Room-temperature operation of a $Co{:}MgF_2$ laser

D. Welford and P. F. Moulton

Schwartz Electro-Optics Incorporated, 45 Winthrop Street, Concord, Massachusetts 01742

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A normal-mode, pulsed $Co{:}MgF_2$ laser has been operated at room temperature for the first time to our knowledge. Continuous tuning from 1750 to 2500 nm with pulse energies up to 70 mJ and 46% slope efficiency was obtained with a 1338-nm Nd:YAG pump laser.

The $Co{:}MgF_2$ laser is a continuously tunable source for the mid-IR covering the wavelength region of 1500–2400 nm. Laser operation was first demonstrated by Johnson *et al.*[1] using flash-lamp excitation. Later research by Moulton resulted in the development of both cw[2] and pulsed *Q*-switched[3] operation using laser excitation. However, to date, liquid-nitrogen[2,3] or thermoelectric[4] cooling has been required for efficient operation. In this Letter we report the first, to our knowledge, room-temperature, pulsed, normal-mode operation of the $Co{:}MgF_2$ laser using laser excitation. At a 10-Hz pulse-repetition rate, continuous tuning from 1750 to 2500 nm with pulse energies up to 70 mJ and 46% slope efficiency was obtained.

The $Co{:}MgF_2$ laser, shown schematically in Fig. 1, consisted of a 1338-nm Nd:YAG pump laser and the $Co{:}MgF_2$ laser. The 39-cm-long Nd:YAG laser cavity had a 2-m-radius high reflector and a flat 84% reflectivity output coupler. The centrally located 5-mm-diameter × 75-mm-long Nd:YAG laser rod was housed in a close-coupled, diffuse-reflector pump cavity with a 6.35-cm (2.5-in.) arc-length xenon flash lamp. Except as noted, the flash lamp was driven from a single-mesh ($C = 35\ \mu F$ and $L = 60\ \mu H$) pulse-forming network at a 10-Hz pulse-repetition rate, with the corresponding laser-pulse duration measured at 90 μsec FWHM intensity. An overall electrical-to-optical conversion efficiency of 1.15% was obtained for the pump laser.

The $Co{:}MgF_2$ laser resonator consisted of a pair of 50-cm-radius mirrors in a confocal arrangement, a Brewster-angled $Co{:}MgF_2$ crystal, and an optional single-plate birefringent tuning element. We used a 46-mm-long, nominally 1% doped $Co{:}MgF_2$ crystal that was cut for σ orientation (perpendicular to the crystal *c* axis) relative to the linear polarization of the resonator. The $Co{:}MgF_2$ laser crystal was longitudinally pumped through the high-reflectivity cavity mirror. A 125-cm focal-length biconvex lens was used to match the pumped crystal volume to the TEM_{00}-mode volume of the $Co{:}MgF_2$ cavity. Thus, the $Co{:}MgF_2$ laser operated in the TEM_{00} spatial mode, even though the pump beam was multimode, because only the TEM_{00}-mode volume of the $Co{:}MgF_2$ crystal was excited.

At room temperature (299 K) the $Co{:}MgF_2$ upper-state lifetime is 36.5 μsec, considerably shorter than the values of 1.65 msec with a liquid-nitrogen-cooled crystal and 210 μsec with two-stage thermoelectric cooling to 225 K. This reduction is almost entirely due to thermally induced nonradiative decay and prevents cw operation of the laser at all but cryogenic temperatures. Pulsed operation with a low and temperature-insensitive pump-energy threshold might be expected only if the duration of the pump pulse was kept shorter than the upper-state lifetime. In an experiment with a thermoelectrically cooled $Co{:}MgF_2$ laser pumped by the Nd:YAG system described above (90-μsec pulse duration), we anticipated that the $Co{:}MgF_2$ laser threshold would significantly increase with the cooler turned off. Yet this was not found to be the case. In further measurements, we observed that the room-temperature threshold did not increase in relation to the equivalent decrease in the upper-state lifetime. Both the threshold energy and slope efficiency were insensitive to the pump-pulse duration. Figure 2 shows a series of input–output curves for the untuned normal-mode $Co{:}MgF_2$ laser operating at 299 K with a 2% transmission output coupler, for FWHM pump-pulse durations that range from 25 to 160 μsec, obtained by changing the pump-laser pulse-forming network. The lasing wavelength was measured to be 2100 nm, and the laser emission bandwidth was approximately 50 nm.

