A Lightweight, Rugged, Solid State Laser Radar System Enabled by Non-Mechanical Electro-Optic Beam Steerers

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ABSTRACT

There is currently a good deal of interest in developing laser radar (ladar) for autonomous navigation and collision avoidance in a wide variety of vehicles. In many of these applications, minimizing size, weight and power (SWaP) is of critical importance, particularly onboard aircraft and spacecraft where advanced imaging systems are also needed for location, alignment, and docking. In this paper, we describe the miniaturization of a powerful ladar system based on an electro-optic (EO) beamsteering device in which liquid crystal birefringence is exploited to achieve a 20° x 5º field of view (FOV) with no moving parts. This FOV will be significantly increased in future versions. In addition to scanning, the device is capable of operating in a "point and hold" mode where it locks onto a single moving object. The non-mechanical design leads to exceptionally favorable size and weight values: 1 L and < 1 kg respectively. Furthermore, these EO scanners operate without mechanical resonances or inertial effects. A demonstration was performed with a 50 kHz, 1 microjoule laser with a 2 mm beam diameter to image at a range of 100 m yielding a 2 fps frame rate limited by the pulse laser repetition rate. The fine control provided by the EO steerer results in an angle precision of 6x10-4 degrees. This FOV can be increased with discreet, non-mechanical polarization grating beamsteerers. In this paper, we will present the design, preliminary results, and planned next generation improvements.

Keywords: Solid State LiDAR, LADAR, electro-optic laser scanner, non-mechanical beamsteerer, liquid crystal waveguide, liquid crystal

1. INTRODUCTION & OVERVIEW

In this paper we will present the design and preliminary test results of fully non-mechanical, real-time 3D solid state laser radar (LADAR) systems. This approach provides a path for unprecedented LADAR performance and very low Size, Weight, and Power (SWaP). These electro-optic (EO) or solid state LADAR systems operate at eyesafe wavelengths, provide dynamic control over very large fields-of-view (FOV) of ultimately up to 120º × 120º per sensor, and a path to low cost in volume. This is enabled by building on several innovations: i) disruptive chip-scale Steerable Electro-Evanescent Optical Refractors (SEEORs) for high speed, continuous, wide-angle, non-mechanical beamsteering, ii) discrete steering Polarization Gratings (PGs) to increase the SEEOR field-of-view (FOV) and to scan the receive aperture, and iii) low capacitance InGaAs sensors for wide FOV receive apertures. These separate technologies have been developed and matured over the past several years. In this paper we present our recent efforts to build upon these past successes by combining these technologies to enable extremely low SWaP, completely non-mechanical solid state-LADAR units. Applications include autonomous cars, terrain mapping, collision avoidance/situational awareness, docking/refueling/recovery, target detection, landing assistance, and others. The low SWaP and cost (SWaP-C) will open up LADAR capabilities to payload and cost constrained platforms such as small unmanned aerial systems (SUAS), handheld and soldier mounted systems, consumer level volumes, and other previously inaccessible platforms. The elimination of all moving parts provides significant benefits: i) enhanced functionality (dynamic frame sizes), ii) vibration immunity, iii) no mechanical wear and tear, and ultimately iv) can reduce the cost when compared to historic mechanical approaches.

The enabling component of these solid state-LADAR units is the electro-optic (EO) laser beamsteerer. These EO beamsteerers have been developed with SBIR and STTR funding. Standalone prototype EO beamsteerers are currently available as low volume prototype products. The top of Figure 1 shows pictures of recent devices. Efforts to increase production volumes and lower costs are ongoing. The current devices are a first generation product and significant performance improvements are expected. These new beamsteerers have been used to make numerous photonic systems, such as scanned illuminators, laser communication modules, and EO scanned LADAR devices. Of particular relevance to this paper is an ongoing NASA SBIR (contract # NNX14CG13C) focused on using these beamsteerers to make small EO scanned LADAR units. The results of this research are discussed in this paper. The bottom of Figure 1 shows a design for an early generation EO scanned solid-state LADAR unit and a picture of the first prototype that is under construction. This unit contains all necessary electronics, lasers, beamsteerers, detectors, and optics. Table 1 summarizes the performance of this first generation prototype and possible performance for future generation device.

