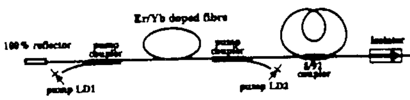
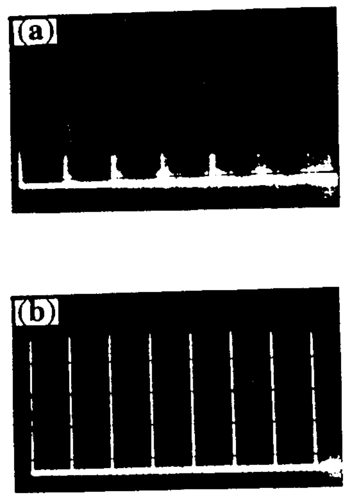


CFJ3 **Fig. 1** Schematic configuration of the self-Q-switched laser.



CFJ3 **Fig. 2** Oscilloscope traces of (a) unstabilized and (b) stabilized output from the self-Q-switched laser.

niques have been used.[1-3] Here, we demonstrate a novel self-Q-switched erbium-doped fiber laser generating 5-15 nsec pulses with a tunable repetition rate from 100 Hz to 10 kHz in all-optical-fiber configuration without using any active intracavity modulation.

The laser configuration is shown in Fig. 1. Er/Yb codoped fiber was pumped employing two laser diodes operating around 970 nm. Feedback was provided by a high-reflecting fiber Bragg grating and the backreflection from a ring interferometer formed by a 8% fused-fiber coupler at 1545 nm and 5 m of single-mode fiber. In order to suppress cw lasing, the feedback from the output end must be eliminated. This was achieved by introducing a low back-reflection fiber-pigtailed isolator, or alternatively by using an angled cleave. Two distinct pulsed regimes of operation were observed in the laser. Without feedback from the interferometer, which was suppressed by introducing loss inside the ring cavity by bending the fiber, the laser operated in a well-known self-pulsating regime with a pulse duration of a couple microseconds and period of ten microseconds.[3] Providing feedback from the ring interferometer, the laser operated in a principally different mode with a lower repetition rate ~10 kHz and pulses more than two orders of magnitude shorter and three orders of magnitude higher peak power. The measured pulse duration was 5-15 nsec, and peak power ~100 W. The repetition rate was dependent on the pump power. An increase in the pump power led to an increase in the repetition rate and did not significantly change the parameters of the output pulse parameters. However, the period was unstable and fluctuated within 10% from pulse-to-pulse. A typical oscilloscope trace is shown in Fig. 2(a). In order to stabilize the repetition rate, one of the pump diodes was modulated at a resonant frequency, which dramatically improved the stability [Fig. 2(b)]. Repetition rate tunability from hundreds of Hertz to 20 kHz was also achieved.

A considerable body of experimental evidence indicates that this new regime of passive Q-switching can be attributed to the distributed Rayleigh backscattering from the fiber enhanced by the interferometer effect. This Q-switching mechanism can be used in other high-gain fiber lasers, and in fact we have observed this in a Ytterbium-doped fiber laser, which is reported.

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1. F. Seguin, T. Oleskevich, Opt. Eng. **32**, 2036–2041 (1993).
2. *IRE-Polus Group* Data sheet: Model ELPD-2000.
3. P. Le Boudec, C. Jaouen, P. L. Francois, J.-F. Bayon, *et al.*, Opt. Lett. **18**, 1890–1893 (1993).

CFJ4 **11:30 am**

High-gain amplification in a liquid-phase epitaxial Nd:YAG waveguide

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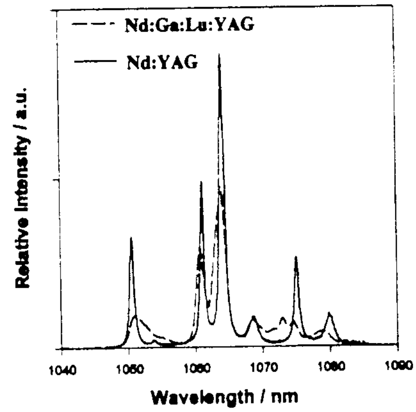
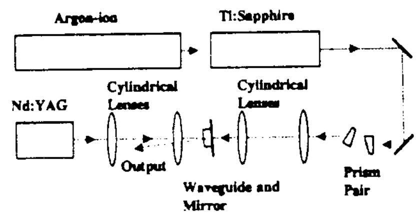
There is a growing appreciation of the possibilities for high-gain amplification in solid-state laser materials pumped by high-average-power diode lasers. So far the emphasis has been on bulk materials, however planar waveguides offer significant benefits. Their geometry is compatible with that of the diode laser and the confinement allows much smaller pumped volumes and hence higher gain for a given pump power. For example, with the waveguide we have used the pumped volume is ~one order of magnitude smaller than could be achieved in a bulk medium of the same length.

