Femtosecond signal processing by second-order spectral holograpy

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We report femtosecond optical signal processing by using second-order spectral holography. Enhanced second-order diffraction from a thermoplastic plate makes possible new signal-processing operations not possible with first-order holography. Experiments resulting in output waveforms equal to the autoconvolution function of the input waveform are described, and the possibility of implementing a simple associative memory for ultrafast optical signals is discussed.

Recent experiments have demonstrated the possibility of extending holography into the ultrafast time domain.[1–7] This permits storage and recall of picosecond and femtosecond optical waveforms as well as signal-processing operations such as time reversal and matched filtering. Applications of such signal-processing capabilities include optimal compression of phase-modulated input signals for dispersion compensation[1,5] and holographic recording of encrypted femtosecond waveforms for secure data storage.[1]

Usually only first-order diffraction is utilized for holography. However, higher-order grating terms can carry additional information and permit more-elaborate signal-processing operations. A simplified associative memory for spatial images based on higher-order diffraction was recently demonstrated by Paek and Jung.[8] In this Letter we demonstrate higher-order holographic processing of ultrafast time-domain signals. We also will discuss the possibility of using this technique for associative recall of shaped femtosecond waveforms.

Our experiments are based on a spectral holography approach.[2] The apparatus, shown schematically in Fig. 1, is similar to that used previously for femtosecond pulse shaping and waveform synthesis[9] and is identical to that used in our previous spectral holography experiments.[1] The first grating and lens spatially disperse the optical frequency components contained within the incident pulses, and the second grating and lens recombine the various frequencies into a single collimated beam. A thermoplastic plate[10] placed midway between the lenses serves as a thin holographic medium, permitting first-order as well as higher-order diffraction. During recording, spatially distinct reference and signal beams are incident upon the apparatus. The reference is a short pulse with a broad and regular spectrum; the signal can be a shaped pulse with information patterned onto its spectrum. Both the reference and the signal beams are derived from a colliding-pulse mode-locked dye laser,[11] which produces 75-fs pulses at a 0.62-μm wavelength. The interference pattern formed between the spectrally dispersed reference and signal beams is recorded on the thermoplastic plate. The resultant spectral hologram can be read out by use of a short-test pulse in order to reconstruct the original signal waveform. The current experimental apparatus provides a spectral resolution of ~0.1 nm, which means that the maximum waveform duration that can be faithfully recorded is ~5 ps. Given the 75-fs reference pulse duration, the corresponding time–bandwidth product is $\Delta\nu\Delta t \sim 70$.

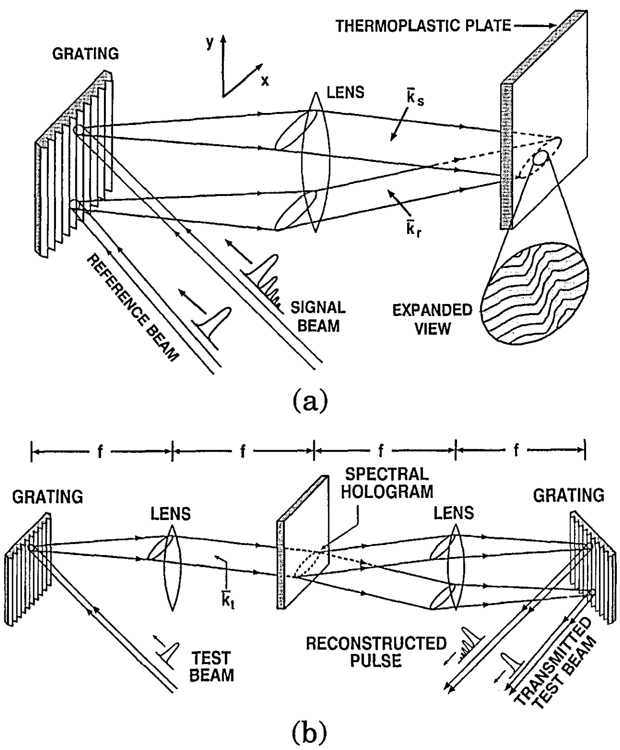

Fig. 1. Apparatus for femtosecond spectral holography: (a) setup for recording the spectral hologram, (b) setup for reading out the spectral hologram.

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Recording and reconstruction of waveforms with significantly higher time–bandwidth products ($\Delta\nu\Delta t \sim 1000$) should be possible by optimization of the spectral resolution.[9]

In the case of second-order diffraction, which can occur when the recorded grating contains second- or higher-order harmonics of the original optical interference pattern, the output field $E_{\mathrm{out}}^{(2)}(\omega)$ resulting from the spectral holography process can be written as follows:

$$E_{\mathrm{out}}^{(2)}(\omega) \sim E_t(\omega)[E_r{}^*(\omega)E_s(\omega)]^2\exp(i\mathbf{K}_3 \cdot \mathbf{r}) + E_t(\omega)[E_r(\omega)E_s{}^*(\omega)]^2\exp(i\mathbf{K}_4 \cdot \mathbf{r}) . \quad (1)$$

