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Harmonic repetition-rate femtosecond optical parametric oscillator

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ABSTRACT We report on a femtosecond optical parametric oscillator (OPO) with a repetition rate of 1 GHz, which is 12 times that of the pump laser used. We also introduce a novel method for operating an OPO with a high harmonic repetition rate which is not determined by the cavity length of the OPO, but rather the cavity length difference between the OPO and its pump laser. Operation of an OPO at 4-times the harmonic repetition rate has been carried out to show the feasibility of this method. The new approach paves the way for constructing a femtosecond OPO working at repetition rates of 10 GHz, or higher, when the pump laser used has a relatively low repetition rate.

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1 Introduction

Femtosecond OPOs operated in the near-IR region with repetition rates up to 10 GHz will become more and more important in the evaluation of optical devices in ultrafast optical communication systems. To date, two papers about OPOs with repetition rates higher than 1 GHz have been published. Robertson et al. [1] reported a 2.5-GHz repetition-rate OPO synchronously pumped by a 2.5-GHz repetition-rate mode-locked diode oscillator amplifier system. This method necessitates a relatively high repetition-rate pump source. Ruffing et al. [2] demonstrated a 1.334-GHz harmonic repetition-rate OPO synchronously pumped by an 83.4-MHz repetition-rate mode-locked Nd:YVO4 system. The repetition rate of the OPO described in this paper was determined by the cavity length of the OPO. In this way, a 10-GHz repetition-rate OPO required a cavity length of only 30 mm for the ring cavity. Therefore it is difficult to realize such a high repetition rate because of the spatial limit. Moreover, the output pulses in the OPOs mentioned in these two papers are both in the ps region. Harmonic repetition-rate generation up to 344 MHz in a fs OPO was first reported by Reid et al. [3]. Recently, a mid-infrared OPO with a repetition rate of 322 MHz by the way of harmonic repetition-rate generation was also reported [4, 5]. Here we report on an fs optical parametric oscillator with a repetition rate of 1 GHz, which is 12 times the harmonic repetition rate of the pump laser. To our knowledge, this is the highest repetition-rate OPO by way of harmonic repetition-rate generation in the fs region. Then we demonstrate a novel method for operating an OPO with a harmonic repetition rate which is not determined by the cavity length of the OPO, but rather the cavity length difference between the OPO and its pump laser. Operation of an OPO at 4-times the harmonic repetition rate has been carried out to show the feasibility of this method. This new approach paves the way for constructing a fs OPO working at repetition rates of 10 GHz, or higher, when the pump laser used has a relatively low repetition rate.

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2 Generation of a 1-GHz repetition-rate fs OPO

The schematic diagram of a Ti:sapphire laser-pumped 1-GHz repetition-rate fs OPO is shown in Fig. 1. The pump source is a home-made Kerr-lens mode-locked Ti:sapphire laser similar to that described in [6]. In order to relieve the critical alignment for the OPO oscillation, we stretched the pulse duration from 22 fs to 45 fs by replacing the two fused-silica prisms with two LaKL21 prisms and setting the separation to 30 cm. Pumped with 7.4 W at 532 nm (from Millennia X of Spectra Physics), the laser produces an average output power of 1.1 W at the wavelength of 800 nm and is tunable from 770 nm to 830 nm. The standing-wave cavity length of the Ti:sapphire laser was 1785.7 mm, corresponding to a repetition rate of 84 MHz.

The singly resonant OPO is configured as a four-mirror folded ring cavity shown in the upper dash block of Fig. 1. The two concave mirrors had a radius of curvature (ROC) of 50 mm. Singly resonant oscillation was ensured by use of the two concave mirrors and one of the plane mirrors with a high reflectivity for the signal wave ($R > 99.9\%$ from 1050 nm to 1200 nm) and high transmission for both the pump and idler waves ($T > 95\%$ from 750 nm to 850 nm, $T > 85\%$ from 2200 nm to 2850 nm). The output coupler had a transmission of 1% at signal wavelengths from 1050 nm to 1200 nm. We set the distance between the two concave mirrors to be 52 mm and allocated a length of 75.2 mm to the arm of the output coupler, a length of 75.2 mm to the arm of the high-reflectivity plane mirror and a length of 93.6 mm to the distance between these two mirrors, so that the total cavity length of the OPO was 297.6 mm and the roundtrip time of the OPO cavity was one

