of Er^{3+} is attainable only by strained MQW lasers, which were until recently limited in their output power. All of these factors conspire to make the Er^{3+} system difficult to operate and wasteful of pump power. Compared to short waveguide devices, EDFAs are much less affected by these factors; they can be very long with low dopant concentration, so that high fluorescence lifetimes are combined with efficient pump absorption, and the erbium can easily be confined to the regions of maximum pump intensity.

The first waveguide Er^{3+} lasers, like the first Nd^{3+} ones, were made in FHD[39] and in Ti:$LiNbO_3$ [40] technologies, in 1991. The first ion-exchanged device was realised in 1992, using K^+-Na^+ exchange in Schott BK-7 glass, a borosilicate.[41] As a consequence of the difficulties described above, the device showed a poor slope efficiency (0.55%) and high threshold (150mW of launched 980nm pump power). The laser operated single-transverse-mode at 1540nm.

The smooth spectrum of Er^{3+}-doped glass, and the low polarisation-dependence, make the FHD and ion-exchange technologies well-suited to the fabrication of optical amplifiers. In 1993, Corning Europe published a conference report of a Tl^+-exchanged waveguide amplifier.[42] Work continued on this device into 1994 in the European Union RACE project LIASON to realise "lossless splitters" (in which an optical amplifier compensates for power reduction through splitting) for optical networks. It quickly became clear that the bulk-doping of ion-exchange hosts is a serious drawback for Er^{3+}-doped amplifiers. As the pump intensity dims towards the edges of the guided mode, the Er^{3+} inversion level drops, and the material becomes a net absorber, reducing the gain and increasing the noise figure for the device. To overcome this, it was necessary to use high NA waveguides to raise the pump intensity across the mode. Since it was also necessary to use rather long, coiled waveguides, 20cm or more in length, waveguide propagation losses of 0.1dB/cm become significant. In a 23cm device, an internal gain of about 9 dB was obtained for an incident 980nm pump power of 230mW.[43] This is much poorer than the performance of EDFAs and even of FHD-deposited silica-on-silicon devices,[44] and below the specifications for the CATV and PONS applications envisaged. Ultimately the Er^{3+}-doped system was dropped in favour of an Er/Yb co-doped system which gave superior results, as discussed below.

The ultimate intention of the LIASON partners was to fabricate a device with pump/signal multiplexing on the integrated optical circuit; this also has potential problems because of the 3-level Er^{3+} system, so that if the signal encounters unpumped Er^{3+} before the multiplexer it will be absorbed. To solve this problem, Corning Europe developed a technique for joining doped and undoped sections of glass,[45] so that the non-amplifying components, such as the multiplexer and the passive splitter, can be fabricated in an Er^{3+}-free region. The boundary between the doped and undoped regions is sufficiently diffuse that there is no effect on the waveguiding properties. Corning also applied thermal tapering to expand the waveguide modes for improved coupling to standard single-mode fibres, while retaining the tightly confined mode required for optimum functioning of the amplifying section.[9]

Since one of the advantages of ion exchange is the possibility of using any of a wide range of glass compositions, the LIASON partners considered the effect of host upon spectroscopy. Given the high Er^{3+} concentrations typical of EDPAs, it is important to try to minimise the deleterious effects of upconversion, in which two excited Er^{3+} ions exchange energy with the ultimate result that one excitation is lost to heat.[25] It is a peculiar consequence of Judd-Ofelt analysis, an approximate theory of rare-earth spectroscopy, [25] that in the case of Er^{3+} the strengths of the desirable transitions for pumping and emission and the undesirable transition which gives rise to the upconversion interaction scale together. The implication of this is that there is no point in seeking a host in which upconversion is absent. It is a more general consequence that the amplifier behaviour of all Er^{3+}-doped hosts is to first order the same (in the absence of ion clustering or impurity quenching sites). To second order, there may be differences, in that the transition spectra may be more or less broad, and more or less flat.

