LENS DESIGN FOR PORTABLE SWIR 3D SENSING

by

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As members of the Master's Committee, we certify that we have read the thesis prepared by **Nikhil Nagarajan**, titled ***Lens Design for Portable SWIR 3D Sensing*** and recommend that it be accepted as fulfilling the thesis requirement for the Master's Degree.

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Professor Leilei Peng Date: 5/5/23

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Final approval and acceptance of this thesis is contingent upon the candidate's submission of the final copies of the thesis to the Graduate College.

I hereby certify that I have read this thesis prepared under my direction and recommend that it be accepted as fulfilling the Master's requirement.

Professor Robert A. Norwood
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Date: 5/8/23

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DEDICATION

To my parents, Vani and Nags.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

LiDAR (or Light Detection and Ranging) typifies an enterprising technology that is the future of remote sensing. By being capable of measuring relative distances, topographical data and creating three-dimensional images, LiDAR possesses the ability to change the environment of numerous industries. This market, which was once valued at $1.32 billion in 2018 is expected to grow to $6.71 billion by 2026, primarily due to an increase in demand for aerial LiDAR systems, which show the promise for this technology and the endless opportunities it will create. The specific LiDAR we will analyze is Flash LiDAR, in which a set of collimating optics and diffractive elements will be added to the system in order to produce multiple projections of an array of sources in the *x*, *y* and *z* directions. Using this method, this thesis will highlight a portable and effective lens design that will be able to conduct three-dimensional sensing in the short-wave infrared (SWIR) region.

1 BACKGROUND

1.1 SWIR

The short-wave infrared (SWIR) is a spectral region that we define as the wavelengths that range between 900 and 1700 nm. SWIR light is known to be highly reflective, unlike mid-wave infrared (MWIR) or long-wave infrared (LWIR). This is because SWIR photons are predominantly reflected or absorbed by an object of interest, rather than being emitted by the object. The systems that incorporate SWIR light typically use InGaAs (indium gallium arsenide) sensors due to their high sensitivity in this wavelength range; below 1000nm, silicon detectors can be used. As such, benefits of SWIR are high contrast for high resolution images, ability to image through glass, means to easily differentiate colors, as well as simple day/night imaging. Typical applications of SWIR light include process quality control, electronic board inspection and surveillance. For this thesis, SWIR will be used for its high-resolution images and for its low-power cost effectiveness that will make the overall design portable.

1.2 3D Sensing

3D sensing is a measurement method that allows one to capture information about depth, length and width of a target area or its surroundings. The two primary methods of 3D sensing are time of flight sensing and structured light illumination sensing. A visual rendering of the two methods is shown in Figure 1 as an illustration for how light travels for each system and the components that are required for the execution of the system.

With regards to the time-of-flight (ToF) method, an emitted pulse is reflected and captured by the sensor, from which the relative distance is calculated by the time it takes for the pulse to be sent and received. Benefits of this method are its simplicity and ease of use; however, it does tend to be correlated with high power consumption as well as low resolution images, due to heat generation and packing density. The alternative method is structured light illumination (SLI), in which a specific infrared pattern is emitted onto a scene and an infrared camera then utilizes the distortion of the known pattern from the scene to determine relative distance. This process produces images with a higher resolution and consumes less power than ToF. When comparing the two methods, it is important to highlight the primary uses of both. ToF excels at capturing distance data at medium to long range and is ideal for general scene measurements. On the other hand, SLI is exceptional at producing high quality images at very short ranges to generate depth information. As such, for the purposes of this project, ToF will be the preferable technology to be used.

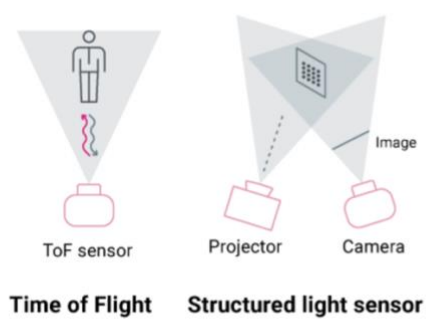


Figure 1:Light path for ToF and structured light methods

1.3 LiDAR

One specific 3D sensing technique is LiDAR, which remotely processes light that is reflected or backscattered from an illuminated target to determine distances and the creation of a three-dimensional rendering of the environment. A LiDAR system consists of a laser, a detector, and a (GPS) receiver. The laser initially sends out a pulsed beam that passes through a set of optical elements and hits its target. The light is then reflected back through a set of receiving optics that then passes light along to the detector. The working principle of this system is to use the measured time interval from when the light leaves the source to when it is captured by the detector (ToF method) as a measure of the distance of the object. An automotive illustration of this is provided in Figure 2.

