

Design and characterization of a refractive pointing system for satellite communications

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ABSTRACT

Free-Space Optical (FSO) communications offer high data rates and enhanced security for space architectures, but demand ultra-precise beam steering to compensate for platform-induced vibrations exceeding standard attitude determination and control subsystem bandwidths. While conventional systems rely on reflective Fast-Steering Mirrors (FSM), this paper presents the design, analysis, and experimental validation of a novel transmissive Fast-Steering Prism (FSP) mechanism. The proposed FSP features two rigid optical windows enclosing a transparent Polydimethylsiloxane (PDMS) gel. Actuating one window forms a variable-angle prism for continuous two-axis beam alignment. Its inline optical path offers an intrinsically compact geometry, facilitating integration into mass- and volume-constrained CubeSat and SmallSat payloads. Actuation is driven by piezoelectric stacks chosen for their rapid dynamic response and nanometer resolution. To overcome their limited stroke, customized compliant flexure mechanisms were designed and optimized via Finite Element Method (FEM) analyses. This optimization accounts for piezoelectric mechanical constraints, amplifying stroke while preserving bandwidth and preventing parasitic stresses on optical surfaces. To withstand orbital thermal environments and laser power absorption, comprehensive thermo-structural and thermo-optical analyses were conducted, guiding material selection to minimize wavefront degradation from temperature-dependent refractive index variations of the gel. A functional prototype was manufactured and experimentally tested. Dynamic response, mechanical stroke, and thermal optical performance were evaluated. The strong agreement between empirical results and theoretical models validates the proposed transmissive FSP architecture for high-precision spaceborne optical pointing.

Keywords: Fast-Steering Prism, Free-Space Optical Communications, Beam Steering, CubeSat

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1. INTRODUCTION

The development of Free-Space Optical (FSO) communications represents a major leap for contemporary space architectures, providing unparalleled data rates, ultra-wide bandwidth, and enhanced link security compared to traditional radio frequencies [1,2]. As space networks transition toward large-scale constellations and deep-space exploration, the requirement to maintain multi-gigabit links across thousands of kilometers while managing severe SWaP-C (Size, Weight, Power, and Cost) constraints becomes increasingly prominent [2]. Achieving the strict alignments necessary for inter-satellite and space-to-ground links requires highly accurate and responsive beam steering [2,3]. Dedicated active mechanisms are essential to achieve fine pointing and compensate for high-frequency platform-induced disturbances, such as micro-vibrations from onboard reaction wheels and structural resonances, which typically exceed the control bandwidth of standard Attitude Determination and Control Systems (ADCS) [4].

While state-of-the-art fine-pointing architectures typically employ reflective Fast-Steering Mirrors (FSM), these devices necessitate off-axis or folded optical paths. This geometric requirement increases the physical volume, total mass, and alignment sensitivity of the optical assembly, complicating the modular design of compact terminals [5]. In contrast, transmissive beam-steering mechanisms provide an inline optical path that is intrinsically more compact. This structural simplification is particularly advantageous for SmallSat and CubeSat platforms subjected to strict mass and envelope constraints [3,6].

To achieve refractive beam deflection, various tunable prism topologies have been investigated, including liquid-filled variable-angle prisms, electrowetting devices, and liquid-crystal spatial light modulators. However, conventional liquid-based refractive systems often suffer from gravitational sagging, thermal convection currents, and slow dynamic response,

rendering them unsuitable for high-power, high-dynamic space communications [7,8]. Furthermore, the transition of such technologies to orbit introduces risks related to vacuum outgassing and material degradation under ionizing radiation [9]. To overcome these limitations, Vanzo et al. [7] introduced a novel Fast-Steering Prism (FSP) concept based on a solid-state elastomeric layer, specifically a transparent Polydimethylsiloxane (PDMS) gel, sandwiched between two rigid optical windows. By actuating one of the windows, a variable-angle prism is formed, enabling continuous two-axis beam steering. While this concept successfully demonstrated refractive tilt correction for short-range terrestrial links, its implementation in orbital payloads requires addressing critical mechanical, dynamic, and thermal challenges associated with high-power laser transmission and extreme temperature cycles.

Building upon this foundational work, this paper presents the design, thermo-structural analysis, and experimental characterization of an FSP mechanism engineered for spaceborne FSO applications. Section 2 details the working principle, mechanical amplifier design, and thermo-optic analysis of the FSP system. Section 3 presents the experimental characterization and results obtained on the prototype. Section 4 provides concluding remarks and outlines future developments.