3.2.3 Er^{3+}/Yb^{3+} co-doped lasers and amplifiers

One of the drawbacks of Er^{3+} as an optically active ion is its low cross-section for pump absorption. In some circumstances, it is advantageous to co-dope the glass host with Yb^{3+}. Yb^{3+} has an extremely large cross-section for absorption around 980nm; it has a long fluorescence lifetime, and is able to transfer its excitation efficiently to Er^{3+} by non-radiative interactions. As long as the Er^{3+} ion decays rapidly to its metastable level, backtransfer of excitation to the Yb^{3+} will not be a problem. The rate of decay of Er^{3+} from the $^4I_{11/2}$ to the $^4I_{13/2}$ level depends upon the phonon energy of the host; phosphate glasses are generally better suited than silicate glasses as hosts for these co-dopants because they have higher phonon energies.

The first Er^{3+}/Yb^{3+} amplifier was reported in 1995, based on single-mode waveguides fabricated by Ag -ion exchange in a phosphate glass.[46] The guides were 4.4 cm long, and gave a net gain of 6dB for 160mW of launched pump power. This technology has since been improved to give about 10dB of net gain for 120mW of injected pump power at 980nm.[47]

At about the same time as this first reported amplifier, two groups reported Er^{3+}/Yb^{3+}-codoped lasers in silicate-based glasses, a rather unusual system.[48,49] Backtransfer was not a problem because the ratio of Er^{3+} to Yb^{3+} was relatively high, compared to the ratio used in co-doped fibre. While the slope efficiencies were rather poor, no better than 5.5%, demonstration of lasing of this system in a silicate glass was promising. Soon afterwards, the technology was extended[50] to realise waveguide amplifiers with propagation losses below 0.1 dB/cm and mode diameters of 5-6μm, giving almost 10dB of fibre-to-fibre net gain for 120 mW of incident 980nm pump power. This performance is essentially the same as for those made in the phosphate glass. Taking account of the scope for optimisation in the rare-earth ion concentrations and in the device length, such performance is in principle sufficient to permit lossless splitters with up to 1x16.

Compared to purely Er^{3+}-doped material, the effect of the Yb^{3+} co-dopant is greatly to enhance the effective pump-absorption cross-section of the Er^{3+}, so that the pump inverts the Er^{3+} much further out into the modal tails. In the case of the silicate glasses, co-doping with Yb^{3+} also appears to permit high Er^{3+} concentrations without clustering, so that short devices can be realised. This reduces the significance of waveguide propagation losses. With these advantages of co-doping, the cost of power loss through Yb^{3+} fluorescence can easily be borne.

3.3 Ion-exchanged devices incorporating laser and amplifier components

3.3.1 Nd^{3+}-doped devices

As is the case with Nd^{3+}-doped waveguide lasers generally, ion-exchanged versions have been incorporated in a number of more complex devices, some involving bulk components[51,52] and others fully integrated. In the latter category are y-junction lasers, in which a coupled cavity configuration is used to obtain line-narrowing[53-55]. In combination with a thermooptic element to control the optical path length in one of the y-branch arms, wavelength tuning and Q-switching have been demonstrated, although single-frequency operation has proven elusive. Single-longitudinal-mode operation has, however, been demonstrated using a Bragg grating as one of the output mirrors of a Fabry-Perot laser.[18]

3.3.2 Er^{3+}-doped and Er^{3+}/Yb^{3+}-co-doped devices

While Er^{3+}-doped ion-exchanged waveguide lasers have remained simple, other technologies have been used to realise sophisticated devices.[56,57] Ion-exchanged amplifiers have, however, been integrated with a 1x2 splitter[50] and connected by fiber pigtail to a 4x1 wavelength combiner.[47] These amplifiers have also been tested in laboratory mock-ups of optical communications systems.[58,59] The performance is reasonable, although the pump power required is high (in excess of 100mW for the necessary gain). In one EU ACTS project, TOBASCO, the work started in LIASON continues with the aim of achieving better amplifier performance and combining it with lossless splitting ratios higher than the 1x2 so far demonstrated. The overall aim of this project is to develop a WDM optical access network based on an existing CATV system, and work is underway to combine the waveguide lossless splitters with gain-flattening elements.

