

Optical-Coherent-Transient Technologies For Wide-Bandwidth and Multidimensional Analog Optical Signal Processing

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Abstract

Optical-Coherent-Transient technologies offer solutions to the demanding high bandwidth and large time-bandwidth product parallel analog signal processing requirements of next generation RF arrayed systems. Novel approaches to true-time-delay beamsteering, correlating array receivers, frequency domain synthesis for arbitrary waveform generation, and adaptive processing for beamforming and jammer-nulling, and passive correlation-based antenna-array imaging are addressed. Wide-bandwidth capabilities in excess of 10 GHz and time delays of several microseconds are simultaneously achievable, providing time-bandwidth-products up to 100,000.

1. INTRODUCTION

Optical coherent transients (OCT) technology is ideally suited to address the high bandwidths (BW) and large time-bandwidth products (TBP) required in next generation RF signal processing systems. OCTs occur due to optical interactions in cryogenically cooled rare-earth doped crystals with narrow homogeneous lines and wide inhomogeneously broadened absorption lines. These interactions simultaneously allow for ultra-high spatial-resolution holographic processing and high spectral-resolution temporal processing. Wide-bandwidth capabilities in excess of 10 GHz and large time delays of 10 μ s are simultaneously achievable, providing a unique capability for extraordinarily large TBPs in excess of 10^5 at every spatially resolvable spot in the crystal.

Previous research involved investigation of the physics of these materials and demonstrated basic applications and capabilities, such as memory and signal correlation, with bandwidths of 40 MHz (limited by acousto-optic modulators) and TBPs of a few hundred. By using wider BW electro-optic modulators, chirped-pulse or spread-spectrum programming, accumulation, signal amplification and more sensitive and efficient OCT materials, a dramatic increase of system BW and TBP can be achieved. This paper outlines techniques to achieve the full potential bandwidth and TBP capabilities of OCT processing for demanding RF signal-processing applications. We present novel approaches to analog optical signal processing (AOSP) applications including 3-dimensional correlations, frequency domain synthesis for arbitrary waveform generation (AWG), true-time-delay (TTD) beamsteering for RF arrays, correlating array receivers, squint-free adaptive phased-array processing for beam forming and jammer nulling of large conformal arrays, and passive correlation-based antenna-array imaging for sparse 2-D arrays.

Multidimensional spatial-spectral holographic processing in the volume of the OCT materials and increased processing gain through time integration (through both analog and post-processing digital accumulation) provides large dynamic range (DR) over a wide bandwidth of operation. Most previous OCT material development has concentrated on memory applications. Current efforts concentrate on optimizing rare-earth ions in crystal hosts for broadband RF signal processing applications in order to further increase their bandwidth, achievable time delay, and sensitivity.

One apparent drawback to OCT processing is the need to cryogenically cool the materials below 10 K to achieve high levels of performance. But this cryo penalty is outweighed by the huge processing throughputs achievable even with only a small degree of parallelism. The enormous demand of the broadband, massively parallel computations required for large antenna-array processing provides a dramatic advantage to the OCT approach over digital signal processing - even including the cost and power penalty of the cryostat.

2. OCT APPROACH TO AOSP

2.1 Overview

OCT solutions offer the potential to simultaneously provide wide bandwidth (10 GHz), large time delay (10 μ s), high TBP (10^5) and processing gain and massive parallelism (10^6). The ability to burn spectral holes in the absorption band of cryogenically cooled, inhomogeneously broadened transitions (IBT) allows the holographic storage and processing of vast amounts of data due to their high spatial and spectral resolutions. Spatially, interfering optical beams produce local absorption changes with molecular resolution allowing high-resolution, volume holography. The spectral interference of two delayed coded waveforms engraves a periodic, spectral modulation of the excited state population of the IBT, which produces an OCT output when illuminated by a coded readout pulse.

The stimulated photon echo is the simplest OCT phenomenon. It is the basic building block behind all of our proposed applications. When two brief light pulses separated in time by τ_{21} illuminate an IBT, a spectral grating is formed (a spectral-spatial grating, if the beams are angled). The period of the spectral grating is $1/\tau_{21}$, which is recorded in the absorption spectrum as long as the coherence time $T_2 > \tau_{21}$. If a third brief pulse illuminates the medium, the grating spectrally filters this read

