FREQUENCY AGILE LIDAR RECEIVER FOR CHEM-BIO SENSING

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1. SUMMARY:

Physical Sciences Inc. (PSI), in conjunction with its subcontractor, VTech Engineering Corp., developed an ultra low noise receiver module (RM) for direct detection LWIR LIDAR systems. The receiver module is compatible with emerging LWIR source technologies, e.g., optical parametric amplifier-based sources, as well as existing frequency-agile CO_2 laser technology. In this paper we present RM performance attributes based on characterization experiments performed in the laboratory, as well as part of the system integration in the ECBC's Frequency Agile LIDAR (FAL) unit. The RM has been demonstrated to be compatible with a 200 Hz shot-to-shot line tuned CO_2 laser in terms of both tuning speed and wavelength accuracy. The system achieves tuning times of less than 5 msec for wavenumber jumps ≤ 10 cm^{-1} and transmission measurement errors of ~0.5% due to etalon absolute positioning uncertainty. The system has been demonstrated to achieve a total Noise Equivalent Power (NEP) of ~ 1.7 nW for an electronic bandwidth of 5 MHz when observing a background of T_{bkgd} = 400K. This represents ~40% improvement over an equivalent detector/preamplifier configuration without PSI's tunable etalon technology.

2. INTRODUCTION:

Recent research indicates that laser absorption and backscatter measurements at long-wavelength infrared (LWIR) wavelengths (λ ~ 8 to 12 μm) enable detection not only of all common nerve and blister chemical agents, but also suggests that LWIR LIDAR can be used for long range standoff detection of biological warfare agent aerosols [1]. As a result of these findings, there exists considerable interest in applying frequency-agile CO_2 laser-based LIDAR for remote sensing of both chemical and biological agents. Increasing standoff range and/or improving detection sensitivities of LWIR LIDAR systems to chemical and biological (CB) agents would be of immense value to the military, particularly if those improvements can be achieved while decreasing the size, weight and/or cost of the sensor package. The technology developed in this effort directly addresses these needs and is suitable for use with both ground and aircraft- based LIDAR systems.

3. DESCRIPTION of TECHNOLOGY and DEMONSTRATED CAPABILITY:

PSI and Vtech Engineering Corp in collaboration with ECBC set out to extend the standoff range and improve detection sensitivity of direct detection LWIR LIDAR systems by developing an ultra low-noise receiver module. The receiver module design is based on the following key attributes: 1) The use of an inexpensive COTS PV MCT, 2) A custom detector amplifier with ultra low input-referenced noise density of 0.8 nV/ $Hz^{0.5}$ that is carefully matched to the electrical properties of the detector and temporal characteristics of the LIDAR transmitter source, 3) The use of PSI's tunable etalon technology to reduce the overall flux on the detector and thereby reduce the background-limited photon statistical (BLIP) noise associated with backscatter measurements, and 4) An innovative f/0.9 optical system designed to eliminate vignetting in the receiver optical train, reduce self-emission from optical components, and fully integrate with the existing 14'' Cassegranian telescope currently employed in the ECBC's FAL system. The rapidly-tunable Fabry-Perot interferometer (etalon) tracks the emission wavelength of the LIDAR transmitter. The low-noise amplifier matched to the receiver detector was developed in order to realize the BLIP noise reduction resulting from the etalon. A schematic of the receiver module in-line with the FAL collection optics is shown in Figure 1.

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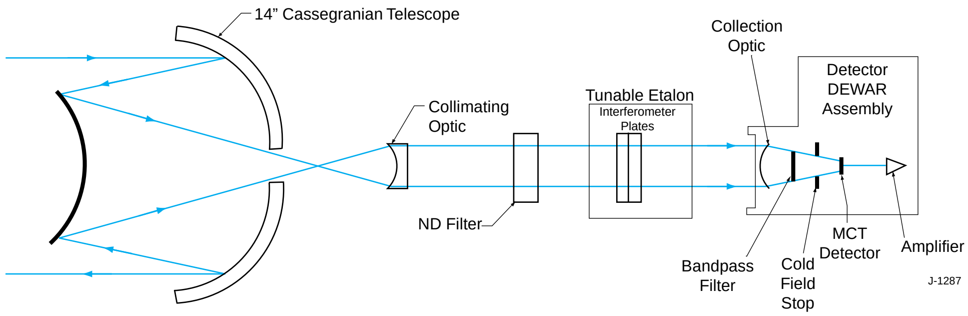

Figure 1. Schematic of the FAL receiver module.

