Demonstration of the Spatial-Spectral Coherent Holographic Integrating Processor (S^2-CHIP) for analog RF signal processing applications

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Abstract

The overall design and an experimental demonstration of the S^2-CHIP, a broadband electro-optic analog signal processor, are presented. The device performs coherent signal processing and integrates multiple correlative acquisition pairs with bandwidths of several GHz and resolves time delays of microseconds with high precision and large dynamic range. High resolution Doppler processing is achievable. Application areas include radar, lidar, and radio astronomy.

1. INTRODUCTION

In a radar range processing system, an optimally encoded RF waveform is transmitted and an antenna receives the scattered target signal that is delayed, attenuated and buried in a noisy background. An analog correlation of the received and reference signals yields the round-trip delay and thus the target's range. Coherent integration of multiple returns increases signal strength and allows for target velocity determination. A spatial spectral (S^2) holographic signal processor has been recently developed as a core-component for a high bandwidth radar-signal processing system [1]. The S^2 material lifetime enables integration of multiple correlative results for range and Doppler processing.

In this paper, we discuss the overall design and preliminary experimental results. These results show the ability to perform range correlation on large data rate (1 Gb/s) biphase-shift-keyed patterns in an S^2 material, Tm:YAG. Results include (1) time delay and range resolution (2) coherent integration of spectral correlations as applied to a radar range processor and (3) dynamic pattern programming.

2. S2-CHIP DESIGN

2.1 Overall concept

The Spatial-spectral Coherent Holographic Integrating Processor, or S^2-CHIP, performs coherent signal processing operations on analog, high bandwidth, and large time bandwidth product optical signals, and integrates the results of multiple acquisitions. Coded RF signals are modulated on a stable optical carrier for processing. A single coherent correlation occurs between two signals in the S^2 material, such as a reference signal and a return signal or, two signals received at different antennas. The S^2-CHIP can determine the delay between these two (or more) signals, while at the same time analyzing Doppler shifts introduced from target movement. The integration of multiple correlation signals relies on the short-term persistence of the S^2 material.

The practicality of the device comes from the fact that the input signals being processed can be of very high bandwidth, while the resultant output signal is low bandwidth. This eliminates the optical-to-electronic bottleneck in the overall device performance.

2.2 Applications / Insertion point

The S^2-CHIP is a coherent integrating processor that could be inserted into several systems requiring high performance evaluation of signals. These include:

<u>Active Radar</u>
- Single-element or large multi-element phased arrays
- Range, mid to high Pulsed Doppler
- Detecting and locating stealth communications
    - Including frequency hopping radio

<u>Radio Astronomy Signal Processing</u>
- Analyzing radio astronomy signals
- Search for Extra-Terrestrial Intelligence

<u>LIDAR and Laser Radar:</u>
- Atmospheric monitoring / wind shear measurements
- Space-based tracking of satellites or other targets

2.3 Design and operation

The device has a stabilized external cavity diode laser (ECDL) as a source for generating a cw optical carrier on which to transmit information. The cw carrier is modulated to create optical pulses to carry the RF modulation of the radar to the crystal. The modulation from the RF domain to the optical domain is achieved by electro-optic phase modulators that change the optical carrier phase in proportion to the sign and magnitude of the applied RF voltage. One modulator is used for the reference waveform, and another one for the received signal from the radar. The S^2 crystal responds to the power spectrum of the optical inputs and stores a S^2 grating. This grating contains the information about the target in terms of the amplitude, frequency and phase variations. The grating is the result of multiple series of optical inputs.

A chirp EOM is used for reading out the S^2 grating. This modulator frequency scans the cw carrier slowly over the stored grating, where it experiences frequency dependent absorption, thereby mapping the programmed spectral features. The output signal is detected by a high sensitivity photoreceiver. This low bandwidth optical to electrical conversion generates a low bandwidth analog electrical signal that is digitized with an high performance low bandwidth A/D converter and rendered digitally for post-processing and analysis.

