Chirped-mirror dispersion-compensated femtosecond optical parametric oscillator

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Received January 3, 1995

We describe the operating characteristics of a femtosecond optical parametric oscillator employing chirped mirrors for intracavity group-velocity dispersion compensation. Pumped by 760 mW of power from a self-mode-locked Ti:sapphire laser, this device provides 100-fs near-transform-limited pulses continuously tunable from 1.18 to 1.32 μm with an average power of 100–180 mW. The limitations of the present setup and strategies for further pulse shortening are discussed.

Ti:sapphire laser-pumped optical parametric oscillators (OPO's) are attractive sources for tunable femtosecond light pulses in the visible[1,2] and near-infrared[2–7] spectral ranges. In principle, they can work without any group-velocity dispersion- (GVD-) compensating device.[3,6,7] Generation of transform-limited pulses shorter than 100 fs (and shorter than the pump pulse), however, necessitates compensation of the GVD that originates from both material dispersion and self-phase modulation in the nonlinear crystal.[2,4,5] Previously this GVD compensation was accomplished by insertion of prism pairs into the resonator.

In this Letter we report on the generation of transform-limited pulses as short as 73 fs from an OPO that uses chirped mirrors.[8] The application of chirped mirrors (CM's) for GVD compensation was recently demonstrated for femtosecond Ti:sapphire lasers.[9] The main advantages of CM's compared with prism pairs are the small insertion losses that lead to high frequency-conversion efficiency and output power of the OPO. The independence of the GVD from cavity alignment and the attainable reduction in the cavity length are attractive from practical points of view. Finally, CM's may become important for the generation of extremely short pulses (<20 fs) that require compensation of higher-order dispersion by use of a hybrid GVD-compensation system consisting of a prism pair and CM's.

The cavity configuration of our noncritically phase-matched KTP OPO[5–7,10] depicted in Fig. 1 has two-times-smaller material dispersion per round trip than a linear cavity. The OPO is pumped by 120–150-fs pulses from a Ti:sapphire laser (Coherent Mira 900). The focal length (10 cm) of folding mirrors M2 and M3 is two times longer than in the setups of Refs. 1, 2, and 4–7 to reduce the sensitivity to resonator misalignment. The transmission of the output coupler (M1) is 5%, and the back high reflector (M4) is mounted upon a piezoelectric translator (PZT) for fine adjustment of the cavity length. The pump beam is focused by an achromatic lens (L; $f = 10$ cm) into the 2-mm-thick KTP crystal. Tuning of the pump laser from 820 to 920 nm shifts the signal pulse wavelength from 1.18 to 1.32 μm. The spectral distribution of the OPO output pulses is characterized by an optical spectrum analyzer and the pulse width by autocorrelation measurements in a 1-mm-long β-barium borate crystal.

The CM's are designed to have a negative GVD of 85 fs^2 and a reflectivity of at least 99.5% over the spectral range from 1.1 to 1.4 μm. To study the influence of the CM's on the pulse duration and spectrum, we have varied the negative intracavity GVD in the cavity in steps by increasing the number of reflections from such mirrors. For comparison, data were taken first for a cavity with standard single-stack mirrors. Mirrors M2 and M4 were then replaced by CM's introducing a negative GVD. We obtained an increase in the negative GVD by inserting two additional CM's (M5 and M6) into the cavity. Using multiple reflections from these two mirrors, we can provide as much as eight times the GVD of one CM in the cavity.

The threshold of the OPO is typically 500 mW. At the pump power of 760 mW used in most experiments the average power-conversion efficiency of the OPO reveals significant saturation owing to the 50% depletion of the pump pulse. The spectral tuning range of the OPO from 1.18 to 1.32 μm is independent of the number of CM's and is limited by the sharp reflectiv-

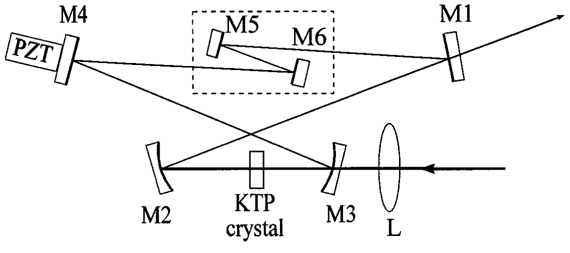

Fig. 1. Setup for the OPO.

