# Extended-cavity, tunable, GHz-repetition-rate femtosecond optical parametric oscillator pumped at 76 MHz

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**Abstract**: We report the generation of tunable GHz-repetition-rate femtosecond pulses in a synchronously-pumped optical parametric oscillator (SPOPO) with extended cavity length pumped by a 76 MHz Kerr-lens mode-locked Ti:sapphire laser. In a SPOPO based on periodically-poled $LiNbO_3$, insertion of a prism pair for dispersion compensation internal to the linear cavity provides stable output pulse trains of up to 14th harmonic of pump repetition-rate (1064 MHz) with 70 mW of average power for 1.45 W of pump. Near-transform-limited pulses down to 216 fs are achieved with wide tunability across 1500-1540 nm by continuous detuning of the SPOPO cavity delay over 8 μm.

**OCIS codes:** (190.7110) Nonlinear optics, Ultrafast nonlinear optics; (190.4970) Parametric oscillators and amplifiers; (190.4400) Nonlinear optics, materials; (190.4410) Nonlinear optics, parametric processes.

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## 1. Introduction

Synchronously-pumped optical parametric oscillators (SPOPOs) represent versatile sources of femtosecond pulses at high repetition rate (*RR*). To date, the majority of femtosecond SPOPOs have been pumped by the Kerr-lens-mode-locked (KLM) Ti:sapphire laser at *RR's* typically below 100 MHz [1,2]. However, ultrashort pulses at much higher *RR*'s approaching GHz and above are of interest for some applications including future optical communication systems [3] and pump-probe spectroscopy [4].

Pump laser repetition-rate ($RR_p$) and SPOPO cavity length ($L_{opo}$) are two parameters that can be varied to increase the SPOPO output repetition-rate ($RR_{opo}$). In the former case, for any

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required $RR_{opo}$ in the GHz range, a very compact pump laser is required. The highest $RR_{opo}$ in the femtosecond regime is 1 GHz in a PPLN-based SPOPO [5,6]. The main shortcoming of this method is the need for custom-designed, very-high-*RR* femtosecond pump laser with sufficiently high power, instead of the widely available commercial KLM Ti:sapphire laser. In the latter case, based on the KLM Ti:sapphire pump laser at *RR*'s below 100 MHz, two approaches deployed earlier involve shortening of the SPOPO cavity. In the first technique, a SPOPO with a cavity length *N*-times shorter than pump laser cavity length ($L_p$) generates a signal pulse train at *N*-times the $RR_p$. The highest $RR_{opo}$ achieved with this scheme is 1 GHz in a KTP-based SPOPO, at 12 times the 84 MHz *RR* femtosecond KLM Ti:sapphire pump laser [7]. The second method is based on the cavity length difference between the SPOPO and its pump laser, instead of $L_{opo}$ alone. Using this technique, a maximum $RR_{opo}$ of 400 MHz (5 times the $RR_p$) has been achieved in a PPLN-based SPOPO with $L_{opo} = (3/5)L_p$ [8]. The short $L_{opo}$ in the above methods leads to increased difficulty in optimum mode-matching between the pump and signal, and prevents the inclusion of additional components inside the SPOPO cavity such as prisms for dispersion compensation to improve pulse quality. Further increases in the *RR* are also extremely difficult due to the physical limitations on the shortest $L_{opo}$ and corresponding rise in the pump power threshold.

Recently, we demonstrated a 1 GHz femtosecond SPOPO pumped by a 76-MHz Ti:sapphire laser using a cavity longer than the fundamental synchronous length [9]. In this approach, femtosecond pulses at *Q*th harmonic of pump repetition rate can be produced by adding $(1/Q)$ of $L_p$ to $L_{opo}$. In this paper, we report successful implementation of dispersion compensation internal to SPOPO cavity using a pair of SF-11 prisms, thus demonstrating the potential of the present approach for inclusion of intracavity components, which is difficult to achieve with schemes based on shortening the SPOPO cavity length. The inclusion of intracavity prism pair has also resulted in extended SPOPO signal tunability, shift into telecommunication wavelength range, improved pulse quality and stability, and higher output powers.

