High-harmonic-repetition-rate, 1 GHz femtosecond optical parametric oscillator pumped by a 76 MHz Ti:sapphire laser

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Received November 13, 2008; accepted November 27, 2008;
posted January 7, 2009 (Doc. ID 103733); published February 6, 2009

We demonstrate the generation of femtosecond pulses in a synchronously pumped optical parametric oscillator (SPOPO) at the harmonics of pump repetition rate using a SPOPO cavity longer than the fundamental synchronous length. The SPOPO is based on a 1 mm crystal of periodically poled $\mathrm{LiNbO_3}$ and pumped by a Kerr-lens mode-locked Ti:sapphire laser at 76 MHz. By increasing the SPOPO synchronous cavity length we have generated output signal pulses at successive harmonics of the pump repetition rate up to the 13th harmonic at 988 MHz, where average signal powers of 30 mW are still available for 1.45 W of pump power. The generated signal pulses at 988 MHz are near transform limited with average durations of 227 fs and a time-bandwidth product of 0.41 for 185 fs input pump pulses. © 2009 Optical Society of America

OCIS codes: 190.7110, 190.4970, 190.4400, 190.4410.

High-repetition-rate, synchronously pumped optical parametric oscillators (SPOPOs) providing femtosecond pulses with tunability in the IR are of interest for time-domain spectroscopy, biophotonics, and optical microscopy. Most femtosecond SPOPOs developed to date are synchronously pumped by the Kerr-lens mode-locked (KLM) Ti:sapphire laser at repetition rates typically <100 MHz [1,2]. For some applications, such as pump–probe spectroscopy [3] or future optical communication systems [4], ultrashort pulses at a gigahertz repetition rate are desirable.

To increase the repetition rate of femtosecond SPOPOs to the gigahertz range three different approaches have been previously adopted. The first involves the use of very compact, gigahertz-repetition-rate lasers for higher-order synchronous pumping of the oscillator. The highest repetition rate achieved with this scheme is 1 GHz in a periodically poled $\mathrm{LiNbO_3}$ (PPLN) SPOPO with a cavity four times that of the pump laser and a power threshold of 580 mW [5]. This method, however, suffers from the need for a custom-designed, very-high-repetition-rate femtosecond pump laser with sufficiently high power, instead of the widely available KLM Ti:sapphire laser. The other two techniques make direct use of the KLM Ti:sapphire laser at 70–100 MHz repetition rate as the pump source. In the first of these techniques a SPOPO with a cavity length N times shorter than pump laser generates a signal pulse train at N times the pump repetition rate [6–8]. The highest repetition rate achieved with this method is 1 GHz in a KTP SPOPO at 12 times the repetition rate of a femtosecond KLM Ti:sapphire pump laser at 84 MHz [8]. The ring-cavity SPOPO was 30 cm long with a threshold of 800 mW. The requirement for a short SPOPO cavity length in the above methods results in a large signal beam waist, leading to increased difficulty in attaining optimum mode matching with the pump. Further increases in repetition rate are also difficult owing to the physical limitations on the shortest attainable SPOPO cavity length and the corresponding rise in threshold. Moreover, the physical limit prevents the inclusion of additional components inside the SPOPO cavity, such as prisms for dispersion compensation to improve pulse quality. The third method is based on the cavity length difference between the SPOPO and its pump laser, instead of the cavity length of the SPOPO alone. Using this technique, a maximum repetition rate of 400 MHz (five times the pump repetition rate) with a pump threshold of 350 mW has been achieved [9]. In this PPLN SPOPO, a cavity length 3/5 of the pump laser cavity length was used, which still enables inclusion of intracavity elements. While the reduction in the SPOPO cavity length in this method is much less severe than the first two techniques, the physical limitations to the SPOPO cavity length will ultimately still be a barrier to the generation of highest harmonics toward gigahertz repetition rates.

