Efficient, high-repetition-rate, femtosecond optical parametric oscillator tunable in the red

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We report efficient generation of tunable femtosecond pulses in the red by internal frequency doubling of an optical parametric oscillator (OPO) based on periodically poled $LiNbO_3$ (PPLN). The OPO, based on a 1-mm-thick PPLN crystal, is synchronously pumped by a femtosecond Ti:sapphire laser at 810 nm, providing signal pulses across 1.33–1.57 μm at a 76 MHz repetition rate. Using a 1-mm-thick crystal of BiB_3O_6 (BIBO) internal to the OPO cavity, we achieve frequency doubling of signal pulses across 665–785 nm with up to 260 mW of average power for 1.51 W of pump. The high nonlinear gain and phase-matching acceptance in PPLN and BIBO permit convenient tuning across the full range by simple detuning of OPO cavity delay. Intracavity dispersion compensation results in near-transform-limited red pulses with durations down to 140 fs for 185 fs input pump pulses. © 2008 Optical Society of America

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High-repetition-rate femtosecond pulses in the visible are of interest for various applications in biophotonics and time-domain spectroscopy. While under strong pumping wavelengths down to 650 nm may be reached by the Kerr-lens-mode-locked (KLM) Ti:sapphire, in practice visible spectral regions below 700 nm are not readily accessible to the this laser or its harmonics.

Optical parametric oscillators (OPOs) synchronously pumped by the KLM Ti:sapphire laser can provide broad tunability in the IR, but for femtosecond pulse generation in the visible alternative frequency conversion schemes have to be devised in combination with the OPO. An early approach based on intracavity frequency doubling of a Ti:sapphire-pumped near-IR femtosecond OPO [1] using noncollinear phase matching in $KTiOPO_4$ combined with β-BaB_2O_4 (BBO) for second-harmonic generation permitted tuning across 580–657 nm with up to 240 mW average power at 11.4% conversion efficiency. Another method has been based on frequency doubling of the KLM Ti:sapphire laser into the blue to pump a visible femtosecond OPO [2]. Using BBO in noncollinear configuration, tunable coverage across 566–676 nm was achieved with up to 100 mW of average power at 4.2% conversion efficiency. Recently, we also reported a femtosecond OPO based on BiB_3O_6 (BIBO) pumped in the blue [3] by the second harmonic of a KLM Ti:sapphire laser and tunable across the entire visible range. Using collinear pumping and angle phase matching, we achieved tuning across 480–710 nm with up to 270 mW of power at 14.2% conversion efficiency. At the same time, in all these experiments wavelength tuning across the full range requires angular phase matching of at least one nonlinear crystal within the OPO cavity, necessitating the realignment of the resonator during tuning.

Here, we describe efficient generation of femtosecond pulses with wide and convenient static tuning in the red by intracavity frequency doubling of an OPO based on periodically poled $LiNbO_3$ (PPLN). Although PPLN has been extensively deployed in Ti:sapphire-pumped OPOs for the generation of the near to mid-IR femtosecond pulses, to our knowledge, it has not been widely exploited for visible femtosecond pulse generation using phase-matched internal frequency upconversion techniques. In a recent report, sum-frequency mixing of the pump and signal in a femtosecond OPO based on MgO:PPLN was deployed to generate yellow radiation [4]. Using collinear pumping, 190 mW of yellow radiation at a fixed wavelength of 589 nm was generated at 14.6% conversion efficiency.

On the other hand, the high nonlinear gain and large phase-matching acceptance in PPLN are attractive for femtosecond pulse generation in the visible, as well as the IR, using additional internal frequency upconversion schemes. Here, we describe such an approach, where we demonstrate efficient generation of femtosecond pulses in the red using a PPLN OPO with BIBO for internal doubling. Owing to the high nonlinear gain in both PPLN and BIBO, and using collinear pumping, we achieve average powers of 260 mW for 1.51 W of Ti:sapphire pump at 17.2% conversion efficiency with tuning across 665–785 nm. Moreover, because of the large spectral acceptance in both crystals, convenient wavelength tuning across the full range is achieved simply by varying the OPO cavity delay [5] without adjustment of any other parameters such as PPLN crystal temperature, BIBO phase-match angle, or pump wavelength. The limit to the cavity-length-tunable range in the red is also set only by the reflectivity of the available OPO mirrors at signal wavelength.