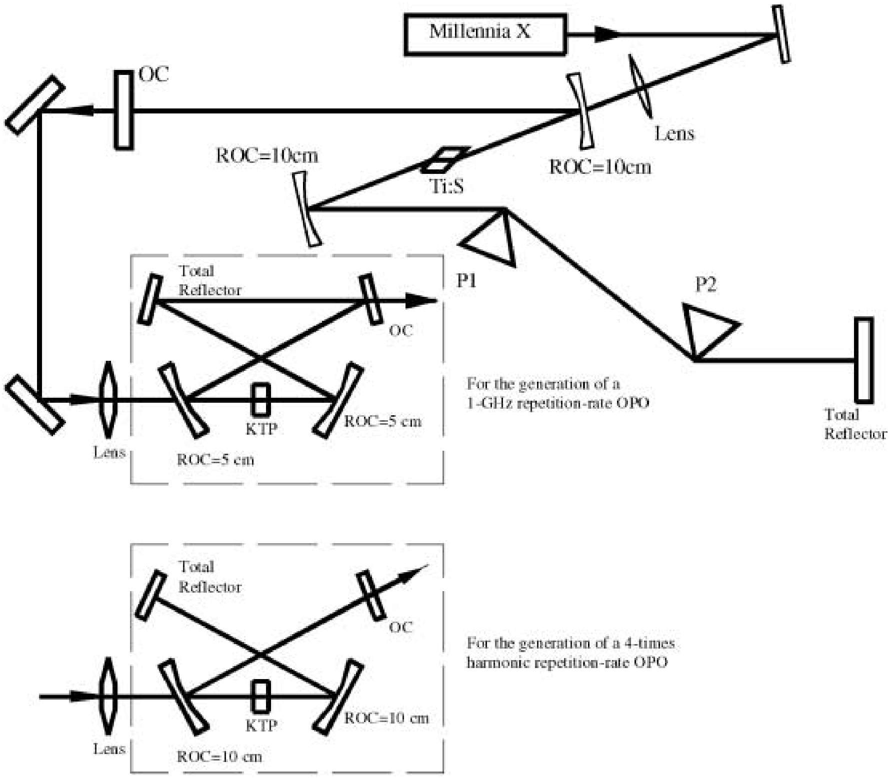

FIGURE 1 Schematic experimental set-up of a harmonic repetition-rate fs OPO, synchronously pumped by a Kerr-lens mode-locked Ti:sapphire laser with a repetition rate of 84 MHz. The *upper dash block* shows the configuration of a 1-GHz repetition-rate ring-cavity OPO and the *lower dash block* shows the configuration of a 4-times repetition-rate linear-cavity OPO

twelfth of that of the pump laser cavity. The incident angle at each mirror was 6°. This cavity design provided a beam waist of approximately 27 μm. With the set of mirrors we used, the ring cavity is of advantage over a linear cavity design at a 1-GHz repetition-rate because the ring cavity has a lower loss per round trip and provides a smaller beam waist, which is helpful for obtaining a high conversion efficiency, due to the good mode matching between the signal beam and the pump beam. Moreover, the ring cavity alleviated the spatial limits.

The KTP crystal (5 mm × 4 mm × 2 mm) was placed at the position of the beam waist of the cavity and was antireflection-coated on both sides for a center wavelength of 1125 nm ($R < 0.2\%$) and the pump wavelength of 800 nm ($R < 1\%$). It was cut for type II ($e \rightarrow e + o$) non-critical phase matching along the x-axis ($\Theta = 90°$, $\Phi = 0°$) and was collinearly pumped so that the pump and resonant signal waves had polarization parallel to the y-axis and the non-resonant idler wave was polarized along the z-axis. This non-critical phase matching crystal geometry and the collinear interaction between the pump and the signal waves maximized the parametric gain.

