Range-Doppler Imaging Using an Analog Optical Signal Processor with Agile Waveform Sets

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***Abstract* — A range-Doppler radar signal processor based upon a spatial-spectral holographic analog optical signal processor is discussed. Such a system has a variety of advantages over conventional range-Doppler signal processors including increased instantaneous bandwidths (>20 GHz), enhanced dynamic range over those bandwidths, and the ability to process a variety of wideband radar waveforms directly at the radar carrier frequency without down conversion. Range-Doppler ambiguity functions are measured showing range resolution <15 cm, Doppler resolution <130 Hz, and >15 dB enhanced imaging due to agile waveform sets.**

***Index Terms* — range-Doppler correlation; analog optical signal processing; spatial-spectral holography.**

I. Introduction

There is a need for flexible range-Doppler radar signal processing systems that can perform matched filtering in real time and provide enhanced discrimination performance. Such systems should be capable of processing a wide variety of waveform sets, be capable of handling large instantaneous bandwidths, and process with high dynamic range any signal ranging from baseband to beyond the K-band.

In a traditional range-Doppler radar system, a coded waveform modulated onto a carrier first passes through a series of amplification and down-conversion stages, each with their own distortions, before being fed to an analog to digital converter (ADC). After digitization, post processing is utilized to determine the range and Doppler shift of the target. Unfortunately, in order to improve the performance and discrimination of the radar systems, both increased bandwidths and enhanced dynamic range of the processed signal are needed. The performance of typical ADC's suffers in dynamic range at higher sample rates, as is well known [1], with an approximate slope of -1 dB per octave of bandwidth. Despite much active research, this trend has not seen significant improvement, with the current state having a specification of 3 or 4 signal-to-noise ratio (SNR) bits at 20 to 40 Gs/s [2,3]. It is this dynamic range limitation, which ultimately limits the use of a variety of pseudo-random noise (PN) coding sets [4,5], which can enhance the discrimination capabilities of current range-Doppler radar systems, especially when used at extremely wide bandwidths.

Photonic approaches to performing analog signal processing functions offer the potential to alleviate many of the restrictions inherent in a traditional receiver chain and allow the use of a wide variety of radar waveforms. Our approach [6-8] offers a photonic processing device where the RF/microwave signals at the antenna are directly up-converted onto an optical carrier and then processed, rather than being down-converted and digitized. Here the optical processing is handled by spatial spectral (S2) materials, which offer broadband, high dynamic range, real time processing, based upon the ultrawide absorption response of ensembles of narrow linewidth rare earth ions doped into crystalline host lattice. These S2 materials, in combination with other commercial-off-the-shelf components, can actively perform matched filtering on a variety of complex waveforms in real time to determine delays between waveforms (range processing), as well as coherently integrate multiple results to increase the signal-to-noise ratio and determine frequency shifts between waveforms (Doppler processing). Our system has recently shown better than 4.5 cm range resolutions and Doppler resolutions better than 125 Hz [7,8].

In this paper, we utilize an optical processor to experimentally measure the range-Doppler ambiguity function of diverse sets of PN coded waveforms specifically designed to improve the range-Doppler image. Here the 378.13 THz optical transition of a cryogenically cooled S2 material was utilized to process these waveform sets without down conversion. Experimental results shown here include range resolutions of 15 cm, Doppler resolutions of 130 Hz, and a 15 dB improvement in the ambiguity functions over previous results. We also examine and demonstrate >15 dB image enhancement capabilities of agile PN coded pulsed waveforms where the code changes for each shot compared to identically coded pulses where the codes do not change.

II. THEORETICAL BACKGROUND

The optimal solution to the range-Doppler signal processing problem is to perform a matched filtering operation on the received signal [9]. Following the analysis in [4], let the transmit waveform be written as,