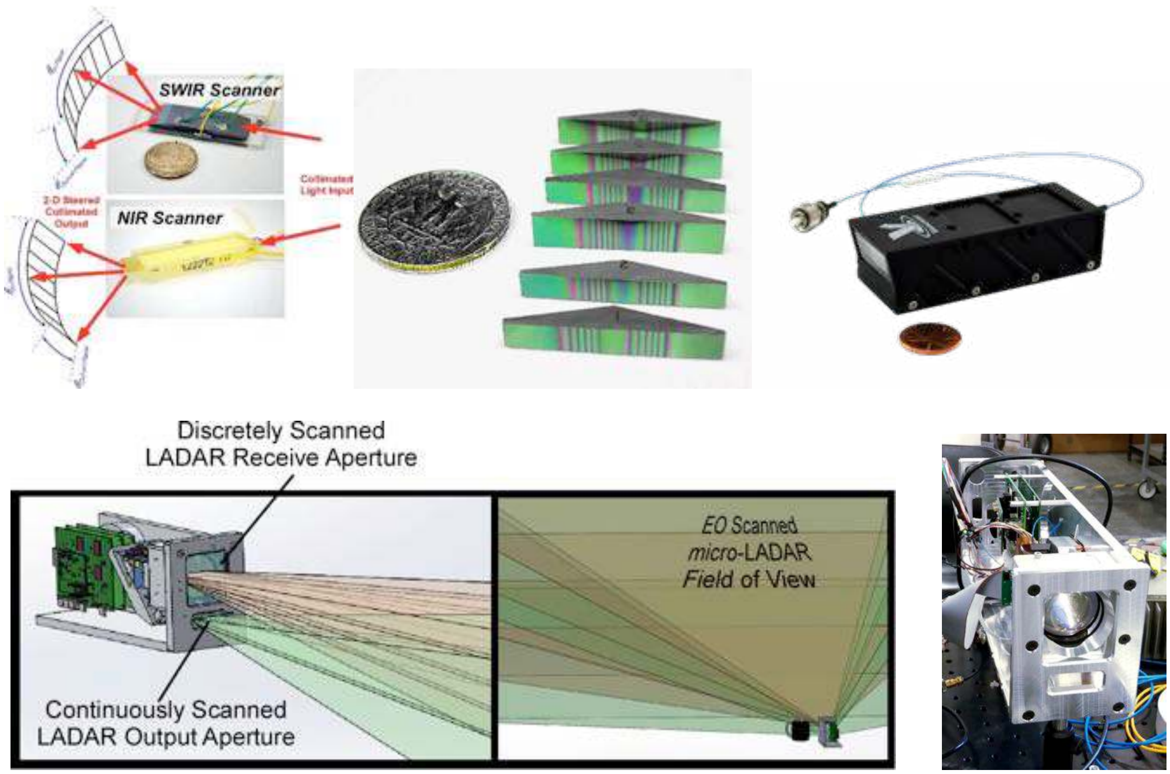

Figure 1: TOP: Pictures of new EO beamsteerers. The left shows wide angle NIR and SWIR beamsteerer chips. The middle shows very compact SWIR chips next to a quarter for scale. The right shows a wide angle SWIR beamsteerer that is packaged in a fiber coupled unit. BOTTOM: On the left is a solid model of our solid-state LADAR device. The launch and return light beams are indicated as the green and red transparent regions. This design contains all necessary electronics, lasers, and optics to collect point clouds. In the middle is a model of the unit next to a coffee cup for scale. The right shows a picture of the prototype unit at the time of writing this paper.

Table 1: Performance capabilities for the EO scanned micro-LiDAR module.

Attribute	First Generation Solid State LADAR Performance	Possible Future Generation Performance
Size	optical breadboard	< 200 cm^3
Power Consumption	< 20 Watts	< 10 Watts [A]
FOV	20°×8°	TBD, up to 120°×20° per sensor
Steering Precision	< 6×10^{-4} degrees [B]	< 6×10^{-4} degrees [B]
Mass	Not optimized	<0.9 kg
Steered Transmit Beam Diameter	1 mm	2-3 mm
Range Resolution	<5 cm	< 2 cm
Maximum Range	0.1 km	1 km
Laser Pulse Energy	~0.5 μJ	5 μJ
Laser Rep Rate	50 kHz	400 kHz
LADAR Image Size	300 × 100	1000 × 1000 (variable)
LADAR Frame Rate	0.5 FPS	10 FPS (variable, dependent on frame size)
Laser Wavelength	1550 nm [C]	1550 nm [C]
Dynamic / Foveated FOV	Yes	Yes
Point and Hold Possible	Yes	Yes
Solid State / No Moving Parts	Yes	Yes

[A] This total system power includes all electronics. For these numbers power consumption is dominated by the fiber laser. We are currently exploring lower SWaP laser sources.
[B] This is limited by how well we can servo out voltage noise on the beamsteerer.
[C] The choice of this wavelength was driven by the desire for eye-safe operation. 9xx nm operation is also viable.

