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Diode-pumped Ho:Tm:YLF laser pumping an $AgGaSe_2$ parametric oscillator

Norman P. Barnes and Keith E. Murray

NASA Langley Research Center, Hampton, Virginia 23681

Mahendra G. Jani

Science and Technology Corporation, Hampton, Virginia 23666

Sarah R. Harrell

University of South Florida, Tampa, Florida 33620

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Tuning of both the pump laser, a Ho:Tm:YLF laser operating on the $^5I_7-^5I_8$ transition, and an $AgGaSe_2$ parametric oscillator has been demonstrated. Tuning of the Ho:Tm:YLF laser is complicated but not frustrated by the existence of both CO_2 and H_2O lines in the vicinity of the laser transition. Tuning of the parametric oscillator was achieved by tuning of the pump laser. Injection seeding of the parametric oscillator on the nonresonant signal was also demonstrated. In addition, the measured efficiencies of the parametric oscillator were compared for two different methods, measuring the parametric-oscillator output energy and measuring the energy depleted from the pump. By comparison of these measurements, the intrinsic efficiency of the parametric oscillator can be determined.

INTRODUCTION

Tuning of the parametric oscillator was achieved by tuning of the pump wavelength. Tuning of parametric oscillators is normally achieved by means of angular tuning of the nonlinear crystal or perhaps by temperature tuning. However, the first method can cause misalignment of the resonator if the parametric oscillator is within the stable resonator condition. Although the second method preserves alignment, it is a slow process. On the other hand, tuning of the pump wavelength can be fast and can obviate the problems associated with resonator misalignment.[1]

Tuning of the pump laser, in this case a Ho:Tm:YLF laser operating on the $^5I_7-^5I_8$ transition, was complicated by the presence of atmospheric absorption features of CO_2 and H_2O. While this complication was initially a nuisance, it demonstrates the capability of the Ho:Tm:YLF laser to measure atmospheric concentrations of these gases. Tuning of the parametric oscillator by tuning of the pump wavelength is of practical importance, since the Ho:Tm:YLF laser is tunable over a relatively wide spectral bandwidth for a lanthanide-series laser, and the tuning rate of the parametric oscillator is much greater than that of the pump laser.

Linewidth control of the parametric oscillator was achieved by injection seeding of the nonresonant signal. While injection seeding was demonstrated previously,[2–4] injection seeding in this case was accomplished by injecting a seed onto the nonresonant wavelength of the parametric oscillator, the signal in this case.

The intrinsic efficiency of the parametric oscillator can be determined by comparing the energy depleted from the pump with the parametric oscillator output energy. A ratio of the parametric oscillator output energy, multiplied by the ratio of the signal wavelength to the pump wavelength, to the energy depleted from the pump is a measure of the intrinsic efficiency of the parametric oscillator.

EXPERIMENTAL ARRANGEMENT

A room-temperature, diode-pumped Ho:Tm:YLF laser was étalon tuned and narrowed to provide the pump laser. Laser-diode pumping was provided by six six-bar laser-diode arrays arranged symmetrically around a Ho:Tm:YLF laser rod. Each laser-diode array was capable of producing a maximum of 360 W of peak power over a current pulse length of 1.0 ms. Laser-diode arrays with a peak emission wavelength of 0.792 μm were used to match the a axis absorption peak of Tm:YLF. Laser-diode arrays were arranged symmetrically around a 4.0-mm-diameter by 20-mm-long Ho:Tm:YLF laser rod. Concentrations of Ho and Tm were 0.005 and 0.040 atomic, respectively.

A 0.25-mm-thick étalon was used to effect both tuning and line narrowing of the pump laser. Reflectivity of the étalon was 0.27 per surface. A resonator consisting of a 5.0-m radius-of-curvature highly reflecting mirror and a 0.80-reflecting flat output coupler was used in these experiments. Q switching was effected with a fused-silica acousto-optic modulator. Since the pulse-evolution time interval of the laser output pulse is relatively long in low-gain systems, a relatively slowly opening Q switch is not a detriment.

