High Resolution Range/Doppler Ladar Using Broadband Coherent Optical Processing

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INTRODUCTION

Coherent laser radar (ladar) can provide extremely high resolution range and velocity information. High resolution range information requires high bandwidth, which is typically achieved through a highly stable optical oscillator seeding a high-power repetitively-pulsed transmit laser. Such a system is limited by the laser's peak power and can result in range and Doppler ambiguities. These problems can be alleviated by replacing the repetitive pulses with a long broadband optical noise waveform, either from an inherently noisy laser or a laser modulated with a pseudo-random coded (PN) or white noise (WN) waveform.[1] Such waveforms enable quasi-continuous operation, low range sidelobes, reduced ambiguity in range-Doppler measurements, and a reduction in the required optical "peak" power delivered to the target. To correlate the return and transmitted signals, this approach requires high-bandwidth, high dynamic range detectors and analog-to-digital converters, which are severely limited in performance.[2]

The University of Colorado, S2 Corporation, and Spectrum Lab at Montana State University have been researching new approaches to processing broadband information using spatial-spectral (S2) holographic optical materials,[3] including spectral analysis, correlation, true-time-delay, waveform generation, and range-Doppler radar and ladar.[4] Here, we review our work on S2 based ladar processing and present recent demonstrations of broadband (>10 GHz processing), 50 Hz Doppler resolution, 40 dB SNR, and unambiguous range-Doppler imaging in an S2 material.[5-11]

An S2 ladar processor has the unique ability to process broadband (>>GHz) signals and achieve high resolution range and Doppler information without a broadband detector or a coherent local oscillator. In the S2 approach to ladar, the bandwidth and dynamic-range limiting heterodyne detector in the focal plane of a conventional ladar receiver is replaced with a spectrally resolved correlating S2 material, as shown in Figure 1. The quantum mechanical interference of the return photons with the reference waveform produces spectral correlative fringes in the S2 material, provided the reference is Doppler matched to the target return. A scan of the spectral fringes with an optical chirp produces a low bandwidth readout of the wideband correlation result, which can be conveniently detected and digitized with wide dynamic range. Post-processing produces a final result with significantly higher range resolution than is possible with conventional ladar detection. A S2 material can also simultaneously process multiple Doppler channels or receive angles.

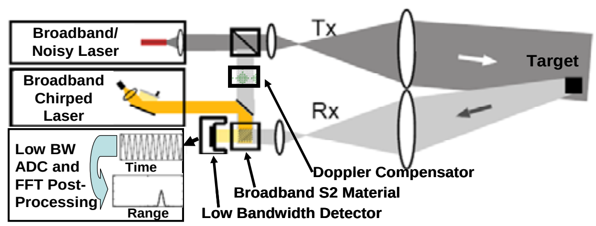

Figure 1. In the S2 ladar system a broadband/noisy laser is transmitted to illuminate the targets, while a portion of the light is used to illuminate the S2 material. The return signal interferes spatially and spectrally with the reference. The resultant S2 grating is readout by a chirped laser that sweeps through the transmitted band. The range information is obtained through FFT post-processing. The spatial dimension can be used for parallel Doppler or multi-beam processing.

BASIC PRINCIPLES OF S2 LADAR

S2 materials consist of narrow-linewidth (less than a MHz) rare-earth ions that are doped into a crystalline host lattice. As illustrated in Figure 2, local variations in the host cause shifts in the center frequency of the individual absorption lines, resulting in an inhomogeneously broadened absorption line (>300 GHz in some materials). The S2 material we use for our demonstrations is Tm:YAG. The individual Tm^{3+} ions are resonant at 793 nm with a homogeneous linewidth of ~25 kHz at a temperature of 4K and an inhomogeneous linewidth of ~25 GHz.. Alternate S2 materials that are especially useful for eye-safe ladar are Er:Eu:YSO, Er:YAG, and $Er:LiNbO_3$ at ~1.53 microns, which exhibit homogeneous linewidths of 50-300 kHz at liquid helium temperatures and inhomogeneous linewidths, Δf_{inh}, of 20-300 GHz.[3]

When a narrowband laser illuminates an S2 material, it excites ions resonant at the laser frequency, f_L, and burns a spectral hole in the absorption line, as illustrated in Figure 2. The depth of the spectral hole in the absorption depends on the integrated power of the laser at the narrow frequency. When a broadband signal illuminates the S2 material, the S2 material records the signal's power spectrum. If the broadband signal consists of a waveform and its delayed replica, the combined power spectrum that is burned into the S2 material is the power spectrum of the waveform modulated by a periodic spectral grating of period $1/\tau$, where τ is an unknown delay. By scanning out the absorption spectrum and determining the spectral modulation frequency (by Fourier transforming the absorption spectrum), the delay can be measured with high resolution. The delay resolution is ~$1/\Delta f_{inh}$, which can be sub-mm for S2 materials with Δf_{inh} = 200 GHz.