Eliminating all mechanics reduces the size weight and power (SWaP) of the system which makes these units suitable for payload constrained platforms such as pod environments, small unmanned aerial systems, and other robotic platforms. High bandwidth scanning (up to 60 kHz demonstrated) enables active vibration cancellation, eliminating the need for fast steering mirrors. Very rapid slewing to targets provides more time to enable engagement with multiple targets. Non-mechanical scanning is fundamentally free of all inertial effects, eliminating the need for compensation gyros on small platforms. EO operation is also free of all mechanical wear and tear, increasing lifetime and reliability. Finally, the simplicity of operation and construction (the beamsteerers are similar to the ubiquitous LCD) will enable much lower procurement and maintenance cost than mechanical solutions.

In the remainder of this paper we will briefly review our beamsteerer technology and how it is fundamentally different from all prior approaches. We will then explain how this is used to realize EO scanned solid-state LADAR units. Finally, preliminary results from our on-going solid-state LADAR development will be presented.

2. New Electro-Optic Laser Scanners: Circumventing the Size, Weight, and Power Limitations of Mechanics

2.1. Replacing Mechanics: The Long-Standing Dream

EO scanners that provide continuous coverage over wide-angles and can provide high speed controlled sweeps over thousands of spots, all in a compact and simple package, simply do not exist. This is not for lack of effort (e.g. DARPA STAB, APPLE, and SWEEPER). Past attempts have yielded wide-angle but discrete-step binary[1-3] and ternary[4,5] angle-switches, but these all require a fine steering element to fill-in the large gaps between the discrete angles (>90% of FOV not addressed). It is this requisite fine steerer that has proven intractable. For the past several decades people have worked primarily on tunable diffraction grating approaches, with most of the effort focused on liquid crystal (LC) optical phased arrays (OPAs) [6-8], but also with efforts on MEMs arrays,[9,10] electro-wetting arrays,[11] and of course acoustooptics. Despite significant advances some inherent limitations with diffractive approaches remain. Importantly, for LC OPAs to scan from one spot to another, i.e., take a step, a slow (5-30 ms) LC relaxation must occur. Therefore, to do a linear spot-to-spot sweep or scan across a 1000 spot FOV, i.e., 1000 steps, one must wait between 5-30 seconds. A 1000 × 1000 raster scan would take between 1 to 8 hours! This is dramatically slower than mechanics and prohibitive for applications such as LADAR image acquisition, wide angle search schemes, high speed tracking, large amplitude jitter compensation, and many more. What is needed is a high-speed, non-diffractive, larger angle continuous scanner. Unfortunately all prior refractive scanning attempts only realize a small voltage control over optical phase, which means only a small scan angle and/or aperture.[12-15] For example, the KTN scanner from NTT only realized 20 spots with a 300 micron wide beam. [14]

We circumvent all of these prior limitations by using our proprietary **S**teerable **E**lectro **E**vanescent **O**ptical **R**efractors (SEEORs). The underlying photonic architecture utilizes a liquid crystal (LC) material as a cladding layer in a slab waveguide to generate large refractive index changes of up to Δn_{eff} =0.04 for the guided wave (Figure 2, top). The evanescent field of the fundamental waveguide mode interacts with the LC layer near the surface of the waveguide where the LC molecules are well-ordered and experience high restoring forces. LC waveguides can exhibit losses under 0.5 dB/cm and have sub-millisecond response times. The liquid crystal layer is held in place by a cover glass as in standard liquid crystal displays (LCD). This architecture decouples the interaction length from the thickness of the LC layer, enabling unprecedented analog voltage control over optical phase (>2 mm tuning over optical phase has been demonstrated), with fast response times and low losses.

The top of Figure 2 shows the structure for vertical or out-of-plane beamsteering. This is achieved by allowing the evanescent field to contact and tunnel into a high-index silicon substrate by tapering the silica subcladding. A simple S-taper results in a Gaussian beam output with $M^2 \sim 1$. The out coupling angle θ into the silicon substrate is given by

$$\sin\theta = \frac{n_{eff}}{n_{silicon}},$$

where n_{eff} is the index of the guided wave and depends on the index of the core, subcladding, and the voltage-dependent index of the LC layer. The output beam exits the waveguide facet near Brewster's angle. Note that steering in air is much larger than steering inside silicon because of the index difference and anamorphic compression at the facet. Devices that steer a 3 milliradian divergence beam over 15 ° have been demonstrated.

