Stable, 9.6 W, continuous-wave, single-frequency, fiber-based green source at 532 nm

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Received January 7, 2009; revised April 3, 2009; accepted April 6, 2009;
posted April 20, 2009 (Doc. ID 106134); published May 12, 2009

We present a stable, high-power, cw, single-frequency green source in a compact and practical design based on a simple single-pass second-harmonic generation of a cw ytterbium fiber laser at 1064 nm in MgO-doped periodically poled stoichiometric $LiTaO_3$. Using a 30-mm-long crystal containing a single grating, we have generated 9.64 W of cw radiation at 532 nm with a fundamental power of 29.5 W at a single-pass conversion efficiency of 32.7%. The output power is naturally stable with a peak-to-peak fluctuation of 7.6% over the first 8 h and 9% over 13 h. Over the entire range of fundamental powers, the generated green output is single frequency with an instantaneous linewidth of 6.5 MHz and frequency stability of <32 MHz over 30 min and has a TEM_{00} spatial profile with $M^2<1.33$. © 2009 Optical Society of America

OCIS codes: 140.7300, 140.3510, 190.2620, 190.4400.

High-power, cw, and single-frequency green sources are of great interest for a variety of applications, including pumping of Ti:sapphire lasers and cw singly resonant optical parametric oscillators (SROs) pumped in the visible [1]. To date, practical realization of such sources has relied almost exclusively on internal second-harmonic generation (SHG) of cw Nd-based solid-state lasers. While these techniques have been proven highly effective, the attainment of stable, high-power, and single-frequency operation generally requires elaborate system designs involving intricate cavity configurations for internal doubling, careful management of thermal effects, and active stabilization, resulting in relatively high complexity and cost. It would be desirable to devise alternative approaches for the development of such sources using more simplified and cost-effective techniques. An attractive approach is the external SHG of high-power cw IR lasers in quasi-phase-matched ferroelectric materials such as MgO-doped periodically poled $LiNbO_3$ (MgO:PPLN) [2], MgO-doped periodically poled stoichiometric $LiTaO_3$ (MgO:sPPLT) [3,4], and periodically poled $KTiOPO_4$ (PPKTP) [5].

The onset of photorefractive damage under exposure to visible radiation has limited the use of MgO:PPLN mainly to the near- and mid-IR. On the other hand, MgO:sPPLT [3,4] and PPKTP [5] are attractive for frequency conversion in the visible because of the increased resistance to photorefractive damage and relatively high effective nonlinearities ($d_{\mathrm{eff}}\sim 10$ pm/V). In PPKTP, thermal issues arising from the absorption of green radiation together with gray tracking have so far limited cw green generation to 6.2 W [5]. MgO:sPPLT has demonstrated to be the most promising material owing to its high photorefractive damage threshold [6] and large thermal conductivity [7] to handle high optical powers. Earlier reports of green generation in MgO:sPPLT include single-pass SHG of a 91.5 W cw Nd:YAG laser, providing 16.1 W at 532 nm at 17.6% efficiency [4]. However, to our knowledge, the development of compact, cw, green sources based on cw fiber laser technology, offering stable, high-power, and single-frequency output with high spatial beam quality, mandatory requirements for the above applications, has not been extensively explored. In this Letter, we describe such a source using a simple design based on an external single-pass SHG of a cw, single-frequency, ytterbium (Yb) fiber laser at 1064 nm in MgO:sPPLT. The source can deliver 9.64 W of cw single-frequency output power at 532 nm at a conversion efficiency as high as 32.7% in a TEM_{00} spatial profile with peak-to-peak power stability of 9% over 13 h and frequency stability of <32 MHz over 30 min. Together with its high passive stability and single-frequency performance, the device offers an attractive, compact, and cost-effective source for many applications, including pumping of Ti:sapphire lasers and high-power cw SROs.

