Laser Crystal Waveguides

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Contents

1 Introduction

Optically-pumped lasers and amplifiers can in principle benefit greatly from a guided-wave geometry in which the pump and lasing modes overlap tightly, the laser mode volume is minimized, and the product of optical intensity and interaction length is not limited by diffraction as in a bulk gain medium. This idea is most successfully embodied in the erbium-doped silica fibre amplifier, and many novel and efficient laser systems have been demonstrated in glass fibre form.

Crystalline gain media, however, offer a range of attractive properties and possibilities which glass cannot match. Large coefficients of absorption and gain per unit length are more easily achieved in crystals with sharp line spectra, which may be strongly polarized, than in glassy gain media with characteristically broad spectral features; thus crystal systems are better suited to the development of genuinely miniature devices of millimetre dimensions than glass fibres, in which fibre lengths of tens or hundreds of cm are generally required. Crystals may also exhibit desirable electro- and acousto-optic properties and nonlinearities by which control functions may be integrated into active devices. Finally, the range of laser transitions which have been demonstrated in crystals is substantially wider than in glass, in which the lanthanide intra-4f-configuration laser transitions account for almost all the lasers realized to date. Crystals not only perform well as transition metal hosts for broadly tunable vibronic lasers; they also have been used to demonstrate 5d-4f inter-configuration transitions of lanthanide ions such as Ce^{3+} at wavelengths in the near uv.

These considerations motivate the attempt to develop new crystalline laser materials adapted for use in guided-wave geometries. Since the active region of the laser crystal is now in the form of a thin planar layer of micron dimensions, a new approach to fabrication is involved; rather than Czochralski-pulling of bulk laser rods the relevant fabrication techniques will be based on epitaxy, or physical and chemical surface treatments such as ion-implantation or thermal indiffusion. Thin crystal layers can in principal be prepared over a wider range of composition and dopant concentration than the corresponding bulk systems, and this may offer interesting degrees of freedom to the laser designer.

This paper will describe some of the approaches currently being explored for the fabrication of novel crystalline waveguide laser systems, including thermal indiffusion of laser activator ions into lithium niobate crystals, implantation of high-energy helium ions, and preparation of high quality garnet layers by liquid phase epitaxy. These materials are enabling new laser transitions to be demonstrated, and the potential performance enhancement of the waveguide geometry is beginning to be realized.

2 The planar waveguide laser geometry

The simplest type of crystal waveguide laser uses a plane-plane Fabry-Perot resonator defined by the polished crystal end-faces, with pump light launched longitudinally into a planar waveguide on the upper surface of the crystal. The design of the guide ideally allows only the fundamental mode to propagate at the laser wavelength, however, in the surface plane the light is unguided and the emerging beam has an elliptical profile. External multilayer dielectric mirrors on thin (~ 200 μm) substrates can be optically contacted to the guide ends and held in place by the surface tension of a drop of index-matching fluid. Such removable mirrors are highly convenient for research and development purposes, but can of course be replaced by dielectric coatings deposited directly onto the guide ends for a more compact and rugged device.

An alternative possibility for a planar guide is a side-pumping geometry, in which pump light is coupled into the guide in a highly elliptical beam propagating at right angles to the laser mode. Since absorption of the pump over the width of the laser mode is small, the coefficient of gain per unit length is also small, thus this geometry demands extremely low guide propagation losses. It is, however, potentially a technique for making use of the output from high-power, high-aspect-ratio pump sources such as diode arrays and bars, and opens the possibility of creating high power waveguide sources.

If the guide fabrication process allows the formation of low loss channels, then more complex resonators can be designed incorporating a range of interesting functions, as recent work on lithium niobate guides shows.

The reduction in lasing threshold achieved by the waveguide geometry can be estimated from the volume of the lasing mode. Consider a longitudinally-pumped laser in which the length l of the gain medium is determined by the absorption coefficient at the pump wavelength. In an unguided laser the optimum spot size for the lasing mode is approximately that which sets l equal to the Rayleigh range; let the corresponding fundamental mode volume for light of free-space wavelength be called V_{bulk}. The mode volumes for guided-wave lasers in this medium would then be of order of magnitude V_{bulk}/α for a planar guide and V_{bulk}/α^2 for a channel guide, where

$$\alpha = \sqrt{\frac{l}{\lambda}}\ NA$$

and NA is the effective numerical aperture of the waveguide. The corresponding reduction in threshold thus becomes more pronounced in less strongly absorbing media in which greater values of l are required to ensure sufficient pump absorption. Lasing in the near infrared in a waveguide structure a few mm long with $NA \sim 0.2$ can therefore in principal exhibit a threshold reduced relative to that of the corresponding bulk device by an order of magnitude for a planar geometry and two orders of magnitude in a channel.