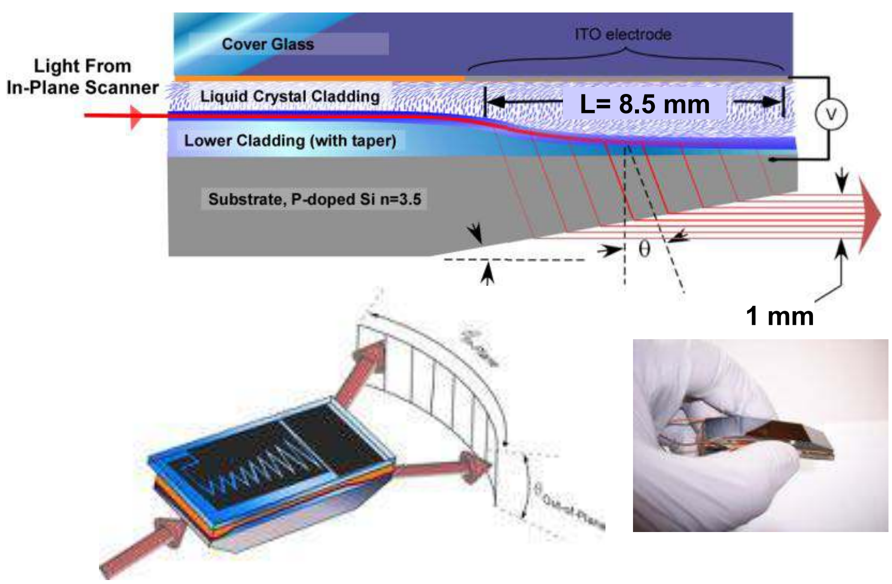

Figure 2. The basic design of a liquid crystal waveguide with a steerable output coupler (top) and the method of patterning ITO electrodes to give in-plane beamsteering (bottom left) along with a finished 2D beam steerer with 40°x10° FOR for a 1 mm beam.

In-plane beamsteering is achieved by patterning the coverplate electrode into a succession of prisms. The LC waveguide enables the index under the prism to be tuned leading to tunable refraction. By increasing the width of the prisms along the propagation direction, the sweep of the beam can be accommodated leading to a "shape optimized" steering electrode as shown in the bottom left of Figure 2. Both right and left steering electrodes can be used to double the steering range.

We have built SEEOR chips that provide 50°×15° of continuous EO scan angle for lasers operating at telecom wavelengths (see Figure 3). For short-wave infrared (SWIR) operation we have demonstrated: i) 270° of 1-D steering; ii) 50°×15° steering in 2D; iii) high speed (60 kHz); and iv) large aperture (1.2 cm) scanning. SEEOR's are compact (~6 cm^3), low power (only milliWatts), and simple (only 3 electrodes). These devices may be built on high index glass for operation at shorter wavelengths, such as in the 8xx and 9xx nm windows. Near-Infrared (NIR) devices are shown in the upper left of Figure 1.

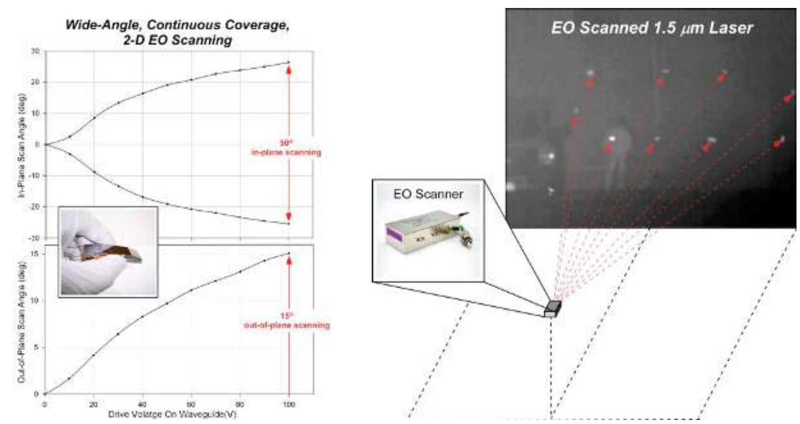

Figure 3: LEFT) Plot of measured EO scan angle as a function of waveguide voltage for an example scanner. The inset picture shows an EO scanner waveguide chip. RIGHT) Superimposed frames from a movie (recorded with an IR InGaAs CCD) showing EO scanning of a 1550 nm laser across a parking lot. The inset picture is of a fiber packaged scanner.

