Broadly tunable continuous-wave solid-state red source based on intracavity-doubled Cr^{4+} :forsterite laser

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ABSTRACT

This work describes the development and characterization of a continuous-wave (cw) room-temperature intracavity-doubled Cr^{4+} :forsterite laser which produces broadly tunable red radiation. Such a source is potentially important in spectroscopy, display technologies, and medical applications. In the experiments, a 2-cm-long Cr^{4+} :forsterite crystal was placed in an astigmatically compensated x-cavity which was end-pumped by a 1064-nm Nd:YAG laser. The crystal which had a small-signal pump absorption of 68% was maintained at 20 °C. An intracavity Brewster-cut SF10 prism was used to tune the output of the laser. Intracavity frequency doubling was achieved by using a periodically poled lithium niobate (PPLN) crystal which had 8 different poling periods. The PPLN crystal was placed inside the resonator between a curved folding mirror and the curved output coupler. The transmission of the output coupler was 2.6% at 1260 nm. The PPLN temperature was maintained at 188 °C. By translating the PPLN crystal through sections with different poling periods, second harmonic generation was obtained in the wavelength region between 613 and 655 nm. With an incident pump power of 6.8 W at 1064 nm, the Cr^{4+} :forsterite laser produced 245 mW of cw output power at 1260 nm and intracavity frequency doubling yielded 45 mW at 630 nm.

Keywords: Solid-state lasers, tunable red lasers, Cr^{4+} :forsterite lasers, intracavity frequency doubling, second harmonic generation, frequency conversion, visible lasers, quasi phase matching, periodically poled lithium niobate.

1. INTRODUCTION

Many important applications such as photodynamic therapy, color displays, and spectroscopy require the use of robust, efficient laser sources which generate light in the orange-red (600-650 nm) region of the electromagnetic spectrum. Because this region cannot be directly accessed by the existing tunable solid-state lasers, various nonlinear conversion schemes have been proposed and utilized¹⁻². One of the most promising candidates for efficient broadly tunable yellow-red generation is the frequency-doubled Cr^{4+} :forsterite laser. With a tuning range extending from 1130 to 1370 nm, Cr^{4+} :forsterite laser has the potential of producing frequency-doubled output from 565 to 685 nm. To date, extensive experimental studies have been performed to investigate the characteristics of pulsed frequency doubling of this laser system in the femtosecond³⁻⁷ and nanosecond⁸⁻¹¹ time scales. In particular, Sennaroglu *et al.* reported the generation of femtosecond red pulses tunable between 605 and 635 nm by externally doubling the output of a regeneratively initiated self-mode-locked Cr^{4+} :forsterite laser in a LiIO_3 crystal³. In these experiments, the conversion efficiency was around 10%. Yanovsky and Wise used a femtosecond Cr^{4+} :forsterite laser to obtain as high as 53% conversion efficiency to 625 nm in an external resonant cavity that contained a barium metaborate crystal⁴. In the experiments reported by Liu *et al.*, single-pass conversion efficiency of 44% was demonstrated by using a LiB_3O_5 crystal to generate 50-fs red pulses⁵. In the nanosecond regime, McKinnie and Oien obtained broadly tunable red-yellow pulses tunable between 590 and 670 nm by external doubling of a gain-switched Cr^{4+} :forsterite laser in a KTP crystal⁸. The conversion efficiency was 7%. More recently, Diettrich *et al.* demonstrated the generation of up to 40 mW of broadly tunable yellow-red output between 590 and 670 nm from a gain-switched Cr^{4+} :forsterite laser by intracavity frequency doubling in a KTP crystal¹¹.

The present work describes the operation of a room-temperature, frequency-doubled Cr^{4+} :forsterite laser in the continuous-wave (cw) regime. Since the available power levels are significantly lower than those obtained in the

pulsed mode, intracavity frequency doubling was employed to increase the conversion efficiency. In the experiments, a 2-cm-long periodically poled lithium niobate (PPLN) crystal was used. By using gratings with different poling periods, broadly tunable orange-red output could be obtained between 613 and 655 nm. At a wavelength of 630 nm, as high as 45 mW of cw output power was obtained. To the author's knowledge, this represents the highest second harmonic power obtained with a Cr^{4+} :forsterite laser in the cw regime. The results of the numerical optimization studies further indicated that a 14-fold increase in efficiency should result by optimizing the focusing inside the PPLN crystal and by stabilizing the fundamental output wavelength of the Cr^{4+} :forsterite laser.

