# Characterization of the polarization state of weak ultrashort coherent signals by dual-channel spectral interferometry

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We demonstrate that dual-channel spectral interferometry in conjunction with a well-characterized reference pulse can be used to time resolve the polarization state of extremely weak ultrashort coherent signals from linear- and nonlinear-optical experiments by measuring the intensity and the phase of two orthogonal polarization components. In this way the signal is completely characterized. © 1997 Optical Society of America

It is well appreciated that by studying the phase and the amplitude of coherent ultrashort signals that are transmitted, reflected, or emitted from materials during linear- and nonlinear-optical experiments one can obtain valuable information about the optical interactions and the fundamental processes in those material systems. Many of the signals of interest (e.g., those from four-wave mixing experiments) are weak and require sensitive measurement techniques. Characterization techniques[1–3] that provide both the amplitude and the phase of an ultrashort pulse have been developed over the past decade, but each requires a nonlinear process. Consequently, both for practical and for fundamental reasons, they are of no use for very weak signals (a few femtojoules per pulse). Recently, in partial response to this need, a method of completely measuring the intensity and the phase of an almost arbitrarily weak coherent signal was demonstrated by use of spectral interferometry[4–9] (SI) with a well-characterized reference pulse.[8,9] To date, however, these (and similar) techniques have been scalar in nature. That is, they have been used to characterize the amplitude and the phase of only a single polarization component.

However, much useful additional information is often carried in the temporal dynamics of the polarization state. For example, when a linearly polarized ultrashort pulse traverses an anisotropic nonlinear material, the emerging light is elliptically polarized and the polarization is rotated. Moreover, the polarization state changes in time from the front to the back of the pulse. In such a case, measurement of the polarization state permits the simultaneous determination of both the nonlinear birefringence and the dichroism, which yields information about the anisotropy in the nonlinear susceptibilities.[10] As another example, it was also recently shown[11] that the polarization state of the ultrafast coherent four-wave mixing signal from semiconductors varies continuously in time and that these dynamics provide useful new information about coherent processes and exciton–exciton interactions in these materials.[11]

The ultrafast ellipsometric techniques[10,11] that were used previously to measure the temporal evolution of the polarization state are cumbersome. They require the tedious rotation of wave plates and polarizers to isolate the various polarization components, and for each orientation of these components, they require the tedious scanning of a time delay to perform a cross correlation of the transmitted signal with a reference pulse in a nonlinear crystal to gain temporal resolution. Not only are such techniques labor intensive but they are limited in sensitivity and temporal resolution because of the nonlinear cross-correlation process. Furthermore, the information provided by such measurements is incomplete. Despite providing temporal resolution of the complete polarization state, previously used techniques[11] determine only the amplitudes and the relative phase of two orthogonal polarization components; however, the temporal evolutions of the individual or overall phases (chirp) are not retrieved.

Here, by using a dual-beam version of the SI techniques previously discussed,[8,9] we demonstrate that both the amplitudes and the phases of two orthogonal components of extremely weak signals can be temporally characterized. This technique not only provides additional information but is linear and therefore is more sensitive than time-resolved techniques that require a nonlinear process. It requires measurements only at a single time delay, and it does not require one to acquire data for various orientations of wave plates and is thus simpler than previous techniques.

The dual-beam geometry that we use to perform spectral interferometric measurements on both $x$ and $y$ components of the signal is shown in Fig. 1. The reference pulse is linearly polarized at 45°, so it has equal $x$ and $y$ components. The experimental signal can have $x$ and $y$ components with arbitrary temporally varying amplitudes and phases. Thus the polarization state of the signal can be represented by an ellipse with a time-varying amplitude, ellipticity angle $\epsilon(t)$, and azimuthal angle $\theta_{\mathrm{sig}}(t)$. As shown in Fig. 1, $\epsilon$ is determined by the ratio of the minor to major axes of the polarization ellipse, and $\theta_{\mathrm{sig}}$ denotes