The $Co{:}MgF_2$ laser input–output insensitivity to pump-pulse duration is a result of the particular shape of the pump pulse, which has a fast rise [Fig. 3(a)]. The inversion in the $Co{:}MgF_2$ gain medium builds to threshold in a time that is short compared with the

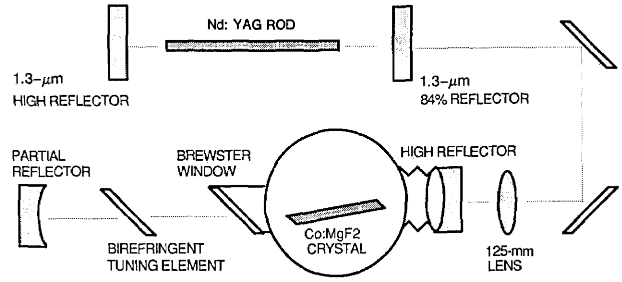

Fig. 1. Schematic diagram of the $Co{:}MgF_2$ laser.

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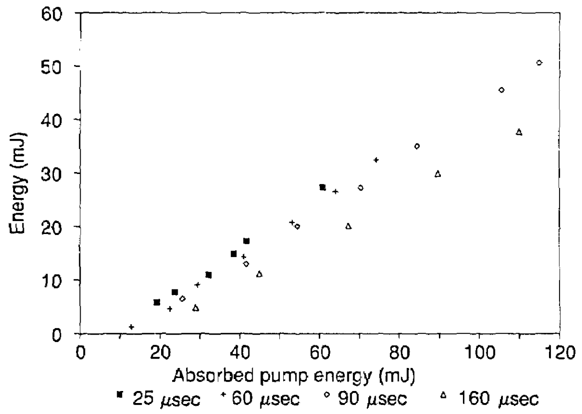

Fig. 2. Input–output data from untuned normal-mode $Co:MgF_2$ laser at 299 K as a function of the pump-pulse duration. The upper-state lifetime is 36.5 μsec.

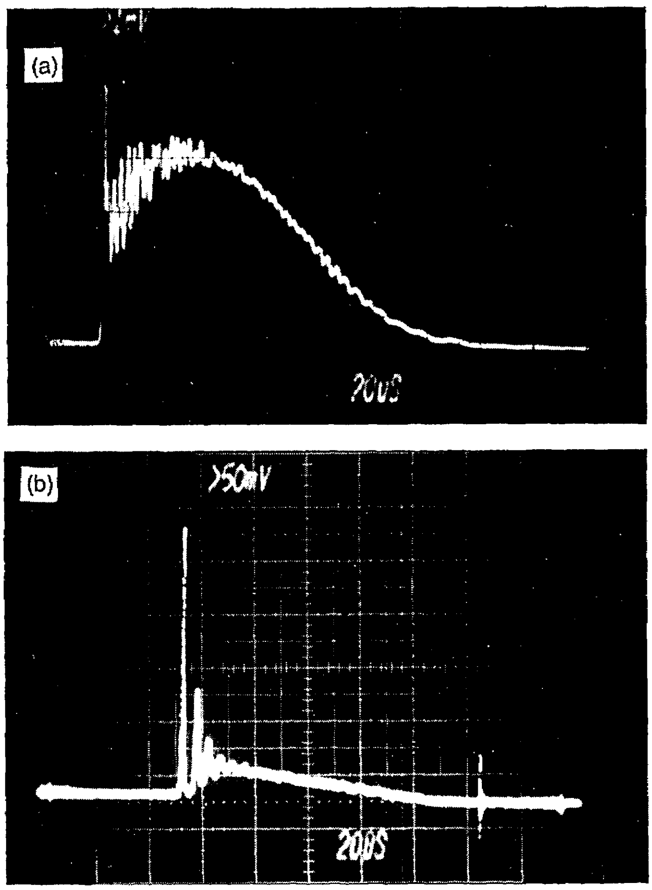

Fig. 3. (a) 211-mJ pump-pulse profile. (b) 10× threshold $Co:MgF_2$ laser pulse at 2.1 μm.