2. EXPERIMENTAL SETUP

Figure 1 shows the experimental setup of the intracavity frequency-doubled Cr^{4+} :forsterite laser. The gain medium was a 20-mm-long, Brewster-cut Cr^{4+} :forsterite crystal with a small-signal differential absorption coefficient of 0.6 cm^{-1} and a crystal figure of merit FOM ($FOM = \alpha_{1064}/\alpha_{1260}$, where α_{1064} and α_{1260} are the respective small-signal absorption coefficients at the pump and laser wavelengths of 1064 nm and 1260 nm, respectively) of 26. The crystal was maintained at 20°C by closed-loop thermoelectric cooling. The Cr^{4+} :forsterite crystal was positioned between two concave high reflectors (M1 and M2 in Fig. 1) inside a modified x-cavity. The high reflectors M1 and M2, each of which had a radius of curvature of 10 cm, were separated by 12 cm. The laser resonator had approximately equal arm lengths which were folded by about 30 degrees to compensate for astigmatism. The total cavity length was 128 cm. The resonator arm with the end high reflector (M3) contained a Brewster-cut SF-10 prism for tuning the laser output. The second arm was folded by a curved high reflector (M4, radius of curvature = 10 cm) and terminated by a curved output coupler (M5, radius of curvature = 10 cm). The transmission of the output coupler was 2.6% at 1260 nm. The Cr^{4+} :forsterite laser was end pumped by a cw 1064-nm Nd:YAG laser (Quantronix model 116) through M1 which transmitted 91% of the pump. A telescope consisting of two 5-cm focal length lenses (L1 and L2) and a focusing lens L3 (focal length=10 cm) were used to optimize the mode matching between the pump and the laser cavities. With a knife-edge, the waist of the focused pump beam was measured to be $36 \mu\text{m}$. An attenuator consisting of a half-wave plate (W1) and a polarizing beam splitter (PBS) varied the pump power level during efficiency measurements. A second half-wave plate (W2) was used to optimize the polarization direction of the pump electric field. In the experiments, the pump polarization was parallel to the b-axis of the Cr^{4+} :forsterite crystal.

Fig. 1: Experimental setup of the intracavity frequency-doubled Cr^{4+} :forsterite laser.

The 20-mm-long PPLN sample (PPLN in Fig. 1) which had a cross sectional area of $0.5\text{mm} \times 5\text{mm}$, contained 8 different gratings with periods that ranged from 9.6 to $12.4 \mu\text{m}$ in $0.4\text{-}\mu\text{m}$ increments. Each grating had a width of

450 μm . The PPLN sample was normal cut and antireflection coated around the fundamental as well as the second harmonic wavelengths. It was gently clamped between two aluminum plates and maintained at temperatures above 140 $^{\circ}\text{C}$ by resistive heating. The sample temperature was monitored with a thermocouple connected to the aluminum holder. The PPLN sample was positioned between the mirrors M4 and M5 which were separated by approximately 16 cm. This particular cavity design with the curved output coupler provided ample space to translate the PPLN sample while optimizing the frequency-doubled output. Gaussian analysis of the resonator gave a calculated 114- μm beam waist for the resonating 1.26- μm fundamental beam inside the PPLN crystal.

3. RESULTS

After lasing was obtained, the cw power performance of the laser was initially optimized without the PPLN crystal in the resonator. The fundamental wavelength was monitored with a scanning spectrometer (Rees, model E202 LSA) which had a resolution of 0.4 nm. In the free running mode, the laser output was at 1.26 μm . With the SF-10 prism, smooth tuning could be obtained between 1.20 to 1.32 μm . After the PPLN sample was placed inside the resonator, second harmonic output was obtained in two beams which exited the resonator through the mirrors M4 and M5. The wavelength-dependent transmission of these mirrors was taken into account in order to determine the actual second harmonic power. Typically, the output spectrum of the Cr^{4+} :forsterite laser contained multiple oscillating modes around the fundamental wavelength with a total spread (FWHM) of approximately 1 nm and a wavelength jitter of ± 0.5 nm. This was attributed to thermal effects inside the Cr^{4+} :forsterite gain medium and possible nonlinear wave mixing in the PPLN crystal. Most stable operation was obtained for PPLN temperatures above 140 $^{\circ}\text{C}$. Even in this temperature range, second harmonic power fluctuations of $\pm 10\%$ were observed mainly due to the wavelength jitter of the fundamental output.

