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Compact, 2.95-GHz repetition-rate femtosecond optical parametric oscillator with tunable pulse repetition frequency

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ABSTRACT

We report a compact femtosecond optical parametric oscillator (OPO) with a tunable repetition rate that is harmonically pumped using a 52.5 MHz Yb-doped fiber laser system. By reducing the OPO cavity length, the repetition rate can be adjusted successively from 1.935 to 2.95 GHz at 52.5 MHz intervals. The multiplication of the repetition rate is achieved by placing a nonlinear crystal in a compact linear cavity, and the minimum cavity length is 47.8 mm. The maximum signal power (205.2 mW) at 2.04 GHz is obtained at an input pump power of 2.35 W and a central wavelength of 1472 nm. The central wavelength of the signal pulses can be tuned from 1383 to 1596 nm. To the best of our knowledge, 2.95 GHz is the highest repetition rate achieved using a femtosecond OPO based on an ultrashort cavity with a length that is *N* times (*N* is an integer) shorter than that of the pump cavity.

1. Introduction

Femtosecond optical parametric oscillators (OPOs) operating in the infrared region with a high repetition rate up to multi-gigahertz levels are required for many applications, such as astronomical spectrograph calibration [1], fiber optical communications [2], and time-resolved spectroscopy [3]. Meanwhile, for practical applications where a compact system architecture is required, for example, in telecommunications and spectroscopy, OPOs pumped by high-power Yb-doped femtosecond fiber lasers offer significant advantages, i.e., they are compact, generate few misalignments, enable the use of non-water-cooling systems, and are insensitive to the environment [4–9]. Moreover, controlling the repetition rate of the femtosecond laser system is crucial in emerging laser micromachining [10,11]. For different materials and different needs, the repetition rate of laser source needs to be optimized in order to obtain high-efficiency and high-quality femtosecond laser ablation. Therefore, along with femtosecond fiber lasers, a compact OPO with a tunable high repetition rate is important for practical applications.

To date, two methods have been adopted to obtain high-repetition-rate femtosecond OPOs: synchronous and harmonic pumping schemes. In the former scheme, a high-power gigahertz-repetition-rate femtosecond laser is required to satisfy the synchronous pump condition. However, such a high-repetition-rate laser is not widely available [12–14]. The latter harmonic pumping technique is further divided into two cases: (1) the cavity length of the OPO is slightly shorter or longer than that of a synchronously pumped OPO [15–19], and (2) the cavity length of the OPO is *N* times (*N* is an integer) shorter than that of the pump laser. Benefiting from the high single-pass gain in the parametric interaction, the signal pulse is amplified only after several cavity roundtrips, resulting in the multiplication of the repetition rate. For the first case, the cavity length of an OPO is long, which limits its practical applications. For the second case, Reid et al. [20] first demonstrated a V-type femtosecond RTA-OPO harmonically pumped by a Kerr-lens mode-locked Ti: sapphire laser at 86 MHz, resulting in an OPO repetition rate of 344 MHz. The linear cavity features a compact system architecture [21–23]. Furthermore, the flexibility of this cavity design is beneficial when a broad repetition rate tuning range is required. However, because of the physical limitations in achieving the shortest V-type cavity length, the highest repetition rate achievable using this method was 1.334 GHz in a picosecond Nd: YVO_4 laser-pumped KTA-OPO [24]. By replacing the concave mirror in the V-cavity with a lens, the limitation of physical size can be reduced and the cavity length can be further shortened, resulting in a higher repetition rate.

In this study, we successfully construct a compact femtosecond OPO using the harmonic pumping technique. By replacing the concave mirror in the V-cavity with a lens, the OPO cavity is more compact and easier to align. Moreover, it is more convenient to adjust the cavity

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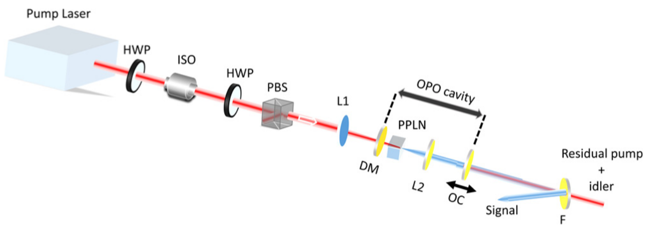

