Channel waveguide laser at 1 µm in Yb-indiffused LiNbO₃

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Received March 1, 1995

We report laser action in a Ti-diffused LiNbO₃ waveguide doped with trivalent Yb ions by thermal indiffusion. Lasing was observed at 1006, 1030, and 1060 nm with thresholds as low as 15-mW launched pump power. We reduced photoreflectivity, which initially permitted only intermittent lasing, by annealing the sample in wet O₂. The annealed sample lased continuously in a cavity formed by high-reflectivity mirrors; however, with a 7% output coupler the output power exhibited instabilities. The greatest value of the output power observed under these conditions was consistent with a slope efficiency of ~16% with respect to absorbed power.

Diffusion is a highly flexible technique for doping crystals. LiNbO₃ is a ferroelectric material into which laser dopant ions can be readily introduced by thermal diffusion at ~1000 °C without alteration of the poling of the crystal because its Curie point is close to 1140 °C. With this method different dopants and levels of doping can be introduced into undoped wafers of LiNbO₃, avoiding the large investment in time and equipment needed to produce bulk-doped samples. Moreover, the dopant species and concentration can be spatially patterned on one substrate, permitting the production of a greater variety of integrated optical devices than is possible with bulk-doped material. LiNbO₃ is of interest for its nonlinear, electro-optic, and acousto-optic properties and also because it is a substrate material suitable for the fabrication of low-loss waveguides. Thus FM mode-locked, 1,2 Q-switched, 3 tunable waveguide lasers and devices 4,5 have been made in both Ti-diffused and proton-exchanged waveguides. Proton-exchange guides have a much lower susceptibility to photorefraction than do Ti guides but will support only extraordinary-polarized light. The fluorescence and laser action from Yb:LiNbO₃, described below, is both ordinary and extraordinary polarized. It was therefore decided that proton-exchange waveguides were not appropriate for this system.

The Yb³⁺ ion has a single metastable excited manifold from which quasi-three-level lasing is possible to levels in the ground manifold that are significantly thermally populated at room temperature. Reabsorption losses at the signal wavelength increase the laser threshold; however, in a waveguide, high pump intensity and correspondingly strong inversion can be produced at much lower pump power than would be the case in a bulk crystal, bleaching the ground-state reabsorption. Although waveguides often suffer in comparison with bulk lasers through their greater propagation losses, for a quasi-three-level system the effective waveguide loss will be similar to that of the bulk material since it is dominated by reabsorption. Moreover, the pump and signal wavelengths can be as little as 28 nm apart, suggesting the possibility of a higher pumping efficiency and lower thermal loading of the crystal than is the case for other rare-earth dopants. The simple energy-level structure of the Yb³⁺ ion should preclude quenching of the excited-state population by excited-state absorption or cross relaxation, so that it should be possible to operate the laser in a strongly inverted condition without serious loss of efficiency owing to parasitic processes. Furthermore Yb:LiNbO₃ is a good candidate for future internal second-harmonic generation because of the absence of any absorption at the second-harmonic wavelengths. For these reasons the Yb dopant ion was seen as an attractive candidate for laser operation in a LiNbO₃ guide. We report here the fabrication and laser operation of Yb³⁺-indiffused Ti-doped waveguides in LiNbO₃. The lasers show instabilities typical of photorefractive damage, a well-known problem in LiNbO₃ that tends to reduce the attractiveness of this material for use in optical devices. 8 However, we have annealed our devices in an oxidizing atmosphere and shown a marked reduction in photorefractivity, as was previously reported. 7 This is to our knowledge the first report of lasing in either waveguide or bulk Yb:LiNbO₃.

A 35-nm layer of Yb metal was evaporated onto a wafer of x-cut LiNbO₃, leaving a region of the sample uncoated for purposes of comparison. The sample was then placed in a P boat inside an 88-mm-diameter tube furnace at 1100 °C for 255 h in a dry O₂ atmosphere flowing at 0.5 L min⁻¹. After the rare-earth diffusion process, sets of 65-nm-thick y-propagating Ti stripes, ranging in width from 4 to 16 µm, were produced by lift-off of an evaporated Ti film from a photoresist mask made by standard photolithographic techniques. The Ti metal was then diffused for 12 h at 1005 °C in a wet Ar atmosphere flowing at 0.5 L min⁻¹. The wafer was subsequently cut into three pieces of lengths 43, 26, and 14 mm. These were end polished perpendicular to the waveguide propagation direction to permit efficient end coupling of the pump laser light into the guides.

