Adaptive all-order dispersion compensation of ultrafast laser pulses using dynamic spectral holography

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The time-varying dispersion of ultrafast laser pulses can be self-adaptively stabilized using real-time dynamic spectral holography in semiconductor photorefractive quantum wells. Dispersion of all orders is compensated by forming a dynamic spectral-domain hologram of a signal pulse (that has a time-varying dispersion) referenced to a stable clock pulse. The hologram is read out using forward-scattering phase conjugation to remove phase distortion to all orders, including drift in the time of flight. We have achieved adaptive cancellation of time-of-flight excursions up to ±15 ps to an accuracy of ±15 fs with a compensation bandwidth of 1 kHz. © *1999 American Institute of Physics.* [S0003-6951(99)02247-0]

Photorefractive semiconductor quantum wells have been shown to have high sensitivity at near-infrared wavelengths and fast response times.[1] They have been demonstrated to have unique femtosecond pulse shaping capabilities[2] and elaborate time-domain processing operations[3,4] based on the principle of spectral holography.[5] The phase or amplitude of individual optical frequency components contained in a femtosecond pulse can be individually manipulated in an adaptive holographic medium to provide temporal pattern recognition, correlation, matched filtering, as well as time-domain phase conjugation.

The principles of spectral holography for femtosecond pulse processing have been shown previously using a thermoplastic plate as a static hologram[6,7] or using computer-generated holograms.[8] However, these demonstrations compensated a fixed amount of dispersion and were not capable of adapting to real-time environment-induced changes in dispersion, arrival time, and other temporal distortions. Recent developments in femtosecond pulse processing have introduced feedback and iteration loops,[9,10] making dynamic processing possible. However, practical applications often require dynamic and self-adaptive phase control and signal processing. In this letter, we take advantage of dynamic holographic photorefractive quantum wells (PRQWs) to demonstrate *dynamic* holographic compensation of time-of-flight and higher-order dispersion of 100 fs pulses with an overall response rate up to 1 kHz (fixed by the write/erase time of the photorefractive gratings), which accommodates most environment-induced phase variations.

Time and dispersion compensation is based on the frequency–time relation for a femtosecond signal pulse. Two coherent incident waves (signal and reference) $E_S(\omega)$ and $E_R(\omega)$ with a common optical frequency ω entering a holographic medium write a hologram with a strength proportional to the interference modulation. In the case of thin holograms in the Raman–Nath regime,[11] both signal and reference beam are diffracted from the hologram (self-diffraction) with multiple diffraction orders that contain amplitude and phase information of the two incident waves. When the signal pulse, or a test pulse identical to the signal pulse, is diffracted from the hologram, the amplitude of its -1 diffraction order is proportional to $E_S^{-1}(\omega) \propto E_S(\omega)E_S^*(\omega)E_R(\omega)$, which is proportional to the product of the signal pulse field $E_S(\omega)$ and its phase-conjugate $E_S^*(\omega)$. If the test field carries the same phase information or distortions as the signal beam, i.e., $E_T(\omega)=E_S^0(\omega)e^{i\Phi(\omega)}$, this phase information $e^{i\Phi(\omega)}$ is canceled in the -1 diffraction order $E_S^{(-1)}(\omega)$ through forward-scattering phase conjugation in the spectral domain. This holds for each frequency component ω in the femtosecond pulse spectrum, and therefore, no spectral phase information of the signal pulse is transferred into this diffraction order. The diffracted pulse takes over the spectral phase of the reference pulse, which is a Gaussian pulse. Any distortions or delays in the signal pulse induced by phase changes, such as time delay or dispersion, are then eliminated as long as they occur slowly enough (<1 kHz) for the photorefractive hologram to track their changes. This is the physical basis of dispersion and time compensation. Pulse-to-pulse timing jitter cannot be removed in our system.