For range Doppler processing, the key idea is to combine aspects of spatial multiplexing to create a bank of parallel filtering operations. In each spatial location, Doppler processing would occur with a shifted carrier frequency for the reference waveform, where accumulation occurs when the carrier and Doppler shift match. In short, the spatial spatial location with the strongest accumulation signal would represent the frequency closest to that experienced by a Doppler shift. An array of dectectors and A/D converters is used.

2.4 Components

2.4.1 Frequency stabilization of external cavity diode lasers

Laser stability is an important consideration, since the system performs coherent processing and the phase stability of the optical carrier could limit the system performance. Research groups at MSU have pioneered frequency stabilization of cw ECDLs to narrow, transient spectral holes as frequency references burned in an S^2 material. [2] ECDLs have been stabilized to 20 Hz precision at 793 nm using Tm:YAG – an achievement of 2 parts in 10^{13}. These levels of stabilization are more than sufficient for a successful implementation of a commercial S^2-CHIP.

2.4.2 Electro-optic modulators E/O and RF electronics

The telecommunications industry has made available high quality components for optical transmission windows through optical fibers at 800 nm, 1300 nm, and 1550 nm, and the associated electronics to drive these systems. These electro-optic modulators and electronics are commercially available off-the-shelf components, with typically specified properties that are ideally suited for use in an S^2-CHIP. Both digital and analog RF driving electronics up to 12 Gb/s are available.

2.4.3 Broadband optical amplifiers

Amplification of broadband phase and/or amplitude modulated optical signals is required for parallel processing. While erbium doped fiber amplifiers are commercially available at 1550 nm, there is no such widely commercially available amplifier system at 793 nm due to a lack of leverage in the marketplace. There are 3 present options for amplification, 1. Injection locking, 2. Semiconductor optical amplifiers, and 3. Raman fiber amplifiers. Research groups at MSU have developed amplification using injection locking of a high power diode laser near 800 nm up to 6 Gb/s [3]. Injection locking is being used in our demonstrations, but other options are being investigated.

2.4.4 S^2 materials

Collaboration between Spectrum Lab, MSU Physics Department and Scientific Materials Corporation has led to the growth, characterization and utilization of high quality S^2 materials. Material parameters of specific interest include, inhomogeneous linewidth (sets system bandwidth), oscillator strength (sets bandwidth and power consumption), material coherence time (sets coherent processing duration), grating lifetime (sets integration time), crystal orientations (determines efficiency), and spectral diffusion (can reduce performance). While materials can be designed and further optimized for future applications, currently available materials can be used to make practical devices. The two material systems of greatest interest for the proposed work are Tm:YAG (0.1 at. %, 793 nm transition) and Er:YSO (0.001 at. %, 1536 nm transition), each offering a 10 ms integration time, and 30 GHz of bandwidth.

2.4.5 Cryocoolers

The S^2-CHIP system requires a compact cryocooler at 5K with a low level of vibration on the 10 Hz time scale. Reliable, turn-key, maintenance-free, closed cycle cryocoolers are currently commercially available for 0.5 W operation at 3.6K and 1.0 W at 5K. A watt of cooling power would handle multiple (~1000) beams in one material sample. The PT4-5 pulse tube cyrocooler available from Cryomech Corp. offer the best combination of specifications, with vibration levels at 20 mm on the 1.4 Hz time scale. The PT405 will be used in the next S^2-CHIP demonstrator. Efforts continue to dampen small vibrations, and sub-3 μm displacement is possible. Present day cryocooler efficiency is currently 10 kW/W (10 kW wall power per 1 watt cooling power). When compared to the power drawn by comparable parallel digital processing systems, this cryo-power penalty becomes insignificant. In the next five years, the market for 4 K cryocoolers is expected to push performance higher while reducing cost due to their use in new magnetic resonance imaging units. A forecast from cryogenic experts for 2008 is that a 1.0 W at 4K pulse tube cryocooler will sell for half the current cost ($20k vs $40k) with twice the efficiency, a more compact design, less vibration, and higher reliability.

