# 1-GHz femtosecond optical parametric oscillator pumped by a 76-MHz Ti:sapphire laser

**Omid Kokabee[1], Adolfo Esteban-Martin[1], Konstantinos Moutzouris[2], Majid Ebrahim-Zadeh[1,3]**
*[1]ICFO-Institut de Ciencies Fotoniques, Mediterranean Technology Park, 08860 Castelldefels, Barcelona, Spain*
*[2]Technological Educational Institution of Athens, Department of Electronics, Athens, 12210, Greece*
*[3]Institucio Catalana de Recerca i Estudis Avancats (ICREA), Passeig Lluis Companys 23, Barcelona 08010, Spain*
*omid.kokabee@icfo.es*

**Abstract:** We demonstrate a ~1 GHz femtosecond optical parametric oscillator synchronously pumped by a 76-MHz Ti:sapphire laser using a cavity longer than the fundamental synchronous cavity length. Near-transform-limited pulses with average durations of 227 fs are generated.

**OCIS codes:** 190.7110, 190.4970, 190.4400, 190.4410

Synchronously-pumped optical parametric oscillators (SPOPOs) represent versatile sources of high-repetition-rate femtosecond pulses. To date, the majority of femtosecond SPOPOs have been pumped by the Kerr-lens-mode-locked (KLM) Ti:sapphire laser at repetition-rates typically <100 MHz. For some applications, such as pump-probe spectroscopy or future optical telecommunication systems, ultrashort pulses at GHz repetition-rate are desirable.

Three different approaches have been previously adopted to increase the repetition-rate of a femtosecond SPOPOs to the GHz range. The first deploys GHz-repetition-rate pump lasers, but suffers from the need for custom-designed, very-high-repetition-rate femtosecond pump laser with sufficiently high power, instead of the widely available KLM Ti:sapphire laser [1]. The other two methods make direct use of the KLM Ti:sapphire laser at 70-100 MHz as the pump source [2-4]. Both techniques are based on cavity length reduction which results in a large signal beam waist, leading to increased difficulty in attaining optimum mode matching with the pump, especially for the generation of highest harmonics towards GHz repetition-rate. Moreover, the physical limit prevents the inclusion of additional components inside the SPOPO cavity such as prisms for dispersion compensation to improve pulse quality.

In this work, we demonstrate, for the first time to our knowledge, a SPOPO producing higher harmonics of the pump repetition-rate with a longer cavity than the pump laser cavity length. In a conventional SPOPO, 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 travelling one round-trip inside the SPOPO cavity, without missing any pump pulse, meets and interacts with the next pump pulse in the sequence inside crystal. In the new method, to generate the $Q$th harmonic of the pump repetition-rate, we set the SPOPO cavity length to be $(n/Q)$ times the pump laser cavity length ($n$ is integer, $n>Q$ and with no common divisor). The $(n-Q).l_p/Q$ difference in 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 $(1/Q).l_p/c$ 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 Fig. 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 a configuration of $Q$=2 and $n$=3. Here, the SPOPO cavity length is 3/2 times the length of pump laser cavity, hence every round-trip in the SPOPO cavity takes 3/2 times that of 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, Figure 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 the 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

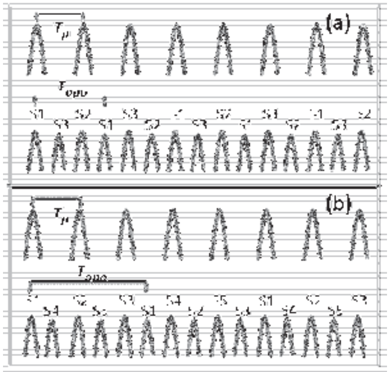

**Fig. 1.** Schematic diagram of the concept to generate high harmonics of the pump repetition-rate for (a) $Q$=2 and $n$=3 and (b) $Q$=2 and $n$=5. In (a) and (b), first row of pulses is pump output pulse train and the second row is SPOPO signal output pulse train (S). $T_p$ is the round-trip time inside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

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 and for the sake of simplicity, the SPOPO is configured in a four-mirror linear cavity with no intracavity dispersion compensation. For every repetition-rate $Q$, the linear cavity length of SPOPO is set to be (1974/$Q$) mm longer than 1974 mm, where $n=Q+1$.

