Rare-earth-doped Planar Waveguide lasers

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Abstract

Research into active, rare-earth-doped planar waveguides is rapidly gathering pace. As with rare-earth-doped optical fibres, the small dimension of the waveguide region allows high gain to be achieved with very modest pump powers. Compared with fibres, the planar geometry potentially offers a number of additional benefits, such as a much higher degree of integration with access to properties available in crystals but not in glass, such as the possibilities of modulation and frequency conversion where the host medium is a nonlinear crystal. A wide variety of host media, in crystals and glasses is currently under investigation, along with a wide variety of techniques for waveguide fabrication and processing. A broad survey of this activity will be given, covering recent results and indicating some future directions.

Rare-earth-doped Planar Waveguide Lasers

Rare-earth doped planar waveguide lasers have a long history, the first such laser being reported in 1972 by J.P. Van der Ziel and co-workers [ref 1]. This was based on an epitaxially grown layer of garnet doped with holmium. Later, for a period around 1977-1980, considerable interest was shown in planar waveguide lasers based on stoichiometric neodymium laser materials [eg ref 2]. Much of the motivation for this work appears to have arisen from a perceived need for compact, reliable laser sources, which at the time was not adequately met by the η existing diode lasers. With the arrival in the early 1980's of cheap, reliable, single transverse mode AlGaAs diode lasers, with powers of a few tens of milliwatt a change of emphasis took place. On the one hand it was quickly demonstrated [ref 3] that the power from such diode lasers was more than adequate to pump a bulk laser such as Nd YAG without the need for a waveguide geometry, a situation which is reinforced by the availability of ever-increasing diode powers. On the other hand it was shown, that with such diodes used to pump rare-earth doped fibres, extremely high gains could be achieved [ref 4]. The subsequent enormous success of the erbium-doped fibre amplifier has meant that, as far as rare-earth doped waveguide devices are concerned, the greatest emphasis has been given to the fibre geometry. However, by highlighting the benefits of waveguide geometries in general, the success of fibre lasers and amplifiers has also given added impetus to investigations of active planar waveguide devices.

Planar waveguides offer a number of features that are not available in fibre devices. For example the host material can be crystalline. This offers possibilities, as in $LiNbO_3$ and $LiTaO_3$, of integrated laser devices in which electro-optic modulation and/or frequency conversion can be incorporated. Integrated mode-locked [ref 5] and Q-switched [ref 6] Nd:$LiNbO_3$ lasers have been demonstrated. The Q-switched laser of ref 6 was also efficiently frequency-doubled in a $LiNbO_3$ waveguide, which was periodically poled to achieve quasi-phase matching. While the frequency doubling waveguide was a separate device in this instance it could in principle be fabricated on the same wafer. This underlines the scope for integration of a number of functions into a compact monolithic device.

The success of the erbium-doped fibre amplifier has prompted developments aimed at producing an analogous device in a planar waveguide format. Results obtained so far from erbium-doped waveguides in $LiNbO_3$ expose some of the constraints and limitations of planar waveguides. The length of waveguide (a few centimetres) is around two orders of magnitude less than the length of fibre in a typical fibre amplifier. This short length is dictated in part by the size of the wafer and in part by the waveguide losses, which are typically 3 to 4 orders of magnitude greater (per unit length) than in a fibre. The short length of the planar waveguide implies the need for a much higher dopant concentration than in the fibre. In the case of erbium this leads to undesirable de-excitation processes between neighbouring erbium ions. While waveguide losses, short guide lengths and high dopant concentrations impose constraints on planar waveguide devices, there are other compensating benefits. For example it is possible to introduce rare-earth impurities into the waveguide region by in-diffusion. This has been achieved simply by depositing a layer of the rare-earth metal on the substrate surface and then in-diffusing by heating the sample. Er [ref 7] and Nd [ref 8] have been diffused into $LiNbO_3$ and Nd [ref 9] into $LiTaO_3$, all producing useful performance as waveguide lasers. These results illustrate an attractive feature of active waveguide devices in that the dopant need only be introduced at the location where it is needed and it need only extend into the substrate to a depth of a few microns. Thus new ways of fabricating doped material can be considered, which obviate the need to grow large doped boules, a notoriously costly and time-consuming process.

