High-energy operation of a Co:MgF$_2$ laser

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We have generated output energies of 900 mJ at 2050 nm from a pulsed, room-temperature, normal-mode Co:MgF$_2$ laser, with average powers as high as 6.5 W. Over the range 1800 to 2450 nm we have obtained pulse energies of at least 100 mJ.

The demonstration of Co:MgF$_2$ laser operation with the crystal at or near room temperature[1] has opened up the possible use of the laser in applications outside the laboratory.[2,3] The upper-state lifetime of the Co:MgF$_2$ laser transition decreases rapidly with increasing temperature because of thermally activated multiphonon relaxation. All the initial studies of the Co:MgF$_2$ system were made with the crystal cooled to cryogenic temperatures, to maintain lifetimes in the millisecond range,[4,5] but efficient pulsed operation can be obtained at room temperature if the pump source is a normal-mode 1318-nm Nd:YAG laser with a sufficiently short pulse duration. In the first reported room-temperature experiments the Co:MgF$_2$ laser output energies were imited to 70 mJ by the available energy from the pump laser.[1] In the research presented here we have developed a new pump source to characterize operation of the device at higher pump energies. The result is an increase in the room-temperature Co:MgF$_2$ laser output energy by more than an order of magnitude.

The Co:MgF$_2$ laser system discussed is shown schematically in Fig. 1. The 1318-nm pump laser was a single oscillator that employed two 6.4 mm × 101 mm 1%-doped Nd:YAG rods placed in series in a folded-resonator arrangement. Each rod was excited by a single, 89-mm discharge-length, xenon flash lamp and was enclosed with the lamp in a flooded, close-coupled pump cavity with silver reflectors. As determined experimentally, a samarium-doped glass filter placed between each rod and lamp significantly increased the 1318-nm performance, presumably by reducing pump-cavity-assisted amplified spontaneous emission. The end faces of one rod were antireflection coated at 1064 nm, and those of the other at 1318 nm.

The pump-laser resonator consisted of one flat 1318-nm highly reflecting mirror (M1), two flat, highly reflecting fold mirrors (M2, M3), and a flat 50% reflectivity output coupler (M4); the total physical length of the resonator was 79 cm. The resonator–mirror coatings were highly transmissive at 1064-nm to prevent oscillation at that higher-gain transition. Each lamp was driven by a semiconductor-switched power supply, which permitted continuous control of the lamp pulse widths over the range 80–500 μs. At total lamp energies as high as 100 J the Nd:YAG laser slope efficiency was 2%, but it was reduced at higher lamp energies, possibly because of amplified spontaneous emission. With 100-μs-duration pulses we were able to obtain, at 1–2-Hz pulse rates, 2.7 J of multimode output energy at a total lamp energy of 200 J, where for 200-μs pulses we could generate 5 J of output energy with 390 J of lamp energy. Because of thermal lensing in the laser rods we did observe an increase in the pump-laser beam divergence with increasing lamp average power, which led to a variation in the beam size focused in the Co:MgF$_2$ crystal.

The longitudinally pumped Co:MgF$_2$ laser consisted of a 50-cm radius-of-curvature concave highly reflecting mirror (M7) through which the pump energy passed, a Co:MgF$_2$ crystal, and a 50-cm radius-of-curvature output coupler (M8). The laser medium, mounted on a thermoelectric cooler to hold the temperature of the crystal fixed near room temperature, had a 6.4 mm × 6.4 mm cross section and was 30 mm long. The crystal had Brewster-angled end faces cut for the σ-polarization state. This orientation was chosen for its higher peak gain cross-section value (11×10^{-22} for σ versus 5×10^{-22} for π). The resonator mirror spacing was 49 cm, the crystal was placed 7.5 cm from M7, and, unless otherwise noted, the output coupler had 5% transmission (T). We employed two flat highly reflecting mirrors (M5, M6) and a 12.5-cm focal-length, plano–convex lens to direct and focus the pump-laser output into the crystal. At all but the highest pump energies the focused beam was small enough in area to excite only the Co:MgF$_2$ resonator TEM$_{00}$ spatial mode, which is calculated to have a 0.045-cm beam radius in the laser crystal.