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$\psi_T(t) = g(t)e^{i2\pi\nu_{RF}t}$ where $g(t)$ is the complex envelope of the transmit signal that has been modulated onto the RF carrier frequency, ν_{RF}. Then the receive analytic waveform, within a range dependent phase factor, can be written as

$$\psi_R(t) = \alpha g(t-\tau_R)e^{i2\pi(\nu_{RF}+\nu_R)(t-\tau_R)}, \qquad (1)$$

where τ_R and ν_R represent the two unknowns, the round trip delay and the Doppler shift from the target, respectively, and α is an attenuation factor. To process the waveform, a matched filter is used [9], matched to a reference waveform given by $\psi_Z(t) = g(t-\tau)e^{i2\pi\nu_Z t}$, where $\nu_Z = \nu_{RF} + \nu$ is a frequency close to ν_{RF} and ν is a small detuning frequency. The output from this filter, with respect to the time when the filter was designed for maximum output, is proportional to $\chi(\tau-\tau_R, \nu-\nu_R)$, which is known as the matched filter response [9] or ambiguity function [4] and is given by

$$\chi(\tau', \nu') = \int_{-\infty}^{\infty} g(t)g^*(t-\tau')e^{-i2\pi\nu' t}dt. \qquad (2)$$

Implementing such a filter (or set of filters) in real time for a variety of complex, frequency agile, broadband waveforms, without any down-mixing is a major challenge for modern radar systems. Our analog optical signal processor can solve this problem, in real-time with high dynamic range.

S2 materials are by definition inhomogeneously broadened atomic absorbers (typically in the visible to infrared region of the spectrum), where the homogenous linewidth defines the spectral resolution and the inhomogeneous linewidth represents the instantaneous processing bandwidth. Most of the recent advances in S2 technology have happened in rare-earth ion doped systems [6-8], where spectral resolutions of 1 to 10 kHz

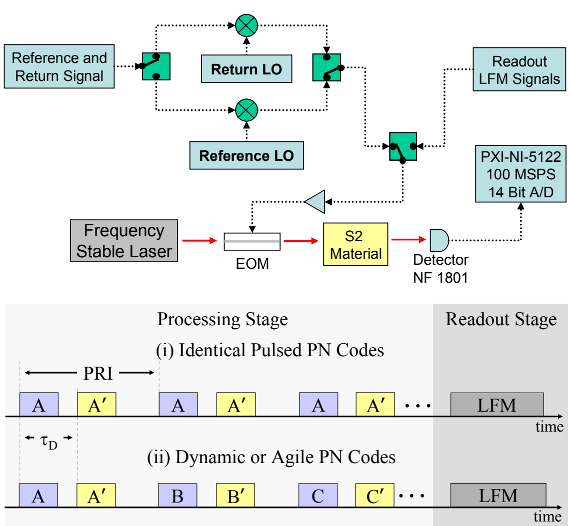

Figure 1. (Top) Experimental schematic showing the RF and optical pathways. (Bottom) A diagram showing the processing and readout stages for two types of coding sequences, (i) identical pulsed PN codes and (ii) agile PN codes, which change shot to shot.

are easily achievable with instantaneous bandwidths greater than 30 GHz, giving effective time-bandwidth products greater than 10^5. These materials process and store their results in the frequency domain, with the upper state lifetime dictating the length of time over which integration, a process where multiple processing results can be coherently combined, and a readout process must occur. It is these unique processing capabilities that make S2 materials well suited to the range-Doppler signal processing problem.

To perform range-Doppler signal processing with S2 materials [7], a reference waveform, given by $\psi_Z(t)$, and the received waveform, given by $\psi_R(t)$, are directly modulated onto a frequency stable optical carrier, through the use of an electro-optic phase modulator (EOPM), without down conversion. The up-converted waveforms, $E_Z(t)$ and $E_R(t)$ representing the reference and the return waveforms modulated onto the optical carrier, subsequently irradiate the S2 material and the combined power spectrum of these waveforms over their full bandwidth is recorded as the square of the sum of the electric field amplitudes, which follows as

$$\begin{aligned}|E_{ZR}(\omega)|^2 = |E_Z(\omega) + E_R(\omega)|^2 = |E_Z(\omega)|^2 + |E_R(\omega)|^2 + \\ E_Z^*(\omega)E_R(\omega) + c.c.\end{aligned}, \qquad (3)$$

where $E_Z(\omega) \leftrightarrow E_Z(t)$ and $E_R(\omega) \leftrightarrow E_R(t)$ denote the Fourier transforms of each waveform. The interference term represents a matched filtering operation between the reference waveform and the return waveform, whose impulse response is proportional to $\chi(\tau-\tau_R, \nu-\nu_R)$.

