Single-frequency operation of a Cr:YAG laser from 1332 to 1554 nm

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We report the first demonstration to our knowledge of broadly tunable, single-frequency operation of a cw Cr:YAG laser. Single-frequency operation was obtained from 1332 to 1554 nm with a maximum output power of 680 mW generated at 1457 nm with 10% conversion efficiency of 1047-nm pump laser radiation. A traveling-wave ring resonator was forced to operate unidirectionally by use of Faraday rotation in the Cr:YAG gain medium with a nonplanar resonator alignment, providing the required compensating polarization rotation. Tuning was accomplished with a single-plate birefringent tuning element, and single-longitudinal-mode operation was obtained by the addition of a 9.5-mm-thick uncoated CaF_2 etalon. An instrument-limited single-frequency linewidth of 2.3 MHz was measured. © 2004 Optical Society of America

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1. INTRODUCTION

The Cr:YAG gain medium exhibits an unusually large gain bandwidth because of the strong vibronic interaction between the electronic levels of Cr^{4+} and the YAG host crystal, despite variations in the crystalline environment of individual Cr ions that may occupy different tetrahedrally coordinated lattice sites.[1,2] The presence of narrow zero-phonon lines in low-temperature fluorescence spectra confirms that the laser transition is essentially homogeneous in nature. The very fast relaxation times (picosecond or shorter) associated with such a strong interaction and the large density of phonon levels ensure that, except for perhaps intense subpicosecond pulses, the gain can also be considered temporally homogeneous. Previous experimental research to narrow the laser bandwidth showed negligible reduction in output power as the number of longitudinal resonator modes was substantially reduced.[1,2] Thus the elimination of spatial hole burning in a cw Cr:YAG laser should lead to efficient single-frequency operation.

In this paper we report the first demonstration to our knowledge of a broadly tunable, single-frequency, cw Cr:YAG laser[3] with a unidirectional ring laser geometry (shown in Fig. 1) similar to those employed in commercial single-frequency dye lasers or Ti:Al_2O_3 lasers. As in other laser-pumped lasers, the system is forced to operate in a single transverse mode by means of limiting the pumped region in the crystal to that capable of supporting only the TEM_{00} mode. An optical diode,[4] typically consisting of a length of Faraday rotator material in a magnetic field and a crystal quartz compensation plate, ensures that the ring laser operates in only one direction, with only a traveling wave in the cavity. With our Cr:YAG laser we used the integrated optical diode concept from the monolithic nonplanar ring oscillator laser[5] where the gain medium acts as the Faraday material and a nonplanar resonator alignment provides the required compensating polarization rotation. Tuning was accomplished with a single-plate quartz birefringent filter, and we used a solid etalon for residual longitudinal-mode rejection.

2. EXPERIMENTAL RESULTS

A. Laser Resonator

The resonator shown in Fig. 1 consisted of four mirrors in an *X* configuration and Brewster-angled intracavity elements, except for the intracavity etalon, to minimize loss. The etalon, which was operated at near-normal incidence, is essentially lossless at resonance transmission peaks. Two 10-cm radius of curvature mirrors, M1 and M2, on either side of the Cr:YAG crystal act as collimation and focusing optics and provide a beam waist in the laser crystal. The pump laser was a TEM_{00} mode, cw Nd:YLF laser[6] focused with a 10-cm focal-length plano–convex lens to match the 50 μm by 90 μm beam waist of the TEM_{00} mode in the Brewster-angled Cr:YAG crystal, thereby ensuring TEM_{00}-mode operation of the laser. Both the symmetric standing-wave resonator and the ring resonator had the same total length of approximately 100 cm.

In addition to acting as focusing mirrors, the two curved optics also correct for astigmatism[7] introduced by the presence of the Cr:YAG crystal. This was achieved by use of a 15.8° angle of incidence with a 2-cm-long Brewster-angled Cr:YAG crystal oriented with the pump and laser electric field vectors along the $\langle 100 \rangle$ direction. The pump laser small-signal transmission of the Cr:YAG crystal was 89%.