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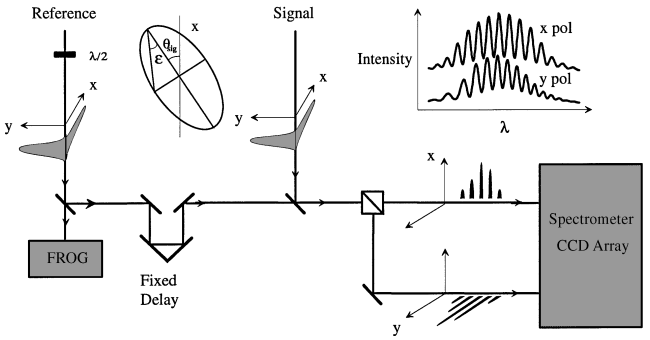


Fig. 1. Schematic representation of experimental geometry used for the dual-beam spectral interferometric characterization of the intensity, the phase, and the polarization state of a coherent ultrashort signal from a linear or nonlinear experiment.

the orientation of the ellipse. One then performs a spectral interferometric measurement on the $x$ and $y$ components of the signal by introducing a fixed time delay between the reference pulse and the signal, by combining the reference and the signal collinearly, by separating the combined reference and signal into $x$ and $y$ components, and by separately dispersing the $x$ and $y$ components with a spectrometer.

Typical spectral interferograms for the $x$ and $y$ components are shown in Fig. 1, and they have the form

$$I^i_{\mathrm{SI}}(\omega) = I^i_{\mathrm{sig}}(\omega) + I^i_{\mathrm{ref}}(\omega) + 2\sqrt{I^i_{\mathrm{sig}}(\omega)}\sqrt{I^i_{\mathrm{ref}}(\omega)} \times \cos[\phi^i_{\mathrm{sig}}(\omega) - \phi^i_{\mathrm{ref}}(\omega) - \omega\tau], \quad (1)$$

where $I^i_{\mathrm{sig}}(\omega)$ and $I^i_{\mathrm{ref}}(\omega)$ are the spectra and $\phi^i_{\mathrm{sig}}(\omega)$ and $\phi^i_{\mathrm{ref}}(\omega)$ are the phases of the signal and the reference pulses, respectively, and where $i$ takes on the values $x$ and $y$ for the two polarization directions. The delay $\tau$ is chosen to yield fringes of a convenient spacing. If the amplitude and the phase of the $x$ component ($y$ component) of the reference pulse are fully known, then the amplitude and the phase of the $x$ component ($y$ component) of the signal and the delay $\tau$ can be retrieved from the corresponding spectral interferogram by one of several fringe inversion techniques[8,9,12] that were discussed previously. In addition, any one of several techniques[1–3] can be used to provide a fully characterized reference pulse. In our case, we chose to use second-harmonic frequency-resolved optical gating (FROG).[13]

For purposes of illustrating and demonstrating this technique, 108-fs FWHM pulses from a mode-locked Ti:sapphire laser operating at a wavelength of 890 nm were split into two parts to provide a reference and a signal. To simulate the signal, we artificially generated an ultrafast pulse with a time-varying polarization state. We accomplished this by first rotating the linear polarization of the signal and then dividing it into $x$ and $y$ components, which propagated through separate arms of a Mach–Zehnder interferometer. The $y$ component of the signal was dispersed and chirped by being focused onto a 2-mm-thick wafer of CdTe that was placed in one arm of the interferometer. The measured fluence at focus was 42 $\mu$J/cm$^2$. The $x$ component propagated through the second empty arm and was not dispersed or chirped. The $x$ and $y$ components from the two separate arms were then recombined collinearly, after traversing equal optical paths, to form the signal. To ensure that the bandwidth of the signal was comparable with (or less than) that of the reference, even after chirping, we restricted the bandwidth of the signal by placing a 12.6-nm bandpass filter before the Mach–Zehnder interferometer.