upper-state lifetime, and it is not significantly depleted by upper-state decay losses. The $Co:MgF_2$ laser is turned on by gain switching, with a characteristic spiked output [Fig. 3(b)] that may be described by a coupled rate-equation analysis.[3,5] The actual pump-pulse shape was used in a rate-equation model of $Co:MgF_2$ laser dynamics,[6] and the theoretical predictions of threshold versus pump-pulse width were in excellent agreement with the experimental data. In particular, the observed small (2×) difference in threshold between the 25- and 160-μsec-wide pump pulses was confirmed by the model. In contrast, models with a smooth, Gaussian-profile pulse show more than an order-of-magnitude increase in pump-energy threshold over the pulse width range of 25–160 μsec. Some reduction in slope efficiency is evident for the longer pump pulses as upper-state decay losses start to have a significant effect in the latter (quasi-cw) portion of the laser pulse.

The internal loss of the $Co:MgF_2$ laser determined from input–output data with different output couplers was less than our experimental-error limit of 0.5%. The estimated emission cross section at 2100 nm was 9×10^{22} cm^2 as determined from threshold data. At pumping energies greater than 200 mJ the output energy starts to fall below that expected from the thresholds and slopes obtained by fitting a linear input–output curve to the data. This effect is due to thermal lensing in the Nd:YAG pump laser, leading to an increased pump volume in the $Co:MgF_2$ crystal and less-efficient coupling of the pump volume to the TEM_{00}-mode volume of the $Co:MgF_2$ laser.

Tuning was accomplished with the addition of a 1.3-mm-thick Brewster-angled quartz birefringent plate with the c axis oriented 57° to the surface normal. This configuration provided continuous tuning with greater than 20-mJ energy from 1750 to 2500 nm, with three sets of mirrors, as shown in Fig. 4 for 211 mJ of absorbed pump energy. The addition of the tuning element produced negligible loss in output energy at the untuned lasing wavelength of 2100 nm and reduced the FWHM bandwidth to 3.5 nm. The tuning curve falls off at 1750 nm as a result of ground-state absorption and at 2500 nm as a result of increased mirror loss and reduced gain cross section.

The research of Barnes and Pollack[7] has indicated that thermal lensing in $Co:MgF_2$ should be small because the refractive-index variation with temperature is of the order of 1 part in 10^6 and the thermal conductivity is known to be large.[8] We have confirmed this

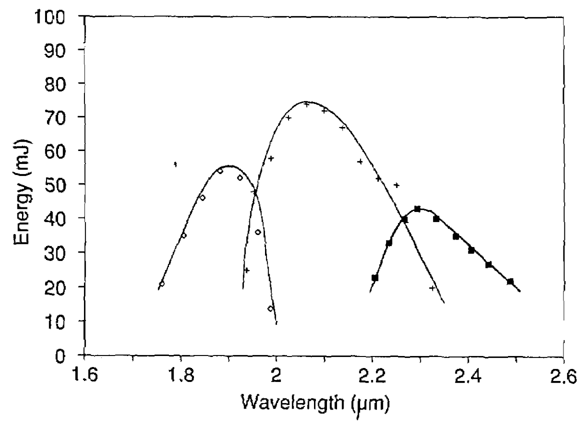

Fig. 4. Tuning curves (using three mirror sets with nominal 2% output coupling) at 299 K for normal-mode operation of the $Co:MgF_2$ laser at an absorbed pump-pulse energy of 211 mJ.

by measuring output-beam profiles of the Co:MgF_2 laser as a function of deposited pump-laser power. We observed, with a pyroelectric-detector array, the beam profile at the focal plane of a 1-m focal-length biconvex lens. The profiles were consistent with a TEM_{00} spatial mode having a full-width beam divergence of 4.3 mrad and remained unchanged for average deposited pump powers of 200 mW to 4 W. The predicted beam divergence for the resonator was 4.2 mrad, in excellent agreement with the measured value. Both the insensitivity of beam divergence to average pump power and the agreement between the calculated and measured values indicate negligible thermal lensing in Co:MgF_2.

Room-temperature operation of the Co:MgF_2 laser is significant for applications outside of a laboratory environment, where the need for cryogenic cooling can present major problems. One potential application is in remote sensing of gases such as H_2O, CO_2, CO, CH_4, N_2O, HF, HI, and NO_2. In addition, extension of the laser tuning range of 2550 nm is feasible and would be of interest for testing low-loss fluoride fibers.

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