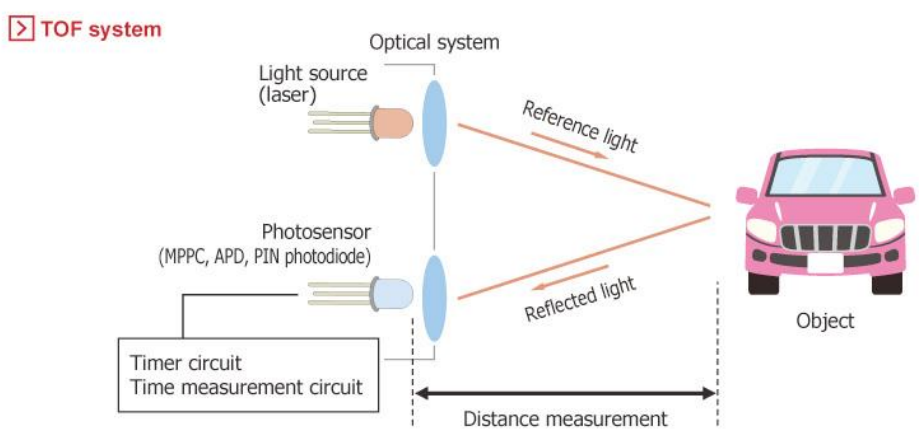


Figure 2: Automotive ToF LiDAR system

Once the detector captures the reflected light signal, the range of a target can be calculated according to the following equation, where R represents range, c is the speed of light and t_{oF} is the time of flight. Equation 1 is highly dependent on the ToF, where the range is characterized by the size of time intervals available in a system, which provides the range limits. Additionally, the pulses must be as short as possible, with fast rise and fall times and high optical power to ensure accurate data processing and high-resolution ranging. This is so that the time intervals can be measured more precisely, yielding times with nanosecond accuracy (roughly a third of a meter) and to ensure that enough of the signal is being captured by the detector because of high scattering of the reflected light.

$$R = \frac{c}{2} t_{oF}$$

Equation 1

2 FLASH LIDAR

2.1 Operation

Flash LiDAR differs from traditional (scanning) LiDAR in that an image can be created with just a single laser pulse and a focal plane array (FPA) rather than requiring a pulse per pixel to scan an entire image. This single emitted pulse disperses in all directions of the target area, which significantly reduces the system's signal-to-noise ratio (SNR) while also capturing an image faster than traditional LiDAR. This technology is also capable of capturing multiple moving targets and generating three-dimensional images of the targets in the current surroundings. Downsides of flash LiDAR, however, are that the detecting distances and FOV are lower than that of the traditional method, therefore, it is not optimal for every LiDAR scenario. Figure 3 below depicts the differences between flash and scanning methods and the resulting image obtained with the two methods.

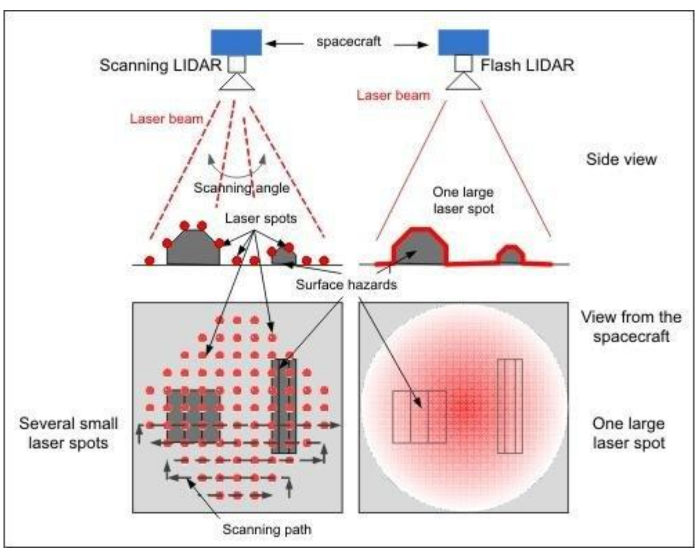


Figure 3: Scanning LiDAR vs. Flash LiDAR

This flash LiDAR system works as the source sends light out at the surface in one large laser spot, which is then captured as one image, with the color gradient representing the topography of the landscape. As only a single image is captured, in contrast to the scanning LiDAR method, the relative image capture time is significantly less.

2.2 Illumination System

The illumination area of the flash LiDAR system is dependent on the area of the source array. As such, the collimating optics within the system need to be picked and aligned according to the source. Once obtaining that, and knowing the final projection requirements, the focal length can then be calculated, using Equation 2. With the object space NA and effective focal length established, the system can then be effectively designed.

$$\frac{Source\ Half\ Width}{Collimator\ Focal\ Length\ (f_c)} = \frac{Central\ Projection\ Half\ Width}{Distance\ to\ Projection}$$

Equation 2

2.3 Imaging System

In order to fully develop this LiDAR system, an imaging module would be necessary to convert image data into depth data, by using one of the aforementioned 3D sensing methods. However, for the purposes of this project, this design will solely focus on the illumination module and the means to obtain the image data. The data can be analyzed according to the user's preferences.

2.4 Applications

Flash LiDAR can serve a multitude of purposes from tracking real world objects to obtaining depth information. In recent years, increased attention has been devoted to developing LiDAR technology to serve the purpose of drone tracking, facial recognition, and predominantly self-driving cars. With this, the automotive and aerospace industries have been the leaders in the development and use of LiDAR and flash LiDAR technology, due to the ongoing replacement of all existing radar-based instruments.

The change from radar to LiDAR has been monumental on account of the significant improvements LiDAR provides. For example, radar cameras in vehicles provide poor depth information, poor resolution, and can easily be affected by exposure to sunlight, as seen with backup cameras. Furthermore, they have angular resolutions of 3° at most, making object detection challenging. LiDAR cameras have been shown to account for these weaknesses by providing high resolution images to 0.1°, while also being immune to most environmental conditions.

The aerospace industry has been seen to have some of the most groundbreaking use of LiDAR, in terms of its novelty and the scale on which these technologies have been developed. Airborne LiDAR has been used for decades to survey ground targets, allowing the capture of an extensive target area in a very short time period, as seen in Figure 4, in which the flight here is scanning the terrain at a height of least 10,000 feet, while moving faster than any ground vehicle. The use of high-resolution 3D images also provides simplicity to spaceflight docking procedures and locating space debris, as ToF based pulsed lasers can obtain distance measurements on the order of microseconds.