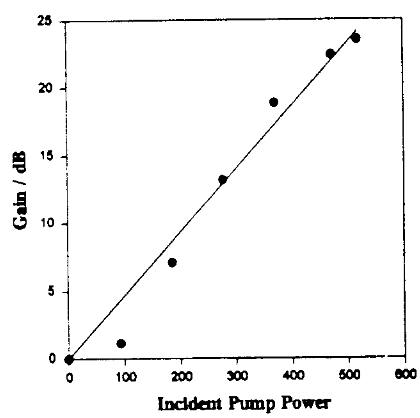
In order to test these theoretical advantages we used a 5-mm-long Nd:YAG planar waveguide grown by liquid-phase epitaxy. Control of the guide refractive index is obtained by codoping with Gallium[1] allowing waveguides of just a few microns depth to be fabricated, although the presence of Ga has an effect on the emission spectrum as can be seen in Fig. 1. The guide we have used had a 3.8-μm-deep guiding region, doped with 1at.% Nd, 12at.% Ga, and 35at.% Lu (the latter compensates for the size-mismatch between Ga and Al). Figure 2 shows the experimental setup used in our initial experiments. A Ti:sapphire pump was used, but focussed using cylindrical lenses and an anamorphic prism pair in such a way as to produce spot sizes that should be achievable with a broad-stripe diode – ~2 μm and ~160 μm ($1/e^2$ intensity half width). A 1.064-μm signal was launched using cylindrial lenses into the opposite end of the waveguide and was double-passed using a butted mirror. The relatively large width of pump region allowed spatial separation of the input and output signal.



CFJ4 **Fig. 1** Emission spectra for Nd:YAG and Nd:Ga:Lu:YAG.



CFJ4 **Fig. 2** Experimental arrangement for the waveguide amplifier.



CFJ4 **Fig. 3** Gain against incident pump power.

We have observed small signal cw gains of over 200 for incident pump powers of 520 mW, corresponding to 250 mW of launched power, see Fig. 3. So far we have obtained up to 20 mW of amplified signal output from this amplifier (0.3 mW input) but with full optimization this figure is expected to rise considerably.

The large gain for low pump powers and the relatively simple experimental setup suggest that planar waveguides could be very attractive for high-average-power diode-pumped amplifiers. The geometry of the planar waveguide, effectively an extreme case of the slab geometry, should be well suited to coping with high thermal loads as cooling can easily be applied very close (within around 10 μm) to the pumped region.

There is considerable scope for further optimization and in particular the use of a broad-stripe diode pump will allow much higher pump powers (4 W) to be coupled into the same volume as used in these experiments. Much higher gains and output powers should result. It is hoped that the results of such diode-pumped operation is presented.

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1. D. C. Hanna, A. C. Large, D. P. Shepherd, A. C. Tropper, I. Chartier, B. Ferrand, D. Pelenc, Appl. Phys. Lett. **63**, 7–9 (1993).

CFJ5 11:45 am

Chromium indiffused $LiNbO_3$ waveguide amplifier

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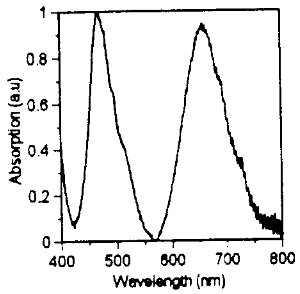
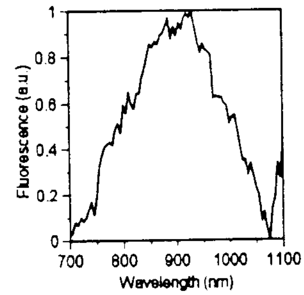
Chromium-doped crystals have attracted considerable attention as diode-pumped replacements for Ti:sapphire lasers. There are two primary reasons for this interest. First, chromium-doped crystals have a broad absorption band around 690 nm, where high-power laser diodes are available. Second, the fluorescence linewidth of the $^4T_2$ to $^4A_2$ lasing transition is extremely broad, covering more than 200 nm. This large linewidth results from vibrational broadening of the $^4A_2$ lower lasing level.

In 1992, a chromium-bulk-doped, lithium niobate ($LiNbO_3$) waveguide amplifier was demonstrated, we believe, for the first time. Recently, waveguide lasers and amplifiers have also been demonstrated in neodymium-bulk-doped $LiNbO_3$.[2] Active ion, bulk-doped $LiNbO_3$ crystals, however, are not readily available, and their optical qualities are often low. In the last few years, these problems have been partially circumvented by thermally indiffusing rare-earth ions into high-quality $LiNbO_3$ substrates. Neodymium, erbium, and ytterbium waveguide lasers and amplifiers have now been fabricated using thermal indiffusion.[3-5] In this paper, we extend this process to chromium, and report the first (to the best of our knowledge) waveguide amplifier in chromium indiffused $LiNbO_3$.