The PPLN crystal (11×0.5×1 mm$^3$) contains eight gratings, equally spaced in period from 20.6 to 22 µm, and is placed on a homemade oven at 100 °C in order to avoid photorefractive damage. The crystal facets 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 a transmission of ~5% over 1.33 to 1.56 µm. The pump, signal and idler beams are all polarized along $z$-axis, hence accessing the largest nonlinear tensor element in PPLN ($d_{33}$~17 pm/V). The OC is mounted on a translation stage for fine tuning of cavity length with precision of microns. Singly-resonant oscillation is ensured by use of mirrors with a high reflectivity (M1, M2, M3: $R>99\%$; OC: $R$~95%) for the signal wave, 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.

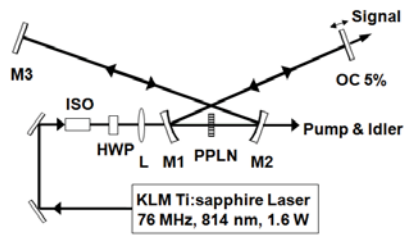

**Fig. 2.** Experimental setup of SPOPO. ISO: optical isolator, HWP: a half-wave plate, L: focusing lens.

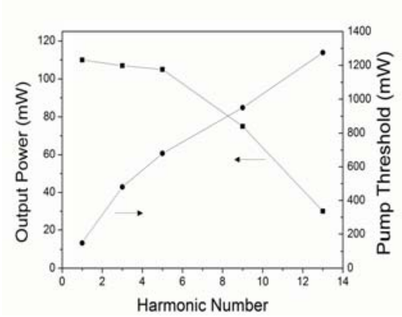

**Fig. 3.** SPOPO output power and pump power threshold versus harmonic number.

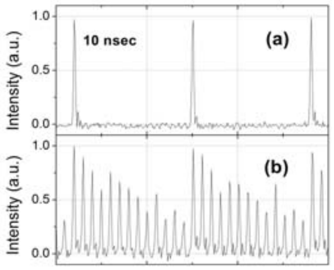

**Fig. 4.** (a) Input pulse train of KLM Ti:sapphire pump laser at 76 MHz, and (b) Output signal pulse train of the femtosecond SPOPO at the 13th harmonic repetition-rate (988 MHz) pumped by this laser.

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

The highest harmonic achieved was 13th, with threshold pump power of 1.25 W. With an input power of 1.45 W after optical isolator and wave-plate, the average signal power through 5% output coupler 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 a repetition rate of 988 MHz are shown in Fig. 4(a) and 4(b), respectively. The observed gradual decrease in signal pulse intensity in the train is expected, due to the intrinsic property of the method. In every thirteen pulses, the most intense pulse is that which interacts directly with a pump pulse and experiences gain, but the next twelve 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 crystals coatings.

Using intensity autocorrelation technique the average signal pulse duration is estimated as 227 fs, assuming sech$^2$ pulse shape, and the corresponding spectrum has a FWHM bandwidth of 11 nm, resulting in a time-bandwidth product of 0.41, and implying near-transform-limited pulses. By increasing the harmonic number from 3rd to 13th, we observed a decrease in pulse duration from 300 to 227 fs and bandwidth from 13 to 11 nm, with the time-bandwidth product reducing from 0.63 to 0.41.

## References

[1] X. P. Zhang, J. Hebling, A. Bartels, D. Nau and J. Kuhl, W. W. Ruehle, and H. Giessen, "1-GHz-repetition-rate femtosecond optical parametric oscillator," Appl. Phys. Lett. **80**, 1873 (2002).

[2] D. T. Reid, C. McGowan, W. Sleat, M. Ebrahimzadeh, and W. Sibbett, "Compact, efficient 344-MHz repetition-rate femtosecond optical parametric oscillator," Opt. Lett. **22**, 525 (1997).

[3] J. Jiang and T. Hasama, "Harmonic repetition-rate femtosecond optical parametric oscillator," Appl. Phys. B **74**, 313 (2002).

[4] J. Jiang and T. Hasama, "Synchronously pumped femtosecond optical parametric oscillator based on an improved pumping concept," Opt. Commun. **220**, 193 (2003).