Fig. 2: Variation of the fundamental (1260 nm) and second-harmonic (630 nm) output power of the intracavity frequency-doubled Cr^{4+} :forsterite laser as a function of the incident pump power.

Figure 2 shows the power efficiency curves for the intracavity frequency-doubled Cr^{4+} :forsterite laser. Lasing was obtained at an incident threshold pump power of 2.9 W. At an incident pump power of 6.8 W, the resonator produced 245 mW of output power at the fundamental wavelength of 1.26 μm , corresponding to a circulating intracavity power of 9.42 W. In order to determine the insertion loss due to the PPLN and the tuning prism, the power performance of the intracavity-doubled Cr^{4+} :forsterite laser was compared with that of a similar setup where the resonator had a flat output coupler with 2.4% transmission at 1.26 μm . In the latter case, the incident threshold pump power was 2.35 W. The round-trip loss of the Cr^{4+} :forsterite crystal was independently measured to be 8.4% at the lasing wavelength. By assuming that the threshold pump power is proportional to the total round-trip loss due to the intracavity elements and output coupler transmission, the added insertion loss due to the PPLN, tuning prism and the folding mirror M4 was estimated to be 3.7%. Most of this loss was due to the PPLN. As can be seen from Fig. 2, at the

fundamental power of 245 mW, a total second harmonic power of 45 mW was obtained at 630 nm. This represents 18 % conversion of the laser output power to its second harmonic. In these measurements, the temperature of the PPLN sample was maintained at 188 °C and the grating with the 10.8-μm poling period was used.

By keeping the crystal temperature at 188 °C and the incident pump power at 6.4W, the PPLN was translated to allow the passage of the fundamental beam through gratings with different periods. By simultaneously rotating the high reflector mirror M3, the laser was tuned to the wavelength that gave the highest quasi-phase-matched second harmonic output at each grating. Quasi-phase-matched second harmonic generation could be obtained with six gratings having the periods of 10, 10.4, 10.8, 11.2, 11.6, and 12 μm. For example, 8.2 mW was obtained at 613 nm by using the grating with the 10-μm period. Similarly, the grating with the 12-μm period gave 3.6 mW at 655 nm. The resulting tuning curve for the second harmonic output is displayed in Fig. 3. Broadly tunable output could be produced between 613 and 655 nm at the PPLN temperature of 188 °C. Note that at a given PPLN temperature, quasi-phase-matched second harmonic generation was obtained at 6 particular wavelengths. Other wavelengths between 613 and 655 nm could be accessed by changing the temperature of the PPLN crystal.

Fig. 3: Tuning curve for the intracavity frequency-doubled Cr⁴⁺:forsterite laser at the PPLN temperature of 188 °C.

4. COMPARISON WITH THEORY

At the incident pump power of 6.8 W, corresponding to a fundamental intracavity power of 9.42 W, 45 mW of second harmonic power was obtained corresponding to a single-pass conversion efficiency of 0.24%. In this section, we compare this measured conversion efficiency with theoretical predictions. For a focused gaussian beam, the power conversion efficiency $P_{2\omega}/P_{\omega}$ (P_{ω} =power at the fundamental wavelength, $P_{2\omega}$ =second harmonic power) of second harmonic generation can be calculated from¹²

$$\frac{P_{2\omega}}{P_{\omega}} = \frac{16\pi^2}{\lambda_0^3} \eta_0 \frac{(d_{eff})^2}{n_{\omega}^2 n_{2\omega}} L h_m(B, \xi) P_{\omega} G(\lambda_0), \quad (1)$$

where λ_0 is the center wavelength, η_0 is the vacuum impedance, n_ω and $n_{2\omega}$ are the respective values of the refractive index at the fundamental and second harmonic wavelengths, d_{eff} is the effective nonlinear coefficient of the medium, and L is the crystal length. For first-order quasi phase matching in PPLN, d_{eff} can be calculated from¹³

$$d_{eff} = \frac{2d_{33}}{\pi}, \quad (2)$$

where $d_{33}=19.5$ pm/V¹⁴ around 1.3 μm . By using Eq. (2), d_{eff} becomes 12.4 pm/V.