Transmission spectra were measured by use of unpolarized white light that was end coupled into a waveguide with a 25× microscope objective. The output end of the guide was imaged onto the entrance slit of an EG&G OMA 2000 cooled Si diode-array spectrometer. Polarized spectra were measured with a Glan–Thompson prism placed in front of the spectrometer. We converted the data to the absorption spectrum, seen in Fig. 1, by first dividing the transmission spectrum obtained from an undoped channel by that of a doped channel and then transforming the
results into a decibel-per-centimeter plot with the aid of standard computer software. With pump light from a Ti:sapphire laser end coupled into the waveguide we investigated the spectrum of guided fluorescence, using the same experimental arrangement.

Figure 1 shows \( \pi \) and \( \sigma \)-polarized white-light absorption spectra measured by use of the 14-mm-long sample. The concentration distribution of \( \text{Yb}^{3+} \) in these samples is thought to be described by a complementary error function because the depletion time of the Yb metal layer was estimated to be close to the total diffusion time. Using the diffusion parameters established for \( \text{Er}^{3+} \), we estimate the average \( \text{Yb}^{3+} \) concentration over the waveguide mode to be \( \sim 1 \times 10^{20} \text{ cm}^{-3} \). Three main absorption peaks at 918, 956, and 980 nm can be seen, and they appear to coincide with those reported for Czochralski-grown bulk-doped \( \text{Yb:LiNbO}_3 \). The 956-nm peak is purely \( \sigma \) polarized, whereas the 918- and 980-nm absorptions appear in both \( \pi \) and \( \sigma \) polarizations.

The polarized fluorescence spectra are shown in Fig. 2. Peaks can be seen at 980 nm (\( \pi \) and \( \sigma \)), 1005 nm (\( \pi \) and \( \sigma \)), 1030 nm (\( \sigma \)), and 1060 nm (\( \pi \)). The energy-level diagram shown in Fig. 3 was deduced from these spectroscopic data, which were found to be consistent with point symmetry \( C_3 \) at the \( \text{Yb}^{3+} \) site. A \( C_3 \) site permits two symmetries of Kramers doublet that we refer to as A and B doublets, where in the notation of Koster et al.\(^{10}\) A transforms as \( \Gamma_4 + \Gamma_5 \) and B transforms as \( \Gamma_6 + \Gamma_8 \). The electric-dipole selection rules are as follows: \( A \leftrightarrow B \) is \( \sigma \) polarized (\( E \) perpendicular to the c axis), \( B \leftrightarrow B \) is \( \pi \) polarized (\( E \) parallel to the c axis), and \( A \leftrightarrow A \) is both \( \pi \) and \( \sigma \) polarized. In this site symmetry the \( J = 7/2 \) ground manifold is Stark split into \( 3A + B \), the \( J = 5/2 \) excited manifold into \( 2A + B \). Possible symmetry assignments for the Stark levels, together with the approximate energies, are shown in Fig. 3; the only inconsistency lies within the 1060-nm transition that should appear in both \( \pi \) and \( \sigma \) polarizations. The \( \sigma \) component may simply be too weak to be distinguished among such broad spectral features. The fluorescence lifetime was measured to be \( \sim 600 \mu s \), a value typical of \( \text{Yb}^{3+} \)-doped noncentrosymmetric oxides.\(^{11}\)

Lasing studies were first carried out with the 43-mm-long sample, with optical feedback of the waveguide laser being provided by the polished end faces alone. The Ti:sapphire laser pump source was tuned to the \( \sigma \)-polarized 956-nm \( \text{Yb:LiNbO}_3 \) absorption and end launched into the waveguide. The pump polarization was rotated before end-fire coupling, to match the polarization of the \( \text{Yb}^{3+} \) absorption. As with the fluorescence measurements, the output from the waveguide was focused into the EG&G spectrometer. Lasing was observed in a 12-\( \mu \)m-wide guide with \( \sim 53 \text{ mW} \) of launched pump power. Laser emissions were observed at 1008, 1030, and 1060 nm. The 1030-nm emission was \( \sigma \) polarized, but the 1008- and 1060-nm lines were \( \pi \) polarized and were often seen lasing simultaneously.