All the highly reflective optics had broadband coatings with reflectivities >99.5% from 1250 to 1600 nm. Several narrower-bandwidth output couplers with transmissions in the 0.5% to 1.75% range were used as described in Subsection 2.D. Our most efficient single-frequency

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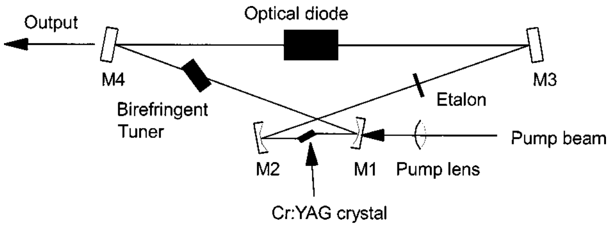

Fig. 1. Single-frequency Cr:YAG laser resonator.

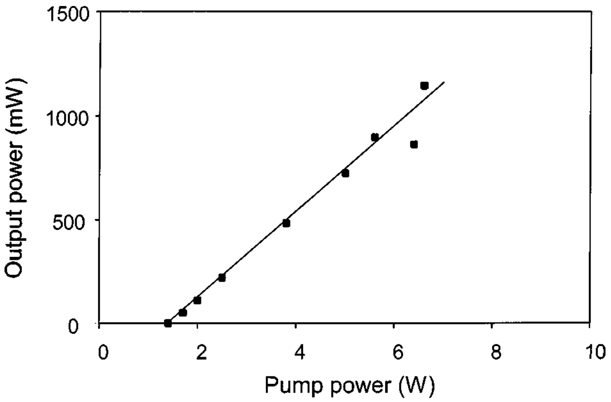

Fig. 2. Untuned Cr:YAG laser output data.

operation was obtained with the 0.5% output coupler. Continuous multimode (longitudinal, not spatial) output powers up to 1.2 W could be obtained with 6.6 W of pump power in an untuned linear resonator operating at approximately 1460 nm as shown in Fig. 2.

The elimination of stress-induced birefringence is critical to reliable and efficient laser operation because YAG is a cubic material with no natural birefringence to mask stress-induced birefringence and Cr:YAG is a low-gain laser material sensitive to small cavity losses, which is why we use Brewster-angled intracavity elements wherever possible. The laser output polarization was always linear with an extinction ratio >100:1. We did not observe any evidence of significant pump-induced bleaching[8] or polarization anisotropy,[1] which would lead to a saturation in output power with increasing pump power, in the Cr:YAG crystal as indicated by the linearity of the output data shown in Fig. 2. The Cr:YAG crystal was cooled with 20 °C water. It should also be noted that we operated the laser for over 500 h without observing any degradation in output power performance.

B. Laser Tuning

We tuned the standing-wave Cr:YAG laser by adding a 0.65-mm-thick, 35-deg cut single-plate quartz birefringent filter to the resonator in a Brewster-angled orientation and rotating the filter assembly about the intracavity beam axis.[9] We evaluated the laser tuning using output couplers with transmissions of 1.25% and 1.75% at 1460 nm and designed to operate over the 1350 to 1550-nm region as shown in Fig. 3. Usable output powers, limited by the output coupler bandwidths, were obtained from 1380 to 1540 nm. The maximum output power of 1.2 W (with 6.6 W of pump power) was the same as the untuned output power, within the accuracy of the measurement, which confirmed that the intracavity loss of the birefringent filter was negligible compared with the 0.1% transmission loss of each of the high-reflectivity mirrors. The laser wavelengths were measured to an accuracy of 0.1 nm with a Burleigh Wavemeter Jr., and the output powers were measured with a Coherent Model 210 optical powermeter.