2. WORKING PRINCIPLE AND SYSTEM DESIGN

The operational principle of the Fast-Steering Prism (FSP) relies on variable-angle refraction through a deformable optical medium. As shown in Figure 1, the device consists of two parallel optical windows enclosing a transparent PDMS gel layer, specifically SYLGARD 527. The upper window is rigidly anchored to the external housing, whereas the lower window is mounted on three actuator assemblies. When the lower window is actuated, the enclosed PDMS gel, thanks to its low stiffness, deforms to accommodate the changing gap, forming a wedge of variable angle θ . The refractive index of the PDMS gel (~ 1.4) closely matches that of the glass substrates, minimizing Fresnel reflection losses at the glass-gel interfaces and avoiding internal optical discontinuities. For small wedge angles, the optical beam deflection angle δ is governed by Snell's law and can be approximated as $\delta \cong (n_{PDMS} - 1)\theta$. By continuously controlling the tip and tilt angles of the moving window, two-axis angular beam steering is achieved. This inline configuration simplifies system integration into optical payloads and allows to significantly reduce the physical envelope of the pointing assembly.

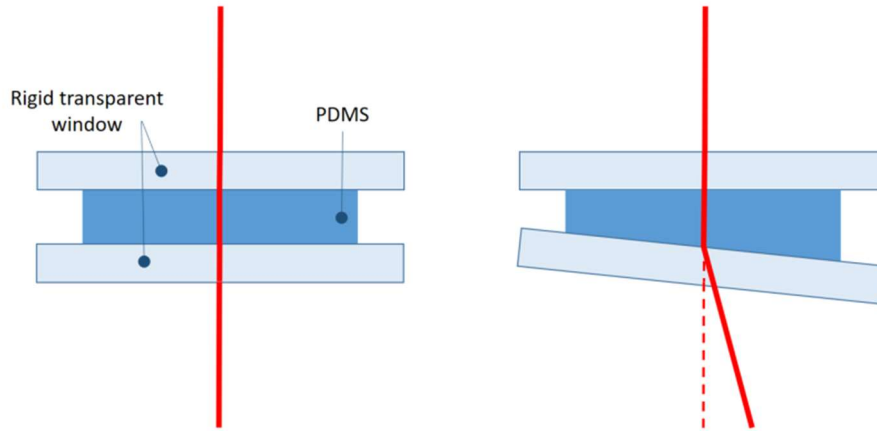


Figure 1. Simplified 2-D representation of the working principle of the proposed FSP. The image on the left represents the undeformed position, the one on the right the beam deflection induced by actuating the bottom window. Not to scale.

To achieve two-axis motion with high precision and fast dynamic response, three actuator assemblies are arranged at 120° intervals around the circumference of the lower window assembly. This tripod configuration provides full control over the tip and tilt degrees of freedom. Figure 2 represents the full architecture of the device.

Piezoelectric stack actuators were selected for their nanometer-scale resolution, high stiffness, and fast response times. In particular, PiezoDrive SCL050518 actuators were selected. They are equipped with strain gauges that allow closed-loop control of the piezo actuation, mitigating the hysteresis and creep issues that piezoelectric actuators usually present.

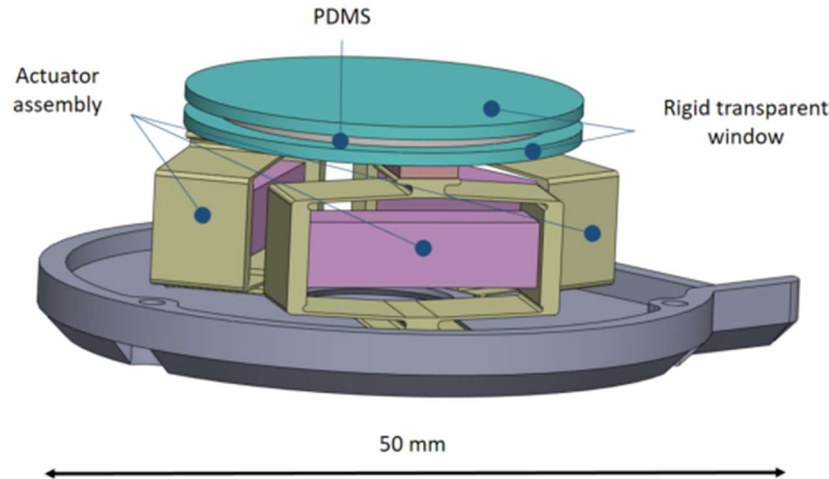


Figure 2. Schematic representation of the system architecture. The outer case has been removed for clarity.