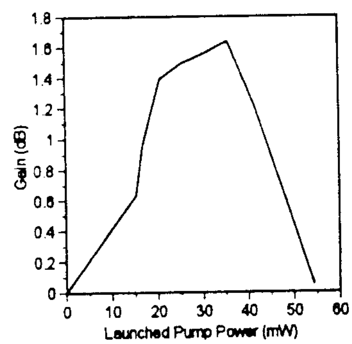
A 600-Å-thick chromium layer was electron-beam evaporated onto an x-cut $LiNbO_3$ substrate. The chromium was then overcoated with a 1000-Å-thick layer of titanium to increase the chromium indiffusion rate. The chromium/titanium stack was diffused for 24 hr at a temperature of 1050°C in a dry, oxygen atmosphere, which flowed at 0.5 liters/min. Following the diffusion step, no visible metal residue was observed on the surface, but the substrate had acquired a green coloration. The chromium absorption spectrum was determined by measuring the difference in transmission between an indiffused sample and an undoped sample using a spectrophotometer. Figure 1 shows the results of the measurement. As expected, the spectrum exhibits two strong absorption bands centered at 469 nm and 657 nm.



CFJ5 Fig. 1 Absorption spectrum for thermally diffused chromium in $LiNbO_3$.



CFJ5 Fig. 2 Fluorescence spectrum for thermally diffused chromium in $LiNbO_3$.



CFJ5 Fig. 3 Net gain of chromium indiffused $LiNbO_3$ at 838 nm with 488-nm pump.

A second x-cut $LiNbO_3$ substrate grown with 5 mol% MgO was coated on one side with a chromium/titanium stack (300 Å/1000 Å). The chromium/titanium stack was diffused for 30 hrs at a temperature of 1050°C in a dry, flowing oxygen atmosphere. Using a lift-off technique, channel openings were formed on a sapphire mask deposited on the substrate. Channel waveguides, directed along the y-axis of the crystal, were then fabricated by proton exchange for 4 hrs at 160°C in adipic acid followed by a two hr anneal at 360°C in a dry oxygen atmosphere. The end-faces of the substrate were polished perpendicular to the waveguide, producing a 17-mm-long device. The fluorescence spectrum (TE) of the device was measured when the waveguide was pumped (TE) at 488 nm with 100 mW. The results, shown in Fig. 2, indicated that the fluorescence peak occurs at 907 nm with a full-width-half-maximum of 219 nm.

The small signal gain was also measured at 838 nm using a Ti:sapphire laser copropagating with the 488-nm pump beam. The net gain of the amplifier, as a function of pump power, is shown in Fig. 3. A maximum gain of 1.64 dB was produced with 35.6 mW of launched pump power. At higher pump powers, the gain decreased, most probably due to photorefractive damage. Pumping in the 650–680-nm range might reduce the photorefractive damage and permit higher gains and laser action to be achieved at room temperature.

1. F. Zhou, *et al.*, Electron. Lett. **28**, 2041 (1992).
2. E. Lallier, *et al.*, J. Quantum Electron. **27**, 618 (1991).
3. J. Amin, *et al.*, Opt. Lett. **19**, 541 (1994).
4. R. Brinkman, *et al.*, J. Quantum Electron. **30**, 2356 (1994).
5. J. K. Jones, *et al.*, Opt. Lett. **20**, 1477 (1995).

CFJ6 12:00 m

Modeling and characterization of erbium: ytterbium glass waveguide lasers

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Erbium-ytterbium (Er^{3+}-Yb^{3+}) codoped glass is an attractive system for short, efficient lasers and amplifiers operating in the long-haul telecommunications range. The pump absorption near 980 nm is increased, and efficient energy transfer between the Yb^{3+} and Er^{3+} ions enables the operation of compact laser devices with low erbium concentrations. This mechanism was first demonstrated by Snitzer in bulk glass.[1] More recently, Er^{3+}-Yb^{3+} codoped fiber lasers[2] and planar waveguide lasers and amplifiers have been demonstrated in silicate[3,4] and phosphate[5] glass. We present simple methods that can be used to model the Er^{3+}-Yb^{3+} codoped glass system and predict laser performance. Experimental results for fabricated waveguide laser devices are discussed.

Figure 1 represents a simplified energy level diagram for the Er^{3+}-Yb^{3+} co-