Table 1: Names, symbols, units, and values of the parameters used in the second harmonic efficiency calculations.

Name of the Parameter	Symbol	Unit	Value
Fundamental center wavelength	λ_0	nm	1259
Vacuum impedance	η_0	Ω	377
Refractive index at the fundamental wavelength	n_ω	1	2.155
Refractive index at the second harmonic wavelength	$n_{2\omega}$	1	2.214
Length of the nonlinear crystal	L	cm	2
Effective nonlinear coefficient of the crystal	d_{eff}	pm/V	12.4
Normalized walk-off parameter	B	1	0
Fundamental beam waist inside the PPLN crystal	ω_0	μm	114
Normalized focusing parameter	ξ	1	0.14
Grating period	Λ	μm	10.8
PPLN temperature	T	$^\circ\text{C}$	188
Beam walk-off and non-optimal focusing correction	$h_m(B, \xi)$	1	0.15
Intracavity fundamental power	P_ω	W	9.42
Acceptance bandwidth of the PPLN crystal	$\Delta\lambda$	nm	0.21
Spectral width of the fundamental beam	$\Delta\lambda_L$	nm	1
Correction due to finite acceptance bandwidth of PPLN	$G(\lambda_0)$	1	0.21
Calculated second harmonic conversion efficiency	$P_{2\omega}/P_\omega$	1	0.0027

The parameter $h_m(B, \xi)$ accounts for the reduction in efficiency resulting from walk-off and non-optimum focusing effects. In this case, we take the normalized walk-off parameter B to be 0. The normalized focusing parameter ξ is given by

$$\xi = \frac{L\lambda_0}{2n_\omega\pi\omega_0^2}, \quad (3)$$

where ω_0 is the beam waist inside the nonlinear crystal. Table 1 lists the names, symbols, units, and values of the parameters that were used in the second harmonic efficiency calculations (Note that the unit of dimensionless parameters is designated as “1” in Table 1). By using these values, ξ is evaluated to be 0.14, giving $h_m(0, 0.14) \sim 0.15$ (see Fig. 2 in Ref. 12).

In Eq. (1), $G(\lambda_0)$ accounts for the limitations arising from the finite phase matching bandwidth of the second harmonic crystal. For quasi-phase-matched second harmonic generation, the acceptance bandwidth $\Delta\lambda$ (FWHM) of the nonlinear crystal is given by¹³

$$\Delta\lambda = \frac{0.4429\lambda_0}{L} \left| \frac{n_{2\omega} - n_\omega}{\lambda_0} + \frac{\partial n_\omega}{\partial \lambda} - \frac{1}{2} \frac{\partial n_{2\omega}}{\partial \lambda} \right|^{-1}. \quad (4)$$

By using the temperature-dependent Sellmeier equation for PPLN¹⁵, $\Delta\lambda$ was calculated to be 0.21 nm, suggesting that further reduction in efficiency resulted since the laser spectral bandwidth was approximately 1 nm. $G(\lambda_0)$ was estimated from

$$G(\lambda_0) = \int_0^\infty d\lambda \left(\frac{\lambda_0}{\lambda} \right)^3 F(\lambda) \rho(\lambda), \quad (5)$$

where $\rho(\lambda)$ is the normalized spectral power distribution of the fundamental beam about the center wavelength. $\rho(\lambda)$ was approximated as a normalized gaussian distribution:

$$\rho(\lambda) = \sqrt{\frac{4 \ln 2}{\pi (\Delta\lambda_L)^2}} \exp \left[-\frac{4 \ln 2 (\lambda - \lambda_0)^2}{(\Delta\lambda_L)^2} \right]. \quad (6)$$

