# 1.9-μm operation of a Tm:lead germanate glass waveguide laser

**D. P. Shepherd, D. J. B. Brinck, J. Wang, A. C. Tropper, and D. C. Hanna**

*Optoelectronics Research Centre, University of Southampton, Highfield, Southampton S09 5NH, UK*

**G. Kakarantzas and P. D. Townsend**

*School of Mathematical and Physical Sciences, University of Sussex, Falmer, Brighton BN1 9QH, UK*

Received December 10, 1993

We report what we believe to be the first planar-technology waveguide laser in the 2-μm region. Laser operation of the $^3H_4$ to $^3H_6$ transition of $Tm^{3+}$ ions in a lead germanate glass host has been observed in an ion-implanted planar waveguide.

The development of coherent light sources in the wavelength region around 2 μm is of interest because of the presence of absorption bands of several important molecules. Lead germanate was shown to be a particularly suitable glass host for operation of the 2-μm $Tm^{3+}$ $^3H_4$ to $^3H_6$ transition in fiber samples[1,2] (see Fig. 1). The maximum phonon energy is greater than in fluoride glasses, leading to efficient population of the upper laser level through nonradiative decay out of the $^3F_4$ pump level. The maximum phonon energy is, however, less than in silicate glasses, leading to an increase in the lifetime of the upper laser level $^3H_4$. This favorable combination of decay rates has permitted us to demonstrate, using a fiber made of modified lead germanate ($55GeO_2-20PbO-10BaO-10ZnO-5K_2O$), thresholds for 790-nm pumping that are easily within reach of single-stripe diode lasers.[1]

Waveguides based on planar technology offer a number of potential advantages over fibers. For example, there is the possibility of diode-bar side pumping for high-power operation.[3] In addition, the active region is readily accessible for fabrication of feedback gratings, possibly through the photorefractive effect. Because high doping levels are possible with this glass, compact single-longitudinal-mode devices may be possible.

Recently it was shown that waveguides could be fabricated in this modified lead germanate glass by use of $He^+$ ion implantation[4] and that, in addition, the losses of these guides were significantly lower than the ~1-dB $cm^{-1}$ value that has been typical for ion implantation.[5] In fact, losses of 0.15 dB $cm^{-1}$ were obtained[4] (compared with 0.02 dB $cm^{-1}$ for the fiber), with index profiles suitable for guiding 2-μm radiation. The effect of the propagation loss can be reduced further by the use of shorter cavity lengths and correspondingly higher doping levels. The use of $Tm^{3+}$ is also attractive because there exists a cross-relaxation process that offers the possibility of 200% pumping quantum efficiency for highly doped samples. To assess the prospects for active waveguide devices in lead germanate glass, we have made an initial investigation of the 2-μm $Tm^{3+}$ laser in a planar waveguide.

The waveguide used in these experiments was a planar guide (i.e., with guiding in one transverse dimension) created by implantation of the polished surface of the Tm-doped glass with 2.9-MeV $^3He^+$ ions at liquid-nitrogen temperature at a dose of $4 \times 10^{16}$ ions/$cm^2$. This was followed by annealing at 200 °C, which was found to be the annealing temperature at which propagation losses were minimized while the index increase in the guide region remained relatively large.[4] The dark mode pattern of the resultant waveguide was investigated, and from this the refractive-index profile shown in Fig. 2 was calculated.[6] Making a simple asymmetric slab waveguide approximation, i.e., ignoring the low-index barrier at the end of the profile, we calculated fundamental mode spot sizes ($1/e^2$ half-width of intensity) to be 3.5 and ~5 μm for the 790-nm pump and 1.9-μm signal wavelengths, respectively. Calculation also indicates that the guide can support two modes at 790 nm and just one at 1.9 μm. It should be noted that the index profile was measured at 633 nm, and so the calculated spot sizes at 790 nm and especially at 1.9 μm are only rough approximations.

