**Miniature Optical Steerable Antenna for Intersatellite Communications Liquid Lens Characterization**

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Miniature Optical Steerable Antenna for Intersatellite Communications Liquid Lens Characterization

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Abstract—Laser communication (lasercom) can enable more efficient links across larger distances compared with radio frequency (RF) systems. However, lasercom systems are typically point-to-point connections that would have difficulty interacting with several concurrently active spatially diverse users, where RF systems can more easily support such scenarios.

Lasercom pointing, acquisition and tracking (PAT) systems have traditionally relied on mechanical beam steering devices, such as fast steering mirrors (FSMs) or gimbals, both of which are subject to potential mechanical failure. In this work we investigate an alternative steering solution using liquid lenses. Liquid lenses are tunable lenses that can non-mechanically alter focal length based on an applied voltage or current. A series of liquid lenses can be used to control beam divergence, and one each offset in the x and y-axes to steer, could be used to achieve laser pointing control. Currently available commercial off the shelf (COTS) liquid lenses are based on electrowetting (manufactured by Corning [1]) or pressure-driven (manufactured by Optotune [2]) operation. In this work, we analyze the suitability of both types of liquid lenses for use in a space-based multiple access lasercom terminal.

Early liquid lens technology first surfaced in 1995 with the control of the shape of an oil droplet through electrowetting [3]. The technology then started to become commercially available with the founding of Varioptic in 2002. However, there is limited data on liquid lens survivability and operation in a space-like environment. Through vacuum testing, we have found that electrowetting-based liquid lenses not only survive, but continue to operate nominally in a very low-pressure environment. The pressure-driven liquid lenses appeared to have issues initially in vacuum testing, with gas bubbles forming in the lens aperture during pump-down. However, after extended exposure to vacuum of approximately two weeks, the gas bubbles diffuse through the lens membrane, and the lenses operate in vacuum.

Steering transfer functions were developed both in ambient and in vacuum conditions for both lens types, and in each case, the differences between the two curves were largely negligible. The electrowetting lenses provide a steering range of 2.7°, both in and out of vacuum, with an approximate slope of 0.046°/V. In testing the Optotune lenses, the steering was limited by the camera detector size, but for a range of -92 mA to 144 mA on the steering lens, the lenses provided for approximately 8.6° of steering with a slope of 0.0367°/V. These steering ranges can be extended to near hemispherical coverage with the addition of a diffuser and wide-angle fish-eye lens [4]. Maximum hysteresis error, the difference in steering angle response when increasing lens voltage or current as opposed to decreasing lens voltage or current, was identified at 0.02° for the Corning lenses and 0.05° for the Optotune lenses. A Zemax beam quality analysis was conducted to see how transmit gain would be affected by refraction through the liquid lenses. Through this analysis, the worst-case link penalties were determined to be -0.5 dB for the Corning lenses at -0.8° steering and -0.4 dB for the Optotune lenses at -1.0° steering. Thus, we see that liquid lenses are likely good candidates for space applications and may perform well in nonmechanical beam steering. We discuss next steps in environmental testing as well as optical layout and control approaches for using liquid lenses in PAT systems for a nanosatellite based optical antenna.

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1. INTRODUCTION

Satellite laser communications provide higher power efficiency and use a currently unregulated part of the spectrum. For many applications, such as distributed sensing, satellites must perform crosslink communications, rather than just uplink and downlink. The major disadvantages of laser crosslinks is the need for more precise pointing and tracking control techniques and the difficulty in achieving broadcast or multicast operation.

Large satellites can use mechanical devices, such as gimbals and motors, to point their transmitter and/or receiver in the right direction. Small satellites, on the other hand, don’t have enough space, allowable mass, and spare power to host those devices, however, because they typically have fewer payloads, they can body-point the spacecraft to support the link.

There is a need for a compact – preferably non mechanical – beam steering device capable of pointing lasers from small satellites. This paper focuses on using liquid lenses to address this challenge.