Large regions of the Cr:YAG laser tuning range overlap with optical absorption in the atmosphere because of water vapor as illustrated in the absorption spectrum shown in Fig. 4. This spectrum was obtained from the U.S. Air Force HITRAN database for a 1-m-long path of air at 1 atm and a partial pressure of water vapor of 6 Torr at 296 K. As a result of the water-vapor absorption, there are wavelength regions through which the laser tuned discontinuously and jumped between several closely spaced wavelengths. Two- and three-plate birefringent filter elements significantly reduced this behavior, but introduced enough additional loss to noticeably reduce output power. Use of a simple intracavity etalon in the ring resonator removes the tendency of the laser to be spectrally unstable.

C. Unidirectional Ring Laser Operation

To obtain unidirectional operation of a ring laser requires differential loss between the two propagation directions. The most common approach is to use an optical diode with a Faraday material that, when placed in a magnetic field,

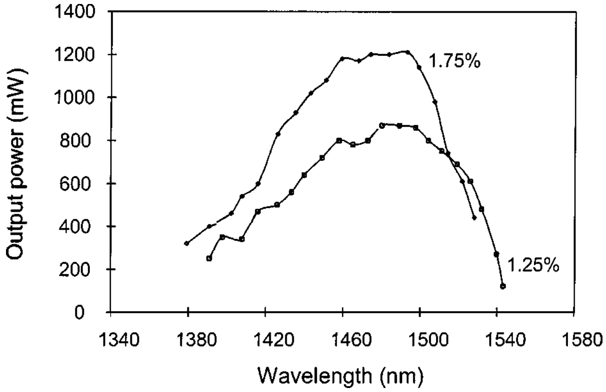

Fig. 3. Cr:YAG laser tuning data obtained with a single-plate birefringent filter. The percentage values next to each curve are the corresponding output coupler transmissions.

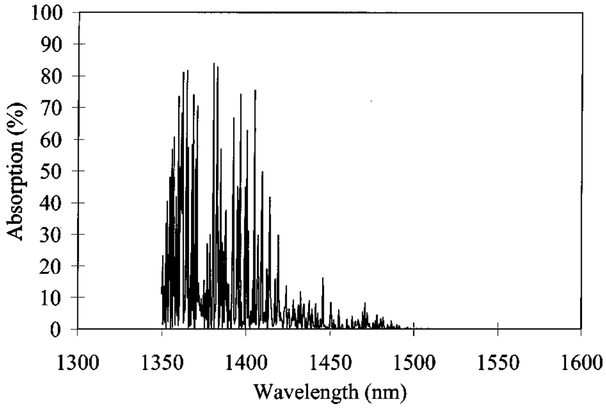

Fig. 4. Water-vapor absorption spectrum for a 1-m-long optical path at a 296 K partial pressure of 6 Torr.

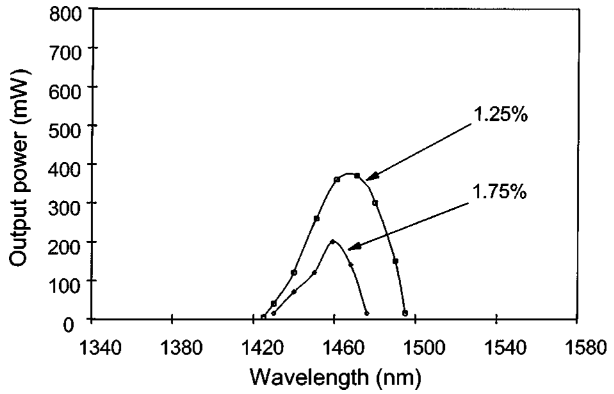

Fig. 5. Single-frequency Cr:YAG tuning curves with a fused-silica etalon in the laser resonator. The percentage values next to each curve are the corresponding output coupler transmissions.