## 2. Concept

In a conventional SPOPO, $L_{opo}$ should be equal to $L_p$ and the generated output pulses have the same *RR* as the pump laser. In this way, every generated signal in the nonlinear crystal, after traveling 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 (see Fig. 1(a)). In the new method, we generate the *Q*th harmonic of pump *RR* while increasing the SPOPO cavity

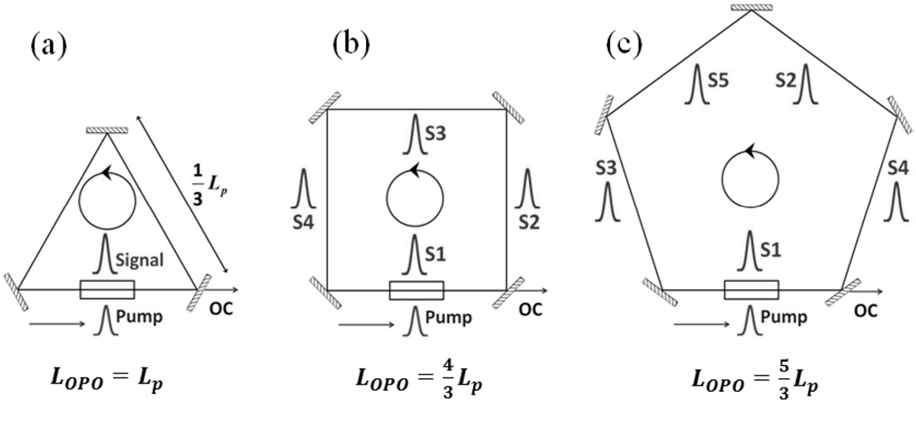

Fig. 1. Comparison of signal gaining in (a) fundamental synchronous SPOPO cavity with two examples for generation of third harmonic of pump repetition-rate ($Q = 3$) for (b) $n = 4$ and (c) $n = 5$. S1 to S5 are the independently generated signal pulses. OC is output coupler.

length by setting $L_{opo} = (n/Q)\ L_p$ with cavity length difference of where $Q$ and $n$ are integer and $n>Q$ with no common divisor. $L_p/c$ and $(n/Q)\ L_p/c$ are round-trip times inside the pump laser and SPOPO cavities, respectively. The difference in round-trip times ($[(n\text{-}Q)/Q]\ L_p/c$) is the extra time that the generated signal pulses should travel in every round-trip inside the SPOPO cavity, which causes the signal and pump pulses to enter the crystal at different instants of time. Overlapping of the signal pulse and any other pump occurs when the arrival time difference becomes an integer multiple of $L_p/c$, or simply after every $Q$ round-trips of signal pulse inside the SPOPO cavity being $n\ L_p/c$. This total time corresponds to the arrival time of next ($n$ + 1)th pulse in the pump pulse train at the crystal. All of the medial $n$ pump pulses generate $n$ independent signal pulses, which finally create a time difference of $(1/Q)\ L_p/c$ between train of pulses inside the cavity [9]. This difference, independent of the value of $n$, results in an output signal pulse train with a repetition-rate $Q$ times that of the pump laser. The $Q$-1 different signal pulses which pass the crystal between every two successive pump pulses do not experience any amplification. The fact that this technique allows the use of different $n$'s for the generation of certain $Q$th harmonic of $RR_p$ provides an extra degree of freedom to deploy different $L_{opo}$ for a given $RR_{opo}$. One example is shown in Fig. 1(b) and Fig. 1(c) for the extended length cavities of the $Q = 3$ and $n = 4$ case and $Q = 3$ and $n = 5$ case. In the setups of Fig. 1(b) and Fig. 1(c), the added length is $\Delta L = L_p/3$ and $\Delta L = 2L_p/3$, respectively, however both SPOPOs are generating the third harmonic of the $RR_p$. Moreover, in both SPOPOs, it can be seen that the distance between two successive signal pulses (for example S1 and S2) - that meet successive pump pulses and are amplified in the nonlinear crystal - is equal to $L_p$, and has two other signals in between. After the pulse S1 hits the output coupler (OC) and before S2, two other signal pulses (S4 and S3 in for the case of $n = 4$ and S3 and S5 in for the case of $n = 5$) hit the output coupler, resulting in the generation of the third harmonic of $RR_p$.