The configuration of the femtosecond OPO is shown in Fig. 1. The pump is a KLM Ti:sapphire laser at 810 nm, providing 140 fs pulses at 76 MHz. After transmission through an isolator, the pulses have durations of 185 fs and an average power of 1.51 W.

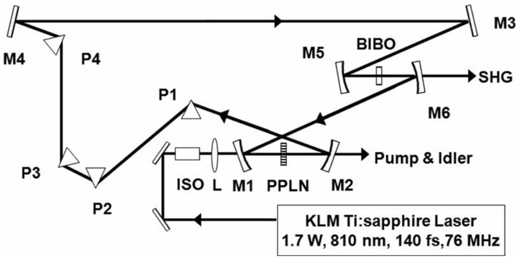

Fig. 1. Schematic of the internally frequency doubled PPLN femtosecond OPO for the generation of red pulses.

The OPO uses a 1 mm PPLN crystal with eight gratings ($\Lambda = 20.6-22.0\ \mu\mathrm{m}$), which is kept at a fixed temperature of $100\,^{\circ}\mathrm{C}$. The crystal end faces are antireflection (AR) coated ($R < 1\%$) over $1.3-1.6\ \mu\mathrm{m}$ and have high transmission ($T > 95\%$) for the pump. A lens of focal length $f = 5$ cm and AR coated ($R < 1\%$) at 810 nm is used to focus the pump beam into the PPLN crystal.

For maximum useful output power in the red, the OPO cavity is configured in a bifocal ring, with four concave reflectors and two plane mirrors. The concave mirrors, M_1 and M_2 ($r = 10$ cm), provide the focus for the PPLN crystal, whereas M_5 ($r = 10$ cm) and M_6 ($r = 7.5$ cm) allow focusing into the BIBO crystal. The plane mirror, M_3, is mounted on a translation stage that allows variation of cavity length with micrometer precision. All mirrors are highly reflecting ($R > 99\%$) over $1.35-1.55\ \mu\mathrm{m}$. M_1 and M_2 are also highly transmitting ($T > 90\%$) at 810 nm. The red output is extracted in one direction through M_6, which has high but variable transmission ($T > 95\%-70\%$) over 665–785 nm. Dispersion compensation is implemented using two pairs of SF-11 prisms spaced 28 cm tip-to-tip internal to the OPO cavity.

We used BIBO for internal doubling because of its large angular and spectral acceptance, low spatial and temporal walk-off, and broadband angle tuning at room temperature [6]. For frequency conversion into the visible, BIBO also offers a higher effective nonlinear coefficient ($d_{\mathrm{eff}} \sim 3$ pm/V) than BBO ($d_{\mathrm{eff}} \sim 2$ pm/V). Unlike our previous experiments [3,6,7] utilizing type I ($e + e \rightarrow o$) interaction in the yz plane, here we use BIBO with type I ($o + o \rightarrow e$) phase matching in the xz plane, providing an effective nonlinearity, $d_{\mathrm{eff}} \sim 2.9$ pm/V, for fundamental wavelengths in the $1.3-1.6\ \mu\mathrm{m}$ range. At the same time, using this geometry we are able to exploit a large spectral acceptance bandwidth ($\Delta\lambda \cdot l > 10$ nm mm), low group-velocity mismatch (GVM < 80 fs/mm), and near-zero group velocity dispersion (GVD $= 50-0\ \mathrm{fs}^2$/mm) over $1.3-1.6\ \mu\mathrm{m}$. These, together with the high nonlinearity of PPLN, permit simplified tuning in the red through simple adjustment of the OPO cavity delay. The BIBO crystal used was 1 mm thick and cut at $\theta = 10°$ ($\phi = 0°$) for frequency doubling at $\sim 1.4\ \mu\mathrm{m}$ at normal incidence. The crystal faces were AR coated ($R < 1\%$) at the signal wavelength.