The SEEOR chips already provide an unprecedented level of EO beamsteering. That said, these chips are a new technology and constantly being improved. Efforts to extend the wavelength to both shorter (NIR) and longer (MWIR) regions are ongoing. Efforts to increase the FOV and /or beamsize are also ongoing. For example, by combining SEEOR technology with emergent discrete steering polarization gratings (PGs)[5] we can increase the FOV of the device (bottom of Figure 5). In a laboratory demonstration we used a two PG stack, procured from Boulder Nonlinear Systems, to increase the total FOV of the refractive scanners by a factor of four (see Figure 4).

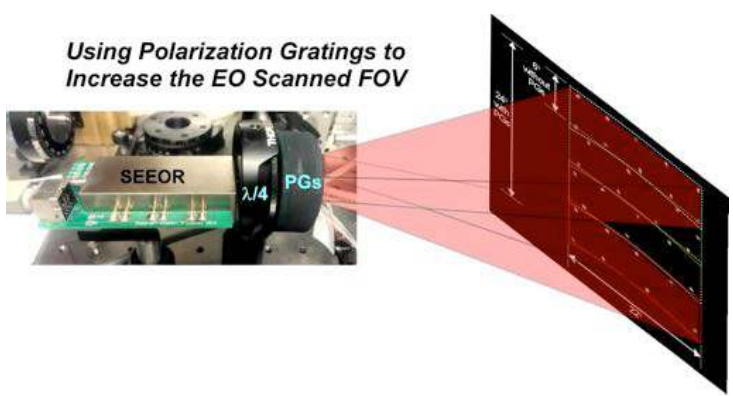

Figure 4: Picture of the SEEOR + PG combination. The setup is beautifully simple. The out-of-plane scan angle is increased by choice of voltage to the PG/LC stack. In this early example we increased the out-of-plane scan angle by a factor of four.

By adding more PG elements to the stack the FOV can be increased further. Figure 5 shows a design concept that utilizes a 6-PG stack to increase the FOV to $120^o \times 120^o$. The bottom of Figure 5 shows a package design for a combined SEEOR+PG beamsteerer.

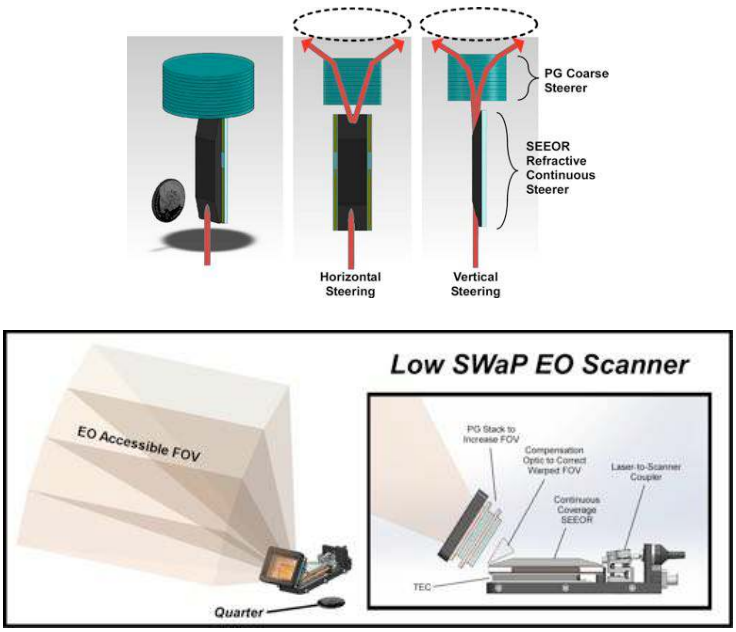

Figure 5: TOP) Drawing of a possible $120^o \times 120^o$ EO laser scanner; to date we have demonstrated $50^o \times 15^o$ of EO beamsteering per SEEOR chip. A rendering of a quarter is included for scale. BOTTOM) Package design with co-packaged SEEOR and PG stack.