In this Letter, we demonstrate a SPOPO producing higher harmonics of the pump repetition rate with a longer cavity than the pump laser cavity length. In a conventional SPOPO, the cavity length of the oscillator (l_{opo}) should be exactly equal to that of pump laser (l_p), and the generated output pulses have the same repetition rate as the pump laser. In this way, every generated signal in the nonlinear crystal after traveling one round trip of the SPOPO cavity, without missing any pump pulse, meets and interacts with the next pump pulse in the sequence inside the crystal. In the new method, to generate the Qth harmonic of the pump repetition rate, we set the SPOPO cavity length to be (n/Q) times the pump laser cavity length (n is an integer, $n>Q$, and with no common divisor). The $\Delta L=(n-Q)\cdot l_p/Q$ difference in the SPOPO and pump cavity lengths compels every generated signal to travel Q round trips inside the new elongated SPOPO cavity to build-up a distance equal to an integer number (n) of pump laser cavity lengths, before meeting the next pump pulse in the nonlinear crystal. This difference, independent of the value of n, causes a time difference of $(1/Q)\cdot l_p/c$ between generated signal pulses, which results in an output signal pulse train with a repetition rate Q times that of the pump laser. Therefore, different values of n could be used for the same repetition rate, providing a degree of freedom to deploy different cavity lengths. Figure 1 shows two examples of this scenario to produce the second harmonic of pump repetition rate with two different values for n. The first row, in Figs. 1(a) and 1(b), is the input pump pulse train, and the second row is the SPOPO output signal pulse train (S). Figure 1(a) corresponds to $Q=2$ and $n=3$. Here, the SPOPO cavity length is 3/2 times the length of pump laser cavity; hence every round trip of SPOPO cavity takes 3/2 times the time between every two consecutive pump pulses. Therefore, the generated signal has to travel two round trips in the cavity to match and meet the next pump pulse. Likewise, Fig. 1(b) illustrates the $Q=2$ and $n=5$ case. In both cases, for different n's, there is no difference in the number of round trips inside the SPOPO cavity, so the amount of loss experienced by the signal pulses is similar. The only difference is the number of individual signal pulses, which are generated by the first pump pulses and are amplified in the next interactions with them. In fact, for every Q and n, n different signals are generated and being amplified in the cavity without overlapping with themselves.

Using this technique, we demonstrate the generation of signal pulses at different harmonics of pump laser repetition rate. The schematic of the experimental setup is shown in Fig. 2. The femtosecond SPOPO is based on PPLN and synchronously pumped by 185 fs pulses at 814 nm from a KLM Ti:sapphire laser at 76 MHz. This repetition rate corresponds to a standing-wave linear cavity length of 1974 mm. To demonstrate the concept, the SPOPO is configured in a four-mirror linear cavity with no dispersion compensation. For every repetition rate, Q, the linear cavity length of the SPOPO is set to be $\Delta L=(1974/Q)$ mm longer than 1974 mm, where $n=Q+1$.

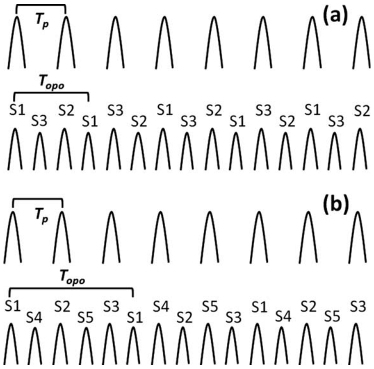

Fig. 1. Schematic of the concept for (a) $Q=2$ and $n=3$ and (b) $Q=2$ and $n=5$. In (a) and (b) the first row of pulses is the output pump pulse train, and the second row is the SPOPO signal output pulse train (S). T_p is the round-trip time inside the pump laser cavity and T_{opo} is the round-trip time inside the SPOPO cavity.