However, because raw piezoelectric ceramics exhibit limited intrinsic stroke (typically on the order of tens of micrometers), a mechanical amplification stage is integrated into each actuator assembly to meet the angular range requirements. The design of these flexural amplifiers requires balancing three competing requirements: geometric amplification, i.e. achieving a sufficient amplification ratio to deliver the target angular steering range; structural bandwidth, meaning maintaining high internal stiffness to keep the first structural resonance frequency well above the required operational bandwidth; and stiffness opposed to the piezo actuation, because higher stiffness means lower displacement achievable by the piezo.

2.1 Mechanical amplifier design

The geometry of the flexure hinges was optimized using Finite Element Method (FEM) analyses. The optimization accounted for the mechanical constraints of piezoelectric ceramics, ensuring that tensile and shear stresses, to which piezo materials are particularly sensitive, remain well below allowable thresholds during maximum displacement. For this reason, it is recommended that actuators operate under continuous compressive preload to prevent mechanical damage during high-frequency dynamic actuation or transient shock events.

During the design phase, parametric FEM simulations were conducted to evaluate the influence of different preloading on the mechanical performance of the amplifier, on top of the structural integrity of the actuator. The analyses revealed a plateau region where the dynamic response and geometric amplification ratio exhibit minimal sensitivity to minor variations in the applied preload force, as shown in Figure 3. Targeting this optimal preload regime during the assembly process ensures predictable kinematic behavior and reduces sensitivity to manufacturing errors.

These simulations also enabled the verification of the stress distribution generated within the mechanical amplifiers. This parameter is critical, as the steel selected for the first iteration exhibited peak stresses approaching the material yield limit when the piezoelectric actuator was operated at its maximum elongation. High operating stress levels are particularly critical when evaluating fatigue life; given that the device is intended to operate continuously at high dynamic frequencies, ensuring extended fatigue resistance is paramount. To address these constraints, the material was switched to Ti-6Al-4V, a high-strength titanium alloy widely employed in aerospace applications. This material substitution significantly reduced the maximum stress relative to the yield strength, thereby ensuring structural integrity and extending the fatigue life of the mechanism.

2.2 Thermo-optical analysis

Thermal stability is a critical factor in spaceborne optical mechanisms, where severe ambient thermal conditions are combined with high internal laser powers. In Free-Space Optical (FSO) communication systems, operating powers often reach several Watts at the standard telecommunication wavelength of 1550 nm. Although the selected elastomer gel, exhibits a relatively high optical transmittance at that wavelength, the residual power absorption within the transmissive

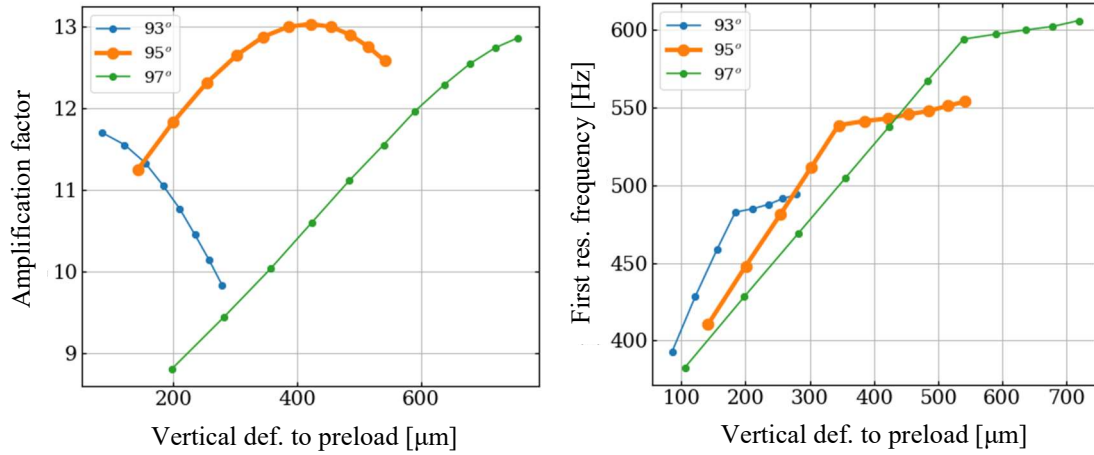


Figure 3. Extract of the results of the FEM analyses on the mechanical amplifier. The left panel represents the geometrical amplification factor as a function of the vertical deformation imposed on the amplifier to preload the piezo actuator. The right panel depicts the first resonance frequency of the actuator assembly. Different colors correspond to different geometries tested. The region around $400\mu\text{m}$ of vertical deformation was targeted, along with the 95° geometry, because it offers the highest amplification factor and lowest sensitivity to variations in the preload, a very useful feature when dealing with such small and difficult to control deflections.