3.1 Fabry-Perot interferometer (etalon)

PSI's etalon technology is described in detail elsewhere [3]. The Tunable Filter Module (TFM) is responsible for the selection of the wavelength centered at specific CO_2 laser emission lines, which is then collected onto the detector. The advantage and innovation in PSI's proposed LIDAR receiver module is in the use of theTFM. The utility of an etalon, as opposed to a diffractive or absorptive filter, in reducing the baseline flux on the detector can be understood as follows. The etalon is reflecting where it is transmitting so the detector "sees its reflection" at all wavelengths outside the etalon passband. Because the etalon is a reflective optical element, it has essentially zero emissivity and exhibits nearly zero self-radiance even when operated at 300 K. In contrast, an absorptive filter would have to be cooled to cryogenic temperature in order reduce its self-radiance to an insignificant level. Similarly, the undiffracted rays from a diffractive filter, such as an AOTF, would need to terminate on a cryogenic surface in order for it to exhibit negligible self-radiance. The low emissivity (ε~0) property of the etalon enables it to be operated at ambient temperature while contributing negligible noise to LIDAR measurements. This gives it a decided advantage over absorptive and diffractive filters in terms of ease of use. For a cryogenically-cooled detector, the etalon reduces the flux on the detector by the ratio of the etalon passband to the spectral width of the bandpass filter placed in front of the detector. The flux reduction factor is typically >30 with PSI's LWIR etalons.

In order to achieve compatibility with the ECBC's pulsed 200Hz frequency-agile CO_2 laser, the TFM needed to satisfy two primary requirements: 1) Tuning times of less than 5 msec (tuning between two consecutive CO_2 laser emission lines) compatible with 200Hz laser operation, and 2) Account for less than 1% transmission error due to etalon positioning errors. Electronically, the TFM incorporates FPGA-based control electronics which allow for fast and stable wavelength tuning. The FPGA-based control system increases the bandwidth of the etalon control loop and maintains active, continuous alignment of the etalon mirrors. Results (shown in Figure 2) from extensive testing of the TFM demonstrate that for 85% of all wavelength jumps/sequence utilized by the ECBC system, the etalon tunes/converges in less than the required 5 msec interval, thus demonstrating the capability to keep track with the scheduled CO_2 laser emission. For wavelength jumps for which the convergence time exceeds 5 msec (i.e. 40 cm^{-1}), non-lasing triggers are inserted in order to allow the etalon to accurately position at the next wavelength (blank insertion slightly reduces the duty cycle of the system). The spectral resolution of the receiver system (etalon Full Width Half Maximum – FWHM) and the peak transmission of the tunable filter as a function of frequency are shown in Figure 3. The system achieves between 10 -18 cm^{-1} FWHM (depending on the operating order) and ~ 80% peak transmission.

	m=2	**m=3**	**m=4**
5cm^{-1} Jump	**<4ms**	**<3.5ms**	**<3ms**
10cm^{-1} Jump	**<5ms**	**<4ms**	**<4ms**
40cm^{-1} Jump	**<10ms**	**<15ms**	**<20ms**
ECBC Wavelength List	**<5ms (80%)**	**<5ms (80%)**	**<5ms (80%)**

Figure 2. Etalon Tuning Performance for each etalon operating order and various frequency jumps. Shown is the maximum converge time for each of the cases.

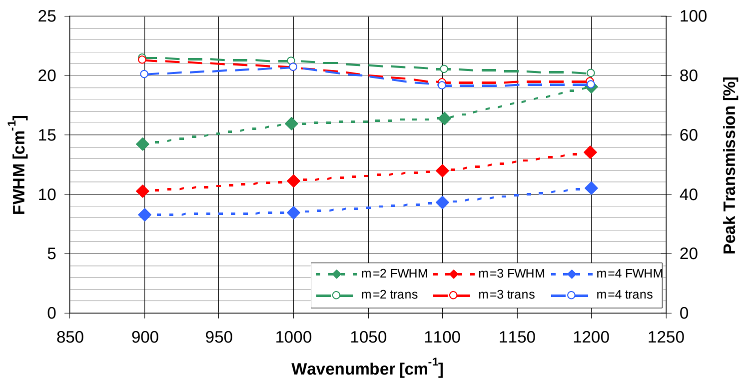

Figure 3. Etalon peak transmission and FWHM (for each etalon order) across the system operating range.

We conducted laboratory experiments in order to measure the receiver system's transmission uncertainty that results from etalon positioning errors. Etalon wavelength stability and position accuracy are critical aspects in the performance of the etalon-based FAL receiver module. If the location of the transmission fringe maximum does not match the location of the FAL CO_2 laser line then the effective laser power incident on the detector is reduced; the SNR also degrades as a result of this scenario. If the transmission wavelength varies from shot to shot at a specific wavelength, then the wavelength variation aliases as measurement noise and degrades CB agent detection sensitivity. We conducted a direct transmission measurement of a narrow LWIR source by employing a Quantum Cascade Laser (QCL) from Maxion technologies. The QCL produces a narrow-band (<0.2 cm^{-1} FWHM) laser line at 9.6μm (1042 cm^{-1}). By moving the etalon away and back onto the QCL line, we obtained a direct measurement of the transmission variance introduced by repeated tuning. The results of these measurements are shown in Figure 4. Each wavelength data point in Figure 4 is an average of 32 separate measurements (etalon scans) and the % error plot is generated based on the ratio of the standard deviation to the mean. It can be observed that the relative transmission measurement error introduced by etalon positioning uncertainty is ~ 0.5%, which is well within the objective of 1% derived based on an analysis of system requirements.