As shown in the 5%-T input–output data of Fig. 2, pumping with 2.7 J of energy (measured between M5 and M6) yielded 900 mJ of output in the 2050-nm wavelength region, at a 2-Hz pulse rate, with a pump-lamp pulse width of 100 μs and a nominal crystal temperature of 282 K. The absolute optical-to-optical conversion efficiency was 33%, and the input–output relation was essentially linear up to the maximum available pump energy. The Co:MgF$_2$ laser output remained diffraction limited up to 700 mJ of output energy and was less than twice diffraction limited above that. The output was linearly polarized

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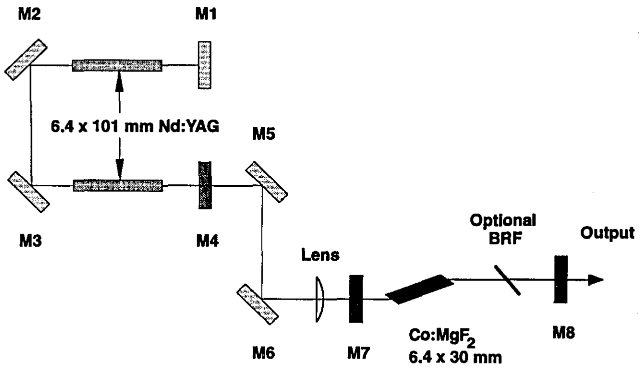

Fig. 1. Optical schematic of the Co:MgF$_2$ laser system. BRF, birefringent filter.

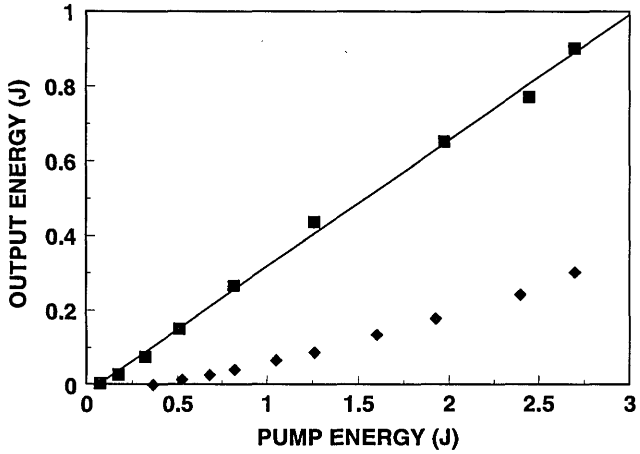

Fig. 2. Normal-mode input–output data for 5%-*T* (■) and 40%-*T* (◆) output mirrors, with a linear (33.6% slope, 60-mJ threshold) fit to the 5%-*T* data.

at all energies. No damage to the laser crystal was observed at full energy, and only slight damage to the coatings on mirror M7 was observed after operation at full energy for several minutes. Slope efficiencies were similar for 80- and 100-μs lamp pulse widths but were reduced by 20% for 150- and 200-μs widths. The actual fraction of energy absorbed by the laser crystal was 73% of the amount shown in Fig. 2, and thus the absorbed energy slope efficiency was 45%, or 70% of the theoretical quantum defect. We observed that the laser threshold for a 100-μs-duration pump pulse was reduced by half when we changed the output mirror to a unit with a *T* of 2%, a result consistent with an intracavity round-trip loss of 1%. This low level of loss contributed to the high observed efficiencies.

We were able to generate as much as 6.5 W of average-power output at 2050 nm from the Co:MgF$_2$ laser at a pulse rate of 9 Hz and at a pump energy of 2.7 J. Operation at higher pulse rates and average powers was not possible because of capacity limits in both the Co:MgF$_2$ crystal cooler and the flash-lamp drivers.

We inserted a 0.61-mm-thick, Brewster-angle, birefringent filter into the Co:MgF$_2$ cavity to tune the laser. With three sets of cavity mirrors we were able to tune over the range 1730–2450 nm, and obtain at least 100 mJ of output energy over the range 1800–2450 nm, for 1.4 J of pump energy. The mirror sets used for the short- and long-wavelength regions had output couplers with only 2% *T*, and thus laser performance away from the center of the tuning range was not optimized for maximum energy output.

