High-power, continuous-wave, second-harmonic generation at 532 nm in periodically poled $KTiOPO_4$

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We report efficient generation of high-power, cw, single-frequency radiation in the green in a simple, compact configuration based on single-pass, second-harmonic generation of a cw ytterbium fiber laser at 1064 nm in periodically poled $KTiOPO_4$. Using a crystal containing a 17 mm single grating with period of 9.01 μm, we generate 6.2 W of cw radiation at 532 nm for a fundamental power of 29.75 W at a single-pass conversion efficiency of 20.8%. Over the entire range of pump powers, the generated green output is single frequency with a linewidth of 8.5 MHz and has a TEM_{00} spatial profile with $M^2<1.34$. The demonstrated green power can be further improved by proper thermal management of crystal heating effects at higher pump powers and also by optimized design of the grating period to include thermal issues. © 2008 Optical Society of America

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Quasi-phase-matched (QPM) nonlinear materials have had a major impact on optical frequency-conversion technology. In particular, the advent of periodically poled $LiNbO_3$ (PPLN) has enabled the development of a new generation of devices with unprecedented performance capabilities. At the same time, the onset of photorefractive damage under exposure to visible radiation has confined the utility of PPLN mainly to the IR. Doping with MgO can partially alleviate this problem, permitting the use of MgO:PPLN at higher powers and lower temperatures [1,2]. However, residual effects of photorefractive damage continue to restrict operation of devices based on MgO:PPLN mainly to the near- and mid-IR.

For frequency conversion in the visible, QPM materials such as MgO-doped periodically poled stoichiometric $LiTaO_3$ (MgO:sPPLT) [2,3] and periodically poled $KTiOPO_4$ (PPKTP) [2,4–7] are attractive alternatives, offering increased resistance to photorefractive damage and relatively high effective nonlinearities ($d_{eff}\sim 10$ pm/V). Advances in material growth and fabrication have also led to the availability of such QPM materials with high optical quality, shorter grating periods, and long interaction lengths (up to 30 mm), enabling the development of frequency-conversion devices for the visible in the cw [2,4–6] and low-intensity pulsed regimes [7].

In this Letter, we report efficient generation of high-power cw radiation at 532 nm in a compact and practical design based on simple single-pass, second-harmonic-generation (SHG) of a cw ytterbium (Yb) fiber laser in PPKTP. Earlier reports of cw SHG in the visible based on PPKTP include intracavity [4], external enhancement [5], and single-pass configurations [6], but the highest cw SH power achieved so far has been 2.3 W in multimode output [4]. As such, power scaling of SHG and performance of the material at increased powers has not been reported, to our knowledge. Here, we demonstrate the generation of 6.2 W of cw, single-frequency radiation at 532 nm with a single-pass conversion efficiency as high as 20.8%. We also investigate thermal issues relating to power scaling of SHG to fundamental powers up to 30 W and discuss strategies for increased output power and efficiency at higher pump powers.

A schematic of the experimental setup is shown in Fig. 1. The fundamental pump source is a cw Yb fiber laser (IPG Photonics, YLR-30-1064-LP-SF). The laser delivers up to 30 W of single-frequency radiation at 1064 nm in a linearly polarized beam with a diameter of 3 mm, M^2 factor <1.01, and a measured instantaneous linewidth of 12.5 MHz. To maintain stable output characteristics, we operated the pump laser at the maximum power and used an attenuator comprising a half-wave plate (HWP) and a polarizing beam splitter to vary the input fundamental power. A second HWP was used to yield the correct pump polarization for phase matching. The fundamental beam was focused to a measured beam waist radius of 37 μm ($1/e^2$-intensity) at the center of the crystal ($\xi=1.28$). The bulk PPKTP crystal is fabricated in-house from a *c*-cut 19-mm-long, 1-mm-thick, and 6-mm-wide flux-grown KTP sample. The c^- face of the crystal was patterned with a photoresist grating

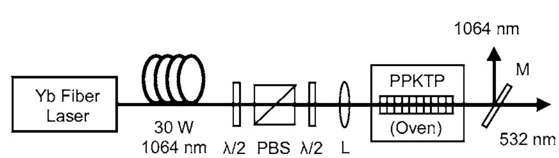

Fig. 1. Schematic of the experimental design for single-pass SHG of cw Yb fiber laser in PPKTP. λ/2, half-wave plate; PBS, polarizing beam splitter; L, lens (f=20 cm); M, dichroic mirror.

