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1-GHz-repetition-rate femtosecond optical parametric oscillator

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We report a 1-GHz-repetition-rate, low-pump-threshold, all-solid-state femtosecond optical parametric oscillator (OPO) based on periodically poled $LiNbO_3$ and pumped by a GHz repetition rate Ti:sapphire laser. The OPO provides nearly transform-limited 65-fs-signal pulses tunable from 1160 to 1320 nm. The pump threshold is about 580 mW, and 43 mW signal power is obtained with 950-mW-pump power. Higher-order quasi-phase-matched sum frequency generation and second harmonic generation processes produce 10 mW blue light at 486 nm and 15 mW red light at 620 nm.

High-repetition-rate femtosecond laser pulses tunable in the infrared and visible spectral range can be widely applied for time-resolved spectroscopy and pump–probe measurements with a high signal-to-noise ratio.[1] Femtosecond optical parametric oscillators (OPOs) operating at high repetition rate in the near-infrared (1.3 and 1.55 μm) are potentially of great importance for optical communication systems to achieve high data rates and high capacity, where optical time-division multiplexing and wavelength-division multiplexing need to be combined.[2] A high-repetition-rate OPO is distinguished by its compact size and can serve as a high-repetition-rate optical clock, e.g., for optical logic circuits.[3] Additionally, femtosecond OPOs provide frequency combs in the near-infrared and in the visible, which is useful for applications requiring a large frequency span, for instance precise optical frequency measurements.[4] Whereas 2.5-GHz-repetition rate has been achieved for a PPLN OPO generating 7.8 ps pulses,[5] femtosecond OPOs reported so far[6] operated below 400 MHz.

In this letter, we describe a 1-GHz-femtosecond periodically probed lithium niobate (PPLN) OPO pumped by a 1-GHz-Kerr lens mode-locked Ti:sapphire laser. The signal pulses of the OPO are as short as 65 fs and tunable from 1160 to 1320 nm with two sets of cavity mirrors.

There basically exist several methods to realize high repetition rate (>300 MHz) operation of a synchronously pumped OPO. It is possible to employ a low frequency laser pulse train to pump an OPO with an N times shorter cavity length, where N is an integer number. Then the OPO emits a pulse train with N times the pump repetition rate. With this method, Phillips *et al.*[6] have demonstrated up to 322 MHz operation of a femtosecond PPLN OPO pumped by an 80.5-MHz-Ti:sapphire laser, and Ruffing *et al.*[7] achieved 1.33 GHz operation of a picosecond KTA OPO pumped by a mode-locked Nd:YVO_4 laser operating at 83.4 MHz. However, this technique involves the following disadvantages: First, the signal pulses experience more roundtrip losses (correspondingly the pump threshold is increased and the tuning range is reduced), since gain is not supplied for every pass through the crystal. Second, the signal pulses have periodically varying intensities. Moreover, the large beam waist of the signal wave in the nonlinear crystal associated with the short OPO cavity length leads to a significant problem concerning mode matching between the pump and the signal. In view of this situation, direct pumping of an OPO by a laser operating with the desired high repetition rate seems to be an attractive alternative. For this approach, a high repetition rate pump laser delivering powerful ultrashort pulses and a low threshold OPO resonator are the key requirements.

In the following, we will describe the experimental performance of a 1-GHz-ring cavity PPLN OPO (see Fig. 1) when pumping with a 1-GHz-Ti:sapphire laser. Synchronous pumping at such a high repetition rate implies an OPO cavity as short as 30 cm, causing a large signal beam waist in the crystal. As shown in Fig. 2(a), the diameter of the signal beam waist in the crystal (D_0) increases quickly with shortening the cavity length (L_{OPO}) at a given curvature radius of the curved mirrors (r) (see, for example, the dashed horizontal line), and D_0 decreases with reducing r at a given L_{OPO} (see the dashed vertical line). In our calculations, we deter-