Liquid lenses are variable focal length lenses that are actuated with applied voltages or currents. By refracting laser light through decentered liquid lenses, beam steering can be achieved. Through a carefully designed optical system incorporating liquid lenses, an omni-directional laser antenna capable of hemispherical coverage could be developed. This would allow for independent laser steering and spacecraft attitude control for small spacecraft.
There are currently two manufacturers of Commercial off The Shelf (COTS) liquid lenses. Prior to this work, the lenses had not yet been tested for space laser communications. The goal of this work is to raise the Technology Readiness Level (TRL) of the lenses in space applications from TRL 1-2 to TRL 4 by testing them in a space-like environment and demonstrating longer lifetime than typical mechanical solutions.

2. BACKGROUND

Optical communication systems use light to transmit information. A key technology that enables the use of laser communication is that which steers the laser beam to the receiver. In space, coarse-pointing is traditionally done with body pointing of the satellite, but adding a fine-pointing capability allows for faster data rates [5]. Most systems use a mechanical fine pointing system to allow the transmitter to precisely steer the beam to the receiver [6]. Coarse-pointing will traditionally have a much higher field of regard that the fine-pointing system [7]. The use of optical communication in CubeSats has been demonstrated [8], but those systems lacked the fine-pointing capability needed for higher data rates. A novel beam steering technique is to use tunable liquid lenses, as demonstrated by Zohrabi, to allow 2-D beam steering [4]. Their system used liquid lenses in combination with a diffuser and fish-eye lens to demonstrate ±75° beam steering with controlled beam divergence using a series of three pressure-driven Optotune lenses. This project looks to add high field of regard (±180°) to a CubeSat through the use of non-mechanical steering devices (liquid lenses) and also to evaluate the ability of this approach to support multiple concurrent spatially diverse links.

3. APPROACH

Functional Description

The core principle behind non-mechanical laser beam steering using liquid lenses is allowing the light to refract through off-axis deformable lenses. By adjusting the focal length of these off-axis lenses, the laser is refracted through different angles. To achieve two-dimensional steering, three lenses are required. The first lens is placed on-axis to focus the beam and control “spot” size on the camera detector, while the second and third lenses are displaced slightly in the x and y axis, respectively, to steer in those two directions. For the purposes of these initial experiments, just two of each type of liquid lens will be utilized for simplicity in control algorithms and software. This allows for analysis of the one-dimensional steering capability of each type of lens.

For these tests, a Raspberry Pi v3 is connected to two liquid lens drive boards, provided by the lens manufacturers, in order to focus and steer the beam in one axis. In the case of the Corning lenses, a voltage is held through a PWM controller to set the lens curvature [1]. In the case of the Optotune lenses, a current is applied to a voice coil that pushes on the liquid lens and sets the lens curvature [2].

A mvBlueFox-IGC camera is used to collect data on beam steering angle, while also providing control feedback to monitor and minimize the laser spot size on the camera detector. The camera is placed at the end of the staged liquid lenses in order for the refracted light to strike the camera detector. The laser spot size is controlled by adjusting the voltage or current on the on-axis liquid lens. The location of the spot provides data on beam steering angle, while the spot size yields the beam divergence.

The integrated temperature sensor in the Optotune lenses will be used to develop thermal heat dissipation models for the liquid lens. Since these lenses are provided high current, heating could pose a large issue, especially in vacuum. Temperature concerns are less of an issue on the Corning lenses due to very low power consumption, so thermal testing is limited to the Optotune lenses for these tests.

System Diagram

Description of Models and Equipment

Sensors—The beam measurements are made through an mvBlueFOX-IGC camera. The camera is used to determine the steering angle of the laser, as well as provide feedback for the focusing lens to minimize spot size on the camera detector. This model is a USB-2.0 camera targeted for space applications with a CMOS detector. The Optotune lenses have an STTS2004 memory module temperature sensor built-in to monitor the temperature of the lenses during operation. The STTS2004 temperature sensor has a resolution of 0.25°C.

Software Tools—The software used to control the Corning and Optotune lenses and interface with the mvBlueFOX camera is written in C++. This software controls lens voltages and currents and finds the centroid of the laser spot on the camera detector. The size of this spot is then used as control feedback for controlling the voltage or current to the focusing lens. Ze-max was the software used to model the optical performance of the lenses. Corning and Optotune supplied Zemax models of their lenses, which were used to quantify beam quality and divergence through the optical train. SolidWorks was used to design the mounts for both the Optotune lenses as well as the Corning lenses.