4. RELEVANT DEVELOPMENTS IN OTHER AREAS

There have been demonstrations of ion exchange in exotic glasses, chosen for their non-linear coefficients[60] or their ability to act as saturable absorbers.[61] It would be very interesting to combine the properties of such glasses with rare-earth-doped lasers, to yield, for example, passively Q-switched sources. On a more speculative note, one recent exciting development has been the demonstration of induced second-order non-linearities in silica fibers through the production of electrets.[62] Although it is difficult to see how a highly stable space charge field is compatible with an ion-exchangeable glass, it would open up a wide range of possibilities if components for electrooptic control could become part of the toolkit of integrated optics in glass.

In a different area, recent years have seen the introduction of excimer lasers as powerful tools for surface processing, both in research and in industry. Such devices afford the means for overcoming the problems of buried waveguides - one can rapidly dig down to expose the evanescent field in a small area, and one can machine complex and precise structures. The characteristics of excimer lasers - beam quality, coherence, power, reproducibility - will inevitably improve, especially in the more immature 193nm sources, enlarging the scope for low-cost, rapid machining of integrated optics.

5. CONCLUSION

The last seven years have seen numerous demonstrations of Nd^{3+}- and Er^{3+}-doped waveguide lasers and amplifiers, in ion-exchanged format as well as in other technologies. Many of the components to realise sophisticated devices have been separately demonstrated in ion-exchanged integrated optics, but they have not been combined with active sections. The lack of fast electronic control also remains a drawback.

Despite recent successes, it is noteworthy that no commercial applications for integrated optical waveguide lasers yet exist. In contrast, microlasers and fibre lasers are commercially established. The applications in which they are successful are for relatively high powers, and demand nothing more sophisticated than CW or Q-switched output at one wavelength range. It seems likely that integrated optical lasers, in whatever technology, will be commercially viable only in applications that demand multifunctional, controllable sources with moderate powers. Such an application might be frequency-stable, or tunable, comb sources for WDM telecommunications systems. A low-cost device of this type might find extensive application in the local loop.

Planar optical amplifiers also remain laboratory subjects. Significant progress has been made in developing EDPAs, but their performance still falls short of fibre devices. Planar amplifiers operating at 1300nm await the development of suitable host glasses, but in the absence of a successful fibre-based amplifier might be more competitive than EDPAs.

If the pace of work continues, it is likely that by the end of the decade versatile integrated optical lasers and amplifiers will exist, many of which will be based on ion-exchanged waveguides. Ion exchange continues to hold out to the optical engineer the promise of sophisticated devices with robust performance at low cost.

ACKNOWLEDGEMENTS

This work was supported in part by the European Union ACTS project AC028 TOBASCO. The Optoelectronics Research Centre is an Interdisciplinary Research Centre partly funded by the UK Engineering and Physical Sciences Research Council. I acknowledge useful discussions with Dr. Jaymin Amin and Dr. James S. Wilkinson.

