Adaptive femtosecond optical pulse combining

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We combine two nominal 100 fs pulses into a pulse train using an adaptive holographic quantum-well film as an adaptive pulse combiner in a two-wave mixing geometry. The two pulses in the combined pulse train are phase-locked and are immune to drifting optical path differences or delay times between the two input pulses. The phase is controlled by the choice of center wavelength. The spectrum of the pulse train is equivalent to the spectral interferogram between two ultrafast pulses. © *2000 American Institute of Physics.* [S0003-6951(00)02249-X]

Adaptive interferometers that self-compensate for mechanical vibrations and laser speckle can contribute to many applications. These include adaptive beam combining,[1] laser-based ultrasound detection,[2,3] laser communication, imaging through turbid media,[4–6] etc. Adaptive beam combining is performed through two-wave mixing in dynamic holographic media, such as in photorefractive quantum wells[7] that perform as adaptive holographic films. We previously demonstrated adaptive laser-based megahertz ultrasound detection in photorefractive quantum wells, approaching within a factor of three of ideal shot-noise-limited detection[8] using cw light. In that application the excitonic nonlinearity in the multiple quantum well (MQW) device induces an excitonic spectral phase that guarantees the appropriate condition of quadrature for maximum homodyne sensitivity. The linear frequency dependence of the excitonic spectral phase furthermore allows nearly transform-limited diffraction of femtosecond pulses from the quantum wells,[9] which have been used in numerous demonstrations.[10,11]

In this letter we demonstrate adaptive femtosecond pulse combining in photorefractive quantum wells. The relative phase between the two pulses is set by the choice of the center wavelength of the pulse, and is self-adaptively phase-locked by the dynamic gratings, independent of relative path differences (time delays) between the coupled pulses.

In a two-wave mixing geometry, the reference pulse is diffracted into the direction of the signal pulse. The amplitude of a spectral component of the signal field $E_s(\omega,L)$ after passing through the dielectric film of thickness L and mixing with the diffracted amplitude of the reference field E_r is given by

$$E_s(\omega,L)=e^{i\delta_0(\omega)}[E_s^0(\omega)+(\tfrac{1}{2}\delta_K(\omega)e^{-i(\omega_0\tau+\phi_P+\pi/2)})E_r^0(\omega)e^{i\omega\tau}], \quad (1)$$

where the term in rounded brackets describes the holographic grating, τ is an adjustable delay time of the reference pulse relative to the signal pulse, and the zero superscripts refer to the incident amplitudes. The complex holographic grating with spatial Fourier index K is given by

$$\delta_K(\omega)=\frac{2\pi n_K(\omega,F_0)L}{\lambda\cos\theta'}+i\frac{\alpha_K(\omega,F_0)L}{2\cos\theta'}, \quad (2)$$

where F_0 is the applied electric field, n_K is the refractive index grating, and α_K is the absorption grating. The holographic *grating* has a phase $\omega_0\tau$ that arises from the reference pulse delay, where ω_0 is the center frequency of the pulse. This phase can be understood as a spatial shift of the intensity fringes caused by the change in path length of the reference beam. In Eq. (1) the diffracted pulse has a phase $\omega\tau$ arising from the delay of the reference pulse. It is important to note that the delay-dependent phase of the holographic grating depends only on the center frequency of the pulse ω_0, while the delay-dependent phase of the diffracted amplitude is a continuous function of frequency ω. Furthermore, the diffracted amplitude acquires a phase ϕ_P from the photorefractive phase shift, and an additional excitonic spectral phase relative to the signal beam, which is given by[8]

$$\psi(\omega)=\tan^{-1}\left[\frac{\lambda\alpha_K(\omega)}{4\pi n_K(\omega)}\right]. \quad (3)$$

