Demonstration of a continuous scanner and time-integrating correlator using spatial–spectral holography

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Abstract

We present a new approach to time-integrating correlation using spatial–spectral holography in which an optically modulated temporal input is spatially scanned by diffracting it from an appropriately programed spatial–spectral grating. The grating required for this scanning operation is programed into the inhomogeneously broadened medium by interfering the image of the traveling-wave diffracted light from an acousto-optic deflector (AOD) with the temporally modulated light from an acousto-optic modulator, thereby recording a spatial–spectral holographic copy of the traveling-wave scanning characteristics of the AOD. This scrolling diffracted field is interfered with a temporally modulated correlation reference and accumulated on a 1-D CCD photodetector array, and is thus quite analogous to an acousto-optic time-integrating correlator (TIC), but without the inherent bandwidth limits of acoustic-wave propagation. This spatial–spectral holographic TIC is experimentally demonstrated at bandwidths of about 30 MHz with 150 resolvable spots and 10 ms of coherent integration time, and the prospect for much wider bandwidth, longer integration time, larger processing gain, and higher resolution are explored.

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1. Introduction

The ability to locally burn spectral holes in the inhomogeneously broadened absorption band of a cryogenically cooled rare-earth-doped crystal allows the holographic storage and processing of vast amounts of data due to the high spatial and high spectral resolutions present in these materials. In the space domain, tilted optical beams interfere to produce a spatial grating modulation of the absorption and index with molecular resolution, which, when illuminated by a Bragg-matched readout beam, allows high-resolution volume-holographic diffraction. In the time domain, the spectral interference of two delayed pulses (or coded waveforms) can engrave a periodic spectral modulation of the population excitation of the inhomogeneous band (a spectral grating), which, when illuminated by a readout pulse, will produce a temporally delayed stimulated photon echo (SPE). In this paper, we present a non-trivial and non-separable combination of the spatial- and

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spectral-grating modulations which enable simultaneous time-delayed and angularly deflected diffractions in order to realize the functionality of a spatial beam scanner and we demonstrate the functionality of this scanner by incorporating it into a time-integrating correlator (TIC) system.

Spatial–spectral holography (SSH) has previously been used to implement signal correlation by recording the spectral interference between a temporal correlation reference waveform and a time-delayed brief impulse as a modulation of the spectral grating, and then reading it out with the signal to be correlated and observing the stimulated photon echo in time [1]. The temporal duration of the stored reference is limited by the coherence time, $T_2$ (typically 10–100 μs), the readout duration is limited by the excited state lifetime, $T_1$ (10 ms in Er$^{3+}$), or bottleneck state lifetime, $T_B$ (10 ms in Tm$^{3+}$), and the processing gain is limited by the ratio of signal bandwidth (or inhomogeneous bandwidth if that is smaller) to homogeneous line width. Such a correlator has a temporal input and temporal output, and operates by integrating across the inhomogeneous spectrum, and thus we refer to it as a spectral-integrating processor.

An alternative paradigm for temporal signal processing with SSH utilizes the narrow frequency selectivity of spectral hole burning (SHB), in which the different frequency components of a temporally modulated input signal are diffracted at different angles by an appropriately pre-recorded spatial–spectral hologram. These different frequency components are then focused by a Fourier transform lens onto a linear detector array (or possibly rastered onto a 2-D detector array) which detects the power spectrum of the signal [2–4]. This system operates analogously to the diffraction of light from a conventional grating, although the extraordinarily high resolution possible with spectral hole burning corresponds to a 1 km long grating, so it is operationally more similar to an acousto-optic (AO) power spectrum analyzer. However, the 1–2 GHz bandwidth limits of acoustic–optics are avoided, so the SHB spectrometer can potentially cover 10–20 GHz (or even more) of bandwidth with sub-MHz resolution.

The temporal input is processed to produce an output that is displayed in space, utilizing spectral filtering and spatial integration for the Fourier analysis, with incoherent temporal integration on the detector array for improving the variance of the power spectral estimate [5].

In this paper, we describe a new interpretation and application of the spectral-hole-burning spectrally multiplexed deflector, that allows instead the calculation of signal cross-correlation between long signals that exceed the coherence-time limit, $T_2$, of the previous spectral-integrating correlators. This is accomplished by coherently time-integrating on a CCD detector array the interference between an image of the temporally modulated and spatially scanned diffracted output of a spatial–spectral holographic scanner (SSHS) with a temporally modulated reference waveform, and thus is directly analogous to an AOTIC [6,7]. However, the AO limits on bandwidth are removed so that multi-GHz operation becomes feasible, and the limits of integration time imposed by the coherence time, $T_2$, of the IBA are also eliminated. The SSHS is, in fact, recorded in a very similar fashion to the spectral-hole-burning spectrometer [4], using an accumulated programing sequence of the spatial–spectral interference between the image of an acousto-optic deflector (AOD) and an acousto-optic modulator (AOM), both driven by identical broadband waveforms. But the operation on the diffracted output field from the SSHS is fundamentally different for the TIC system, since we coherently detect the diffracted field in an image plane by interfering with a modulated reference, rather than incoherently detecting the individual spectral components in the Fourier plane for the SHB spectrometer. This paper is organized as follows. We begin with a brief review of the capabilities of photon-echo processing in cryogenically cooled rare-earth doped crystals. We then show how to record the spatial-scanner functionality into an SSHS and provide a brief theoretical overview of the holographic copying of the traveling-wave character of an AOD into a spatial–spectral hologram. Then we show the design and experimental results of a spatial–spectral holographic time-integrating correlator (SSH-TIC). And finally, we discuss the
prospect for the extension to wider bandwidth operation than is possible using AO.