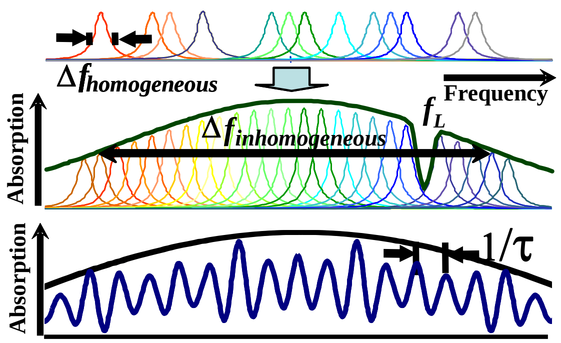

Figure 2. Top: The individual ions in a host material have narrow homogeneous resonant linewidths whose resonant frequencies are shifted in the material. Center: The collection of individual lines forms a broad collective inhomogeneous absorption line. A spectral hole is burned at f_L. Bottom: A spectral interference pattern is burned into medium with spectral modulation period $1/\tau$.

For simplicity, consider the case of collinear illumination of the S2 material by two optical signals: one is a portion of the optical transmit (reference) waveform that has a controlled frequency-shifted, f_c, introduced and other is the ladar optical return signal. The return signal is the sum of returns from multiple targets, each a delayed, attenuated replica of the reference pulse that is Doppler shifted due the longitudinal velocity, v_i, of its corresponding target. Let τ_i be the delay to the i^{th} target. The Doppler shift on the i^{th} return signal is $f_D=2f_Lv_i/c$ for a monostatic ladar. For each target, the material records a broadband spectral interference grating that has a period $1/\tau_i$, provided that the reference and return have identical frequency shifts (i.e. if $f_c=f_D$). For a reference waveform of duration T and a material lifetime T_1, a frequency mismatch of either 1/T or $1/T_1$ between the reference and return will wash out the spectral interference grating. The Doppler resolution is thus the greater of 1/T or $1/T_1$. Finer Doppler resolution can be obtained by sequential processing of multiple waveforms. The broadband (>>GHz) spectral interference grating can be read out using a frequency-swept laser and conventional low-bandwidth (<100MHz) detectors and digitizers. The S2 ladar's range resolution is determined by the bandwidth of the reference signal and material, not the detector bandwidth.

Note that for the case described, the complete Doppler processing requires a distinct frequency shift of the reference waveform for each Doppler channel. This requirement can be met exploiting the S2 material's massive spatial parallelism and simultaneously process over 1000 distinct spots in a single 1 cm^3 crystal.

COLINEAR S2 LADAR EXPERIMENT

The experimental setup for collinear S2 LADAR processing is shown in Figure 3.[6,9,11] A frequency-stabilized external-cavity diode laser (ECDL)[12] was passed through an electro-optic phase modulator (EOPM) where a long 2 Giga-sample per second PN coded waveform was applied. Its duration of 100 ms was longer than the material lifetime (10 ms) in order to ensure that the Doppler resolution was material limited. The modulated light was split into a reference path, which passed through an acousto-optic modulator, AOM1, whose frequency shift was stepped to probe each of the Doppler bins, while the transmit path simulated a single point target return by traveling through an AOM2 and a long fiber delay and then reflecting off a piezo actuated mirror. These stages provided an absolute Doppler shift, a ~1 μs delay, and a vibrational content to the optical return waveform. The reference and return waveforms were combined and sent through the cryogenically cooled (4.2K) 0.1% Tm:YAG crystal for range-Doppler processing.