Here $E_t(\omega)$, $E_r(\omega)$, and $E_s(\omega)$ are the complex spectral amplitudes of the test, reference, and signal fields, respectively; $\mathbf{k}_t$, $\mathbf{k}_r$, and $\mathbf{k}_s$ are the propagation vectors of these beams before the hologram; and $\mathbf{K}_3 = \mathbf{k}_t - 2(\mathbf{k}_r - \mathbf{k}_s)$ and $\mathbf{K}_4 = \mathbf{k}_t + 2(\mathbf{k}_r - \mathbf{k}_s)$ are the directions of the second-order reconstructed beams. When both test and reference beams may be considered delta functions, the output along $\mathbf{K}_3$ is proportional to $[E_s(\omega)]^2$. In the time domain, this output corresponds to the autoconvolution of the original signal waveform. This special case is demonstrated in our experiments. Another interesting special case occurs when both test and signal are patterned in time. As we discuss below, the output along $\mathbf{K}_4$ can under some circumstances correspond to a simple associative recall operation.

Usually second- and higher-order diffraction are much weaker than first-order diffraction. However, by tuning the intersection angle between reference and signal beams, one can enhance the higher-order diffraction from thermoplastic plates.[12] For first-order diffraction, thermoplastic plates have a bandpass spatial frequency response (peaked at ~20° in our experiments). Efficient second-order diffraction is achieved by a decrease in the recording angle by a factor of 2 and an increase in the exposure. We have performed spectral holography experiments with both first- and second-order diffraction. Holograms were written under control of a Newport Corporation Model HC-300 recording system. In the case of first-order diffraction, we used a 20° recording angle and a recording energy of the order of 4 nJ, corresponding to an exposure of $\sim 2.4 \times 10^{-5}$ J/cm^2 in a 4-ms exposure time. This yielded a first-order diffraction efficiency in the vicinity of 10% (second-order diffraction was very weak under these conditions). For second-order diffraction, the recording angle was 10°, and the optimum recording energy was ~40 nJ. This resulted in a typical second-order diffraction efficiency of ~5%, which under these recording conditions was substantially stronger than the first-order diffraction.

Data demonstrating second-order spectral holography are shown in Fig. 2. Holograms were recorded with unshaped signal pulses delayed with respect to the reference beam and were then read out with a short test pulse. Intensity cross-correlation measurements of the original signal pulses are plotted in Fig. 2(a). Data are plotted for three separate experimental trials, denoted A, B, and C, corresponding to signal pulses delayed by 0, 0.5, and 1 ps, respectively. The reconstructed output was measured for both first- and second-order diffraction. For first-order diffraction (not shown), the reconstructed pulses occur at the same delay as the input signal pulses.[1] The output pulses reconstructed along $\mathbf{K}_3$ in the case of second-order diffraction are shown in Fig. 2(b). The pulses occur at delays of 0, 1, and 2 ps, respectively, equal to double the input delays. This doubling of the delay corresponds to the autoconvolution function expected for second-order spectral holography. One may also understand these results by recalling that a delay τ in the time domain corresponds to a linear phase factor $\exp(-i\omega\tau)$ in the frequency domain. Because the output along $\mathbf{K}_3$ is proportional to $[E_s(\omega)]^2$, the phase factor becomes $\exp(-2i\omega\tau)$, which corresponds to an output pulse delayed by 2τ, consistent with our observations.

In principle, higher-order spectral holography can be used to implement associative memories for femtosecond temporal waveforms. Optical implementations of associative memories, which permit recall of a complete image, with error-correction capability, in response to a partial replica of the desired image, have received considerable attention. Recent experiments demonstrate that the simple ghost-image associative memory first discussed in the early days of holography[13,14] can easily be implemented for spatial domain signals by use of second-order diffraction.[8] Analogous experiments may be possible in the ultrafast time domain.

We are interested in the situation in which the reference is a short unshaped pulse, the signal is stored in the hologram, and the test represents a partial or corrupted version of the signal. In this case we set $E_r(\omega) = 1$ in relation (1). The resultant expressions for the second-order diffraction output along $\mathbf{K}_4$ are then as follows:

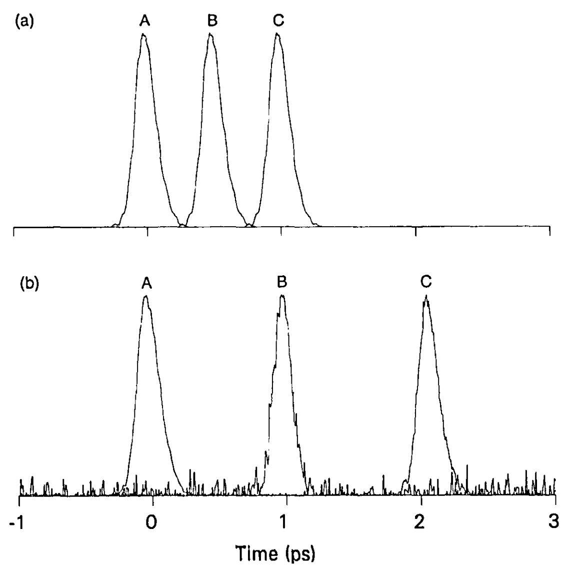

Fig. 2. Cross-correlation measurements of (a) input signal pulses delayed by 0 (A), 0.5 (B), and 1.0 ps (C), respectively, and (b) output pulses resulting from second-order diffraction from the corresponding spectral hologram.

