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Passively Q-switched Nd-doped waveguide laser

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A passively Q-switched waveguide laser operating at 1.054 μm has been demonstrated in a Nd-doped phosphate glass. The channel waveguide was fabricated by K-ion exchange from a nitrate melt. Passively Q-switched pulses were achieved by placement of an acetate sheet containing an organic saturable-absorbing dye within the laser cavity. The resulting pulse train consisted of pulses with a FWHM of ~25 ns and peak powers of 3.04 W. With an 80% transmitting output coupler, cw operation of the laser provided 5.2 mW of output power at 1.054 μm for 229 mW of absorbed 794-nm pump power.

Rare-earth-doped waveguide lasers have been demonstrated in a number of different glass[1-3] and crystalline[4-6] substrates. Q-switched waveguide lasers have produced pulses with high peak power.[7,8] Here we report the operation of a passively Q-switched waveguide laser fabricated in a Nd-doped phosphate glass. The Q-switching element used for this laser was a saturable-absorbing dye incorporated in an acetate sheet. By passively Q switching such a device, one can obtain high peak powers without the complexity of an active electro-optic gating device within the laser cavity. To our knowledge, this is the first report of a passively Q-switched solid-state waveguide laser.

The base glass composition used here is the same as that reported previously.[9] In this case, however, the Nd_2O_3 doping level was increased to 1 mol. %. Channel waveguides were fabricated by K-ion exchange through apertures in a 300-nm-thick Al film. The apertures ranged in width from 2.5 to 7.5 μm. The exchange process was carried out in a KNO_3 melt at 375 °C for 6 h. After the exchange the Al mask was stripped off, and the sample's end faces were polished for end-fire coupling. The finished length of the waveguide substrate was 17 mm.

After the ion exchange and removal of the Al mask, the surface morphology of the substrate was measured with atomic force microscopy (AFM). An AFM cross section of the waveguide revealed a depression associated with the ion exchange measuring approximately 7.25 μm wide and 0.85 μm deep. These dimensions correspond to the waveguide formed from the 6-μm-wide aperture. A cross section of the AFM trace is shown in Fig. 1. AFM traces also revealed that the surface quality of the glass in the bottom of the depressions was as smooth as that of the unexchanged surface. Both locations had a peak-to-peak surface roughness of ~20 nm. These depressions were most likely the result of tensile stress in the waveguide region and/or etching of the substrate surface during the exchange process, although etching is unlikely because of the observed smoothness of the depression. The exchange process created waveguides that supported several width modes and one depth mode at the pump wavelength of 794 nm. At 1.054 μm, the lasing wavelength, the waveguides supported one transverse mode. Using the optimum coupling method,[10] we found that an upper limit for the waveguide loss was 3 dB/cm at 1.054 μm.

The sample was evaluated for cw and Q-switched operation in an extended-cavity configuration. In both cases the pump source was a cw Ti:sapphire laser operating at 794 nm. Optical feedback was provided by two dielectric mirrors. The input mirror had a reflectance of 99.6% at the lasing wavelength and a transmittance of 85% at the pump wavelength. This mirror was held to the pump input facet of the waveguide by a small clip. The laser output mirror was held in an adjustable mount ~500 mm from the other end of the waveguide. A 10× microscope objective was used to couple light between the waveguide and the output mirror. Two different mirrors were used for the laser output coupler; the first had a transmittance of 5% at 1.054 μm, and the second had a transmittance of 80%. When the laser was operated in the Q-switched mode a saturable absorber was placed on the output facet of the waveguide. A schematic representation of the extended-cavity setup is depicted in Fig. 2.

During cw operation the laser, with a total cavity length of ~525 mm, lased in the TM_{00} mode independent of the pump polarization. The waveguide had a single-pass absorption of 95% at the pump wavelength. With the 5% output coupler the laser reached threshold at approximately 60 mW of absorbed pump power and had a slope efficiency of 0.7%. For this output coupler the maximum output power at 1.054 μm was 2.0 mW for an absorbed pump power of 302 mW. When the 80% output cou-

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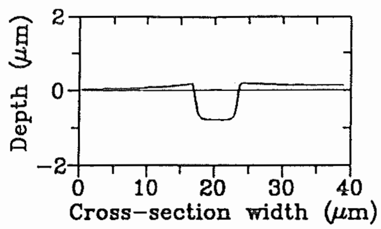


Fig. 1. Cross-sectional view of an AFM trace showing a depression in the waveguide region.

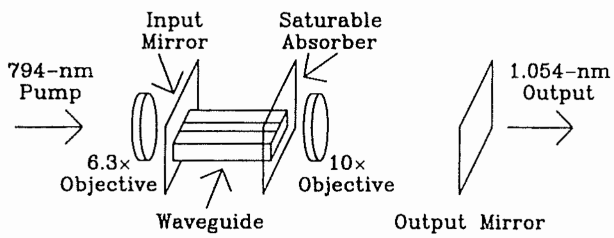


Fig. 2. Schematic of the extended-cavity laser showing the location of the feedback mirrors and the saturable absorber.