The implanted sample was end polished such that the faces were parallel and scratch free up to and including the important top few micrometers. The length of the polished sample was 1.05 cm. We

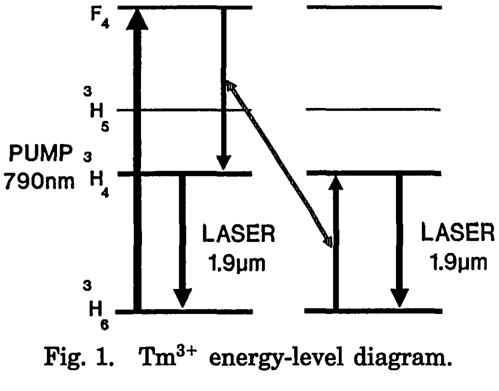

Fig. 1. $Tm^{3+}$ energy-level diagram.

0146-9592/94/130954-03$6.00/0

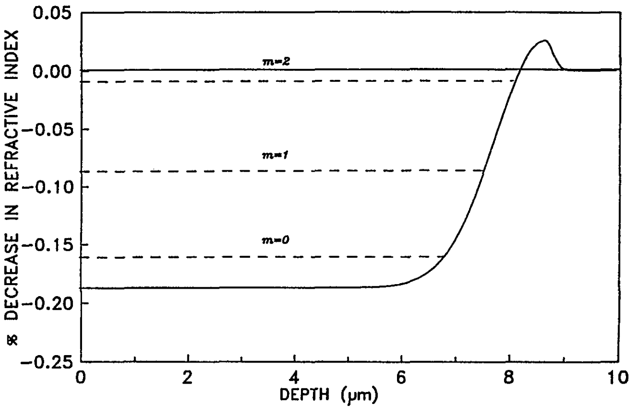

Fig. 2. Calculated refractive-index profile at 633 nm.

used a Ti:sapphire laser as the pump source, and various microscope objectives to find optimum end-launch conditions. Using a 10× objective, we observed an overall guide transmission of 77.5% when the Ti:sapphire laser was tuned off the absorption to 749 nm. Assuming the propagation loss to be 0.15 dB $\mathrm{cm}^{-1}$, as was measured for similarly implanted guides at 633 nm, this implies a launch efficiency of 80%. This figure is consistent with that found for optimized launching conditions in other ion-implanted guides. The 10× objective produces a 4-$\mu$m spot size at the entrance to the guide, which is a close fit to the calculated and experimentally observed 790-nm fundamental mode sizes of 3.5 and 4.1 $\mu$m, respectively. The latter was found by observation of the transmitted beam focused on the CCD camera of a beam analyzer. The beam analyzer also provided confirmation that optimum launching leads to propagation of the fundamental mode only.

To permit the use of short cavity lengths (~1 cm), we chose the doping level to be 2 wt. % $\mathrm{Tm_2O_3}$, a factor of 10 higher than that previously used in fibers. At this level of doping, concentration effects are important. In particular, there is the well-known cooperative process[7] whereby an ion excited in the $^3F_4$ state interacts with a neighboring ion in the ground state to produce two ions in the $^3H_4$ state (see Fig. 1). Thus it is possible to excite two Tm ions to the upper-level for every pump photon absorbed. Comparing the decay rates of the $^3F_4$ level for the lightly doped and heavily doped samples and making the assumption that the above-mentioned cooperative process is the only significant one occurring over the range of pumping conditions used in our experiments, we calculated a pumping quantum efficiency of 155%. There was no observable difference between the $^3H_4$ fluorescence lifetimes in the guide and bulk regions, both having a value of ~0.9 ms.