The configuration of the experimental setup is similar to our previous work [5]. The fundamental pump source is a 30 W, cw, single-frequency Yb fiber laser (IPG Photonics, YLR-30-1064-LP-SF) at 1064 nm. The laser delivers a linearly polarized output beam with a diameter of 3 mm, M^2 factor of <1.01, and a nominal linewidth of 89 kHz. Using a wavemeter (HighFinesse WS-U 30), we measure the frequency stability of the laser to be <120 MHz over 1 h and <50 MHz over 30 min. The nonlinear crystal is 30 mm MgO:sPPLT (HC Photonics, Taiwan), containing a single grating ($\Lambda=7.97$ μm), and housed in an oven with a temperature stability of $\pm 0.1°$C. The crystal faces have low reflectivity ($R<0.5\%$) at 1064 nm and high transmission ($T>99\%$) at 532 nm [1]. A dichroic mirror ($R>99\%$ at 1064 nm; $T>94\%$ at 532 nm) separates the generated green from the input fundamental.

To optimize the SHG, we used several focusing conditions corresponding to different values of the focusing parameter, $\xi=L/b$ [8]. Here L is the crystal length and $b=kw_{\mathrm{op}}^2$ is the pump confocal parameter, with $k=2\pi n_p/\lambda_p$, where n_p, λ_p, and w_{op} are the refrac-

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tive index, wavelength, and waist radius of the fundamental beam inside the crystal, respectively. We measured the maximum generated second-harmonic (SH) powers and corresponding optimum phase-matching (PM) temperatures using seven different focusing conditions, $\xi=0.32$, 0.81, 1.23, 1.74, 2.48, 4.50, and 6.60 at a fixed fundamental power of 29.5 W at the input to the crystal. The results are shown in Fig. 1. For weak focusing ($\xi<2.48$), the maximum SH power increases with higher ξ, whereas for tight focusing ($\xi>2.48$), it decreases with increasing ξ. Interestingly, the extrapolated power curve has a clear peak near $\xi\sim2.84$, corresponding to the theoretical prediction for optimum SHG in the cw (or long-pulse) limit [8]. We obtained a maximum SH power of 9.64 W at $\xi=2.48$ ($w_{\mathrm{op}}\sim31$ μm), corresponding to a single-pass conversion efficiency of 32.7%.

It is also clear in Fig. 1 that the PM temperature decreases with tighter focusing. This is to be expected since crystal heating effects owing to various absorption mechanisms including green-induced IR absorption (GRIIRA) of fundamental, two-photon absorption (TPA) of fundamental and green, and linear absorption at both wavelengths are stronger under tight focusing, leading to a greater thermal load in the crystal and therefore necessitating lower externally applied heat to the sample. GRIIRA is not expected to make a significant contribution to crystal heating at these power densities because of its suppression owing to MgO doping [6]. To investigate the role of TPA, we recorded crystal transmission at fundamental power levels up to 30 W and in the green at up to 9 W using a commercial cw green source (Coherent, Verdi-10). We obtained a linear increase in the transmitted power with input power at both wavelengths, thus also confirming the absence of TPA. From the measurements, we deduced a linear absorption loss of 1.58%/cm at 532 nm and 0.17%/cm at 1064 nm, implying a far higher contribution to crystal heating from the absorption of green than fundamental. This is also evident in Fig. 1, where at a fixed fundamental power of 29.5 W, we observe a strong correlation between the generated green power and the corresponding PM temperature. On the other hand, given the significant linear absorption of 0.17%/cm at 1064 nm, the role of fundamental absorption to crystal heating cannot be entirely ignored. To verify this contribution, under the focusing condition of $\xi=1.74$, we rotated the fundamental polarization to generate a green power of less than 100 mW at 29.5 W of fundamental. By increasing the fundamental power from 1 to 29.5 W, we observed a drop in the PM temperature from 52.5°C to 51.6°C, clearly indicating still a significant contribution of fundamental absorption to thermal effects. These studies thus confirm that thermal effects in the MgO:sPPLT crystal were owing neither to GRIIRA nor TPA but a result of intrinsic linear absorption of IR and green. It has been suggested that the maximum available SH power is limited by the thermal effects resulting from either only the absorption of fundamental [9] or only the SH power [4]. Our present studies together with our earlier report [10] confirm that the thermal effects are owing to the absorption of both fundamental and SH power, with the major contribution from the green.