Other Hardware—The first liquid lens under analysis is the Optotune SY-EL-16-40-TC-VIS-20D pressure driven liquid lens. This lens has a 16 mm aperture with a tuning range of -10 diopters to 10 diopters. The operating temperature range for this lens is -20°C to 65°C. The lens is composed of an optical fluid housed in a thin transparent membrane. To change the curvature of the lens, a ring pushes against this membrane, forcing the lens to change shape. This mechanism is illustrated below in Figure 2. This image was provided in the Optotune SY-EL-16-40-TC-VIS-20D data sheet [2]. The lenses are controlled with USB drivers provided by the manufacturer.
The second liquid lens is the Corning Varioptic A-39N0 electrowetting liquid lens. This lens has a 3.9 mm aperture with a tuning range of -5 diopters to 15 diopters. The operating temperature range for this lens is -20°C to 60°C. The lens is composed of an oil droplet submerged in an electrolyte. As voltage is applied between the electrolyte and electrode, the oil is forced into different curvatures. This mechanism is illustrated below in Figure 3. This image was provided in the Corning Varioptic data sheet [1]. The lenses are controlled with USB drivers provided by the manufacturer.

The most useful test we would like to perform is to characterize how the steering system, based on liquid lenses, affects the divergence of the beam that is being steered. Multiple factors support that this study is essential: a) decentered lenses contribute to wavefront errors, and b) the liquid lenses are of spherical shape - the more voltage applied, the lower the radius of curvature of the sphere, which means that spherical aberration will increase as the laser is steered towards higher angles. Both of these should negatively impact the laser beam quality and cause error in the beam divergence.

A common factor used to describe the quality of a laser beam is called $M^2$, also known as the beam quality factor. $M^2$ is a unitless number that describes how close a laser beam is to an ideal Gaussian beam. If $M^2$ is exactly one, the beam is Gaussian and will have ideal divergence and lowest diffraction. The higher the number is, the less Gaussian will the laser be, and the faster it will diffract, making its divergence higher.

However, due to the difficulty of determining the $M^2$ (or the beam divergence) on the real hardware precisely and without expensive equipment, we decided to perform the analysis within a Zemax optical simulation. This proved feasible as we were able to obtain Zemax models of both the Corning and Optotune lenses. The focus of this test was to produce a plot of the expected beam divergence error as a function of the steering angle (in a 2D steering setup) for both of the liquid lenses under analysis. To determine the $M^2$ factor and the final divergence angle, we utilize the Zemax Physical Optics Propagation (POP) toolbox, which propagates the wave through each optical surface - from the optical fiber all the way to the output aperture - taking into account diffraction and aberration at each surface.

4. Results

Survivability Testing
Both the Corning Varioptic A39N0 electrowetting liquid lens and the Optotune EL-16-40-TC pressure driven liquid lens were subjected to a soft vacuum of approximately 5 Torr
for a period of 72 hours. Baseline steering results were collected prior to vacuum and immediately after removal from vacuum. In addition, pictures and video were recorded prior to, during, and after vacuum testing to identify any obvious visual changes in lens appearance.

Figure 4. Corning A39N0 in soft vacuum.

In soft vacuum, the Corning lenses did not undergo any visually apparent physical changes. No liquid leaks occurred and there were no obvious deformations in the lens aperture. An image of the lens in soft vacuum can be seen in Figure 4.

The beam steering capability of the Corning lenses from pre, post, and three days post vacuum testing are all shown in Figure 5. The lenses were commanded to six focused settings for ten seconds each. Only one lens, the steering lens, was exposed to vacuum in order to minimize potential damage to hardware.

Although not depicting identical performance, this data verifies operability and the same basic performance of the lens after being exposed to the vacuum environment. It is important to note that this figure does not definitively show that the lenses had altered performance after vacuum. There are many factors that could have affected these results, including mechanical changes to the system alignment when extracting and inserting the lens into the optical setup.

Figure 5. Corning A39N0 vacuum survivability.

