# Overcoming Intra-Cavity Nonlinear Phase Limitations in Cavity-Enhanced Optical Parametric Chirped Pulse Amplification through Cavity-Locking

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**Abstract:** In cavity-enhanced OPCPA, nonlinear phase shifts imparted on the intracavity pump pulse limit pump power loading and degrade system performance. We show that cavity-locking offsets these effects, maintaining dramatic bandwidth extension and high conversion efficiency.
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Optical parametric chirped-pulse amplification (OPCPA) has emerged as a means of providing intense few-cycle optical pulses for applications including ultrafast time-resolved spectroscopy, and high-harmonic generation. The bell-shaped pump intensity profile and the time-varying wave-vector mismatch of the interacting pulses, however, result in a non-uniform small-signal gain limiting conversion efficiency and bandwidth. We have proposed cavity-enhanced OPCPA (C-OPCPA) [1] as a method to overcome these limitations. In C-OPCPA, pump pulses are coherently combined in a low finesse enhancement cavity transparent to signal and idler containing an OPA crystal in which a signal is amplified (see Fig 1a). If the pump has a narrow bandwidth (BW) and the seed is sufficiently chirped, the cavity passively shapes the intra-cavity pump profile to attain optimized gain profiles. Additionally, through impedance matching, conversion efficiencies and gain bandwidths beyond that of the single-pass OPCPA are achievable. Our previous numerical study, however, did not include cavity-locking dynamics or the strong nonlinear phase shifts due to $n_2$ generated in a PPLN crystal at high intracavity intensity. Here, employing a numerical model treating three-wave mixing in the presence of both realistic intensity-dependent nonlinear-phase shifts and cavity-loading, we find that cavity-locking can be used to offset nonlinear phase-shifts detrimental to operation of C-OPCPA, allowing octave-spanning gain while maintaining high conversion efficiency.

C-OPCPA dynamics can be understood by considering the intracavity parametric conversion as a nonlinear, time-varying, intracavity loss, where each temporal coordinate is independent (when, for instance, the interacting pulses are long enough for dispersion to be neglected). Temporal coordinates with initially low conversion (i.e., nonlinear loss) experience greater enhancement, which increases conversion and compensates the initially low loss. In steady state, C-OPCPA therefore reshapes the interacting pump pulse according to the time varying enhancement:

$$Enhance = \frac{T}{\left|1-\sqrt{R\times(1-loss(t))}\times e^{i\delta(t)}\right|} = \frac{T}{\left|1+R\times(1-loss(t))-2\sqrt{R\times(1-loss(t))}\times\cos(\delta(t))\right|}\ ,\ (1)$$

where T/R is the transmission/reflection coefficient of the output/input coupler, loss(t) captures linear loss as well as nonlinear loss via conversion, and δ(t) captures the cumulative roundtrip phase (linear and nonlinear). C-OPCPA relies on loading sufficient pump power to maintain high conversion. At low pump powers when nonlinear phase effects in the enhancement cavity are negligible, the pump power is fully loading at each temporal coordinate and is limited only by linear losses. However, at high powers when intracavity nonlinear conversion occurs, a phase profile develops on the intracavity pump arising from the parametric process and from self phase modulation (SPM). These phase effects can prevent cavity loading, limiting enhancement.

Phase shifts from parametric amplification are relatively small since the they are proportional to the fractional pump depletion, which is low compared to the intracavity pump pulse, since low intracavity conversion per pass is its stationary point of operation and corresponds to high overall conversion efficiency. SPM, however, is particularly detrimental since the resulting phase shifts are strongest at high intracavity powers. Temporal coordinates with initially low conversion may never attain the full enhancement necessary to drive up the conversion due to intensity dependent, self-phase-modulation-induced phase shifts manifesting during the build up process that limit pump power loading. Thus, under the conditions of an interferometrically stable enhancement cavity, the relative strength of quadratic and cubic nonlinear effects, (i.e., $d_{eff}$, and $n_2$), determines the ability of the cavity to load pump power and overcome limitations set by the gain profile in parametric amplifiers.

This is illustrated by the blue and black curves in Fig 1b which show the intracavity pump profile, reflection, fractional conversion and intracavity pump phase for various simulation conditions. A 100-nm wide, 1.55-μm, 6ps signal with 2μW of power is amplified in a C-OPCPA system pumped with narrowband, 8-W, 6ps, 1.03 μm pulses. The cavity has a 10% output/input coupler and a 5-mm PPLN crystal. The laser repetition rates and cavity FSR are all matched to 80-MHz. The blue curves are for an $n_2$ simulated at ~1/10$^{th}$ the actual value of lithium niobate, while the black curves are for a realistic value ($3x10^{-15}$ $cm^2/W$). As shown, the fractional conversion is substantially decreased at high $n_2$ and overall the conversion efficiency is lowered from 75% to 26%. With large $n_2$, excess phase due to SPM limits loading and conversion, although phase from SPM is cancelled by phase from parametric amplification over a limited temporal range. For small $n_2$ the phase shifts are small, and proper pump loading and high conversion is achieved.