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**Fig. 1.** \( \text{Yb:LiNbO}_3 \) waveguide absorption in the 14-mm sample.

**Fig. 2.** \( \text{Yb:LiNbO}_3 \) waveguide fluorescence.

**Fig. 3.** Energy-level diagram and selection rules for \( \text{Yb:LiNbO}_3 \).
The spot size of the output beam from a 12-μm-wide guide, defined as the radial distance from the peak intensity to the point at which the intensity falls to 1/e^2 of this value, was measured with a CCD camera and image analyzer (Big Sky Software Corporation beam view analyzer) and found to be 2.5 μm and single mode in the z direction at both the pump and the laser wavelengths. In the z direction the beam was double mode.

Waveguide losses were estimated at 837 nm, outside the Yb^{3+} absorption band, by comparison of the transmission of the different-length devices. We estimated the losses for guides in the undoped portion of the substrate by assuming the same launch efficiency as in doped channels and directly comparing the transmission of one length of guide with the doped counterpart. The losses in undoped guides were of the order of 0.5 dB cm^{-1}, whereas losses in doped waveguides were found vary from guide to guide over the range 1–3 dB cm^{-1}, depending on the particular waveguide. The higher losses in the doped guides were attributed to the greater surface roughness occurring on these channels as a consequence of incomplete diffusion of the Ti metal. We verified this by showing that a further 20-h diffusion at 1005 °C produced waveguides with smooth surfaces and losses of the order of 0.5 dB cm^{-1}. Thus we conclude that the diffusion coefficient for Ti in Yb-indiffused LiNbO_{3} is somewhat less than that of undoped material.

In evaluating the laser performance of the 14-mm sample we increased the feedback by using two thin lightweight mirrors with >99.9% reflectivity at the emission wavelengths. These were directly butt coupled to the end faces of the crystal and held in place by the surface tension of a drop of fluorinated liquid. When this configuration was pumped at 956 nm, lasing occurred at a threshold of 15 mW of launched pump power. Lasing again ceased after ~1 s because induced photorefractive damage led to increased propagation loss in the waveguide.

In both the 43- and 14-mm-long samples and at all three laser wavelengths, photorefractive damage led to erratic lasing that lasted for less than 1 s. To reduce the photorefractive effect seen in these samples, we employed a technique used by Betts et al., in which the crystals were oxidized so as to lower the Fe_{2}^{3+}/Fe_{3}^{3+} ratio. We implemented this technique for the 14-mm-long sample by heating it at 500 °C for 14 h in wet O_{2} flowing at 0.5 L min^{-1}. After oxidation the stability and longevity of the laser output appeared to be greatly improved, and with two high-reflectivity mirrors (>99.9% reflectivity), cw operation was observed for more than 1 min. It was difficult to measure a slope efficiency with the high-reflectivity mirrors in place, so to test the output efficiency of this device we replaced one of the high-reflectivity mirrors by an output coupler with a transmission of 2% at 1060 nm and 7% at 1008 nm, the residual pump light being filtered from the orthogonally polarized signal with a Glan–Thompson polarizing cube. Lasing was seen in this configuration at a threshold of 85 mW of launched pump power. Owing to residual photorefractivity, however, the output power was found to vary by more than an order of magnitude for constant pump power. Although an absorbed power slope efficiency could not therefore be determined, the peak output powers measured imply a slope efficiency of ~16%. Above 130 mW of launched pump power the output intensity was found to become very unstable, and no increase in the emitted power could be observed. The oxidation conditions appropriate for reducing the photorefractive effect are currently under investigation, and it is hoped that they will lead to improved laser performance.

We have demonstrated what we believe is the first Yb^{3+}:LiNbO_{3} laser, which has lased at several wavelengths with modest pump power thresholds. The performance at present is severely limited by photorefractive damage and high waveguide losses. We have realized some improvement in the photorefractive degradation by annealing in oxidizing conditions, and we are studying the optimization of this treatment. Periodic poling is also being considered as another method for lessening photorefractive damage. Surface roughness, a major cause of loss, has already been greatly reduced in samples that have been further diffused at 1005 °C. We anticipate that these improvements will lead to a significantly more efficient and stable performance for this novel solid-state laser system.

References