2. Photon-echo physics

For rare earths such as Tm\(^{3+}\), Eu\(^{3+}\), Pr\(^{3+}\), or Er\(^{3+}\) doped into inorganic crystals such as YAG, LuAG, or YSiO\(_3\), at cryogenic temperatures of 4 K or less, the ions have homogeneous line widths and coherence times of about 10 kHz and 100 \(\mu\)s, respectively, while the disorder of the local environment in the crystal shifts the local resonance frequency to cover an inhomogeneously broadened bandwidths of 1–25 GHz or even up to 200 GHz in LiNbO\(_3\) [8]. This combination of long time delays of hundreds of microseconds and high bandwidths of many 10 s of GHz allows temporal holographic signal processing applications with high data rates, and with potential time-bandwidth (TB) products (a measure of the number of degrees-of-freedom of the processed waveform) approaching \(10^6\), although the practical limits related to spectral diffusion and excitation-induced dephasing (EID) may limit the practical TB to \(10^4\) [9]. Since beams with waists as small as 10 \(\mu\)m can illuminate crystals with apertures of 1 cm\(^2\) or more, then the potential for parallel operations at nearly a million resolvable spots is conceivable, although crosstalk limitations due to beam waist spreading in volumetric crystals may provide a smaller practical limit. On the other hand, in a 1 cm\(^3\) crystal, holographic angular multiplexing of tilted plane waves or shift multiplexing of spherical waves can avoid the crosstalk limit due to the overlap of expanding beams and provide up to \(10^9\) individually addressable parallel processors each with TB of \(10^4–10^6\). Limitations on the available optical power and the power spectral density required to record and read out an efficient spectral grating may provide a substantially more modest limit on the number of spatial–spectral channels available for such a massively parallel photon-echo signal processor. In this paper, we present a parallel bank of photon-echo processors configured as a linear ramp of time delays with 150 resolvable positions in a linear row, demonstrating this capability for parallel processing.

When two beams intersect in such an inhomogeneously broadened absorber, they record a spatial–spectral holographic interference pattern, which a third beam can diffract from in both space and time to produce a stimulated photon echo. Two sequential temporally modulated beams \(s_1(t)\) and \(s_2(t)\) (propagating along \(\vec{k}_1\) and \(\vec{k}_2\), respectively) record a spectral interference pattern (with grating vector \(\vec{K}_G = \vec{k}_2 - \vec{k}_1\)) that is then read out by beam \(s_3(t)\) propagating along \(\vec{k}_3\), producing a SPE output propagating with wave vector \(\vec{k}_4\). The SPE is given by the causal correlation–convolution integral \([1,10,11]\) integrated over the crystal volume, and represented in the time or frequency domains as

\[
o(t, \vec{k}_4) = A \int_V e^{-i\vec{k}_4\cdot\vec{r}} \int_0^t s_1(t_3) e^{i\vec{k}_3\cdot\vec{r}} \times \int_{-\infty}^{t_3} s_2(t_2) e^{i\vec{k}_2\cdot\vec{r}} \times s_3^*(t_2 + t_3 - t) e^{-i\vec{k}_1\cdot\vec{r}} \times e^{-2i\pi(\vec{t}_2 - \vec{t}_1)\cdot\vec{r}} \times \frac{1}{\Delta k} \int \frac{dt_2}{t_2} \frac{dt_3}{t_3} \frac{1}{d^3r}
\]

\[
\simeq A \text{sinc}(\Delta k L/2) \int [(S_1^*(\omega)S_2(\omega)\star l(\omega))S_3(\omega)] \text{d}\omega \text{d}^3r,
\]

where \(A = -4i\sqrt{\pi n_0|p|^2/\hbar^3}a\), and \(\Delta k = \vec{k}_3 + \vec{k}_2 - \vec{k}_1 - \vec{k}_4\), and \(l(\omega)\) is the coherence-time resolution-limiting Lorentzian. Even though this triple-product linear filter approximation is only valid in the small signal regime, it still provides valuable insight even when the signals start approaching the large-signal regime \([1,11,12]\). Choosing \(s_1(t)\) as a correlation reference, \(s_2(t)\) as a brief pulse, and reading out with an unknown waveform \(s_3(t)\) produces a correlation \(o(t) = s_1(t) \star s_3(t)\), while other configurations have been used for data storage and retrieval \([13–16]\), phase conjugation \([17]\), time-reversal \([18]\), convolution \([1]\), and true-time-delay \([19–21]\). Most of these previous approaches relied purely on the time-domain processing capabilities of photon echoes, and used neither the available space domain parallelism, nor spatial Fourier optical processing, nor Bragg angle multiplexed volume holography techniques in conjunction with the temporal photon echoes.
3. Traveling-wave SSHS