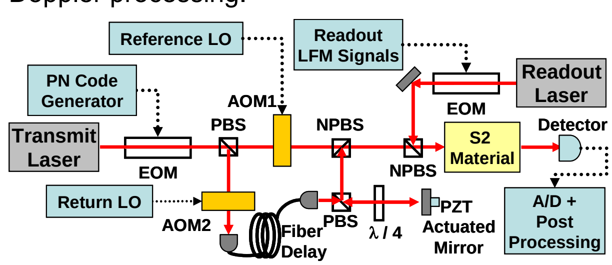

Figure 3. Collinear experimental setup for the S2 range Doppler ladar processor.

The readout laser was phase locked to, but frequency offset from, the transmit laser. This laser was phase modulated by another EOPM to create spectral sidebands, one of which was swept over the programmed spectral grating with a 1 GHz bandwidth in 100 µs. Another AOM (not shown) was used to gate the readout signal, while AOM1 and AOM2 were used to subsequently block the reference and return paths. The readout chirp waveform beat with the generated echo chirp waveform on a 125 MHz photodetector. This time record was then digitized and post-processed to obtain the range data. An array of Doppler bins was emulated by sequentially frequency shifting the reference beam with AOM1 and repeating the programming/readout with a wait time greater than the material lifetime time between each measurement. In practice, other spots in the crystal could be used to form the Doppler array.

Figure 4 shows the measured range-Doppler profile obtained when the target was not vibrating. The Doppler axis is normalized to the emulated Doppler shift produced by AOM2. Figure 5 shows range (left) and Doppler (right) cross-sections, which highlight the sub-nanosecond delay resolution (~6 cm range resolution), the 50-Hz Doppler resolution, and ~40 dB SNR. Figure 6 shows the Doppler profile for a target with a complex Doppler signature, produced by dithering the piezo-mounted mirror shown in Figure 3 at ~ 500 Hz. The vibrational tones are resolved as sidebands and their levels match those of an independent cw Doppler measurement. The range profiles for each of the major peaks maintained their sub-nanosecond range resolution.

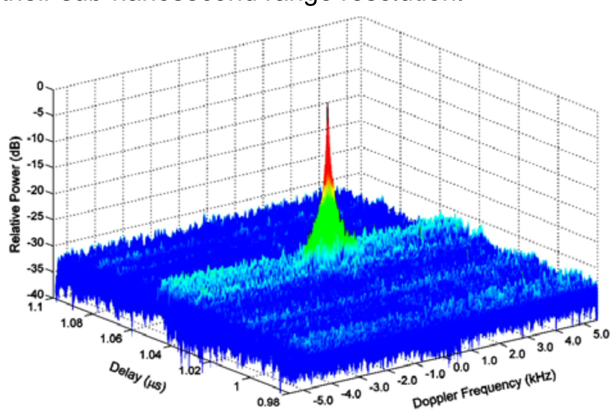

Figure 4. Range-Doppler ladar profile for non-vibrating target with a delay of ~1µs.

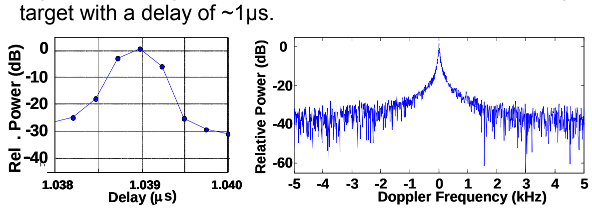

Figure 5. Left: Zoom of the range profile at the zero Doppler. Right: Doppler profile at target range:

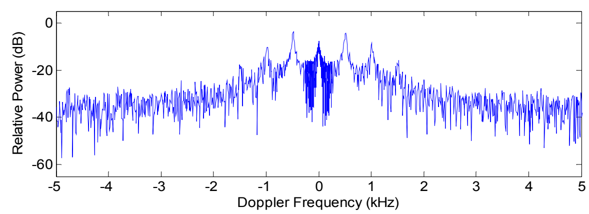

Figure 6. The Doppler profile at the at the target range for the vibrating target oscillating at ~500Hz with a delay of ~1µs.