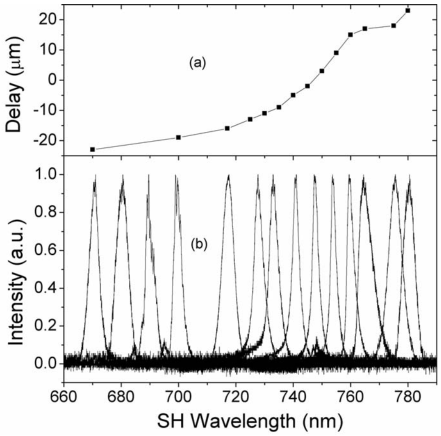

Fig. 2. (a) Cavity length detuning versus second-harmonic red wavelength. (b) Typical spectra of generated red pulses across the tuning range.

Wavelength generation in the red was achieved by continuous tuning of the OPO signal in the near-IR through adjustment of cavity delay. The PPLN temperature, grating period, and pump wavelength all remained fixed. The BIBO crystal was also maintained at a fixed angle at normal incidence ($\theta = 10°$). The calculated FWHM spectral acceptance bandwidth for doubling in the 1 mm BIBO crystal varies between ~ 10 and ~ 60 nm for fundamental wavelengths from 1.33 to $1.57\ \mu\mathrm{m}$. Nevertheless, we found that the red output could be tuned across the entire 120 nm range (665–785) at a fixed crystal angle by adjusting the cavity delay over $46\ \mu\mathrm{m}$. This, we believe, is due to the broadening of the phase-matching bandwidth by the large nonlinear gain in PPLN and BIBO and the high intracavity fundamental signal intensity. The static cavity length tuning avoided the need for realignment of the OPO during tuning, resulting in simplified tuning and improved efficiency. The cavity length tuning range and the corresponding red spectra are shown in Figs. 2(a) and 2(b), respectively, indicating spectral bandwidths from ~ 2.4 to ~ 5.6 nm. We attribute the variation in spectral bandwidths in the red to deviations in the OPO mirror GVD across the signal wavelength range. Since the prism sequence is not adjusted during cavity length tuning, variations in mirror GVD across the tuning range result in changes in the net intracavity dispersion and thus varying spectral bandwidths in the red. This variation can be over-

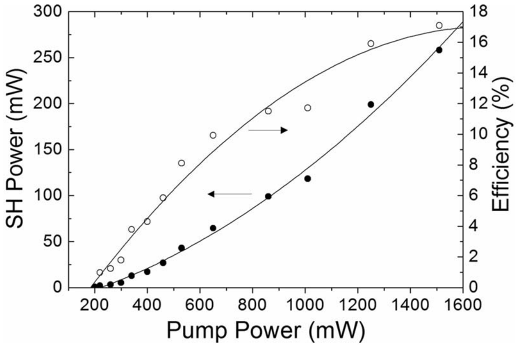

Fig. 3. Variation of the generated second-harmonic average power and conversion efficiency at 670 nm versus pump power at 810 nm.

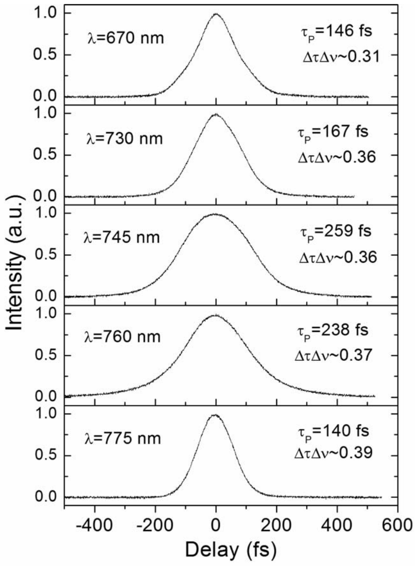

Fig. 4. Intensity autocorrelation traces of the generated red pulses across the tuning range.

come by using GVD-controlled chirped mirrors. The total tuning range in the red was limited only by the reflectivity of the available mirrors at the signal wavelength, and so could be readily extended to longer or shorter wavelengths using better optimized coatings.