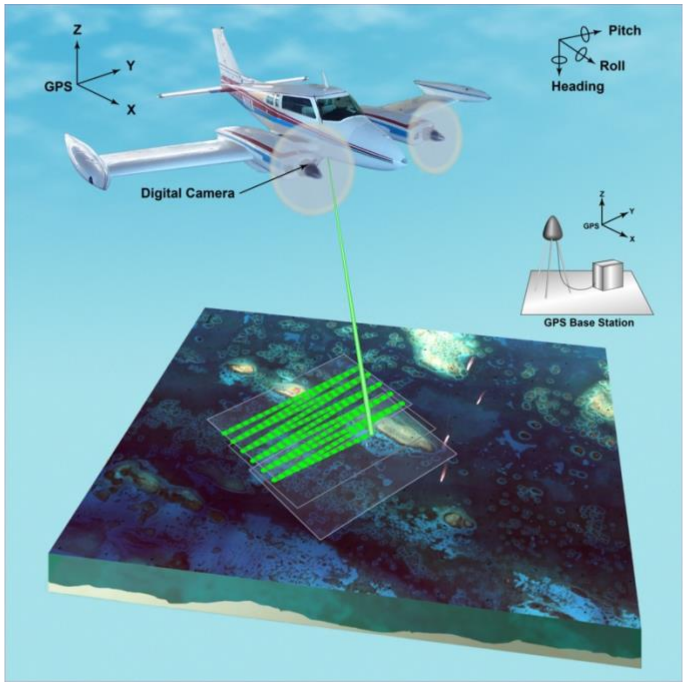


Figure 4: Airborne LiDAR

Brand new LiDAR based applications are being created every day as seen with Ball Aerospace's efforts for example. One of their new systems, called LOAMS (LIDAR Orbital Angular Momentum Sensor) will assess “unique angular momentum effects of light beams as they hit and interact with particles and molecules in the atmosphere” (Ball). Another system being developed measures components of vector wind fields by using two lasers and two telescopes pointing in two directions at the same time to study the impacts of aerosol (including pollution, dust, and smoke transport), on the Earth's energy and water cycles, air quality and climate (Ball). These new developments show that this technology can not only save time for data collecting but the promise for LiDAR in coming years, as it can provide and analyze real-time data of Earth and space that has been otherwise hard to collect.

3 OPTICAL MATERIAL

3.1 PMMA

Polymethyl methacrylate (PMMA) is a transparent plastic material also known also as acrylic polymer that is used for various purposes such as phone displays and car windows. Key reasons for this include its high optical quality, low cost, tensile and flexural strength as well as its resistance to UV light and other atmospheric conditions, making it a malleable and resilient plastic. It serves as the ideal compact and cost-effective alternative to glass as well as plastics such as polycarbonate. Limitations for this material, however, include poor impact resistance, limited heat resistance and potential cracking under load pressure. Nevertheless, the properties of PMMA make it one of the optical industry standards for polymeric optical elements.

The initial design for this system included PMMA as a reference material to determine how the system could be built for generic purposes. By creating the system with PMMA and then implementing the material of interest, the system was able to be designed to be faster, as the number of elements and overall size of the system remained relatively the same.

3.2 POLYCALC – N5

The material that will be used in place of PMMA for this design will be Polycalc-N5. This medium has a refractive index of 1.7525, compared to PMMA’s 1.4918. One reason for the use of this material is that due to the increase in index value, the overall size of the elements will decrease, allowing for a more compact system. The index difference can be seen in Figure 5, where a typical optical polymer is compared to Polycalc. The letters "NIR" are magnified to be about 50% larger in the Polycalc case. By using this material, details of the target can be discerned without foregoing significant size constraints.

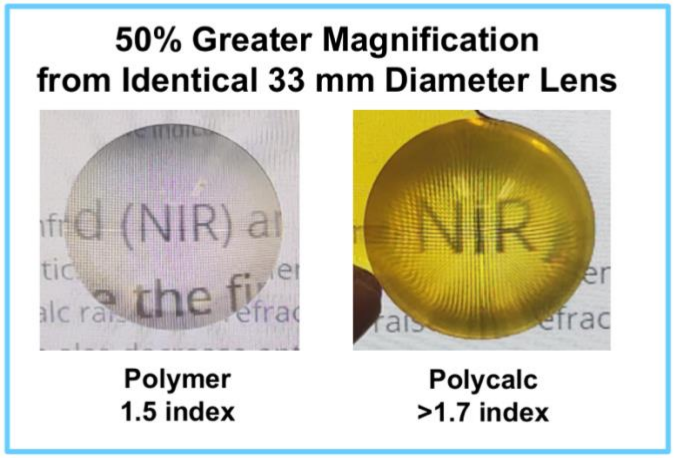
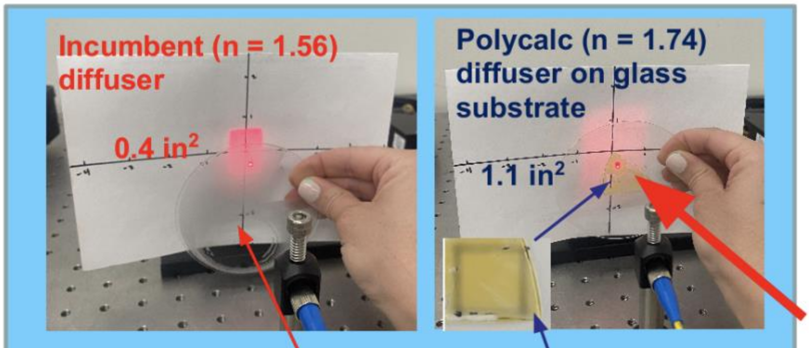


Figure 5: Traditional polymer vs. Polycalc-N5

Polycalc's structure allows for it to be produced using low-cost materials while being wafer scalable, which permits fast, high yield production. Additionally, the properties of Polycalc-N5 allow for high thermal stability which can be a significant consideration in the case of outdoor, consumer electronic, and automotive applications. Furthermore, the illuminated area using this material as a diffuser is notably increased, compared to typical optical polymers as seen in Figure 6.