DIFFRACTIVE S2 LADAR EXPERIMENT

Angled illumination is an alternative to the collinear setup, which has potential advantages of angular multiplexing and zero background detection. The angled experimental setup (shown in Figure 7) was used in the first proof-of-concept demonstration of S2 ladar processing using WN waveforms.[5,8] An ECDL was frequency locked to a spectral hole, had a 10 kHz linewidth,[12] and was amplified to 120 mW. The reference was a 75 MHz random-noise waveform modulated onto an optical carrier by an AOM. The return signal was generated by combining sets of fiber and free-space delays. The reference, return, and readout signals are angled with respect to each other in a box geometry (see insert in Figure 7). The S2 material here is a 5x10x10 mm 0.1% Tm: YAG crystal at 4.8 K. The readout was generated by driving an AOM with a rf chirp with chirp rate of 1.875 MHz/µs and bandwidth of 75 MHz. The diffractive output beam is in a distinct direction with respect to the input beams and is heterodyne detected with a clean version of the readout laser. The post-processed range profile for various sets of delays is shown in Figure 8. The measured resolution of 4 m a little larger than the 2 m resolution expected for a 75 MHz bandwidth system, but sufficient to resolve the 5.5 free-space delay differences.

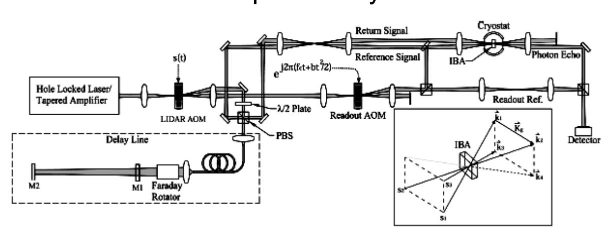

Figure 7. Experimental setup for diffractive S2 LADAR.

The experiment was extended to >10 GHz processing and readout by introducing sinusoidal modulation (at 500 Hz) of the transmit laser frequency to effectively broaden the reference waveform, by scanning the readout laser's PZT over ~16 GHz to generate the readout chirp, and by employing a spectral linearization algorithm in the post processing of the data to compensate for instabilities in the readout optical chirp.[7,10]

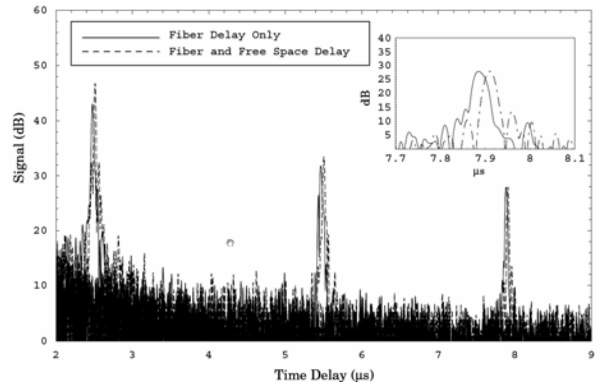

Figure 8. Experimental results for 248, 547, and 789 m fiber delay lines with and without a 5.5 m free-space delay using random-noise.

The results in Figure 9 demonstrate a range resolution of 12.8 mm, which corresponds to ~12 GHz of processing bandwidth. The sidelobes on the range peak are due to an artifact of the spectral linearization and feedback from a fiber etalon. The setup was also used to demonstrate the simultaneous processing of multiple Doppler bins in different spatial locations.[7,10]

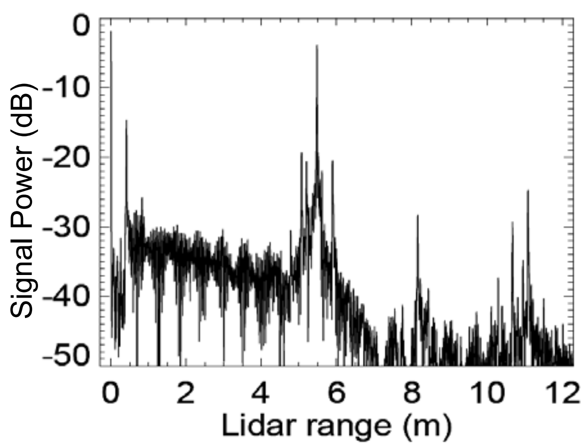

Figure 9. Results from the laser range experiment after spectral linearization showing range resolution of 12.8 mm.

SUMMARY

A new approach to ladar reception and processing that uses quantum interference in an S2 holographic material is presented. The S2 ladar approach enables wideband (>10 GHz), Doppler-resolved, high dynamic range correlative ladar processing of coded or noisy waveforms, as well as parallel Doppler processing and multi-beam operation.

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