Internally Frequency-Doubled PPLN Femtosecond Optical Parametric Oscillator Tunable in the Visible

A. Esteban-Martin,[1] O. Kokabee,[1] and M. Ebrahim-Zadeh[1,2]
[1]ICFO-Institut de Ciencies Fotoniques, Mediterranean Technology Park, 08860 Castelldefels, Barcelona, Spain
[2]Institucio Catalana de Recerca i Estudis Avancats (ICREA), Passeig Lluis Companys 23, Barcelona 08010, Spain
e-mail: adolfo.esteban@icfo.es

Abstract: Statically tunable femtosecond pulses in the red are generated by internal doubling of a PPLN-based OPO in BiB_3O_6. Cavity-delay tuning across 665-785 nm at average power of 260 mW in 140-fs pulses is demonstrated.

OCIS codes: 190.7110, 190.4970, 190.2620, 190.4400, 140.7300, 140.3600, 190.7220

Tunable, high-repetition-rate femtosecond pulses in the visible are of interest for applications in optical microscopy, frequency metrology, time-domain and molecular spectroscopy. However, this range remains largely inaccessible to ultrafast laser technology based on Kerr-lens-mode-locked (KLM) Ti:sapphire laser and its harmonics.

Synchronously-pumped optical parametric oscillators (OPOs) can extend the wavelength range of ultrafast lasers to new spectral regions, providing wide tunability. An early approach based on intracavity frequency doubling of a Ti:sapphire-pumped near-infrared femtosecond OPO [1] using non-collinear phase-matching in $KTiOPO_4$ (KTP) combined with second harmonic generation (SHG) in β-BaB_2O_4 (BBO) permitted tuning across the range 580-657 nm with an average power of 240 mW at 11.4% efficiency. Another method has been based on frequency doubling of the KLM Ti:sapphire laser into the blue to directly pump a femtosecond OPO in the visible [2]. Recently, we also reported a femtosecond OPO based on BiB_3O_6 (BIBO) synchronously pumped in the blue [3] by the second harmonic of a KLM Ti:sapphire laser. Using collinear pumping and angular phase-matching, we achieved tuning across 480-710 nm with up to 270 mW of output power at 14.2% conversion efficiency. At the same time, in all these experiments, wavelength tuning across the full range requires the angular phase-matching of at least one nonlinear crystal within the OPO cavity, necessitating the re-alignment of the resonator during tuning.

Here, we present efficient generation of femtosecond pulses with wide and convenient static tuning in the red using an OPO based on periodically-poled $LiNbO_3$ (PPLN) with BIBO for internal doubling. Although PPLN has been extensively used in Ti:sapphire-pumped OPOs for femtosecond pulse generation in the infrared, to our knowledge, it has not been widely exploited for visible pulse generation using phase-matched internal frequency upconversion techniques. Here we describe such an approach where, by taking advantage of the high nonlinear gain in PPLN and large phase-matching acceptance in BIBO, we achieve convenient tuning in the red only through the variation of the OPO cavity length without adjusting any other parameters.

The OPO (Fig. 1) is synchronously pumped directly by a KLM Ti:sapphire laser, providing an average power of 1.51 W at 810 nm in 185-fs pulses at 76 MHz. The OPO is based on a 1-mm-thick PPLN crystal containing eight gratings with period from 20.6 to 22.0 μm. The crystal is kept at 100 ºC to avoid photorefractive damage.

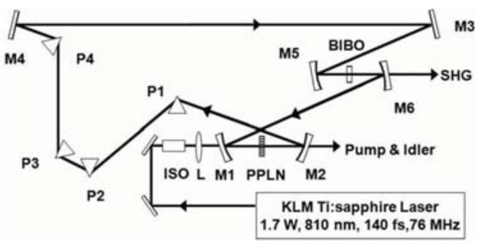

Fig. 1. Schematic of the internally doubled PPLN femtosecond OPO for the generation of red pulses.

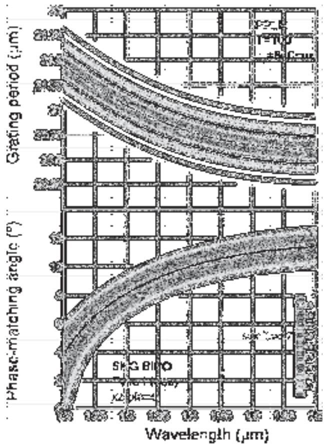

Fig. 2. Phase-matching diagrams for PPLN and SHG in BIBO showing the variation of the normalized gain coefficient, $\mathrm{sinc}^2(\Delta\kappa l/2)$.

The crystal end-faces are AR-coated (R<1%) over 1.3–1.6 µm and have >95% transmission 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. The resonator is arranged in a bifocal ring, comprising four concave reflectors and two plane mirrors. The concave mirrors M1 and M2 (r=100 mm) provide the focus for the OPO crystal, whereas M5 (r=100 mm) and M6 (r=75 mm) allow focusing into the doubling crystal. The plane mirror M3 is mounted on a translation stage that allows variation of the cavity length with precision of microns. All OPO mirrors are highly reflecting (R>99%) over 1.35-1.55 µm. The mirrors M1 and M2 are also >90% transmitting for the pump at 810 nm. The red output is extracted through M6, which has high but variable transmission (T>95% to 70%) over 665-785 nm. Dispersion compensation is implemented by using two pairs of SF-11 prisms spaced 28 cm tip-to-tip internal to the OPO cavity.