Material/Index	Acrylate/1.56	Polycalc/1.74
Field-of-View	74° x 53°	102° x 84°

Figure 6: Illuminated area test

When comparing popular existing materials to Polycalc, Figure 7 shows that this new material prevails in the category of image quality, environmental effects, scalability as well as the previously mentioned cost and refractive index. The current materials are applicable in specific circumstances; however, each has a critical flaw. In relation to glass, the production of it, specifically the molding, is relatively expensive and time consuming. With conventional polymers, there is typically a scaling issue, as they are made using injection molding, which permits polymers of only one size to be produced. If the size is to be changed, another injection molding module with different specifications is needed. Polycalc, on the other hand, relies on wafer molding, in which the wafer size can be increased using the same machine to increase the number of optical elements produced, ultimately reducing the complexity of production. Finally, with metalenses, a blur is produced when imaging a target due to the properties that metasurfaces use to focus light.

Consequently, Polycalc is the most well-rounded material for near infrared imaging and LiDAR applications.

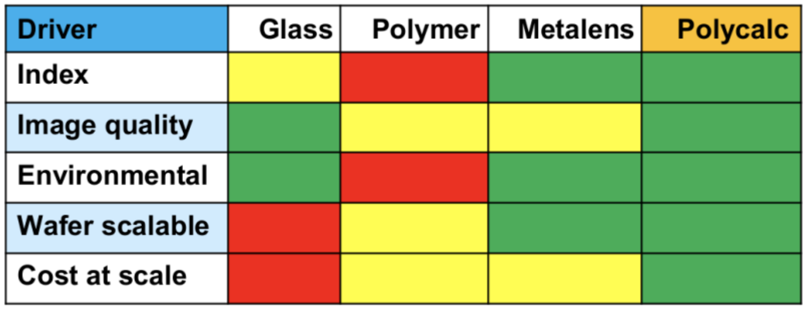


Figure 7: Optical material property comparison

4 PRELIMINARY DESIGN

4.1 Goal

The ultimate goal of this project was to create a novel lens system that can track objects and environments in real-time while scanning in the SWIR range (940 nm). Additionally, the system had the requirements of being portable, cost-effective, and built with as few lens elements as possible. The preliminary design that is laid out below follows a sequential transmitting flash LiDAR system set to project at a meter's distance. Furthermore, the object space numerical aperture and source active area dimension in the system are 0.2 and 1.6 mm x 1.6 mm, respectively, representing common industry values.

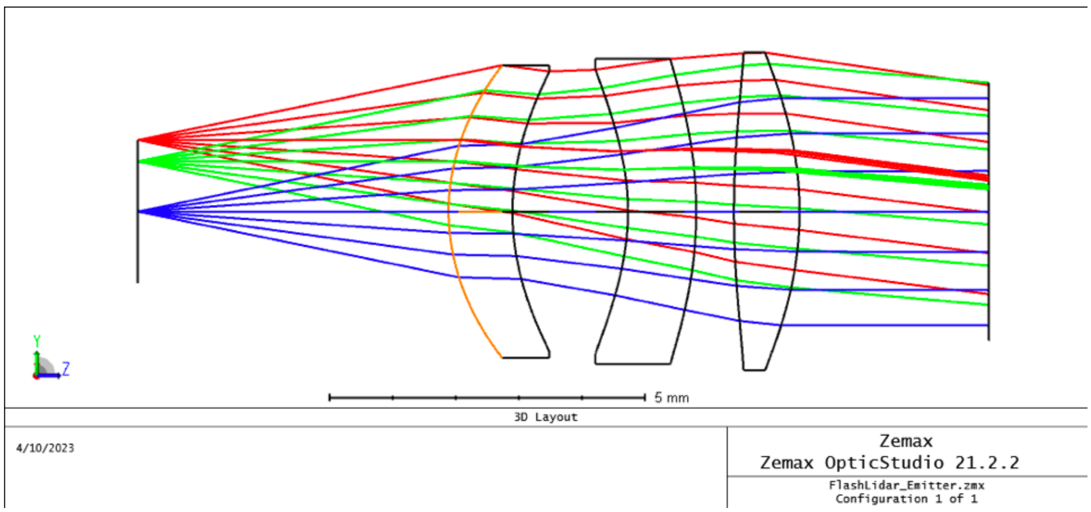
4.2 Design

Table 1 displays the number of elements, lens thicknesses/radii and the material being used (PMMA). The lens design manager (LDM) set up the basis for optimization as well as the template for which the final design would be drawn up from. This aspheric system displays the optimal setup for a straightforward flash LiDAR system.