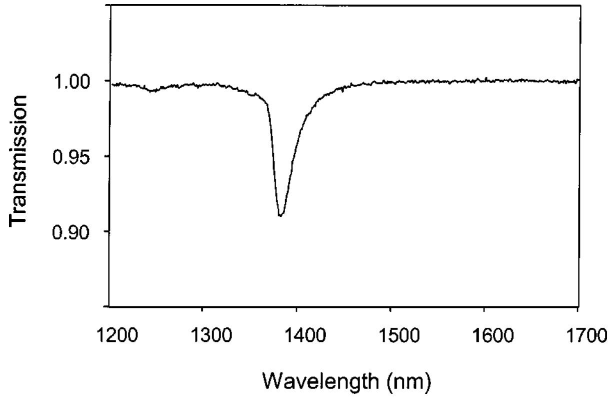

Fig. 6. Transmission of the 8-mm-thick uncoated fused-silica etalon.

introduces a nonreciprocal polarization rotation combined with a reciprocal polarization rotator such as an optically active material (e.g., quartz) and a polarization-sensitive loss mechanism (e.g., Brewster-angled interfaces).[4]

Candidate Faraday materials for the 1300–1600-nm region include bulk yttrium iron garnet, bismuth iron garnet thin films, or cerium-doped phosphate glasses. The most commonly used Faraday material, terbium gallium garnet, is not suitable for use at wavelengths longer than 1400 nm because of the onset of optical absorption.

We tried yttrium iron garnet, terbium gallium garnet and Cr:YAG crystals as Faraday rotators and used a nonplanar ring resonator design to provide the polarization counterrotation.[10] The yttrium iron garnet presented so much insertion loss that the laser would not operate. The terbium gallium garnet and the Cr:YAG both forced the resonator to operate unidirectionally, with Cr:YAG providing the lowest loss, which was further reduced by use of the laser crystal itself as the Faraday rotator in place of an additional crystal. A Nd:Fe:B ring magnet placed on top of the laser crystal heat sink provided the magnetic field. Rotating the magnet by 180° and realigning the resonator for the corresponding compensating polarization reversed the propagation direction of the laser.

Use of nonplanar resonator geometries in a ring configuration to rotate polarization is well understood and has been used in monolithic Nd:YAG nonplanar ring oscillator laser structures to obtain unidirectional operation in conjunction with the Faraday effect in the gain medium.[5] In a planar resonator composed of discrete elements in which one or more mirrors are tilted to form a second plane, the round-trip polarization rotation is equal to the angle between the two planes in the small-angle limit.[10] Referring to Fig. 1, we positioned the beam on mirror M3 to be higher than on the other mirrors such that the out-of-plane deflection was equal to the polarization rotation of the Faraday element. The net result was the formation of an ideally compensated optical diode. Experimentally this configuration can be adjusted during operation for maximum output power to optimize the optical diode compensation.

D. Single-Frequency Operation

The addition of a fused-silica etalon of an 8-mm thickness to the untuned unidirectional ring laser provided sufficient frequency selectivity that it operated in a single longitudinal mode. This finding implied that we should be able to tune the laser and maintain single-frequency operation by use of the single birefringent tuning plate used in the standing-wave laser and the etalon. Figure 5 shows single-frequency tuning data from 1430 to 1495 nm for this configuration. The longer wavelength limit was a result of overcoupling of the resonator as the Cr:YAG gain diminishes and was resolved by use of lower output coupling.

Comparison with our standing-wave-resonator tuning data indicated the onset of significant intracavity absorption below 1430 nm.[2] A transmission spectrum of the fused-silica etalon (see Fig. 6), obtained with a Perkin-Elmer Lambda 9 spectrophotometer, clearly indicated the presence of an OH^- absorption feature strong enough to extinguish the Cr:YAG laser below 1430 nm. We replaced the fused-silica etalon with a 9.5-mm-thick CaF_2 element; and using a 0.5% transmission output coupler, we obtained higher output powers and a broader tuning range as shown in Fig. 7. This tuning data is comparable to the standing-wave laser performance.