Epitaxial growth is one such method: not a new method as indicated by ref 1 above, but one which is now being revisited to good effect. Liquid phase epitaxial growth of Neodymium doped YAG (Ytterbium Alummium Garnet) on an undoped YAG substrated has proved to be very effective in that it has produced very low loss guides (less than 0.1dB/cm) and this has allowed the demonstration of diode-pumped devices with low threshold and high slope efficiency [ref 10]. A particularly interesting configuration is the side-pumped epitaxial waveguide, since it is ideally compatible with the otherwise inconvenient spatial emission pattern of high power diode bar lasers. The low threshold and efficient operation of a side-pumped epitaxial NdYAG laser [ref 11] indicates the potential for convenient and compact, multiwatt, high brightness sources based on this approach. Another direction in which waveguides in NdYAG in particular, but in other laser materials in general, show promise is in offering much reduced thresholds for 3-level or quasi-3-level lasers. For a laser with a three-level scheme a certain pump intensity is needed to achieve sufficient gain to overcome the losses due to reabsorption by the populated lower laser level. The presence of these reabsorption losses means that waveguide propagation losses can be relatively insignificant, so that for three-level lasers the full benefit of the reduced pump requirement due to waveguide confinement is seen. In four level lasers the extra loss of the guide compared with that of bulk material somewhat reduces the degree of benefit seen from the waveguide confinement. Significant threshold reductions have now been demonstrated in epitaxial waveguides, in NdYAG on the quasi-3-level 946nm transition and in YbYAG on the 1.03μm transition [ref 12]. Many other important 3-level transitions, eg. the 2μm transition in TmYAG should also benefit very significantly from the adoption of a waveguide geometry. The epitaxial growth technique is of course applicable to a very wide range of materials and therefore offers the prospect for extending waveguide techniques very broadly. Much interest would for example be generated by the ability to produce low loss waveguides in materials suitable for upconversion lasing. Upconversion lasing has been particularly successful in optical fibres where the waveguide confinement allows the required high intensity to be achieved at low pump power. To extend this technique to the compact geometry of a planar waveguide would be very attractive as a route to compact visible light sources. One aspect of the epitaxial growth which still needs to be addressed is that it only produces guides which are planar in the sense that guidance is in one dimension, whereas to reap the full benefit of a waveguide geometry requires channel waveguides. Various approaches could be tried, including that of providing confinement via low index side walls produced by the technique of ion-implantation.

Ion implantation has proved to be a particularly versatile technique for fabricating waveguides in a range of materials, crystalline and glass, including a number of laser materials [13]. While the losses, of ~ 1dB/cm typically, for waveguides produced by implantation, are currently greater than for techniques such as ion-exchange, epitaxial growth etc, examples of losses lower than 0.2dB/cm have been seen, giving encouragement that low losses may be generally achievable in due course. Ion-implantation has enabled waveguide lasers to be demonstrated in hosts such as YAG, $LiNbO_3$, YAP, BGO, as well as various nonlinear optical crystals. Techniques for fabricating channel waveguides have been successfully developed leading to demonstrated thresholds for NdYAG of as low as 1/2 milliwatt [14]. On the basis of such numbers it would seem feasible to achieve low thresholds, well within the capabilities of diode laser, even for broad linewidth materials of wide tunability. Excellent waveguides made via ion-implantation have been demonstrated, although so far no lasing achieved, in well-known tunable laser materials such as alexandrite. However since such lasers also tend to be limited to an inherently low gain per unit length, the requirement for low propagation loss is particularly stringent. This emphasises the need for further developments aimed generally at reducing waveguide losses.

While planar technology offers the additional options, compared to fibres, of working with crystalline hosts, by no means all of the planar developments have been confined to crystals. Considerable benefits are seen for the incorporation of an amplifying section into otherwise passive planar glass devices, such as star couplers, splitters etc., to compensate for the splitting loss. A number of approaches have been taken to the development of active rare-earth doped waveguides in planar glass devices. These include flame hydrolysis deposition of the doped glass, followed by reactive ion-beam etching to define the waveguides [ref 15]; sputter deposition followed by ion-beam sputtering [ref 16]; ion exchange [ref 17], etc. Clearly a very wide range of possible fabrication procedures exist and while it is too early to pass judgement, some indication of the promise is provided by the demonstrated net gain of 13.7dB in Er doped waveguides fabricated via the flame hydrolysis route [18].

Active rare-earth doped planar waveguide devices are still in their infancy, with a wide variety of fabrication approaches and host materials being investigated. Results so far give some encouragement that a number of useful devices could emerge, ranging from high gain amplifiers and high power diode-bar pumped lasers, to compact integrated Q-switched/mode-locked lasers and visible upconversion lasers.

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