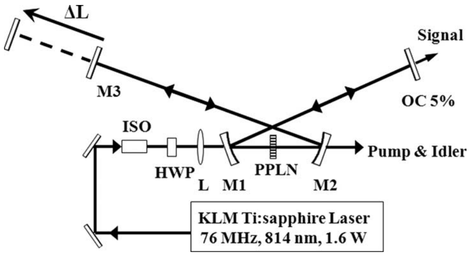

Fig. 2. Experimental setup of the femtosecond SPOPO generating optical pulses at high harmonics of the pump repetition rate. ISO, optical isolator; HWP, half-wave-plate; L, focusing lens.

The PPLN crystal (11 mm × 0.5 mm × 1 mm) contains eight gratings ($\Lambda=20.6$ to 22.0 μm) and is maintained at 100°C to avoid photorefractive damage. The crystal faces are antireflection (AR) coated ($R<1\%$) for 1.3–1.6 μm and have high transmission ($T>95\%$) for the pump at 814 nm. The pump beam is focused into the crystal using a 5 cm focal length lens, which is AR coated ($R<1\%$) for the pump. The SPOPO cavity consists of two spherical mirrors, $M1$ and $M2$ (each with $r=100$ mm), one plane high reflector ($M3$) and a plane output coupler (OC) with ~5% transmission over 1.33 to 1.56 μm. The pump, signal, and idler beams are all polarized along the z axis, hence accessing the largest nonlinear tensor element in PPLN ($d_{\text{eff}}\sim 17$ pm/V). The OC is mounted on a translation stage for fine tuning of cavity length with precision of micrometers. Singly resonant oscillation is ensured by use of mirrors with a high reflectivity ($M1$, $M2$, $M3$: $R>99\%$; OC: $R\sim 95\%$) for the signal but high transmission for pump and idler ($M1$, $M2$: $T>95\%$). Because of the lack of intracavity dispersion control, the SPOPO was operated near 1350 nm for maximum output stability.

By carefully increasing the SPOPO cavity length (ΔL) through adjustment of the $M2-M3$ arm, we successfully obtained and examined 3rd, 5th, 9th, and 13th harmonics of pump repetition rate, corresponding to 228, 380, 684, and 988 MHz. Figure 3 shows the variation of measured SPOPO output power and threshold with the harmonic number at different harmonics of the pump repetition rate. The output power

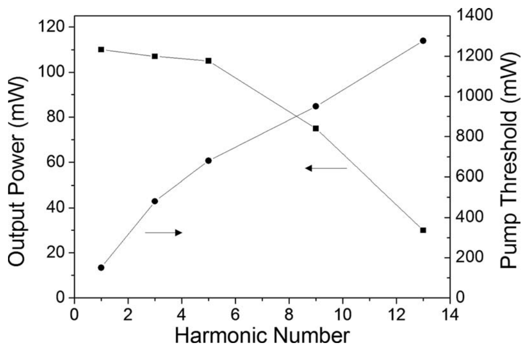

Fig. 3. SPOPO output power and pump power threshold versus harmonic number.

remains relatively constant up to the fifth harmonic, owing to the small increase in circulating signal loss relative to the ~5% output coupling used, but decreases for higher harmonics owing to the increasing intracavity loss arising from higher number of signal round trips in the absence of gain. At the same time, there is a corresponding increase in SPOPO threshold, which is again to be expected given that increments in the harmonic number are equivalent to more round trips in the cavity, hence resulting in more loss for the circulating signal. The SPOPO will continue to operate if the first generated signal by a pump pulse does not vanish owing to the losses before reaching and meeting the next pump pulse.