In this paper, we show how to extend spectrally integrating time-domain photon-echo processing to a spatio-temporal processing domain in which a modulated optical signal is scanned linearly in space by the diffraction from an appropriately programed spatial–spectral holographic grating scanner. This 1-D scanner is perhaps the simplest non-separable spatio-temporal diffraction functionality that allows a demonstration of the parallel and mutually coherent processing capabilities of spatial–spectral holography, and it allows an investigation of the requirements and limitations to programming such a parallel array of photon echoes. This photon-echo scanner performs a function that is in some senses analogous to an AOD, in which a temporally modulated RF input $s(t)$ is displayed as a scrolling tapped delay line, $s(t - x/v)$, at an acoustic velocity $v$. In fact, the spatial–spectral grating responsible for producing a scanned diffraction was recorded in the experiments presented here by interfering the image of the traveling-wave diffraction from an AOD with a modulated signal produced by an AOM when both are driven by the same chirp waveform, as shown in Fig. 1. The input signal applied to both the AOD and AOM can be considered to be a band-limited impulse for simplicity but any spectrally uniform signal spanning the full device bandwidth (such as a chirp, pseudo-noise sequence, or broadband random noise) can be utilized as well, with a much higher optical efficiency than the impulse. When this recorded spatial–spectral grating is re-illuminated by a Bragg-matched temporally modulated optical beam propagating along the direction of the recording beam (or a Bragg degenerate tilted version) then the diffraction will scan just like the AOD at a velocity scaled from the AOD velocity by the magnification of the imaging system. This spatial–temporal holographic reconstruction of the scanning behavior of the AOD is just a generalization of the associative wavefront reconstruction property of conventional spatial holograms when illuminated by one of the exposing spatial fields [22]. In the SSH case, the complete spatio-temporal characteristics of the object AOD are reproduced in the scanned output. A related approach has been used by Le Gouoet et al. [2–4] to implement a power spectrum analyzer by Fourier transforming with a lens the diffracted output of the spatial–spectral holographic scanner and placing an integrating photo-diode array in the Fourier plane, in exact analogy to the AO spectrum analyzer [23]. Their system can instead be thought of as a frequency-multiplexed set of spectrally selective diffraction gratings with diffraction angle proportional to offset RF frequency from the carrier, and the relative phase of these different frequency components is of course unimportant, since each is individually mod-square detected by the detector array at the Fourier plane where they are separated.

We demonstrate here for the first time that the SSHS does indeed faithfully reproduce the fully coherent scanning behavior of the AOD. This demonstration was performed implicitly by building an interferometric TIC, which requires phase-locked coherence between the diffractions of different frequency components originating from different spatial locations in the SSH.

4. SSH theory

A pair of spatio-temporal fields, $E_j(F, t)$, where $j = 1, 2$, incident on a cryogenically cooled, inhomogeneously broadened absorber (IBA)
medium will engrave a spatial–spectral holographic grating in the atomic ground-state (and also possibly the excited-state) population distribution which will holographically modulate the dielectric properties in both space and frequency. The propagation of the fields into the volume of the IBA crystal is most easily represented in terms of the spatio-temporal Fourier transforms of these fields incident at the planar IBA material boundary, \( z = 0, \mathcal{F}_x' \{ E_1(\bar{x}, t) \} = \mathcal{E}_o(\bar{k}_T, \omega), \) where \( \bar{x} = (x,y), \bar{k}_T = (k_x, k_y), \) and \( \mathcal{F} \) is the operator representing Fourier transformation with respect to the subscript variables. Propagation and interference can be represented in terms of the Fresnel diffraction operator [24] represented as a phase advancement of the transverse spatial Fourier components throughout the volume of the crystal of index \( n \) (assumed isotropic for simplicity),

\[ E(\bar{r}, \omega) = \mathcal{D}_z \{ E(\bar{x}, t) \} \]

\[ = \mathcal{F}_T^{-1} \left\{ \mathcal{E}_o(\bar{k}_T, \omega) e^{-i(o\omega - z\sqrt{\omega/(\omega\gamma^2 - k_T^2)}} \right\}, \]

where \( \bar{r} = (x,y,z), z \) measures the depth of propagation into the crystal, and \( \mathcal{F}_T^{-1} \) is the inverse Fourier transform operator. Two spatio-temporally modulated beams that propagate into the IBA crystal will interfere locally (in \( \bar{r} \) and \( \omega \)) and the term responsible for the SPE goes as \( E^*_o(\bar{r}, \omega) E_2(\bar{r}, \omega) \). The accumulation of the spectral grating leads to a spatial–spectral hologram throughout the crystal volume which is blurred out by convolution with a Lorentzian, \( l(\omega) \), of line width \( 1/T_2 \), as given by

\[ G(\bar{r}, \omega, t_0) = \int e^{i\omega(t - x/v)} E^*_o(\bar{r}, \omega) E_2(\bar{r}, \omega) \frac{T_2}{1 - i(\omega - \omega_o)/T_2} d\omega. \]