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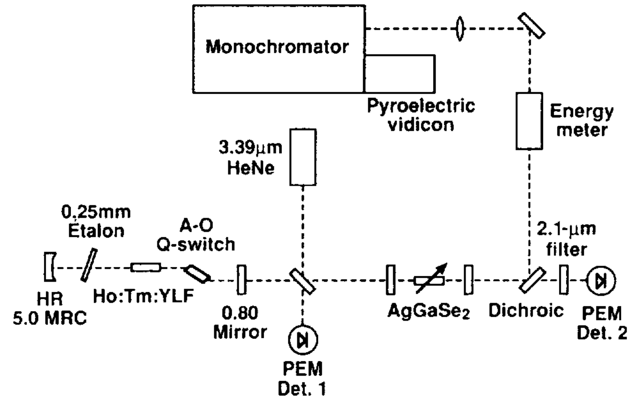

Fig. 1. Experimental arrangement. HR 5.0 MRC, highly reflecting 5.0-m radius-of-curvature mirror; A-O, acousto-optic modulator; PEM Det.'s, pyroelectric energy meter detectors.

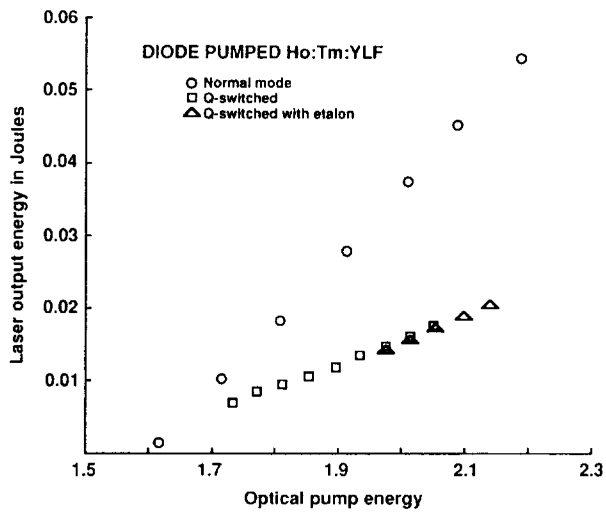

Fig. 2. Ho:Tm:YLF laser output energy versus optical pump energy from laser diodes.

An $AgGaSe_2$ crystal provided a sufficiently high gain to achieve satisfactory performance. The length of the nonlinear crystal was 25 mm, and the ends were polished and antireflection coated. The nonlinear crystal was cut so that the optic axis was 47.6° to the surface normal of the nonlinear crystal. Flat mirrors, coated to be highly reflective between 4.5 and 5.5 μm and antireflection coated for the pump wavelength, were used to form a resonator 40 mm in length. No lens was needed between the pump laser and the optical parametric oscillator.

Injection seeding was provided by a continuous-wave HeNe laser operating on the 3.39-μm transition. An optical schematic of the experimental arrangement appears in Fig. 1. Under normal conditions ~2.0 mW of power were available for seeding experiments in one or two longitudinal modes of the 3.39-μm laser. A dichroic mirror was used to combine the pump and the seed lasers into a collinear beam.

The diagnostics permit simultaneous measurement of the incident and the transmitted pump beams as well as the parametric-oscillator output energy. Two HgCdTe pyroelectromagnetic detectors sampled the pump beam before and after it transversed the parametric-oscillator resonator. Outputs of the HgCdTe detectors were recorded on a digital oscilloscope. Processing the output of the oscilloscope yielded the area under the detected pulses of the matched detectors, even with pulses distorted by pump depletion. Output energy from the parametric oscillator was also measured on a pyroelectric energy meter.

EXPERIMENTAL RESULTS

Even at room temperature the diode-pumped Ho:Tm:YLF laser demonstrated an optical-to-optical slope efficiency of nearly 0.1. The performance of the laser as a function of the optical pump energy is given in Fig. 2. Normal mode operation displayed a threshold energy of ~1.6 J and a slope efficiency of ~0.097 even though the laser was confined to operation on TEM_{00} modes. Little degradation in performance occurred when the étalon was inserted into the laser resonator. Maximum Q-switched laser output energy was limited by the capability of the laser-diode array and was slightly over 20 mJ for an optical pump energy of 2.14 J. The pump-pulse length varied from 151 ns at 13.3 mJ, roughly corresponding to the parametric-oscillator threshold, to 106 ns at the maximum output of 20.4 mJ.

