Highly efficient blue-light generation from a compact, diode-pumped femtosecond laser by use of a periodically poled KTP waveguide crystal

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We present a simplified, potentially portable, and highly efficient blue-light source from a periodically poled KTP waveguide crystal with a compact femtosecond Cr:LiSAF laser. This light source generates 5.6 mW of blue average output power at 424 nm with 27 mW of incident fundamental in a single-pass extracavity arrangement at room temperature. The overall system efficiency of electrical power to blue light is 0.5%, and the internal second-harmonic generation conversion efficiency is as high as 37%. The slope efficiency of 5.5% pJ^{-1} at low pulse energies is, to our knowledge, the highest slope efficiency yet reported for frequency conversion into the blue spectral region. © 2003 Optical Society of America

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Compact and practical laser sources operating efficiently in the blue spectral region offer ease of implementation in a wide range of applications such as high-density optical storage, biomedical imaging, and the study of protein-dynamics, which requires coherent blue radiation in femtosecond pulses.[1] One of the most efficient routes to achieving high conversion efficiency into the blue spectral region is exploiting the high nonlinearity of a suitable doubling crystal with the characteristically high peak powers associated with subpicosecond or femtosecond pulses. We have recently demonstrated a practical route to designing a portable, rugged battery-powered femtosecond blue-light source with an electrical-to-optical conversion efficiency of 1%, which is to our knowledge the most efficient source of femtosecond blue pulses reported to date.[2] Although this system used birefringent phase matching in a bulk crystal of $\mathrm{KNbO_3}$, quasi phase matching (QPM) in a wave-guided nonlinear crystal represents an alternative methodology. KTP is especially suitable as a nonlinear crystal for second-harmonic generation (SHG). It can be wave guided and periodically poled to readily satisfy QPM conditions at room temperature for a pulsed laser with single-mode spatial beam characteristics.

As a fundamental pump source, we used a compact, low-threshold, and highly efficient femtosecond Cr:LiSAF laser, pumped with single narrow-stripe laser diodes.[3–5] The cavity, illustrated in Fig. 1, consists of a 3-mm (5.5 at.% doped) Cr:LiSAF laser crystal, two dichroic high reflectors, a semiconductor saturable absorber mirror (SESAM) mode-locking element, an output coupler, and a single prism for wavelength tuning and group-velocity dispersion compensation.[6,7] The laser produces near-tranform-limited pulses of ~170-fs duration at a repetition rate of 330 MHz.

To attain efficient SHG from this Cr:LiSAF laser, we used QPM in a length of a periodically poled KTP (ppKTP) waveguide. This crystal sample was initially fabricated to facilitate a nonresonant injection seeding scheme[8] and consisted of a Bragg grating section adjacent to the ppKTP waveguide section. Although such a Bragg grating results in a poor overall transmission of the fundamental beam (reflecting as much as 26%), the backreflection did not appear to affect the performance of the Cr:LiSAF pump laser. The KTP crystal was 1 mm thick and contained several adjacent waveguides, which were

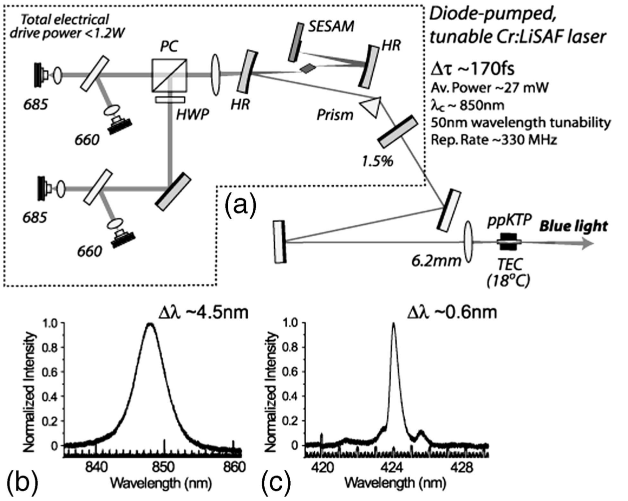

Fig. 1. (a) Schematic of the single-pass, frequency-doubled mode-locked Cr:LiSAF laser. 660, 685, pump laser diode wavelength; PC, polarization cube; HWP, half-wave plate; HR, high reflector; 1.5%, output coupler; TEC, thermoelectric cooler; ppKTP, waveguide doubling crystal. Corresponding (b) fundamental and (c) second-harmonic (SH) (blue) spectra.

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fabricated by ion exchange.[9] These waveguides had dimensions of ~4 μm × ~4 μm and were separated by 50 μm. The length of the entire crystal was 11 mm, and it was poled for the frequency doubling of 850 nm. The length of the quasi-phase-matched section was 8 mm, with grating periods that ranged from 3.86 to 4.06 μm. The length of the Bragg grating section was 3 mm, with a standard grating period of 4.0 μm.