## 3. Experimental setup

We demonstrate the technique, first with arranging and optimizing the SPOPO in the fundamental synchronous length in a four-mirror linear cavity including intracavity dispersion compensation elements, and then by changing the cavity length (ΔL) by moving one of the mirrors (M3), as shown in the schematic of the SPOPO experimental setup in Fig. 2. The SPOPO setup, without dispersion compensation elements, is similar to our previous study [9]. The oscillator is based on a periodically-poled $LiNbO_3$ (PPLN) crystal (11 mm × 0.5 mm × 1 mm) and is synchronously pumped by 185-fs pulses at 814 nm from a KLM Ti:sapphire laser at 76 MHz. The crystal facets are antireflection (AR)-coated (R<1%) over a signal tuning range of 1.3–1.6 µm and have high transmission (T>95%) for the pump. Singly-resonant oscillation is ensured by use of high reflectivity mirrors (M1, M2, M3: R>99%; OC: R~95%)

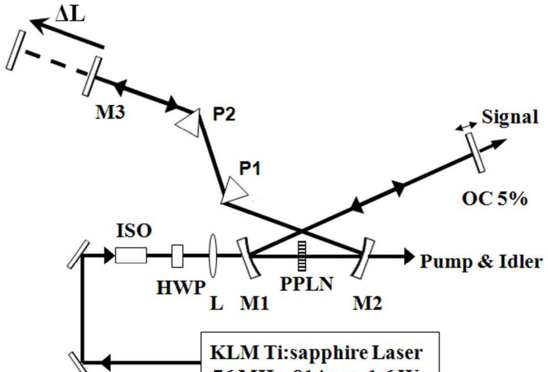

Fig. 2. Experimental setup of the synchronously pumped femtosecond SPOPO generating optical pulses at high harmonics of the pump repetition-rate. ISO: optical isolator, HWP: a half-wave plate, L: focusing lens, P1 and P2: pair of SF11 prisms.

for the signal, but high transmission for the pump and idler (M1, M2: T>95%). A pair of equilateral dispersing SF11 prisms is deployed for dispersion compensation. By proper alignment of the prisms at Brewster angle to minimize reflection losses and adjusting their separation, up-chirping of the signal pulse in the nonlinear crystal due to self-phase-modulation and positive group delay dispersion in optical elements could be removed. In our system, a tip-to-tip separation of 28 cm between prisms resulted in the best near-transform-limited pulses in the fundamental harmonic generating configuration. The trains were monitored with an InGaAs photo-detector (New Focus 1444, 20 GHz, 18.5 ps) and a fast oscilloscope (LeCroy, Wavepro 735Zi, 3.5 GHz, 20GS/s).

## 4. Results and discussion

In comparison with our previous study [9], proper dispersion compensation results in distinguishable improvements in signal pulse quality and stability, output power, pump threshold, signal wavelength and tunability. With $RR_p$ = 76 MHz, every $Q$th harmonic can be achieved by adding $\Delta L = (1974/Q)$ mm to the fundamental $L_{opo}$ where $n = Q + 1$. Highest achieved stable harmonic of $RR_p$ is the 14th, corresponding to 1064 MHz. The pulse trains corresponding to the KLM Ti:sapphire laser at 76 MHz and the SPOPO output signal pulses at the 14th harmonic are shown in Fig. 3(a) and 3(b), respectively. The observed decrease in signal pulse intensity in the train is expected, due to the intrinsic property of the method. In every set of fourteen pulses, the most intense pulse is that which interacts directly with a pump pulse and experiences gain, but the next thirteen 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. A vivid effect of insertion of pair of prisms can be observed in dramatic changes in intensity autocorrelation and spectrum of output signal pulses at 14th harmonic, as shown in Fig. 4. Without the prism pair, the SPOPO