	Surface Type	Comment	Radius	Thickness	Material	Coating	Clear Semi-Dia	Chip Zone	Mech Semi-Dia	Conic	TCE x 1E-6	2nd Order Term	4th Order Term	6th Order Term	8th Order Term	1
0	OBJECT Standard ▾		Infinity	4.929 V			1.131	0.000	1.131	0.000	0.000					
1	STOP Even Asphere ▾		3.327 V	1.013 V	PMMA		2.311	0.000	2.311	-0.273 V	-	0.000	-9.605E-04 V	-1.096E-04 V	8.007E-06 V	
2	Even Asphere ▾		4.004 V	1.833 V			2.215	0.000	2.311	-0.844 V	0.000	0.000	-9.865E-04 V	4.782E-05 V	-2.699E-05 V	
3	Even Asphere ▾		-3.850 V	1.082 V	PMMA		2.242	0.000	2.412	-5.516 V	-	0.000	-1.372E-03 V	1.427E-04 V	5.565E-06 V	
4	Even Asphere ▾		-6.733 V	0.600 V			2.412	0.000	2.412	1.508 V	0.000	0.000	-3.998E-04 V	4.788E-04 V	-1.611E-05 V	
5	Even Asphere ▾		16.054 V	1.040 V	PMMA		2.500	0.000	2.511	-3.401 V	-	0.000	2.629E-04 V	-3.037E-04 V	1.351E-05 V	
6	Even Asphere ▾		-5.428 V	3.000			2.511	0.000	2.511	-5.495 V	0.000	0.000	-3.348E-03 V	2.985E-04 V	-4.498E-06 V	
7	Standard ▾		Infinity	1000.000			2.038	0.000	2.038	0.000	0.000					
8	IMAGE Standard ▾		Infinity	-			141.335	0.000	141.335	0.000	0.000					

Table 1: Preliminary design LDM

Figure 8 shows a six-element system that was optimized to yield a collimated output across the field of view to ensure that dots across the source array area were of reasonable size on the scene of interest. Although the system is meant to be observed in the far-field, at a distance of one meter away, the results of the fields at Surface 7 (displayed by the solid vertical line at the far-right end of the system) can represent the performance of the spots



at the far-field, due to the multitude of aberrations that will be in play in this system. The far-field illumination produced from this system is then displayed in Figure 9 as a measure of how the scanning spots will establish themselves.

Figure 8: Preliminary design near-field layout

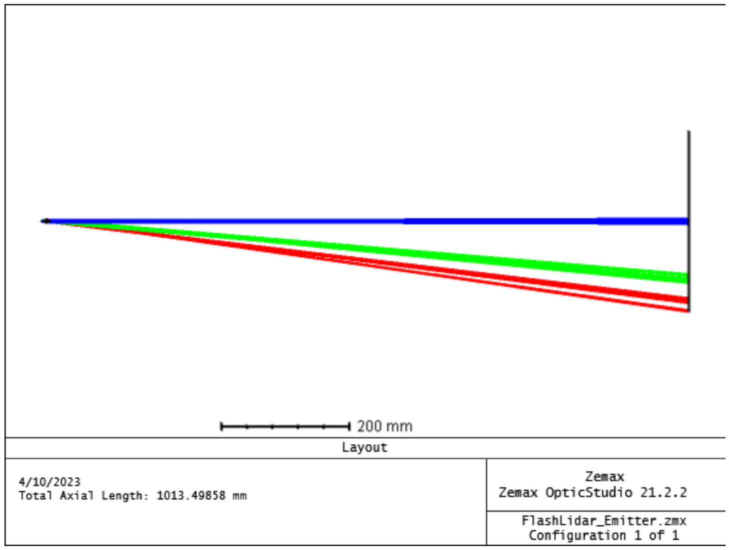


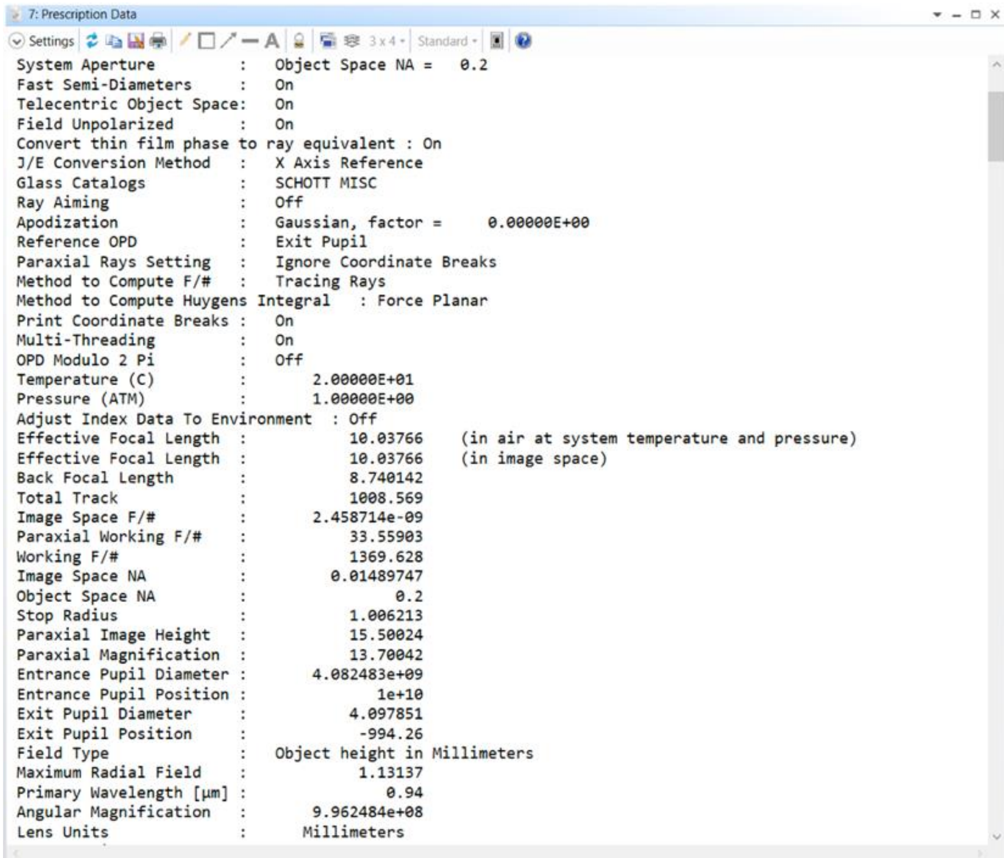
Figure 9: Preliminary design far-field layout

4.3 Numerical Aperture

The numerical aperture of the system is set at a value of 0.2, as the source has not been finalized. This value will stay constant throughout the design iterations. With the emission NA set at 0.2 and the wavelength set at 940 nm (acting as control variables), the rest of the design will solely be based off how the material deflects light within the system.