The readout of this spatial–spectral grating occurs when a third field propagates into the IBA, locally multiplies by \( G \), and then the diffracted component propagates to the output face. Diffracted contributions throughout the crystal thickness \( L \) and the IBA material inhomogeneous line shape, \( g(\omega) \), need to be integrated, giving

\[ E_d(\bar{x}, t) = \int_0^L dz \int d\omega e^{i\omega t} g(\omega) \times \mathcal{D}_L \{ \mathcal{D}_z \{ E_3(\bar{x}, \omega) \} G(\bar{r}, \omega, t_0) \} \]

\[ = \int_0^L dz \int d\omega g(\omega) e^{i\omega t} \mathcal{D}_L \{ \mathcal{D}_z \{ E_3(\bar{x}, \omega) \} \} \mathcal{D}_z \{ E_1(\bar{x}, \omega) \} \mathcal{D}_z \{ E_2(\bar{x}, \omega) \} l(\omega). \]

When the spatial characteristics of \( E_3 \) appropriately match \( E_1 \) (generalized Bragg matching [25]) and the temporal characteristics of \( E_1 \) match \( E_2 \) except for a delay (e.g. linear phase factor in the spectral domain), then the spatial propagation operators holographically cancel and the full spatio-temporal characteristics of field \( E_3(\bar{x}, \omega) \) resolvable with the coherence-time line-shape spectral blurring are coherently stored in the SSH, and available for Bragg-matched readout by \( E_3 \).

An AOD illuminated by a Bragg-matched Gaussian beam produces a diffracted beam for an applied signal \( s(t) \) that can be represented either in the time domain as a traveling wave, or in the frequency domain as Doppler-shifted plane waves propagating at an angle proportional to their frequency,

\[ E_2(x,y,t) = e^{-i(\omega t - k_0 x)} p_0(x)q(y) s(t - x/v) \]

\[ = e^{-i(\omega t - k_0 x)} \int_{-\infty}^{0} S(\Omega) T_2(x,y) e^{i\Omega t} d\Omega, \]

where \( \Omega \) is the RF angular frequency which is only integrated over a single sideband (SSB), and the window function of the illuminated AOD is

\[ p_0(x)q(y) = \left[ II \left( \frac{x}{X} - 0.5 \right) e^{-[(x-x_0)/a_x]^2} e^{-y_0(y/2\Omega)^2} \right] \times \left[ II \left( \frac{y}{Y} \right) e^{-(y/a_y)^2} \right], \]

where \( II \) is a unit width rectangle function, the device width is \( X \), height is \( Y \), and the elliptical Gaussian beam width is \( a_x \) by \( a_y \), centered at \( x_0 \) (with respect to the transducer at \( x = 0 \)), and the acoustic attenuation is quadratically frequency dependent. The corresponding Fourier response function is \( P_0(k_x) = \mathcal{F} \{ p_0(x)q(y) \} \). For a more complete description of AOD behavior the frequency-dependent transmission response \( T_0 \) can be used [26], which represents the frequency-dependent
Bragg-matched acoustic diffraction,
\[
T_\Omega(x, y) = H(\Omega)B(\Omega)F^{-1} \left\{ \delta(k_x - \Omega/v) + b_y k_y^2 \right\} Q(k_y).
\]

\(H(\Omega)\) represents the transducer electro-acoustic bandwidth (typically tuned over one octave), and \(B(\Omega) = \text{sinc}(\Delta k L/2)\) is the AO Bragg-matched bandwidth with the details of the frequency dependence of \(\Delta k(\Omega)\) depending on the device design (typically parabolic for birefringent or phase-array devices). For the ideal traveling-wave scanner model the out of the plane acoustic curvature \(b_y\) is set to zero, so the delta-function Fourier transforms to \(e^{-iQ/k}\), and the image of the AOD on the IBA crystal is
\[
E_2(x, y, t) = e^{-i(\omega t - M(k_0 + \hat{k}_d)\cdot x)} Q(y/\lambda F_y) p(x/M) \times \int_{-\infty}^{0} S(\Omega)H(\Omega)B(\Omega)e^{iQ(t-x/v_M)} d\Omega.
\]

This diffracted AO field is imaged onto the SSH crystal with magnification \(M\) in the \(x\) dimension (so \(v_M = v/M\)) and focused in the \(y\) dimension with a cylinder \((F_y)\) to a line focus of width \(a_2 = \lambda F_y/a_y\).

The temporally modulated and tilted reference wave (with wave vector \(\hat{k}_\text{r}\)) has a spatial profile designed to maximally overlap with the AOD object wave
\[
E_1(x, y, t) = e^{-i(\omega t - \hat{k}_\text{r} \cdot x)} e^{-i(x-x_0/M)(a_x/M)^2} e^{-(y/a_y)^2} \delta(t),
\]
where \(\delta(t)\) is the single-sideband temporal-modulation signal and it occurs first, before the acoustics propagates into the deflector aperture. After recording the SSNS, the scanner readout field applies a different temporally modulated waveform covering at most the bandwidth spanned by the product \(|S(\Omega)|^2 H(\Omega)B(\Omega)\) and with a possible Bragg degenerate tilt \((\hat{k}_d \cdot \hat{k}_\text{r} - \hat{k}_0) = 0\),
\[
E_3(x, y, t) = e^{-i(\omega t - \hat{k}_\text{r} \cdot x) x} e^{-i(x-x_0/M)(a_x/M)^2} e^{-(y/a_y)^2} \tilde{\delta}(t),
\]