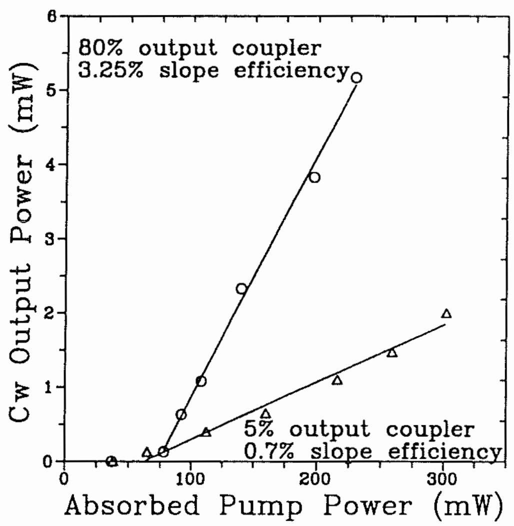


Fig. 3. Cw laser output as a function of absorbed pump power for two different output couplers. Slope efficiencies of 3.25% and 0.7% were obtained for the 80% and the 5% output couplers, respectively. The laser output wavelength was 1.054 μm, and the pump wavelength was 794 nm.

pler was used the threshold pump power increased to ~75 mW, and the slope efficiency increased to 3.25%. Maximum output power increased to 5.2 mW, with 229 mW of absorbed pump power. These data are shown in Fig. 3. The method for calculating pump absorption was given previously.[6]

For passive Q switching of the laser, a saturable absorber was held to the output end of the waveguide substrate with a small clip. The saturable absorber consisted of an organic dye, bis(4-dimethylaminodithiobenzil)nickel, incorporated into an acetate sheet that was 127 μm thick. Saturable absorbers having optical densities of 0.3 and 0.4 were used. Little difference in the Q-switched pulse output was seen for these two saturable absorbers, except that higher pump powers were required when the 0.4-optical-density absorber was used. As illustrated in Fig. 4, the width of the Q-switched pulses was directly related to the cavity length of the laser. By increasing the distance from the end of the waveguide to the output coupler it was possible to increase the width of the Q-switched pulses. The inset of Fig. 4 shows the output spectrum under Q-switched operation. The linewidth of the Q-switched laser was 0.3 nm, which was near the 0.2-nm resolution limit of the automatic spectrometer used to collect the data. Typical pulses for a cavity length of 525 mm are shown in Fig. 5. The pulse width for this cavity length was 20–30 ns FWHM. Because of data-acquisition artifacts these traces are composed of an overlay of several pulses. Peak pulse power obtained from individual pulses was as high as 0.9 W for the 5% output coupler and 3.04 W for the 80% output coupler. Individual-pulse output power was essentially unaffected by input pump power. However, the frequency of the pulses increased with pump power, yielding higher average power. The pulse frequency ranged from 6.67 to 50 kHz.

Passive Q switching was also performed with the high-powered, multitransverse-mode, Ag-ion-exchanged waveguide laser that was reported previously.[9] We assumed that a higher cw output power would lead to higher Q-switched pulse power. This, however, was not the case. We found that the peak power, the duration, and the frequency of this laser were essentially the same as those observed for the single-transverse-mode, K-ion-exchanged waveguide laser. It appeared that a limitation of the saturable absorber was reached. During evaluation of the single-mode laser the saturable absorber became permanently partially bleached, which resulted in pulses that had lower peak power and were much wider than those obtained for a fresh piece of the absorber. In the case of the multimode laser, when it was pumped sufficiently hard, the acetate sheet suffered catastrophic burns at the focus of the intracavity objective.

The results for our single-mode Q-switched laser compare favorably with results for similarly Q-