This waveguide advantage is unfortunately very quickly lost if propagation losses in the guided structure significantly exceed those in the bulk medium. In the example of the previous paragraph, should the net losses in the planar waveguide structure amount to ~10x the output coupling used in the bulk system (in which it is assumed that propagation losses are negligible), then there will be no reduction of threshold. There will, moreover, be a disastrous effect on the slope efficiency, which may drop by a very large factor for the planar cavity, in which internal losses now dominate the useful output coupling loss. A key aspect of the development of waveguide crystalline media is therefore the endeavour to identify and eliminate the sources of excess propagation loss in guides.

One class of laser system which is more tolerant of such losses is the three-level, or quasi-three-level laser, in which lasing terminates on a thermally-populated level. The performance of such a laser is typically limited by reabsorption losses at the laser wavelength rather than by background propagation losses. In a guided wave geometry the lasing transition can be more strongly inverted at a given coupled pump power than in the bulk, with benefit also to the slope efficiency of the laser.

3 Thermal diffusion of dopants into lithium niobate

Lithium niobate is an obviously attractive candidate for waveguide

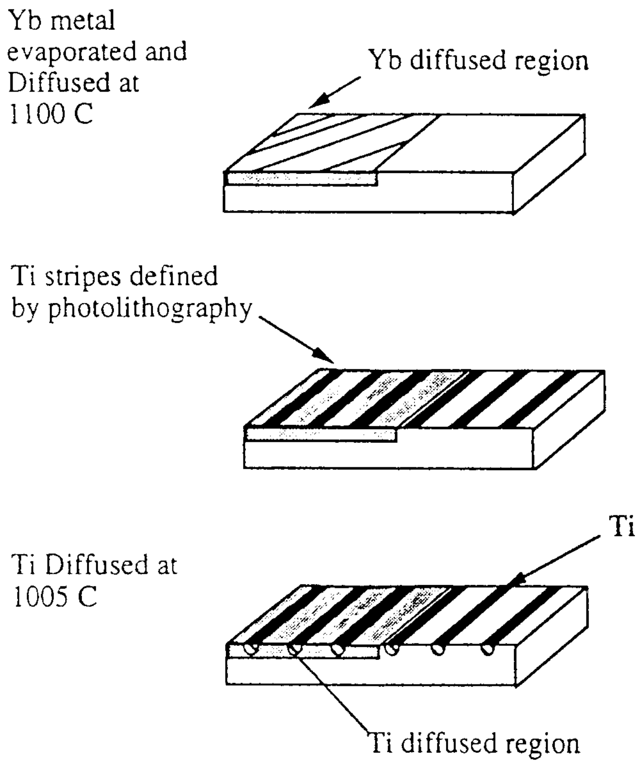

Fig. 1 Stages in the fabrication of a Ti channel guide in $LiNbO_3$ diffusively doped with Yb

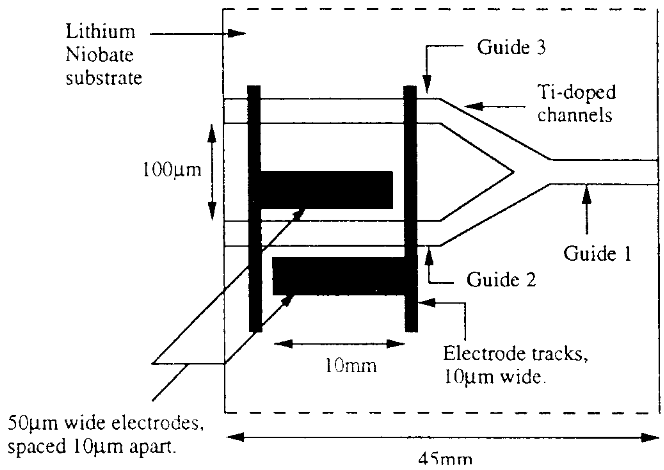

Fig. 2 Tunable Y-branch $Nd:LiNbO_3$ laser after [6]

laser operation because of the existence of a mature technology for the fabrication of low-loss (~ 0.1 dB cm^{-1}) waveguides by proton exchange or Ti indiffusion. Trivalent lanthanide ions can be substitutionally incorporated into the crystal structure, probably at the Nb^{5+} site, and several such bulk lasers have been reported.

In early work on this system waveguides were fabricated in bulk-doped crystals, with the lanthanide dopant incorporated from the melt. Such crystals are not readily available; even at a concentration of only ~1/2 atomic % the dopant alters the melt phase diagram enough to present a new problem in crystal growth, and several trial runs are needed with great expense in labour, time and materials.