The Optotune lenses, on the other hand, underwent obvious physical changes during initial exposure to soft vacuum. While pumping down the chamber, large bubbles gradually began to form in the lens aperture. This is shown in Figure 6. When the chamber was returned to ambient conditions, the size of the bubbles decreased slightly, but did not vanish entirely, even after sitting in ambient conditions for 24 hours. The lens was again exposed to the soft vacuum, and the same result occurred.

Figure 6. Optotune EL-16-40-TC in soft vacuum.

However, after extended vacuum exposure of two weeks, the gas molecules diffused through the lens membrane, and no more bubbles formed during subsequent vacuum exposure. The survivability test was repeated, and the results are shown in Figure 7.

Figure 7. Optotune EL-16-40-TC vacuum survivability.

Since these curves are almost identical, and no more bubbles formed in the lens aperture, the Optotune lenses passed basic vacuum survivability testing.

1-D Steering

Corning—For a 1 mm offset from the optical axis in the steering lens, the Corning A39N0 lenses are able to steer the beam in ambient conditions $1.31^\circ$ left of center and $1.41^\circ$ right of center. This results in a total steering range of $2.72^\circ$. In vacuum, these performance metrics are almost identical, with errors on the order of $1E^{-2}$°. These results are summarized in the Table 1.

Figure 8 depicts the steering capability of the Corning liquid lenses as a function of steering lens voltage, which ranges from 30 V to 59 V. The focusing lens is adjusted with an automated controller to find a corresponding voltage for a focused “spot” on the camera. This data depicts ten total sweeps of this voltage range.
Figure 8. Corning ambient steering as function of 1 mm offset steering lens voltage.

Figure 9. Corning ambient vs vacuum steering capability.

Table 1. Corning steering capability summary

|                | Ambient | Vacuum |
|----------------|---------|--------|
| Right Steer (30 V) | 1.4061° | 1.3930° |
| Left Steer (59 V)   | -1.3143° | -1.3151° |
| Total Steer         | 2.7204° | 2.7082° |
| Approx. Slope       | 0.0461°/V | 0.0459°/V |

This plot shows that for this small angle steering, the angle vs voltage curve is relatively linear, with an approximate slope of 0.0461°/V. The curve passes through 0° of steering angle at approximately 45 V, indicating that the lens is transitioning from concave to convex.

The test setup was transferred into a cylindrical vacuum chamber and brought to approximately 10^{-5} Torr. In vacuum, the voltage range from 30V to 59V was swept through four times. In Figure 9, the steering vs voltage plots for ambient and vacuum are overlaid in order to easily identify differences. For this range of voltages, the steering capability of the lenses is essentially the same. For the ten sweeps in ambient and four sweeps in vacuum, the curves are perfectly overlaid following the same approximately linear path. The slope of the vacuum curve has an approximate slope of 0.0459°/V, almost exactly that of the ambient performance. Figure 19 in Appendix A shows the vacuum steering capability with no ambient overlay.

This is an excellent result in the context of using these lenses for the space-based laser terminal. These lenses can be expected to perform similarly in the space environment, so drastic special considerations do not need to be taken in the design of the laser antenna.

The steering data can be further reduced by breaking the curves into two parts: one depicting increasing voltage and the other depicting decreasing voltage. Again, these curves follow almost identical paths, however, hysteresis can be identified in the region between 37 V and 40 V. This is shown in Figure 10.
Figure 10. Corning steering capability for increasing and decreasing voltage.

Figure 11. Corning ambient hysteresis zoom on region of interest.

Zooming in on the region around this voltage range, the hysteresis becomes clearer. As voltage is increased from 37.5 V to 40.5 V, the steering angle is consistently lower than when decreasing voltage. This is shown in Figure 11. The maximum identified hysteresis is approximately 0.02° occurring at 38.25 V. This is a very small error and should not pose a significant challenge in the full terminal design.

The same result can be seen when looking at the same region for vacuum performance. Vacuum hysteresis plots can be found in Appendix A.