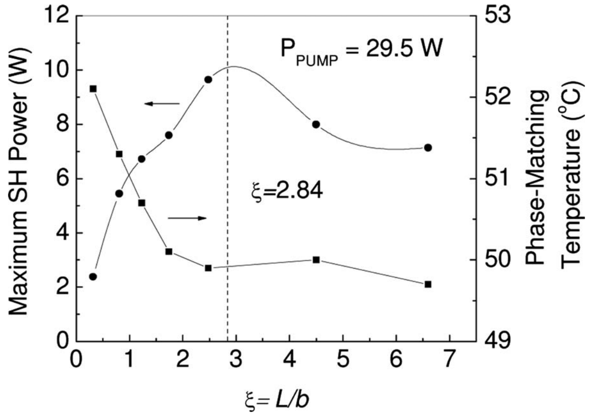

Fig. 1. Maximum SH power and corresponding PM temperature as a function of the focusing parameter, L/b. The vertical dashed line corresponds to the optimal focusing condition ($L/b\sim2.84$) prescribed by Boyd and Kleinman [8].

From the measurement of green power in Fig. 1, the normalized conversion efficiency was calculated to vary from 0.42%/W at $\xi=0.32$ to 1.26%/W at $\xi=6.60$, with a maximum of 1.70%/W at $\xi=2.48$. The normalized efficiency is not limited by fundamental linewidth, since the spectral acceptance of the 30 mm crystal calculated from Sellmeier equations [11] is 0.082 nm (FWHM), far wider than the fiber laser linewidth of 89 kHz.

To characterize the power scalability of the SHG, we recorded the SH power and efficiency at $\xi=2.48$ ($w_{\mathrm{op}}\sim31$ μm) up to the maximum available fiber laser power, as shown in Fig. 2. We obtained 9.64 W of green for the full fundamental power of 29.5 W at a single-pass efficiency of 32.7%. The quadratic increase in the SH power and the corresponding linear variation in efficiency are maintained up to a fundamental power of 22 W (Fig. 2), after which saturation occurs. The saturation effect is also evident from the

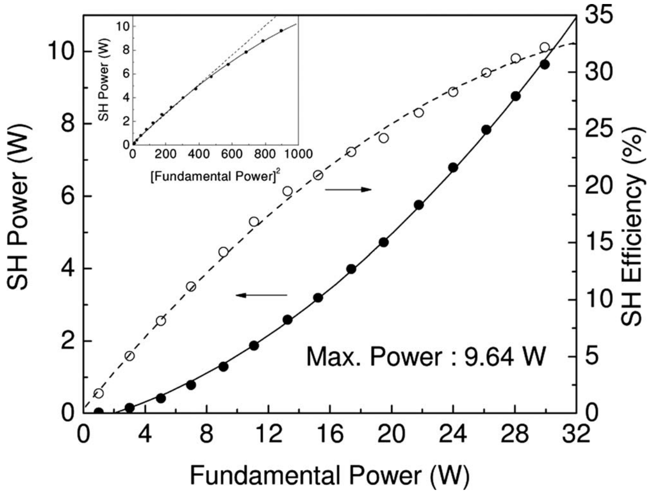

Fig. 2. Dependence of the measured cw SH power and the corresponding conversion efficiency on the incident fundamental power. Inset, variation in the SH power as a function of square of the fundamental power.

deviation of the linearity of the SHG power with the square of fundamental power (inset of Fig. 2) and is attributed to the pump depletion, backconversion, and thermal phase-mismatch effects in the MgO:sPPLT crystal. We believe that further increases in the SH power beyond 9.64 W will be possible using a pump beam waist of ~29 μm (ξ=2.84) and improved thermal management to overcome saturation.

The frequency stability of the generated green, measured at 9.64 W using a wavemeter (HighFinesse, WS-U 30), is shown in Fig. 3. Under free-running conditions and without thermal isolation, the green power exhibits a peak–peak frequency fluctuation of <115 MHz over 90 min, with a short-term stability of <32 MHz over 30 min. The transmission fringes obtained through a confocal scanning interferometer (FSR=1 GHz, finesse=400), shown in the inset of Fig. 3, also verify the single-frequency spectrum with an instantaneous linewidth of ~6.5 MHz. Similar behavior was observed throughout the pumping range with the same linewidth, confirming robust single-mode operation at all fundamental powers.