In Eq. (6), $\Delta\lambda_L$ is the spectral linewidth (FWHM) of the fundamental beam. The phase matching function $F(\lambda)$ appearing in Eq. (5) is further given by

$$F(\lambda) = \sin^2 \left[\frac{\Delta k L}{2} \right], \quad (7)$$

where the wave vector mismatch Δk between the fundamental and the second harmonic waves can be calculated by using

$$\Delta k = \frac{4\pi}{\lambda} (n_{2\omega} - n_\omega) - \frac{2\pi}{\Lambda}. \quad (8)$$

In Eq. (8), Λ is the grating period. In general Δk is a function of temperature T , wavelength λ , and grating period Λ . Efficient quasi-phase-matched second harmonic generation will take place at any combination of T , λ , and Λ for which $\Delta k=0$. Note that in this particular case ($T=188^\circ\text{C}$ and $\Lambda=10.8\text{ }\mu\text{m}$), $\Delta k=0$ at $\lambda=1259\text{ nm}$. By using the temperature-dependent Sellmeier equation for PPLN, Δk can then be calculated as a function of λ at a fixed value of T and Λ . By using Eqs. (5)-(7) and the fixed parameter values given in Table 1, $G(\lambda_0)$ was calculated to be 0.21 giving a theoretical estimate of 0.27% for single-pass second harmonic conversion efficiency at $P_\omega=9.42\text{ W}$. This is in very good agreement with the experimentally measured value of 0.24%. The slight discrepancy may be attributed to misalignment effects and possible imperfections in the fabrication of the PPLN crystal.

As can be seen from Eq. (1), the second harmonic conversion efficiency can be further increased by optimizing the fundamental beam focusing inside the PPLN crystal and by improving the stabilization of the laser wavelength. Theoretically, optimum focusing is obtained for $\xi=2.84$, suggesting that, without changing the crystal length, a different cavity design can be used to reduce the fundamental beam waist inside the PPLN crystal to $26\text{ }\mu\text{m}$. In this case, $h_m(B, \xi)$ becomes 1, giving rise to an approximate 7-fold increase in efficiency. In addition, the spectral width of the fundamental beam can be reduced by using an intracavity tuning element with better wavelength selectivity such as a three-stage birefringent filter¹⁶. As an example, if the laser linewidth is reduced to 0.4 nm, $G(\lambda_0)$ becomes 0.47. If both improvements are achieved, the expected single-pass conversion efficiency will increase by a factor of 14 to 3.5%. This corresponds to a total second harmonic output of approximately 650 mW and a conversion efficiency of 9.5% from the 1064-nm pump to 630-nm red output. We note in passing that the optimum output coupler transmission of Cr^{4+} :forsterite lasers is around 6.4 %¹⁷. In other words, the round-trip loss due to the single-pass conversion efficiency of 3.5% will be comparable to the optimum output coupler transmission. This suggests that power performance comparable to what is reported here should be obtained from the Cr^{4+} :forsterite laser by replacing the output coupler with a high reflector.

5. CONCLUSIONS

In conclusion, this paper provided a detailed description of a cw room-temperature, intracavity frequency-doubled Cr⁴⁺:forsterite laser capable of producing broadly tunable orange-red radiation. At an incident 1064-nm pump power of 6.8W, as high as 45 mW of output power was obtained at 630 nm. Frequency conversion was achieved with a 2-cm-long PPLN crystal. By using gratings with different periods, tunable orange-red output was generated between 613 and 655 nm. At the maximum intracavity fundamental power of 9.42W, a conversion efficiency of 0.24% was obtained. The experimentally measured second harmonic generation efficiency is in very good agreement with the predictions of the theoretical model that takes into account the limitations resulting from non-optimal focusing and the finite acceptance bandwidth of the nonlinear crystal. Simulations further suggest that a 14-fold increase in single-pass conversion efficiency should be possible by optimizing the focusing inside the PPLN crystal and by reducing the spectral width of the fundamental beam.

ACKNOWLEDGMENTS

This project was supported by the Turkish Academy of Sciences.

