Pulse shaping in volume reflection holograms

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Ultrashort pulses are shaped by reflection from dynamic volume holograms recorded in azo-dye-doped epoxies. The spectral resolution and controllability of the reflection geometry are optimal for this application.

Continuing improvements in mode-locked laser technology have resulted in robust cross-spectrally coherent optical sources. To take advantage of the high bandwidths of mode-locked sources in time-domain systems, methods for modulating the spectra of ultrashort pulses have recently been developed. Fourier plane filtering achieves this goal by modulating spectral components of pulses in the Fourier domain. Holographic filtering has been used to modulate the spectrum of pulses in Fourier plane and Fresnel geometries. Volume holographic techniques are of particular interest for their spectral sensitivity and their capacity to achieve spatial as well as temporal modulation of ultrashort pulses. In this Letter we describe a demonstration of holographic pulse shaping with the use of reflection holograms. Reflection holograms are optimal for this application because they support maximal spectral sensitivity and because pulse coding is spatially local and, therefore, easily controllable in reflection geometries. Several researchers have considered volume or spectrally sensitive holograms recorded with ultrashort pulses. Such approaches are useful for storing shaped pulse profiles but are less useful for arbitrary pulse creation.

In this Letter, advantages of reflection geometries for holographic pulse shaping are considered and pulse shaping by bulk reflection holograms in azo-dye-doped epoxy is reported. Limitations on the bandwidth of diffracted pulses are derived, and it is shown that reflection holograms should be used to produce the maximum bandwidth. Holographic filtering is performed by diffracting pulses from volume holograms. A hologram consists of multiple gratings with various spatial frequencies. Each grating in the hologram may be Bragg matched with one spectral component of the incident pulse. By controlling the amplitudes and phases of these gratings, one may control the amplitude and the phase of each spectral component in the diffracted signal. This method of pulse shaping may be implemented in bulk materials or in integrated-optical waveguides. Dynamic control of a hologram may be achieved by using real-time materials or by electrically modulating the strength of permanent gratings in electro-optic materials.

Figure 1 shows the geometry of a reflection holographic pulse-shaping system. A pulse propagating in the x direction passes through a hologram of length \( L \). The incident field can be expressed as \( E_i(kx - \omega_0 t) \), where \( k = \omega_0/c \), \( \omega_0 \) is the center frequency of the pulse, and \( c \) is the speed of light in the material. The hologram is expressed as a modulation of the dielectric constant of the material, which is given by \( \epsilon(r) = \epsilon_a [1 + V(r)] \), where \( \epsilon_a \) is the average dielectric constant of the material. The hologram may be recorded to diffract the beam in any direction; however, the controllable information content of the scattered pulse is maximal in the reflection geometry.

The information content of a shaped pulse can be approximated by its time–bandwidth product. The temporal duration of a holographically scattered pulse increases from one times the propagation time through the hologram for transmission geometries to twice the propagation time for reflection geometries. The bandwidth of the scattered pulse is determined by the spectral resolution of the hologram. Figure 2 is a \( k \)-space diagram that illustrates why the reflection geometry yields the maximum bandwidth. A pulse propagating in the \( x \) direction consists of frequencies ranging from \( \omega_1 \) to \( \omega_2 \). The wave vectors corresponding to the minimum and the maximum frequencies in the incident pulse are given by \( k_1 = \omega_1/cx \) and \( k_2 = \omega_2/cx \), respectively. The grating vectors that diffract \( k_1 \) and \( k_2 \) by an angle of \( \theta^* \) are \( K_1 \) and \( K_2 \). Each grating actually diffracts a narrow band of frequencies in the same direction. As \( \theta \) gets smaller, the difference between \( K_1 \) and \( K_2 \) decreases, which means that the frequency selectivity of each...

Fig. 1. Experimental setup of a holographic pulse-shaping system. M's, mirrors; BS, beam splitter.

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The amount of information that may be encoded on the hologram is accomplished by modulating the index of refraction of the material with a 10-THz modulation bandwidth, providing 500 bits of information. Since the reflected field is to a first approximation the temporal image of the spatial modulation \( v(x) \), pulse shaping in a reflection hologram decreases. The maximum difference between \( K_1 \) and \( K_2 \) is achieved when \( \theta = 180^\circ \), which corresponds to a reflection hologram. In this case, the band of frequencies diffracted by each grating is minimized and the maximum modulation bandwidth of the pulse spectrum is obtained.

In the reflection geometry of Fig. 1, the hologram can be expressed as a modulated reflection grating \( V(r) = v(x)\exp(jKx) \), where \( K = 2k \) is the Bragg frequency for a reflection grating at the pulse center frequency. If the grating is weak enough that multiple-scattering events in the hologram can be neglected, then the reflected signal when the incident field is a temporal impulse is approximately \( v[(x + ct)/2]\exp[j(kx + \omega_0 t)] \). This assumption can be shown to be accurate even for relatively strong holograms with diffraction efficiencies as high as 60% at the center wavelength of the pulse.0 Of course, dispersive effects may in practice also shape the reflected pulse. Since the reflected field is to a first approximation the temporal image of the spatial modulation \( v(x) \), pulse shaping in a reflection hologram is accomplished by modulating the index at the spatial location corresponding to the desired temporal event. The spatial locality in pulse coding should greatly simplify pulse-shaper design. In an integrated-optical geometry, for example, longitudinal modulation of the reflectivity of a distributed Bragg reflector could result in a compact and efficient pulse shaper. The minimum temporal feature that can be encoded onto the reflected signal is approximately equal to the temporal width of the incident pulse, \( \tau \). The minimum spatial resolution along \( x \) that is useful in recording \( v(x) \) is equal to the spatial extent of the incident pulse in the hologram, \( \sigma r \). The duration of the reflected pulse, \( T = 2L/c \), is the propagation time through the hologram and back. The amount of information that may be encoded on the reflected pulse is given by the time–bandwidth product \( T(1/\tau) \). Therefore a 100-fs pulse reflected from a 5-mm-long hologram in a material with a refractive index of 1.5 may produce a 50-ps pulse with a 10-THz modulation bandwidth, providing 500 bits of information.