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of 9.01 μm period and was covered with an Al film over 17 mm length at the center, keeping a 1 mm free zone on each side of the grating. The actual length of the grating is thus 17 mm. The crystal was poled by applying 5-ms-long electric field pulses of 2.5 kV/mm in magnitude [8]. The PPKTP is housed in an oven with a temperature stability of ±0.1°C. The crystal faces are antireflection coated ($R<1\%$) at 1064 nm and 532 nm. A dichroic mirror, M, coated for high reflectivity ($R>99\%$) at 1064 nm and high transmission ($T>99\%$) at 532 nm, extracted the generated green output from the fundamental.

To characterize the PPKTP sample, we first determined the dependence of SHG power on crystal temperature. To avoid unwanted contributions from thermal effects, we performed the measurements at a low fundamental power of 1 W, resulting in 8.3 mW of green output at a phase-matching temperature of 30.8°C. The result is shown in Fig. 2. The solid curve is a sinc^2 fit to the data, confirming the expected temperature dependence of SHG. The FWHM of the curve is $\Delta T=3°C$, which is slightly wider than the calculated value of 2.62°C from the Sellemier equations [9]. The effective interaction length can be defined as $L_{eff}=L\times 2.62/3=14.84$ mm, where $L=17$ mm is the physical length of the grating. The discrepancy between the physical length and measured effective length is attributed to imperfections in the grating structure and nonideal focusing.

We performed measurements of SHG efficiency and power up to the maximum fiber laser power of 30 W, with the results shown in Fig. 3. The fundamental power was measured at the input to the crystal, while the generated green power was corrected for the 6% transmission loss of mirror M. We obtained 6.2 W of green power at the full input power of 29.75 W, representing a single-pass conversion efficiency of 20.8%. As evident in Fig. 3, the quadratic increase in SH power and corresponding linear variation in efficiency are maintained up to 15 W of input power, after which saturation sets in. Beyond this value, SH power increases linearly with fundamental power. The saturation effect is attributed to depletion of the fundamental [2] and thermal phase mismatch in the PPKTP crystal, owing to a number of factors. These include green-induced IR absorption (GIIRA) of fundamental, two-photon absorption (TPA) of fundamental and generated green, and linear absorption at both wavelengths.

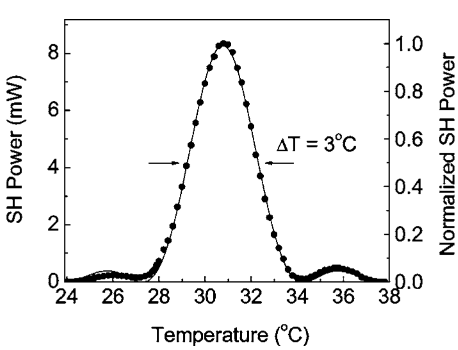

Fig. 2. Temperature dependence of SH power (filled circles) and the sinc^2 fit (solid curve). The resulting temperature bandwidth is 3°C.

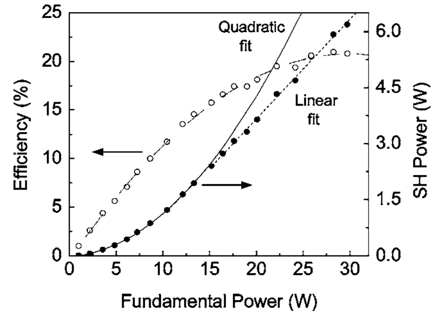

Fig. 3. Dependence of the measured SH power and the corresponding conversion efficiency on the incident fundamental power.

To verify any contribution from GIIRA to thermal dephasing, we focused 6 W of green radiation from a cw laser at 532 nm (Coherent, Verdi-10) to a beam radius of 34 μm inside the crystal to obtain similar maximum green power density (0.33 MW/cm^2) as in the SHG experiments. The arrangement resulted in the simultaneous focusing of the fundamental fiber laser IR beam to a waist radius of 28 μm inside the crystal, close to 37 μm used in the SHG experiments. We then measured the variation in transmitted IR power at different green power levels over 10 min periods. However, we observed no difference in the transmitted IR power with and without green radiation, indicating the absence of GIIRA up to the maximum green power of 6 W. We also investigated the possible role of TPA by recording the crystal transmission at both fundamental and green wavelengths at power levels up to 30 W and 6 W, respectively. We obtained a linear increase in transmitted power with input power at both wavelengths, from which linear absorption losses of 0.3%/cm at 1064 nm and 4.5%/cm at 532 nm were deduced, in agreement with previous results [10]. These measurements thus confirmed that thermal dephasing in the PPKTP crystal was also not due to TPA, but a result of intrinsic linear absorption of IR and green, leading to increased heating at higher powers. We determined a normalized conversion efficiency of ~1.2%/W below 15 W of fundamental power, monotonically decreasing to ~0.7%/W with the rise in input power to 29.75 W, confirming increased thermal dephasing due to linear absorption at higher powers. The normalized efficiency values do not account for absorption losses in the crystal. From the normalized efficiency of 1.2%/W and the focusing parameter of $\xi=1.28$ ($h\sim 0.85$), the effective nonlinearity is calculated as $d_{eff}\sim 7.63$ pm/V for the 17 mm grating, corresponding to $d_{33}\sim 12$ pm/V. This value is 77.9% of previous results [11], which we attribute to crystal absorption of the green and IR, laser linewidth, and imperfections in the grating structure such as missing periods and duty factor variations. Considering the absorption losses of 0.3%/cm at 1064 nm and 4.5%/cm at 532 nm, we determined a normalized efficiency of ~1.33%/W below 15 W of fundamental power, resulting in $d_{eff}\sim 8.6$ pm/V, corresponding to