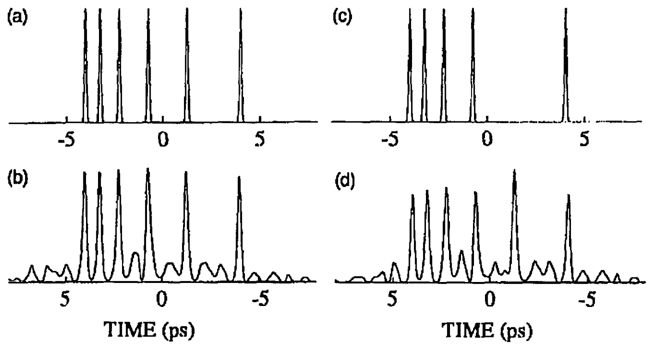

Fig. 3. Computer simulations of a simple ghost-image associative memory. (a) Recorded signal $e_s(t)$, (b) reconstructed output when $e_t(t) = e_s(t)$, (c) test waveform with one missing pulse, (d) reconstructed output for test waveform with one missing pulse. For the reconstructed outputs [(b), (d)], the time axis is inverted to facilitate comparison between the two plots.

$$E_{\mathrm{out}}^{(2)}(\omega) \sim [E_t(\omega)E_s{}^*(\omega)]E_s{}^*(\omega),$$
$$e_{\mathrm{out}}^{(2)}(t) \sim [e_t(t) \otimes e_s(t)] * e_s(-t). \qquad (2)$$

Here $e_{\mathrm{out}}^{(2)}(t)$, $e_t(t)$, and $e_s(t)$ are the time-domain representations of the output, test, and signal waveforms, respectively, and $\otimes$ and $*$ denote the correlation and convolution operations, respectively. From relations (2) we see that second-order spectral holography performs the double-correlation operation required for associative memories. If $e_s(t)$ has a sharply peaked correlation function and if $e_t(t)$ is close to e_s, then the first correlation ($e_t \otimes e_s$) is close to a delta function. The convolution of this delta function with $e_s(-t)$ should produce an output waveform similar to the original signal waveform (but time reversed).

Computer simulations shown in Fig. 3 illustrate the potential for error correction of ultrafast temporal waveforms. Our simulations apply to one-dimensional temporal signals but are otherwise similar to simulations that might be performed for two-dimensional spatial images. The recorded signal e_s [Fig. 3(a)] is a sequence of six femtosecond pulses, with interpulse spacings chosen to yield a sharp correlation function. In the simulation only a single waveform is recorded on the hologram. Figure 3(b) shows the reconstructed output waveform calculated from relations (2) for a test waveform identical to the signal ($e_t = e_s$). The output is similar to the recorded signal, although low-intensity noise is now evident between the original pulses. This noise, which arises because $e_t \otimes e_s$ is only approximately a delta function, would limit the number of distinct waveforms that could be stored simultaneously. Figures 3(c) and 3(d) show the reconstructed waveform [Fig. 3(d)] that results when one of the original pulses is missing in e_t [Fig. 3(c)]. The output is similar to that shown in Fig. 3(b); thus the missing pulse is restored. Similar results (not shown) are obtained when two pulses are missing from e_t, although the noise between pulses is increased. These simulations indicate the possibility of using second-order spectral holography for associative recall and error correction of femtosecond optical signals.

It is worth noting that most associative memory models involve intermediate thresholding between correlation operations; this reduces noise of the sort evident in Fig. 3. Although thresholding for spatial signals is readily performed, thresholding of ultrafast temporal waveforms is more difficult, and this motivates our consideration of ghost-image systems, which do not require thresholding. Without thresholding, of course, the class of signal waveforms (as well as the storage capacity) permitting satisfactory associative recall is restricted. The key requirement seems to be that signals have strongly peaked autocorrelations. Note, however, that signals produced by binary phase-only filters, which can have sharply peaked autocorrelations,[15] do not work well. For phases of 0 and π, we have $E_s(\omega) = \pm 1$, $[E_s(\omega)]^2 = 1$ and, from relations (2), $E_{\mathrm{out}}^{(2)}(\omega) = E_t(\omega)$. Therefore the output is equal to the test waveform, and error correction is not achieved. Thus a sharply peaked correlation function alone is not sufficient to guarantee favorable operation. Detailed criteria delineating precisely what class of signals are most suitable have to our knowledge not been reported.

In summary, we have demonstrated femtosecond optical signal processing by using second-order spectral holography. The current experiments demonstrate autoconvolution of femtosecond signals; the possibility of simple associative memories for ultrafast waveforms is also discussed. Additional femtosecond signal-processing operations may be possible by spectral holography with third- or even higher-order diffraction.

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