This phase varies nearly linearly with frequency, representing a group delay of the diffracted pulse given by

$$\tau_{\text{group}}=\frac{d\psi(\omega)}{d\omega}\approx T_2, \quad (4)$$

where T_2 is the dephasing time of the quantum-confined excitons. In the transverse-field photorefractive quantum well the group delay is approximately 200 fs. All contributions to the *spatial* phase in Eq. (1), including distorted wave fronts (speckle), are included in the complex wave amplitudes and are compensated by the dynamic grating. The important feature of Eq. (1), when it is transformed from the spectral domain to the time domain, is that the diffracted pulse is delayed by a time $\tau_{\text{group}}+\tau$, but the optical phase of the diffracted pulse is locked at the value $(\psi(\omega_0)+\phi_P+\pi/2)$, which is independent of the adjustable delay τ. This absolute phase can be externally controlled by the choice of center frequency ω_0 and by the field dependence of the photorefractive phase shift ϕ_P.

The samples used in our experiments were photorefractive multiple quantum wells grown by molecular beam epi-

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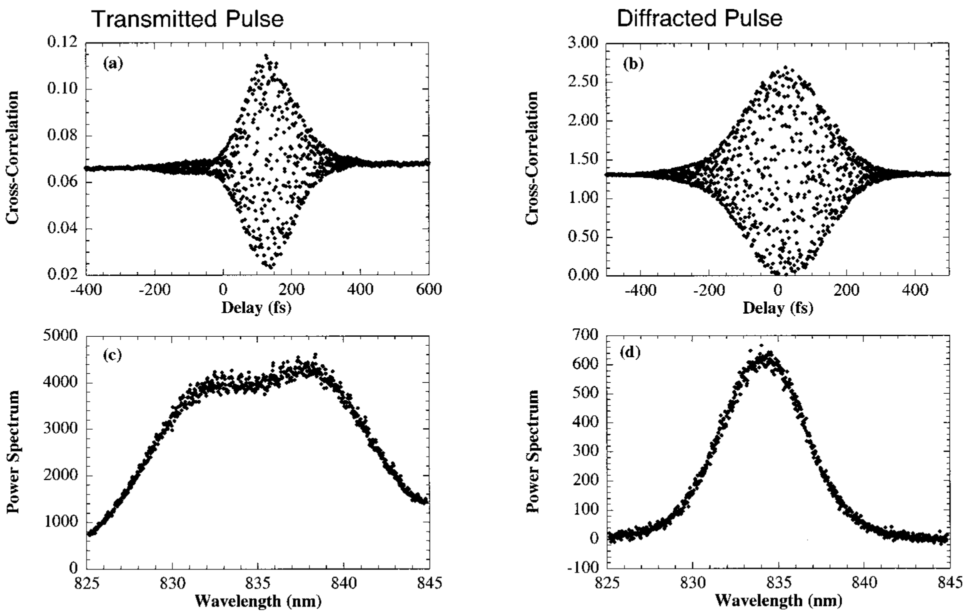

FIG. 1. Showing the cross correlations (a) and (b), and the spectra (c) and (d), of transmitted signal and diffracted reference pulses, respectively. The quantum well sample was under an applied transverse field of 10 kV/cm.

taxy (MBE). The structures consisted of MBE $Al_{0.3}Ga_{0.7}As$/GaAs MQWs grown on semi-insulating GaAs substrates. Capping and stop-etch layers were grown on a semi-insulating GaAs substrate at 600 °C, followed by a MQW layer grown at 600 °C consisting of a 100 period superlattice of 70 Å GaAs wells and 60 Å $Al_{0.3}Ga_{0.7}As$ barriers. The samples were proton implanted at a flux of 2×10^{12} cm^{-2} at 160 keV and then at a flux of 1×10^{12} cm^{-2} at 80 keV to make them semi-insulating with uniform defect densities. The substrate is opaque and is removed for transmission studies. Two coplanar gold contacts are evaporated on the top layer with a device aperture of ~1 mm.