We investigated end-light fluorescence emission of the 1-cm-long guide and bulk regions, using a monochromator and a PbS detector and end-pumping with a Ti:sapphire laser at 790 nm, with the results shown in Fig. 3. The fluorescence curves have been normalized to have the same area underneath but have not been corrected for the detector response, leading to a reduction in the height of the 1.5-$\mu$m emission band. The figure shows only a slight difference in fluorescence in the bulk and the guide regions, much less than the differences that have been seen for some ion-implanted waveguides.[8]

We formed the laser cavity by butting lightweight mirrors onto the end faces of the sample, using the surface tension of a drop of fluorinated liquid to hold them in place. These mirrors had 92% transmission at 790 nm and were highly reflecting from 1.8 to 2 $\mu$m. Using a 10× objective to launch the pump light, we observed laser action at a power level incident upon the input mirror of 284 mW. This corresponds to an absorbed power threshold of 190 mW (the pump absorption was measured to be 77% in both the guide and bulk regions for this sample length). However, with a 4× objective, which produced only a 62% launch efficiency, a lower incident power threshold of 167 mW was observed, corresponding to an absorbed power of just 89 mW. The improved threshold could be due to the fact that the average pump mode size in the unguided plane is reduced by a factor of ~2, thus giving an improved overlap of pump and laser modes. This is consistent with the reduction in the absorbed power threshold. We could in principle obtain optimum planar performance by focusing independently in the guided and unguided planes. The output efficiency of the laser was not measured because output coupling mirrors were not available.

The laser output was observed to be TM polarized, despite the fact that no observable difference was found in the index profiles at 633 nm for TM and TE polarizations. Lasing occurred over the range 1.906–1.940 $\mu$m at a pump level 1.6 times above threshold, with a peak at approximately 1.92 $\mu$m. At this wavelength the emission cross section is close to its maximum, while the absorption cross section is small (see Fig. 3). The absorption cross section, although small, is, however, significant when one is calculating the threshold because the ground-state manifold is still heavily populated.

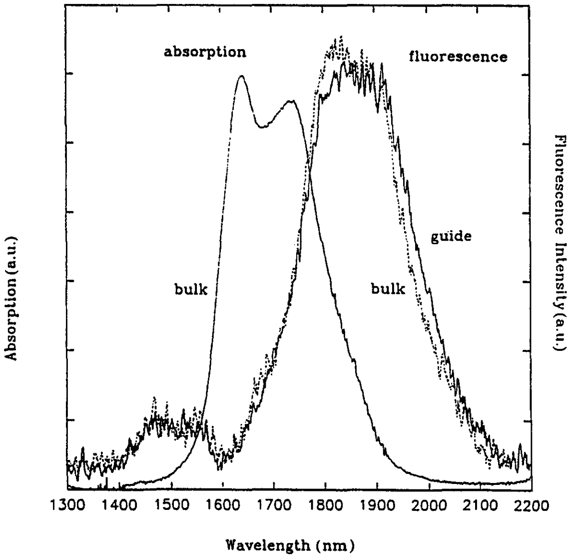

Fig. 3. Fluorescence spectra of the guide and bulk regions, together with the bulk absorption spectrum of $\mathrm{Tm^{3+}}$.

We have derived an expression for the expected absorbed pump power threshold for cw operation, taking into account reabsorption at the lasing wavelength, from the pump-propagation equation and the rate equations for the $^3F_4$ and $^3H_4$ levels, as follows:

$$P_{\text{th}} = \frac{\pi h \nu L[\alpha + N_t \sigma_a(l)]}{2[\phi \tau_u \sigma_e(l) + (\phi \tau_u + \tau_p)\sigma_a(l)]} \times ({W_{px}}^2 + {W_{sx}}^2)^{1/2}({W_{py}}^2 + {W_{sy}}^2)^{1/2}, \qquad (1)$$

where $\nu$ is the pump frequency, $\sigma_e(l)$ is the emission cross section at the lasing wavelength ($4.2 \times 10^{-25}$ m$^2$), $\sigma_a(l)$ is the absorption cross section at the lasing wavelength ($0.3 \times 10^{-25}$ m$^2$), $\tau_u$ is the fluorescence lifetime of the $^3H_4$ level (0.9 ms), $\tau_p$ is the fluorescence lifetime of the $^3F_4$ level (83 $\mu$s), $\phi$ is the pumping quantum efficiency (1.55), the $W$'s are average waist spot sizes for the pump ($p$) and the signal ($s$) in the guided ($y$) and unguided ($x$) directions, $\alpha$ is the propagation loss (3.45 m$^{-1}$), $L$ is the length of the sample (1.05 cm), and $N_t$ is the total population density of Tm$^{3+}$ ions ($3.48 \times 10^{26}$ m$^{-3}$).