which yields an output from the SSNS given by
\[
E_d(x, y, t) = e^{-i(\omega t - (M\hat{k}_0 + \hat{k}_d) \cdot x)} \times \left[ e^{-i(x-x_0/M)(a_x/M)^2} e^{-(y/a_y)^2} \right]^2 \times \mathcal{F}^{-1} \left\{ q(k_y \lambda F_y) \right\} \times \int_{-\infty}^{0} R(\Omega)|S(\Omega)|^2 H(\Omega)B(\Omega) \times e^{i\Omega} P_\Omega(M\hat{k}_x - \Omega/2\pi\nu) d\Omega \approx e^{-i(\omega t - (M\hat{k}_0 + \hat{k}_d) \cdot x)} \times \left[ e^{-i(x-x_0/M)(a_x/M)^2} e^{-(y/a_y)^2} \right]^2 \times L\left(\frac{x}{v_M}\right) P\left(\frac{x}{\lambda F_y}\right) p\left(\frac{y}{\lambda F_y}\right) \left( t - \frac{x}{v_M} \right),
\]
where \(L(x/v_M) = e^{-x/(x/v_M)^2/2T_2}\) is the exponential coherence loss scaled into space by the magnified acoustic velocity, \(v_M = v/M\). This shows that when the recording signal power spectrum \(|S(\Omega)|^2\) is flat over the device bandwidths spanned by \(H(\Omega)B(\Omega)\) (corresponding to recording with an impulse, chirp, or white noise) that the diffracted field from the SSH scanner duplicates the full spatio-temporal characteristics of the AOD scanner as long as the coherence lifetime exceeds the phonon lifetime and time delay in the illuminated portion of the AOD. If desired, an additional tilt, \(\hat{k}_d\), can be added to the diffracted field to allow simple spatial filtering to separate the diffraction from the writing beams.

5. AOTIC

Since the SSH TIC is based on copying the operation of an AOD into an SSH, and then using the SSNS in the topology of a classic interferometric acousto-optic time-integrating correlator [6,7], the implementation of this type of AO processor will be described first. As seen in Fig. 2, the diffracted field from a slow-shear wave TeO2 AOD (in which \(v = 0.62 \text{ mm/\mu s}, b_y = 42 \text{ and } x_0 = 18 \text{ dB/\mu s/GHz}^2\) is Schlieren imaged onto a 1-D CCD detector array via a 4-F imaging system with a DC block in the Fourier plane. This
traveling-wave modulation is interferometrically combined with an off-axis modulated plane wave reference signal produced by the collimated diffracted field from an AOM. An RF signal, \( s(t) \), is applied to the AOD and diffracts the Bragg-matched incident plane wave with a scrolling time-delay modulation that is characteristic of AODs. The SSB diffracted signal, \( \tilde{s}(t - x/v, \phi) \), is imaged onto the CCD, where it is interfered with a SSB temporally modulated reference signal, \( \tilde{r}(t) \), from the reference AOM. In typical radar applications, the reference signal is a broadband high TB reference signal, such as a broadband chirp or noise-like waveform, with a reference delay \( \tau_d \), \( \tilde{r}(t) = \tilde{s}(t - \tau_d) \), and this is correlated with the radar echo consisting of a complex linear superposition of delayed copies of the reference plus uncorrelated noise, \( s(t) = \sum_m |a_m|e^{i\phi_m} s(t - \tau_m) + n(t) \). A correlator is then the optimal linear detector to measure the delays \( \tau_m - \tau_d \), amplitudes \( a_m \), and phases \( \phi_m \), as the positions, amplitudes, and phases of the carrier of each correlation peak. The fringe pattern caused by the interference of the two described signals is given by

\[
I(x) = \int_0^T |r(t)e^{i2\pi u_0 x} + s(t - x/v)|^2 \, dt
= \Re \left\{ e^{i2\pi u_0 x} \int_0^T r^*(t)s \left( t - \frac{x}{v} \right) \, dt \right\} + \text{bias},
\]

where \( u_0 \) is the spatial frequency of the tilted reference wave, and \( \Re \) represents the real part. The temporal integral over the time window \( T \) is due to the accumulation of photo-generated charge within each CCD pixel, which can readily integrate over a time approaching 0.1–1 s at room temperature, and with CCD cooling, integration can be extended to many minutes. The intensity distribution on the CCD is thus the correlation of \( s(t) \) and \( r(t) \) riding on a spatial carrier, as well as background terms, as illustrated graphically in Fig. 2. For matched signals with bandwidth \( B \), the correlation peak is a sharp spike whose shape is the Fourier transform of the signal power spectrum with spatial width on the CCD \( \sigma = BM \), for magnification \( M \), and it is modulated by a carrier spatial frequency \( u_0 > 1.5/\sigma \). Therefore, the CCD pixel spacing, \( \Delta_x = \frac{1}{\sigma} \), must be fine enough to ensure adequate Nyquist sample of the carrier and correlation, \( \Delta_x < \frac{1}{4 u_0} + 1/\sigma \). The correlation peak is produced at a CCD position \( x = \tau_d u \), where \( \tau_d \) is the relative time-delay. The goal of this research is to successfully replace the AOD with an SSH that is appropriately programed to duplicate the traveling-wave scrolling delay line function.