The femtosecond light source used in this work is a mode-locked Ti–sapphire laser with nearly transform-limited output pulses with pulse widths of 130 fs, characterized by the intensity autocorrelation and power spectrum. The central wavelength of the laser is tuned to 836 nm to exploit the heavy-hole excitonic nonlinearity of the GaAs/AlGaAs quantum wells for holographic recording. The photorefractive quantum well sample is described in Ref. 1.

The optical layout for our demonstration of spectral and temporal dispersion compensation consists of a spectral four-

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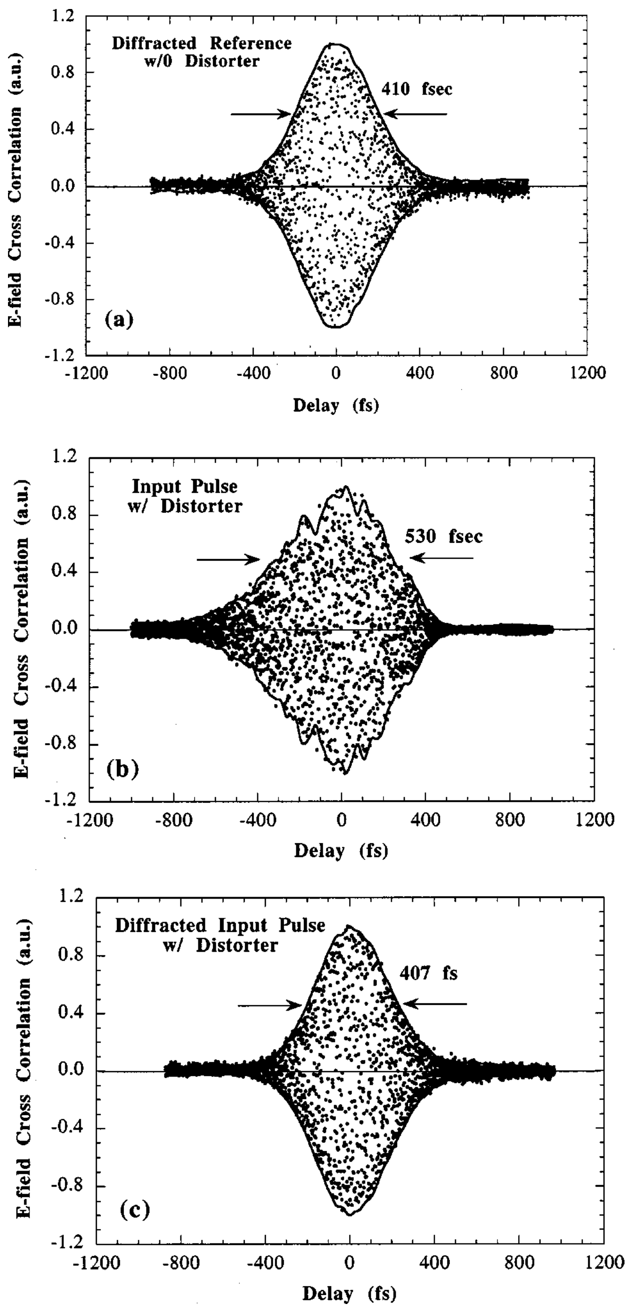

FIG. 1. Electric-field cross-correlation functions of (a) the diffracted reference pulse, (b) the distorted signal pulse before diffraction, and (c) the diffracted signal pulse with the distortion-compensated reference to a nearly transform-limited reference pulse with 130 fs pulse width.

