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Optomechanical design of laser diode collimators for free space communications

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ABSTRACT

Free space optical communication systems require high quality laser diode collimators capable of long term operation in the space environment. A four-element collimator with all-spherical surfaces was designed and built using conventional fabrication technologies and specialized assembly techniques. Final assemblies demonstrated 1/50-wave rms wavefront errors and no destabilizing feedback to the laser diode source. Advanced collimator designs employing aspheres reduce the collimator design complexity and cost while maintaining optical performance. Examples of these advanced designs, based on lens molding technologies, demonstrate suitability to space applications.

INTRODUCTION

Free space optical communication systems have focused on laser diodes as sources because of their small size, low power requirements, and ability to be directly modulated. However, unlike larger solid-state (Nd:YAG) or gas (CO2) sources, laser diodes emit strongly diverging beams that require collimation.

Typical laser diode collimator (LDC) designs are not suitable for space communication system requirements. The space environment places special demands on the collimators, requiring optomechanical designs specifically optimized for the extreme optical, mechanical and thermal requirements of such applications.

Collimators utilizing conventional spherical lens technologies have been built which provide high quality performance. Advanced LDC designs using aspheric surfaces provide equivalent performance. These designs, based on high-volume manufacturing techniques such as lens molding, offer advantages in terms of weight, ease of assembly, and cost.

The stability of the laser diode can be adversely affected by feedback from LDC. An additional design optimization step has successfully reduced feedback and eliminated output fluctuations.

PERFORMANCE REQUIREMENTS

LDCs for space applications differ from ground-based or fiberoptic LDCs in three major areas: optical performance characteristics, environmental concerns, and unique operational requirements. The important characteristics and conditions that apply to laser diode systems in these three areas can be derived from recent NASA programs such as the Advanced Communications Technology Satellite, the Laser Power Summing System, and the Direct Detection Laser Transmitter (see Table 1).

The optical performance characteristics of free space LDCs must at least be equivalent to those of alternative laser sources such as Nd:YAG, which can provide wavefront errors of approximately 1/20-wave rms. Improved wavefront errors provide improved communication link margins. Therefore, a reasonable goal for LDCs is 1/50-wave rms wavefront error. Optical specifications for this activity required an LDC able to accept beam divergences of 35-40 degrees in the perpendicular plane. Today's laser diodes permit significantly smaller NAs, however, due to their narrower beam divergences.

Table 1. Requirements for Laser Diode Collimators for Free Space Communications

Performance	wavefront	0.05 wave rms, required 0.02 wave rms, goal
	NA	0.4–0.6
	wavelength	780–860 nm
	transmittance	0.96 required
Environment	radiation	1×10^6 rads (Si) at geosynchronous orbit, minimum survive man-made radiation at low earth orbit, goal
	thermal	277–297K, operational 233–333K, storage
Operational	feedback	1×10^{-5}, maximum
	size	8-mm diameter × 12-mm length

The space environment adds several critical limitations to the design of any optical system. Radiation–tolerant optical substrates, coatings and cements must be employed. Typically, a satellite in geosynchronous orbit has a lifetime of four to seven years. This length of time requires hardware that can tolerate a cumulative radiation dose of 1E+6 rads (Si). LDCs in low earth orbit may be required to withstand even higher radiation levels.

The thermal range over which LDCs must operate changes as the hardware ages. This change usually occurs because the spacecraft's thermal radiators, which dump excess heat into space, lose their efficiency with time. During non–operational modes such as preflight storage or launch and on–orbit storage, the LDCs could experience a thermal range of 100 K.

Space flight hardware must always address the issues of minimum volume and weight requirements. The original NA required an optical design with a short back focal length (or working distances). Current laser diodes would permit longer working distances as a result of the reduced NAs.

Operational feedback from optical surfaces in the LDC can destabilize a laser diode, detrimentally affecting its output. Therefore feedback to the laser diode source must not exceed 0.001%. This requires a detailed narcissus computation during the lens design process and is among the parameters that are minimized during optimization of the LDC.

GENERALIZED DESIGN CONSIDERATIONS

A LDC was designed to meet the requirements in Table 1 for a laser diode source with wide beam divergence and an external etalon for frequency stabilization.

Conventional optical designs for LDCs are available using three, four or even five lens elements with all–spherical surfaces. Five–element designs cannot meet the goal of 1/50–wave rms wavefront error for the assembled collimator.

Optical material limitations and availability affect the optical design. The number of commercially available glasses suitable for the radiation environment of space is very limited. Radiation–hard coating materials for space applications are also rare. This places severe constraints on the designer.

The mechanical design of the conventional LDC must be optimized for optical performance, size, weight, structural issues, thermal and assembly considerations. Mount design effects on manufacturing and thermal variations must be evaluated and adjusted to minimize mechanically induced perturbations in the LDC's wavefront. The mount must also withstand the shock and vibration environments encountered during space launch. Finally, the assembly and testing methods should be straightforward, requiring minimum labor and time. Advanced LDC designs are possible which reduce some or many of these factors without a reduction in performance.