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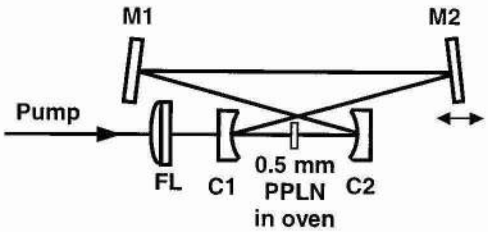

FIG. 1. Ring cavity of the PPLN OPO. M1, M2, flat mirrors; C1, C2, curved mirrors ($r=-100$ mm); FL, focusing lens ($f=60$ mm).

mined the optimum distance between the two curved mirrors (L_{CC}) providing a good signal mode. Figure 2(b) illustrates our criteria to optimize L_{CC}. It is important to notice that the beam waists in the sagittal (D_{0X}) and tangential (D_{0Y}) planes are slightly different due to astigmatism. Therefore, the stability curves in Fig. 2(b) for the sagittal (dash–dotted line) and the tangential (solid line) planes are shifted with respect to each other when plotted in dependence on L_{CC}. Stable OPO operation is confined to the common range of the two stability curves, which decreases with increasing incidence angle θ of the signal beam on the curved mirrors. In order to obtain most stable operation of the OPO, we optimized L_{CC} to the value corresponding to the intersection between the two stability curves, e.g., $L_{CC}=105$ mm for $L_{\mathrm{OPO}}=1200$ mm, $r=-100$ mm, and $\theta=5°$, where $D_0=D_{0X}=D_{0Y}\approx 60$ μm. In principle, a shorter L_{CC} would decrease the beam diameter in the crystal. However, this results, besides the astigmatic beam distortion, in an increased spot diameter on C1 and C2 and therefore enhanced diffraction losses. This is shown by the dashed and dotted curves in Fig. 2(b). On the other hand, the astigmatism and the stable operation conditions set an upper limit to θ. The sizes of the mirrors and mirror holders may largely increase this angle when reducing r. Too small curvature radius also causes a spatial inhomogeneity of the reflectivity specifications of the curved mirrors. In consequence, the value of r can hardly be smaller than -75 mm. According to Fig. 2(a), $r=-75$ mm and $L_{\mathrm{OPO}}=30$ cm correspond to a D_0 as large as 120 μm. For perfect mode matching, a similarly large pump focus diameter in the crystal would be required. Then, the intensity of both the pump and the signal would be largely reduced in the interaction area. Therefore the efficiency of the OPO is reduced and the pump threshold is largely increased. At high pump repetition rate, where a much smaller pulse energy is provided, the decrease in the efficiency and increase in the pump threshold become especially critical.

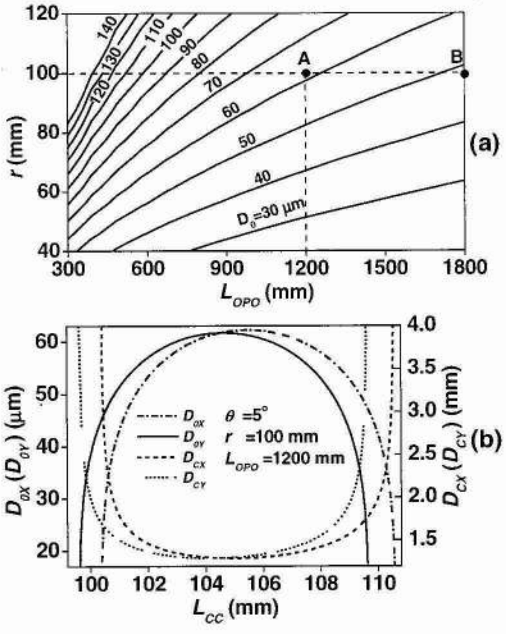

FIG. 2. (a) Contour lines of the diameter of the signal beam waist (D_0) in the crystal vs cavity length (L_{OPO}) and curvature radius of the curved mirrors (r). (b) Variation of the beam waist in the PPLN crystal in the sagittal (D_{0X}) and tangential (D_{0Y}) planes as a function of L_{CC}. The dashed and dotted lines show the beam diameters in the sagittal (D_{CX}) and tangential (D_{CY}) planes on C1 and C2 as a function of L_{CC}.

