Alignment Tolerance Analysis for Divided-Pulse Nonlinear Compression

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Recent work has pushed self-phase modulation (SPM)-based spectral broadening to higher pulse energies and peak powers in both hollow-core fiber (HCF)[1] and multipass cells (MPC's).[2] While these demonstrations have shown that spectral broadening using gas-based SPM can handle very high pulse energies, they also show that the process is limited by gas ionization. They must therefore employ large-core fibers or large focal spots in the MPC to avoid gas ionization.

This work is focused on a more-scalable method to improve the energy limits of SPM-based pulse compression: divided-pulse nonlinear compression (DPNLC) (illustrated in Fig. 1). In DPNLC, a high-energy pulse is divided into multiple low-energy pulses that are spectrally broadened, recombined back into a high-energy pulse, and then compressed to a short duration.[3] The low-energy pulses have peak intensity below the gas ionization intensity threshold. As demonstrated in our previous work, DPNLC has the advantage of preserving the amount of spectral broadening, whereas the large-core fibers and large MPC modes reduce the amount of broadening obtained.[4]

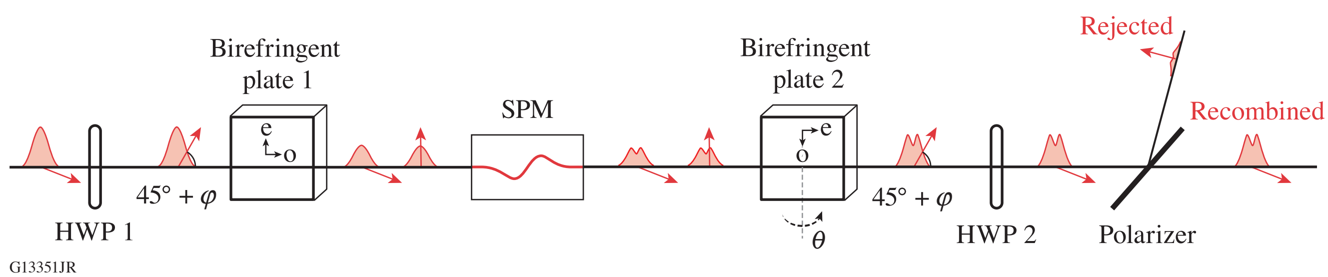

Figure 1
Apparatus for divided-pulse nonlinear compression analyzed in this summary. Birefringent plates with extraordinary axis "e" and ordinary axis "o" are used to divide one pulse into two low-energy, orthogonally polarized pulses. Red arrows indicate the pulse's polarization, and the distorted pulse shape after the SPM stage indicates an arbitrary reshaping by nonlinear processes in the SPM stage. The angles φ and θ represent angular errors in polarization and crystal AOI, respectively.

The alignment of the birefringent plates must be quite precise to divide and recombine the pulses with high efficiency. Previous authors have analyzed the precise alignment tolerances with computationally expensive numeric solutions of the nonlinear Schrödinger equation.[5,6] We have developed an analytic model that describes the output pulse from a DPNLC system that we expect to be a faster, more-flexible tool for tolerancing such systems. The most-sensitive alignment errors are errors φ in the incoming pulse polarization angle (equivalent to an error of φ in the birefringent plate axes) and errors θ in birefringent plate 2's angle of incidence (AOI) [which is modeled as a retardance $\Delta\phi(\theta)$]. We developed an analytic expression for the recombination efficiency of two-pulse DPNLC after accumulating Φ_{NL} nonlinear phase, which is shown in Eq. (1). The infinite sum can be simplified, as in Eq. (2), to quickly prescribe angular tolerances by using the $n = 0$ and the $n = 1$ terms and a small angle approximation for the retardance.