The spectral interferograms for the $x$ and $y$ components of the signal pulse are shown in the inset at the upper right of Fig. 1. The spectral intensities $I^x_{\mathrm{sig}}(\omega)$ and $I^y_{\mathrm{sig}}(\omega)$ and phases $\phi^x_{\mathrm{sig}}(\omega)$ and $\phi^y_{\mathrm{sig}}(\omega)$ for the $x$ and $y$ components of the signal (not shown) were extracted from these interferograms as described previously,[9] and the corresponding time-varying pulse intensities $I^x_{\mathrm{sig}}(t)$ and $I^y_{\mathrm{sig}}(t)$ and phases $\phi^x_{\mathrm{sig}}(t)$ and $\phi^y_{\mathrm{sig}}(t)$ are shown in Fig. 2. The temporal evolution of the polarization state associated with this signal as characterized by the total intensity, $I^x_{\mathrm{sig}}(t) + I^y_{\mathrm{sig}}(t)$, the azimuthal angle $\theta_{\mathrm{sig}}(t)$, and the ellipticity angle $\epsilon(t)$ is given in Fig. 3, and the polarization ellipses that correspond to these data are sketched in Fig. 4 for time delays selected to emphasize the temporal variation of the polarization state.

This experiment clearly demonstrates that SI, when performed on two orthogonal polarization components and with a fully characterized reference pulse, is an excellent method for determining the temporal dynamics of the polarization state of ultrashort signals. Although it has been suggested that SI might be used to

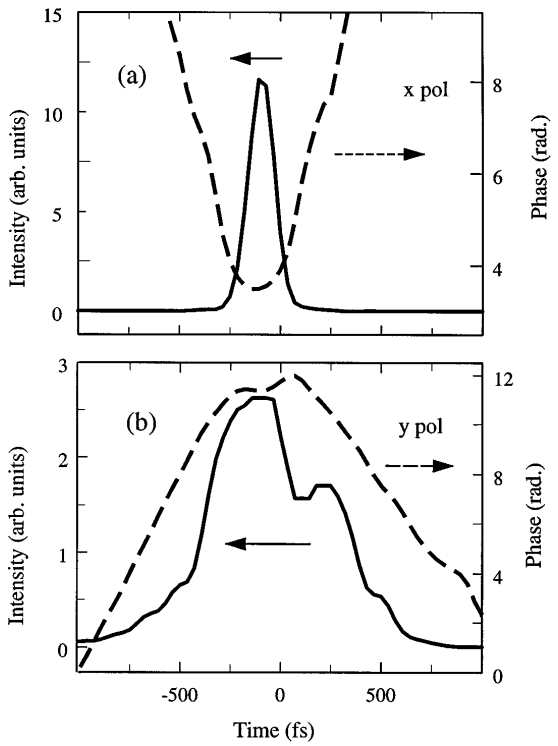


Fig. 2. Temporal intensities and phases (a) for the $x$ component, $I^x_{\mathrm{sig}}(t)$ and $\phi^x_{\mathrm{sig}}(t)$, and (b) for the $y$ component, $I^y_{\mathrm{sig}}(t)$ and $\phi^y_{\mathrm{sig}}(t)$, of the signal corresponding to the spectral interferograms shown in Fig. 1.