A Millennia (Coherent Inc.) pumped Kerr-lens mode-locked Ti:sapphire (Clark MXR NJA-3) was used as the source for these experiments which produced transform-limited pulses of 125 fs at the exciton wavelength of 830 nm. These pulses were input into a Mach–Zender interferometer and interfered at the MQW sample to produce an interference pattern with a fringe period of 30 μm, similar to the experimental setup in Ref. 1. In this letter the two pulses will be identified as the signal and reference pulses. The signal pulse is the pulse transmitted through the MQW, and the reference pulse is the pulse that diffracts to combine with the transmitted signal pulse. The holographic space-charge grating in the photorefractive quantum well is a quasi-cw grating that is written by the time-average intensity of the two beams. The ratio of the intensities of the coupling beams was set so the signal beam was half the intensity of the reference beam (0.36 and 0.8 mW/cm^2 average intensity, respectively) to maximize the visibility of the coupling effects. Once the coupling was optimized using four-wave mixing, both the spectrum and cross correlation of the coupled pulse were recorded. The cross correlation was performed by recording the interference of the transmitted pulse with a transform-limited control pulse on a silicon photodiode.

Figures 1(a) and 1(c) show the cross correlation and spectrum of the transmitted signal pulse after traversing the MQW with an electric field of 10 kV/cm applied parallel to the wells. Figures 1(b) and 1(d) show the cross correlation and spectrum of the diffracted reference beam. The diffracted pulse is slightly broadened due to the limited bandwidth of the quantum-well electroabsorption.[9] Because the excitonic phase shift for this device varies nearly linearly with wavelength, the diffracted pulse undergoes no phase distortion on diffraction but it acquires a group delay of ~200 fs. The shapes of these cross correlations were symmetric with respect to a change in the sign of the applied field.

Figure 2 shows the cross correlations and spectra of the combined pulse train under mixing with applied fields of +10 and −10 kV/cm. The cross correlation of the signal beam under mixing in a negative field, shown in Fig. 2(a), exhibits an interference null on the trailing edge of the pulse. This null is caused by destructive interference of the trailing diffracted pulse with the transmitted pulse. When the applied field sign is reversed the interference null disappears in Fig. 2(b). The photorefractive phase shift ϕ_P is dependent on the applied field, and flips sign under change in sign of the field.[12,13] At the high fields used in the experiment, the phase change upon flipping the field is nearly equal to π, converting destructive interference into constructive interference between the diffracted and transmitted pulses when the direction of the field is flipped.

The spectra of the combined pulses in Figs. 2(c) and 2(d) also change upon flipping the sign of the applied field. The change in the photorefractive phase shift changes the photorefractive gain spectrum, which is observed as a shift in the dip in the spectrum. However, in our experiment, recording the spectrum of the combined pulse train is identical to the use of spectral interferometry to characterize the relative phase of two ultrafast pulses.[14] Although in this experiment the physical delay is set to zero ($\tau=0$), the group delay time between the two pulses in the diffracted pulse train determines the fringe density in the spectral interferogram. The group delay τ_{group} is not dependent on the sign of the electric field, keeping the fringe density the same in both Figs. 2(c) and 2(d). But the phase of the diffracted pulse *is* sensitive to the sign of the field, which is seen in the shift of the interference fringe in the recorded spectrum.