2.4.6 Frequency swept laser pulses

The S^2-CHIP system will utilize a frequency swept laser pulse to readout the grating, which can be created with an electro-optic element either external or internal to the laser cavity. Either of these methods could be used and are being presently explored.

2.4.7 Photoreceivers and A/D converters

The readout process leverages the enormous performance and cost advantage of using low bandwidth photoreceivers and analog-to-digital converters. A photoreceiver would need only a 1 MHz bandwidth and, near 800 nm using a Si photoreceiver cell and transimpedance amplifier, the dynamic range could exceed 90 dB. Current off the shelf analog-to-digital converters at 2.5 MS/s have specified 16-bit quantization performance. Such devices enable the full use of the processing material's dynamic range.

2.5 S^2-CHIP device features

The device using a currently available S^2 material, Tm:YAG, offers analog signal processing applications the following:

- Large signal processing bandwidths (30 GHz)
- Large time bandwidth product signals (>1000)
- Analog waveform processing
- Large dynamic range
- Pulse repetition frequencies from ~1 kHz – 1 MHz
- Coherent integration over 10 ms, up to 1000 shots
- Doppler shift resolution of ~ 100 Hz
- Agile coding ability (transmitted waveform changes from shot to shot)
- Reconfigurability on the ~ms timescale

3. THEORY FOR EXPERIMENT

The present demonstration was done in context of a radar range correlator. Future work will focus on high PRF Doppler processing in a similar context. To summarize, in radar range and Doppler processing applications, a pulse sequence is transmitted and the received signal is delayed, attenuated, and buried in noise after being reflected by a target. Correlation between the return and transmitted signals yields the round-trip time of flight as a delay τ. When the reference and return signals are modulated onto the same optical carrier, an S^2 processor records their spectral interference with a modulation period $1/\tau$. The S^2

material's persistence time allows for coherent integration of multiple acquisitions. Integration of N coherent correlations increases the intensity of the correlation peak by N^2, while the noise grows as N. The integration time also provides resolution for frequency analysis of return signals to determine Doppler shifts from a moving target according to its velocity.

Readout was performed with a low power transmitted chirp pulse which experiences frequency dependent absorption. The resultant signal is detected, A/D converted, and post-processed to extract delay information. The chirp rate should be less than $(1/\tau_m)^2$ where τ_m is the maximum resolvable delay, in order to ensure sufficient spectral resolution. For example, if the chirp rate is 1.0 MHz / μs, then for 1 GHz grating bandwidth the latency is 1.0 ms, and the required detection bandwidth is 1 MHz.

For the experimental demonstration, each programming shot consisted of an M-bit bi-phase shift keyed (BPSK) waveform (i.e. radar reference signal) and a single time delayed replica (i.e. radar return signal), where a unique pulse pair n = 1, 2, …N was introduced at the pulse repetition frequency (PRF). The delay is fixed for all shots. Dynamic coding was performed, where each programming shot contains a unique, zero-mean BPSK waveform and its time delayed replica. Using dynamic codes in coherent integration enhances the primary frequency component while the other spectral features (e.g., temporal sidelobes) change each shot.

4. EXPERIMENTAL RESULTS

4.1 Summary

Results on (1) time delay and resolution (2) coherent integration of spectral correlations and (3) dynamic pattern programming are presented. An optical beam stabilized to sub-10 kHz over 10 ms by locking to a transient spectral hole in Tm:YAG [2], was electro-optically encoded and amplified with injection locking [3] before irradiating the S^2 material. This demonstrator system has been assembled and utilizes existing technology and materials.

4.2 Experimental setup

Figure 1 shows the main components of the experimental setup. A cw Ti:Sapphire laser was centered at 793.380 nm and frequency stabilized to a transient spectral hole in one spatial location of a 4 mm long Tm:YAG (0.1 at. %) sample at 5.0 K. The stabilized laser was split into two beams for processing and readout. The processing beam was modulated by an electro-optic phase modulator (EOM) driven by a pulse pattern generator. The light was continuously BPSK modulated, such that each pattern was modulated at 1 Gb/s and between any patterns the light was square wave (…101010…) modulated at 1 Gb/s. After modulation, the processing beam was amplified by injection locking a high powered slave diode laser. The readout beam was modulated by an acousto-optic modulator (AOM) driven by an arbitrary waveform generator to create a linear frequency chirped pulse around a 265 MHz carrier. A cube was used to combine the beams, which were focused to a ~50 μm spot in the sample. The beams were then incident on a 125 MHz photodetector.