In order to record the spatio-temporal characteristics of the AOD into the SSH in a coherent fashion, the system shown in Fig. 1 was built. A broadband RF signal, \( s(t) \), (a pulse is illustrated, but chirps were used in the experiments) is injected simultaneously into the AOD and the AOM. The diffracted light from the AOM is collimated and incident on the entire crystal immediately, and acts as pulse one of the three-pulse photon-echo sequence, while the spatio-temporal diffraction from the AOD is telescopically imaged with a Schlieren filter onto the SSH and acts as pulse two. Note, however, that the temporal separation of these two pulses varies linearly in space, because of the scrolling time-delay diffraction from the AOD. Once the SSHS has been prepared, the readout process by a new signal, \( r(t) \), is relatively straightforward. This modulated signal, generated by the programing/readout AOM, and whose bandwidth falls within that of the prepared SSHS, can now act as pulse three of the photon-echo sequence and diffract off the SSH in both space and time. This produces a scanned diffracted field that holographically recreates the field that would have diffracted off the AOD had the electrical signal...
r(t) been applied to the transducer of the programing AOD. By building a TIC around the prepared SSHS, we will test if the recording and readout processes are indeed coherent, since the TIC can not operate properly if the detailed phase relationships between each of the angular and frequency components diffracted by the SSHS is not preserved to duplicate that produced by the AOD. If, and only if, the SSHS offers a fully coherent replacement for the AOD will the SSH TIC give a correlation peak.

6. SSH-TIC experiment

The experimental setup of the SSH-TIC is shown in Figs. 3 and 4 which illustrates the recording phase for the SSHS and readout/TIC phases, respectively. The 7 mW of output from a hole-locked laser [27,28] is injected into a tapered amplifier chip, resulting in 140 mW of narrow linewidth optical radiation at 793 nm. The input to the amplifier is opto-isolated, and PM fiber-coupled. The highly anamorphic and astigmatic tapered-amplifier output is collimated and then circularized with a cylindrical lens, opto-isolated, and finally coupled back into a matched 5 μm core 800 nm PM output fiber. The tapered amplifier produces 500–600 mW of output power in weakly filamented lobes as well as substantial amplified spontaneous emission in a diffuse halo, but the coupling into the PM fiber selects mostly the desired amplified signal. The fiber coupled amplifier achieves about 13 dB of PM fiber-to-fiber gain.

This relatively high power is needed because hundreds of parallel photon-echo channels are recorded in a relatively large area of the 0.1% doped Tm³⁺:YAG crystal. The total illuminated beam area measures 2.6 mm wide by 50 μm tall, rather than the typical 20–30 μm diameter Gaussian beam typically used for 1-D photon-echo experiments and spectral-integrating correlators. The crystal area illuminated is thus nearly 200 times larger, so in addition we accumulated the scanner recording over a sequence of exposures.
To determine the appropriate amount of accumulation in this geometry, we performed a simple 1-D photon-echo experiment using 30 MHz bandwidth temporally overlapping linear frequency chirps (TOLFC) spread out spatially to cover a 6 mm × 50 μm area. Note that this was a larger area than the final experiment utilized, because at the time we were using a different optical system than in the final SSH-TIC experiment. After a sequence of accumulated exposures, we measured the diffraction efficiency, as shown in Fig. 5. Our simulations of the accumulation process employing various models of laser frequency jitter, as well as previous studies, indicate that accumulation requires excellent laser stability, ideally well under 10 kHz. Stabilized accumulation should result in a quadratic increase of photon-echo intensity peak size with number of accumulated programing sequences, eventually rolling off when the IBA approaches saturation. Without hole-locking, the free-running ECDL linewidth degraded to greater than 100 kHz; and although single shot echoes were easily produced, accumulation of multiple engraving sequences quickly washed out the spectral grating, resulting in smaller echoes. Since we did see a quadratic increase in echo size for the first 2–5 pulses, followed by a regime where the echo efficiency increased linearly and then saturated after 20–25 cycles, we estimate that laser linewidth may not be as good as 10 KHz, but certainly was much better than 100 kHz. Thus, when recording the SSHS we typically accumulated for 25 repetitions, and then switched to a readout mode that lasted for the bottleneck lifetime in Thulium of $T_B = 10$ ms. Alternatively, a continuous mode could be used in which as the chopper rotates, exposure cycles are alternated with readout cycles during which SSHS time-integrated correlations are performed, and the CCD detector array can continue to integrate for 0.1 s on chip, and even longer after analog-to-digital conversion using digital averaging. Such long coherent integration is important because it enhances the processing gain, $PG = \frac{SNR_{out}}{SNR_{in}}$, which is the ratio of output signal-to-noise ratio (SNR) to input SNR, and is ideally given by the product of the processing bandwidth, $B$, to the integration time, $T$, (divided by the duty factor for such an interleaved correlation). This is to be contrasted with incoherently averaging a sequence of photon-echo correlation peaks from a conventional spectrally integrating correlator (for example using averaging on an oscilloscope), which results in an increase of SNR that only increases with the square root of the number of averages. A single long continuous exposure could be used with a never ending random-noise waveform applied to both AOD and AOM, but then an angularly multiplexed (in the direction of Bragg degeneracy) readout scheme would need to be employed. Since we found excessive scatter of the recording light from the crystal and other components into the CCD, we instead used a chopper to time-multiplex the recording and SSHS readout to produce the TIC.