4.4 Prescription Data

The detailed information about the specifications of the system is laid out in the prescription data, Figure 10, which highlight the important factors that will be used to compare this design to the final design. Additionally, the system explorer data shown in Figure 1, displays the control variables of the system, such as wavelength, field data and the relative weights that will be used to check the final design.



```
System Aperture          :   Object Space NA =    0.2
Fast Semi-Diameters      :   On
Telecentric Object Space:    On
Field Unpolarized        :   On
Convert thin film phase to ray equivalent : On
J/E Conversion Method    :   X Axis Reference
Glass Catalogs           :   SCHOTT MISC
Ray Aiming               :   Off
Apodization              :   Gaussian, factor =      0.00000E+00
Reference OPD            :   Exit Pupil
Paraxial Rays Setting    :   Ignore Coordinate Breaks
Method to Compute F/#    :   Tracing Rays
Method to Compute Huygens Integral    : Force Planar
Print Coordinate Breaks :    On
Multi-Threading          :   On
OPD Modulo 2 Pi          :   Off
Temperature (C)          :       2.00000E+01
Pressure (ATM)           :       1.00000E+00
Adjust Index Data To Environment  : Off
Effective Focal Length   :           10.03766     (in air at system temperature and pressure)
Effective Focal Length   :           10.03766     (in image space)
Back Focal Length        :           8.740142
Total Track              :           1008.569
Image Space F/#          :       2.458714e-09
Paraxial Working F/#     :           33.55903
Working F/#              :           1369.628
Image Space NA           :         0.01489747
Object Space NA          :                0.2
Stop Radius              :           1.006213
Paraxial Image Height    :           15.50024
Paraxial Magnification   :           13.70042
Entrance Pupil Diameter :        4.082483e+09
Entrance Pupil Position :               1e+10
Exit Pupil Diameter      :           4.097851
Exit Pupil Position      :            -994.26
Field Type               :   Object height in Millimeters
Maximum Radial Field     :            1.13137
Primary Wavelength [µm] :                0.94
Angular Magnification    :       9.962484e+08
Lens Units               :      Millimeters
```

Figure 10: Preliminary design prescription data

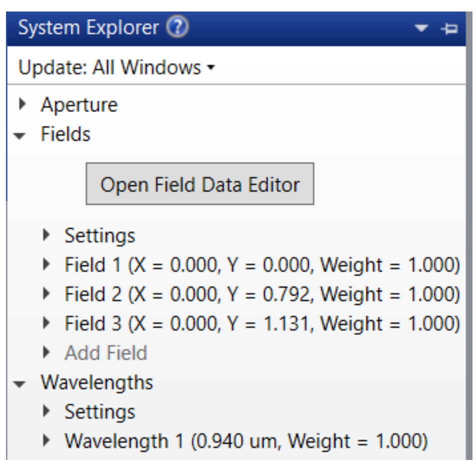


Figure 11: Preliminary design system explorer

5 FINAL DESIGN

5.1 Design

The updated design is based upon the preliminary design and includes the new material, Polycalc-N5, with the primary goals of creating a more compact design or increasing the numerical aperture. The lens design manager with the respective thicknesses and radii for each surface are seen below in Table 2. The object NA and source dimension of this system stay constant when compared to the preliminary design.

Surface 0 Properties — Configuration 1/1

	Surface Type	Comment	Radius	Thickness	Material	Coating	Clear Semi-Dia	Chip Zone	Mech Semi-Dia	Conic	TCE x 1E-6	Par 1(unused)	Pa	Pa	Par 4(unused)	Par 5(unused)
0	OBJECT Standard		Infinity	4.765 V			1.131	0.000	1.131	0.000	0.000					
1	STOP Even Asphere		3.257 V	0.780 V	POLYCALC-N5		2.261	0.000	2.261	-0.294 V	-	0.000	-1...	-1...	-6.240E-05 V	0.000
2	Even Asphere		3.861 V	1.341 V			2.179	0.000	2.261	-0.809 V	0.000	0.000	-9...	4.4..	-4.530E-06 V	0.000
3	Even Asphere		-3.837 V	0.739 V	POLYCALC-N5		2.216	0.000	2.423	-4.155 V	-	0.000	-1...	1.8..	4.308E-05 V	0.000
4	Even Asphere		-7.321 V	0.150 V			2.423	0.000	2.423	2.043 V	0.000	0.000	-1...	4.6..	-3.580E-05 V	0.000
5	Even Asphere		32.716 V	1.045 V	POLYCALC-N5		2.533	0.000	2.569	-26.... V	-	0.000	-1...	-2...	2.670E-05 V	0.000
6	Even Asphere		-4.949 V	3.000			2.569	0.000	2.569	-7.223 V	0.000	0.000	-2...	2.7..	-1.696E-05 V	0.000
7	Standard		Infinity	1000.000			1.981	0.000	1.981	0.000	0.000					
8	IMAGE Standard		Infinity	-			161.968	0.000	161.968	0.000	0.000					

Table 2: Final Design LDM

Next, one can see how this data is displayed in a two-dimensional view (Figure 12), with the source displaying three different fields, to draw comparison with the preliminary model. As the index of Polycalc-N5 is greater than that of PMMA, the elements were able to be moved closer together when compared to the preliminary design. In addition, the far-field view displayed in Figure 13 shows the three fields still displayed at a meter away. The difference is that the fields are more concentric, providing a more focused scan pattern. This will also allow for easier translation to depth data once the image data is captured for additional processing.