Optotune—With a 5 mm offset from the optical axis in the steering lens, the Optotune SY-EL-16-40-TC-VIS-20D lenses have enough optical power to steer the beam off of the camera detector in the optical setup used. Thus, the lenses were not utilized to their full potential in this testing. However, for the current range of -92 mA to 144 mA, in ambient conditions, the beam deflection was 4.99° left of center and 3.67° right of center. This results in a total steering range of 8.67°. As with the Corning lenses, the vacuum performance was nearly identical to the ambient performance. These results are summarized in Table 2.

Table 2. Optotune steering capability summary

| Right Steer (-92 mA) | Ambient | Vacuum |
|----------------------|---------|--------|
| -4.9903°            | 3.5887° |
| Left Steer (144 mA) |         |        |
| -4.9996°            |         |        |
| Total Steer         | 8.6562° | 8.5882°|
| Approx. Slope       | 0.0367°/mA | 0.0367°/mA |

Figure 12 shows the steering angles provided by the Optotune liquid lenses for a 5 mm offset from the optical axis as current is varied between -92 mA and 144 mA. During this testing, the current of the focusing lens is adjusted in order to focus the laser spot on the camera detector. In Figure 12, ten sweeps of the voltage range are conducted, alternating between increasing and decreasing current.

The curve for steering angle as a function of applied current
follows a mostly linear path, although distinct sections of concave up and concave down can be seen, with the transition occurring at 0 mA. This is when the lens, in an ideal case, is completely flat with no optical power.

Over the ten sweeps, the transfer function remains largely constant. The angular error between passes is on the order of < 0.1° at the maximum. This is likely due to temperature fluctuations. As current is run through the lens, heating occurs. This slightly alters the steering transfer function due to the fluid expanding in volume, causing an increase in optical power, which, according to Optotune, is a linear relationship with temperature [2]. In the ambient testing, the temperature ranged from 19.75°C to a maximum of 22.0°C. The temperature rose steadily throughout testing due to the applied currents.

As was the case with the Corning lenses, the vacuum steering transfer function for the Optotune lenses has mostly the same features as the ambient steering transfer function. The vacuum curve is shown in Figure 20. The steering range is almost identical, and the same dual-concavity curve is formed. There are no significant variations between different passes through the current range. The temperature for vacuum testing increased steadily from 21.5°C to 23.125°C. This is actually less of a temperature increase than when testing in the ambient condition. This is a surprising result since the heat generated from lens operation has a more difficult time dissipating in vacuum.

In Figure 13, the vacuum and ambient steering transfer functions for the Optotune lenses are overlaid. For this range of applied currents, the steering is almost identical for the range of ~100 mA to 100 mA. Above this range, the curves seem to diverge, with the vacuum condition producing larger steering angles for a given applied current. This difference is likely a result of the higher lens temperature in vacuum. There is no atmosphere to cool the lenses through convection, so the average lens temperature was higher when testing in vacuum. The higher optical power at higher temperatures is consistent with this result.

Thus, the differences in steering between vacuum and ambient, and even consecutive sweeps in vacuum or consecutive
sweeps in ambient, can largely be attributed to fluctuations in lens temperature. The optical power variations are minor, and, in the context of using these lenses as the basis for an optical hemispherical antenna, can be negated with a sufficiently tuned controller.

The steering data was again divided between increasing and decreasing current in order to identify hysteresis. Hysteresis was identified in the current range from 50 mA to 100 mA. This is shown in Figure 14.

Thus, it can be seen that for increasing current, optical power seems to be slightly higher than for decreasing current. Realistically, this difference is very small, and should be negligible in beam steering applications with a suitable controller. Maximum hysteresis is 0.05° occurring at 90 mA.

**Thermal Testing**

The Corning lens did not undergo thermal testing since they operate on the electrowetting principal which is based on voltage differences, which do not draw large currents like the Optotune lens (the cause of heating in the Optotune lenses). The Optotune lens was set to the maximum current allowed in the driver software (294 mA) and the temperature was tracked using the temperature sensor built into the lens. This test was performed in the ambient environment due to the complications that arose with the initial vacuum testing of the Optotune lenses. The lens temperature followed a first-order heating response that took around 30 minutes to reach its steady-state temperature of 45°C. The software has an ability to set the maximum operating temperature of the lens (which was set to 45°C). As the lens reached 45°C, the software held the current constant, even as 45°C was surpassed. In Figure 15, the temperature response due to constant current input can be seen.