REFERENCES

1. H. Scheife, T. Sandrock, E. Heumann, and G. Huber, "Pr, Yb-doped upconversion fibre exceeding 1W of continuous-wave output in the red spectral range," in *OSA TOPS on Advanced Solid-State lasers*, vol. 10, Clifford R. Pollock and Walter R. Bosenberg, eds., (Optical Society of America, Washington, DC), pp. 79-82, 1997.
2. W. R. Bosenberg, J. I. Alexander, L. E. Myers, and R. W. Wallace, "2.5W, continuous-wave, 629 nm solid-state laser source," in *OSA TOPS on Advanced Solid-State lasers*, vol. 19, Walter R. Bosenberg and Martin M. Fejer, eds., (Optical Society of America, Washington, DC), pp. 68-71, 1998.
3. A. Sennaroglu, C. R. Pollock, and H. Nathel, "Generation of tunable femtosecond pulses in the 1.21-1.27 micron and 605-635 nanometer wavelength region by using a regeneratively initiated self-mode-locked Cr:forsterite laser," *IEEE J. Quantum Electron.* **30**, pp. 1851-1861, 1994.
4. V. P. Yanovsky, and F. W. Wise "Frequency doubling of 100-fs pulses with 50% efficiency by use of a resonant enhancement cavity," *Opt. Lett.* **19**, pp. 1952-1954, 1994.
5. X. Liu, L. Qian, and F. W. Wise, "Efficient generation of 50-fs red pulses by frequency doubling in LiB₃O₅," *Opt. Commun.* **144**, pp. 265-268, 1997.
6. J. M. Evans, V. Petricevic, R. R. Alfano, Q. Fu, "Kilohertz Cr:forsterite regenerative amplifier," *Opt. Lett.* **23**, pp. 1692-1694, 1998.
7. T-M Liu, S-P Tai, and C-K Sun, "Intracavity frequency-doubled femtosecond Cr⁴⁺:forsterite laser," *Appl. Opt.* **40**, pp. 1957-1960, 2001.
8. I T. McKinnie, A. L. Oien, "Tunable red-yellow laser based on second harmonic generation of Cr:forsterite in KTP," *Opt. Commun.* **141**, pp. 157-161, 1997.
9. S. M. Giffin and I. T. McKinnie, "Tunable visible solid-state lasers based on intracavity frequency doubling of Cr:forsterite in KTP," *Opt. Lett.* **24**, pp. 884-886, 1999.
10. N. Zhavoronkov, V. Petrov, and F. Noack, "Powerful and tunable operation of a 1-2-kHz repetition-rate gain-switched Cr:forsterite laser and its frequency doubling," *Appl. Opt.* **38**, pp. 3285-3293, 1999.

11. J. C. Diettrich, I. T. McKinnie, and D. M. Warrington, "Tunable high-repetition-rate visible solid-state lasers based on intracavity frequency doubling of Cr:forsterite," *IEEE J. Quantum Electron.* **35**, pp. 1718-1723, 1999.
12. G. D. Boyd and D. A. Kleinman, "Parametric interaction of focused gaussian light beams," *J. Appl. Phys.* **39**, pp. 3597-3639, 1968.
13. M. M. Fejer, G. A. Magel, D. H. Jundt, and R. L. Byer, "Quasi-phase-matched second harmonic generation: tuning and tolerances," *IEEE J. Quantum Electron.* **28**, pp. 2631-2654, 1992.
14. I. Shoji, T. Kondo, A. Kitamoto, M. Shirane, and R. Ito, "Absolute scale of second-order nonlinear-optical coefficients," *J. Opt. Soc. Am. B* **14**, pp. 2268-2294, 1997.
15. D. H. Jundt, "Temperature-dependent Sellmeier equation for the index of refraction, n_e , in congruent lithium niobate," *Opt. Lett.* **22**, pp. 1553-1555, 1997.
16. D. R. Preuss and J. L. Gole, "Three-stage birefringent filter tuning smoothly over the visible region: theoretical treatment and experimental design," *Appl. Opt.* **19**, pp. 702-710, 1980.
17. A. Sennaroglu, "Optimum crystal parameters for room-temperature Cr⁴⁺:forsterite lasers: experiment and theory," *Opt. Commun.* **174**, pp. 215-222, 2000.

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