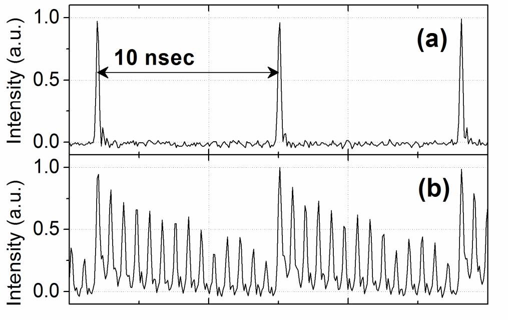

Fig. 3. (a) Input pulse train of KLM Ti:sapphire laser at 76 MHz, and (b) Output signal pulse train of the femtosecond SPOPO at 14th harmonic of pump laser repetition-rate (1064 MHz).

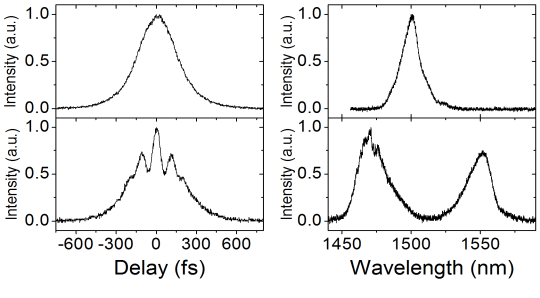

Fig. 4. Intensity autocorrelation and corresponding optical spectrum of SPOPO signal pulses at the 14th harmonic of pump laser repetition-rate (1064 MHz) with (up) and without (down) pair of SF11 prisms inserted for dispersion compensation.

is unstable and the recorded spectrum shows a double peak with distorted intensity autocorrelation. On the other hand, after the insertion of the prism pair, the average signal pulse duration is estimated as 216 fs, assuming sech$^2$ pulse shape, and the corresponding spectrum has a full-width at half-maximum (FWHM) bandwidth of 15 nm, resulting in a time-bandwidth product of 0.43, and implying near-transform-limited pulses. In contrary to the SPOPO without dispersion compensation, where the output signal wavelength is limited to around 1350 nm [9], a static and continuous tuning of central wavelength of output signal pulses is now possible through 1440-1570 nm in the 3rd harmonic, down to 1500-1540 nm in14th harmonic, by changing the cavity delay over 25 μm and 8 μm, respectively. Figure 5 shows SPOPO output signal wavelength tuning bandwidth and the corresponding amount of required SPOPO cavity delay detuning at different harmonics of $RR_p$.

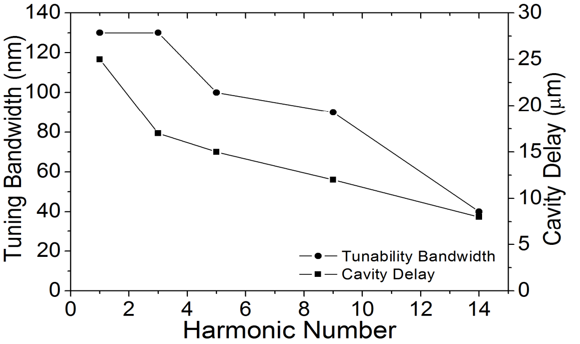

Fig. 5. SPOPO output signal wavelength tuning bandwidth and corresponding amount of required SPOPO cavity delay detuning at different harmonics of pump repetition- rate.

Gradual reduction in the tuning bandwidth, which can be seen in the figure, is related to the increased loss in comparison to the gain for some parts of the pulse tuning bandwidth. In the fundamental synchronous cavity, the attainable signal tuning bandwidth is limited by sudden variation in the SPOPO mirror group delay dispersion (GDD) for wavelengths below 1440 nm, which prevents generation of signal pulses and results in the constant tuning bandwidth up to the 3rd harmonic [2].