Intracavity frequency-doubling is achieved in a 1-mm-thick BIBO crystal inserted into the additional secondary focus of the OPO cavity. The crystal is cut at θ=10º in the optical xz-plane for type I (o+o→e) frequency doubling [4], providing an effective nonlinearity, d_{eff}~2.9 pm/V. The crystal faces were AR-coated (R<1%) for the signal. Calculations presented in Fig. 2 show the favorable characteristics of the combination of the high nonlinearity of PPLN together with the large spectral acceptance bandwidth of BIBO in the 1.2-1.6 µm fundamental wavelength range, permitting simplified tuning across the red only through adjustment of the OPO cavity delay, without the need to vary any other parameters such as pump wavelength, PPLN grating period or BIBO crystal angle. The cavity length tuning range (665-785 nm) is shown in Fig. 3(a), and the corresponding red spectra across the tuning range are presented in Fig. 3(b), where spectral bandwidths ranging from ~2.4 nm to ~5.6 nm are measured. The limit to the cavity-length-tunable wavelength coverage in the red is also set only by the signal reflectivity of the available OPO mirrors, and so could be extended to shorter or longer wavelengths in the visible range using suitable mirrors. This is currently under investigation and the results of these studies will be reported.

Figure 4 shows the red average output power and conversion efficiency at 670 nm, where the highest power was obtained, versus pump power at 810 nm. The generated red power reaches 260 mW at the maximum available pump power of 1.51 W, corresponding to a conversion efficiency of 17.2%. The pump depletion is 70% at the maximum input pump power of 1.51 W. The Ti:sapphire pump power threshold for the frequency-doubled OPO was 200 mW.

Temporal characterization of the generated red pulses was performed using the intensity autocorrelation in a 300-µm KDP crystal cut at θ=60º for type I (o+o→e) phase-matching. Pulse durations from 140 fs to 270 fs were measured, with time-bandwidth products from 0.31 to 0.46, implying near-transform-limited performance. The variation in pulse duration across the tuning range is consistent with the variation in the corresponding spectra presented in Fig. 3(b), and is attributed to changes in mirror GVD over the signal wavelength range. Fig. 5 shows a typical autocorrelation profile and the corresponding spectrum at 728 nm, confirming a nearly transform-limited pulse with a time-bandwidth product of 0.31 (sech^2 pulse shape).

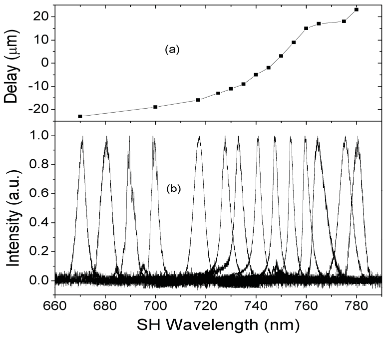

Fig. 3. Cavity length detuning versus second harmonic red wavelength (a) and typical spectra of generated red pulses across the tuning range (b).

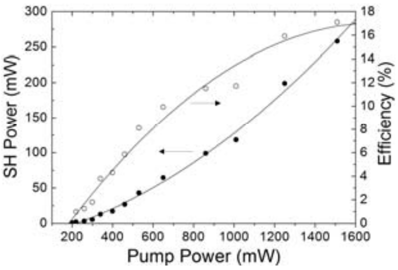

Fig. 4. Variation of the generated second harmonic average power and conversion efficiency at 670 nm versus pump power at 810 nm.

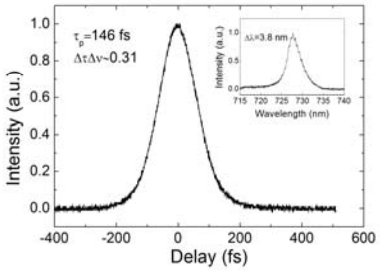

Fig. 5. Intensity autocorrelation trace and spectrum (inset) of the red pulses at 730 nm. The time duration of ~146 fs and the spectral bandwidth of ~3.8 nm result in near-transform-limited pulses with Δν.Δτ~0.31

References

[1] R. J. Ellingson and C. L. Tang,"High-power, high-repetition-rate femtosecond pulses tunable in the visible," Opt. Lett. **18**, 438 (1993).
[2] T. J. Driscoll, G. M. Gale, and F. Hache,"Ti:sapphire 2nd-harmonic-pumped visible range femtosecond optical parametric oscillator," Opt. Commun. **110**, 638 (1994).
[3] M. Ghotbi, A. Esteban-Martin, and M. Ebrahim-Zadeh,"BiB_3O_6 femtosecond optical parametric oscillator," Opt. Lett. **31**, 3128 (2006).
[4] M. Ghotbi and M. Ebrahim-Zadeh," Optical second harmonic generation properties of BiB_3O_6," Opt. Express **12**, 6002-6019 (2004).