**Zemax Beam Quality Testing**

To characterize the beam quality, two Zemax models were developed, one for the Corning electrowetting lenses, and one for the Optotune pressure-driven lenses, both in a similar 2D steering configuration with the first lens controlling the output beam collimation and the second decentered lens controlling the beam steering angle.
Figure 16 shows how the steering lens voltage impacts both the beam quality and beam divergence. From the 1-D steering tests conducted earlier, the region around 45 V is where no beam steering occurs. As expected, the least beam aberrations occur at low steering angles centered around 45 V. The far extremities of this plot show the $M^2$ value rapidly increasing above 5 V and below 35 V.

Another surprising result is the effect the liquid lenses have on beam divergence. Beam divergence actually gets lower as steering lens voltage increases. This is because for high steering lens voltages, the focusing lens must expand the beam to maintain a focused spot on the camera detector. Thus, beam divergence is actually improved. The $M^2$ value does not seem to be the dominant factor in beam divergence for the Corning lenses.

Beam quality follows a similar curve for the Optotune lenses, shown in Figure 17. The primary difference is that for the larger lens aperture, beam quality has a larger effect on the beam divergence. Thus, for the farther extremes of lens curvature, the beam divergence becomes much worse along with the beam quality.

Figure 18 illustrates how the beam steering impacts transmit gain for the laser terminal. For positive steering angles, transmit gain is actually improved. This is due to the focusing lens acting as a beam expander, lowering the beam divergence. The worst case values for transmit gain are approximately -0.5 dB for the Corning lenses and -0.4 dB for the Optotune lenses.
5. SUMMARY

The primary value of this project is in providing a starting point and proof of concept for use of liquid lenses, specifically, the Corning Varioptic A39N0 electrowetting lens and the Optotune EL-16-40-TC pressure driven liquid lens, in space applications. These results have shown that the Corning deformable lenses do not only survive exposure to vacuum, but remain fully operable in vacuum with almost identical functionality when compared to the ambient performance. The same result was shown with the Optotune lenses after extended vacuum exposure allowed the air bubbles to diffuse out of lens aperture. Not only does this allow a path forward for use in non-mechanical beam steering, but also in any other application requiring liquid lenses in space.

This project has also characterized beam steering dynamics of the Corning and Optotune lenses both in and out of vacuum. This data will be essential to the development of a full hemispherical laser antenna. Although beam steering is currently limited to approximately 2.7° and 8.5°, respectively, the steering range can be expanded dramatically by extending the optical tube and adding an optical diffuser and fisheye lens [4].

Summary of Findings

The Corning A39N0 lens provided a steering range of 2.7°, both in and out of vacuum. The curves of steering angle vs voltage follow an approximately linear curve with an average of 0.046°/V. No major differences could be detected between ambient and vacuum performance. Hysteresis was identified in comparing steering angle in increasing vs decreasing voltages. The maximum hysteresis error was small at only 0.05°.

The Optotune EL-16-40-TC lens provided a steering range of 8.5°, both in and out of vacuum. The curves of steering angle vs current follow an approximately linear path. As with the Corning lens, no major differences could be detected between ambient and vacuum performance. The maximum hysteresis error was small at only 0.02°.

A Zemax beam quality analysis determined a worst case link penalty of -0.5 dB in worst case steering angles for the Corning lens. Optotune lenses provide slightly better link parameters due to a larger aperture.

Future Work

Current testing is ongoing for a full thermal vacuum (TVAC) test for both types of liquid lenses. If this test is successful, we will expand this system to full 2-D steering with the addition of another offset liquid lens. We will work towards increasing the maximum steering angle through the use of a relay lens, diffuser, and fisheye lens, while keeping the system compact for use in small satellites. Ideally, this will lead to full hemispherical beam coverage. Additional, we are currently investigating the feasibility of supporting multiple concurrent spatially diverse links through this system architecture.

APPENDICES

A. ADDITIONAL FIGURES

Steering Plots

![Corning A39N0 Liquid Lens Vacuum Steer Angle vs. Voltage: 1 mm Offset](image)

Figure 19. Corning vacuum steering as function of 1 mm offset steering lens voltage.
Hysteresis Plots

Figure 20. Optotune 5mm offset vacuum steering as function of steering lens voltage.