The use of thermal diffusion to introduce laser dopant ions into the surface of an otherwise undoped $LiNbO_3$ substrate to a depth sufficient to accommodate an optical waveguide represents, by comparison with bulk doping, an immense saving of expense and effort. It has been shown that despite the large charge on the trivalent lanthanide ion it can be indiffused without destroying the poling of the ferroelectric crystal at temperatures as high as 1000°, at which µm depths can be achieved in diffusion times of order 10^2 hours. The steps involved in fabricating such a structure are shown schematically in *Fig. 1*. Not only have efficient Er- [1] and Nd-doped [2] lasers been made in this way, but also Q-switched [3] and mode-locked [4] lasers have been demonstrated which exploit the large electro-optic susceptibility of $LiNbO_3$ in an integrated geometry. More recently an $Er:LiNbO_3$ laser which incorporates a distributed Bragg reflector made by dry etching has been reported. Oscillation of this 6-cm-long device on just two axial modes is described [5].

Another type of structure is shown in *Fig. 2* which illustrates a tunable Y-branch laser in Nd-diffused material [6]. The resonant frequencies of this laser cavity are determined by the requirement for constructive interference at the junction of the Y, thus greatly spaced out by a vernier effect compared to those of a simple Fabry-Perot laser of the same length. Electro-optic tuning of the cavity frequency is thus possible by altering the optical path length of one branch of the Y. This device operated at a centre wavelength of 1092.7 nm with a total tuning range of 2.3 nm.

The first demonstration of lasing in $Yb:LiNbO_3$ has been reported in a diffusion-doped sample: oscillation at wavelengths of 1007, 1030 and 1060 nm was observed in channel guides at room temperature [7]. More recently a 1850-nm transition in diffusion-doped $Tm:LiNbO_3$ channels has been made to lase. At present the efficiency that can be achieved with these dopants appears to be some-

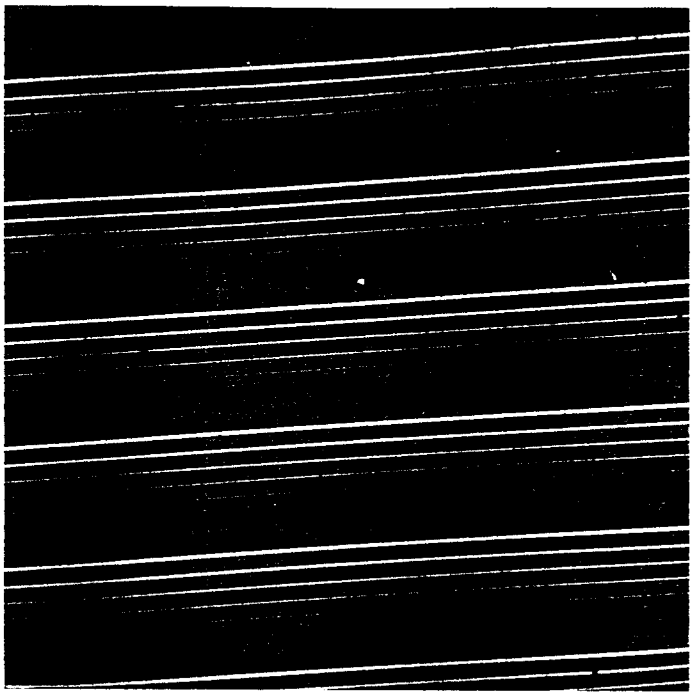

Fig. 3 Ion-implanted channel waveguides on the surface of a Nd:YAG crystal, magnification x 100

what limited by photorefractive effects, however these are very sensitive to the composition and thermal history of the material, and it may well be possible to reduce them to acceptably low levels. A particularly exciting development is the combination of diffusion-doping with periodic poling [8]. This may offer the possibility of greatly reducing photorefractive effects, as well as enabling efficient intracavity doubling of laser radiation.

4 Formation of waveguides by ion implantation

The implantation of high energy (few MeV) He and H ions into crystals is an attractively versatile technique for the fabrication of optical waveguides. It has been used to make lasing guides in a number of chemically and structurally dissimilar crystals, including garnets ($Y_3Al_5O_{12}$, $Gd_3Ga_5O_{12}$), the perovskite $YAlO_3$, and the ferroelectrics $Bi_4Ge_3O_{12}$ and $LiNbO_3$. The ion damage mechanisms which modify the structure and refractive index of the implanted layer are diverse and complex, and have been reviewed in the monograph by Townsend, Chandler and Zhang [9].