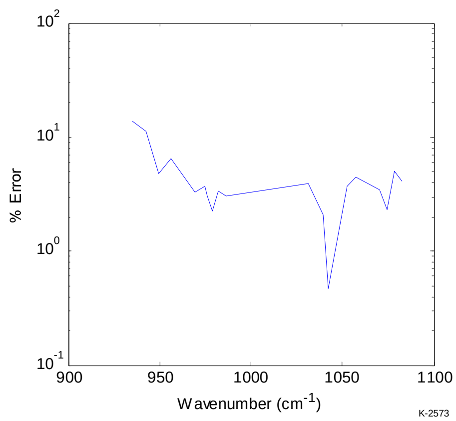

Figure 4. Percent transmission error vs. etalon position scanned over the QCL. The QCL emits at 1042 cm^{-1}, where the % transmission error is ~ 0.5%.

3.2 Detector and Custom Amplifier

The detector is a Judson single element PVMCT, 0.5 mm diameter Model #J19D11-DM1-R500U-60-CSCF-PSI, Part # 440098. The detector mounting bracket was custom designed to support the integration of the collection lens assembly inside the dewar for reduction of self-radiance of optical components. A low-noise amplifier matched to the receiver detector was developed in order to realize the BLIP noise reduction resulting from the etalon. The transimpedance preamplifier architecture was optimized around the IR detector diode. A portion of the preamplifier was physically located within the cryogenic dewar with the IR photodiode (this stage consists of a JFET transistor with the detector attached to its gate). By placing the first stage preamplifier components within the dewar, both the thermal noise from this stage and any stray capacitance at the input are reduced. Both of these reductions help to lower the input referred noise added by the preamplifier. The other portion of the preamplifier was located directly outside the dewar and was operated at room temperature. The majority of the preamplifier circuitry is located on this printed circuit board (PCB); circuitry to control and adjust bias conditions, monitor dewar temperatures, and buffer the preamplifier output are located on the warm electronics board. The following are the technical specifications of the custom system amplifier: 1) Input-referenced noise density of 0.8 nV/ $Hz^{0.5}$; 7.5 nA rms input referred current noise (< 1.5 nW NEP * 5A/W => < 7.5 nA); 5 kHz to 5 MHz signal pass band.

3.3 Integrated System

The system was successfully integrated in the ECBC FAL unit, as shown in Figure 5.

Figure 5. RM integrated in ECBC's FAL system.

3.4 Performance characterization of the receiver module

The performance of the system was measured in both laboratory, as well as fully integrated conditions (i.e. RM integrated in the ECBC FAL system observing aerosols/atmosphere laser returns; NB: the FAL/RM system will be demonstrated for the detection of bio aerosols in future field experiments to be conducted by ECBC). Below, we present the results obtained in the laboratory where we empirically measured system noise equivalent power (NEP) and demonstrated key technical objectives. The etalon was tuned to a single wavelength and the receiver system (optics, etalon, detector/amplifier) observed a blackbody held at 400K.The baseline noise (i.e. $NEP_{asymptote}$ due to detector thermal noise, preamp noise; Johnson voltage, current and leakage noise) was measured by observing a gold mirror positioned in front of the detector window. The measuring of the gold mirror essentially provides an approach for reducing NEP_{BLIP} to ~ 0, as the detector, which is kept at 77K is starring at itself. The gold mirror was removed and the system allowed to observe the blackbody at 400K (etalon tuned to a single wavelength). The total RMS noise was then measured when the etalon was tuned in m=2, m=3 and m=4. The NEP_{BLIP} was calculated as follows:

$$NEP_{BLIP}(nW) = \frac{\sqrt{(RMS_{Total})^2 - (RMS_{Gold\_Mirror})^2}}{D_{responsivity}(A/W) \cdot Gain(k\Omega) \cdot (10^6)} \qquad (1)$$

A summary of the results is presented in Figure 6. The utility of the etalon can be readily observed as the system without the etalon yields an NEP_{total} of 2.42 nW (when observing 400K BB) which represents ~ 40% higher noise level than in cases when the etalon is inserted in the optical path (NEP_{total} ~ 1.7 nW). These empirical measurements are also in good agreement with modeling results.

@5MHz, T_{bkgd}=400K	m=2	m=3	m=4	No Etalon
NEP-Det/Preamp	1.54nW	1.54nW	1.54nW	1.54nW
NEP-Blip (Measured)	0.73nW	0.64nW	0.61nW	1.86nW
NEP-Blip (Measured)		0.48nW		1.59nW
Measured NEP_{total}	1.70nW	1.67nW	1.66nW	2.42nW
Modeled NEP_{total}		1.61nW		2.21nW

Figure 6. System NEP: Measured and Expected.

CONCLUSIONS: The RM has been demonstrated to be compatible with a 200 Hz shot-to-shot line tuned CO_2 laser in terms of both tuning speed and wavelength accuracy. The system has been demonstrated to achieve a total Noise Equivalent Power (NEP) of ~ 1.7 nW for an electronic bandwidth of 5 MHz when observing a background of T_{bkgd} = 400K. This represents ~40% improvement over an equivalent detector/preamplifier configuration without PSI's tunable etalon technology.

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