2.2. Utilizing SEEORs for a Solid-State LADAR Device

The SEEOR scans a nearly diffraction limited beam continuously over the FOV. While the SEEOR and/or SEEOR+PG stack can provide a large FOV the clear aperture of the output beam is about 1.5 mm, which is too small for sensing a LADAR return signal through the waveguide. We could expand this aperture, but that we decrease the accessible FOV.

To circumvent this problem we utilize a discretely scanned staring sensor that bypasses the waveguide to give a much larger etendué. This bi-static approach is the most common detection method among LADAR manufacturers. In a typical non-scanned system the imaged spot just fills the detector area to minimize detection of background light. For our EO-scanned launch beam this presents a problem because the spot will sweep across the detector. Our answer is to use custom low capacitance InGaAs to enable a larger detector area while keeping the capacitance (rise time) low. In this configuration the active area of the detector is necessarily larger than that for a non-steered beam by a factor N equal to the number of resolved spots of the beamsteerer. Hence, the background radiation collected from the non-illuminated area will reduce the signal-to-noise (SNR) ratio by $\sqrt{N}$ when compared with fixed, monostatic LADAR which would reduce the range of the LADAR. To mitigate the increase in background noise we utilize a slightly segmented return sensor (see **Error! Reference source not found.**). In this way most of the background photons can be ignored. Segmentation also reduces the detector capacitance, which is necessary to give fast detector response laser pulses that are typically 2 to 10 ns. For this effort we had a custom InGaAs PIN diode array (16 elements) manufactured.

Both the output from the continuous scanner and the segmented return-array can have their FOV synchronously steered into segments with the discrete PG elements, as shown in **Error! Reference source not found.**.

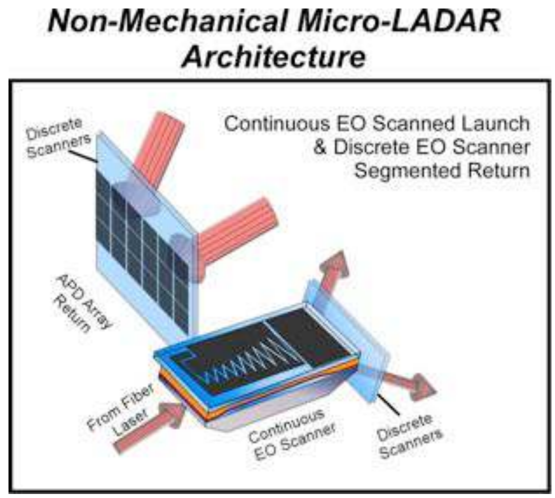

Figure 6: Schematic of the EO scanner Micro-LADAR architecture. A small diameter (< 2mm) out-going laser pulse is launched through a very wide FOV EO scanner comprised of continuous and discrete scanning stages. The return light is received through a synchronized discrete scanning stage onto a segmented array

This approach provides an optimal trade-off between scanned LADAR and a flash approach. The spatial resolution of flash ladar is given by the diode array size and all diodes must be illuminated simultaneously. With our scanned LADAR the spatial resolution is giving by the scanner resolution and the detector elements are sequentially illuminated so that one timing circuit can be sequentially switched onto each detector element. This flying-spot LADAR scanners can have reduced cost and require less optical power when compared to a purely flash approach. This approach also adds flexible; it can provide a dynamic FOV, point-and-hold, low density/high speed frames, and much more. We believe this architecture provides the best combination of performance attributes: fully non-mechanical, wide FOV, amenable to a low SWaP laser, and overall system simplicity.

3. Solid-State LADAR Prototype & Demonstration

Figure 7, Figure 8, and **Error! Reference source not found.** show details of a first generation EO scanned LADAR system. This system was not optimized for size and significant reductions are planned in future designs. Figure 7 shows details of the package interior with important components identified. The launch aperture is below the receive aperture, and quite a bit smaller. A compact fiber laser is coupled to a SEEOR continuous scanner. This continuous scanner is mounted in a way that allows adjustment to the exit angle to align it with the exit aperture. Once the beam leaves the continuous scanner it passes through a zero order quarter wave plate to render the light circularly polarized. This beam can be EO steered over a 20 × 5 degree FOV. The beam then enters into a single stage LC/PG stack to increase the FOV of 20 × 8 degrees. The return light is collected by a 50 mm diameter lens. The light first passes through a solar filter. Figure 8 shows a detailed view of the receiver housing. This housing is designed to be light tight to prevent false triggers to the timing electronics. A flash detector (hard to see in the pictures) detects the zero time of the laser pulse prior to entry into the SEEOR beamsteerer. A double-stack of LC/PGs is used to increase the receiver FOV from 20×2.5 degrees to 20×8 degrees, which is the FOV of this first generation unit. Again, future designs will have significantly larger FOV The receiver housing allows adjustment between the receiver lens and the custom InGaAs array. This is aligned so that the focal depth of the lens is just in-front or behind of the array. In this way, aberrations are evenly distributed across the array. This can be done because the angular position is given not by the array but by the launch beamsteerer.

