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Phase Control and Measurement of Ultrashort Optical Pulses

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ABSTRACT

We have used the Direct Optical Spectral Phase Measurement (DOSPM) technique to characterize the cubic phase tuning ability of our pulse stretcher. We have compared the measured phase to the phase determined from cross-correlation measurements.

Keywords: Ultrafast phenomena, optical phase measurement, Chirped pulse amplication

2. INTRODUCTION

Chirped Pulse amplification (CPA)[1,2] has permitted the production of high intensity ultrashort pulses from high energy storage capacity solid state materials such as Nd:Glass[1,2], Ti:Sapphire[3,4], and Cr:LiSAF[5]. By reducing the peak power of the pulse by a factor of several thousand during amplification, CPA greatly reduces the deleterious effects of nonlinear interactions between the pulse and the amplifying material. This has permitted the development of laser systems which produce pulse of high peak power (50 TW)[6], very short pulse duration (< 40 fs)[7] and high focused intensity (~ 10^{19} W/cm^2)[8].

CPA works by propagating the initially short pulse from the oscillator through a dispersive delay line composed of a diffraction grating and a focusing optic[9]. The chirped pulse is amplified and then recompressed in a second dispersive delay line having the opposite sign of dispersion[10]. Stretching in the pulse stretcher is achieved by producing a frequency dependent phase shift. This phase function is typically expanded in a Taylor series to identify the effect of each term. The expanded phase function has the form

$$\phi(\omega) = \phi_0 + \phi_1(\omega - \omega_0) + \phi_2(\omega - \omega_0)^2 + \phi_3(\omega - \omega_0)^3 + \phi_4(\omega - \omega_0)^4 + \ldots$$

where the numerical factors in the Taylor expansion have been included in the coefficients for simplicity. The zero and first order terms contribute an overall phase shift and time delay to the pulse, respectively, and are physically unimportant. The second order, or quadratic term produces a linear frequency dependent delay, or chirp on the pulse and is primarily responsible for pulse stretching. The higher order terms (cubic, quartic, etc.) produce a nonlinear chirp on the pulse and it is incomplete compensation of these terms by the compressor which can give rise to wings on the pulse that may have a negative effect on experiments. Incomplete cancellation can occur because of imaging errors (chromatic or spherical aberrations) in the stretcher focusing optic or because of the different functional form of the phase function of the material of the amplifier chain compared to the phase function of the stretcher and compressor.

We have recently developed and demonstrated[11, 12] a new pulse stretcher in which the focusing optic is an air spaced doublet lens. This lens gives us nearly independent, continuous control over the magnitude and sign of the cubic and quartic phase of the stretcher. A diagram of the pulse stretcher is shown in figure 1. The phase tuning of the stretcher is achieved by a method related to pulse shaping techniques. When the lenses are displaced or separated with respect of each other or the stretcher optic axis they produce an imaging (spatial) phase error. However, since the spectrum is spatially dispersed on the lenses the imaging phase error becomes a frequency dependent phase change. The stretcher lenses are described in detail in ref [12].

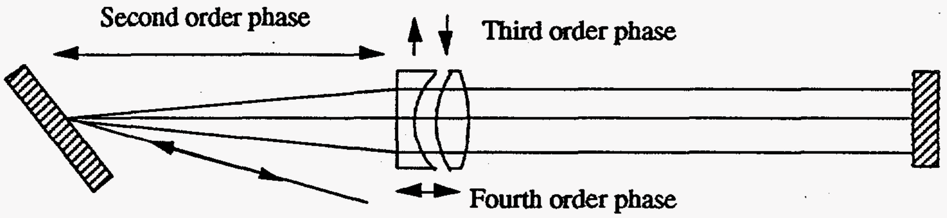

Figure 1. Diagram of the modified pulse stretcher with the air-spaced doublet lens. The arrows indicate the adjustments necessary for phase tuning.