$d_{33} \sim 13.5$ pm/V for a 14.8 mm PPKTP crystal with 50% duty factor. As the missing periods are included in the effective length, the deviation in the calculated d_{33} from earlier value [11] can be due to the grating duty factor and the laser linewidth. However, using the Sellmeier equations [9], the calculated FWHM spectral acceptance of the 17 mm crystal (0.157 nm) is much wider than the laser linewidth (12.5 MHz), confirming the discrepancy due to duty factor of the grating.

To gain further insight into thermal effects in the PPKTP crystal, we recorded the SHG phase-matching temperature at different fundamental powers. Although no significant shift in the phase-matching temperature was observed at the lower input powers, a monotonous decrease in phase-matching temperature, at a rate of 0.19°C/W, was measured above 15 W, further confirming crystal heating at higher input powers. At lower powers, linear absorption does not significantly affect the phase-matching temperature, whereas at higher powers it heats the crystal, reducing the optimum value for phase matching and thus requiring a reduction in crystal temperature for maximum green generation. Since phase matching for the present PPKTP sample is near room temperature, further optimization of the crystal temperature using Peltier cooling or the use of a grating period with a higher phase-matching temperature could potentially lead to increased green power and efficiency at the higher input powers up to 30 W and above, with the possibility of power scaling of green beyond 6 W. Proper management of the generated heat or inclusion of the crystal heating effects in the grating design are other possible strategies to achieve the highest SH power and efficiency.

We analyzed the output spectrum at 532 nm using a scanning confocal interferometer (free spectral range, 1 GHz; finesse, 400). A typical fringe pattern at 25 W of fundamental power (5 W of green), is shown in Fig. 4, verifying single-frequency operation. The instantaneous linewidth, measured directly without accounting for the interferometer resolution, is 8.5 MHz. The same behavior was observed throughout the pumping range with similar linewidth, confirming robust single-mode operation at all pump powers.

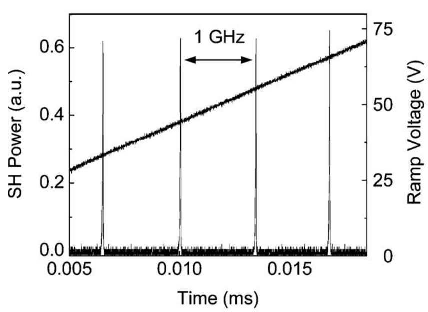

Fig. 4. Single-frequency spectrum of the green output recorded by a scanning Fabry–Perot interferometer.

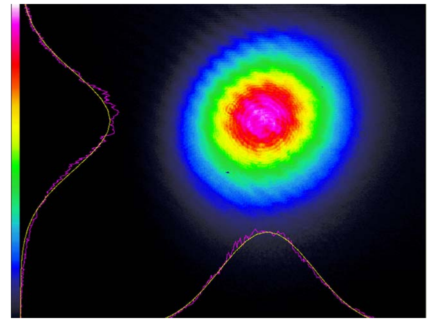

Fig. 5. (Color online) TEM_{00} energy distribution, beam profiles, and Gaussian fits (solid curves) of the generated green beam in the far-field.

The far-field energy distribution of the green output beam at 5 W together with the intensity profile and the Gaussian fits, recorded at 25 W of input power, are shown in Fig. 5. Using a 25 cm focal length lens and scanning beam profiler, we measured M^2 values of the beam as $M_x^2 \sim 1.29$ and $M_y^2 \sim 1.31$, confirming TEM_{00} spatial mode. Similar M^2 values were measured at different input power levels, showing a small variation in M_x^2 from 1.25 to 1.29 and M_y^2 from 1.2 to 1.34.

We have thus generated 6.2 W of cw, single-frequency radiation at 532 nm at 20.8% efficiency in a highly compact and practical design using simple single-pass SHG of a cw Yb fiber laser in PPKTP near room temperature. With proper thermal management and optimized grating design, further improvements in green power and efficiency as well as power scaling are feasible.

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