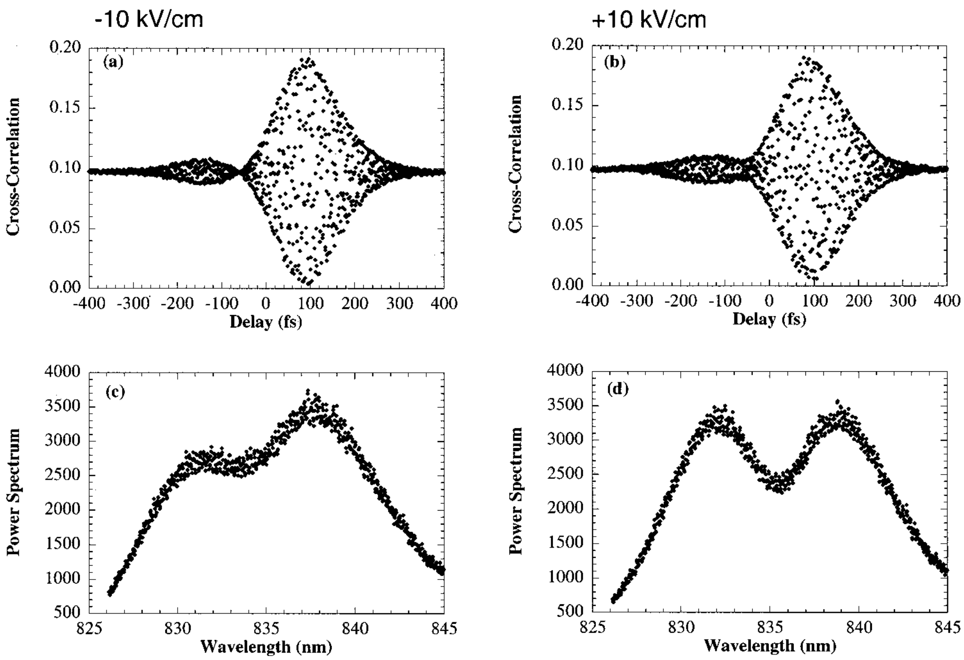

FIG. 2. Showing the cross correlations (a) and (b), and the spectra (c) and (d), of the coupled pulse train with a dc field of −10 and +10 kV/cm applied to the MQW devices, respectively. The dip in the spectrum is an interference fringe between the signal and diffracted pulses caused by the relative group delay.

To demonstrate that the beam combiner compensates changes in the optical path difference (time delays between the two input pulses), experiments were performed investigating the sensitivity of the position of the interference null shown in Fig. 2(a) on a changing physical delay [the parameter τ in Eq. (1)] between the coupling beams. Figure 3 shows no change in the position of the interference null when the adjustable delay was scanned through 120 fs (the coherence length of the pulses being used). This demonstrates that the phase between the combined pulses is constant even though the diffracted pulse is delayed in the pulse train. In other words, the adaptive hologram compensates the phase of the diffracted pulse, while having no effect on the delay itself.

It is important to point out that in laser-based ultrasound applications the requirement for maximum homodyne detection sensitivity is quadrature in *relative* phase between the local oscillator (reference) and signal. In these adaptive pulse combination experiments we can alter the relative phase by adjusting either the center wavelength or the electric field to achieve quadrature. But once the quadrature is set, it is immune to mechanical vibrations (that alter delays) or speckle. The photorefractive quantum wells therefore ensure quadrature even in the presence of low-frequency mechanical vibrations, thus opening up this technique for adaptive interferometric applications using ultrafast pulses. In conclusion, the operation of an adaptive pulse combiner is demonstrated that combines pulses with a constant relative phase despite variable arrival times of the pulses. The adaptability of this device makes it suitable for high-bandwidth interferometric techniques (such as laser-based ultrasound) where low frequency noise (e.g., mechanical vibrations) is problematic.

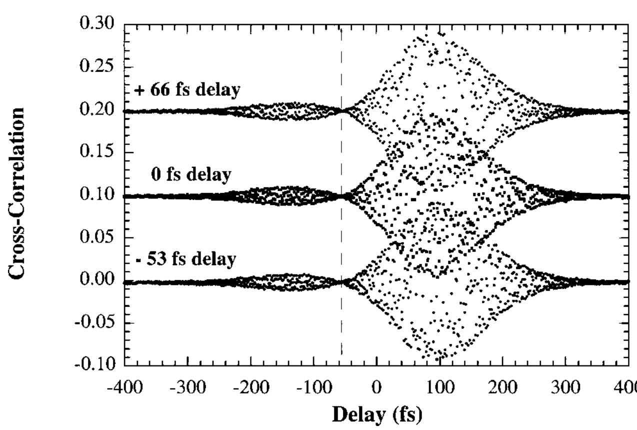

FIG. 3. Showing the change in the cross correlation of the coupled beam as the time delay between the incident pulses is changed from −53 to +66 fs. The interference null is unaffected by the change in the physical path length between the incident pulses.

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