Figure 3 shows the average output power and conversion efficiency at 670 nm, where the highest red power was obtained, versus pump power at 810 nm. The generated red power reaches 260 mW at the maximum pump power of 1.51 W, representing a conversion efficiency of 17.2%. The depletion at the pump power of 1.51 W is 70%. We were able to generate average powers >150 mW over ~60% and >100 mW over ~70% of the tuning range. At the extreme of the tuning range at 785 nm, practical powers of 70 mW were still available. The decline in the generated red power above 770 nm is mainly due to reduction in signal reflectivity of cavity mirrors. The pump power threshold for the frequency-doubled OPO was 200 mW.

Temporal measurements of the red pulses were performed using intensity autocorrelation in a 300 μm KDP crystal cut at $\theta=60°$ for type I $(o+o \rightarrow e)$ phase matching. Figure 4 shows recorded background-free autocorrelation profiles across the red tuning range. Pulse durations from 140 to 270 fs were measured, with time-bandwidth products from 0.31 to 0.46, implying a near-transform-limited performance. The variation in pulse duration across the tuning range is consistent with the variation in the corresponding spectra in Fig. 2(b) and is similarly attributed to changes in mirror GVD over the signal range. We thus expect that the use of suitable chirped mirrors with controlled GVD will enable the generation of red pulses with uniform durations of ~140 fs across the tuning range. A typical autocorrelation profile and spectrum at 728 nm are shown in Fig. 5, confirming a time-bandwidth product of 0.31.

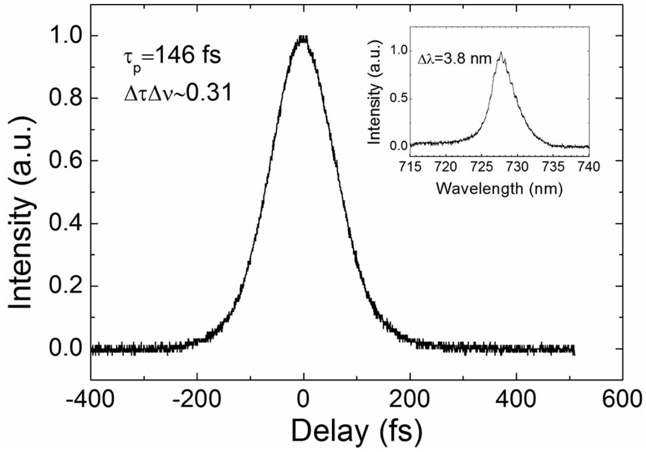

Fig. 5. Intensity autocorrelation trace and spectrum (inset) of the red pulses at 730 nm. The time duration of ~146 fs and the spectral bandwidth of ~3.8 nm result in near-transform-limit pulses with a time-bandwidth product of $\Delta\nu.\Delta\tau \sim 0.31$ (sech^2 pulse shape).

In conclusion, we have demonstrated a Ti:sapphire-pumped femtosecond OPO for the red based on PPLN in combination with BIBO, providing wide, continuous, and static tuning across 665–785 nm. The use of collinear pumping, a ring resonator, and intracavity dispersion control has enabled the generation of 260 mW of red power at 17.2% conversion efficiency with pulses down to 140 fs. The obtained tuning range is limited only by the available mirrors and can be extended into orange, yellow, and green using suitable coatings. The static cavity delay tuning offers promise for rapid wavelength scanning or modulation using piezoelectric control of the OPO cavity length.

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References

1. R. J. Ellingson and C. L. Tang, Opt. Lett. **18**, 438 (1993).
2. T. J. Driscoll, G. M. Gale, and F. Hache, Opt. Commun. **110**, 638 (1994).
3. M. Ghotbi, A. Esteban-Martin, and M. Ebrahim-Zadeh, Opt. Lett. **31**, 3128 (2006).
4. F. Ruebel, P. Haag, and J. A. L'huillier, Appl. Phys. Lett. **92**, 011122 (2008).
5. J. Seres and J. Hebling, J. Opt. Soc. Am. B **17**, 741 (2000).
6. M. Ghotbi and M. Ebrahim-Zadeh, Opt. Express **12**, 6002 (2004).
7. M. Ghotbi and M. Ebrahim-Zadeh, Opt. Lett. **30**, 3395 (2005).