path remains a primary design concern. To accurately quantify this effect, the optical absorption at 1550 nm of a sample of Sylgard 527 was measured experimentally. In the nominal operational scenario considered for this payload, the incident laser beam carries a power of 3 W, resulting in approximately 0.13 W of thermal power absorbed within the internal gel volume, given its 1 mm design thickness. Because PDMS possesses a low thermal conductivity ($\sim 0.15 \frac{\text{W}}{\text{mK}}$), dissipating this absorbed thermal energy is challenging, giving rise to localized thermal gradients across the optical clear aperture. FEM simulations were carried out to model the thermal distribution under an operational ambient temperature envelope ranging from 0°C to 40°C . The absorbed 0.13 W power was discretized across the gel volume to approximate a Gaussian intensity profile matching the beam shape. The resulting thermal distributions (sample shown in Figure 4) indicated that while differential thermal expansion across the mechanical interfaces remains within acceptable structural margins, thermo-optic effects pose a far more critical issue.

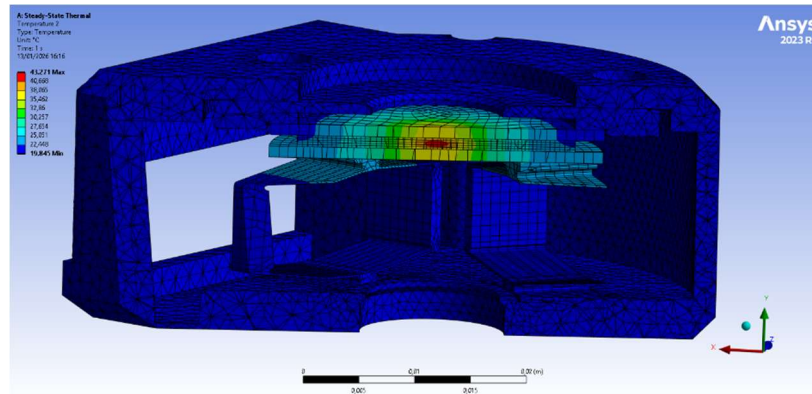


Figure 4. Steady-state temperature distribution for the case with BK7 windows and 1 mm-thick PDMS layer. Cross section along a diameter of the clear aperture.

Due to the thermo-optic coefficient of PDMS ($\frac{dn}{dT} = -4 \cdot 10^{-4} \text{ K}^{-1}$), localized temperature variations induce non-uniform refractive index profiles. The resulting Optical Path Difference (OPD) along the propagation axis y can be evaluated as:

$$\Delta OPD(x, z) = \int_0^d \frac{dn}{dT} \Delta T(x, y, z) dy$$

where d is the thickness of the PDMS layer and $\Delta T(x, y, z)$ is the local temperature variation relative to the reference state. Integration of the refractive index profile over the gel thickness revealed significant Wavefront Errors (WFE), exceeding the $\lambda/10$ RMS requirement for the device. To mitigate this degradation, a two-fold design optimization was implemented:

- substrate material selection

The baseline BK7 glass windows were replaced with sapphire substrates. Sapphire provides a significantly higher thermal conductivity ($\sim 30 \frac{W}{m K}$) compared to BK7 ($\sim 1.1 \frac{W}{m K}$), facilitating heat dissipation from the gel toward the metallic housing. The maximum temperature difference is reduced to $6.2^\circ C$, from $23.3^\circ C$ in the BK7 window case. The calculated improvement in WFE is shown in Figure 5.