In essence, the S2 material acts as a real time programmable matched filter, where the desired waveform to match must simply illuminate the material prior to the arrival of the return waveform. In general, this matched filtering operation can be applied to a variety of modulation schemes, where all that is required is that the reference and the return illuminate the waveform within the coherence time of the medium and that the up-converted waveforms be within the inhomogeneous absorption band.

In order to retrieve the stored results, an appropriate linear frequency modulated (LFM), or chirped, optical waveform is used [6-8]. This allows a wideband temporal map of the spectral features to be created in a manner that generates relatively low bandwidth optical intensity modulation, which can be photodetected and digitized with large dynamic range (e.g. a digitizer with 14-16 bits at 100 Ms/s). The apparatus used to create a broadband optical frequency chirped pulse included an EOPM driven by a digitally chirped RF source [8].

III. Experimental Demonstrations

Figure 1 (top) shows the experimental setup that was utilized for demonstrations. A frequency stabilized optical carrier at the 378.13 THz Tm:YAG transition is utilized as the source. Laser light was coupled into a single EOPM that was used to modulate the light with RF waveforms for processing (reference and return signals) and for creating the chirped optical waveform for readout (in a collinear geometry).

After the EOPM, the light is focused to a ~100 μm spot at the center of the 14 mm long Tm:YAG crystal with a 0.05 atomic percent doping level of Tm, which was cooled to 4K inside an optical cryostat. The transmitted light is subsequently collected with a lens and focused onto a low noise AC coupled photodetector (New Focus 1801), and digitized at 100 MSPS with 14 bits of vertical resolution (National Instruments 5122).

As shown in Figure 1, proper timing of a fast switch allowed signals to be applied to the single EOPM in two stages, the processing and then the readout stage. For processing, PN codes were created by a pulse pattern generator (PPG) and a set of fast switches was utilized to drive the reference and the mock return pulses to different mixers each driven by a controllable RF local oscillator (LO). Here the return LO is driven at $\nu_{RF} + \nu_R$, chosen to be 2.9 GHz, to mimic a Doppler shifted S-band signal and the reference LO is driven at ν_Z. The processing stage, illustrated in Figure 1 (bottom), consisted of a set of PN coded pulses, where each pulse was 1450 bits in duration at a data rate of 1 GBPS, each pulse had a delayed replica at a delay of τ_R=1.5 μs, and the set consisted of either 2500 identical or agile coded pulse pairs at a pulse repetition frequency (PRF) of 333.33 kHz, giving a total waveform duration of ~7.5 ms. The mimicked return pulse was frequency shifted by otherwise identical to its respective reference pulse. The RF signal for readout was an LFM tone that was created digitally with a second PPG at 12 GBPS.

In order to map out the ambiguity function given by (2), a hardware control routine was developed that allowed first the processing stage for a given reference carrier ν_Z, then the readout and data storage stage, followed with a delay to allow the spectral features to fully decay away (~100 ms). The routine then stepped the reference carrier frequency by a small amount (typical increments ranged from 1 Hz to 100 Hz) and then repeated the processing stage for the new carrier. The reference carrier was stepped over a wide range of frequencies to allow ample sampling of the ambiguity function in regions of interest. This approach worked well for laboratory conditions, while an actual field deployable device could utilize the spatial degrees of freedom in the S2 material to implement parallel Doppler processing as discussed in [7].

Figure 2 shows range profiles for the matched Doppler case, $\nu = 0$ Hz, where the top left plot shows the processing result for the identical PN coded pulses, and the top right plot shows the processing results for the agile PN coded pulses. In the identical PN coded case, code dependent temporal sidelobe structure is apparent at ~30 dB down from the peak, limiting the ability of the system to image weak returns that would fall within such structure. However, in the agile PN coded case, the S2 material performs a unique matched filtering operation for each shot, and through the integration of different sidelobe structure for each shot, improves and enhances the imaging capabilities of the system [4,5]. For this