Fig. 1. Schematic illustration of experimental setup for ∼2 GHz-repetition-rate OPO harmonically pumped by a Yb-doped fiber laser. HWP, half-wave plate at 1040 nm; ISO, isolator; PBS, polarizing beam splitter; L1, focusing lens, highly transmissive for the pump; DM, dichroic mirror; L2, focusing lens, highly transmissive for the signal; OC, output coupler; and F, filter.

length to control the repetition rate. The maximum repetition rate is 2.95 GHz, corresponding to a minimum standing-wave cavity length as short as 47.8 mm. The OPO operates up to the 56th harmonic of the pump laser repetition rate. The repetition rate can be adjusted successively from 1.935 to 2.95 GHz at 52.5 MHz intervals without changing the cavity structure. The characteristics of the signal output power and pump threshold variation at different repetition rates at a central wavelength of 1472 nm are investigated. A maximum signal power of 205.2 mW at 2.04 GHz is obtained for an input pump power of 2.35 W. Moreover, the signal wavelength can be tuned by changing the grating period of the crystal, covering a range from 1350 to 1625 nm. Such a high-repetition-rate OPO providing femtosecond pulses with tenability in the IR are of interest for time-domain spectroscopy, biophotonics, and optical microscopy. The signal spectrum covers the communication band, which makes it potential in future optical communication. Moreover, the tunable repetition frequency plays an important role in the field of laser micromachining. To the best of our knowledge, 2.95 GHz is the highest repetition rate achieved from a femtosecond OPO based on a compact linear cavity design.

2. Experimental structure

A schematic illustration of the experimental setup is presented in Fig. 1. The pump laser used is a home-made Yb-doped femtosecond fiber laser amplifier, which delivers 100-fs pulses with an average output power up to 3.0 W at a central wavelength of 1040 nm and a repetition rate of 52.5 MHz. A half-wave plate (HWP) and a polarizing beam splitter (PBS) are employed to change the pump power. The pump beam is focused into the nonlinear crystal inside the cavity using a 100 mm focal length lens, L1. The OPO is configured as a compact linear standing wave cavity, which includes only a dichroic mirror (DM) that is highly reflective for the signal and highly transmissive for the pump and idler, a lens with a focal length of 25 mm, and an output coupler (OC) with 2% transmission across 1350–1650 nm. The filter is used to separate the signal beams from the pump and idler beams. The OPO cavity is highly compact to operate at a high repetition rate.

The OPO crystal is a 3-mm-long periodically poled MgO: $LiNbO_3$ (PPLN) crystal with a multiperiod design. The period of the grating varies from 27.5 to 31.6 μm. Both sides of the crystal are antireflection coated, from 1030 to 1080 nm (R < 1%) for the pump, from 1380 to 1800 nm (R < 1%) for the signal, and from 1800 to 4500 nm (R < 5%) for the idler. The pump beam waist at $1/e^2$ the peak intensity is approximately 110.0 μm. The distance between the DM and the crystal is fixed at approximately 5 mm, so the pump mode is fixed. The initial cavity length is approximately 74.5 mm, corresponding to a repetition rate of 1.935 GHz. The repetition rate of the idler is 52.5 MHz as that of the pump because the OPO is operating in single resonant signal oscillation and the idler cannot circulate in the cavity. Therefore, we only focus on the high repetition rate signal. The OC is mounted on a linear translation stage with a travel distance of 25 mm to continuously change the cavity length and the corresponding repetition rate. Lens L2 is mounted on another linear translation stage, which is also moved once the cavity length is changed to optimize the signal mode for maximum output power.

