Impact of the Optical Parametric Amplification Phase on Laser Pulse Compression

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Optical parametric chirped-pulse amplification (OPCPA) has been widely used to provide high gain over broad bandwidths suitable for sub-20-fs pulses with multijoule energies, corresponding to petawatt peak powers.[1–3] Precise control and measurement of a system's spectral and spatial phases are required for Fourier transform–limited pulse compression and diffraction-limited focusing, respectively. Phase accumulated during optical parametric amplification (OPA) can degrade the compressibility and focusability of the pulse, reducing peak intensity. OPA is a three-wave mixing process where energy is transferred from a strong pump wave to a weak signal wave with the production of a third wave, called the "idler," to conserve energy and momentum. For efficient energy transfer, this process must be phase matched. Significant phase mismatch leads to reduction in gain and, as shown by Bahk,[4] can lead to signal phase accumulation. In this summary, we investigate signal phase accumulation from pump wavefront errors and evaluate the potential impact on signal pulse compression.

Broadband phase matching can be achieved by matching the group velocity of the signal and idler pulses using the amplifier material's birefringence and a noncollinear angle between the pump and signal.[5,6] Figure 1 shows relative orientation of the pump, signal, and idler k vectors to the crystal axis (O), with a noncollinear angle α.

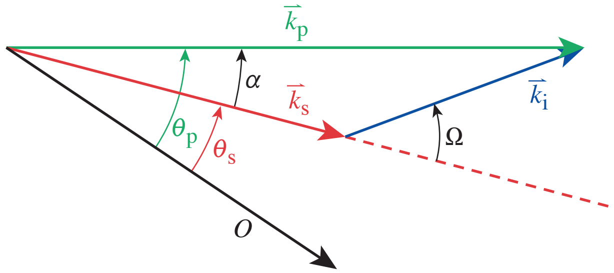

Figure 1
Phase matching between the wave vectors of the three beams: pump, signal, and idler. O is the optical axis of the nonlinear crystal.

The phase mismatch in the z direction is given by Eq. (1):

$$\Delta k = k_p \cos(\alpha) - k_s - \sqrt{k_p^2 \cos^2(\alpha) - k_p^2 + k_i^2}\,. \tag{1}$$

The sensitivity to pointing, caused either by global angular errors or local from wavefront aberrations, is given by the derivatives with respect to θ_p or θ_s for the pump and signal, respectively.[7] The resulting signal phase errors can be expressed analytically for the small-signal case or calculated numerically for higher-efficiency amplifiers.[7] In particular, modification of the signal spectral phase $\phi_s(\omega)$, an important parameter for determining pulse compression, can be evaluated for a range of pump and signal angular deviations from the optimum phase-matched condition.

As a test case, we chose the final amplifier of the Multi-Terawatt optical parametric amplifier line (MTW-OPAL), all-OPCPA system.[3] This amplifier uses 70% deuterated potassium dihydrogen phosphate (DKDP) crystals pumped by the second harmonic of MTW to amplify 1.5-ns pulses centered at 920 nm with 140-nm bandwidths up to 11 J before recompression to sub-20 fs. For amplification, the pulse is chirped before the amplifier to 100,000× the Fourier transform limit; therefore, the interaction between the pump and the 140-nm-wide signal at a given time is essentially monochromatic. The sensitivity of the signal phase for this amplifier for a given angular error of the signal or pump is shown in Figs. 2(a) and 2(b), respectively. Curves for deuteration levels ranging from 70% to 100% are shown—the maximum range suitable for this system; they can be adjusted during the crystal growth with the relative amounts of hydrogen and deuterium. Changing the deuteration level requires changing the noncollinear angle α for optimum phase matching.[8] This, in turn, affects the phase-mismatch sensitivity and therefore the sensitivity of the signal phase to angular deviation. In the case of pump deviation [Fig. 2(a)], reducing the deuteration level causes an increase in pump-deviation sensitivity; for signal deviation [Fig. 2(b)], the opposite holds.