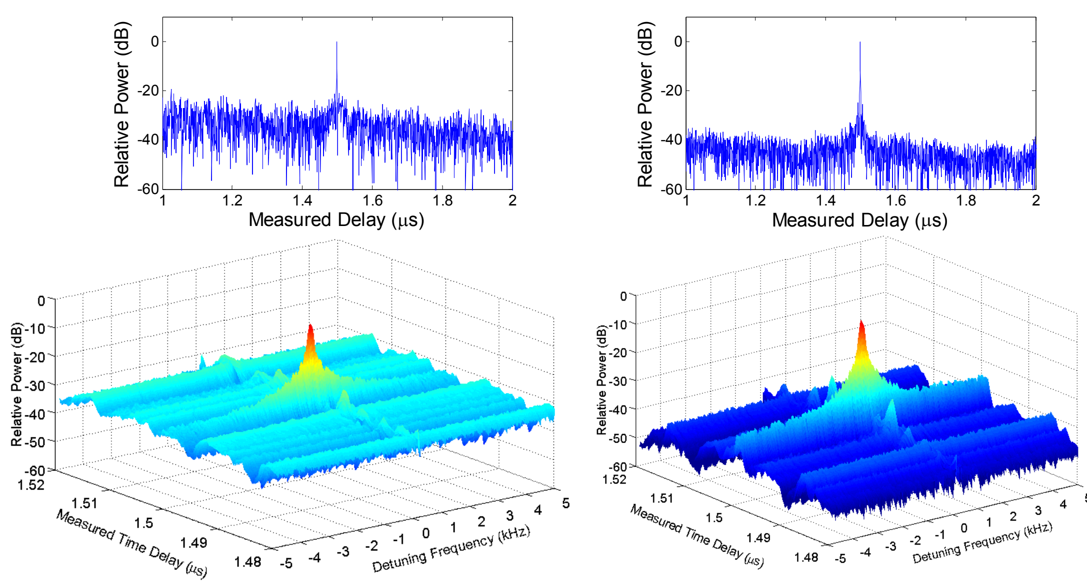

Figure 2. (Top) Experimental range profiles for the matched Doppler case, $\nu = 0$ Hz and τ_R = 1.5 μs, (top left) for a set of identical coded PN pulses with a peak to sidelobe ratio of ~30 dB and (top right) for a set of dynamic coded PN pulses which improves the peak to noise ratio to ~43 dB. (Bottom) Full ambiguity functions where the detuning frequency, ν, is stepped in increments of 10 Hz around zero Doppler, with delay of 1.5 μs, (bottom left) for the set of identical coded PN pulses and (bottom right) for a set of agile coded PN pulses. Through comparison, a substantial improvement of 15 dB in the range-Doppler image is seen, due to the enhanced discrimination capabilities of the agile waveform set.

agile coding, the actual sidelobe structure is expected at an RMS relative power level of -65 dB, which is below the experimental noise floor of ~ -50 dB.

Using the control routine described above, the ambiguity functions were captured for both of the coding scenarios. The bottom plots of Figure 2 show these ambiguity functions for (left) the identical PN coded case and (right) the agile PN coded case. The detuning frequency was stepped in 10 Hz increments around zero Doppler to ±5 kHz and a narrow range window of 100 ns is shown. The enhanced discrimination capabilities of the agile coded waveforms are apparent with a better range-Doppler image as compared to the identical coded range-Doppler image, an improvement of ~15 dB.

Repetitive pulsed range-Doppler radar systems have a Doppler ambiguity at the PRF. As the duty cycle of the pulsed PN coded waveform increases, the waveform begins to act more like a continuous pulse, removing the Doppler ambiguity while maintaining high Doppler resolution. Also, the broadband and agile nature of the PN coding provides unambiguous range while maintaining high range resolution. In these demonstrations, the duty cycle was nearly 50%, and the ambiguity in the Doppler domain begins to be reduced. This is apparent in Figure 3, where the top plot shows the zero Doppler match and the ±1 PRF ambiguities for the peak delay at 1.5 µs, where the ±1 PRF ambiguities are reduced in strength by ~4 dB, close to the expected value for the sinc function roll off due to the pulse coding duration. The lower plots detail the central peak, indicating a measured 3 dB full width of 130 Hz as expected for the Doppler resolution.

