Characterization of complex space-time optical fields

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ABSTRACT

We consider interferometric techniques for capturing ultra-fast pulsed images. We analyze the signal-to-noise performance and information capacity of pulsed image detection systems and we briefly discuss the possibility of improving detection systems using spectral holographic image capture.

Keywords: pulse shaping, ultrafast optics, quantum control, spectral holeburning, interferometric imaging.

1. INTRODUCTION

Source and pulse shaping technologies have matured to the extent that one can reasonably expect to program optical fields to 10-100 fs temporal resolution and 1-10 um spatial resolution over 100 ps temporal and 1 cm spatial windows. As an example, we have previously demonstrated pulsed image programming over a 1.5 mm square spatial aperture and a 10 ps temporal aperture to 200 fs temporal resolution and 50 um spatial resolution[1]. Using the tremendous information bandwidth available in such signals, one can imagine precise analysis and control of the dynamics of many variable quantum systems in space and time. We have shown, for example, that a pulsed image interacting with a spatially distributed array of two-level systems could be used to excite subwavelength scale features[2].

Three major challenges hinder the goal of controlling spatio-temporal quantum processes:

- *Characterization tools are substantially less developed than pulse shaping tools.* One can program fields with 100 ps bursts of 10^{15} bits per second or more. Obviously one cannot directly detect such data rates. Repetitive detection schemes, while useful and powerful, are applicable only to repetitive phenomena and yield averaged, rather than truly transient, results. The nature of the average taken, the signal-to-noise ratio, and the information content of the detected signal depend on the mechanisms of the measurement. The variety and reach of measurement techniques must be extended to explore single shot, chaotic and complex phenomena.
- *Dynamical models of many variable quantum systems are insufficiently developed.* Given the novelty of multi-dimensional pulse shaping and the complexity of the underlying phenomena, it is not surprising that models of the response of quantum systems to space-time fields are undeveloped. Since quantum dynamics is nonlinear and since nonlinearity is necessary to distinguish coherent time shapes, the detailed models are essential in predicting system response. The problem of optimizing system and field parameters to obtain a target response is more complicated. This problem must be overcome to demonstrate applications.
- *The energy available in complex shaped wavepackets is too small.* At low intensities, linear effects dominate the quantum dynamical response and no novel effects result from the use of space-time fields. While the intensities needed to observe nonlinear effects are not enormous, substantial reductions in intensity are inherent in the process of transforming a single mode short pulse into a complex spatio-temporal signal.

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Despite the major difficulties these issues represent, the potential long-term rewards in atomic scale control over materials and device fabrication, extremely high density data storage, and ultrafast highly parallel information processing are more than sufficient to motivate detailed analysis.

This paper focuses on the first challenge: characterization tools for complex field analysis. We address the question: *In what sense are the pulsed images described in the first paragraph detectable?* We specifically consider the signal-to-noise performance and information capacity of linear interferometric imaging systems for pulsed image analysis. Of course, the major flaw in interferometric analysis is the need for repetitive sampling. We briefly consider whether or not this difficulty might be alleviated by developing image capture systems. This paper considers methods for capturing and analyzing ultrafast pulsed images using linear interferometry and spectral holography.

2. IMAGING INTERFEROMETRY AND NOISE

In this section, we review pulse detection schemes and our work on interferometric cross-correlators. Ultrafast pulses are most often detected and analyzed using nonlinear correlation or streak cameras. Power and phase matching constraints make it difficult to extend nonlinear techniques to imaging applications. Streak cameras trade spatial dimensions for temporal resolution and thus cannot be extended to 3-D applications. Kerr gating[3] and Kerr-Fourier gating[4] have been used to recover the 3-D space-time amplitude of scattered fields for optical tomography. We have focused on interferometric techniques for complex pulse reconstruction.

The temporal structure of an unknown field cannot be extracted from purely linear measurements. To obtain temporal information from linear measurements, some *a priori* knowledge of the fields being detected is required. For example, if the temporal structure of a reference pulse has been characterized by nonlinear measurements, then the reference can be used in a linear cross-correlator to analyze the structure of a signal. Since pulse characterization systems rely on repetitive sampling, the reference and signal must consistently strike the receiver at correlated times. This requirement generally means that the reference and signal are derived from the same source. In typical implementations, interferometric cross-correlation systems measure the phase and amplitude of the impulse response of a scattering object or excited material. Similar systems have long been used to measure the characteristics of materials in dispersive Fourier transform spectroscopy[5-8]. More recently, a number of applications of interferometric scanners to profilometry and interference microscopy have been demonstrated[9-11]. Interferometric imaging of 3-D objects is particularly promising[12,13]. If the temporal shape of the reference signal is well characterized, interferometric cross-correlators can be used for wave packet analysis[14] and 3-D space-time field detection[1].

