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Renault, A.A.L.; Kandula, D.Z.; Witte, S.; Wolf, A.L.; Zinkstok, R.T.; Hogervorst, W.; Eikema, K.S.E.

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from the compressor, given its stable construction and small compression ratio of 1:2000 [13].

Both the IR and He–Ne laser beams are recombined individually with their respective reference beams behind the amplifier. The IR beam is attenuated by using 2% beam splitters and a 10^{-5} filter to match the intensity with that of the reference pulses. Also, an interference filter is inserted here (bandwidth 10 nm, with a wavelength centered at either 750, 795, 850, or 900 nm), so that the wavelength dependence can be investigated. A home-built spectrometer is used to measure spectral fringes from the IR pulses on a CCD. The delay between amplified and reference pulses is set such that as many as 10 fringes are visible over the 10 nm bandwidth. A spatial interference pattern is recorded on the same CCD as a length reference by recombining the He–Ne laser beams at a small angle on a 50% beam splitter.

Measurements of the phase are performed by recording every third pulse of the amplifier for several minutes. The phase is extracted from the two interference patterns by using a Fourier method described in [14], taking the difference in wavelength between the He–Ne and the amplified beam into account. In Fig. 2 the result is shown for a typical measurement at 850 nm. The pump laser intensity stability is 1% in this case, while the amplifier output stability ranges from 6% at 750 nm to 1.3% at 900 nm. The IR and He–Ne phase individually fluctuate because of external influences, but the difference is rather stable. With the NOPCPA switched off, a minimum phase noise detection limit of 0.09 rad (rms) is found at 795 nm. For the measurement of Fig. 2, correcting for this detection limit, a rms phase noise of 0.27 rad at 750 nm, 0.23 rad at both 795 and 850 nm, and 0.10 rad at 900 nm (1/63 of an optical cycle) results.

Theoretically the phase of the amplified beam is influenced mostly by the parametric process itself and slightly by (cross-)phase modulation due to nonlinear

Fig. 2. (Color online) Evolution in time of the interference pattern for (a) He–Ne and (b) NOPCPA ($\lambda=850$ nm) together with the derived phase traces, which are also depicted in (c) (He–Ne, red; raw NOPCPA, black), as well as the corrected phase noise of the NOPCPA (see text).

refractive index effects. For the latter, phase fluctuations of the order of 0.01 rad are expected, based on a calculated nonlinear phase shift of 0.36 rad for the amplifier and a pump intensity variation of a few percent. The influence on the phase of the signal beam due to parametric amplification is given by [15]

$$\varphi_s(L) = \varphi_s(0) - \frac{\Delta k}{2} \int_0^L \frac{f}{f + \gamma_s^2} dz. \quad (1)$$

Here $f = 1 - I_p(z)/I_p(0)$ is the fractional pump intensity depletion, and $\gamma_s^2 = \omega_p I_s(0)/\omega_s I_p(0)$. In this expression L is the interaction length, Δk is the phase mismatch, I_s is the seed intensity, and ω_s and ω_p are the seed and pump frequencies. Equation (1) states that there is a coupling between the pump intensity and the phase of the seed pulse. To estimate the influence of this effect, numerical simulations have been performed for a three-pass NOPCPA system using a split-step Fourier algorithm [16]. In Fig. 3 the results are shown for the calculated phase-matching conditions and shifts, together with the calculated and experimental spectrum for the measurement depicted in Fig. 2. From Fig. 3 it can be seen that the pump-induced phase shifts are proportional to $-\Delta k$, as predicted by Eq. (1).

A direct quantitative comparison with the experiment is hampered by the extreme sensitivity of Δk to the angles in the three different amplifier passes. This means that the experimental Δk is difficult to determine. It is, however, clear that the calculated phase shifts as a function of pump-power variations are several times lower than the typical values seen in the experiment, especially at 750 nm. We attribute this to a combination of slightly differently aligned

Fig. 3. (Color online) (a) Measured spectrum of the amplified NOPCPA output (black trace), along with a simulated spectrum for phase-matching angle $\theta=23.887^\circ$ and noncollinear angle $\alpha=2.40^\circ$ (green or light gray curve) and the phase mismatch curve ΔkL for a 5 mm long BBO crystal with the phase-matching angles as used in the simulation (red or thin black curve). (b) Total pump-induced phase shift introduced by a complete pass through the amplifier according to Eq. (1). (c) Wavelength-dependent phase shift resulting from a 5% increase in pump intensity.

passes (leading to larger Δk), possible (pump) beam pointing fluctuations, and the influence of pulse-to-pulse intensity variations on the phase readout.

To detect the correlation between the (pump) intensity and the phase we use Spearman's rank correlation coefficient (RC), as it is particularly suited for noisy datasets [17]. An RC of (-1) signifies full (anti) correlation, while 0 means no correlation. With sufficient gain the RC should in principle increase for a larger Δk , and change sign together with Δk . For the spectrum shown in Fig. 3 no significant correlation could be detected between pump intensity and output phase. However, the situation is different when the NOPCPA is less well aligned, leading to a bigger Δk and a strongly modulated spectrum. Significant (anti)correlations can then sometimes be observed, such as the case where the phase-pump intensity RC changes sign from $+0.4$ at 750 nm to -0.3 at 795 nm. In this situation oversaturation (backconversion) was observed at 795 nm. At other wavelengths the RC is normally too small to draw conclusions.

To further study the Δk effects at a fixed wavelength of 795 nm, we deliberately induced a strong phase mismatch by rotating the last crystal from $\theta \approx 23.8^\circ$ to $\theta + 0.06^\circ$. The pump intensity was modulated by about 10% to make the measurement more sensitive to correlations. The result is shown in Fig. 4; the RC changed sign from $+0.4$ to -0.2 , in qualitative agreement with simulations. A strikingly big phase jump of 1.7 rad is seen that is not present when the NOPCPA system is switched off. Such a big phase shift is theoretically possible if the integral in Eq. (1) would stay large for a big Δk . This can be explained by assuming an average pump power of 7 GW/cm² (20% higher than initially estimated).

In conclusion, we demonstrated phase-stable TW-class parametric amplification for the first time. On

average the phase stability is better than $1/25$ of an optical cycle across the amplified spectrum for the measured pump laser fluctuations of 1% rms. The measured phase noise is several times larger than numerically simulated, but qualitative agreement is found for the expected Δk dependence. The average phase stability of $1/25$ of an optical cycle gives an upper bound for the influence on the carrier-envelope phase when the pulses would be fully compressed, demonstrating that TW peak power few-cycle laser pulses can be produced with NOPCPA.

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Fig. 4. (Color online) Influence of the phase-matching angle on the phase of the NOPCPA. (a), (b) NOPCPA spectra for two different phase-matching angles, separated by 0.06° . (c) NOPCPA intensity at 795 nm (black) and pump intensity (red or gray). (d) Phase evolution with (red or gray) and without (black) the NOPCPA switched on (For RC between pump intensity and phase, see text).