Continuous tuning of the Ho:Tm:YLF laser was initially prevented by the existence of CO_2 and H_2O absorption features in the atmosphere. Measured tuning curves of the Ho:Tm:YLF laser appear in Fig. 3 along with the position of the atmospheric absorption lines. Also shown is the expected tuning curve of the 0.25-mm étalon as a function of the external angle. It may be noted that the observed tuning curve follows the predicted tuning curve only in broadly general terms. It appears that the observed wavelengths are clustered in regions of minimal atmospheric absorption. In a separate experiment

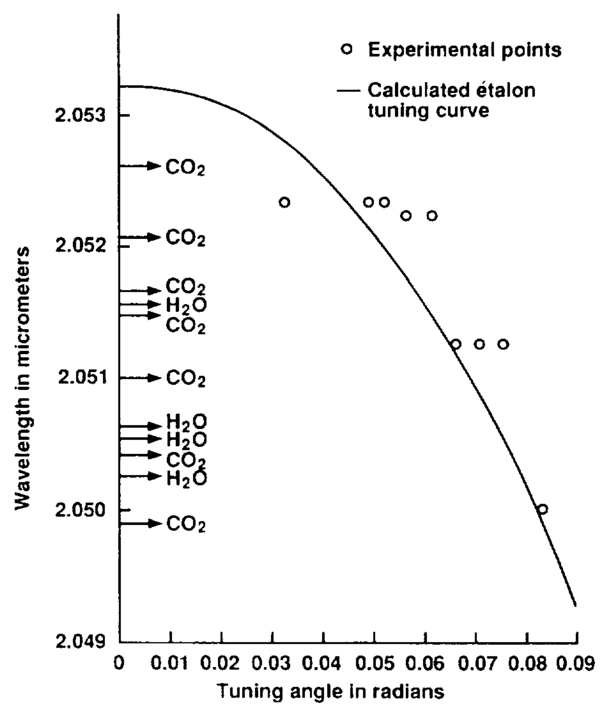

Fig. 3. Measured tuning curve of Ho:Tm:YLF laser, showing atmospheric absorption features and the expected étalon tuning curve.

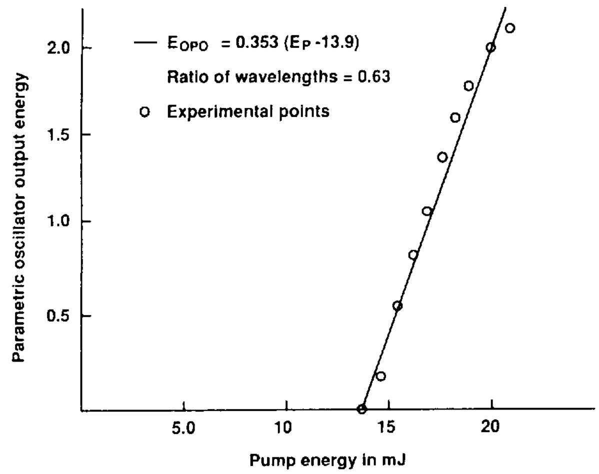

Fig. 4. Parametric-oscillator output energy versus pump energy (unseeded).

performed considerably later, with the Ho:Tm:YLF laser placed in a box purged with dry N_2, a continuous tuning curve could be obtained. Similar tuning curves were obtained for flash-lamp-pumped Ho:Tm:Er:YLF lasers at reduced temperatures.[5,6] Unfortunately programmatic considerations did not permit sufficient time to repeat the parametric-oscillator tuning experiment.

Even with no injection seeding a slope efficiency of 0.35 could be obtained from the parametric oscillator. Such performance is comparable with that of other $AgGaSe_2$ parametric oscillators[7–11] as well as that of $ZnGeP_2$ parametric oscillators.[12] With the parametric oscillator operating at 3.25 μm the output energy was recorded as a function of the pump energy, and the results are shown in Fig. 4. In this case the Ho:Tm:YLF laser was operating at 2.052 μm. The threshold for operation at this wavelength was ~14 mJ, and the slope efficiency was 0.35. The maximum slope efficiency would, of course, be limited by the ratio of the pump wavelength to the output wavelength, the signal in this case. For operation at 3.25 μm this ratio is ~0.63. The total optical efficiency of the parametric oscillator is approximately 0.1.

Operation of the parametric oscillator was limited to ~1.5 times threshold by the energy available from the diode-pumped Ho:Tm:YLF laser. The pump-beam radius was measured by a knife-edge technique to be 1.12 mm. At maximum pump energy this corresponds to an energy density of 1.04 J/cm^2. While laser-induced damage was not a serious problem, no systematic study of the laser-induced damage threshold was undertaken. Focusing was not used, which avoided this problem.