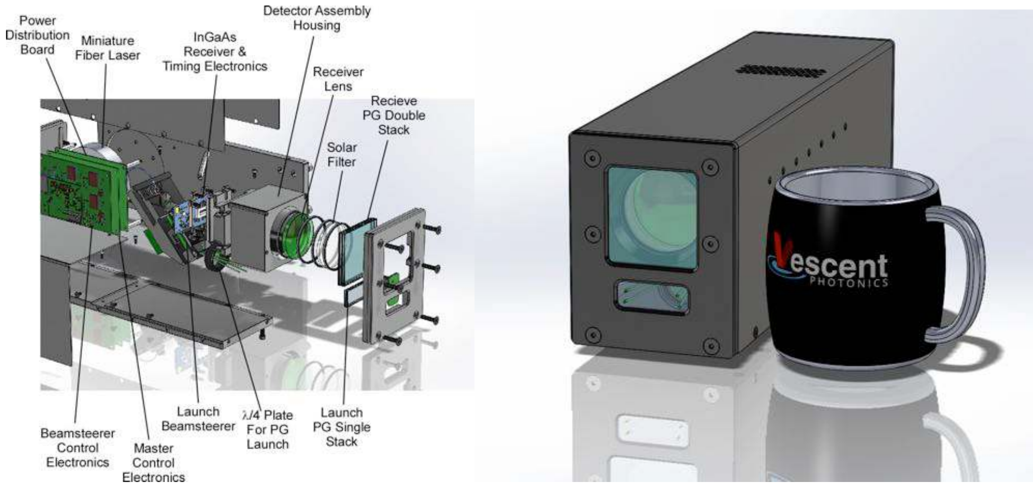

Figure 7: Solid models for the EO scanned LADAR unit with some key components identified.

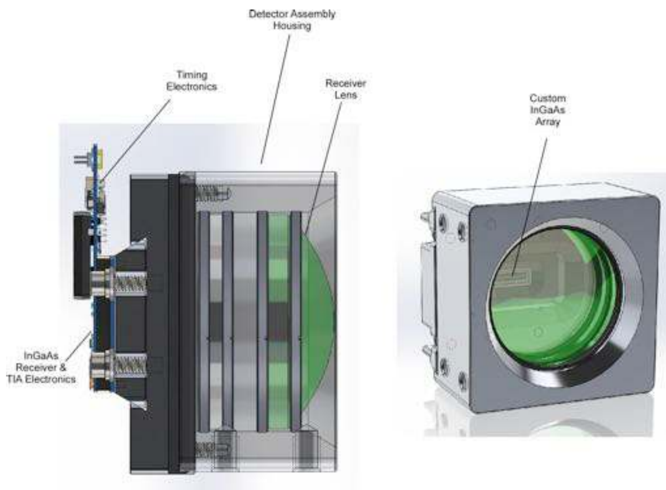

Figure 8: Solid model of the detector housing assembly. This unit is designed to be light tight to prevent unwanted returns.

The electronics inside the unit includes the beamsteerer driver board, with SEEOR temp control daughter board, a power distribution board, and the master control board or "brain board" that handles the computer interface. The timing electronics are mounted directly behind the InGaAs array and communicate with the brain board via a digital interface. A sheet metal shield is used to keep dust off of the beamsteerer and all other freespace optical components. We will perform a dust-seal around this part of the assembly. The fiber laser is mounted directly to a metal support wall; this will serve as a heat sink for the laser.

A picture of the first generation device, as it is being assembled, is shown in Figure 9. This first unit was not designed for minimal volume, but rather as a proof of concept unit. Most of the volume is for electronics, which may be put on an ASIC, which would significantly reduce cost. In this unit the PGs are not yet incorporated; they are still being fabricated. The left side Figure 10 shows the unit setup to point down a hallway that is approximately 100 feet long. The middle and right side of Figure 10 shows two different perspectives of the acquired point cloud. The FOV for this system is currently 20º×5º. Based on the S/N for these single-shot (not averaged) point clouds we are confident we will exceed the target specifications list in the middle column of Table 1.