For all experiments, the processing waveforms were 512 bits (512 ns) BPSK sequences and the PRF was 100 kHz. The processing beam power was 2.5 mW. The readout beam power was 100 μW and chirped over ~40 MHz at a rate sufficient to resolve the longest time delay. Higher readout bandwidths will give larger dynamic range.

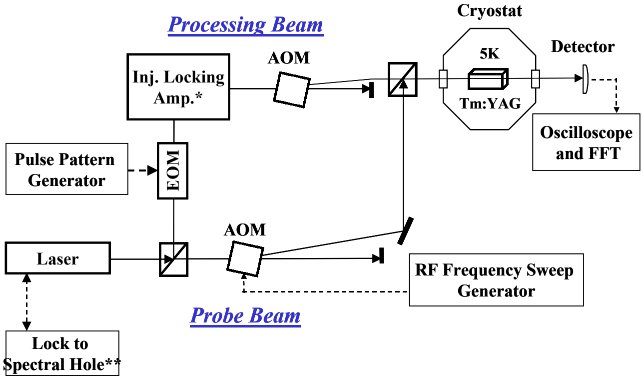

Figure 1 Depiction of basic demonstrator system used. * Injection locking optical amplifier; **Frequency locking the laser linewidth to a transient regenerated spectral hole, technologies developed at MSU.

4.3 Results

Figure 2 shows the results of processed time delay profiles ranging from 0.6 - 1.0 μs that were extracted from the power spectrum of transmitted readout signal. Plotted is the log magnitude squared of the Fast Fourier Transform of the data. The peak widths depend on the readout bandwidth and the peak signal decreases with increasing time delay due to finite material coherence time. Under these conditions, dynamic range >40 dB and range jitter <1 ns were observed. Higher temporal resolution and dynamic range is expected at higher readout bandwidths.

For coherent radar returns, integrated signal processing leads to signal enhancement and noise averaging. Figure 3 plots the calculated RMS values for the peak strength versus the number of programming shots (log-log scale), with a fixed delay (1 μs) with four different powers in the processing beam, each varying in factors of 2. The processing powers were 2.5 mW, 1.25 mW, 0.625 mW and 0.3125 mW. Each data set shows that the

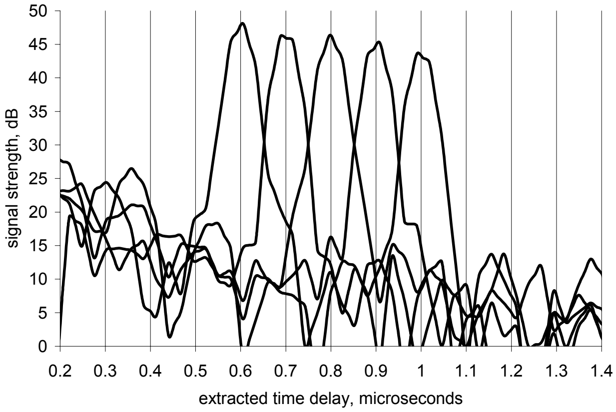

Figure 2 Time delay over 0.6-1.0 μs, showing 40 dB dynamic range. The processing sequences were repeated for 200 shots at 100 kHz, where each shot consisted a unique dynamic 512 bit pattern with 1 Gb/s BPSK modulation and its delayed replica.