We have used the technique of Direct Optical Spectral Phase Measurement (DOSPM)[13] to characterize the cubic phase tuning of our stretcher. DOSPM does not iteratively determine the electric field of the pulse like the FROG technique[14], but rather, as the name implies, measures the optical phase directly. The technique, an offshoot of pulse shaping techniques developed by Wiener and Heritage[15], is shown schematically in figure 2. It is the temporal analog of the Young's double slit experiment in which a phase difference between the two slits causes a shift in the interference patter. In DOSPM, the pulse is injected into a zero dispersion pulse stretcher in which a mask is placed in the fourier transform plane. The mask consists of a pair of slits which let through two narrow frequency slices. The resulting pulse shape is measured by cross-correlation with an unaltered pulse. The pulse out of the pulse stretcher has a Sinc function envelope whose width is determined by the width of the slits, modulated by a sinusoidal modulation whose temporal period is the inverse of the spacing between the two frequency slices. The phase of the modulations with respect to the peak of the Sinc envelope is the phase difference between the two frequency slices. By keeping one slit at the peak of the spectrum and varying the other slit to positive and negative offsets the frequency dependent phase may be directly determined. DOSPM can also be performed by placing a mask in the fourier transform plane of a non-zero dispersion stretcher followed by a standard pulse compressor. This capability means that the technique can be incorporated into existing system with a minimal modification.

3. EXPERIMENT

The experimental setup consisted of an oscillator followed by a pulse stretcher and compressor and then a cross-correlator. The DOSPM mask is installed in the fourier plane of the stretcher. The oscillator was a Spectra-Physics Tsunami running at 800 nm with 100 fs pulses. The pulse stretcher and compressor use 1800 line/mm Milton Roy gold coated holographic gratings. The stretched pulse duration was 175 ps. The recompressed pulse is characterized by taking a cross-correlation with a pulse directly out of the oscillator with the mask out of the pulse stretcher. Then the mask is placed in the stretcher and the DOSPM technique is used; a series of cross-correlations are taken as a function of slit position to determine the frequency dependent phase. The phase determined by DOSPM can then be compared to that determined by fitting to the cross-correlations. Figure 3 shows a sample of the raw DOSPM data with delay running along the horizontal axis and frequency offset vertical. The data is composed of 32 cross-correlations each of which is 13.66 ps in range. The separation between the slits ranges from a minimum of 2.52 nm at the center to 9.27 nm at the edge corresponding to a range of frequency difference from 1.19 THz to 4.30 THz at 800 nm. The phase is determined from each individual cross-correlation in real-time by fourier transforming and finding the phase corresponding to the peak of the non-zero frequency component.

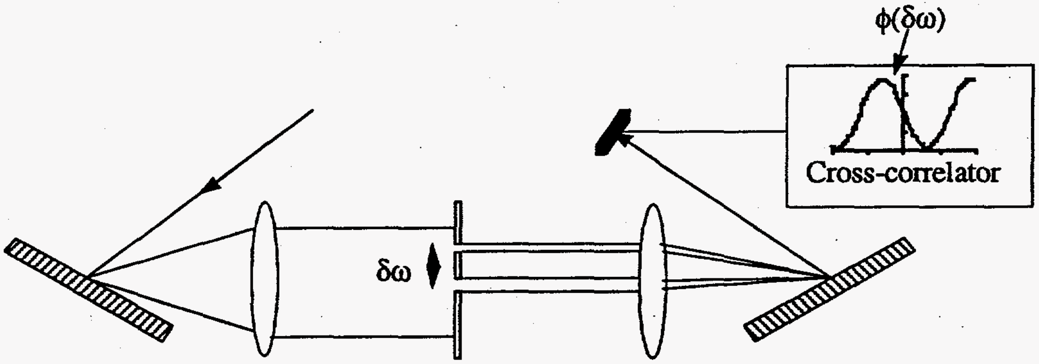

Figure 2. Diagram of the DOSPM setup.

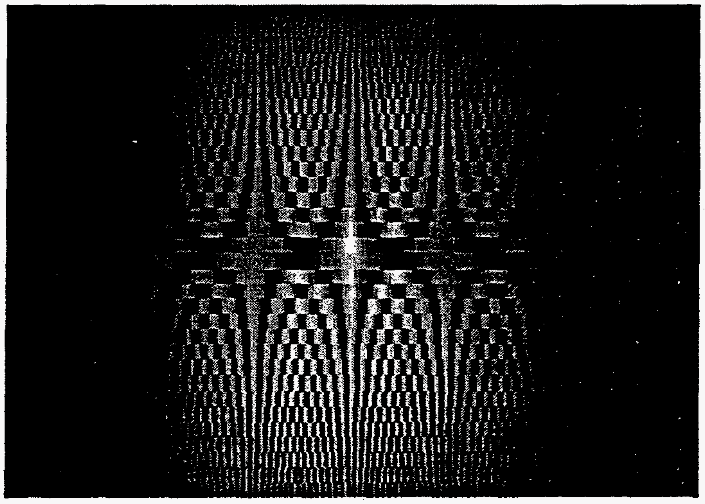

Figure 3. Example of raw DOSPM data with time running horizontally and frequency difference running vertically. As we move away the center of the data vertically the frequency offset increases and the modulation period is reduced.