In view of the growing list of applications, it is important to develop a sound understanding of the information detection capabilities of interferometric cross-correlators. Generally speaking, existing analyses are sufficient for spectroscopic applications. However, a number of recent applications focus on cross-correlation measurements for extraction of phase, spatial patterns and complex dispersion characteristics which are not covered in analyses of autocorrelating spectroscopy. For concreteness, we focus on analysis of pulses encoded by linear scattering processes here. Extensions to nonlinear scattering processes are straightforward. While cross-correlators are similar to Fourier transform spectrometers, which have well understood noise characteristics[15,16], several important distinctions make an updated analysis essential. Fourier transform spectrometers have generally been used in the far infrared, where less positioning accuracy is necessary and where the "multiplex" or Fellget noise scaling advantage of interferometric spectroscopy is important. In the near IR and visible ranges, Fourier transform spectrometers have no fundamental noise advantage over grating devices but still support the throughput or Jacquinot advantage. As translation stage technology has improved, therefore, more groups have used interferometric techniques for visible field analysis.

Phase sensitive detection of scattering from spatially or spectrally complex objects can dramatically increase the information content one expects to extract from a cross-correlation measurement relative to conventional Fourier spectroscopy. In this context, it is important to fully analyze noise sources and place upper bounds on the total information capacity of interferometric systems. One might expect these bounds to take a form similar to diffraction limits in imaging systems. The information capacity of an imaging system can roughly be approximated by its space bandwidth product, *i.e.* the area of the aperture times the area of the spatial frequency bandpass. An upper bound on the information capacity of an interferometric imaging system is the product of its space-bandwidth and time-bandwidth products, where the time bandwidth product is equal to the temporal bandwidth of the illumination source times the temporal extent of the correlation detected. Unfortunately, an interferometric system cannot reach this upper bound for arbitrarily long correlation times because noise in the reconstructed signal increases with increasing time-bandwidth product.

We use the system sketched in Fig. 1 to analyze a scattering object, such as a 3-D pulse shaper. A polychromatic field is split into beams which scatter from the object and from a mirror on a variable translation stage. The reflected object and reference fields are recombined and detected by a photodetector array. We consider the incident field as a plane scalar wave under the assumption that the effects of polarization and spatial nonuniformity can be accounted for by multiplicative factors. We consider the analytic signal of the field $V(t)$ [17]. The reference field is a time delayed version of the incident field, $V(t-\tau)$. The object field can be represented by the cross correlation between the incident field and the scattering impulse response of the object, $h(x,y,t)$. $h(x,y,t)$ represents the spatial and temporal pattern which an incident impulse would excite. Since the scattering process is linear, the object field for an arbitrary incident field is $V(t)*h(x,y,t)$.

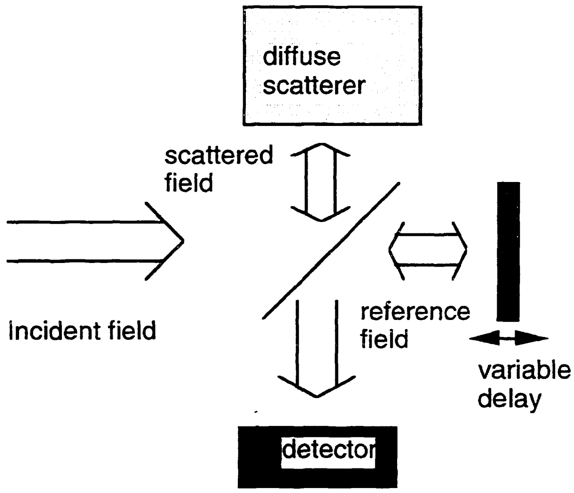

Figure 1. Scattering Geometry.