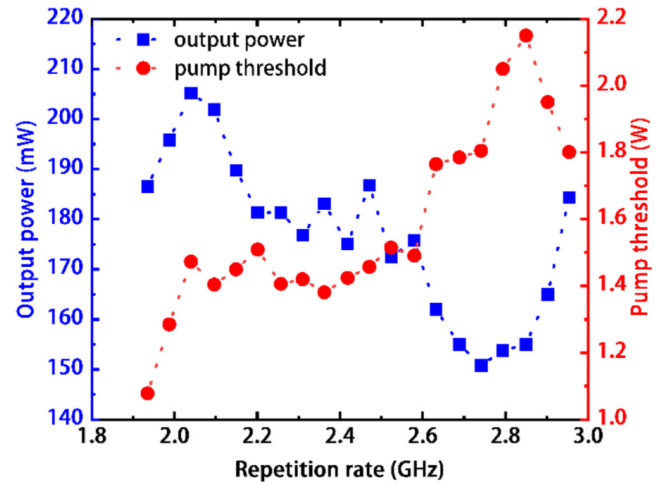

Fig. 2. Output signal power and pump threshold as a function of the repetition rate.

3. Result and discussion

The cavity length is reduced to achieve higher repetition rates. Limited by measured frequency range of our radio frequency (RF) spectrum analyzer (9 kHz∼3 GHz), the highest repetition rate in the experiment is 2.95 GHz, corresponding to the 56th harmonic of the pump laser repetition rate. The minimum cavity length is approximately 47.8 mm. At each repetition rate, the cavity is in the stable region calculated by the element position and ABCD matrix. We investigate the characteristics of the signal output power variation for an input pump power of 2.35 W at different repetition rates and a central wavelength of 1472 nm, as shown in Fig. 2. The maximum signal power is 205.2 mW at 2.04 GHz. Fig. 2 also shows the variation of the pump threshold with the repetition rate. The pump threshold is 1.8 W at a repetition rate of 2.95 GHz. When the repetition rate is increased, the change in the cavity length is accompanied by a change in the cavity mode size as well as an increase in loss and output times. Moreover, the cavity mode is sensitive to the position of the lens based on the ABCD matrix. All of the reasons result in a non-monotonic change in the output power and threshold. The output power and pump threshold curves are relatively flat in the range of 2.2–2.6 GHz. As a result, we choose to measure the conversion efficiency and spectrum tuning range at 2.36 GHz.

To investigate the power scaling property of the OPO, we have measured the variation in the output signal power and conversion efficiency with the pump power at a central wavelength of 1472 nm and a repetition rate of 2.36 GHz, as shown in Fig. 3. The average output signal power increases monotonously with the average pump power, yielding a maximum power of 184.3 mW at 2.35 W pump, whereas the conversion efficiency exhibits saturation. The maximum conversion efficiency is ∼8.3% from the pump to signal when the pump power reaches 2.05 W and the conversion efficiency decreases slightly when the pump power is above 2.05 W due to pump back-conversion [25]. The conversion efficiency and its trend are similar to that in the harmonically pumped 1-GHz OPO [22] Further increasing the pump power will result in a decrease in the conversion efficiency and the excitation of higher-order modes. Moreover, the generated idler will cause more heating of the OC arising at higher pump power, which degrades the optimal alignment of the cavity. Hence, we limit the pump power to 2.35 W. At such a pump peak power density of 3.7 GW/cm^2, no crystal damage was observed. The inset of Fig. 3 shows the output signal power continuously recorded over 60 min under 1.75 W pump

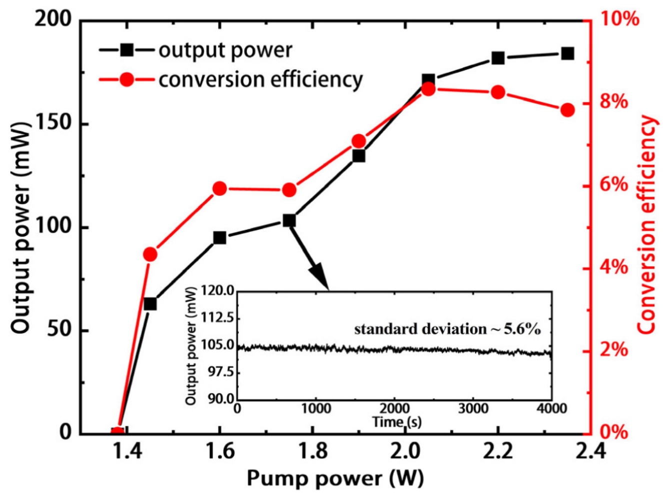

Fig. 3. Output signal power and conversion efficiency from pump to signal as a function of the pump power. The inset shows the output signal power under 1.75 W pump versus time.

which is below the saturation pump power in order to investigate the stability of the OPO. The power standard deviation is 5.6%. The slow power drop is due to the drift of the cavity length, and the power stability can be improved by introducing feedback control of cavity length.

