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All-solid-state continuous-wave tunable blue-light source by intracavity doubling of a diode-pumped Cr:LiSAF laser

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We describe a diode-pumped cw $\text{Cr}^{3+}:\text{LiSrAlF}_6$ laser that produces 190-mW cw output at 860 nm. By frequency doubling in a KNbO_3 crystal we generate 13 mW of second-harmonic light tunable from 427 to 443 nm.

Compact and efficient all-solid-state lasers emitting in the blue-green wavelength range are desired for many applications, such as optical data storage, undersea communications, spectroscopy, and medical applications. Many solutions exist for developing a blue laser source. Direct frequency doubling of GaAlAs laser-diode radiation^{1,2} is well suited to the 420–430-nm spectral range, for which laser-diode sources are commercially available. Longer blue wavelengths are generated by frequency mixing of a Nd:YAG laser at 1064 nm, with a laser diode at a fixed wavelength in the range 800–860 nm.³ By intracavity doubling of a Nd:YAG laser operating at 946 nm⁴ it is also possible to generate blue light at 473 nm. These sources have a high doubling efficiency, but they are not tunable.

Compact sources generating tunable blue light could be particularly useful for spectroscopic experiments. One possibility is an intracavity-doubled Ti:sapphire laser,⁵ but this solution requires a cumbersome and expensive Ar-ion pump laser. To solve this problem, one could use a new solid-state material such as $\text{Cr}^{3+}:\text{LiSrAlF}_6$ (Cr:LiSAF) because it can be diode pumped. A tunable blue-light source by intracavity frequency doubling of a Cr:LiSAF laser was reported previously,⁶ but in that study the pump source was a cw Kr-ion laser emitting in the red wavelengths.

In this Letter we describe an all-solid-state continuously tunable blue source using an intracavity-frequency-doubled cw Cr:LiSAF laser.

The Cr:LiSAF crystal was discovered in 1989 by Payne *et al.* at the Lawrence Livermore National Laboratory.⁷ It has an absorption band in the red between 600 and 700 nm and can be pumped by red laser diodes.⁸ Its large fluorescence bandwidth leads to tunable laser emission between 750 and 1000 nm,⁹ and blue-light generation is thus possible by second-harmonic generation in a nonlinear crystal. We used a KNbO_3 crystal cut for noncritical phase matching at 860 nm at room temperature. This crystal is the most efficient frequency converter for the 800–900-nm wavelength range¹⁰ and, in fact, has a figure of merit 60 times higher than that of KTP.¹¹ For the sake of

simplicity we have decided to use intracavity doubling as opposed to frequency doubling in an external resonant cavity, which would require a phase control loop.

The Cr:LiSAF crystal, from Lightning Optical Corporation, was doped with a Cr^{3+} concentration of 3% by weight, and the absorption was 98% of the pump power. The crystal was plano-Brewster cut, and the central path was 3 mm. To pump this Cr:LiSAF crystal, we used two different single-stripe GaAlInP laser diodes with an emitting wavelength of 670 nm. The first one came from Spectra Diode Laboratories (SDL; Model 7432) and produced 500 mW of cw output power for a 1.06-A driving current. The emitting area was $250 \mu\text{m} \times 1 \mu\text{m}$. The second diode was produced by Applied Optonics (AO), with an output power of 400 mW for a driving current of 0.8 A and an emitting area of $100 \mu\text{m} \times 1 \mu\text{m}$. The pump optics are presented in Fig. 1. A first objective ($f = 15 \text{ mm}$; N.A., 0.6) collimated the diode beam. Then a cylindrical afocal system with a magnification of 6 modified the beam in the direction parallel to the junction of the diode. Depending on the diode, we used two different objectives to focus the beam into the laser crystal. For the SDL diode we used an objective with a short focal length ($f = 50 \text{ mm}$; N.A., 0.5) in order to have a spot size of $140 \mu\text{m}$ in the crystal. Because of the short working distance of this objective we had to pump the crystal on its plane face. For the other diode, because of its smaller emitting area, it was possible to use an objective with a longer focal length

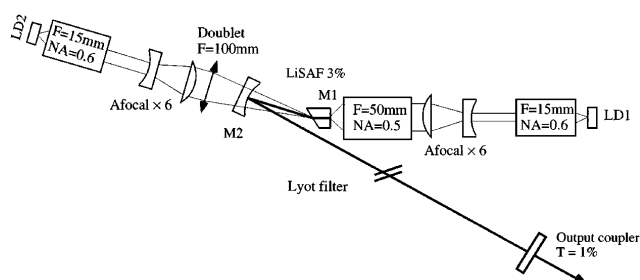


Fig. 1. Experimental setup. LD1, SDL diode; LD2, AO diode.