In the first phase of the experiment, shown in Fig. 3, the SSH is programmed with the scrolling time-delay functionality of a Bragg cell by injecting a 50 μs chirp spanning 60–90 MHz into a slow-shear wave AOD and imaging the 30 mW of diffracted output onto the SSH. At the same time, an identical chirp is injected into an AOM, whose diffracted output (40 mW) is anamorphically

![Fig. 5. Accumulation of a spectrally integrating photon-echo grating using temporally overlapped linear frequency chirps (TOLFC) when the 140 mW total power programing and readout beams are spread out to cover a 6 mm × 50 μm spot as required for parallel SSH processing. Over 100-fold increase of the resulting photon-echo efficiency is achieved after 20–25 accumulation repetitions, each separated by several coherence times, $T_2$. The initial nearly quadratic increase of echo efficiency with the number of programing sequences up to 4–5 is evidence for good hole-locked laser stability.](image-url)
expanded, overlapped, and aligned at a tilted angle with the AOD image on the SSH, thereby recording a spatial spectral grating in the Tm$^{3+}$:YAG crystal. The magnification of the imaging system was chosen as $M = 0.6$ to optimally project a 4.3 mm (Gaussian $1/e^2$ width) aperture of the AOD, corresponding to 6.9 $\mu$s of delay into a 2.6 mm $\times$ 50 $\mu$m area of the SSH, while taking into consideration various experimental constraints such as the numerical aperture of the available lenses as well as the closest distance that these elements could be placed to the crystal. Since we are illuminating about 4 mm of the AOD, in which the acoustic velocity is 620 m/s, the spatio-temporal diffraction from the AOD records a linearly increasing time delay ramp at different spatial locations in the IBA crystal, ranging from 0 to 6.4 $\mu$s (referenced to the undelayed signal from the AOM). This time delay ramp spans a little less than the coherence time, $T_2$, so the available time delay will not be limited by the coherence time but instead by the illuminated aperture of the AOD. During this programming phase, the chopper (located after the cryostat) is closed, thus preventing light from the AOD from reaching the 1-D CCD. In the readout phase shown in Fig. 4, the AOD is turned off, the chopper opens, and the SSB waveform $\bar{s}(t)$ that is to be correlated (generated by the programing AOM) illuminates the SSH, resulting in a spatio-temporally scanned diffraction $\bar{s}(x-x/v_{M})$ in the same direction and with the same velocity, $v_{M}$, as the magnified image of the acoustic wave in the AOD had at the time of programing. Around the time of the SSH diffraction, the correlation reference signal $\bar{r}(t)$ is generated in a second (TIC reference) AOM, and is interfered with the echoed, scanned output from the SSHS. We chose the power of the TIC reference beam so that it consumes about half of the dynamic range of the CCD, so that the correlation peak interference can be optimally detected. The photogenerated charges are locally accumulated on the 1-D CCD for a time $T$ that can be longer than the lifetime $T_1$ (in our case $T = 50$ ms and $T_B = 10$ ms), as long as the grating is periodically re-written.

The CCD captures a time-integrated, interferometric correlation peak, which is modulated by high spatial-frequency fringes and riding on top of a nonuniform bias that is also corrupted with coherent artifacts, as shown in the upper trace of Fig. 6. The position of the correlation peak depends on the time-delay, $\tau$, between the signals injected into the programing/readout AOM and the TIC-reference AOM (see Figs. 3 and 4). Since the correlation peak is modulated by a spatial carrier, high-pass filtering can eliminate the slowly varying bias term, as well as most of the fixed pattern and coherent artifact noise, as shown in the second trace. Finally, to get the incoherent correlation peak, the spatial carrier is removed by down conversion, giving the final correlation peak as shown in the lowest trace of Fig. 6, which accurately portrays the 2 $\mu$s delay which was present between the signals diffracted off the SSH and the TIC reference AOM.