For our pulse-shaping experiments, a beam of wavelength \( \lambda_w = 514 \) nm from an Ar+ laser is collimated and split into two write beams that interfere in a sample to form a reflection grating for the probe beam. The probe beam is a pulse with center wavelength \( \lambda_p = 776 \) nm that is generated by a passively mode-locked Ti:sapphire source. The pulse width is determined to be <100 fs by measuring the second-order autocorrelation. The period of the grating written in the material is \( \Lambda = \lambda_w/2 n \sin(\phi) \), where \( n = 1.54 \) is the refractive index of the material and \( \phi \) is the half-angle between the write beams in the material. A reflection grating for the probe beam is obtained when \( \Lambda = \lambda_p/2n = 252 \) nm, which requires that \( \phi = 41.5^\circ \). This angle is achieved by use of a prism to couple the write beams into the material. We use an equilateral prism made of flint glass with a refractive index of 1.72 and index-matching fluid. To obtain a small angular separation of the signal beam from the probe beam, we record a grating with \( \Lambda \) slightly larger than what is required for a reflection hologram. Reflections from the air–sample interfaces are also angularly separated from the signal. The longitudinal modulation \( v(x) \) of the grating is obtained by spatially modulating the intensity of one of the write beams, as shown in Fig. 1. Because of the angle of the write beams in the sample, modulation of the grating in this manner is not purely one dimensional. This causes some broadening of temporal features in the reflected signal and reduces the effective modulation bandwidth.

The holographic material in the sample is made by doping Methyl Red into Epo-Tek epoxy 301, which has a refractive index of 1.54. The mechanism for hologram formation is cis–trans isomerization of Methyl Red on absorption of light at 514 nm.0 This isomerization causes a modulation of the refractive index. The strength of the modulation is maximized when the write beams are orthogonally polarized with respect to each other. The diffraction efficiency of a 1-cm-thick reflection hologram recorded in this material is <1%. The holographic recording time is of the order of 1 s, and the dark decay time is several minutes. Faster decay times may be obtained by exposing the material to a single write beam. The probe beam is not absorbed by the Methyl Red.

The pulse shape of the reflected signal is determined by measuring its first-order cross correlation with the probe beam. The probe beam is monitored by a nonlinear second-order autocorrelator. The second-order autocorrelation corresponds to a probe duration of approximately 100 fs. Since the probe is well characterized and since the duration of the reflected signal is much longer than the probe, first-order cross correlation with the probe is sufficient to determine the shape of the signal. To perform the cross correlation, we extract part of the probe beam from the source and allow it to pass through a variable-delay path before recombining it with the reflected signal. The probe and the signal recombine with a small angle between them so that a linear interference pattern is formed when they overlap. The strength of the interference is measured as a function of the variable delay by imaging the interference pattern onto a CCD array. The variable

Fig. 2. A k-space diagram of a diffracted pulse.
delay is provided by reflecting the source from a mirror on a motorized linear translation stage. At each position of the motor, the output from the CCD array is digitized by an 8-bit frame grabber with 512 points in each line across the interference fringes. A fast Fourier transform of each of 10 lines in the image is taken separately, and the strength of the interference is determined by summing the spectral components in the fast Fourier transform corresponding to the interference fringe frequency.

The cross correlation of a pulse reflected from a 5-mm-long single grating is shown in Fig. 3. As expected, the duration of the reflected pulse is 50 ps, which corresponds to the transit time through the hologram and back again. To record a modulated hologram, we inserted a printed mask with 1-mm lines in one of the write beams. A 1-cm-long grating modulated with a square wave of period 2.5 mm was formed. The cross correlation of a pulse reflected from this hologram is shown in Fig. 4. Temporal broadening of the signal that is due to the angle of the modulation can be observed. However, because the bandwidth of the modulation is much less than the maximum limit, the features in the signal can easily be resolved. The decreasing amplitude of the reflected pulses is explained by absorption of the beam by the epoxy and by inhomogeneities in the sample and in the write beams. Repetitive sampling noise introduced by the interferometric cross-correlation system is significant in these measurements. Noise reduction can be achieved through mechanical phase stabilization and the addition of an imaging system with lower noise and wider dynamic range.

We have demonstrated holographic pulse shaping in bulk azo-dye-doped epoxies by spatially modulating a dynamic reflection grating in the material. Future research will include the recording of spatial images on reflected signals by modulation of holograms in three dimensions and the fabrication of pulse shapers in optical waveguides. In bulk materials, absorption of the write beams must be weak so that the modulation of the refractive index across the spatial extent of the probe beam is uniform. In waveguides, stronger holograms are possible with the use of strongly absorbed unguided recording beams or electrically modulated permanent gratings. Existing techniques for fabricating distributed Bragg reflectors may be used to fabricate permanent reflection gratings with high diffraction efficiencies that can be modulated optically or electrically for pulse shaping. With these pulse-shaping techniques, temporal signals with terahertz bandwidths may be produced for high-speed communications and spectroscopic applications.

References