The highest harmonic achieved was 13th, with pump power threshold of 1.25 W. With an input power of 1.45 W after the optical isolator and wave plate, the average signal power through 5% OC was 30 mW at 1350 nm. The pulse trains corresponding to the KLM Ti:sapphire laser at 76 MHz and the SPOPO output signal pulses in the 13th harmonic at 988 MHz are shown in Figs. 4(a) and 4(b), respectively. The trains were monitored with an InGaAs photodetector (20 GHz, 18.5 ps) and a fast oscilloscope (2 GHz, 10 GS/s). The observed gradual decrease in signal pulse intensity in the train is expected, owing to the intrinsic property of the method. In every 13 pulses, the most intense pulse is that which interacts directly with a pump pulse and experiences gain, but the next 12 pulses only encounter loss during their subsequent round trips. This reduction in signal intensity could be improved by optimization of output coupling as well as mirror and crystal coatings.

Intensity autocorrelation measurements of SPOPO signal pulses were performed in a 1 mm type I ($o+o \rightarrow e$) $\mathrm{LiIO_3}$ crystal ($\theta=24°$). A typical autocorrelation profile at the 13th harmonic and corresponding spectrum near 1350 nm are shown in Fig. 5. The average pulse duration is estimated as 227 fs (assuming sech^2 pulse shape), and the spectrum has a FWHM bandwidth of 11 nm, resulting in a time-bandwidth product of 0.41. By increasing the harmonic number from 3rd to 13th, we observed a decrease in pulse duration from 300 to 227 fs, with the time-bandwidth product reducing from 0.63 to 0.41. This behavior can be attributed to increased signal losses at higher harmonics, which result in reduced intracavity intensity, thus lowering the effects of the self-phase modulation responsible for positive chirping of signal pulses. This is consistent with the observed improvement in spectral quality and narrowing of the FWHM bandwidth from 13 to 11 nm from the 3rd to the 13th harmonic.

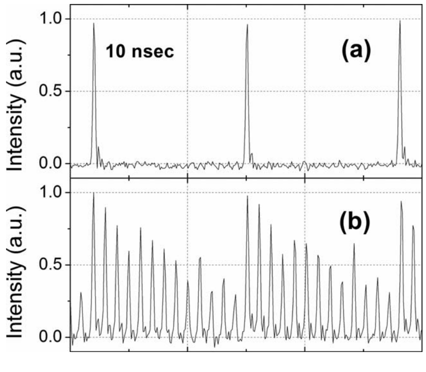

Fig. 4. (a) Input pulse train of Ti:sapphire pump laser at 76 MHz and (b) output signal pulse train of the femtosecond SPOPO at the 13th harmonic repetition rate (988 MHz) pumped by this laser. The irregularity in the intensity of successive pulses in each train is owing to detection electronics.

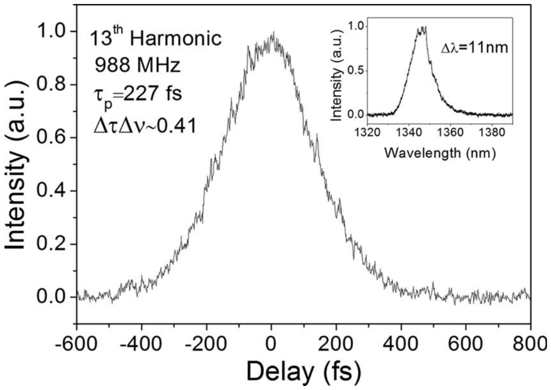

Fig. 5. Intensity autocorrelation and corresponding optical spectrum of SPOPO signal pulses at the 13th harmonic repetition rate (988 MHz).

We have thus demonstrated a ~1 GHz femtosecond SPOPO pumped by a 76 MHz Ti:sapphire laser using a cavity longer than the fundamental synchronous length, with the highest harmonic limited by the rise in the SPOPO threshold above the available pump power. The technique also offers promise for realization of future multigigahertz ultrafast optical communication systems using miniature mode-locked semiconductor pump lasers.

We acknowledge partial support from Spanish Ministry of Education and Science through the Consolider Program (CSD2007-00013). The authors thank Jens Biegert and Olivier Chalus for the loan of the fast oscilloscope.

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