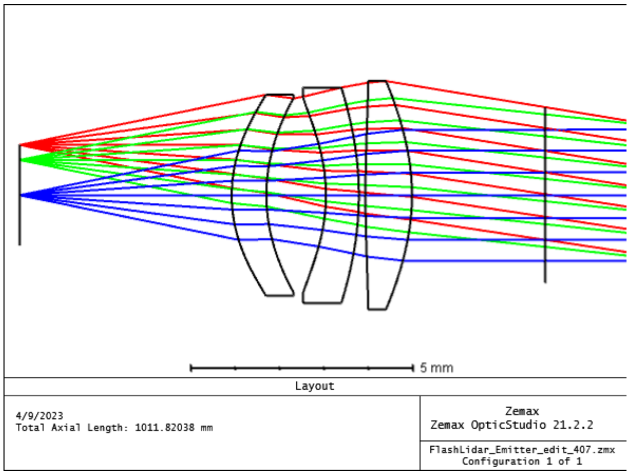


Figure 12: Final design near-field layout

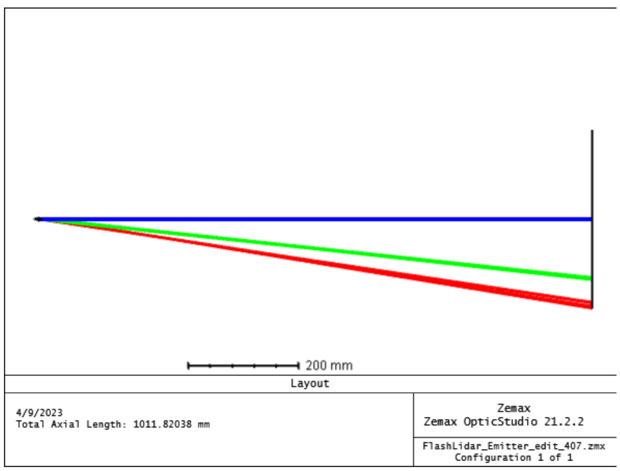


Figure 13: Final design far-field layout

5.2 Package Volume

While both the preliminary and final designs have the same overall system projection length of a meter, what can be noted is the smaller package size of the final design. After considering the higher index material, the package length has decreased to approximately 4 mm, or 1.3x smaller.

Although constraining the size of the system is beneficial to the goal of the project, manufacturing it yields complications. To produce elements at the size suggested requires careful effort with an increased likelihood of error. One potential solution to this issue is to use an integrated mounting system that allows for easier assembly with lenses at this scale.

5.3 Numerical Aperture

A significant difference between the two designs presented is the aperture size, which was optimized to be as large as possible with the custom material. The new design has an image space NA of approximately 1.5x larger than the preliminary design which signifies a larger range at which the system can convey light. This in turn allows for fewer LiDAR modules needed to obtain the same scanning region, which reduces the overall cost and size of the system as well.

5.4 Prescription Data Comparisons

	Preliminary Design	**New Design**
Effective Focal Length (EFL)	10.03766	7.62716
Angular Magnification	$9.96 * 10^8$	$1.31 * 10^9$

Numerical Aperture	0.0746	0.1145
Size (mm)	5.5624	4.0783

Table 3: Design improvements

The primary differences between the two designs are shown in Table 2 above, in which the magnification, NA and size of the Polycalc-N5 system are all significantly better than the PMMA design, which was our goal. Diving into the details, most of the statistics were able to be taken from the prescription data shown in Figure 14, however, the NA was calculated according to Equation 3. Furthermore, to show that the systems were identical in other aspects, proving that the material was the cause for the better performance, the fields, wavelength, and object space aperture are shown in Figure 15.