wave-mixing (SFWM) apparatus in the horizontal plane for spectral holography, and a femtosecond pulse shaper[12] to intentionally generate time-varying pulse distortions and delays. As the beams enter grating No. 1, the optical frequency components of each beam are spatially spread horizontally in the $x-y$ plane and then collimated by cylindrical lens No. 1. The optical frequency components of the two beams enter the PRQW device with equal incident angle θ and write a hologram $m(x)$ with each position x corresponding to a specific frequency ω in the pulses. The signal beam $E_S(\omega)$, as well as the test beam (which is split from the signal beam and is, therefore, a replica of the signal pulse) originates from the pulse shaper. The spectral phase of the signal/test pulses can be dynamically altered using a phase distorter driven by a piezoelectric transducer. The power of each beam was approximately 400 μW measured in front of the PRQW device and the beam diameter was 2 mm before entering the spectral four-wave-mixing apparatus. A dc electric field is applied to the device in a transverse geometry[1] with the field direction (z) parallel to the quantum well layers. The temporal shape of the pulse was measured by interferometric electric-field cross correlation[13] and the spectral phase was measured by spectral interferometry[14] relative to a reference pulse directly from the laser.

To demonstrate spectral and temporal dispersion compensation using dynamic holography, a distorted pulse is intentionally generated from the pulse shaper. Figure 1 shows the temporal patterns of the diffracted reference pulse, with the distorted and compensated signal pulses. When the signal beam is undistorted, its autocorrelation envelope fits a Gaussian shape with a full width at half maximum (FWHM) of 260 fs, and its measured spectral phase is flat. Assuming a Gaussian pulse shape, the pulse width (intensity FWHM) of the laser is 130 fs. The output pulse from the hologram (the -1-order diffraction of the test beam) is also nearly Gaussian with a FWHM of $t_{SR}=410$ fs [Fig. 1(a)] with a phase that is flat within the pulse bandwidth. Using the reference pulse width of $t_R=130$ fs, this gives[15] a width of the diffracted pulse of $t_D=\sqrt{t_{SR}^2/2-t_R^2}=259$ fs. Using the spectral bandwidth of the diffracted pulse of 4 nm measured by a spectrometer, the time–bandwidth product is calculated to be $t_D\Delta\nu=t_D\Delta\lambda c/\lambda^2=0.445$, which is close to that of a diffraction-limited Gaussian pulse (0.441). The broadening of the diffracted pulse relative to the reference pulse is caused by the limited bandwidth of the excitonic nonlinearity in the PRQW device.[15] When the phase distorter, here a sapphire wafer with a curved surface, is introduced in the signal beam at the Fourier plane in the pulse shaper, the signal pulse becomes severely broadened and distorted with a FWHM of more then 530 fs [Fig. 1(b)]. But, no significant broadening is observed in the diffracted output pulses [Fig. 1(c)], showing the ability of spectral holography to perform all-order spectral dispersion compensation.

Included in the dispersion compensation is the ability to dynamically eliminate drift in the arrival time of ultrafast pulses by compensating the linear phase in the spectral domain. A pulse arriving ''too late'' can be adaptively forced to advance in time, and vice versa. Of course, we do not achieve superluminal propagation of energy. Delays in the signal pulse alter the spectral hologram that in turn alters the path of the diffracted spectrum of the test pulse inside the pulse shaper. Figure 2 shows the experimental results. With the arrival time of the original input signal pulse defined as zero [Fig. 2(a)], the input signal pulse is delayed by 1.5 ps [Fig. 2(b)], corresponding to approximately a 450 μm delay in space. Using this delayed pulse as the input of the hologram (as both signal and test beam), the diffracted output [Fig. 2(d)] shows no time delay with respect to the diffraction of the undelayed input [Fig. 2(c)], whose arrival time is also defined as zero. The compensation range of the time drift of the spectral holography is tens of picoseconds in our system, corresponding to a free-space delay up to several millimeters. This compensation range is limited only by the system spectral resolution of approximately 0.2 nm in our