The power stability near the maximum green power of 9.64 W is shown in Fig. 4, demonstrating a peak–peak fluctuation of 7.6% over the first 8 h and 9% over 13 h. The power fluctuation is attributed mainly to changes in the laboratory environment, so further improvements in power stability, below 3%, are expected through thermal isolation of the system and better temperature control. The far-field energy distribution of the green beam at 9.64 W, together with the intensity profile and the Gaussian fits along the two orthogonal axes, are shown in the inset of Fig. 4. Using a focusing lens (f=25 cm) and scanning beam profiler, we measured M^2 values of the green beam to be $M_x^2 \sim 1.29$ and $M_y^2 \sim 1.23$ with an ellipticity of ~0.96, confirming the TEM$_{00}$ spatial mode. Similar M^2 values were measured at different input power levels, showing a small variation in M_x^2 from 1.11 to 1.29 and M_y^2 from 1.17 to 1.33.

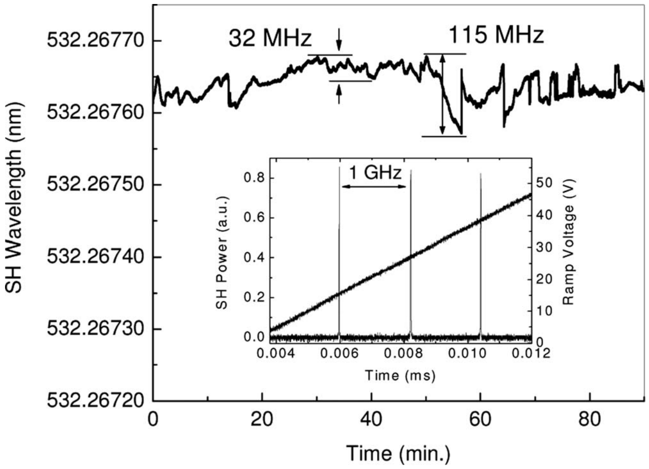

Fig. 3. Frequency stability of green beam at 9.64 W over 90 min and (inset) corresponding single-mode spectrum.

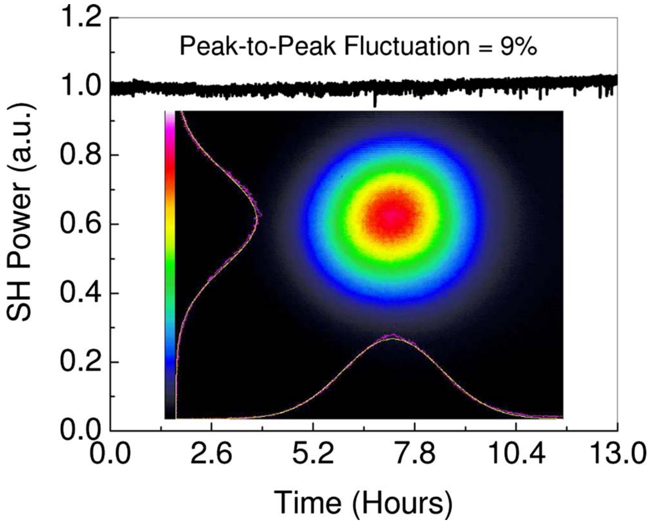

Fig. 4. (Color online) Green output power stability at 9.64 W over 13 h and (inset) far-field TEM$_{00}$ energy distribution and intensity profiles of the generated green beam.

In conclusion, we have generated 9.64 W of cw single-frequency radiation at 532 nm with a conversion efficiency as high as 32.7% using a simple single-pass SHG of a cw Yb fiber laser in MgO:sPPLT near room temperature. The source exhibits good long-term passive frequency and power stability and a TEM$_{00}$ spatial profile with $M^2 < 1.33$. With more stringent thermal control and optimized focusing, further improvements in green power and efficiency as well as power scaling are feasible.

We acknowledge support from the Spanish Ministry of Education and Science through grant TEC2006-12360 and the Consolider project (CSD2007-00013).

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