REFERENCES

1. K. Takada, H. Yamada, Y. Hida, Y. Ohmori, and S. Mitachi, "Rayleigh backscattering measurement of 10m long silica-based wave-guides", *Electron. Lett.* **32(18)**, pp.1665-166, 1996.
2. S.-H. Ko, R. H. Doremus, X. S. Guo, and W. Landford, "Refractive index gradient in the surface of a zirconium fluoride glass by exchange with chlorine", *J. Mater. Res.* **5(1)**, pp. 202-205, 1990.
3. R. V. Ramaswamy, and R. Srivastava, "Ion-exchanged glass waveguides: a review", *J. Lightwave Technol.* **6(6)**, pp. 984-1002, 1988.
4. K. J. Malone, N. A. Sanford, and J. S. Hayden,"Integrated-optic laser emitting at 906, 1057, and 1358nm", *Electron. Lett.* **29(8)**, pp. 691-693, 1993.
5. Y. Hibino, T. Kitagawa, M. Shimizu, F. Hanawa, and A. Sugita, "Neodymium-doped silica optical waveguide laser on silicon substrate", *IEEE Photonics Tech. Lett.* **1(11)**, pp. 349-350, 1989.
6. K. Shuto, K. Hattori, T. Kitagawa, Y. Ohmori, and M. Horiguchi, "Erbium-doped phosphosilicate glass waveguide amplifier fabricated by PECVD", *Electron. Lett.* **29**, pp. 139-141, 1993.
7. M. Mahapatra, and J. M. Connors, "Thermal tapering of ion-exchanged channel waveguides in glass", *Optics Lett.* **13(2)**, pp. 169-171, 1988.
8. H. Zhenguang, R. Srivastava, and R. V. Ramaswamy, "Low-loss small-mode passive waveguides and near-adiabatic tapers in BK-7 glass", *J. Lightwave Technol.* **7(10)**, pp. 1590-1596, 1989.
9. P. Camy, *Réalisation d'un amplificateur optique dans la bande 1.5μm des télécommunications*, PhD Thesis, Université Pierre et Marie Curie, Département de Physique, Paris, pp. 160-164, Dec. 1996.
10. X. H. Zheng, and R. J. Mears, "Planar optical waveguides formed by erbium ion exchange in glass", *Appl. Phys. Lett.* **62(8)**, pp. 793-795, 1993.