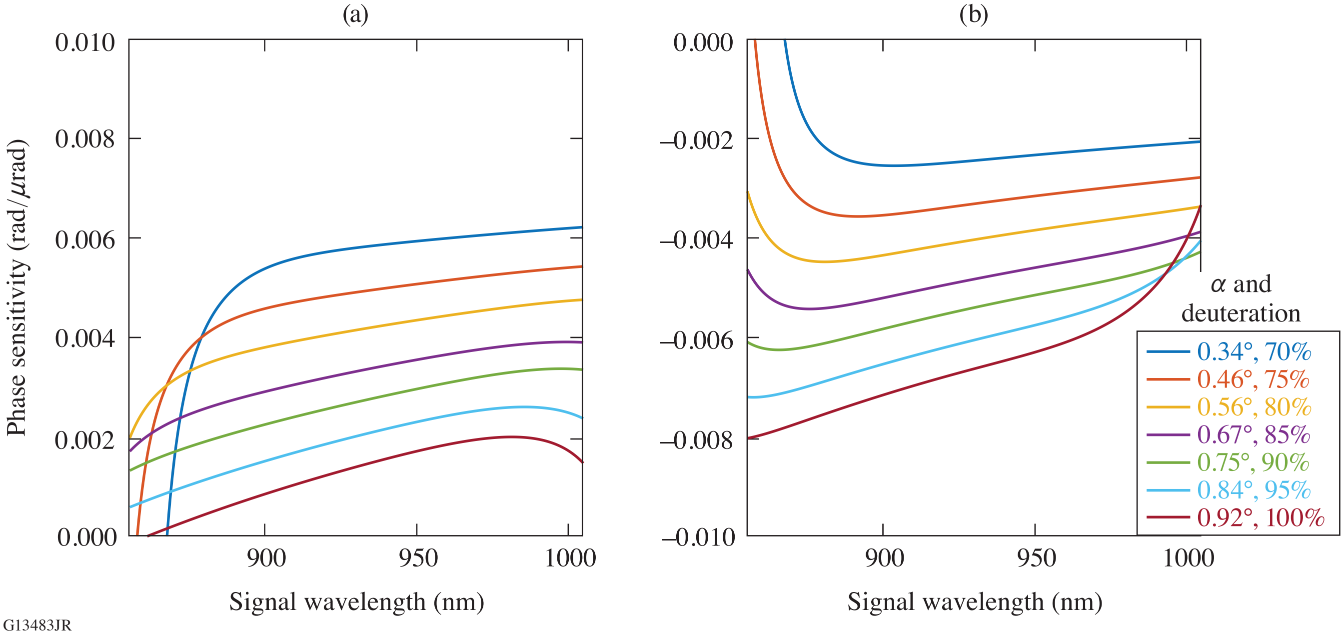

Figure 2
(a) Pump and (b) signal phase sensitivity across the signal wavelength for different deuteration levels and corresponding noncollinearity.

One point to note is that the phase sensitivity (in units of radians per microradian) is small but not zero and, in particular, can vary significantly across the signal bandwidth from 830 to 1010 nm. This variation in phase—a spectral phase error—can be problematic when it also has a spatially varying component, as would happen if the pump or signal angles vary locally. A number of cases were evaluated,[7] one of which is shown in Fig. 3, where the pump wavefront produces a local angular error of 500 μrad. This would produce a reduction in gain by ~50%, leading to local beam profile distortion. It would also change the local pulse (as shown in Fig. 3) with a shift of ~5 fs that, averaged over the beam profile, could cause a pulse broadening in the focal plane. Thankfully, in the case of the MTW-OPAL Laser System, wavefront slopes of this magnitude are not present and phase plates must be added to produce these effects.[9] Nonetheless, this analysis is valuable in determining the suitability of a given pump laser to ensure there are no spatiotemporal pulse-broadening effects that degrade the peak intensity achieved by the laser.

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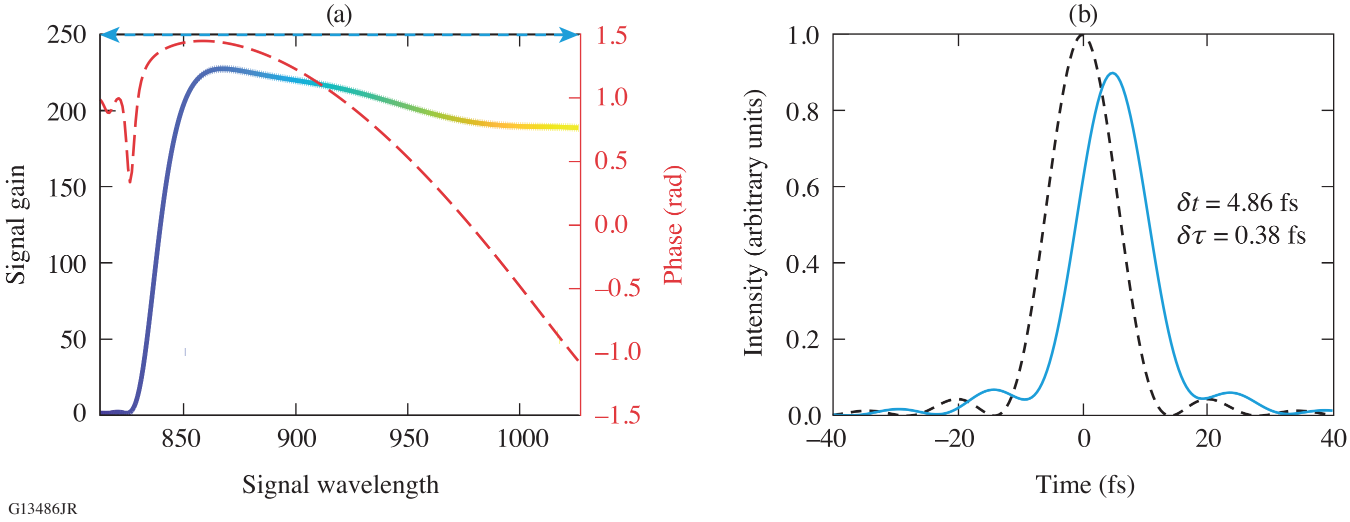

Figure 3
(a) Impact of angular error on signal gain and spectral phase. (b) Impact on the compressed pulse assuming equivalent gain across the spectrum (to show spectral phase effects). δt is the temporal shift of the peak, and $\delta\tau$ is the change in pulse full width at half maximum from the nominal 13 fs.

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