The focal lens had a focal length of 70 mm and was antireflection-coated for the pump wave. The pump beam was focused into the KTP crystal through one of the concave mirrors to form a beam waist of 25 μm, which corresponded to a peak intensity of 15 GW/cm^2. Alignment is much more difficult for an OPO than that for a laser because no energy is stored in a non-linear crystal and the oscillation will start only when all the cavity parameters are set suitably. As the first step, we aligned the OPO cavity using an antireflection-coated Nd:YAG crystal as described in [7]. After the oscillation of the Nd:YAG laser, the laser crystal was replaced by the KTP crystal, which was mounted on the same optical holder. We obtained operation of the 1-GHz repetition-rate OPO with a threshold pump power of 800 mW. With a pump power of 1.1 W, the average signal output power was measured to be 35 mW. Figure 2a shows the pulse trains of the mode-locked Ti:sapphire laser and the OPO. The upper one is the output pulse train of the 1-GHz repetition-rate OPO, which was monitored by a NEW FOCUS 1611-AC receiver (1-GHz bandwidth and 400-ps rise time). The lower is the output pulse train of the pump laser, which was monitored by a home-made receiver with an ns-level rise time because no other high-speed receiver was available at the time. The pulse train of the Ti:sapphire laser consists of one higher and three lower peaks, which indicates that there is a small amount of power between pulses. The higher-peak pulses in the upper pulse train are the first signal pulses generated in the OPO. It is noted that 11 succeeding signal pulses follow them. When we monitored the pulse train of the signal wave using the NEW FOCUS receiver, we did not separate the signal beam and the residual pump beam. The two beams were superimposed in the receiver. This is the reason why the peaks of the first signal pulses are apparently higher than those of the following ones. The estimated cavity loss in one round trip for the signal wave is 1.7%, of which 1% is from the output coupler and 0.4% is due to the double-side reflection from the KTP crystal, and another 0.3% is from the three highly reflective mirrors. With such an estimated cavity loss, we would intuitively expect the intensity of the signal pulses to diminish over successive pulses in the train. But in fact the decline in the intensity of the 11 succeeding pulses in Fig. 2a is hardly visible. We conclude that the cavity loss for the signal wave is much smaller than that we estimated. The output signal pulse spectrum and the pulse duration are shown in Fig. 2b. This kind of typical asymmetric double-peak pulse spectrum is due to the effects of self-phase modulation (SPM), time-dependent