Ion-implanted channel guides have been fabricated in Nd-doped garnets using a lithographically-patterned electroplated gold ion-stopping mask. The photograph in *Fig. 3* shows sets of guides in graduated thicknesses on the surface of a Nd:$Y_3Al_5O_{12}$ crystal under magnification of x100. All except the narrowest of the channels (4- and 6-µm widths) exhibited laser action when pumped at 807 nm. The 20-µm wide channels exhibited the lowest lasing thresholds of ~ 500 µW absorbed power. With suitable output coupling, slope efficiencies of nearly 30 % with respect to absorbed power could be demonstrated in this structure [10].

In the laser systems investigated so far, ion-implanted guides appear to exhibit propagation losses of ~ 1 $dBcm^{-1}$ or more, limiting the efficiency which such devices can achieve. The sources of such loss have not been unambiguously identified, but it is likely that ion-damage induces some additional optical absorption in the irradiated surface. There is, however, some evidence that ion implantation can produce low loss guides in some materials such as the germanate glass for which a propagation loss of ~ 0.2 $dBcm^{-1}$ was reported [11].

5 Liquid phase epitaxy

Some of the most efficient laser crystal waveguides reported to date have been garnet layers of high optical quality fabricated by a liquid-phase epitaxy technique [12]. Layers of $Y_3Al_5O_{12}$ (YAG) doped with Ga to enhance the index, Lu to restore the lattice-match, and the desired lanthanide laser ion, are grown onto an undoped defect-free YAG substrate using a PbO-B_2O_3 flux at ~1000°C. A further undoped capping layer is often grown over the guiding layer to reduce propagation losses.

In an early experiment with a Nd-doped epilayer, the threshold for 1064-nm lasing in a *planar* guide was found to be only 670 µW of incident power, despite the relatively weak optical confinement in this sample, in which Nd doping (1.5 at %) alone was used to enhance the refractive index of the guiding layer relative to substrate and cladding layers of undoped YAG, giving a small Δn of ~0.05. This exceptionally low threshold is indicative of a very small waveguide propagation loss, estimated to be ≤ 0.05 $dBcm^{-1}$. With suitable output coupling the guide exhibited a slope efficiency of 40 % with respect to incident power when pumped by a single-mode GaAlAs diode [13].

The low propagation loss exhibited by this guide has stimulated work on the side-pumped geometry described in Section 2. The best value of slope efficiency reported to date is 19 % with respect to launched power [14], a promising result considering that the overlap of pump and lasing modes is inevitably less strong than with longitudinal pumping. The interesting feature of side-pumping is the prospect of scaling to high output power in a long guide pumped by high power diode arrays or bars. The high quality of the waveguide produced by the liquid phase epitaxial growth technique is an essential prerequisite for efficient operation of such a device.

The 1030-nm Yb:YAG laser is currently attracting much interest as a tunable high-power bulk laser system, in which, however, high pump power density and careful heat management are necessary for efficient operation [15]. The waveguide geometry offers an alternative approach to both problems. An Yb-doped garnet epilayer guide pumped by a 968-nm diode has emitted over 250 mW of laser radiation at 1048 nm with a slope efficiency in excess of 77 %, corresponding to a near-quantum-limited performance on this quasi-three-level transition [16].

6 Summary

An extensive range of fabrication techniques is currently being used in the effort to develop planar laser and amplifier devices. This article has considered only those which produce crystalline layers, and which have some proven device potential. The huge variety of surface treatments which may be brought into play to create novel laser gain media in waveguide form is an appealing feature of this field of research; however as the present article attempts to show, the advantages of a guided-wave geometry are quickly lost unless the chosen fabrication technique creates guides of sufficiently high quality. The development of liquid phase epitaxy to make low-loss laser crystal waveguides is a significant advance, which will focus interest in other epitaxial growth techniques which may be applied to dielectric gain media.

A major advantage of the planar over the rod-type bulk geometry is that the high aspect ratio confers excellent thermal loading characteristics. Coupled with the high-power pump sources now available, this extends the prospect of active devices which combine high gain with high output power and good mode quality in an extremely compact and robust form. Such devices might be expected increasingly to take over applications which have traditionally been the preserve of gas lasers, with marked advantages in the size, efficiency and eventually cost of the resulting systems.

A particularly interesting new area has opened up in *active* integrated optic devices based on lanthanide-indiffused lithium niobate. A wavelength-tunable filter incorporating gain has been demonstrated [17], and many „0 dB" components useful for telecommunications, such as lossless splitters, are now realizable. This is a promising field for future work. Elsewhere effort continues to meet the fabrication challenges posed by the great potential of the waveguide geometry. As yet, for example, no fluoride crystal waveguide laser has been reported. Fluorides are some of the most versatile of all laser crystal hosts, for short wavelengths, infrared-to-visible conversion, and efficient Cr^{3+}-ion operation. Whether such lasers will eventually be fabricated in a planar format remains to be seen.

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