We model the field at the detector array as $\alpha V(t-\tau)+V(t)*h(x,y,t)$, where α is a scaling constant used to adjust the relative intensities of the two paths. The detector generates a signal proportional to the intensity of the field integrated for a time T[18]. We model the detector signal as

$$I(x,y,\tau)=\int_0^T \left|\alpha V(t-\tau)+V(t)*h(x,y,t)\right|^2 dt \tag{1}$$

Our goal is to use $I(x,y,\tau)$ to reconstruct the object impulse response, $h(x,y,t)$. In principle, we can do this by taking the Fourier transform of $I(x,y,\tau)$ with respect to τ. For $\omega > 0$ and assuming that $V(t)$ is a stationary signal and that T is much longer than the duration of the impulse response and the correlation time of $V(t)$, the Fourier transform of $I(x,y,\tau)$ is

$$\mathrm{I}(x,y,\nu)=\alpha\left|\mathrm{V}(\nu)\right|^2 H(x,y,\nu), \tag{2}$$

where we make use of the fact that the negative frequency components of the analytic signals are zero. $H(x,y,\nu)$ can be obtained over the bandwidth of $\mathrm{V}(\nu)$ by dividing Eq. (2) by $\alpha\left|\mathrm{V}(\nu)\right|^2$. Given $H(x,y,\nu)$, we can reconstruct a bandlimited version of the object impulse response by inverse Fourier transforming.

In practice, $I(x,y,\tau)$ is detected at discrete points in space-time. In single spatial channels systems, $I(x,y,\tau)$ may be recorded continuously in time as the reference delay is scanned. In receiver noise dominated systems, continuous recording coupled with bandpass filtering may be useful for noise reduction[15]. In the visible and near-IR spectral ranges, however, there is little fundamental difference between continuous and discrete recording systems. Noise arises in the reconstructed signal from two primary sources: intensity and current fluctuations and positioning error and stability. An analysis of the impact of these sources is presented in Ref. [19], where it is shown that the expected value of the discrete Fourier transform of $I(x,y,\tau)$ is

$$\langle \mathrm{I}(n')\rangle = \alpha^* e^{-\pi^2 v_o^2 \sigma_\chi^2} \int_{-\infty}^{\infty} dv e^{j\pi(N-1)\left(\frac{n'}{N}-\delta v\right)} \frac{\sin\left(N\pi\left(\delta v - \frac{n'}{N}\right)\right)}{\sin\left(\pi\left(\delta v - \frac{n'}{N}\right)\right)} \left\langle |\mathrm{V}(v)|^2 \right\rangle H(v)$$
$$+\alpha e^{-\pi^2 v_o^2 \sigma_\chi^2} \int_{-\infty}^{\infty} dv e^{j\pi(N-1)\left(\frac{n'}{N}+\delta v\right)} \frac{\sin\left(N\pi\left(\delta v + \frac{n'}{N}\right)\right)}{\sin\left(\pi\left(\delta v + \frac{n'}{N}\right)\right)} \left\langle |\mathrm{V}(-v)|^2 \right\rangle H^*(-v) \tag{3}$$

where σ_χ is the variance of the positioning error, δ is the temporal sampling period, N is the number of samples taken, and v_o is the signal center frequency. The transverse spatial dependence of the signal has been dropped for notational convenience. $\langle \mathrm{I}(n')\rangle$ is the convolution of the target spectrum and a comb function and is periodic in n' with period N. In the range $0 < n' < N/2$, $\langle \mathrm{I}(n')\rangle$ represents $\left\langle |\mathrm{V}(v)|^2 \right\rangle H(v)$ to an approximate resolution of $1/N\delta$ as long as the period of the comb function is large enough to satisfy the Nyquist criterion, $\delta > 2/v_{\max}$, where $v_{\max}$ is the largest frequency at which $\left\langle |\mathrm{V}(v)|^2 \right\rangle H(v)$ is nonzero. It is also possible to calculate the variance of $\langle \mathrm{I}(n')\rangle$ and from the variance and mean to estimate a signal-to-noise ratio. This yields

$$\mathrm{SNR} = \frac{\exp\left(-2\pi^2 v_o^2 \sigma_\chi^2\right) P_s}{\sqrt{4 v_B^2 \delta^2 N P_s + v_B \delta \left(1 - \exp\left(-2\pi^2 v_o^2 \sigma_\chi^2\right)\right) P_s^2}} \tag{4}$$

where P_s is the number of photogenerated electrons needed to saturate the detector and v_B is the bandwidth of the source.