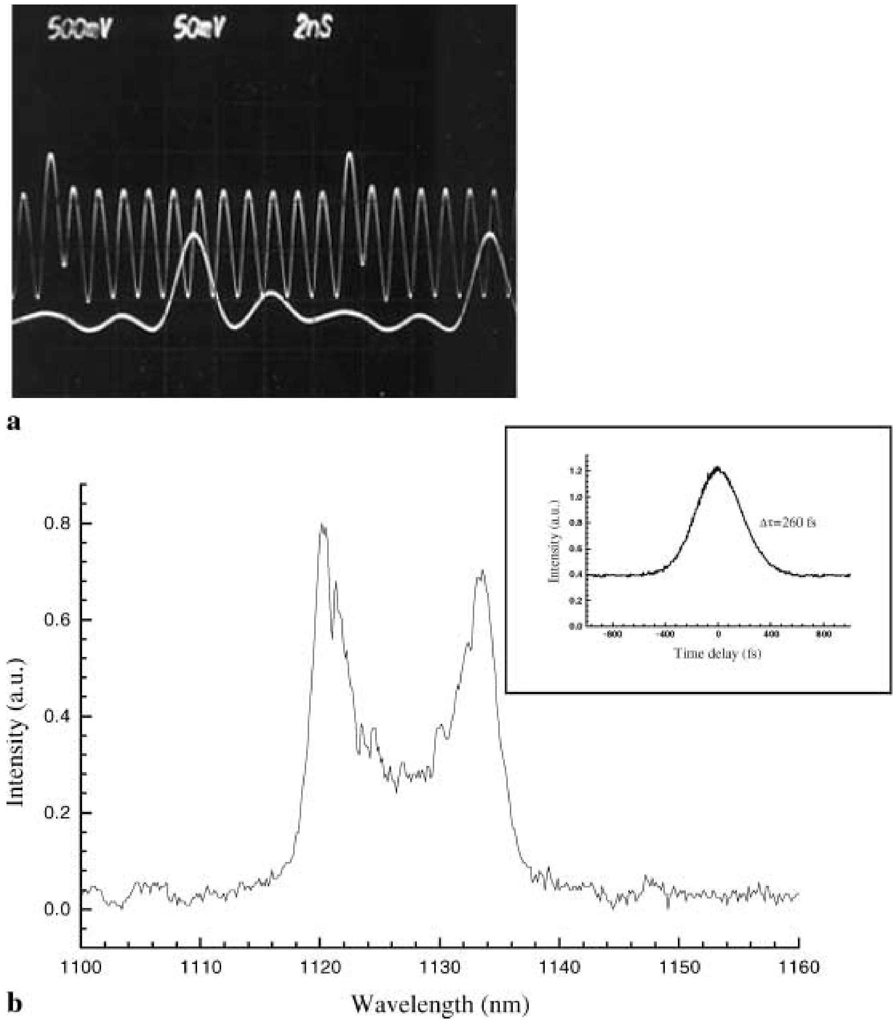

FIGURE 2 **a** Output pulse trains of an 84-MHz repetition-rate Kerr-lens mode-locked Ti:sapphire laser and a 1-GHz repetition-rate fs OPO synchronously pumped by it. The *upper trace* shows the OPO signal wave pulse train. The *lower trace* shows the pulse train of the Kerr-lens mode-locked Ti:sapphire laser. **b** Spectrum of the output signal pulses of a 1-GHz repetition-rate fs OPO. The corresponding intensity autocorrelation profile of the output signal pulses is shown in the *inset*

gain and cavity-length detuning. SPM induces a double-peak structure in the spectrum, then time-dependent gain causes the spectrum to become asymmetric, and the asymmetry changes dramatically with cavity-length detuning [8–10]. The output pulse duration was measured to be 260 fs by the way of intensity autocorrelation. Such a broad pulse duration is due to no intracavity dispersion compensation.

There was not enough space for the accommodation of prism pairs to compensate for the intracavity dispersion. Therefore, chirped mirrors will be employed in place of the present mirrors to produce transform-limited pulses. We have designed chirped mirrors to compensate for the group delay dispersion (GDD) of our 2-mm-thick KTP crystal. Improvements in the output pulse duration will be reported elsewhere.

The tuning curve of the OPO as a function of pump wavelength is shown in Fig. 3. With the Ti:sapphire laser used in this experiment, a tuning range from 1105 nm to 1180 nm was achieved for the signal wave. The tuning range of the idler wave was calculated to be from 2540 nm to 2793 nm. During the period of wavelength tuning, the cavity length of the OPO needed only a small readjustment to keep the OPO oscillating, compensating for the change of the refractive index of the signal wave. The experimental data shows excellent agreement with the calculated tuning curve obtained from the Sellmeier equation given by Bierlein et al. [11].

To increase the repetition rate from 1 GHz to 10 GHz by the way of harmonic repetition-rate generation, we had to set the cavity length of the ring-cavity OPO to 30 mm. It was very difficult to realize such a high repetition rate because of the spatial limit. Therefore, we introduced a novel method for the

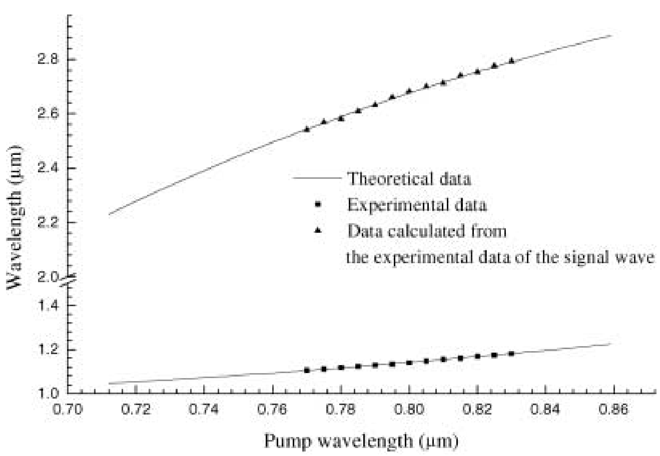

FIGURE 3 Experimental tuning curves of the OPO as a function of pump wavelength for the signal wave (*solid circles*) and the idler wave (*solid triangles*). The *solid curves* are the calculated tuning curves obtained by use of the Sellmeier equation given in [11]

generation of high harmonic repetition rate which was not determined by the cavity length of the OPO, but rather the cavity length difference between the OPO and its pump laser. In this way, the spatial limits for high harmonic repetition-rate generation were overcome.