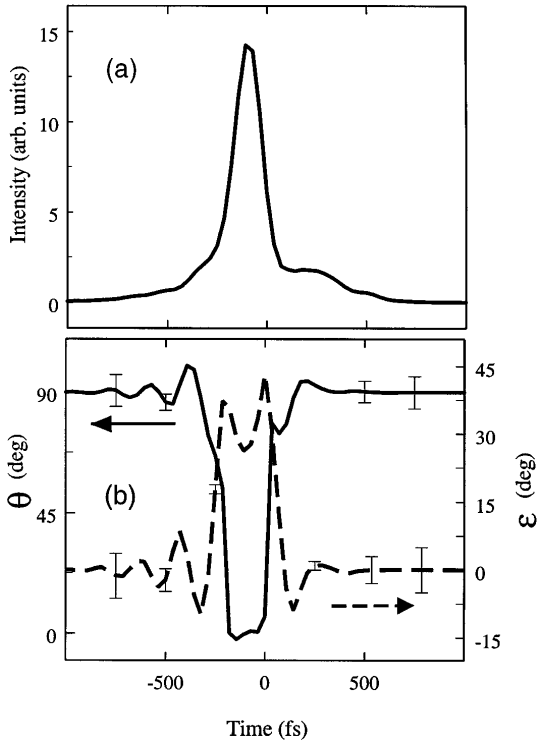


Fig. 3. (a) Total intensity $I^x_{\mathrm{sig}}(t) + I^y_{\mathrm{sig}}(t)$ and (b) azimuthal angle $\theta_{\mathrm{sig}}(t)$ and ellipticity angle $\epsilon(t)$ that temporally characterize the complete polarization state corresponding to the data of Fig. 3.

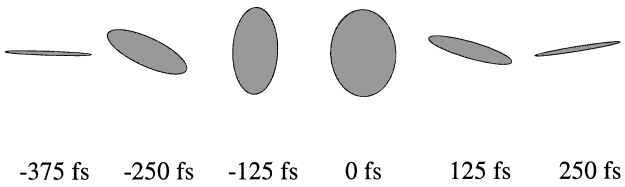


Fig. 4. Sketches of polarization ellipses corresponding to the data of Fig. 3 for selected time delays.

determine the polarization state of the unknown signal pulse (see Note 22 of Ref. 8), to our knowledge this is the first actual use of SI for this purpose. The technique used here is readily recognized as an extension of the dual-quadrature SI discussed in Ref. 8, except that in the experiment reported in Ref. 8 the reference pulse was circularly polarized, rather than linearly polarized as it is here, and the orthogonal component of the reference was used to yield quadrature in the spectral interferograms to improve the signal-to-noise ratio rather than to measure the polarization state. Our technique should also be readily recognized as a dual-beam version of the technique of temporal analysis by dispersing a pair of light E fields (which has acquired the acronym TADPOLE) described in Ref. 9, with FROG providing the fully characterized reference pulse. Consequently, in the spirit that led to the acronyms FROG and TADPOLE, it has been suggested that we refer to this technique as POLLIWOG (POLarized Light Interference versus Wavelength of Only a Glint).[14]

Although this technique is a straightforward extension of existing SI techniques,[8,9] it is nevertheless a useful one, which has many advantages over currently used techniques for determining the polarization state. The currently used techniques[10,11] require a tedious and repetitive set of measurements. Typically[11] an analyzer and a half-wave plate are placed in the signal path. To select the various polarization components (e.g., the Stokes parameters), one rotates the half-wave plate and repeats the measurement with and without an additional quarter-wave plate inserted into the signal path. For each orientation and for each combination of these components, a complete nonlinear cross correlation must then be performed as a function of the time delay $\tau$ between the transmitted component of the signal and the reference. From such a measurement[11] one can directly obtain the temporal evolution of the individual intensities $I^x_{\mathrm{sig}}(t)$ and $I^y_{\mathrm{sig}}(t)$ and the phase difference $\phi^x_{\mathrm{sig}}(t) - \phi^y_{\mathrm{sig}}(t)$, but information about the individual phases $\phi^x_{\mathrm{sig}}(t)$ and $\phi^y_{\mathrm{sig}}(t)$ is not obtained. Moreover, the nonlinear cross correlation limits the sensitivity of the of the technique. By comparison, notice that a single, simpler linear SI measurement provides all this information with a sensitivity that has been shown to extend into the zeptojoule ($10^{-21}$ J) regime.

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13. E.g., K. W. DeLong, R. Trebino, J. Hunter, and W. E. White, J. Opt. Am. B **11,** 2206 (1994), and references therein.
14. According to *Webster's New Collegiate Dictionary*, glint is defined as "a tiny bright flash of light."