This situation can be greatly improved by higher-order synchronous pumping, i.e., by choosing $L_{\mathrm{OPO}}=N\cdot L_P$ with $N=2$, 3, 4, etc. where L_P is the cavity length of the pump laser. For such a configuration, the OPO repetition rate remains as high as that of the pump without increasing the roundtrip losses. Because of the much longer OPO cavity, higher-order synchronous pumping enables high intensity interaction between the pump and the signal by reducing the signal beam waist, and mode matching can easily be improved through optimizing the focal length of the focusing lens (f) and the values of r and L_{CC}. Obviously, all signal pulses have equal intensities in higher-order synchronous pumping, which is very important for applications such as nonlinear spectroscopy.

In our experiments, a compact ring cavity femtosecond Ti:sapphire laser[1] pumped by a 10-W-diode-pumped solid-state laser was used to pump the PPLN OPO. It uses chirped mirrors for dispersion control and produces (intracavity) 23-fs-transform-limited pulses chirped to ~40 fs by the output coupler. The corresponding spectral bandwidth is 30 nm centered at 800 nm. The repetition rate is tunable from 300 MHz to 3 GHz by simple rearrangement of the cavity mirrors. Figure 1 shows the cavity configuration of the PPLN OPO. The PPLN crystal is 0.5 mm long and was heated to 100 °C to remove photorefractive effects. It contains multiple poling gratings with periods ranging from 20.5 to 21.5 μm and was coated on both sides for high transmission of wavelengths ranging from 700 to 900 nm and from 1100 to 1300 nm. The OPO output coupler (M1) has a transmission of 2%. Other cavity mirrors (C1, C2, M2) have a reflection rate of about 99.8% for the spectral range from 1100 to 1300 nm. For 1 GHz operation, we employed fourth-order ($L_P=30.2$ cm, $L_{\mathrm{OPO}}=120.8$ cm) synchronous pumping. Using curved mirrors with $r=-100$ mm, the signal beam waist in the crystal is about 60 μm according to Fig. 2(a) (point A). We chose a focusing lens of $f=60$ mm, so that the diameter of the pump beam at the focus is also about 60 μm. We found the best OPO performance (power and stability) at $L_{CC}=105$ mm [in good agreement with the calculated result in Fig. 2(b)]. The pump pulse rate of 1 GHz excites four signal pulse trains (S1–S4) each operating at 250 MHz, which are delayed sequentially by one repetition period of the pump laser (1 ns) from each other. The pump pulse train synchronizes the four signal pulse trains to each other. The sequence of S1–S4 creates a 1-GHz-signal pulse train. This has been confirmed by a repetition rate measurement using a fast photodiode.

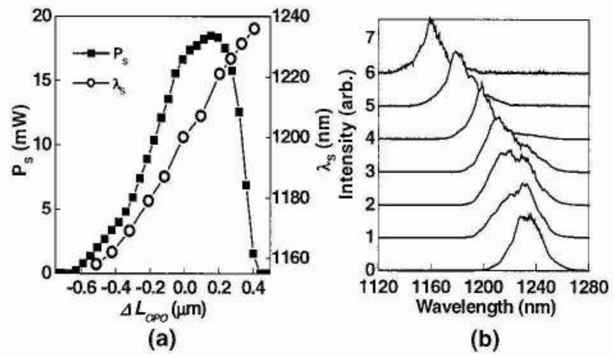

FIG. 3. Tuning characteristics of the PPLN OPO. (a) Signal power (P_S) and signal wavelength (λ_S) vs change of cavity length (ΔL_{OPO}); (b) signal spectra over the tuning range.