3 New concept for the generation of high harmonic repetition rate

In this section we will describe in detail the novel method for the generation of high harmonic repetition rate as determined by the cavity length difference between the OPO and its pump laser. We use the example of generating fourth-harmonic repetition rate (shown in Fig. 4) to demonstrate the novel method. The pump laser is assumed to have a repetition rate of 100 MHz, corresponding to a linear cavity length of 1500 mm and a time interval of 10 ns between each two adjacent pulses. We call this pulse train the "parent-train" and the pump laser the "parent-pump". We divide the pump pulse train into three descendant pulse trains and call them "sub-train1", "sub-train2" and "sub-train3", respectively. Sub-train1 is made up of the pulses denoted by "①" in Fig. 4. Sub-train2 and sub-train3 consist of the pulses denoted by "②" and "③", respectively. Each of these three sub-trains consists of pulses with a time interval of 30 ns, corresponding to travelling three round trips in the parent-pump. Therefore, we can assume that the three sub-trains are generated from three separate pump lasers respectively. All three pump lasers have a cavity length of 4500 mm and a repetition rate of 33.3 MHz. Corresponding to the three sub-trains, we call the three imaginary pump lasers "sub-pump 1", "sub-pump 2" and "sub-pump 3", respectively. The time delay between sub-train1 and sub-train or between sub-train2 and sub-train3 is 10 ns exactly.

A linear-cavity OPO is used as an example. The cavity length of the OPO is set to be 1125 mm so that the cavity length difference between the OPO and parent-pump is 375 mm, which is one fourth of the cavity length of the parent-pump. Now we consider the working procedure among the OPO and the three sub-pumps. Note that the cavity length of the OPO is one fourth that of sub-pump1. The first pulse in sub-pump1 is incident on a non-linear crystal in the OPO and generates an OPO pulse. The generated OPO pulse does not disappear immediately after the first pulse in sub-pump1 disappears. Although the OPO pulse obtains no gain during travel in the OPO cavity until the second pulse in sub-pump1 arrives, it remains in the cavity with a small amount of energy loss. Each round trip of this OPO pulse generates an output pulse through an output coupler. After travelling four round trips in the OPO, the OPO pulse meets the second pulse of sub-pump1 and obtains parametric gain. Then comes a new cycle. In this way of harmonic repetition-rate generation, the output pulse train of the OPO has a repetition rate of 133.3 MHz, which is determined by the cavity length of the OPO. The time interval between each two consecutive pulses in the train is 7.5 ns. Obviously, the energy of the output pulse decreases gradually. However, if the cavity loss in the OPO is small enough, the energy of the succeeding pulses will be only a few percent less than that of the previous one. Similarly, both sub-pump2 and sub-pump3 generate OPO pulse trains with a repetition rate of 133.3 MHz. The time interval between each two adjacent pulses in each train is 7.5 ns. We call these three OPO pulse trains "OPO-train1", "OPO-train2" and "OPO-train3", respectively.

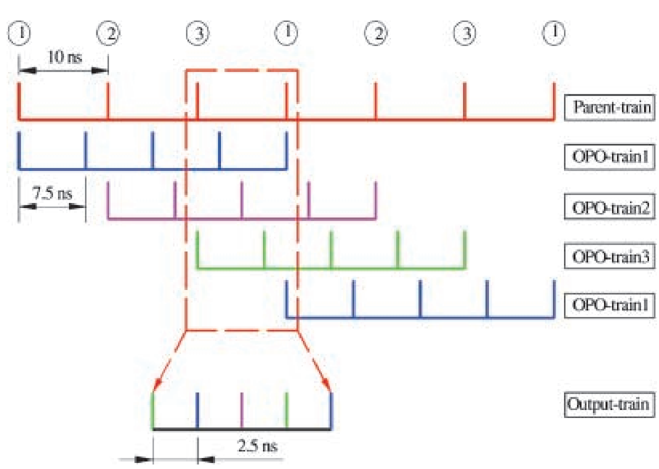

FIGURE 4 Schematic diagram for explaining how to produce a fs OPO with a harmonic repetition rate determined by the cavity length difference between the OPO and its pump laser