11. E. Snoeks, G. N. Van den Hoven, A. Polman, B. Hendriksen, and M. B. J. Diemeer, "Doping fibre-compatible ion-exchanged channel waveguides with erbium by ion-implantation", *Proc. European Conference on Integrated Optics*, p. 3-38, Neuchâtel, 1993.
12. A. Béguin, T. Dumas, M. J. Hackert, R. Jansen, C. Nissim, "Fabrication and performance of low loss optical components made by ion exchange in glass", *J. Lightwave Technol. 6(10)*, pp. 1483-1487.
13. P. Benech, D. Persegol, and F. SaintAndre, "Glass ion exchanged Mach-Zehnder interferometer to stabilise the frequency of a laser diode", *J. Phys. D: Appl. Phys.* **23(5)**, pp. 617-619, 1990.
14. S. I. Najafi, P. Lefebvre, J. Albert, S. Honkanen, A. Vahid-Shahidi, and W.-J. Wang, "Ion-exchanged Mach-Zehnder interferometers in glass", *Appl. Optics* **31(18)**, pp. 3381-3383, 1992.
15. R. G. Walker, and C. D. W. Wilkinson, "Integrated optical waveguiding structures made by silver ion-exchange in glass. 2: Directional coupler and bends", *Appl. Optics* **22(12)**, pp. 1929-1936, 1983.
16. R. A. Betts, and F. Lui, "Broadband polarisation splitting couplers in ion-exchanged glass", *Electron. Lett.* **26(7)**, pp. 450-452, 1990.
17. M. Haruna, and J. Koyama, "Thermooptic deflection and switching in glass", *Appl. Optics* **21(19)**, pp. 3461-3465, 1982.
18. J. E. Román, and K. A. Winick, "Neodymium-doped glass channel waveguide laser containing an integrated distributed Bragg reflector", *Appl. Phys. Lett.* **61(23)**, pp. 2744-2746, 1992.
19. J. E. Roman, and K. A. Winick, "Photowritten gratings in ion-exchanged glass waveguides", *Optics Lett.* **18(10)**, pp. 808-810, 1993.
20. W. K. Chan, A. Yi-Yan, and R. Bhat,"Tip-chip bonding: solder bonding to the sides of substrates", *Electron. Lett.* **28(18)**, pp. 1730-1732, 1992.
21. A. Yi-Yan, W. K. Chan, T. S. Ravi, T. J. Gmitter, R. Bhat, and K. H. Yoo, "Grafted InGaAsP light emitting diodes on glass channel waveguides", *Electron. Lett.* **28(4)**, pp. 341-342, 1992.
22. R. G. Walker, and C. D. W. Wilkinson, "Integrated optical ring resonators made by silver ion-exchange in glass", *Appl. Optics* **22(7)**, pp. 1029-1035, 1983.
23. O. G. Hellesø, P. Benech, and R. Rimet, "A Michelson interferometer and reference mirrors integrated on glass", *Meas. Sci. Technol.* **6**, pp. 1362-1367.
24. G. Zhang, S. Honkanen, A. Tervonen, C.-M. Wu, and S. I. Najafi, "Glass integrated optics circuit for 1.48/1.55- and 1.30/1.55-m-wavelength division multiplexing and 1/8 splitting", *Appl. Optics* **33(16)**, pp. 3371-3374, 1994.
25. W. M. Yen, and P. M. Selzer, eds., "Laser spectroscopy of solids", Springer-Verlag, Berlin, 1981.
26. M. V. Babukova, V. A. Berenberg, L. B. Glebov, N. V. Nikonorov, G. T. Petrovskii, and V. S. Terpugov, "Investigation of neodymium silicate glass difused waveguides", *Sov. J. Quantum Electron.* **15(9)**, pp. 1304-1305, 1985.
27. S. Iraj Najafi, W.-J. Wang, J. F. Currie, R. Leonelli, and J. L. Brebner, "Fabrication and characterization of neodymium-doped glass waveguides", *IEEE Photonics Tech. Lett.* **1(5)**, pp. 109-110, 1989.
28. E. Lallier, J. P. Pocholle, M. Papuchon, C. Grezes-Besset, E. Pelletier, M. De Micheli, M. J. Li, Q. He, D. B. Ostrowsky, "Laser oscillation of single-mode channel waveguide in Nd:MgO:LiNbO$_3$", *Electron. Lett.* **25(22)**, pp. 1491-1492, 1989.
29. H. Aoki, O. Maruyama, and Y. Asahara, "Glass waveguide laser", *IEEE Photonics Tech. Lett.* **2(7)**, pp. 459-460, 1990.
30. E. K. Mwarania, L. Reekie, J. Wang, and J.S. Wilkinson, "Low-threshold monomode ion-exchanged waveguide lasers in neodymium-doped BK-7 glass", *Electron. Lett.* **26**, pp. 1317-1318, 1990.
31. N. A. Sanford, K. J. Malone, and D. R. Larson, "Integrated-optic laser fabricated by field-assisted ion exchange in neodymium-doped soda-lime-silicate glass", *Optics Lett.* **15(7)**, pp. 366-368, 1990.
32. E. K. Mwarania, J. Wang, C. Piraud, Y. T. Chow, L. Reekie, and J. S. Wilkinson, "Monomode glass waveguide lasers pumped by a single-stripe laser diode", *OSA Proc. Advanced Solid State Lasers*, **10**, pp. 270-272, 1991.
33. H. Aoki, O. Maruyama, and Y. Asahara, "Glass waveguide laser operated around 1.3μm", *Electron. Lett.* **26(22)**, pp. 1910-1912, 1990.
34. J. J. Zayhowski, "Microchip lasers create light in small spaces", *Laser Focus World* **April**, pp. 73-78, 1996.
35. H. Aoki, E. Ishikawa, and Y. Asahara, "Nd^{3+}-doped glass waveguide amplifier at 1.054μm", *Electron. Lett.* **27(25)**, pp. 2351-2353, 1991.
36. A. N. Miliou, X. F. Cao, R. Srivastava, and R. V. Ramaswamy, "15-dB amplification at 1.06μm in ion-exchanged silicate glass wave-guides", *IEEE Photonics Technol. Lett.* **5(4)**, pp. 416-418, 1993.
37. J. M. Jouanno, D. Barbier, and A. Kevorkian, "Optical amplification and lasing at 1054nm in waveguides realised by ion-exchange in a high-Nd-doped phosphate glass", *Proc. 7th European Conference on Integrated Optics*, eds. L. Shi, L. H. Spiekman, X. J. M. Leijtens, pp. 153-156, Delft University Press, Delft, 1995.
38. T. Ohtsuki, S. Honkanen, N. Peyghambarian, M. Takahashi, Y. Kawamoto, J. Ingenhoff, A. Tervonen, and K. Kadono, "Evanescent-field amplification in Nd^{3+}-doped fluoride planar waveguide", *Appl. Phys. Lett.* **69(14)**, pp. 2012-2014, 1996.