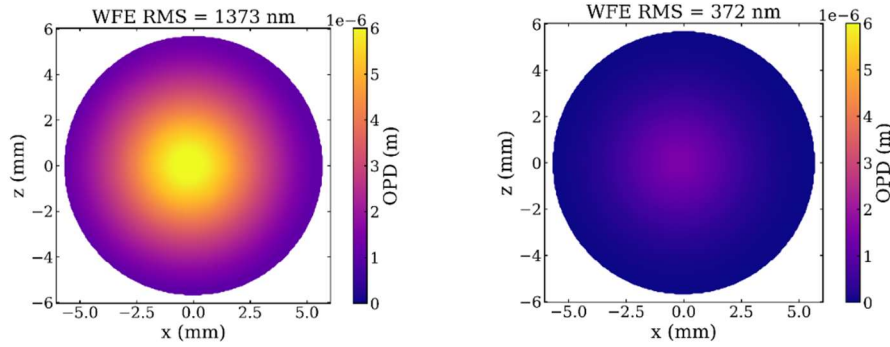


Figure 5. WFE calculated for the BK7 (left) and sapphire (right) window cases.

- PDMS layer thickness reduction

To further lower the total absorbed power and minimize internal thermal resistance, the thickness of the PDMS gel was reduced to 0.6 mm. While a thinner gel layer restricts the maximum achievable mechanical steering angle, it successfully restricts the thermal WFE to within the performance requirements (Figure 6).

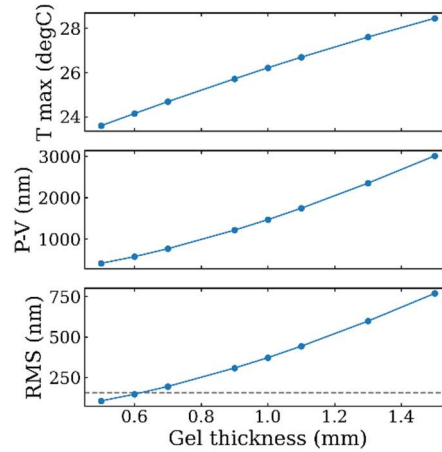


Figure 6. Effect of the PDMS gel thickness on the steady-state temperature of the gel (external case temperature $20^\circ C$) and WFE (peak-to-valley and RMS). The values refer to the sapphire window case. The dashed line represents the $\lambda/10$ requirement.

3. PRELIMINARY EXPERIMENTAL RESULTS

To test the design and the assembly and integration procedure, a prototype was manufactured. It features the same geometries and materials of the final design, with two notable exceptions: the piezo stack actuators (P-883.51 from PI), that have a smaller range and do not include strain gauges for closed-loop control, and the transparent windows, for which BK7 is employed. While the latter is expected to mostly only have an effect on the thermal behavior of the device, the difference in the piezo actuation would yield a significantly lower range and impose some differences in the preloading level.

The first to be tested was the actuator assembly. After imposing the computed deflection ($100\mu\text{m}$) on the amplifier, in order to achieve the desired preload, the piezo actuator was glued to it (Figure 7). Three samples were produced, which also allowed to test the repeatability of the manufacturing process and assembly procedure. The deflection, while controlling the piezo over a $[0-100]$ V range, was measured through an optical microscope, yielding $175\pm 5\mu\text{m}$. This result closely matches the $181\mu\text{m}$ expected from the FEM analysis, confirming the mechanical amplifier can provide an amplification factor greater than 11.

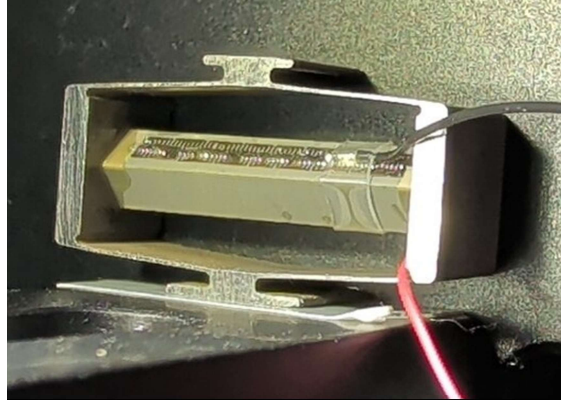


Figure 7. Actuator subassembly under test. The piezo actuator in use has the same dimensions as the one that will be employed in the final device, but shorter range and no strain gauges for closed-loop control.

The full prototype was then assembled (Figure 8) and the WFE was measured on the whole clear aperture, yielding 15nm RMS (within $\lambda/10$), ensuring no significant WFE was induced by the windows or the assembly procedure. To measure the angular range of the device, the setup depicted in Figure 9 was employed. Actuators were tested to their full range one by one, keeping the other two grounded. The distance between the centroids at the two extremes of the range was then computed for each actuator, and is shown in Figure 10.