The laser tuned smoothly over the 1332–1515-nm range with unstable behavior and reduced output powers

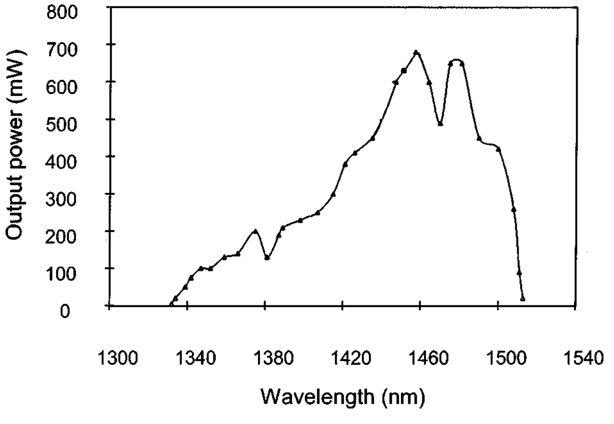

Fig. 7. Single-frequency Cr:YAG tuning curves with a CaF_2 etalon in the laser resonator and an output coupler transmission of 0.5%.

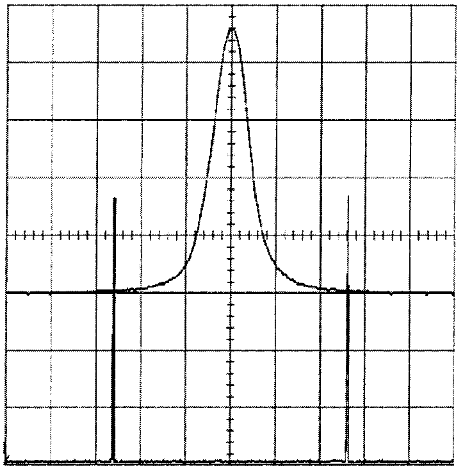

Fig. 8. Scanning Fabry–Perot interferometer output showing single-frequency operation of the Cr:YAG laser. The lower trace is a scan over approximately two free spectral ranges and shows two transmission peaks separated by 2 GHz. The upper trace is a 100 times expansion of the single laser longitudinal mode with an instrument-limited FWHM of 2.3 MHz.

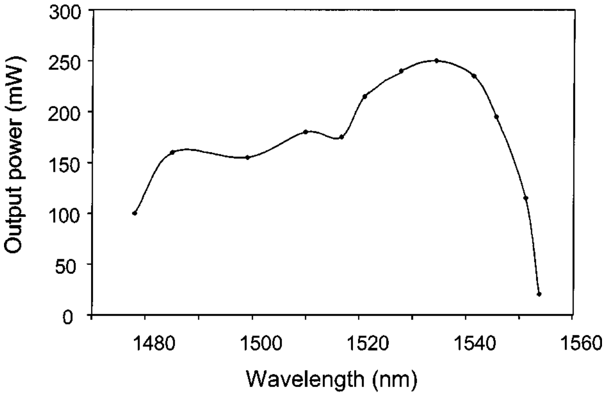

Fig. 9. Extended wavelength single-frequency Cr:YAG tuning curve with a CaF_2 etalon in the laser resonator and an output coupler transmission of 0.1%.

due to water-vapor absorption in the region near 1380 nm.[2] This effect can be removed by use of a sealed dry-nitrogen-purged enclosure. In addition, we recommend that an undoped-YAG etalon be used instead of the CaF_2 because it has a higher refractive index and hence a higher finesse, thereby improving its frequency selectivity.