39. T. Kitagawa, K. Hattori, M. Shimizu, Y. Ohmori, and M. Kobayashi, "Guided wave laser based on erbium-doped silica planar lightwave circuit", *Electron. Lett.* **27(4)**, pp. 334-335, 1991.
40. R. Brinkmann, W. Sohler, and H. Suche, "Continuous-wave erbium-diffused LiNbO$_3$ waveguide laser," *Electron. Lett.* 27(5), pp. 415-416, 1991.
41. T. Feuchter, E. K. Mwarania, J. Wang, L. Reekie, J. S. Wilkinson, "Erbium-doped ion-exchanged waveguide lasers in BK-7 glass", *IEEE Photonics Technol. Lett.* **4(6)**, pp. 542-544, 1992.
42. D. Trouchet, A. Béguin, P. Laborde, C. Lerminiaux, "Er^{3+} glass waveguide amplifier using the ion-exchange technique", *OFC/IOOC Technical Digest '93*, pp. 106-107, 1993.
43. P. Camy, J. E. Román, M. Hempstead, P. Laborde, C. Lerminiaux, "Ion-exchanged waveguide amplifier in erbium-doped glass for broad-band communications,"*OSA Topical Meeting on Optical Amplifiers & Their Applications*, 1995 OSA Technical Digest Series **18**, pp. 181-184, Optical Society of America, Davos, 1995.
44. K. Hattori, T. Kitagawa, M. Oguma, Y. Ohmori, M. Horiguchi, "Erbium-doped silica-based waveguide amplifier integrated with a 980/1530nm WDM coupler", *Electron. Lett.* **30(11)**, pp. 856-857, 1994.
45. P. Camy, *Réalisation d'un amplificateur optique dans la bande 1.5 m des télécommunications*, PhD Thesis, Université Pierre et Marie Curie, Département de Physique, Paris, pp. 164-170, Dec. 1996.
46. D. Barbier, P. Gastaldo, B. Hyde, J. M. Jouanno, A. Kevorkian, "Amplification in Erbium Doped Microguides Realised on Phosphate Glass", *Proc. 7th European Conference on Integrated Optics*, eds. L. Shi, L. H. Spiekman, X. J. M. Leijtens, pp. 241-243, Delft University Press, Delft, 1995.
47. D. Barbier, M. Rattay, F. Saint Andre, A. Kevorkian, J. M. P. Delavaux, E. Murphy, "Amplifying four wavelengths combiner based on erbium-ytterbium doped planar integrated optical modules," *Proc. of European Conference on Optical Communications '96*, paper We.D.2.2, pp 3.161-3.164, Oslo, 1996.
48. G. L. Vosser, C. J. Brooks and K. A. Winick, "Planar Er:Yb glass ion exchanged waveguide laser", *Electron. Lett.* **31(14)**, pp. 1162-1163, 1998.
49. J. E. Román, P. Camy, M. Hempstead, W. S. Brocklesby, S. Nouh, C. Lerminiaux, A. Béguin, J. S. Wilkinson, "Ion-exchanged Er/Yb waveguide laser at 1.5 μm pumped by a laser diode", *Electron. Lett.*, **31**, pp. 1345-1346, 1995.
50. P. Camy, J. E. Román, F. W. Willems, M. Hempstead, J. C. van der Plaats, C. Prel, A. Béguin, A. M. J. Koonen, J. S. Wilkinson, and C. Lerminiaux, "Ion-exchanged planar lossless splitter at 1.5 μm", *Electron. Lett.*, **32**, pp. 321-332, 1996.