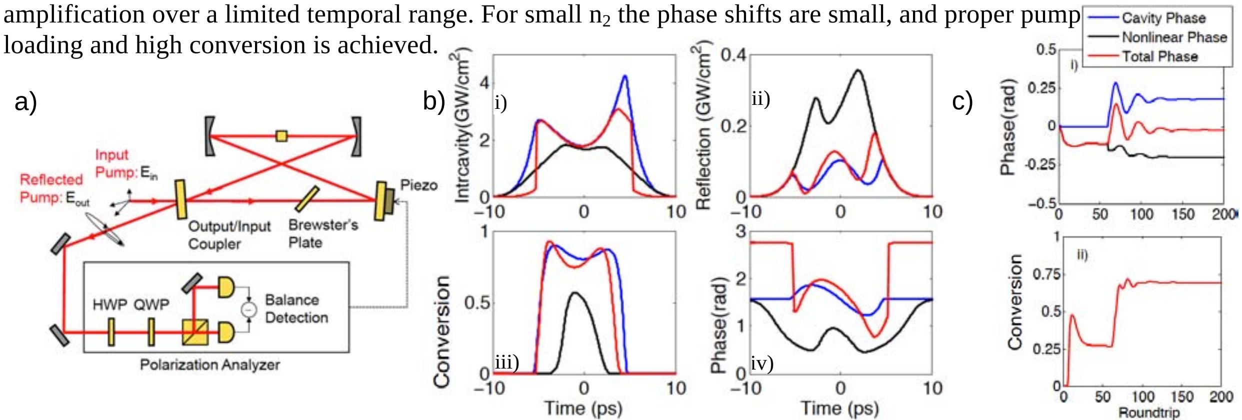


**Fig 1** a) C-OPCPA with HC cavity locking. b) (i)-intracavity pump power, (ii)-reflected power, (iii)-conversion, (iv)-intracavity phase profile, after output/input coupler; π/2 is needed for perfect loading. c) Average phase (i) and total conversion (ii), for each roundtrip. Cavity-locking is activated after 60 roundtrips.

Although the large $n_2$ degrades system performance, the action of the cavity-lock can compensate the detrimental nonlinear phases. The cavity locking technique used in this work, the Hänsch-Couillaud [2] method (see Fig 1a), analyzes the elipticity induced on the reflected beam and produces an error signal that is proportional to a weighted average of δ(t), the cumulative roundtrip phase shift experienced by the intracavity pulse at a temporal coordinate:

$$HC\ Error\ Signal \sim \int_{-\infty}^{\infty} I^{(i)}(t)\left(\frac{1-loss(t)}{loss(t)^2}\right)\delta(t)dt \quad , (2)$$

In Eq. (2) above, $I^{(i)}(t)$ is the incident pump profile, T is the transmission, and loss(t) includes linear loss and nonlinear conversion. This error signal is fed back to a piezo-mounted cavity mirror which counteracts the roundtrip phase by imparting its own phase through the mirror displacement: $\phi_{Cavity}=\Delta L\times 2\pi/\lambda_{pump}$, where ΔL is the piezo displacement. Thus, the average roundtrip phase shift can then be made zero or tuned to an offset value. The red curves in Fig 1b illustrate that the cavity lock adjusts the average phase such that the effects of SPM are cancelled, and good loading and conversion is achieved. Fig 1c shows how the modelled cavity-lock converges. Initially the lock is off and as power builds up an average phase develops limiting conversion. However when the lock is switched on the phase shift from the piezo mounted mirror cancels the nonlinear phase shift and conversion recovers.

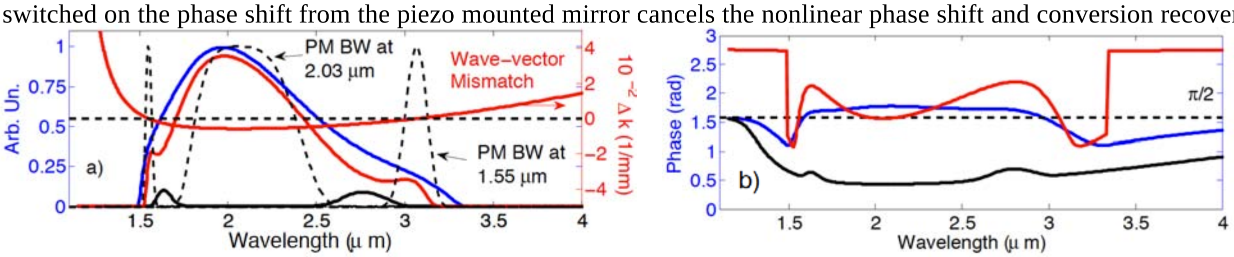


**Fig 2** a) Conversion with low $n_2$/no cavity-lock (blue), large $n_2$/no cavity-lock (black), and large $n_2$/with cavity-lock (red). Also shown phase-matching bandwidth at 1.55mm and 2.03mm (black,dashed), and wave-vector mismatch (red) b) Corresponding intracavity phases.

The role of the cavity-lock in achieving octave-spanning gain is illustrated in Fig 2. When $n_2$ is low, the cavity can properly reshape the intracavity pump pulse to have a large gain bandwidth. When a realistic, large $n_2$ is applied, conversion is drastically cut and the bandwidth is limited. The action of the lock, as shown in Fig 2b, however, is to keep the phase profile properly biased and the gain is recovered.

In conclusion, we have presented detailed simulations illustrating the role of cavity-locking in C-OPCPA system performance. We have shown that the action of the lock is to impart a phase offset via the piezo mounted mirror that on average cancels the nonlinear phase, dominated by SPM, which would otherwise prevent the cavity from reaching enhancement values for proper operation. We predict that large conversion efficiencies and octave spanning gain bandwidths are accessible for the simulated parameters.

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[2] T.W Hänsch, B. Couillaud. "Laser Frequency Stabilization by polarization spectroscopy of a reflecting reference cavity," Opt. Comm. **35**(3), 441-444 (1980).