Figure 8. Fully assembled prototype.

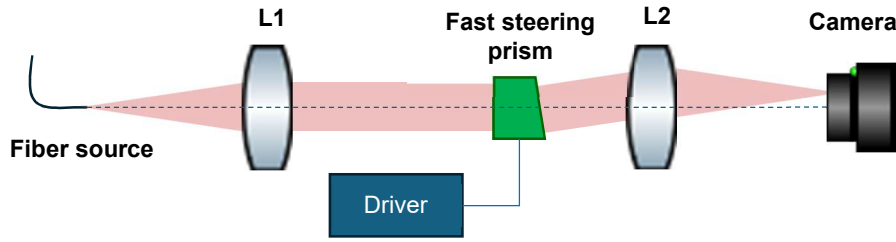


Figure 9. Test setup for the measurement of the angular range achievable by the device.

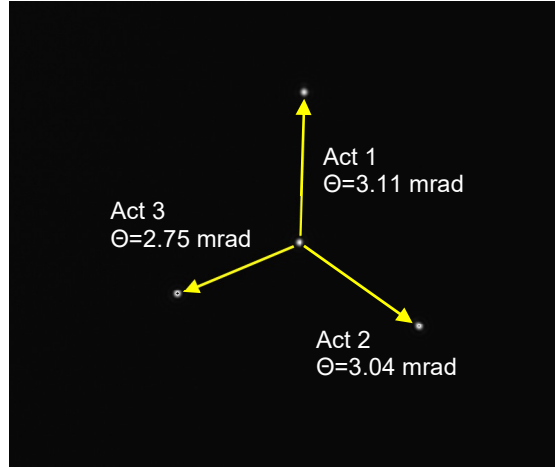


Figure 10. Positions of the centroid of the deflected beam, actuating one actuator at a time and grounding the other two.

The smaller angular range compared to the 5 mrad requirement can be attributed to a number of different factors. The first, as already mentioned, is that the piezo actuators employed for this first prototype have a stroke about half of that offered by the ones selected for final design (12 μm compared to 23 μm). The final actuators will also have a built-in strain gauge that will allow to correct for any inhomogeneity between the three actuators and their hysteresis and creep effects. A second factor can be identified in the development status of the electronic driver: at the time of testing it did not allow to control the three actuators at the same time. This made it impossible to test the full range, that is obtained by applying the maximum voltage to one actuator and the minimum to the others. Instead, only the case with the two inactive actuators grounded was tested. From geometrical considerations, it can be estimated that, once the full electronics is available, a $\sim 15\%$ improvement in the angular range can be achieved. Finally, a novel method of gluing the actuator assemblies to the bottom window is being developed, which is expected to improve the angular range by about 20%. All this considered, the test proved the range is well above the requirement.

4. CONCLUSIONS AND FUTURE DEVELOPMENTS

This paper presented the optomechanical design, finite element analysis, and preliminary experimental validation of a novel transmissive Fast-Steering Prism (FSP) for optical beam steering in space applications. By providing an inline refractive path, the proposed architecture avoids the folded optical geometry inherent to conventional Fast-Steering Mirrors, delivering a significantly more compact layout ideal for mass- and volume-constrained SmallSat and CubeSat platforms. Comprehensive thermo-structural and thermo-optic analyses guided key design optimizations, including the selection of Ti-6Al-4V titanium alloy for the flexure amplifiers to ensure structural integrity and high fatigue life under continuous dynamic operation. Furthermore, substituting BK7 with high-conductivity monocrystalline sapphire substrates, combined with an optimized PDMS gel layer thickness, successfully mitigated thermal-induced wavefront errors caused by laser power absorption at 1550 nm. A functional prototype was manufactured and assembled, confirming the feasibility, alignment precision, and repeatability of the assembly procedure. Experimental testing validated the static numerical models, demonstrating an angular steering range compliant with payload requirements. Ongoing and upcoming work focuses on the full experimental characterization of the system's dynamic performance, specifically evaluating the step-

input response, resonance modes, and closed-loop control bandwidth. Following dynamic validation, an upgraded space-representative prototype incorporating the final closed-loop strain-gauge piezoelectric actuators and sapphire optics will undergo complete thermo-vacuum and dynamic testing, paving the way for the deployment of transmissive FSPs in spaceborne optical communications terminals.

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