The drop in output power in the region near 1470 nm is not due to water-vapor absorption, but is due to excited-state absorption of laser photons from the Cr^{4+} $^3T_2$ state and is an inherent characteristic of Cr:YAG. The laser excited-state absorption pathway requires resonance overlap between the $^3T_2$ and $^3T_1$ manifolds that according to our data appears to occur from 1460 to 1480 nm, which is consistent with the previously reported 1460–1500-nm range.[1]

A scanning Fabry–Perot interferometer (Burleigh, Model SA-Plus-200) was used to monitor and verify single-frequency operation. Figure 8 shows a typical interferometer spectral scan. The lower trace covers approximately two free spectral ranges and shows two transmission peaks separated by one free spectral range or 2 GHz. The upper trace is a 100 times expansion of a single longitudinal mode with an instrument-limited FWHM bandwidth of 2.3 MHz. The Schawlow–Townes linewidth[11] for the laser mode should be <1 kHz, but we expect resonator fluctuations to broaden the effective laser linewidth to a value approaching 1 MHz over a 1-s time interval. Longer-term drift due to temperature tuning of the resonator will be significantly larger in magnitude. No attempt was made to either passively or actively stabilize the laser, which was built with off-the-shelf mechanical components, and we did observe longitudinal-mode hops occurring more often when the laboratory was noisy as would be expected. Active stabilization of resonator length has enabled similar solid-state lasers to attain linewidths substantially less than 1 MHz.

We were not able to measure the output beam quality of the laser for lack of suitable instrumentation, but we were able to conclude from the consistency of scanning interferometer data as the output power was adjusted that the laser always oscillated in a single spatial mode, which we believe was the TEM_{00} mode.

The long-wavelength tuning limit shown in Fig. 7 is due to increasing output coupling loss. The high-reflectivity mirrors each have approximately 0.1% transmission from 1300 to 1600 nm. We estimated that the laser could tolerate only 0.1–0.3% output coupling for longer wavelength operation with the current high reflectors. Figure 9 shows the single-frequency tuning curve obtained with a 0.1% transmission output coupler with lasing out to 1554 nm with up to 250 mW in output power at 1534 nm. This optic was a narrow-bandwidth optical parametric oscillator mirror that did not allow laser operation below 1478 nm. The three high-reflectors all had approximately 0.1% transmission. Hence the total output power from all four resonator mirrors was approximately four times greater than the values shown in Fig. 9 that were measured at the 0.1% output coupler, which is consistent with the data shown in Fig. 7. Improved high reflectors with <0.05% transmission should enable single-frequency operation of the Cr:YAG laser beyond 1600 nm (laser operation from 1335 to 1635 nm with unspecified output powers was reported by Naumov *et al.*[12] when a high reflector was used as the output coupler) with >1-W output powers from 1440 to 1540 nm.

3. CONCLUSION

We have demonstrated broadly tunable, single-frequency operation of a cw Cr:YAG laser from 1332 to 1554 nm with output powers as high as 680 mW at 1457 nm. The low-gain cross section of Cr:YAG places severe restrictions on the allowable total intracavity loss, which requires novel low-loss solutions to spectral control of the laser. However, the low gain provides the benefit that the differential loss required between longitudinal modes at different wavelengths within the laser gain bandwidth (to ensure single-frequency operation at any desired wavelength) is less than would be required in high-gain systems such as dyes or titanium sapphire. Hence we needed only a single-plate birefringent tuning element, a low-finesse uncoated CaF_2 etalon, and a low-differential-loss optical diode. The optical diode used the Faraday effect of the gain medium itself to reduce the intracavity component count, and we eliminated the need for a quartz compensation plate by use of an out-of-plane resonator alignment. In effect, the optical diode introduced no additional losses to the resonator for the forward direction, while introducing sufficient loss to the backward direction to ensure unidirectional operation.

This reseach was developed with the aim of developing a broadly tunable, single-frequency seed source for use with near- to mid-IR optical parametric oscillators (OPO) used in spectroscopic and remote sensing applications. In some cases this role can be fulfilled with diode lasers over a limited wavelength range.[13] However, the higher powers available from the Cr:YAG laser described here are beneficial to injection seed a pulsed OPO because the instantaneous parametric generation process and small number of resonator round trips do not readily allow for spectral control at lower seed powers. The idler tuning range of a signal wavelength seeded, 1047-nm pumped OPO operating from 1332 to 1554 nm, i.e., the Cr:YAG laser tuning range, is 4893–3209 nm.

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