Now we consider the time delay between these three OPO pulse trains. Because the time delay between sub-pump1 and sub-pump2 is 10 ns and the time interval between each two adjacent pulses in OPO-train1 or OPO-train2 is 7.5 ns, the time delay between OPO-train1 and OPO-train2 becomes 2.5 ns. Similarly, the time delay between OPO-train2 and OPO-train3 is also 2.5 ns. The time delay of 2.5 ns can be easily found from Fig. 4. Since these three OPO-trains are actually generated by the parent-pump, the pulses of the three OPO-trains are superimposed to form an output pulse train. We call this output pulse train "output-train". From the enlarged diagram of the dash block in Fig. 4, we find that in the output-train, the time interval between each two adjacent pulses is 2.5 ns and five OPO pulses are generated during the time interval of two adjacent pulses of the parent-pump (e.g. No. 3 pulse and the following No. 1 pulse). Therefore, the output-train generated from the OPO has a repetition rate of 400 MHz, corresponding to 4-times the repetition rate of the parent-pump. This repetition rate is determined by the 375-mm cavity length difference between the OPO and the parent-pump. So, if we set the cavity length of the OPO to 1875 mm, we also obtain a 400-MHz repetition-rate OPO.

This novel method is suitable to be applied to the operation of a 10-GHz repetition-rate OPO. Suppose the pump laser has a repetition rate of 1 GHz, corresponding to a linear cavity length of 150 mm and a time interval of 1 ns between each two adjacent pulses, then using a linear-cavity OPO with a cavity length of 135 mm or 165 mm, corresponding to a cavity length difference of 15 mm with the pump laser, it is possible to generate a 10-GHz repetition rate. This novel method overcomes the spatial limits for a 10-GHz repetition-rate OPO. Moreover, it improves flexibility in that OPOs with several different repetition rates can be set up with only one set of optics. In the next section, we design an experiment for fourth-harmonic repetition-rate generation to demonstrate the feasibility of this new method.

4 Experiment for the generation of fourth-harmonic repetition rate

In this section, we illustrate an experiment to generate fourth-harmonic repetition rate by the new method. The experimental set-up is shown in Fig. 1. The pump laser is still the 84-MHz repetition-rate Kerr-lens mode-locked Ti:sapphire laser. The OPO is configured as a four-mirror folded linear cavity shown in the lower dash block of Fig. 1. All the optics and the non-linear crystal are the same as those used in the experimental set-up described in Sect. 2, except for the two concave mirrors. The two concave mirrors had a radius of curvature of 100 mm, with a high reflectivity for the signal wave ($R > 99.9\%$ from 1050 nm to 1200 nm) and high transmission for both the pump and idler waves ($T > 95\%$ from 750 nm to 850 nm, $T > 85\%$ from 2200 nm to 2850 nm). The OPO was a singly resonant oscillator. The cavity length of the OPO was set to 1339.3 mm. The cavity length difference between the OPO and the pump laser was 446.4 mm, which is one-fourth of the cavity length of the Ti:sapphire laser. The estimated cavity loss in one round trip for the signal wave was 2.3%, larger than the value in the 1-GHz experiment in Sect. 2 because a linear cavity is used here. The linear cavity design has the advantage of simple cavity-length allocation over a ring cavity. Furthermore, a ring cavity OPO for the generation of fourth-harmonic repetition rate pumped by the 84-MHz Ti:sapphire laser requires a cavity length of 2678.6 mm or 4464.3 mm. This would necessitate the use of a colossal OPO. The calculated beam waist in this cavity was 25 μm. The pump beam was focused onto the KTP crystal to form a beam waist of 24 μm, which corresponded to a peak intensity of 16 GW/cm^2. By carefully adjusting the cavity length of the OPO, we successfully obtained a 336-MHz repetition-rate OPO with a threshold pump power of 600 mW. With a pump power of 1.1 W, the average signal output power was measured to be 40 mW. The output signal pulse train of the OPO in Fig. 5 was monitored by the NEW FOCUS 1611-AC receiver and shows the repetition rate was 4-times that of the pump laser. The two smaller peaks between two succeeding signal pulses in the signal pulse train are due to the electronic ring produced by the fast receiver. The pulse duration was measured to be 320 fs by intensity autocorrelation.