The temporal duration of the object field is $T = N\delta$, and its information content is approximately Tv_B. If T is fixed, then increasing N increases the SNR. If δ is fixed near the Nyquist sampling rate, however, and T is increased, then the SNR falls. When the SNR falls below some critical value, information can no longer be detected. Thus, in contrast to spatial imaging systems, increasing the temporal aperture may actually decrease the information capacity of a space-time imaging system. One can estimate the information detected per spatial channel by an imaging cross correlator as

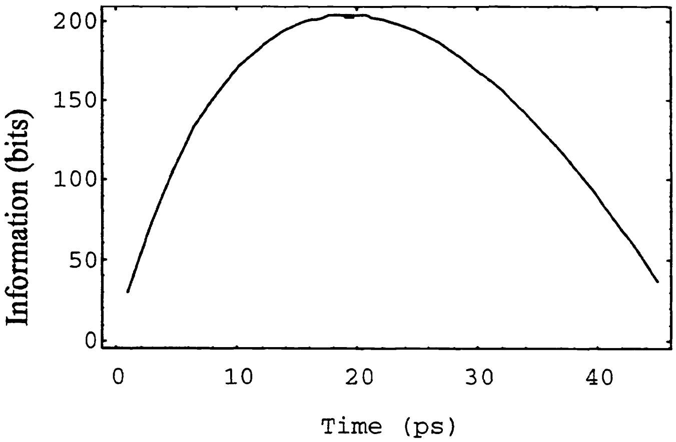

Figure 2. Information detected as a function of signal duration for $\lambda = 800$ nm, $v_B = 19$ THz, P_s=500,000, and $\sigma_\chi = 5$ nm.

$$H = v_B T \log_2 \frac{SNR}{SNR_{\min}} \tag{5}$$

where SNR_{min} is the SNR corresponding to the minimum detectable signal. As an example, Fig. 2 shows H as a function of T for $SNR_{min}=100$. As shown in the figure, under typical conditions one can expect to detect only a few hundred or a few thousand bits per spatial channel. While the overall information detected may be large (10^9 bits or more for a megapixel CCD), the information detected by interferometric cross-correlation is probably less than the information one can encode on ultrafast images.

3. EXPERIMENTAL NOISE MEASUREMENTS

We have constructed an imaging interferometric cross correlator for use in pulsed image detection and interferometric microscopy. Our cross correlator is based on a Michelson interferometer that ties together the following three subsystems: a spatially coherent broadband source, an imaging system, and a positioning system. In time domain applications, our source is a mode-locked Ti:sapphire laser. For temporally insensitive applications, the broadband source is a dye-fluorescence source pumped by an argon-ion laser. The beam of the laser is focused to a 5 um area in a dye jet to produce a point fluorescence source radiating in the range of 560-600 nm. The back fluorescence off the dye is collimated using the same lens which focused the original laser beam and is split off using a beam splitter. A notch filter rejects the argon laser lines, which leaves a collimated, spatially coherent, broadband source. The imaging system is based on the Princeton Instruments cooled CCD array capable of 16 bits of dynamic range. It interfaces to a microcomputer for image storage and processing. The CCD captures two images simultaneously, one image is the interference pattern from the scattered and reference beams, and the other is the fringe pattern from a HeNe reference laser used to stabilize the optical path.

The positioning system has three degrees of freedom. Two degrees (x and y) are used to position the scattering object. This positioning is done using two flexure stages with piezo actuators and inductive sensors in a closed loop feedback setup. Using this setup gives us a resolution 2 nm with a repeatability of 20 nm. The third degree of freedom is the change in the reference optical path length. This is controlled by mounting a mirror on an electromotive stage in a similar feedback setup as the x-y axis. However, electrical feedback is just used to gain some stability and to make the mirror position linear with applied voltage. To obtain precise optical path length measurements, we use a reference laser (Spectra Physics frequency stabilized HeNe) which is placed slightly above and parallel to the signal beam. The fringe pattern produced from this HeNe line is then captured with the CCD and Fourier transformed to extract the phase. By maintaining a careful history of the phase of the HeNe line, the absolute reference mirror position can be determined. The interferometrically determined position is fed back to the electrical control circuit for path length adjustment. The exact position is also saved during image capture. This technique allows absolute measurement accuracy of less than a nanometer over several millimeters of travel. The step positioning resolution is currently 3 nm.

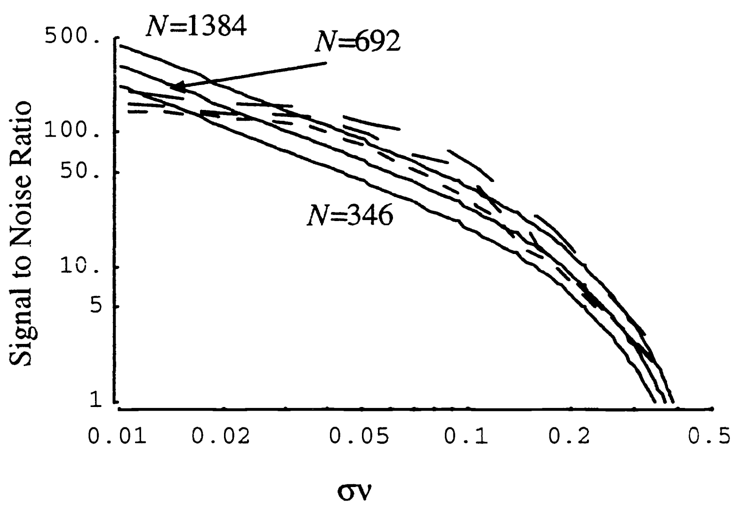

Figure 3. Signal-to-noise in interferometric cross correlation as a function of reference positioning error.