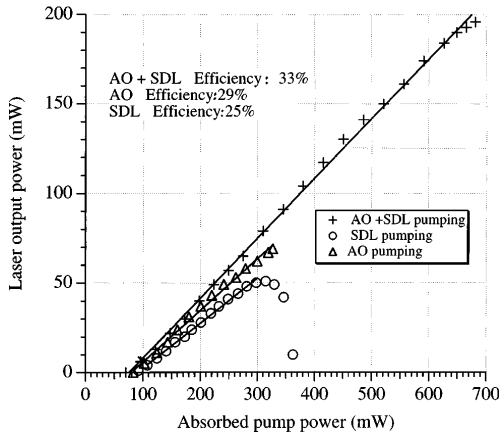


Fig. 2. Output power versus absorbed pump power in cw operation for the fundamental.

($f = 100$ mm, doublet) for almost the same spot size, and thus the crystal could be pumped by the Brewster face through a mirror cavity. When the transmission of the reshaping optics is taken into account, the total absorbed pump power was 680 mW.

The cavity consisted of three mirrors. The first, M1 (highly reflective for 760–960 nm, antireflective for 670 nm) was directly coated on the Cr:LiSAF crystal. The second, M2, was a curved mirror (highly reflective for 800–900 nm) with a radius of curvature of 150 mm. The third was a plane output coupler with 1% transmission between 800 and 900 nm. The laser cavity configuration produced a collimated beam between the curved mirror and the output coupler, making it possible to add intracavity components such as a birefringent filter.

With this cavity we obtained a power of 190 mW at 860 nm, in a purely cw regime, for 680 mW of absorbed pump power and with a threshold of 80 mW (Fig. 2). The slope efficiency η_s was 33%. We obtained this curve by increasing the power of the two diodes simultaneously and found that pumping on both sides was more efficient than pumping on one side (Fig. 2). A first explanation could be as follows: By measuring the spot sizes at the focus point with a CCD camera for the two diodes we found a spot of $10 \mu\text{m} \times 140 \mu\text{m}$ for the SDL diode, compared with $30 \mu\text{m} \times 110 \mu\text{m}$ for the AO diode (the difference in the direction perpendicular to the junction is due to aberrations introduced by the doublet). Upconversion losses^{???} or thermal effects such as the decrease of lifetime with temperature are locally more important for the SDL diode than for the AO diode. This fact could explain the difference of efficiencies observed in Fig. 2. In particular, we calculated that upconversion losses, which are proportional to the square of excited-state population density N , were approximately ten times higher for the SDL diode on the axis of the laser at the focus point. The laser output roll-off that occurred with the SDL diode and that vanished with pumping on both sides could be explained by a decrease of N induced by laser operation with AO diode pumping.

To compare the performance of this diode-pumped laser with that of a Kr-pumped Cr:LiSAF laser, we calculated the intrinsic slope efficiency η_0 (Ref. ???):

$$\eta_0 = \eta_s(T + L)/T, \quad (1)$$

where T is the transmission of the output coupler and L represents the passive losses per round trip. L was determined from the analysis of Findlay and Clay^{???} and was found to be equal to 0.7%. We obtained an intrinsic slope efficiency of 56%, which is close to that obtained with a Kr-pumped Cr:LiSAF laser (53%, as reported in Ref. ???). The laser output was linearly polarized parallel to the c axis of the crystal. With the Lyot filter inserted in the cavity we achieved tunability from 800 to 920 nm with a maximum output of 180 mW in the range 850–880 nm.

We therefore modified the laser configuration (Fig. 3) and introduced a 5-mm-long KNbO₃ crystal at the focal point of a second cavity formed by two concave mirrors (M3 and M4). The radius of curvature (100 mm) of these mirrors was chosen so that the Rayleigh length was equal to the KNbO₃ crystal length. The spot size of the fundamental wavelength in the crystal was calculated to be $70 \mu\text{m}$. The two mirrors had a high reflectivity between 800 and 900 nm and a transmission of 90% in the blue range. The KNbO₃ crystal was also antireflection coated at both the fundamental and second-harmonic wavelengths to minimize the insertion losses (round-trip losses <1.5%). The crystal was cut for noncritical phase matching at 860 nm and a temperature of 20 °C. In this case we achieved tunability by changing the temperature of the doubling crystal. To perform this, we put the KNbO₃ on a copper plate whose temperature was controlled by a Peltier element and an analog temperature controller. This system permitted tuning over the range 10–80 °C, corresponding to the 427–443-nm wavelength range.