$$NA = nsin(\arctan\left(\frac{1}{2 * F/\#}\right))$$

Equation 3

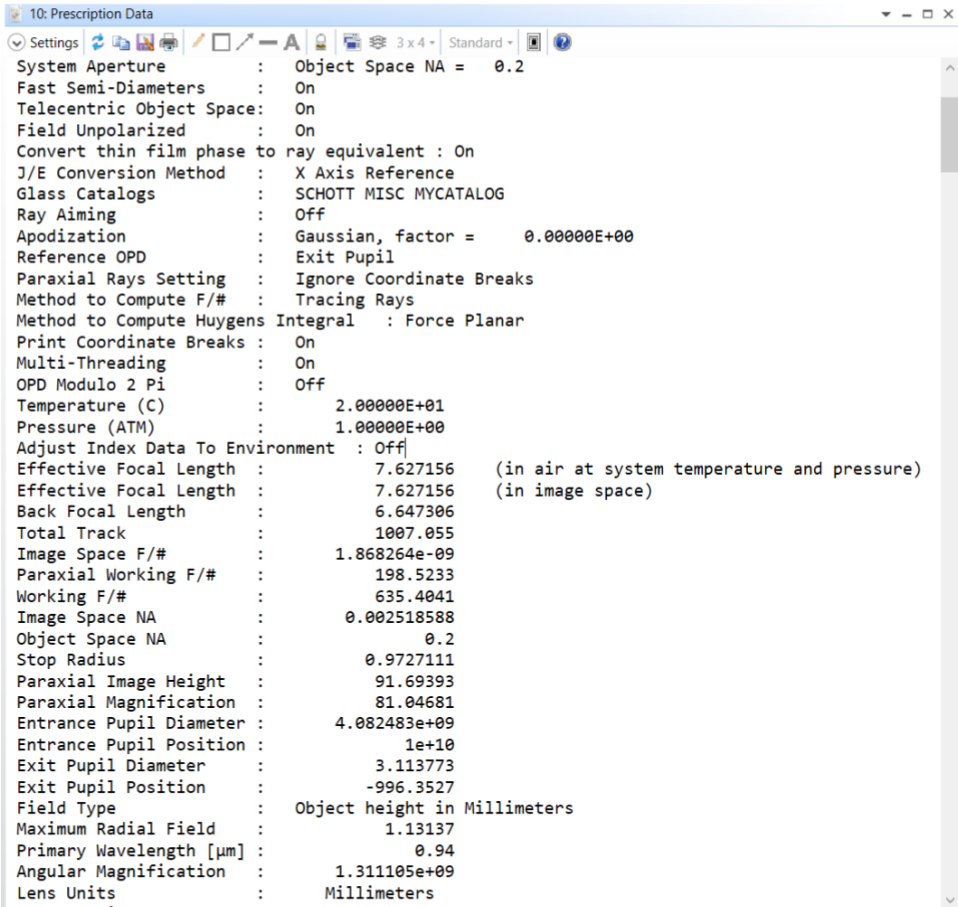


Figure 14: Final design prescription data

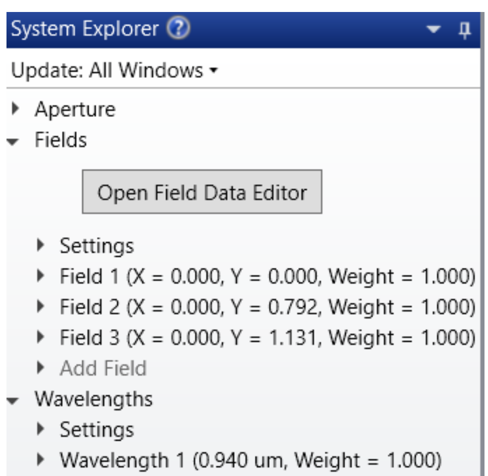


Figure 15: Final design system explorer

6 CONCLUSION

The ultimate intent of this project was to determine if Polycalc-n5 would be a viable material to use in a flash LiDAR system and determine if it would be beneficial to use over existing polymers. From the final lens design model, it can be discerned that this system is not only functional, but also saves space and provides the user with a larger numerical aperture than before. While the fabrication of the system is the only matter in question, there are ways to produce the system at reasonable cost. As such, a flash LiDAR can indeed be created using this previously shown design in figure 12.

Future work that can be implemented with this design include creating multiple projections and increasing the field of view. As this final design focuses on one projection at the (0,0) order, one additional alteration of this design could be to add more projections as shown in Figure 16. By incorporating multiple diffraction gratings into the system, projections at different orders can be instilled to create an array of images in whatever desired sequence needed.

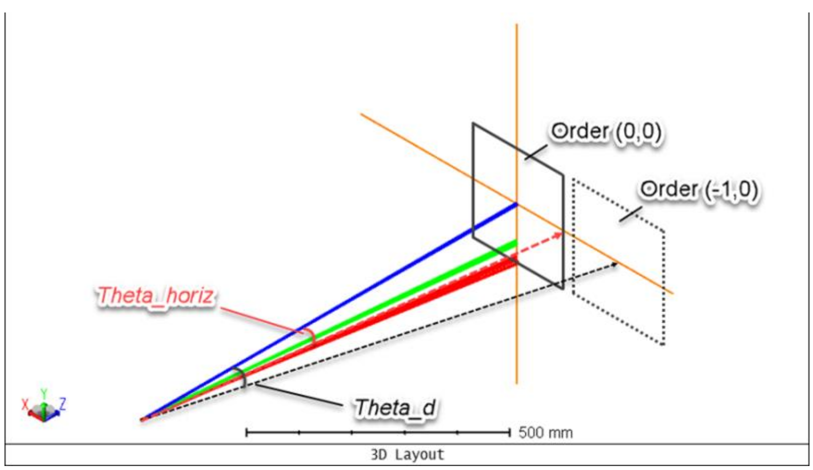


Figure 16: Potential far-field layout with diffraction grating system

Another plan to improve the functionality of this system would be to increase the field of view, by adding a receiver module into the system. The resulting effect is shown in Figure 17. Although this may increase the package size of the LiDAR unit, the FOV increase may be justifiable depending on the needs of the system.

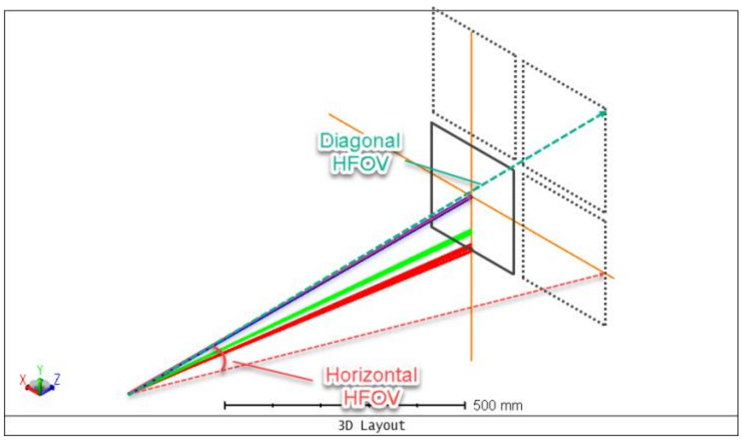


Figure 17: Potential far-field layout with receiver system

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