pulse and an echo is emitted τ_{2l} later. Since the IBT has a linear response over a broad dynamic range, the echo can be viewed as the impulse response of the OCT medium with programmed TTD. Thus, when illuminated by a RF modulated optical signal, the OCT response is a precisely delayed version of the optical waveform. More complex impulse responses can be recorded using the wide dynamic range and excellent spectral resolution of the crystal by changing the two programming pulses. For instance, if pulse 2 is temporally structured and pulse 1 is brief, the impulse response of the medium mimics pulse 2 delayed. If instead pulse 1 is a waveform, the impulse response is a delayed, time-reversed version of pulse 1. The medium can also be programmed with several sets of programming pulses -- the results being an accumulated superposition of the impulse responses of these sets. This type of programming can be used to make an OCT media perform AWG, TTD, correlation and convolution, and adaptive processing. The additional spatial holographic capabilities allow for isolation and coherent summing of the impulse responses, time-space image processing, phase conjugation, and angular or spatial multiplexing for array processing.

Two sequential temporally modulated beams $s_1(t)$ and $s_2(t)$ record a spatial-spectral interference pattern $S_1^*(\nu)S_2(\nu)$ in the IBT. When read out by beam $s_3(t)$, the echo output is given by the causal correlation-convolution integral [1-3] represented in the time or frequency domains as

$$o(t) = A \int_{-\infty}^t S_3(t_3) \int_{-\infty}^{t_3} S_2(t_2) S_1^*(t_2 + t_3 - t) e^{-2(t-t_3)/T_2 - (t_3-t_2)/T_1} dt_2 dt_3$$

$$\approx A \int S_1^*(\nu) S_2(\nu) S_3(\nu) e^{i2\pi\nu t} d\nu. \quad (1)$$

The correlation between signals s_1 and s_2 is written into a spectral grating in the material with a coherence-time windowing function. This is subsequently read out by a convolution with the readout s_3 . This triple product linear filter has extensively demonstrated and is the basis of the proposed systems discussed below [2-4].

The temporal and spatial characteristics of OCT media make OCT processing a perfect match for AOSP. Materials available today have bandwidths of 10 to 200 GHz, coherence times of 1 to 1000 μ s, and integration times of microseconds to seconds. As an example, Tm:YAG operating at 793 nm has 20 GHz bandwidth, 10 μ s coherence time, and 10 ms integration time, for a TBP of 200,000. The crystal optical quality is excellent, and readily allows for better than 100x100 imaging and parallel-channel array processing. Thus, currently available crystals have potentially huge space-time bandwidth products. The major present limitation to OCT processor performance is accessing the material's potential. Recently developed techniques and supporting technologies greatly facilitate unlocking the potential of OCT materials.

2.2 OCT True-Time-Delay

OCT processors can produce variable time delays of up to several microseconds with picosecond resolution on signals with bandwidths in excess of 10 GHz. Recent experiments have shown these aspects in part. First, OCT variable delay was demonstrated on a 4 GB/s signal using a pulsed laser and Tm:YAG. The measured bandwidth, 1 ps accuracy, and 7 ps resolution were all measurement limited, but frequency domain measurements

indicated 20 GHz of programmed BW was achieved [5]. Second, variable delay and processing with chirped programming was demonstrated [6]. This work focused on scaling up TTD systems to arrays with spread-spectrum/chirped-pulse programming to reduce power requirements. For chirped programming, there is the added ability to vary delays by varying the frequency offset

between the programming pulses, $e^{i2\pi f_0 t} e^{i\pi b t^2} = e^{i\pi b(t+f_0/b)^2} e^{-i\pi f_0^2/b}$. Precise delay tuning is reduced to frequency generation by this technique, so that no physical propagation delay is required. Typical results are shown in Figure 1, demonstrating simultaneous correlation and variable TTD. Third, chirps have been used to program wideband OCT TTD, where several microseconds of delay over a 2 GHz bandwidth was demonstrated [7].

We plan to demonstrate an OCT TTD processor with 10 GHz of bandwidth that is capable of handling several array elements and with specifications that match phased-array system requirements. Multi-casting capabilities will also be explored. Accumulation and refresh versus single shot programming further lowers the optical power requirements with high efficiency. With heterodyne detection of single-side-band, carrier-suppressed TTD, the instantaneous TTD bandwidth can be positioned anywhere from baseband to 100 GHz.