4. RESULTS

Figure 4. shows the frequency dependent phase determined by DOSPM as a function of the transverse offset of the second lens in the stretcher. Figure 5. shows the corresponding cross-correlations. The multiple peaks seen in the cross-correlation data are characteristic of the presence of cubic phase. The locations of these peaks are very sensitive to the amount of cubic phase and completely insensitive to the amount of quadratic or quartic phase. In Figure 6. the square points are the amount of cubic phase as a function of displacement determined by fitting the phase curves in figure 4 to a third order polynomial. The diamond points are the cubic phase determined by fitting to the cross-correlation curves. The agreement between both measurements is excellent and yield a slope of -4.4×10^{-4} ps^3/mm for the cubic phase tuning of our stretcher.

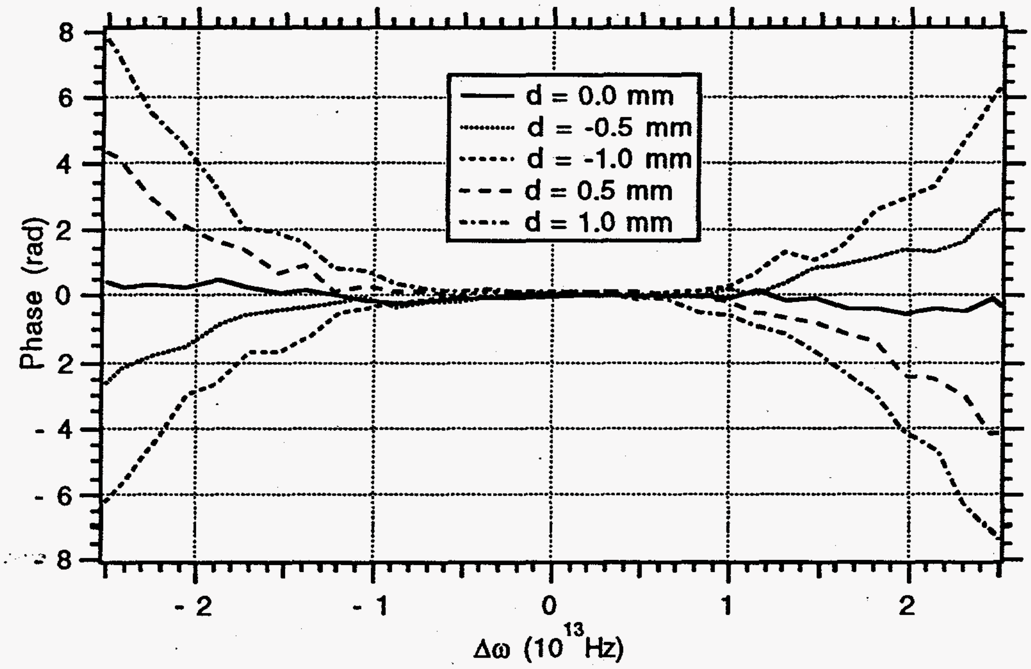

Figure 4. Phase as a function of frequency offset as determined by the DOSPM technique for several values of the displacement of the second stretcher lens relative to the optic axis of the stretcher.

5. CONCLUSION

In conclusion, we have used the DOSPM phase measurement technique to characterize the magnitude of the cubic phase introduce by lens displacements in our new stretcher design. We have compared the phase determined by DOSPM to that determined by fitting to cross-correlation of the stretched and recompressed pulse with a pulse directly from the oscillator and find excellent agreement. We have therefore verified quantitatively the ability of our stretcher to tune cubic phase.