The basic model for noise in our imaging interferometric cross correlator is confirmed in the data presented in Fig. 3, which shows the experimental signal to standard deviation ratio as a function of reference positioning error for the autocorrelation of our dye jet source. The solid lines are theoretical curves based on Eq. (4) for the indicated values of N. The dashed curves present experimental data. Considering the complexity of the process modeled, the agreement between theory and experiment is good.

4. IMAGE CAPTURE

Holographic capture of a pulsed field could alleviate two limitations of interferometric pulsed image analysis:

- Gated temporal windows in a repetitively reconstructed field could be analyzed interferometrically with lower signal-to-noise than the complete temporal aperture.
- Single shot or few shot pulsed fields could be repetitively reconstructed for interferometric analysis of unstable or chaotic phenomena.

To date, demonstrations of holographic pulse shaping and pulse capture have focused on many shot recording processes over brief windows. In this section we consider the possibility of extending this work to address pulse characterization issues.

Four classes of holographic techniques are relevant to ultrafast optics. The first class is classic holography, which uses monochromatic illumination to form diffractive structures. This approach can be used to shape pulses but is not relevant to pulse capture. The second two approaches are light-in-flight and spatial-spectral holography. Light-in-flight holography refers to spatial index modulations formed by colliding pulse trains. Spatial-spectral holography refers to spatial index modulations formed by spectrally decomposed pulse trains. Both light-in-flight and spatial-spectral holography could be used to capture pulsed images, but the recording energies required for these techniques makes them unattractive for complex 3-D field capture. The fourth class of holography might be called spectral-spectral holography. This approach achieves time domain-signal storage by modulation of the spectral dependence of the index or absorption. Homogeneous segments of an inhomogeneous absorption line can be independently modulated by spectral hole burning. As proposed by Mossberg, in a two-level system, interference between temporally separated signals can be used to capture a time sequence in a spectral hole burning system[20]. The recording quantum efficiency of this type of spectral holography is very high compared to standard holographic methods because information is recorded directly in spatially localized transitions. In spatial holography, information is distributed over wavelength scale features created by tens or hundreds of thousands of transitions.

Spectral holograms require localized transitions arising from dopant or gas dynamics. The most common media are rare earth doped materials, which support localized 4f to 4f transitions that are relatively isolated from the crystal field. Glass hosts, rather than more commonly used crystals, will be necessary to obtain bandwidths consistent with ultrafast operation in rare earth materials. Demonstrations of ultrafast signal storage using accumulated photon echoes have been completed by Rebane *et al*[22] and Zeylikovich *et al*[21] in organic materials. These media require approximately 100 mJ/cm^2 to record a spectral hologram. This energy is comparable to the energy needed to record a hologram in a photorefractive medium, although the reconstruction efficiency will be much worse for the photorefractive medium in ultrafast applications. The energy required for a complete repetitively sampled interferometric imaging sequence is only about 10 $\mu J/cm^2$ for a 10-100 ps pulse sequence.

The goal of an image capture system would be to record a complex field such that it can be repetitively reconstructed for analysis. To obtain single shot image capture, new hole-burning materials must be tried. The critical parameters in this process will be the ratio of the energy reconstructed from the spectral hologram to the recording energy, the number of reconstructions one can make, the temporal duration of the holographic effect, and the reconstruction fidelity. Demonstrations to date have focused on persistent media in which the lifetime is very long and the number of reconstructions allowed is fairly large, but the recording efficiency and reconstruction energy are relatively poor in these media. In pulsed image analysis systems, the lifetime of the hologram must be several seconds to allow several thousand CCD images to be recorded. One approach to efficient image capture might be to look for trade-offs between persistence and higher recording efficiency.

We have reviewed interferometric imaging systems for pulsed image characterization and we have suggested that these systems might be improved by developing complementary spectral holography systems. As suggested in the text, a great deal of work remains to be done on these systems and on developing applications for this technology.

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