Figs. 4 (a) and (b) show respectively the measured autocorrelation trace operating at a repetition rate of 2.95 GHz and the signal spectrum is centered at 1472 nm. The signal spectrum exhibits a full-width-at-half-maximum bandwidth of 28 nm, corresponding to a transform-limited (TL) pulse duration of 113 fs assuming a Gaussian shape. The measured signal pulse duration is 134 fs, which is slightly longer than the TL pulse duration. The near TL signal pulse can be attributed to the simplicity of the cavity. The small number of cavity elements makes the cavity have small net dispersion.

The spectral tuning property of the OPO is investigated at a repetition rate of 2.36 GHz, as shown in Fig. 5(a). The central wavelength of the signal pulses can be continuously tuned from 1383 to 1596 nm, and the wavelength of the idler ranges from 2985 to 4193 nm, as determined by energy conservation. The strong dips on the shorter wavelengths are associated with water absorption lines. The asymmetric structure of the spectrum is caused by time-dependent gain and cavity-length detuning [15]. The output signal powers at different tuning wavelengths are shown in Fig. 5(b). The output power is 78 mW at a central wavelength of 1383 nm, 45.2 mW at 1596 nm, and 189.8 mW (which is the highest) at 1472 nm under a 2.35 W pump. The inadequate coating bandwidth and reduction in parametric gain cause the drop of the output power at both ends of the tuning range. The measured pulse durations are also shown in Fig. 5(b), where it can be seen clearly that the pulse durations of signals are in the range of 120–160 fs and they are negatively correlated with the measured spectral bandwidth for most measurement points. The pulse width tends to decrease as the central wavelength increases. This is because the positive dispersion of the PPLN decreases and the negative dispersion of the lens increases as the signal wavelength increases, thereby resulting in a decrease in the net dispersion.

A photodetector (EOT, ET3500) and a RF spectrum analyzer (RIGOL, RSA3000E) are used to measure the repetition rate of the output signal. Typical RF spectra are recorded for both a frequency window of 2 GHz span (30 kHz resolution) and a window of 1 MHz span (100 kHz resolution), as depicted in Fig. 6. The RF spectrum clearly shows that the signal oscillates at a maximum repetition rate frequency of 2.95 GHz. The lower combs represent the repetition rate frequency of the pump laser (~52.5 MHz) and its harmonics. As shown in Fig. 6, the

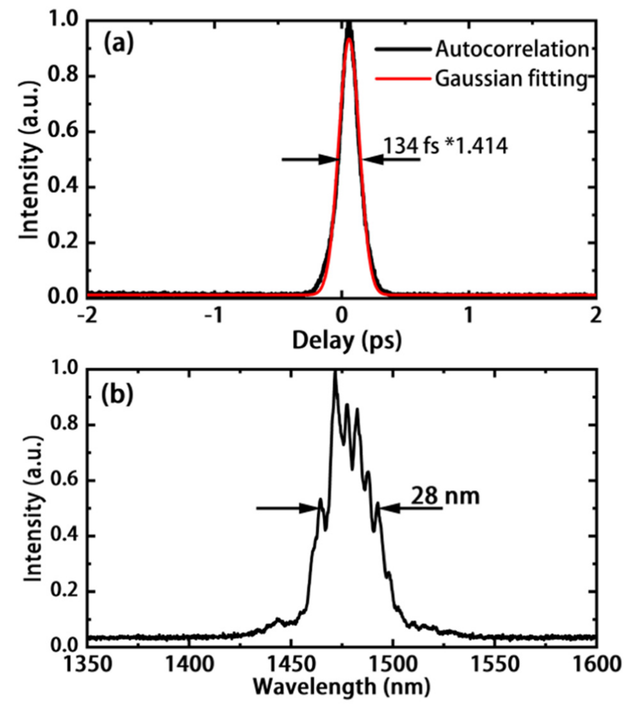

Fig. 4. (a) Measured autocorrelation trace and its Gaussian fitting. (b) Signal spectrum with a full-width-at-half-maximum bandwidth of 28 nm.