The ppKTP waveguide crystal was placed in a simple extracavity single-pass arrangement, requiring minimal beam-manipulation optics. The fundamental light from the Cr:LiSAF laser was tuned to 848 nm (the peak of the ppKTP wavelength acceptance bandwidth) and was launched into the waveguide with a single 6.2-nm focal length aspheric lens (N.A. = 0.4) in the configuration in Fig. 1(a). With 27 mW of average fundamental power at 848 nm, output powers as high as 5.6 mW were achieved by the blue spectral region with a spectral width of 0.6 nm at 424 nm. The corresponding infrared-to-blue optical efficiency in this femtosecond regime is therefore 21%. However, because the waveguide crystal was not antireflection coated, an ~9% Fresnel reflection loss of the fundamental was experienced at the front crystal facet. Accounting for the 26% reflection losses of the fundamental wavelength due to the Bragg grating, as well as an observed 40% transmission of fundamental power through the waveguide, led to an estimated experimental coupling efficiency, η_c, of 70%. Assuming lossless propagation in the waveguide and this 70% coupling efficiency ($\eta_c = 0.7$), we report an internal SHG conversion efficiency of as much as 37% (Fig. 2). This corresponds to 2.1 mW of blue light being generated for 8.9 mW of incident fundamental. Accounting for a 10.3% Fresnel reflection loss of the blue light, F_{SH}, at the end facet ($F_{\mathrm{SH}} = 0.897^{-1}$), the internal efficiency is therefore $2.1F_{\mathrm{SH}}/8.9\eta_c = 0.37$. No waveguide is strictly loss free, so this value of 37% describes a lower limit of the internal SHG performance. With the Cr:LiSAF source laser requiring no more than 1.2 W of total electrical drive, the generation of 5.6 mW of average power in the blue spectral region corresponds to an overall electrical-to-blue-light efficiency of 0.5%.

Figure 2 presents the experimental dependence of SH efficiency on input power. The slope efficiency of low powers allows an estimation of the nonlinear coefficient, ${d_{\mathrm{eff}}}^{(2)}$, with Eq. (1):

$$\eta = \frac{8\pi^2 |{d_{\mathrm{eff}}}^{(2)}|^2}{\varepsilon_0 \mathrm{c} n^3 \lambda^2} \frac{WL}{\alpha A_{\mathrm{eff}}}, \qquad (1)$$

where η is the experimental internal SH efficiency taken from Fig. 2 for pulse energies as high as 3 pJ, α is the group-velocity mismatch of the KTP waveguide, A_{eff} is the effective cross section of the waveguide, L is the sample length, and W is the fundamental pulse energy. For our ppKTP waveguide we calculate ${d_{\mathrm{eff}}}^{(2)} = 4.6$ pm V^{-1}. This is lower than that quoted for bulk ppKTP (7.8 pm V^{-1} and 11.4 pm V^{-1})[10,11] because of the unavoidable imperfect mode overlap of the fundamental and SH waves within the multimode waveguide [$d_{\mathrm{eff}} = (2/\pi)d_{33}\beta$, where β is an overlap integral and is <1].

As can be seen from Fig. 2, the dependence of internal SH efficiency on input power is characterized by a maximum efficiency of 37%. A further increase in fundamental pulse energy then leads to a saturation and subsequent decrease in the efficiency of the SH process. The reason for this saturation and decrease of SH efficiency is not completely understood, but several effects have been discussed in the literature. Explanations include the presence of a nonlinear phase shift arising from cascaded $\chi^{(2)}$ processes,[12] two-photon absorption (TPA) of the SH wave,[11] and absorption of the fundamental beam induced by the presence of the SH wave.[13] From those listed above, TPA or a similar source of nonlinear absorption of the SH wave is the most probable effect that may simultaneously explain the observed saturation of SH efficiency (Fig. 2) as well as the measured nonlinear losses of the SH wave.

To illustrate the role of nonlinear absorption at 424 nm (the SH wavelength) in our experiment, we used a simple model in a plane-wave approximation to plot the theoretical prediction of the influence of TPA on the SHG efficiency [Fig. 3(a)]. The key parameter used in this model is the ratio $\mathrm{Im}\{{\chi_{zzzz}}^{(3)}\}/[{d_{\mathrm{eff}}}^{(2)}]^2$, where $\mathrm{Im}\{{\chi_{zzzz}}^{(3)}\}$ is the imaginary part of the third-order nonlinear susceptibility tensor.[14] In our model we set the value of $\mathrm{Im}\{{\chi_{zzzz}}^{(3)}\}/[{d_{\mathrm{eff}}}^{(2)}]^2$ based on the experimentally observed maximum nonlinear loss (25%) of total transmitted power through the waveguide during the SHG process, i.e., $[P_{\mathrm{out}}(\omega_1) + P_{\mathrm{out}}(\omega_2)]/P_{\mathrm{in}}(\omega_1) \sim 0.75$.