In Eq. (1) the loss that is due to reabsorption occurs through the two terms involving $\sigma_a(l)$. The term in the numerator involves the total ion population density, with the term in the denominator adjusting for the fact that not all the population is in the ground level because the $^3F_4$ and $^3H_4$ levels are also populated. The value of the pumping quantum efficiency $\phi$ is dependent on the decay rates of the various routes out of the $^3F_4$ level. The relationship between $\phi$ and $\tau_p$ is such that, by a higher concentration, there should always be a net increase in the size of the denominator in Eq. (1) because the effect of the increase in $\phi$ outweighs the effect of the decrease in $\tau_p$. Thus, if we were to increase the total population density $N_t$ while reducing the length so that $N_tL$ were constant, the numerator would decrease as a result of the reduction in $L$, while the denominator would increase, leading to a decrease in threshold. With this host it should be possible to dope at levels for which $\phi \sim 2$, which should correspondingly reduce the threshold and increase the slope efficiency.

The signal spot sizes were not measured because the CCD camera used was not sensitive out to 1.9 $\mu$m. Therefore the calculated 1.9-$\mu$m guided spot size of 5 $\mu$m was used, and it was assumed that the average unguided spot sizes of the pump and the signal were the same (109 $\mu$m). From these figures an absorbed power threshold of ~90 mW was calculated. Considering the uncertainty in the values used, the possible error in the calculated value is quite large, but the good agreement with the experimental value is encouraging because similar calculations suggest that channel waveguides should have thresholds of less than 10 mW, easily within reach of single-stripe diode-laser pumps.

We have demonstrated what we believe to be the first 2-$\mu$m planar-technology waveguide laser. We believe that this is also the first waveguide laser in which the waveguide has been fabricated in a glass host by ion implantation. The low loss of the guide is confirmed by the lower observed threshold. The agreement between theoretical and experimental thresholds suggests that channel waveguides in this laser medium should have thresholds of less than 10 mW, thus offering the possibility of pumping by low-power diode lasers while also offering the advantages of a planar geometry in terms of additional functions.

## References

1. J. R. Lincoln, C. J. Mackechnie, J. Wang, W. S. Brocklesby, R. S. Deol, A. Pearson, D. C. Hanna, and D. N. Payne, Electron. Lett. **28,** 1021 (1992).
2. J. Wang, J. R. Lincoln, W. S. Brocklesby, R. S. Deol, C. J. Mackechnie, A. Pearson, A. C. Tropper, D. C. Hanna, and D. N. Payne, J. Appl. Phys. **73,** 8066 (1993).
3. D. C. Hanna, A. C. Large, D. P. Shepherd, A. C. Tropper, I. Chartier, B. Ferrand, and D. Pelenc, Opt. Commun. **91,** 229 (1992).
4. G. Kakarantzas, P. D. Townsend, and J. Wang, Electron. Lett. **29,** 489 (1993).
5. S. J. Field, D. C. Hanna, A. C. Large, D. P. Shepherd, A. C. Tropper, P. J. Chandler, P. D. Townsend, and L. Zhang, Electron. Lett. **27,** 2375 (1991).
6. P. J. Chandler and F. L. Lama, Opt. Acta **33,** 127 (1986).
7. T. Y. Fan, G. Huber, R. L. Byer, and P. Mitzscherlich, IEEE J. Quantum Electron. **24,** 924 (1988).
8. S. J. Field, D. C. Hanna, D. P. Shepherd, A. C. Tropper, P. J. Chandler, P. D. Townsend, and L. Zhang, IEEE J. Quantum Electron. **27,** 428 (1991).