Efficient second-harmonic generation at 384 nm in periodically poled lithium tantalate by use of a visible Yb–Er-seeded fiber source

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We generated 56 mW of average power at 384 nm in periodically poled lithium tantalate by use of a visible fiber source based on a variable-pulse format seeded Yb–Er amplifier and frequency upconversion in periodically poled KTP. The feasibility of high-average-power, wide ultraviolet wavelength–range fiber-based sources is evaluated. © 2000 Optical Society of America

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A range of nonlinear frequency-conversion techniques was demonstrated recently in which a host of periodically poled materials were used in combination with traditional cw, pulsed, and diode laser sources. Current advances in lithographic techniques and materials engineering have led to increasingly shorter poling periods and permitted efficient upfrequency conversion in the blue and the ultraviolet. However, the choice of the traditional solid-state, diode-pumped, or diode laser sources limits the range of accessible wavelengths for blue and ultraviolet generation. Additionally, the linear absorption of periodically poled KTP (PPKTP) and periodically poled lithium niobate militates against the use of these materials for high-power generation in the wavelength range significantly below 400 nm.

Recent progress in parallel pumping techniques has brought about a new class of compact, all-fiber format pump sources with average power levels in excess of 10 W and with controllable temporal and spectral characteristics. These sources, which are capable of providing high peak powers over a wide spectral range, can readily replace the diode-pumped solid-state lasers that have been traditionally used in conjunction with periodically poled materials. As much as 50–80%-efficient second-harmonic generation in the green and the red has been reported with PPKTP and periodically poled lithium niobate in combination with ytterbium and erbium fiber sources. This type of fiber-based visible source can deliver a continuous choice of wavelengths from 510 to 800 nm at average power levels of as much as several watts and can be used for effective second-harmonic generation in the wide-ultraviolet range. The range from 300 to 390 nm can be reached with short-period- poled nonlinear materials, and the shortest ultraviolet wavelength limit depends on the absorption of the nonlinear material. Lithium tantalate is the most attractive choice for such applications. Although it has a relatively smaller nonlinearity than KTP or lithium niobate, lithium tantalate can be poled with periods as short as 1.75 μm (Ref. 7) and has a photorefractive damage threshold nearly twice as high as that of lithium niobate. It is also transparent in the ultraviolet to 280 nm. Thus periodically poled lithium tantalate (PPLT) is a perfect material for upfrequency conversion into the ultraviolet with high-peak- and average-power fiber sources.

In this Letter we demonstrate the highly efficient generation of ultraviolet radiation in PPLT by use of a powerful visible fiber-based source. 56-mW average power was generated at 384 nm by 159-mW power at 768 nm derived from a fiber source based on a variable-pulse format seeded Yb–Er amplifier with following frequency upconversion in PPKTP.

A schematic of the experimental configuration is shown in Fig. 1. A commercial 28-dBm Yb–Er-doped fiber amplifier with a maximum saturated power of 650 mW was employed. Control of fundamental wavelength, bandwidth, and pulse parameters was achieved by direct gain switching of the seeding distributed-feedback semiconductor laser at 1536 nm, which provided ~15 μW of average seeding power to the input of the amplifier. The format of the seed laser rf signal could be varied from nanosecond through picosecond pulse durations at repetition rates from 1 to 25 MHz. This variability permitted balancing the requirement for high peak powers that are needed for high conversion efficiencies in the
PPKTP element against the need to keep under control spectral broadening in the fiber amplifier caused by fiber nonlinearity. With a peak power of as much as 300 W the optical bandwidth of the infrared source was less then 0.05 nm. This value did not exceed the 1.5-nm phase-matching bandwidth of the PPKTP and permitted maximum frequency upconversion into the second-harmonic signal at 768 nm. A graded-index lens fused to the fiber output of the amplifier provided optimal focusing conditions with a focus waist size of 50 μm. The polarization state of the output of the amplifier was adjusted with a polarization-controlling loop, which provided a better than 10⁻⁶ extinction ratio. The uncoated 1-cm-long PPKTP sample had a 23-μm period grating with a 50/50 domain duty cycle for the optimal first-order quasi-phase-matched second-harmonic generation at room temperature. Because of the 22.5°-wide temperature bandwidth of the phase matching, no temperature stabilization of the PPKTP element was required. Figure 2 illustrates typical spectral and temporal profiles of the pulsed source at a 2.6-MHz repetition rate with an initial fundamental pulse duration of 960 ps (FWHM). At a 1.3-MHz repetition rate with a 1.6-ns input pulse duration, a 37% peak power conversion efficiency was obtained and 192 mW of average output power at 768 nm was produced. The fluctuations of the absolute power level of the visible signal were found to be less than 1% during several hours of continuous operation.