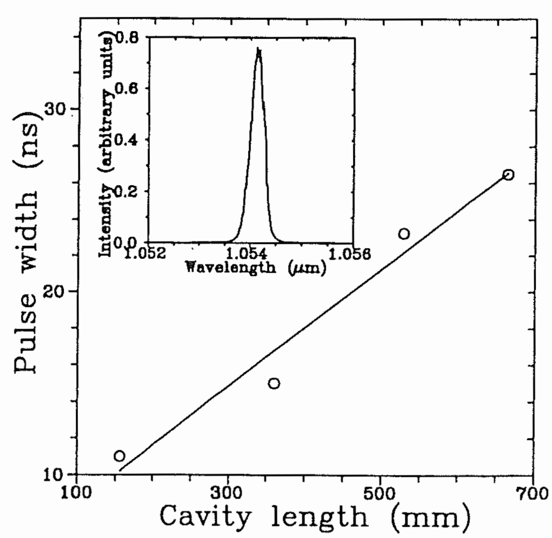
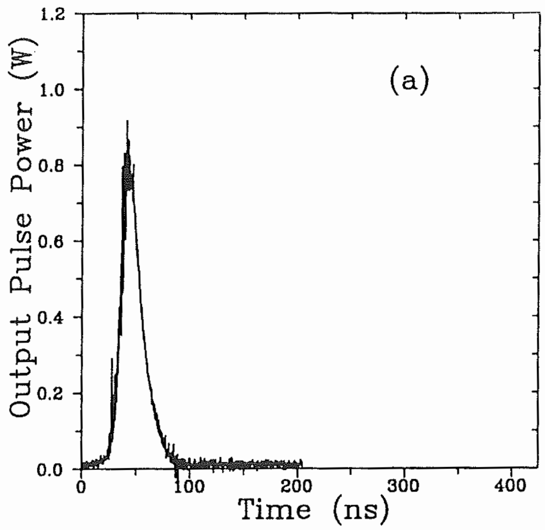


Fig. 4. Q-switched pulse width as a function of laser cavity length. The inset shows the Q-switched laser line at 1.054 μm. The laser linewidth was 0.3 nm.



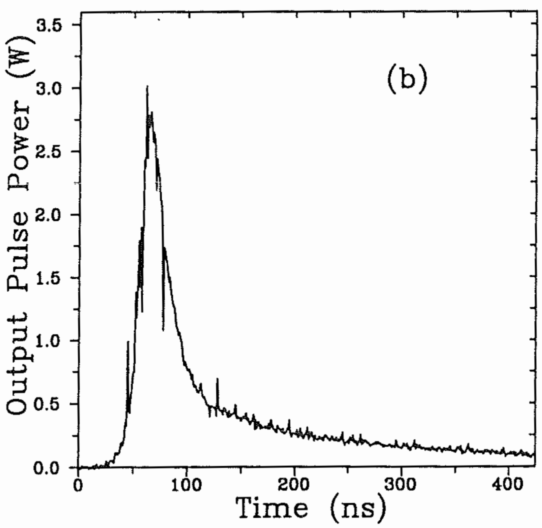


Fig. 5. Q-switched pulses for a cavity length of 525 mm and a 0.3-optical-density saturable absorber. (a) 5% Output coupler, (b) 80% output coupler.

switched fiber lasers.[7] In both cases the Q-switched pulse power was insensitive to pump power, whereas the period of the pulses was highly pump dependent.

Two attempts were made to observe mode-locked pulses under the Q-switched pulse envelope. The first used a fast detector and a sampling oscilloscope, the second used a fast detector and a rf spectrum analyzer. Neither method was effective in detecting mode locking.

The theoretical maximum output power and duration of the Q-switched pulses were calculated in a manner similar to that of Ref. 11. This treatment used the following parameters: input mirror reflectivity, 0.996; index of refraction of the waveguide, 1.504; pump mode radius, 4 μm; waveguide loss, 3 dB/cm; stimulated emission cross section, 3.62×10^{-20} cm^2; length of gain media (waveguide), 17 mm; length of air cavity, 508 mm; transmission of waveguide end face, 0.96; transmission of the saturable absorber's surfaces, 0.97 each; transmission through the saturable absorber when not bleached, 0.5; transmission through the saturable absorber when bleached, 0.85; and output mirror reflectivities for our two different configurations, 0.95 (5% output coupler) and 0.2 (80% output coupler). The stimulated emission cross section was determined by a Judd–Ofelt analysis on the substrate material.[12–14] The transmission of the saturable absorber was measured with a diode-pumped Nd:YLF laser operating at 1.047 μm. The theoretical calculations assumed uniform pump intensity along the length of the waveguide and single-transverse-mode pumping and laser operation. For the case of the 5% output coupler our calculations predict a peak output power of 0.4 W, with an approximate pulse duration of 48 ns. For the 80% output coupler a theoretical peak output power of 6.3 W and a pulse length of 67 ns were calculated. We believe that, for the 80% output coupler, the experimental results were hampered by an apparent degradation of the saturable absorber. This explanation is further justified by the inability of the multimode laser to produce Q-switched pulses of greater than 3 W, even though it exhibited substantially lower waveguide loss.

In conclusion, we have demonstrated passively Q-switched pulses by using a waveguide laser fabricated in a Nd-doped phosphate glass and an intracavity saturable absorber. Presumably, a monolithic structure in which the output mirror is attached directly to the saturable-absorber sheet, similar to the research reported in Ref. 7, could be used for the waveguide laser. Additionally, it may be possible to load the surface of the guide with a form of the saturable absorbing dye. Furthermore, semiconductor saturable absorbers need to be examined for use as possible passive or active Q-switching or mode-locking material for waveguide lasers.

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