The efficiency of the parametric oscillator can be obtained by measurement of either the parametric-oscillator output energy or the energy depleted from the transmitted pump beam with two matched detectors sampling the pump beam before and after it transverses the parametric-oscillator resonator. The integrated area under the observed pulses can be plotted as a function of the pump energy. The integrated area for detector 1, the detector that samples the pump before it transverses the parametric-oscillator resonator, is directly proportional to the pump energy. The integrated area for detector 2, the detector that samples the pump after it transverses the parametric-oscillator resonator, exhibits a direct relationship only below the parametric-oscillator threshold. Above threshold the area no longer displays a direct relationship.

The parametric-oscillator output energy correlates well with the depletion of the transmitted pump energy. Since both a signal and an idler photon are generated, but only the signal photon energy is measured, the measured parametric-oscillator output energy can be multiplied by the ratio of the signal wavelength to the pump wavelength for comparison. Depletion of the pump energy can be determined by use of the direct relation between the integrated area from detector 2 and the transmitted pump energy. Pump energy can be determined by use of the integrated area from detector 1.

The slope of the direct relationship between the parametric-oscillator output energy and the energy depleted from the pump indicates that the intrinsic efficiency of the parametric oscillator is somewhat higher than is inferred from a measurement of the parametric-oscillator output energy. Measured parametric-oscillator

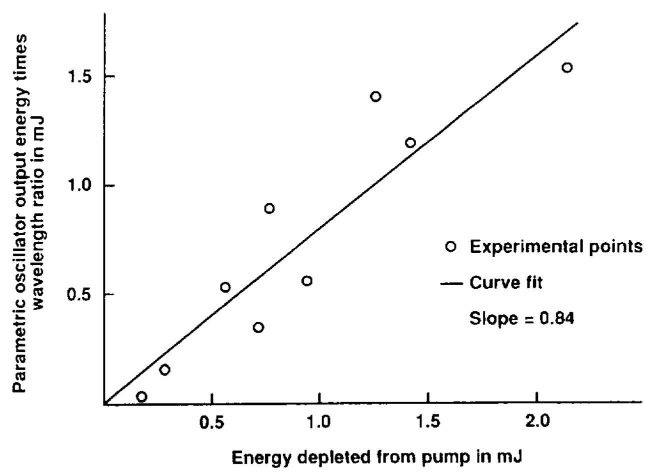

Fig. 5. Correlation of the parametric oscillator output energy with the energy depleted from the pump energy.

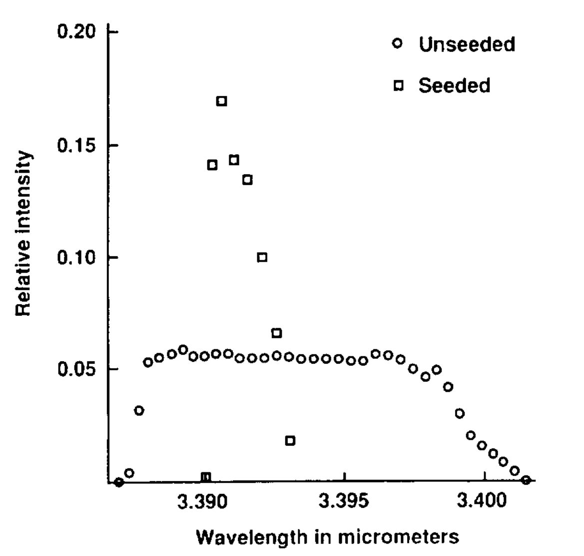

Fig. 6. Unseeded and seeded relative output from the parametric oscillator.

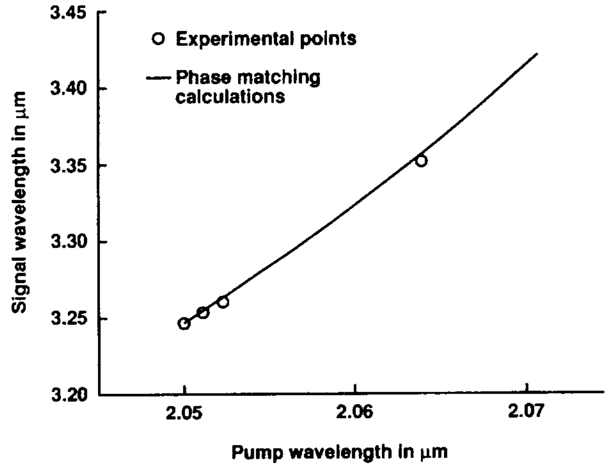

Fig. 7. Measured and observed wavelength of the signal versus the pump wavelength. The results of the detailed phase-matching calculations rather than the linear approximation are shown.