$$\eta = \frac{1}{2}\left\{1 + \sin^2(2\varphi) + \cos^2(2\varphi)\cos\left[\Delta\phi(\theta)\right]\sum_{n=0}^{\infty}\frac{(-1)^n\left[2\Phi_{\mathrm{NL}}\sin(2\varphi)\right]^{2n}}{(2n)!\sqrt{2n+1}} - \cos^2(2\varphi)\sin\left[\Delta\phi(\theta)\right]\right.$$
$$\left.\times\sum_{n=0}^{\infty}\frac{(-1)^n\left[2\Phi_{\mathrm{NL}}\sin(2\varphi)\right]^{2n+1}}{(2n+1)!\sqrt{2n+2}}\right\}. \tag{1}$$

$$\eta_{\mathrm{small}} = 1 - \frac{\cos^2(2\varphi)}{2}\left[\frac{2\Phi_{\mathrm{NL}}{}^2\sin^2(2\varphi)}{\sqrt{3}} + \frac{2\Phi_{\mathrm{NL}}\Delta\phi(\theta)\sin(2\varphi)}{\sqrt{2}} + \frac{\Delta\phi(\theta)^2}{2}\right]. \tag{2}$$

We have experimentally verified the validity of the model by measuring the recombination efficiency across angular errors with excellent agreement, as shown in Fig. 2. The figure plots the results of recombining our homebuilt 1.2-ps, 10-mJ pulses at a wavelength of 1030 nm after the accumulation of nonlinear phase in an HCF and division and recombination using 12-mm-thick, x-cut calcite plates. We should also note that a correction for amplified spontaneous emission (ASE) and pre-/postpulses is included in the plots in Fig. 2 because the ASE does not acquire significant nonlinear phase in the HCF and therefore has a different recombination efficiency.

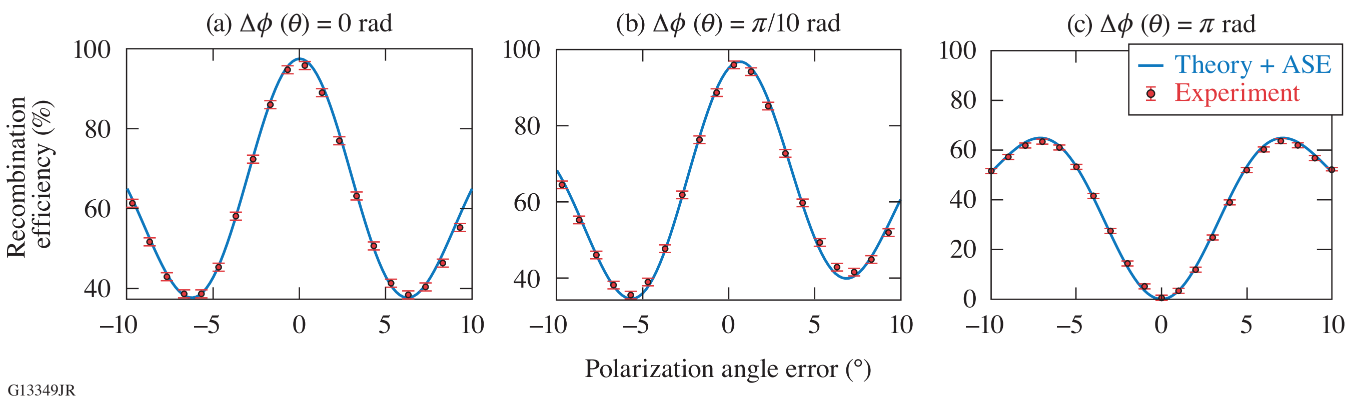

Figure 2
Experimental confirmation of angular tolerances model. The recombination efficiency is measured with errors in both the incoming polarization angle and AOI on plate 2 and is found to agree well with Eq. (1).

A useful consequence of the recombination efficiency expression is that the AOI can be used to compensate for polarization errors. The polarization angle tolerance becomes quite tight for large nonlinearity. For the 8.4-rad nonlinearity demonstrated in our lab and prescribing the angular tolerance to maintain >95% recombination efficiency, AOI compensation can loosen our angular tolerance from 1.0° to 2.8°, a tolerance that is easy to meet by hand.

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