Next, we investigated the range of delays that could be accommodated by the SSH TIC by incrementally increasing the delay between the signal and the reference. Fig. 7 is an overlay of several of the resulting correlation peaks produced in real time by the CCD through digital high pass filtering, mod-squaring, and low-pass filtering, and shows delay measurements from 0.5–5.5 $\mu$s, although peaks were visible from 0–6 $\mu$s. Even...
though the correlation peak shape differs slightly from that in Fig. 6 (due to the somewhat limited real-time processing capabilities of the 1-D CCD) the FWHM of both types of processing is identical at 40 ns. The ratio of processable time-delay and the correlation peak width gives the number of resolvable time-delays, as well as the number of resolvable spots that were programed into the SSH by the AOD—in our case $N_{SSH} = 6 \mu s/40 \text{ ns} = 150$. For an AO-TIC system with the same time-aperture and bandwidth, the fundamental limit on the number of resolvable spots is given by the AOD’s TB product, which for the overlapping 3 dB bandwidth of the AOD and AOM of $B = 30 \text{ MHz}$ and Gaussian $1/e^2$ illuminated AOD aperture of $T_A = 6 \mu s$ yields $N_{AO} = T_A B_A = 180$. The nonuniformity across the correlation window for both the AO-TIC and SSH-TIC are limited by the spatial profile of the TIC correlation reference beam and the beam illuminating the AOD, as well as acoustic attenuation in the AOD, while the SSH-TIC is also limited by the AOM intensity profile at the SSH and by the $T_2$ coherence lifetime. Our experiment shows that there was little if any additional degradation due to the use of a SSH copy of the AOD for the traveling-wave deflector in the interferometric TIC, rather than the AOD itself.

7. Discussion

The SSHS behaves precisely like an AO device that is illuminated by an appropriate Bragg-matched CW beam, but in some systems AODs are illuminated by modulated beams, or one AOD is imaged onto another and the multiply diffracted output is used [24]. In these type of multiplicative geometries the AOD generates new frequencies given by sum or difference of applied RF frequencies, and it is important to realize that in this regard the SSHS is fundamentally different than an AOD. The SSHS is a programable spatio-temporal filter that can arbitrarily spatially rearrange temporal frequency components that are incident on the spatial–spectral hologram, but since moving gratings are not available in an SSH as they are in an AOD, no new temporal frequency components can be generated. Thus the SSHS cannot be used as a replacement for an AOD in multiplicative AO signal processors, but instead can only be used in systems that only use 1 AO device, such as the power spectrum analyzer [3], AO signal excisors [33], or in additive architectures that achieve signal multiplication through an interferometric combination of modulated fields as in the interferometric TIC presented here. Another interesting possibility is hybrid systems that use AODs for low bandwidth multiplicative operations, and combine these with SSHS for ultra-wide bandwidth additive interferometric optical signal processing. For example by combining the 1-D SSH-TIC demonstrated here with a pair of multiplicative AODs driven by counter-propagating chirp waveforms it is possible to make an array of Doppler compensated correlation outputs as required for a time-integrating ambiguity function processor [34].

Since we have demonstrated that we can precisely copy the behavior of an AOD into an appropriately engraved SSH, and then use it in a system normally implemented using the AOD, we must wonder why this would be useful, since the
holographic copy of the AOD has all of the limitations of the AOD in terms of bandwidth, time-aperture, and resulting TB product. The answer is that the SSHS can be programmed with more complex scan patterns, for instance a 2-dimensional raster can be implemented with an appropriate Doppler compensated crossed AOD (or scan mirror) to vertically tilt or displace the 1-D scanner [3]. In addition, by using a chirped laser that is synchronized with a scanner, Le Gouët et al. have shown how to produce the same type of scanner, but without any bandwidth restriction due to the AOD, but instead limited only by the material bandwidth and linear sweep range of the frequency scanned laser [3]. This approach also enables the dynamic reprogramming of the SSHS bandwidth and scan range enabling spectral zooming onto features of interest within a rapid reprogramming time of only 10 ms for Er\textsuperscript{3+} or Tm\textsuperscript{3+}-based materials [4]. But our principal goals in the experiments presented here is to provide an initial demonstration of the fully coherent time-domain scanning functionality of the SSHS, and its complete equivalence to an AOD within the context of an interferometric TIC, thereby unambiguously demonstrating the spatio-temporal wavefront reconstruction capabilities of the SSH.

We also investigated the limitations on resolution, the requirements for laser power and accumulation, the approaches to read–write multiplexing, and the feasibility of extending the simple 1-D SSHS scanner and TIC to more complicated multidimensional hybrid-AO SSH systems.

8. Conclusion

We have demonstrated an SSHS that coherently diffracts an incident temporally modulated single-sideband optical signal as a scanned traveling wave that achieved 150 resolvable time delays. Our initial demonstration used only 30 MHz of bandwidth and 6 \(\mu\)s of the aperture of a TeO\textsubscript{2} slow-shear wave AOD as the object that was interfered with a similarly modulated beam from an AOM in the volume of a cryogenically cooled inhomogeneously broadened absorber to record the SSHS. To demonstrate the operation of the SSHS it was illuminated by a modulated chirp and the image of the diffracted traveling-wave signal was combined with a delayed version of the same modulated chirp as an off-axis correlation reference and the interference was detected on a 1-D CCD to produce a time-integrating correlation peak. This TIC has a longer coherent integration time and larger processing gain than previous spectrally integrating SSH correlators, although the current implementation has no advantage over AOD-based TIC since the SSHS is just a copy of the AOD. However, this technology has the potential for an alternative chirped laser based recording scheme that can achieve the scanning function of the AOD, but at bandwidths approaching the full inhomogeneous bandwidth of 20 GHz, and using a 2-D scan aperture a raster scan with \(10^5\) spots and 200 KHz resolution should be achievable.

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