Including both outputs passing through the two curved mirrors M3 and M4, we obtained a power $P_{2\omega}$ for the second harmonic of 13 mW for a pump power of 680 mW, leading to an optical–optical efficiency of 2%. The laser threshold was 100 mW of absorbed pump power. We tuned the blue emission wavelength by simultaneously adjusting the birefringent filter to vary the fundamental wavelength and modifying the temperature of the KNbO₃ crystal to preserve the phase-matching conditions. We observed blue-light generation between 427 and 443 nm with no decrease of the output power (Fig. ???). This can be explained in terms of the constant output power in this fundamental wavelength range. The stability of second-harmonic generation was tested for a period of 25 min, and we found a relative standard deviation

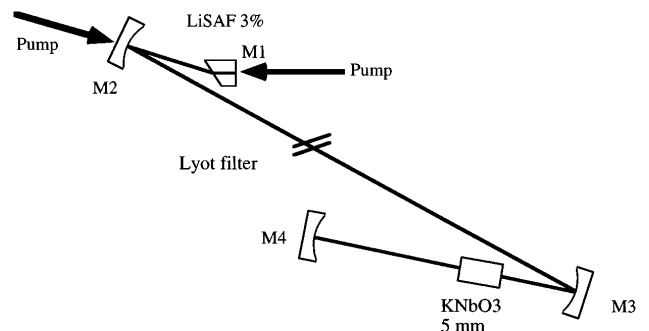


Fig. 3. Experimental setup for intracavity second-harmonic generation.

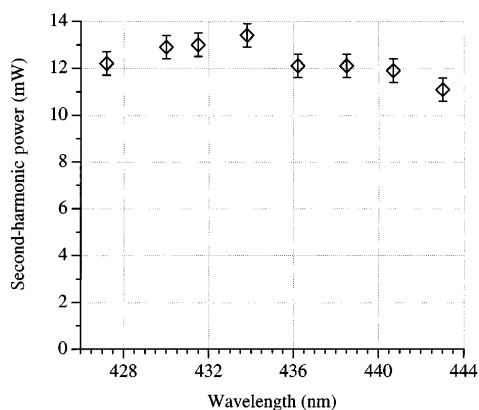


Fig. 4. Second-harmonic output power versus the wavelength.

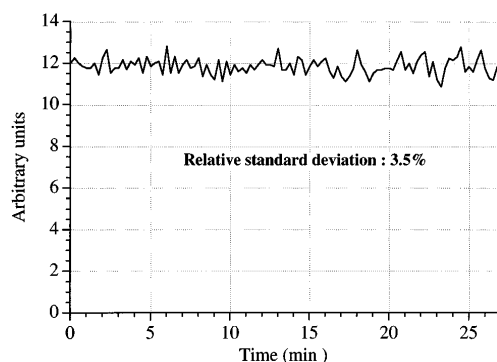


Fig. 5. Stability of the second-harmonic generation.

better than 3.5% (Fig. ???). The large number of axial modes (~ 2800) existing in the cavity could explain this relatively good stability. The signal-to-noise ratio (in amplitude) was ~ 30 dB in the 10 Hz–1 MHz region, the output beam was TEM_{00} , and the spectrum was 0.8 nm wide.

We also tested the laser performances in the gain-switched regime by switching the current of the laser diodes. In the fundamental wavelength we obtained pulses of 800 ns with an energy of $4 \mu\text{J}$ at a repetition rate as high as 14 kHz. By adding the doubling crystal we could observe pulses with a duration of 1 μs and an energy of $0.2 \mu\text{J}$ at a repetition rate of 14 kHz for the second-harmonic wavelength.

Several possibilities for improving this laser exist. First, to have only one blue output, we can replace mirror M4 by a mirror with a double-stack high-reflection coating in both the fundamental and second-harmonic wavelength ranges. Second, a tunability from 420 to 460 nm could be obtained by extension of the temperature excursion of the KNbO_3 crystal from -20 to 150°C . Finally, we believe that we could increase the output power by replacing the SDL diode by an AO diode, yielding fewer thermal problems. Furthermore, with a lower Cr^{3+} concentration (1.5%)

we could decrease the absorption coefficient of the crystal and thus thermal problems and upconversion losses, and it could be possible to add two other AO diodes to the system.

In conclusion, we have described what is to our knowledge the first diode-pumped cw blue laser source with 15-nm tunability (427–443 nm) producing as much as 13 mW of output. The efficiency was 2%, and the stability of second-harmonic generation was better than 3.5%. We believe that we could increase this power by using four AO diodes and a 1.5%-doped crystal.

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