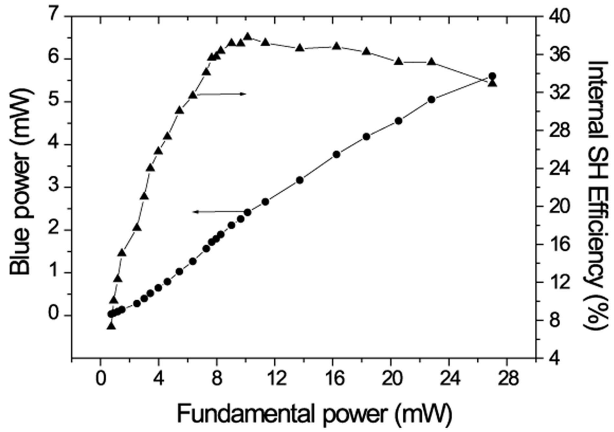

Fig. 2. Generated blue average power and slope efficiency of the internal SHG process for the ppKTP waveguide crystal.

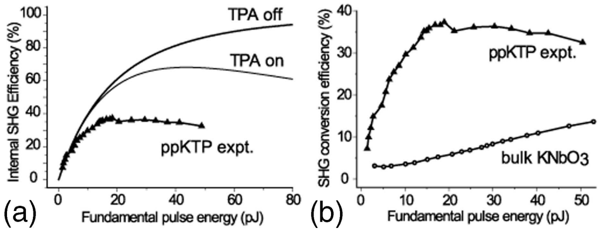

Fig. 3. (a) Saturation of SHG efficiency in our waveguide ppKTP experiment. (b) Comparison of our ppKTP waveguide results with a similar SHG configuration with a bulk $KNbO_3$ crystal[2] at low pulse energies.

Table 1. Comparison of Our Results with Other Efficient Blue-Generation Experiments in Bulk and Waveguide Nonlinear Crystals

Number	Sample	λ_{SH} (nm)	L (cm)	η_{slope} (% pJ^{-1})	η_{slope} (% pJ^{-1} cm^{-1})	Ref.
1	$KNbO_3$–bulk	430	0.3	0.3	1.0	15
2	$KNbO_3$–bulk	430	0.3	0.25	0.73	2
3	ppKTP–waveguide	423	0.26	0.04	0.15	11
4	ppKTP–waveguide	424	0.8	5.5	6.9	

In Fig. 3(a) our experimental results are compared with the calculated effects of TPA on the SHG efficiency at these nonlinear losses of 25%. Previously, a similar saturation and subsequent decrease in efficiency was observed by Weiner *et al.*[15] in noncritically phase-matched, bulk $KNbO_3$ under conditions of tight focusing. The TPA of the SH wave that we demonstrate here can also explain the saturation and decrease of SHG efficiency in the bulk $KNbO_3$ case. Indeed, Weiner describes the observed saturation as one that cannot be explained by linear loss or by nonlinear absorption of the fundamental. Rather, nonlinear absorption of the SH light is responsible for the saturation of the SHG conversion efficiency at higher powers.

The superiority of the ppKTP waveguide is evident in Fig. 3(b) when comparing the slope efficiency (η_{slope}) of our experimental data with that of investigations in bulk $KNbO_3$. At low pulse energies the slope efficiency in our ppKTP experiment is calculated to be 5.5% pJ^{-1} whereas in the $KNbO_3$ experiments[2,15] the slope efficiencies were only 0.25 and 0.3% pJ^{-1}. The efficiency reported here of 5.5% pJ^{-1} in the ppKTP waveguide is, to our knowledge, the best yet reported for frequency conversion into the blue spectral region (Table 1).

The highest reported efficiency for frequency doubling of femtosecond pulses in any spectral region is 50% pJ^{-1}, which was achieved in a very long sample ($L = 5.6$ cm) of periodically poled lithium niobate for a fundamental wavelength of 1558 nm.[12] Therefore, to make effective comparisons of efficiency, it is more convenient to express the slope efficiency per unit length (% pJ^{-1} cm^{-1}). This indicates that our result (6.9% pJ^{-1} cm^{-1}) is close to this reported record efficiency of frequency doubling of femtosecond pulses (9% pJ^{-1} cm^{-1}).[12]

Further temporal and spectral characterizations are ongoing, and we believe there is evidence to suggest the conversion efficiencies reported here can be significantly improved. Specific planned modifications include the use of antireflection coatings on the ppKTP waveguide crystal to reduce the facet reflectivities from 9% to <1%, the optimization of the coupling optics to better match the focused pump beam to the waveguide entrance, the removal of the unnecessary Bragg grating section, and the use of an aperiodically poled crystal structure to increase the SHG efficiency of the broad spectral bandwidth femtosecond pulses.

In conclusion, we have demonstrated a competitive methodology for the highly efficient generation of blue light from a compact, robust, and potentially portable Cr:LiSAF laser and a ppKTP waveguide crystal at room temperature. As much as 5.6 mW of blue average power is generated with only 27 mW of fundamental power at an internal SHG efficiency as high as 37% in a simple extracavity arrangement.

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