Second-harmonic generation of light at 544 and 272 nm from an ytterbium-doped distributed-feedback fiber laser

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We report external cavity second-harmonic generation of light at 544 and 272 nm based on an ytterbiumdoped distributed-feedback fiber laser. The nonlinear crystal used to generate light at 544 nm is LiNbO₃, and the maximum output of the cavity is 845 mW, corresponding to a conversion efficiency of 55%. In a second frequency-doubling step, using a β -BaBa₂O₄ crystal, we generate up to 115 mW of light at 272 nm with a conversion efficiency of 14%. © 2007 Optical Society of America

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Energy efficient continuous wave (CW) coherent light sources in the visible and UV range are in high demand for many applications in science. The most common sources today in the blue-green range are based on frequency doubling of light from rare-earthelement-doped solid-state lasers. Indeed, commercial have traditionally systems been based on neodymium-doped solids, which have proved very successful in delivering high-power and singlefrequency light in the green and blue range through efficient second-harmonic generation¹ (SHG).

Sources of this type are at present an obvious choice for further frequency doubling into the UV range, and recently a record high power of 5 W at a wavelength of 266 nm was achieved by using two stages of frequency doubling of light from a Nd:YVO₄ laser.²

As single-mode rare-earth-element-doped distributed-feedback (DFB) fiber lasers have become commercially available,³ an alternative to the neodymium-based systems has emerged. With a linewidth of a few tens of kilohertz and an output of several watts, these lasers constitute an excellent starting point for intracavity SHG into the visible part of the spectrum. Given that this can be performed with a high efficiency and without any appreciable distortion of the beam profile, further SHG into the UV range is feasible. Moreover, because of the broad gain profiles of these fiber lasers, a far broader spectrum could be addressed with a laser system of this sort, as compared with what is at present possible with rareearth-doped laser systems using a crystal matrix, such as those based on Nd:YAG.

Non-DFB fiber lasers have received a lot of attention in recent years and have, for instance, been used for frequency doubling into the visible.⁴ With an output of tens of watts, they allow easy and efficient SGH by using periodically poled nonlinear crystals without the need for the external cavity. Their use in science is, however, limited by their broad linewidths (typically ~0.1 nm).

Here we present a 544 nm source based on SHG of CW light from a 1088 nm ytterbium-doped germano-

silicate glass DFB fiber laser. Subsequently this source is used in yet another frequency-doubling stage to generate light at 272 nm.

For the conversion from 1088 to 544 nm, we have chosen LiNbO₃ as our medium for SHG. LiNbO₃ was chosen instead of e.g., LiB₃O₅ (LBO) because of its higher nonlinear coefficient, and 7% magnesium doping was chosen to ensure a low degree of photorefractivity.⁵ Furthermore, the fact that type I noncritical phase matching can be achieved at the relevant wavelength implies a nearly diffractionlimited output beam, promoting it for tasks requiring strong focusing of visible light as well as for further SHG into the UV regime. To achieve noncritical phase matching and to avoid fluctuations in the SHG power, the crystal is placed inside a home-built oven where the temperature is maintained at ~161°C to within a few hundredths of a kelvin.

The setup for this first frequency-doubling stage is shown in Fig. 1. The DFB fiber laser (Koheras Boostik) provides light at 1088 nm, with a linewidth



Fig. 1. Schematic of the setup used for SHG of light from the DFB fiber laser. OI, optical isolator; EOM, electro-optic modulator L1–L4, mode-matching lenses; M1–M4, cavity mirrors; PZT, piezoelectric transducer; PD, photodetector.

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specified to be <35 kHz (averaged over $125 \ \mu$ s), coupled through a polarization-maintaining fiber. By controlling the length of the fiber laser cavity with a piezoelectric transducer, the frequency can be tuned over a total range of 5.8 GHz at 1088 nm at a scan rate up to 20 kHz. Through temperature tuning, the frequency can be tuned about 2.3 GHz/K at 1088 nm.

To prevent feedback from, e.g., the cavity, an optical isolator with \sim 55 dB damping is inserted right after the fiber laser. A telescope (L1 and L2) ensures correct mode matching to the cavity, which is held resonant by using the Pound–Drever–Hall technique.⁶ The maximum power before the cavity is about 1550 mW.

The external cavity is set up in a bow-tie configuration (distance M1-M2, 26.6 cm; distance M3-M4, 6.3 cm; folding angle, 10°), with two plane mirrors (M1, M2) and two concave mirrors (M3, M4), each having a radius of curvature of 5 cm. The crystal, which has a length of 15 nm, is located at the waist between the two curved mirrors. To avoid excessive temperature gradients due to absorption, the waist was chosen to be $\simeq 28 \ \mu m$, a little larger than the optimal value of $21 \ \mu\text{m}$, calculated from Boyd– Kleinman theory.⁷ The crystal is antireflex coated on both end faces for light at the fundamental as well as the SHG wavelength. The measured residual reflections are 0.2% and 1.0%, respectively. The total passive cavity loss, including scattering losses and reflection losses at mirrors M2, M3, and M4 (R=99.9%), is about 1.5%. The incoupling mirror, M1, has a reflectivity of 94.0%, a value chosen to have the cavity approximately impedance matched at input powers of 1-2 W, with a single-pass nonlinear coefficient measured to be $\simeq 1.62 \times 10^{-3} \text{ W}^{-1}$.