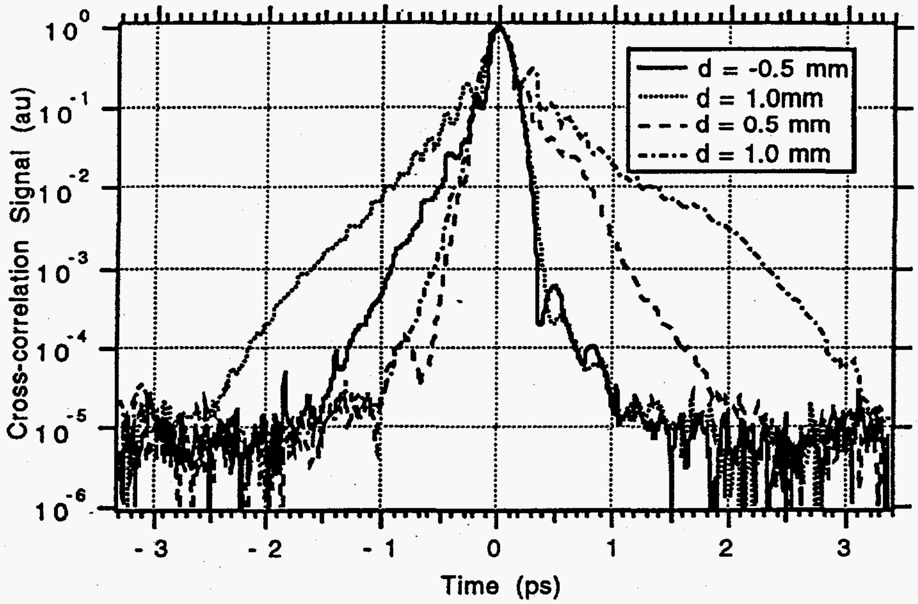

Figure 5. Cross-correlation of the stretched and recompressed pulse with a pulse directly from the oscillator as a function of the displacement of the second stretcher lens with respect to the stretcher optic axis.

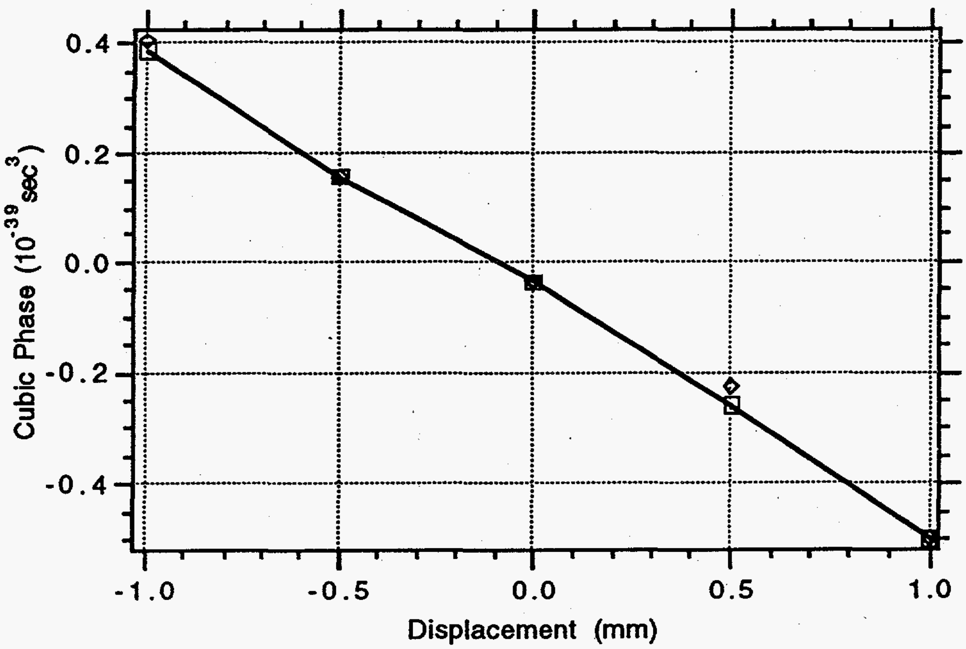

Figure 6. Cubic phase vs. displacement for the DOSPM data shown in figure 4 (squares) and for the cross-correlation data shown in figure 5 (diamonds).

6. ACKNOWLEDGMENTS

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