Figure 21. Corning steering capability for increasing and decreasing voltage.

Figure 22. Corning vacuum hysteresis zoom on region of interest.

Figure 23. Optotune steering capability for increasing and decreasing voltage.

Figure 24. Optotune ambient hysteresis zoom on region of interest.

Figure 25. Optotune steering capability for increasing and decreasing voltage.
B. Test Setup Images

Figure 26. Lab fabricated Optotune mount with set 5 mm steering lens offset.

Figure 27. Vacuum chamber used for 1D steering tests.

Figure 28. Full test setup with lenses and camera.

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REFERENCES

[1] Corning Varioptic Lenses: Market-leading adjustable lens solutions for industrial applications. Corning, 2018.
[2] Datasheet: EL-16-40-TC Electrically Tunable Lens. Optotune, 2019.
[3] C. B. Gorman, H. A. Biebuyck, and G. M. Whitesides, “Control of the Shape of Liquid Lenses on a Modified Gold Surface Using an Applied Electrical Potential across a Self-Assembled Monolayer,” Langmuir, Vol 11, No. 6, pp. 2242-2246, Feb. 1995.
[4] M. Zohrabi, R. H. Cormack, and J. T. Gopinath “Wide-angle nonmechanical beam steering using liquid lenses,” Optics Express, Vol. 24, No. 21, Oct. 2016.
[5] Carrasco-Casado et al., “Optical communication on CubeSats — Enabling the next era in space science,” 2017 IEEE International Conference on Space Optical Systems and Applications (ICSOS), Naha, 2017, pp. 46-52. doi: 10.1109/ICSOS.2017.8357210
[6] Hans Dieter Tholl, "Novel laser beam steering tech-
niques,” Proc. SPIE 6397, Technologies for Optical Countermeasures III, 639708 (5 October 2006); doi: 10.1117/12.689900

[7] E. Miller et al., “A prototype coarse pointing mechanism for laser communication,” Proc. SPIE 10096, Free-Space Laser Communication and Atmospheric Propagation XXIX, 100960S (24 February 2017)

[8] T. S. Rose et al., “LEO to ground optical communications from a small satellite platform,” Proc. SPIE 9354, Free-Space Laser Communication and Atmospheric Propagation XXVII, 93540I (16 March 2015)

**Biography**

**Faisal Fogle** received a B.S. in Astronautical Engineering as the Outstanding Cadet in Astronautics from the United States Air Force Academy (USAF) in 2018. While a Cadet at USAFA, he served as an instructor pilot for the 94th Flying Training Squadron, teaching underclass cadets the basics of glider flying. After commissioning as a 2nd Lt in the United States Air Force, he went on to study at the Massachusetts Institute of Technology as a Lincoln Laboratory Military Fellow, where he is currently pursuing his S.M. in Aerospace Engineering. Following completion of his S.M., he will attend Euro-NATO Joint Jet Pilot Training (ENJJPT) at Sheppard AFB, TX.

**Ondrej Čierny** is a graduate student in the Department of Aeronautics and Astronautics at MIT specializing in pointing, acquisition, and tracking systems for nanosatellite laser communications. He received his BS degree in automation and robotics from the Slovak University of Technology (2015) and his MS degree in space science and technology from Luleå University of Technology and University of Würzburg (2017).

**Kerri L. Cahoy** is an Associate Professor of Aeronautics and Astronautics at MIT and leads the Space Telecommunications, Astronomy, and Radiation (STAR) Laboratory. Cahoy received a B.S. (2000) in Electrical Engineering from Cornell University, and M.S. (2002) and Ph.D. (2008) in Electrical Engineering from Stanford University. Dr. Cahoy previously worked as a Senior RF Communications Engineer at Space Systems Loral, as a postdoctoral fellow at NASA Ames. Cahoy currently works on nanosatellite atmospheric and ionospheric sensing missions (MicroMAS, NASA TROPICS, AERO/VISTA), optical communications (NASA CLICK), and exoplanet technology demonstration (DARPA DeMi) missions.