2.3 OCT Correlators

OCTs correlators hold the potential to process signals with greater than 10 GHz instantaneous bandwidth and TBP in excess of 10^5 . These correlators can coherently process phase and amplitude modulated signals, continuously in real-time, and combine temporal processing with conventional spatial Fourier processing to achieve huge space-time bandwidth products. Choosing $s_1(t)$ in Eq. 1 to be a correlation reference, $s_2(t)$ to be a brief pulse, and by reading out with an unknown waveform $s_3(t)$ produces a correlation $s_{out}(t) = s_1(t) \otimes s_3(t)$. However, this scales poorly to wide bandwidths because of the low energy in a brief pulse. Optical power requirements can be reduced by several orders of

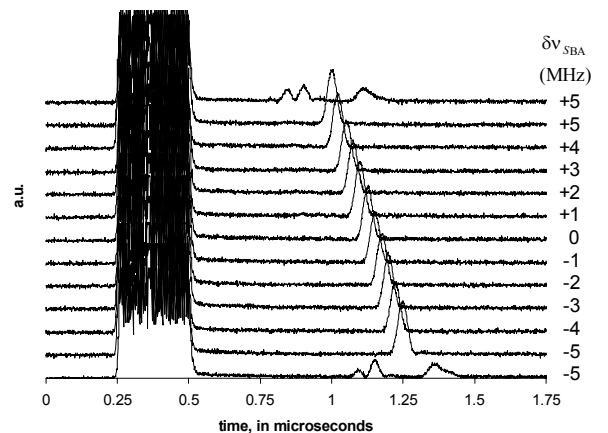


Figure 1. Experimental results of OCT variable TTD correlator using chirped pulse frequency shifting, demonstrating the frequency tuned time delays for use in linear array beamsteering. At +5 and -5 MHz, the time-reverse pattern was entered resulting in convolution of the pattern instead of correlation.

magnitude using accumulation and refresh techniques or by using spread spectrum codes or modulated chirped pulses, which add Fourier domain quadratic phase factors, $C_j(v)$, to the recording waveforms. When $C_1^*(v)C_2(v)C_3(v)$ is constant over the data bandwidth, the same correlation function is produced with lower power. Arbitrary spectral gratings can be programmed. This can be achieved in a generalized manner by using binary amplitude or phase modulated, spectrally dense codes, such that the desired analog pattern is effectively programmed without brief pulses. Amplification of the modulated waveforms (codes or chirps) significantly relaxes the power requirements. We have demonstrated faithful correlation of 30-bit codes at low bandwidths using AO modulators (limited to 40 MHz), and are currently in the process of demonstrating a 1 GHz correlator with a TBP of 1000. OCT correlators can operate at over 10 GHz and have huge space-time bandwidth products by combining the spectral domain (TBP = 10^5) with traditional spatial Fourier image processing. Coherent summing techniques can yield large processing gain without significant array power scaling penalties.

2.4 AOSP Using OCT Scanners

By recording the scanning function in an OCT medium, OCT scanners can be programmed to operate as acousto-optic (AO) deflectors, but with BWs over 10 GHz and TBPs over 10^5 . Time-domain recording of an impulse and traveling spot or stabilized frequency-domain recording of a chirped laser and tilting plane wave can be utilized [8]. The scan pattern can be a linear scan with up to 10^4 spots or a folded raster scan with a TBP of 10^6 .

Such an OCT scanner can be used for a broadband high-resolution (possibly folded) spectrum analyzer with high DR by using a logarithmic response CMOS detector. The interference between two counter-propagating OCT scanners can be accumulated on a detector array to form a time-integrating correlator with ~ 10 GHz BW, and processing gains of 10^7 . A counter-propagating pair of slowly chirped AO devices operating on the 2 scanned beams and propagating in the orthogonal direction to the 1-D scanner enables a high BW Doppler compensated correlation producing a 2-D time-integrated ambiguity function. These and other architectures based on the scanner functionality recorded in OCT media will be demonstrated and characterized for radar signal processing applications with TBP in excess of 10^5 and BW near 10 GHz.

2.5 OCT Arbitrary Waveform Generation

OCTs AWG can produce multi-GHz complex waveforms with TBP approaching 100,000, large bandwidth (10 GHz), and large dynamic range (12-bit), with arbitrary phase and amplitude control. These waveforms can be recalled continually on demand, and can be produced on a carrier frequency up to 100 GHz by heterodyne detection of a single-side-band waveform with a low phase-noise spectral-hole-locked tunable-reference laser. The spectral interference of a brief pulse with a waveform will allow it to be replayed using another brief pulse as in time-domain memory applications, but replacing the pulses with chirps or other matched broadband codes could yield far better efficiency. A series of programming pulses can be used to specifically craft the appropriate grating that can then be used to create the optical waveform. The OCT material can also be used to create and capture an arbitrary waveform with adaptive feedback loops.