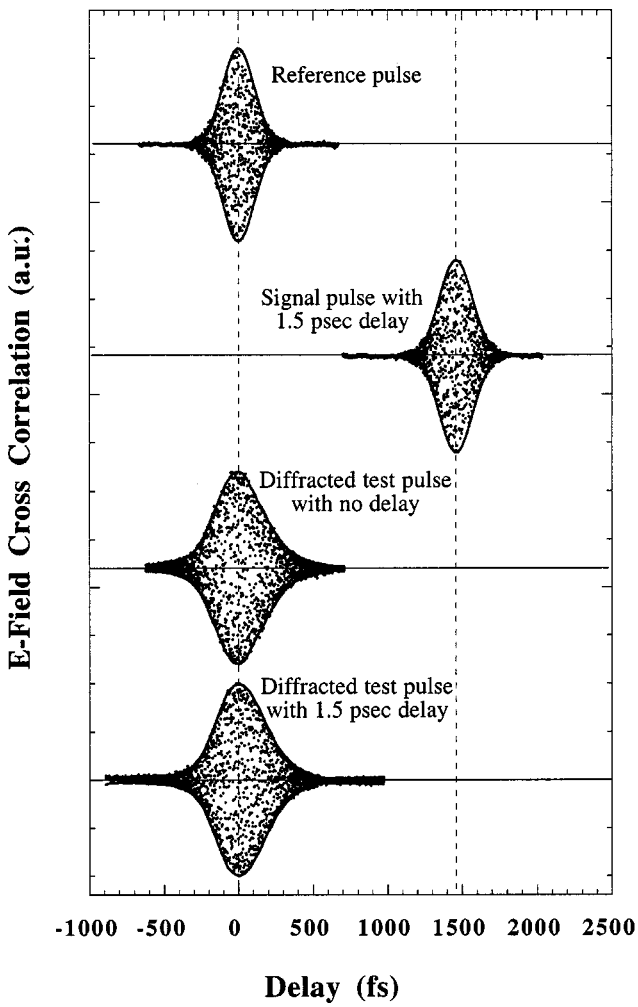

FIG. 2. Electric-field cross correlation showing the reference pulse and the delayed signal pulse on the top two traces, and the diffracted test pulse with and without the 1.5 ps delay on the lower two traces. Diffraction of the delayed test pulse from the spectral hologram removes the linear spectral phase, adaptively stabilizing the arrival time of the diffracted pulse.

system. Longer time delays would produce denser fringes in the hologram in the *x* direction. As the fringe density reaches the resolution of the system, the modulation of the hologram decreases, which reduces the diffraction efficiency. In the other limit, the accuracy within which the time of flight can be compensated is approximately 15 fs in our experiment, which is limited by the number of photorefractive fringes that can fit within the 1 mm aperture of the photorefractive quantum well device.

Perhaps the most important feature of the photorefractive quantum wells is their ability to self-adaptively compensate time-varying dispersion. This feature allows the dynamic holograms to track the changing phase up to the response rate of the semiconductor material. We directly measured the adaptive compensation bandwidth of the PRQW devices in the spectral holography system by monitoring an error signal as a function of frequency in a homodyne-mixing arrangement in which the delay on the signal was shifted by approximately 10 ps using a piezoelectrically driven mirror. No significant error signal was observed up to 1 kHz, demonstrating high-fidelity adaptive compensation of the time-varying phase for frequencies generated by most environmental disturbances.

The procedure described in this letter requires a coherent reference pulse to write the spectral hologram. Access to such a pulse is easy for local applications, but difficult to provide for long-distance communication. Local applications include the real-time elimination of timing drift or dispersion drift in laboratory experiments for which long-term stability is necessary. In addition, pulse synchronization experiments from multiple laser sources may benefit from timing drift stabilization. For long-distance applications, it would be necessary to seed a local oscillator to provide the reference pulse at the receiver.

In conclusion, we have experimentally demonstrated *dynamic* compensation of arrival-time and higher-order dispersion drift of femtosecond pulses using dynamic spectral holography with photorefractive quantum wells as the dynamic holographic medium. We have shown that the compensation bandwidth can reach kHz or higher, depending on the intensity, and adapts to most environment-induced phase-drift rates in femtosecond pulses, which are usually slower than 1 kHz.

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