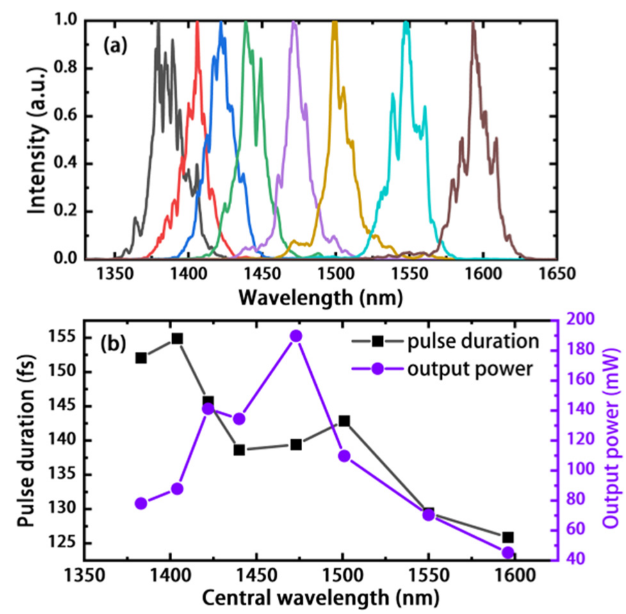

Fig. 5. (a) Signal spectra of the compact OPO, exhibiting central wavelength tunability from 1383 to 1596 nm. (b) Variations in average output signal power and measured pulse durations across the tunable wavelength range.

repetition rate of the signal is located at the 56th harmonic of the input pump. The inset of Fig. 6 shows that the signal-to-noise ratio is higher than 40 dB at a 100 kHz resolution, indicating the stability of the OPO operation [21]. Although higher repetition rates cannot be measured due to the limit of the maximum RF bandwidth (3 GHz), the length of the OPO cavity can be further shortened, and the repetition rate can reach 4 GHz calculated by the cavity length.

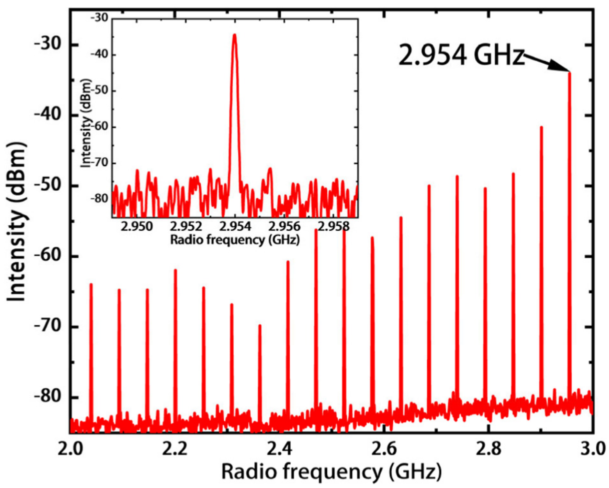

Fig. 6. RF spectrum spanning 1 GHz from 2 to 3 GHz with 30 kHz resolution. Inset: RF spectrum over a 1 MHz span with 100 kHz resolution.

4. Conclusions

In conclusion, we demonstrate a compact femtosecond OPO with a multi-gigahertz repetition rate, and the maximum repetition rate is 2.95 GHz, corresponding to a minimum cavity length of 47.8 mm. By reducing the OPO cavity length, the repetition rate can be adjusted successively from 1.935 to 2.95 GHz at 52.5 MHz intervals. The signal power at a central wavelength of 1472 nm is investigated at different repetition rates. A maximum signal power of 205.2 mW at 2.04 GHz is obtained for an input pump power of 2.35 W. Characteristics such as the pump threshold, pulse duration, spectra tuning, and power scaling have also been investigated. The repetition rate can be further improved by replacing the DM mirror with a PPLN crystal coating. In addition, the repetition rate can be adjusted automatically using motorized stages. The design is simple and compact and hence potentially useful for practical applications.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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