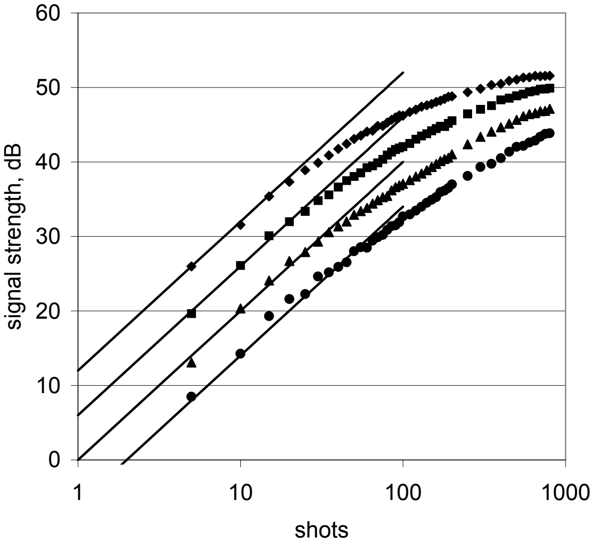

Figure 3. Accumulation dynamics rms peak signal strength versus N programming shots for 2.5 mW programming power (top curve) and decreasing factors of 2 in power versus ideal coherent accumulation N^2 (solid lines).

processed signal strength initially grows ideally as the square of the number of shots, as expected, but then exhibits power dependent roll-off due to saturation before reaching a steady state. In general, for lower power more shots can be ideally coherently integrated. For 0.3125 mW, the satuation point is roughly 85 shots, while for 2.5 mW it is roughly 15 shots. When the power was raised to 5 mW (not shown here) the integration varied, indicating coherent saturation of the individual processing shots.

Dynamic or agile coding is a desirable feature for advanced radar systems. Figure 4 shows the evolution of the signal and side-lobe strengths for agile and single pattern programming. The signal growth for both is nearly identical. But, while the fixed side lobes of single pattern grow with the signal, the varying side-lobes of dynamic patterns average out. An enhancement ~25 dB in the dynamic range under these conditions was achieved by using dynamic coding at 800 shots.

The performance of these preliminary demonstrations begin to show the necessary bandwidth, frequency resolution, integration time and dynamic range required for modern high performance radars. Further increases in processing and readout bandwidths are being implemented along with range-Doppler processing.

5. SUMMARY

In summary, coherent signal processing and integration of up to 800 dynamically changing shots was demonstrated. The processing data rate was 1 Gb/s. The demonstration used an Tm doped YAG crystal held at 5.0K, a frequency stabilized continuous wave laser, commercially available telecom components, and a low-power chirped pulse probe. Time delays of 0.6 to 1.0 μs were programmed and extracted. We believe that the techniques introduced here represent substantial progress towards a practical, high performance, multi-GHz, analog coherent integrating temporal processor.

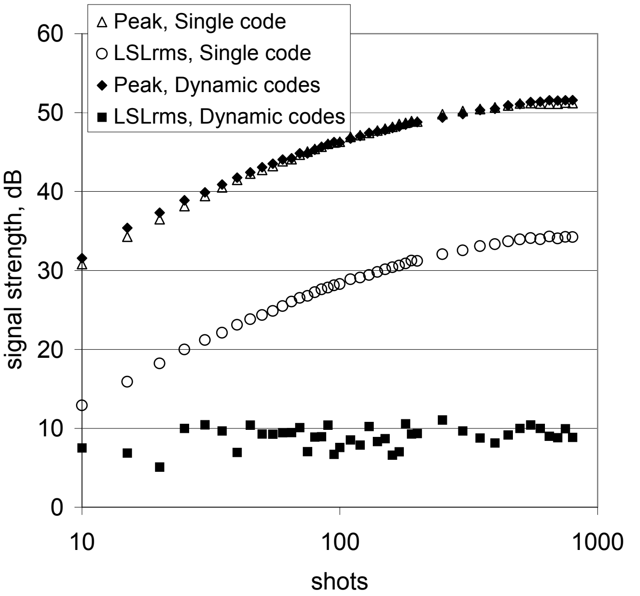

Figure 4. The effect of agile processing with dynamic patterns is shown. The 'Peak' and the calculated rms left sidelobe 'LSLrms' values are plotted for both agile programming with dynamic patterns and accumulation with fixed pattern.

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8. BIBLIOGRAPHIES

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