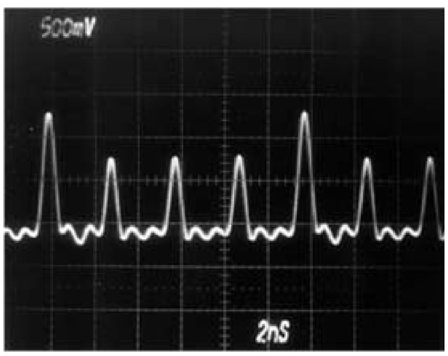

FIGURE 5 Output pulse train of an OPO with a repetition rate of 336 MHz, corresponding to four-times the repetition rate of the pump laser. Note that the cavity length of the OPO is 1339.3 mm. The cavity length difference between the OPO and the pump laser is 446.4 mm, which is one fourth of the cavity length of the pump laser

The experiment has shown the feasibility of the novel method, but 336-MHz repetition-rate generation is far from our goal of 10-GHz, and the threshold pump power of 600 mW for the OPO is very high. In order to obtain high parametric gain in the future, we will choose periodically poled $LiNbO_3$ (PPLN) as the parametric gain medium in the OPO because of its high effective non-linear coefficient. A new Kerr-lens mode-locked Ti:sapphire laser with a repetition rate of 1 GHz and high average output power will be constructed to replace the present Ti:sapphire laser as a pump source. New improvements to the 10-GHz repetition-rate OPO will be reported at a later date.

5 Summary

We have reported a fs optical parametric oscillator with a repetition rate of 1 GHz, which is 12 times that of the pump laser used. We also demonstrated a novel method for operating an OPO with a high harmonic repetition rate which is not determined by the cavity length of the OPO, but rather the cavity length difference between the OPO and its pump laser. The feasibility of this method has been verified by experiment. This approach paves the way for constructing a fs OPO working at a 10-GHz, or higher, repetition rate when the pump laser used has a relatively low repetition rate. There is no spatial limit to obtaining a 10-GHz harmonic repetition-rate OPO by this new method.

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REFERENCES

1 A. Robertson, M.E. Klein, M.A. Tremont, K.J. Boller, R. Wallenstein: Opt. Lett. **25**, 657 (2000)
2 B. Ruffing, A. Nebel, R. Wallenstein: Appl. Phys. B **67**, 537 (1998)
3 D.T. Reid, C. McGowan, W. Sleat, M. Ebrahimzadeh, W. Sibbett: Opt. Lett. **22**, 525 (1997)
4 P.J. Phillips, S. Das, M. Ebrahimzadeh: Appl. Phys. Lett. **77**, 469 (2000)
5 M. Ebrahimzadeh, P.J. Phillips, S. Das: Appl. Phys. B **72**, 793 (2001)
6 J. Jiang, T. Hasama, Z. Zhang, T. Sugaya, T. Nakagawa: Opt. Commun. **183**, 159 (2000)
7 A. Nebel, C. Fallnich, R. Beigang, R. Wallenstein: J. Opt. Soc. Am. B **10**, 2195 (1993)
8 A. Hache, G.R. Allan, H.M. van Driel: J. Opt. Soc. Am. B **12**, 2209 (1995)
9 C. Fallnich, B. Ruffing, A. Nebel, R. Beigang, R. Wallenstein: Appl. Phys. B **60**, 427 (1995)
10 T. Kartaloglu, K.G. Koprulu, O. Aytur, M. Sundheimer, W.P. Risk: Opt. Lett. **23**, 61 (1998)
11 J.D. Bierlein, H. Vanherzeele: J. Opt. Soc. Am. B **6**, 622 (1989)