In Fig. 2, the SHG power $(P_{2\omega})$ is plotted as a function of the fundamental power (P_{ω}) . As is seen, up to 845 mW of 544 nm light has been produced, corresponding to an efficiency of 55% or 57% when taking a 3% reflection loss, due to the crystal surface and the output coupling mirror, and a mode matching of 98% into account. High power levels (>700 mW at



Fig. 2. SHG power $(P_{2\omega})$ as a function of incident fundamental power at 1088 nm (P_{ω}) . Error bars correspond to an estimated 5% error in the measured power.



Fig. 3. Schematic of the setup used for the second frequency-doubling stage. L3, L4, mode-matching lenses; M5–M8, cavity mirrors; PZT, piezoelectric transducer; PD, photo detector; HPW, half-wave plate; QWP, quarter-wave plate.

544 nm) have been found to be stable to within 10% over several hours.

We have also characterized the quality of the 544 nm light beam by measuring the M^2 value,⁸ defined as $M^2 = \pi w_0 \theta / \lambda$, where w_0 is the minimal beam waist and θ is the beam divergence. Following the procedure of Ref. 8, we find an M^2 value of 1.05 ± 0.02 along the horizontal axis and 1.08 ± 0.02 along the vertical axis. As expected for an SHG beam originating from a noncritical phase-matching process, the beam profile is almost a perfect Gaussian and hence a good starting point for the generation of UV light at 272 nm.

The setup for SHG of 272 nm light from 544 nm is shown in Fig. 3. At this wavelength noncritical phase matching cannot be obtained, so type I critical phase matching in a β -BaB₂O₄ (BBO) crystal is employed.⁹ The walk-off associated with this process is about 85 mrad, and as a result the SHG beam will be non-Gaussian. The crystal is 8 mm long and has been antireflection coated on both end faces at the relevant wavelengths, with residual reflections of 0.2% and 0.6% for the fundamental and the second harmonic, respectively. The cavity is in a bow-tie configuration (distance M5-M6, M7-M8, 13.6 cm; folding angle, 6.3°) with mirrors M5 and M6 both being plane mirrors with a reflectivity at 544 nm of 99.0% and 99.9%, respectively; the two remaining mirrors, M7 and M8, both have a radius of curvature of 10 cm and a reflectivity of 99.9% at 544 nm. The outcoupling mirror, M8, has a transmission of 85.0% at 272 nm. Total passive losses amount to $\simeq 1\%$. The crystal is located at the waist ($\simeq 29 \ \mu m$) between the two curved mirrors, near the optimum value evaluated from Boyd-Kleinman theory.⁷ The cavity is kept resonant with the 544 nm light by using a Hänsch–Couillaud-type locking scheme.¹⁰

The results of this second frequency-doubling step are summarized in Fig. 4. For an input of 730 mW at 544 nm, we achieve a conversion efficiency of 14%, corresponding to 115 mW at 272 nm. Taking losses at the output coupling mirror of 15% into account, the internal conversion efficiency is found to be 17%. The considerably lower conversion efficiency of the second frequency-doubling stage is due to several parameters: the input power, which is much lower than for the first SHG stage; the nonlinear coefficient of the



Fig. 4. SHG power $(P_{4\omega})$ as a function of incident light power at 544 nm $(P_{2\omega})$. Error bars correspond to an estimated 5% error in the measured power.

BBO crystal at 544 nm, which is inferior to that of the LiNbO₃ crystal at 1088 nm; the walk-off due to the critical phase-matching situation, which leads to partial destructive interference of SHG light produced along the crystal; and, finally, imperfect mode matching (95%) that is due partly to the slightly eliptical beam profile of the 544 nm light, as indicated by the difference in the measured M^2 values. Taking all of this into account, the measured efficiency is about 30% less than that predicted by the Boyd–Kleinman theory. This discrepancy might be due to slightly higher passive cavity losses than given above and a lower nonlinear coefficient than specified by the crystal manufacturer.

The power stability of the UV light reflects that of the 544 nm source. At input powers above 700 mW, changes of up to 20% are seen over several hours, whereas on a timescale of tens of microseconds the fluctuations are below 5%.

The frequency stability of the system is set by the temperature stability of DFB fiber laser which results in drifts in frequency at 272 nm of $\sim 100 \text{ MHz/h}$.

The overall power conversion efficiency from 1088 to 272 nm is 8% (input to usable power), which is similar to that of a previously reported 175 mW 272 nm source based on a Ti:sapphire laser operated at 817 nm.¹¹ A 275 mW source at 280 nm also based on two consecutive frequency-doubling stages of light from a DFB fiber laser was also reported recently.¹² It differs, however, in the use of an LBO crystal for the nonlinear medium in the first, IR-to-visible, doubling stage and in having a slightly lower conversion efficiency in this stage.

To summarize, we have demonstrated that an vtterbium-doped DFB fiber laser can serve as a reliable source for CW SHG into the green part of the visible region with a high conversion efficiency and a very good beam quality. Furthermore, we have shown that DFB fiber lasers may be used to create coherent CW UV radiation around 272 nm with an efficiency comparable with alternative methods. Finally, we note that since laser action can be achieved with ytterbium-doped germanosilicate glass fibers over a wavelength range of ~ 975 to ~ 1200 nm,¹³ the presented work should be easily extendable to a fairly large part of the spectrum around 550 nm and 275 nm. Applying similar SHG techniques to DFB fiber lasers based on erbium¹⁴ (emission range \sim 1500 to \sim 1600 nm) and thulium¹⁵ (emission range \sim 1700 to \sim 2100 nm) may further enlarge the accessible wavelength range in the visible and near-UV region. Consequently, we expect rare-earth-elementdoped DFB fiber lasers in combination with SHG to be applied extensively in the future.

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