The 768-nm output beam had a profile with $M^2 \sim 1$ and was focused in a 3-cm-long, 0.3-mm-thick uncoated PPLT sample. The focusing waist radius $W_{\text{min}}$ was 27 μm. The sample was poled with seven domain periods from 2.32 to 2.44 μm and a 50/50 domain duty cycle for first-order quasi-phase-matched second-harmonic generation of 768 nm. The PPLT was kept in a temperature-stabilized oven and was maintained at ±277 °C with better than 0.1 °C stability. The phase-matching profile of second-harmonic generation at 277.1 °C was measured (see Fig. 3) in the 2.44-μm period PPLT domain with a modulated, tunable, fiber-delivered diode laser source, which permitted wavelength selection near 1536 nm with 10⁻³-nm precision. The measured FWHM phase-matching bandwidth of the PPLT sample was $\Delta_\lambda = 0.04$ nm. This value is two times wider than the theoretically estimated width $\Delta_\text{th} = 0.02$ nm. Correspondingly, the value for the effective length of the second-harmonic generation near the quasi-phase-matching maximum yields $L_{\text{eff}} = L_\text{th} \Delta_\lambda^{-1} = 15$ mm, where $L = 30$ mm is the physical length of the PPLT crystal. The wider-than-expected wavelength bandwidth of the second-harmonic generation could be attributed to three factors: First, the temperature gradients in the heating element and inhomogeneous heating of the 3-cm-long crystal widen the quasi-phase-matching bandwidth of PPLT. Second, errors in border positions and duty factor of the poled domains increase in a ferroelectric with decreasing size of the poling period. Third, the temperature instability that is due to the limited precision of the control electronics could be a contributing factor. Indeed, the precision of temperature stabilization in the experiment was 0.1 °C, one half of the expected value of the temperature bandwidth of the PPLT. We are planning to clarify the contribution of each these factors by using shorter PPLT crystals.

With 159-mW internal average pump power at 768 nm and a 1.5-ns pulse duration at a 1.3-MHz repetition rate, 56 mW of average power at 384 nm was produced in PPLT. This corresponds to a 40% peak power, or 35% average power, conversion efficiency into the second-harmonic signal at 384 nm (see Fig. 4). No reduction in conversion efficiency nor photorefractive damage of the PPLT sample during a few hours of continuous operation was observed. At low peak powers, the normalized second-harmonic conversion efficiency of the PPLT sample in first-order quasi-cw operation can be conveniently estimated as

$$\eta = \frac{P_{2\omega}}{L P_\omega^2} = \frac{2 \omega^3 d_{\text{eff}}^2 \xi}{\pi n_\omega n_{2\omega} \epsilon_0 c^4},$$

![Fig. 2. Typical spectra and temporal waveforms of the seeded fiber source at (right to left) fundamental, red, and ultraviolet wavelengths. The pulse repetition rate is 2.6 MHz.](image)

![Fig. 3. Spectral profile of quasi-phase-matched second-harmonic (SH) generation in 3-cm-long PPLT at 277.1 °C.](image)
where $P_{2\omega}$ and $P_\omega$ are second-harmonic and fundamental beam peak powers, respectively, $L$ is the crystal length, $\omega$ is the frequency of the fundamental beam, $d_{\text{eff}}$ is the effective nonlinearity of the periodically poled material, $\xi$ is the Boyd–Kleinman focusing factor, $\varepsilon_0$ is the permittivity of the free space, and $c$ is the speed of light. For the experimental focusing conditions the Boyd–Kleinman factor was $\xi = \lambda L / (2\pi W_{\text{min}}^2 n_\omega) = 2.2$. The measured normalized conversion efficiency was $1.7 \times 10^{-3}$ (cm W)$^{-1}$. This corresponds to $d_{\text{eff}} = 2.2$ pm/V, which is approximately one half of that reported elsewhere. However, when we take into account the fact that in our experiment $L/L_{\text{eff}} \sim 2$, the upper estimate for $d_{\text{eff}}$ is 4.4 pm/V, which is in accordance with values reported by other authors.

Using the experimental value of $d_{\text{eff}} = 2.2$ pm/V and taking into account the depletion of the 768-nm pump at higher peak powers (solid curve in Fig. 4), we estimate that, with a 5-W average power commercial Yb–Er amplifier, 1 W of average power near 380 nm can be produced. A relatively wide tunable wavelength range in the ultraviolet, from 300 to 390 nm, can be reached with seeding sources from wavelengths within the Yb and Er gain windows in conjunction with PPLT.

In conclusion, we have achieved 35% average efficiency in generation of ultraviolet light in periodically poled lithium tantalate by using high-efficiency cascaded second-harmonic generation in the red followed by sequential doubling to the ultraviolet. The versatile, variable-pulse format visible red source based on a seeded Yb–Er-doped fiber amplifier and second-harmonic generation in PPKTP demonstrated high average and peak powers, wavelength stability, and narrow linewidths. Taking into account pump depletion and the estimated effective nonlinearity of PPLT, we believe that the generation of as much as 1 W of average power in the ultraviolet is feasible with commercially available 5-W Yb–Er fiber amplifiers.

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References