Starting from synchronous SPOPO cavity and by increasing the harmonic number of $RR_{opo}$, a gradual decrease in output power and increase in pump threshold power is expected due to the increased loss in every extra round-trip for each added harmonic number. Results of our experimental investigation are in accordance with this, as shown in Fig. 6. The output power remains relatively constant up to the 5th harmonic, due to the small increase in circulating signal loss relative to the ~5% output coupling used, but decreases for higher

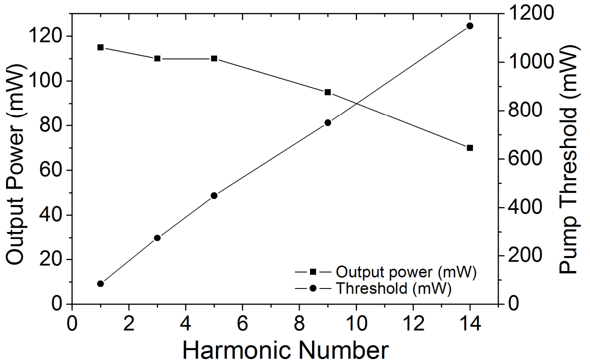

Fig. 6. SPOPO output power and pump power threshold versus harmonic number.

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harmonics, due to the increasing intracavity loss arising from higher number of signal round-trips in the absence of gain. At the same time, SPOPO pump power threshold increases almost linearly with the increment in harmonic number, which is 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 due to the losses before reaching and meeting the next pump pulse. In comparison with previous study [9], however, we have shifted the output signal wavelength from around 1.35 μm to telecommunication range, but we have increased the output power by more than a factor of two, and decreased the pump threshold power by around 200 mW for the 13th and also the highest achievable harmonic of $RR_p$. Moreover, we investigate the output signal power by changing the SPOPO pump power for 14th harmonic with pump threshold of 1.15 W. As shown in Fig. 7, we can imply that by increasing the pump power the signal increases accordingly, still leaving room for higher pump power without any saturation.

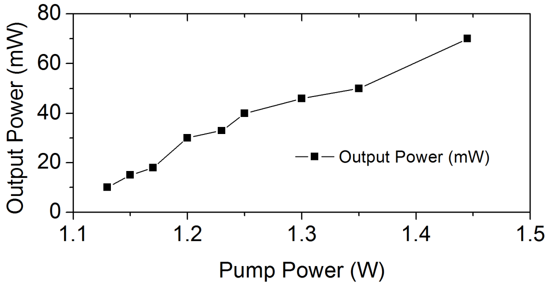

Fig. 7. SPOPO output power versus pump power at the 14th harmonic of pump laser repetition-rate (1064 MHz).

## 5. Conclusions

In conclusion, we have demonstrated a tunable, dispersion-compensated, GHz-repetition-rate femtosecond SPOPO using a 76 MHz Kerr-lens mode-locked Ti:sapphire pump laser, with an oscillator cavity longer than the fundamental synchronous length. Using a 1-mm-thick PPLN crystal as the SPOPO gain medium and by deploying internal dispersion compensation in a linear cavity configuration, we achieved stable near-transform-limited output signal pulses up to 14th harmonic of pump laser repetition-rate corresponding to 1064 MHz, with average output power of 70 mW for 1.45 W pump power and extended tuning into the telecommunication wavelength band. The demonstrated technique also offers promise for realization of future multi-GHz ultrafast telecommunication systems using miniature mode-locked semiconductor pump lasers. As an example, for a 1-GHz pump source with a cavity length of 150 mm, a SPOPO with a slightly longer cavity length of 150 + 15 mm will provide output pulses at 10 times higher repetition rate (10 GHz) using this method. This would not be attainable with other methods based on shortening of the SPOPO cavity length, because of physical limitations.

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