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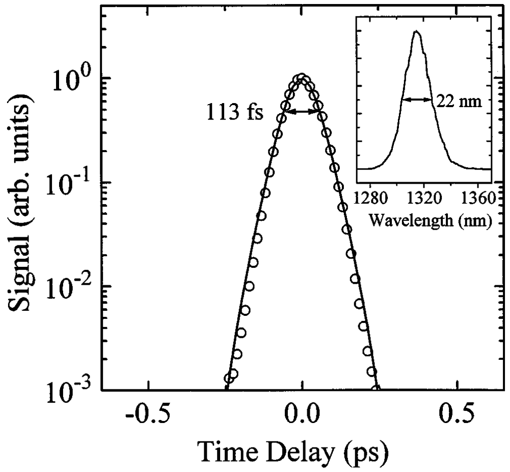

Fig. 2. Autocorrelation curve (open circles) of the pulses generated at 1.315 μm by the OPO with four chirped mirrors. The solid curve is a fit to a sech^2 t pulse shape. Inset: Spectrum of the pulse.

ity drop of the standard single-stack mirrors at short wavelengths and the tunability of the pump laser at long wavelengths. The losses associated with the exchange of the single-stack mirrors for CM's or the additional insertion of CM's are negligible. For the configuration that uses four reflections from CM's the signal power is $\geq$100 mW over the entire tuning range and reaches its maximum of 180 mW at 1.2 μm. The corresponding average power conversion efficiency at 1.2 μm is $\eta = 24\%$ for the signal beam. Such a high conversion efficiency has been reported for prism-pair-compensated OPO's in only one paper,[2] to our knowledge.

Figure 2 shows the autocorrelation curve and the spectrum (inset) at $\lambda_s = 1.315$ μm when four CM's are used. The spectrum has a single peak and is symmetric, unlike the output spectra of OPO's without GVD compensation. The autocorrelation curve fits a sech^2 t pulse shape well over 3 orders of magnitude. From the bandwidth of 22 nm and the pulse duration of 73 fs, we calculate a time–bandwidth product of 0.28, which is slightly smaller than the value for a transform-limited pulse.

Figure 3 shows the time—bandwidth product of the pulse, assuming a sech^2 t pulse shape, for the OPO involving two, four, and eight reflections by CM's for GVD compensation as well as for an OPO without GVD compensation. The data display a continuous reduction of the time–bandwidth product with increasing numbers of CM's from more than four times the transform limit (without any CM) to less than 1.4 times the transform limit (eight CM's) over the whole tuning range. For wavelengths longer than 1.265 μm the use of eight CM's produces transform-limited pulses. It should be mentioned that in all our experiments the cavity length was adjusted for maximum output power of the OPO and that a slightly shorter cavity length yields longer pulse durations but narrower spectra and smaller time–bandwidth products.[7] For measuring the data presented in Fig. 3 only the cavity length of the OPO was matched to the changing cavity length of the pump laser at each wavelength, whereas the GVD of the CM compensator remained fixed.

Next we discuss the different contributions to the resultant GVD. The positive GVD that is due to the material dispersion of the KTP crystal (dashed curve in Fig. 4) continuously decreases with increasing wavelength. The GVD induced by the self-phase modulation in the KTP crystal[5] is also positive and manifests itself by the increased chirp of the OPO pulses for increasing intracavity power. In our OPO the intracavity power has a maximum at 1.2 μm. The chirp transfered from the slightly upchirped pump pulses to the OPO pulses[11] is also positive and is (depending on the wavelength) 0.65–0.80 times the chirp of the pump pulses from the Ti:sapphire laser. Single-stack mirrors M1 and M3 contribute less than ± 20 fs^2. We determined the negative GVD of the CM's, depicted as the solid curve in Fig. 4, by analyzing the frequency-dependent reflection of a Gires–Tournois interferometer formed by the CM and a semitransparent gold mirror.[12] The significant wavelength dependence reveals considerable deviations of the CM's from the design parameters, because the theory predicts an almost constant GVD of the CM (see the dotted curve in Fig. 4). The origin of this discrepancy is not yet clear, but we expect substantially improved performance data from the next set of CM's. The GVD of the CM's has a minimum at 1.24 μm, where the time–bandwidth product of the OPO pulses reaches its maximum value (see Fig. 3). After eight reflections on the CM's, the negative GVD left after compensation of the material dispersion of the KTP crystal amounts to -170 fs^2 and -740 fs^2 at $\lambda_s = 1.24$ μm and $\lambda_s = 1.30$ μm, respectively. The smaller value is clearly insufficient for compensation of the GVD associated with self-phase modulation.