The small gain cross section of the Co:MgF$_2$ laser transition leads to a large laser saturation fluence, of the order of 100 J/cm^2. In preparation for *Q*-switching experiments we replaced the 5%-*T* output coupler with a 40%-*T* mirror, to reduce the intracavity fluence level for a given output energy. The laser threshold increased to 365 mJ, but, unexpectedly, the input–output data (Fig. 2) were nonlinear and showed reduced efficiency compared with data with the 5%-*T* mirror, with a slope efficiency of 8% near threshold that rose to 19% for pump energies above 1.6 J. With a Brewster-angle, fused-silica, acousto-optic *Q* switch inserted in the laser cavity and the high-transmission output coupler we generated single-pulse *Q*-switch energies of 20 mJ, with pulse durations of 55 ns at 2050 nm at a pump energy of 1.26 J. For the same pump energy we obtained 45 mJ of energy in normal-mode operation. Damage to mirror M7 precluded further investigation of *Q* switching.

In analyzing our data, we first considered the observed laser thresholds. Applying the rate-equation analysis of Ref. 6 and assuming a gain cross section of 1×10^{-21} cm^2, we predicted threshold with the 5%-*T* mirror to be 55 mJ, in the limit of a pump-beam area in the crystal small compared with that of the cavity mode. This is in good agreement with the threshold of 60 mJ estimated by extrapolation of the slope data in Fig. 2. For the 40%-*T* mirror we calculated a 370-mJ threshold, also in good accord with our experiments. The agreement is surprising given the low slope efficiency that we obtained with the mirror.

To understand better what might cause the reduced slope efficiency for the large output coupling we considered two effects, transient heating of the laser crystal and bleaching of the pump absorption. We estimated the magnitude of both effects, using an approximation that the pump-beam volume was equal to that of the cavity mode, an approach that places a crude lower bound on the results. Because of the low fluorescence quantum efficiency of the laser medium, we can assume that for pump levels below threshold all the pump energy is converted into heat. Our calculations of the single-shot heat rise in the crystal at 365 mJ of pump energy (the high-transition-mirror threshold energy) indicate an increase of the order of 10 K, based on a crystal heat capacity of 3.8 J/cm^3 K. Figure 3 plots our upper-state lifetime data versus temperature in the range 273–373 K, and from this we estimate that the lifetime for a crystal maintained at a steady-state temperature of 282 K would drop at least 20–25% from the beginning to the end of the pump pulse. At pump levels over threshold additional heating would occur, at a rate now set by the energy deficit between the pump and laser photons. For pump bleaching we calculate that, based on an absorption cross section of 3.6×10^{-21} cm^2,[5] the pump saturation fluence for Co:MgF$_2$ is 42 J/cm^2 and the corresponding 282-K saturation intensity

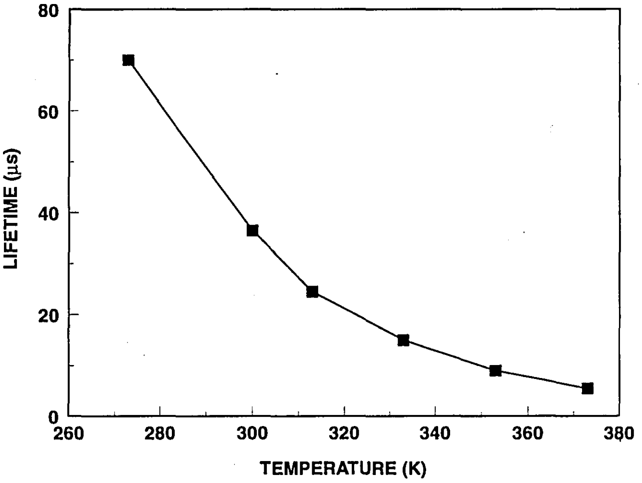

Fig. 3. Measured upper-state ($^4T_2$) lifetime of Co:MgF$_2$ versus temperature (■), with a piecewise linear fit.

is 0.7 MW/cm^2. We estimate that for 365 mJ of energy in 100 μs the pump intensity in the crystal would be at least 0.6 MW/cm^2, and thus bleaching of the pump transition would be an issue. For a more involved analysis of the performance of the Co:MgF$_2$ laser at high pump energies and output couplings we clearly need a laser model that includes transient heating and bleaching and considers the spatial as well as temporal aspects of pumping and laser action in the crystal.

The energy and average-power levels obtained by the Co:MgF$_2$ laser system studied here are sufficient for applications such as laser medicine and long-distance, non-range-resolved remote sensing. Significantly, we have yet to reach an energy or average-power limit set by fracture of the Co:MgF$_2$ crystal. To generate higher Q-switched outputs we would benefit from a more sophisticated design model for the laser as well as improvements in the damage thresholds for mirror coatings in the 2-μm wavelength region.

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