2.6 OCT Array Processing

OCTs are ideal for large, wideband, antenna-array processing. The narrow homogeneous linewidths (10 kHz) provide a capability for large time delays (10 μ s of delay is needed for squint-free TTD processing of arrays 3 km across), high bandwidths of 10 GHz or more, and simultaneous high spatial resolution readily handles 10^6 elements. These capabilities enable TTD array processors for beam-steering, spatio-temporal adaptive processing, adaptive nulling, and RF imaging. We're exploring both adaptive beam forming and jammer nulling based on the isomorphism between the OCT integral representation and the LMS adaptive array algorithm and the capability to form high resolution images through correlation based processing.

There is a strong similarity between the OCT signal formation and the time-delay-and-sum correlation-cancellation-loop adaptive beam forming (ABF) algorithm for signals $s_j(t)$ from the j th element of an antenna array

$$o(t) = \sum_{j=1}^N \int_0^{T_A} s_j(t-\tau) \int_{-\infty}^t s_j^*(t_1-\tau) f(t_1) dt_1 d\tau \quad (2)$$

where the feedback signal is $f(t_1) = d(t_1) - o(t_1)$. In this algorithm, each antenna signal is correlated with the feedback error signal. The results are convolved with the antenna signals and summed over all elements. It can be shown that the OCT output is the desired correlation-convolution adaptive filter for array processing with additional smooth windowing. The broadband real-time capabilities of this OCT array processing greatly exceed the capabilities of alternative array-processing systems.

2.7 OCT Passive RF array imaging

Lens-less RF imaging using sparse, random, antenna arrays is exceedingly computationally demanding, requiring a cross correlation between every antenna signal and every other signal as the frequency dependent coefficient of a component in (\vec{k}, ω) - space determined by the element separation and frequency. Spatial Fourier transformation of the samples in (\vec{k}, ω) - space at each frequency forms a monochromatic RF image, which can be detected, and different frequency component images are scaled proportional to their RF frequency and summed. A novel OCT based AOSP solution to this demanding application can use a fiber-fed, coherently-modulated array cohered with a photorefractive crystal. The cohered output is spatially Fourier transformed with a lens onto a thin OCT crystal, in which each pair of antennas interferes and accumulates a spatial-spectral grating with \vec{K}_G -vector proportional to their separation. After accumulating for about the bottleneck lifetime T_B , a frequency scanned plane-wave laser reads out the gratings that are Fourier transformed and detected on a CCD array. As the laser frequency is scanned, the system magnification is synchronously varied over a range corresponding to the bandwidth ratio of the maximum to minimum RF frequencies. Time integration of these multi-frequency images on the CCD followed by digital accumulation can produce high DR images after a few seconds, or time varying images at video rates. Such a system could be designed for the Allen Telescope Array with 360

elements operating at 1-10 GHz by using a rapidly zoom-able 10:1 zoom lens.

2.8 OCT Material Development

OCT processor performance is dependent on the spectral properties of OCT materials, and optimized performance requires fine-tuning of these properties for each application. Optimized parameters can vary considerably from application to application. Two examples are Tm^{3+} (793 nm) and Er^{3+} (1536 nm) materials that have TBP's up to 10^8 and bandwidths up to 200 GHz. TBP is limited by the ratio of inhomogeneous to homogeneous linewidths. The bandwidth is determined by inhomogeneous linewidth and oscillator strength. The coupling between bandwidth, wavelength, storage and coherence decay times, branching ratios, phonon relaxation, and spectral diffusion all must be understood to reliably predict and optimize processor performance.

Montana State University together with the Scientific Materials Corporation have developed several techniques that enable them to tune specific material parameters while maintaining a high degree of control over other material parameters, providing excellent potential for OCT device performance. Most previous OCT material development has concentrated on memory applications. Our concentration is to optimize rare-earth ions in crystal hosts for broadband RF signal processing applications in order to further increase their bandwidth, achievable time delay, and sensitivity. The development of higher oscillator strengths will directly lead to further improvements in the photon budget. Recent developments in stabilization of lasers to OCT crystals, amplification, wideband materials, improved OCT crystal parameters, multi-GHz OCT demonstrations, and programming of gratings with wideband EO modulators set the stage for practical OCT RF signal processing solutions.

3. RESULTS

We have assembled our test facility for evaluating broadband OCT programming. Material preparation for growing new Tm^{3+} and Yb^{3+} doped crystals has been completed. The initial spectroscopic study of the first Yb:YAG indicates a factor of 2.4 improvement in oscillator strength over Tm:YAG. We plan to present results of 6 Gb/s processing in Tm:YAG, further progress

in OCT material development, and developments in the demonstration and performance of various OCT processors.

4. ACKNOWLEDGEMENTS

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