In summary, we show experimental measurements of range-Doppler ambiguity functions using an analog optical signal processor. The processor has the capability to perform real-time matched filtering of complex, broadband waveforms. Experimental values included range resolution of 15 cm, Doppler resolution of 130 Hz, and a 15 dB enhancement in the ambiguity functions over previous results. We also demonstrated a 15 dB image enhancement by using agile PN coded pulsed waveforms versus identically coded pulses.

REFERENCES

[1] R.H. Walden, "Analog-to-digital converter survey and analysis," IEEE Journal on Selected Areas in Communications, vol. 17, no. 4, pp. 539-550, (1999).

[2] W. Cheng, R. Stevens, F. Rupp, C. Engels, W. Ali, M. Choi, D. Devendorf, S. Ding, L. Linder, K. Liu, T. Tat "40 GSPS ADC-DAC Components for the ADAM Receiver-Exciter ASIC, Proceedings of GomacTech2004, Monterey, CA (2004)

[3] F. Stroili, J. Huggett, D. Jansen, R. Elder, D. Rowe, M. Vadipour, R. Chan, M. Feng, "Multifunction Receiver-on-Chip Technology for Electronic Warfare Applications", Proceedings of GomacTech2004, Monterey, CA (2004)

[4] J. Guey and M. R. Bell, "Diversity of Waveform Sets for Delay Doppler Imaging," IEE Trans. Inform. Theory, vol. 44, no. 4, pp. 1504-1522, (1998).

[5] M. R. Bell and S. Monrocq, "Diversity Waveform Signal Processing for Delay-Doppler Measurement and Imaging," Dig. Sig. Proc., vol. 12, pp. 329-346, (2002).

[6] K. D. Merkel, R. Krishna Mohan, Z. Cole, T. Chang, A. Olsen and W. R. Babbitt, "Multi-Gigahertz radar range processing of baseband and RF carrier modulated signals in Tm:YAG," J. Lum. 107 62-74 (2004).

[7] T. L. Harris, W. R. Babbitt, K. D. Merkel, R. K. Mohan, Z. Cole, and A. Olson, Multi-Gigahertz Range-Doppler Correlative Processing In Crystals," Proc. SPIE, vol. 5362, no. 1, pp. 31-42, (2004).

[8] R. Reibel, K. D. Merkel, D. E. Benson, T. Chang, R. K. Mohan, and W. R. Babbitt, "Ultra-Wideband Analog Optical Signal Processing of Complex Waveforms For Range-Doppler Radar Measurements", Proc. GomacTech2005, Las Vegas, NV (2005).

[9] P. Peebles, Radar Principles, John Wiley & Sons, New York, (1998).

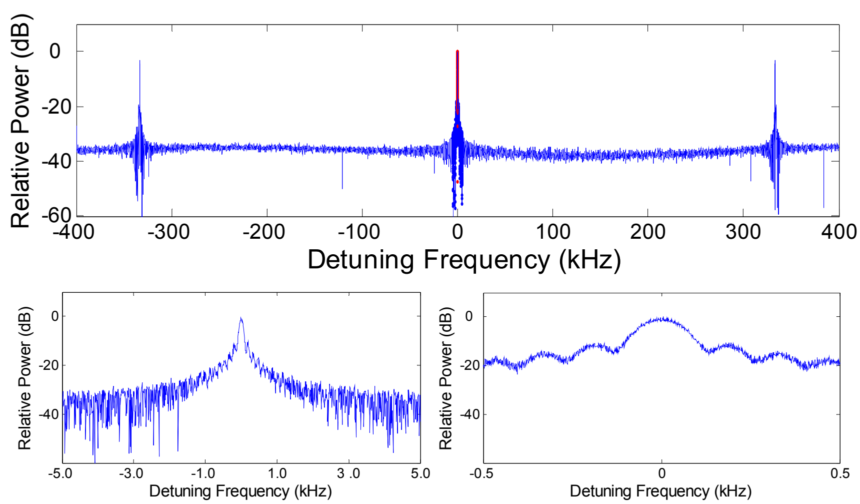

Figure 3. (Top) A Doppler profile for the peak ρανγε δελαψ ατ 1.5□µs showing the two first order ambiguities due to the PRF of ~333 kHz, with scan steps of 100 Hz. (Bottom) Individual zooms of the main peak in the upper plot. The zero Doppler gives a measured 3 dB FW of 130 Hz.