output energy scaled by the ratio of signal-to-pump wavelengths is plotted versus the energy depleted from the pump beam in Fig. 5. The slope of the curve is 0.84 rather than 1.0. As is expected, some of the signal energy is lost through absorption in the nonlinear crystal and through less than unity transmission through the parametric-oscillator mirror. Thus the intrinsic efficiency of this particular device is a factor of ~1.19 higher than is inferred from the measured energy.

Seeding of the parametric oscillator on the nonresonant signal was demonstrated by observation of the spectral line narrowing concomitant with the introduction of the 3.39-μm seed beam. For these experiments the angle of the $AgGaSe_2$ crystal was adjusted for generation of a 3.39-μm signal. Spectral properties of the output of the parametric oscillator were measured with a monochromator with a pyroelectric vidicon replacing the output slits. A 0.5-m Ebert monochromator with a 300-g/mm grating was used for these experiments. Output slits were removed and replaced with a pyroelectric vidicon with a resolution element size of 63 μm in the horizontal dimension. The input slit width was also set at 63 μm to match the size of the resolution element of the pyroelectric vidicon. The output of the pyroelectric vidicon could be read out element by element. The results of this procedure are plotted in Fig. 6 for both seeded and unseeded operation.

At the highest pump energy, ~1.5 times threshold, the parametric oscillator achieved significant conversion near the peak of the pump pulse. When the parametric oscillator was seeded, significant conversion was achieved somewhat earlier. More detailed information on the temporal effects of seeding is presented elsewhere.[4]

Seeding the parametric oscillator reduced the spectral bandwidth from 0.011 to 0.002 μm. If seeding is not employed, the spectral output is nearly constant over the spectral bandwidth. Care was taken to ensure that the pyroelectric vidicon was not saturated during measurement. When approximately 2.0 mW of 3.39-μm radiation was introduced to the parametric oscillator collinear with the pump beam, the spectral bandwidth decreased to ~0.002 μm. As such the parametric oscillator has a measured spectral bandwidth commensurate with the measured spectral bandwidth of the pump laser.

Tuning of the parametric oscillator by tuning of the pump has been demonstrated. When the angle and the temperature of the nonlinear crystal are held fixed but the pump wavelength is varied, the signal and the idler wavelengths adjust themselves to minimize the phase mismatch. Thus tuning the pump laser will cause a concomitant change in the signal wavelength. Variation of the signal wavelength with a varying pump wavelength is shown in Fig. 7. As can be seen, a relatively small change in the pump wavelength can cause a significantly larger change in the signal wavelength. Differences between the observed tuning rate and the linear tuning rate, calculated above, can be ascribed to the slight curvature noticeable in the figure. As noted previously,[13] a linear approximation of the phase-matching condition is not necessarily a good approximation in the mid-infrared.

SUMMARY

Tuning of the Ho:Tm:YLF laser has been demonstrated in the near infrared and is found to depend on atmospheric absorption. However, with a purged box, atmospheric absorption effects can be mitigated. With this laser as a pump, an $AgGaSe_2$ parametric oscillator achieved a threshold of 14 mJ and a slope efficiency of 0.35 when operating at 3.25 μm. Parametric-oscillator efficiency was determined by measurement of the parametric-oscillator output energy at the nonresonant wavelength and by measurement of the energy depleted from the transmitted pump beam. From a comparison of these measurements, the intrinsic efficiency of the device was inferred.

Injection seeding was demonstrated by injection of the seed laser onto the nonresonant signal. When injection seeded, the measured spectral bandwidth decreased from 0.011 to 0.002 μm, which approaches the resolution limit of the measurement system. Tuning of the parametric oscillator was accomplished by tuning of the pump laser. A tuning rate of 7.9 was observed; that is, the signal wavelength tunes a factor of 7.9 times faster than the pump. A linear approximation to the tuning rate is 9.1. Differences between the observed tuning rate and the linearly approximated tuning rate can be resolved through a more detailed calculation of the conditions that satisfy the phase-matching conditions.

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