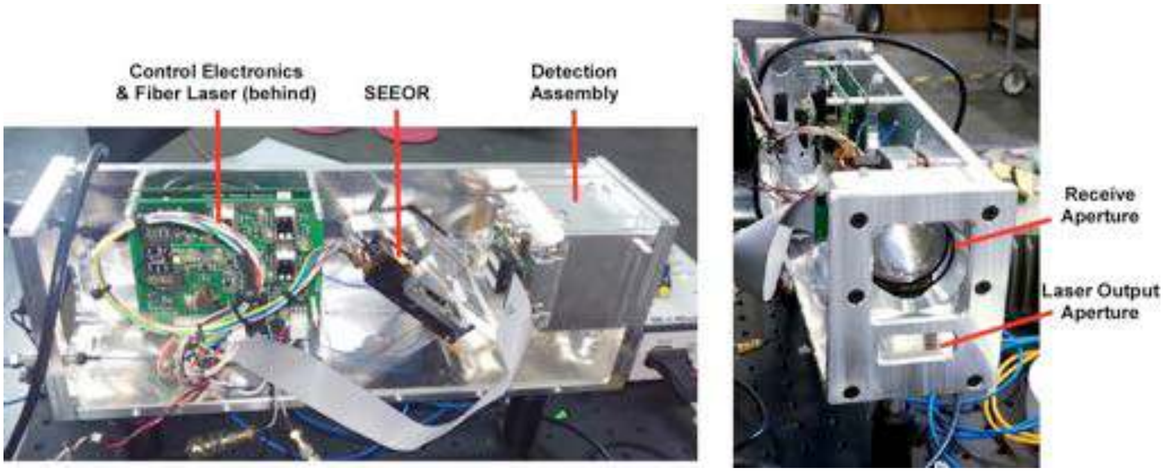

Figure 9: Picture of the first generation solid-state LADAR unit as it is under construction. The left shows a side view and the right shows a front-on view. As can be seen, much of the volume is electronics (which can be significantly reduced) and empty space. Future, much more compact versions, are planned.

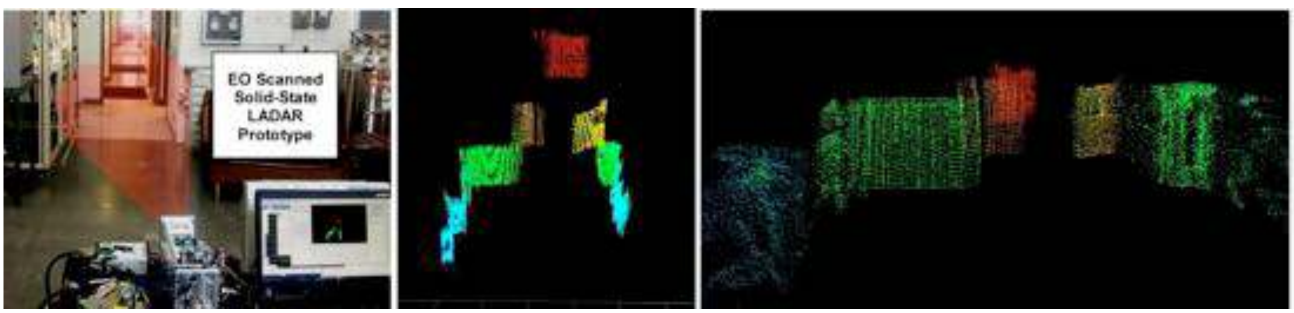

Figure 10: LEFT) Picture of the prototype as it is aimed to image down a hallway. The transparent red area is approximately the scene images with the unit. MIDDLE & RIGHT) Different perspectives of a single-shot acquired point-cloud.

4. CONCLUSIONS

In this effort we demonstrated the feasibility of utilizing novel electro-evanescent refractive beamsteerers to build a no-moving parts EO scanned LADAR unit. This included: i) development of a larger aperture 16-segment receive optic, ii) the control electronics for driving both the EO scanned launch and the timed pixel receive, and iii) a first generation package for the unit. This proof of concept unit demonstrated that a no-moving parts LADAR system is possible. Future versions will have dramatically reduced volume and power consumption and a larger FOV. Eliminating all moving parts opens up a path to increase the lifetime, lower the cost, and reduce the size weight and power. This will have application on autonomous vehicle, unmanned aerial systems, surveillance, and many more.

5. ACKNOWLEDGMENTS

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