As previously observed for prism-pair-compensated OPO's,[2,4,5] our device also emits visible light at the sum frequency of the OPO signal and the pump, and of the OPO idler and the pump, as well as at the sec-

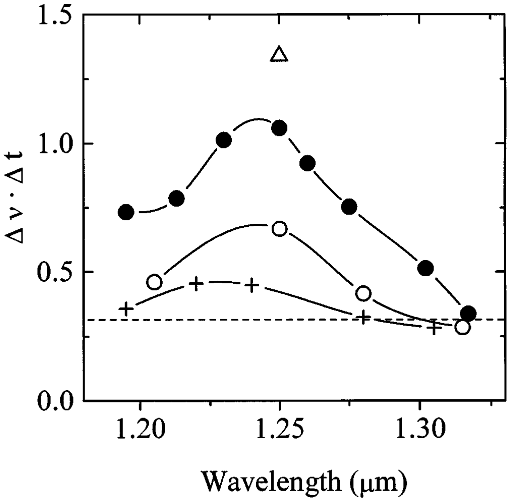

Fig. 3. Products of the measured width (FWHM) of the spectrum and the pulse duration at different wavelengths for OPO resonators using two (●), four (○), eight (+), and no (Δ) reflections from CM's for GVD compensation. The horizontal dashed line indicates the corresponding products for Fourier-transform-limited sech^2 t-shaped pulses.

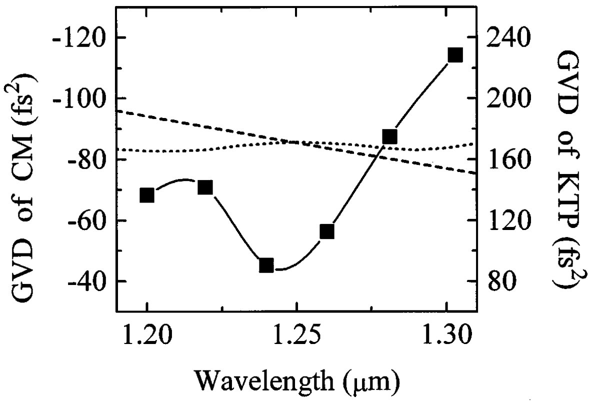

Fig. 4. Calculated (dotted curve) and measured (filled squares) GVD for one CM (left scale). The solid curve is a guide to the eye. The dashed curve is the GVD that is due to the material dispersion in the KTP crystal (right scale).

ond harmonic of the OPO signal. The first process is nearly phase matched, as indicated by the sharp resonance of blue-light generation at $\lambda_s = 1.185\ \mu$m. Calculations predict phase matching at this wavelength for sum-frequency generation with the pump polarized in the z direction and the signal polarized in the y direction of the nonlinear crystal. (For the notation of the crystal optical axes see Ref. 13.) We have to use a y-polarized pump. However, in case of a slight misalignment of the pump beam polarization with respect to the crystal orientation, two phase-matched processes can occur. The y component of the pump generates the OPO signal, whereas the much smaller z component produces blue light together with the signal. The strong variation of the blue-light intensity observed for small rotations of the pump beam polarization supports this interpretation. For 900-mW pump power a pump polarization angle of 30° with respect to the y direction creates the maximum blue (>5 mW), while the OPO signal drops by 30%. The power of the blue pulses decreases by 1 order of magnitude if the OPO is tuned 30 nm away from the blue maximum. Cross correlations (320 fs) with the pump in a 1-mm β-barium borate crystal yield an upper limit of 260 fs for the duration of the blue pulses. Thus the OPO can deliver femtosecond pulses with three different tunable wavelengths. Inasmuch as the generation of the blue light causes decreasing OPO power and additional GVD because of cascaded second-order effects,[14] careful optimization of the pump polarization is recommended if the experiment does not use the blue output.

Complete compensation of the positive GVD in the region around $\lambda_s = 1.24\ \mu$m requires more than eight reflections on the CM's or new CM's with a larger negative chirp. According to our calculations, properly designed CM's should yield GVD up to -145 fs^2. This value is almost constant over a range of 200 nm, which is considerably broader than the OPO tuning range determined by the reflectivity of the single-stack mirrors. Such improved CM's would probably generate transform-limited signal pulses shorter than 100 fs across the entire tuning range of the OPO. Further shortening can most likely be achieved if the SPM in the crystal is enhanced by the use of shorter pump pulses or by an increase of the intracavity power. In this case, compensation of the larger positive GVD probably requires a hybrid GVD compensator consisting of a prism pair and CM's. Then the third-order dispersion of the prism pair can be compensated by the third-order dispersion of specially designed CM's.

In summary, we have described an OPO that utilizes CM's for intracavity GVD compensation. This device provides near-transform-limited femtosecond pulses between 1.18 and 1.32 μm. The measured conversion efficiency of as much as 24% is considerably higher than values reported previously for OPO's with prism-pair compensators. Slight rotation of the pump pulse polarization permits efficient generation of a synchronized pulse in the blue by sum-frequency mixing between the pump and the OPO signal beam.

The authors thank G. Mak for helpful discussions and a careful reading of the manuscript. J. Hebling thanks the Deutsche Forschungsgemeinschaft for financial support.

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