The output characteristics of the OPO as a function of L_{OPO} are presented in Fig. 3. For 900-mW-pump power (measured before FL), the highest signal output power is about 18 mW, and the pump threshold of the OPO was measured to be lower than 790 mW. The OPO oscillation is maintained for a 1.0-μm-cavity mismatch range [Fig. 3(a)]. Figure 3(a) also depicts the shift of the output wavelength from 1160 to 1235 nm with ΔL_{OPO}. Some typical signal spectra are presented in Fig. 3(b). Nearly transform-limited 65-fs-signal pulses were measured at 1220 nm with 34 nm bandwidth (see Fig. 4), resulting in a time-bandwidth product of 0.445.

The OPO efficiency can be further improved by choosing a shorter focal length for FL and a larger L_{OPO}. Then the OPO is pumped with higher intensity and has a smaller signal beam waist, providing a higher parametric gain. For 1 GHz operation, we replaced FL by an $f = 50$ mm achromat, increased the cavity length of the OPO to $L_{\mathrm{OPO}} = 6L_P = 181.2$ cm and heated the crystal to 125 °C. According to Fig. 2(a) (point B), the signal beam waist can be reduced to less than 50 μm. More than 43 mW of signal power was measured for 950 mW pumping and the pump threshold was lowered to about 580 mW (pump pulse energy 580 pJ). Raising the crystal temperature from 100 to 125 °C increased the efficiency by 20%.

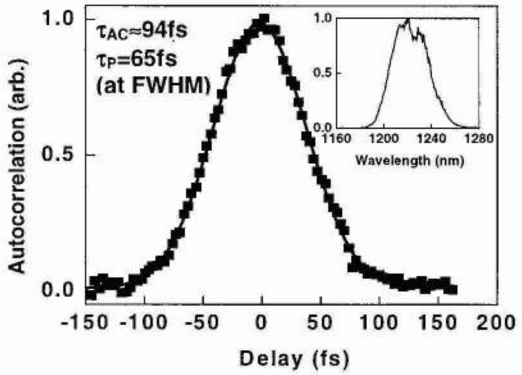

FIG. 4. Intensity autocorrelation measurement (filled squares) of the signal pulses, pulse duration is denoted by τ_P. The solid line is the Gaussian fit to the measurement data. Inset: corresponding spectrum.

When M2 was replaced by a chirped mirror[8] (group delay dispersion ≈ -100 fs^2, $R > 99.8\%$ from 1100 to 1300 nm), the signal pulse duration remained unchanged. However, the signal spectral bandwidth was narrowed and the tuning range was shifted to 1230–1320 nm.

Due to an ~56% poling duty cycle in the PPLN,[9] efficient sum frequency generation between the signal and pump and second harmonic generation of the signal produced 10-mW blue light at 486 nm and 15 mW red light at 620 nm for a pump power of 900 mW.

In conclusion, we have demonstrated 1 GHz operation of a femtosecond PPLN OPO. Higher-order synchronous pumping has been used to increase the interaction efficiency between the signal and pump beams. Transform limited 65-fs-signal pulses tunable from 1160 to 1320 nm were obtained with a conversion efficiency of about 4.5% when pumping with 950 mW at 800 nm. The OPO has a pump threshold as low as 580 mW at 1 GHz. In our present setup we utilized standard components designed for an 80 MHz OPO. Substantial improvement of the conversion efficiency seems feasible, e.g., by use of a smaller radius for the curved mirrors, more compact mirror holders, and reducing the disturbing photorefractive effects by higher heating or Mg doping of the $\mathrm{LiNbO_3}$. The low threshold of the present setup enables the use of additional folding mirrors leading to a very compact OPO which can easily be integrated with the pump laser into one device. Inserting appropriate mirror sets into the OPO cavity, generation of 1.55 μm signal pulses at 1 GHz should also be possible.

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