51. N. A. Sanford, K. J. Malone, and D. R. Larson, "Extended-cavity operation of rare-earth-doped glass waveguide lasers", *Optics Lett.* **16(14)**, pp. 1095-1097, 1991.
52. J. A. Aust, K. J. Malone, D. L. Veasey, and N. A. Sanford, "Passively Q-switched Nd-doped waveguide laser", *Optics Lett.* **19(22)**, pp. 1849-1851, 1994.
53. E.K. Mwarania, D.M. Murphy, M. Hempstead, L. Reekie, J.S. Wilkinson, "Integrated Q-switched multiple-cavity glass waveguide laser," *IEEE Photonics Tech. Lett.* **4**, 235-237 (1992).
54. N. A. Sanford, K. J. Malone, D. R. Larson, R. K. Hickernell, "Y-branch wave-guide glass laser and amplifier", *Optics Lett.* **16(15)**, pp. 1168-1170, 1991.
55. N. A. Sanford, J. A. Aust, K. J. Malone and D. R. Larson, "Linewidth narrowing in an imbalanced Y-branch waveguide laser", *Optics Lett.* **18(4)**, pp. 281-283, 1993.
56. T. Kitagawa, F. Bilodeau, B. Malo, S. Thériault, J. Albert, D. C. Johnson, K. O. Hill, K. Hattori, and Y. Hibino, "Single-frequency Er^{3+}-doped silica-based planar waveguide laser with integrated photo-imprinted Bragg reflectors", *Electron. Lett.* **30(16)**, pp. 1311-1312, 1996.
57. I. Baumann, D. Johlen, W. Sohler, H. Suche, and F. Tian, "Acoustically tunable Ti:Er:LiNbO$_3$-waveguide laser", *Proc. 20th European Conference on Optical Communication*, Post-deadline Papers, pp. 99-102, Florence, 1994.
58. J. C. van der Plaats, F. W. Willems, W. Muys, A. M. J. Koonen, P. Camy, C. Prel, A. Béguin, M. Prassas, C. Lerminiaux, J. E. Román, M. Hempstead, and J. S. Wilkinson,"Ion-exchanged planar lossless splitter for analog CATV distribution systems at 1.5 μm," *Proc. of OSA Topical Meeting on Optical Amplifiers and Their Applications*, paper SaC3, 1996.
59. J. M. P. Delavaux, Y. K. Park, E. Murphy, S. Granlund, O. Mizuhara, D. Barbier, M.Rattay, G. Clauss, A. Kevorkian, and J. A. Nagel, "High performance Er-Yb planar waveguide amplifiers as in-line and preamplifiers in 10Gb/s fiber systems experiments", *Proc. of European Conference on Optical Communication '96*, paper ThB3.6, pp 5.23-5.26, Oslo, 1996.
60. G. DeMarchi, F. Gonella, P. Mazzoldi, G. Battaglin, E. J. Knystautas, and C. Meneghini, "Non-linear glasses by metal cluster formation: synthesis and properties", *J. Non-Cryst. Solids* **196**, pp.79-83, 1996.
61. K. Shimomura, H. Murata, M. Izutsu, and T. Sueta, "Saturable absorption in ion-exchanged CdS$_x$Se$_{1-x}$-doped glass waveguides", *Jpn. J. Appl. Phys. Part 2* **32(6B)**, pp. L840-L842, 1993.
62. P.G. Kazansky, V. Pruneri, and P. St. J. Russell, "Blue-light generation by quasi-phase-matched frequency doubling in thermally poled optical fibres", *Optics Lett.* **20**, pp. 834-845, 1995.