Candidate designs that satisfied these diverse requirements were analyzed for rms wavefront error over a 1 degree field of view. The analysis included random assembly errors, narcissus and thermal effects on the wavefront, and additional factors such as the availability of radiation-hardened materials. A four-element design based upon conventional technologies was selected for fabrication and testing.

LDC of CONVENTIONAL DESIGN

The four-element design selected for manufacture utilized three different radiation-hardened glasses and was achromatized for operation from 780 to 850 nm. All lenses were manufactured using conventional fabrication methods, were coated with radiation-hard antireflection coatings, and included lenses from 4 to 7 mm in diameter.

The mount design shown in Figure 1 consists of two lens cells and a spacer inside a barrel. Two lens elements are mounted in each cell with a space-qualified UV-cured cement, and the thickness of the spacer between the cells was adjusted during assembly to optimize collimator performance. The overall size of the assembled collimator was approximately 11 mm long and 8 mm in diameter.

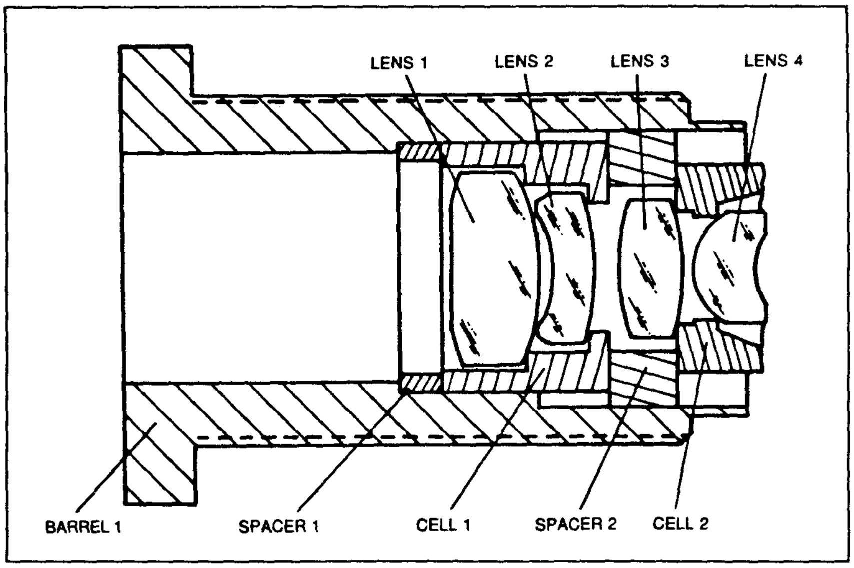

Figure 1. The laser diode collimator assembly includes two lens cells and a spacer inside a barrel. This design utilized conventionally fabricated optical elements.

The lens elements were aligned in the cells using a special laser alignment fixture (LAF). This device uses an interferometer to position each lens and monitor its locations during the cementing process. Trial assembly of the cells in a barrel established the proper spacer thickness to focus the collimator assembly. The two cells and spacer were then aligned and cemented in the barrel using the LAF. An assembled LDC is shown in Figure 2.

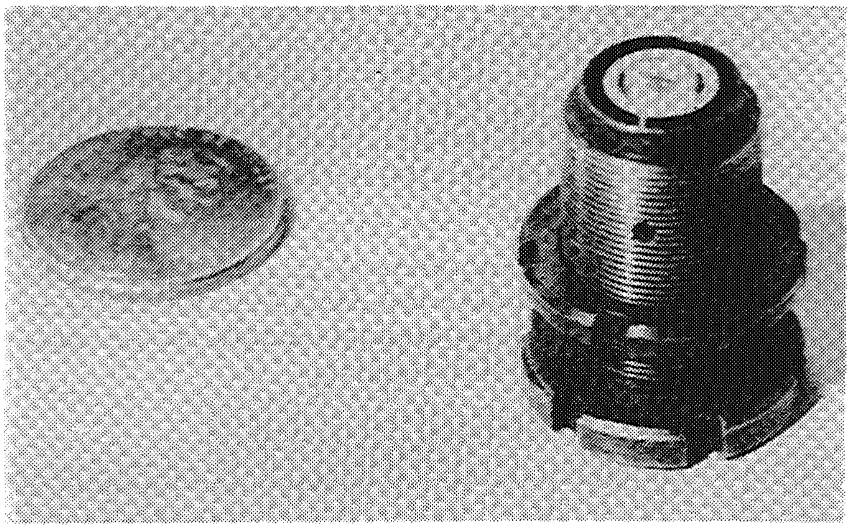

Figure 2. The assembled laser diode collimator.

The test setup for focusing the LDCs used a Diolite laser diode source and a Ladite interferometer (see Figure 3). A microscope objective reimaged the energy from the laser head on a 10 µm pinhole. The LDC under test recollimated the energy from the pinhole, and a beam expander enlarged the beam entering the interferometer (see Figure 3A). To reduce the potential errors in the evaluation of the final assemblies, this test setup was modified by removing the all optics between the laser diode and the LDC under test (i.e., the Diolite's optics, the microscope objective and the pinhole). Thus the assembled LDC was tested as it would later be used, collimating the laser diode source directly (Figure 3B) rather than indirectly, as with the previous method.

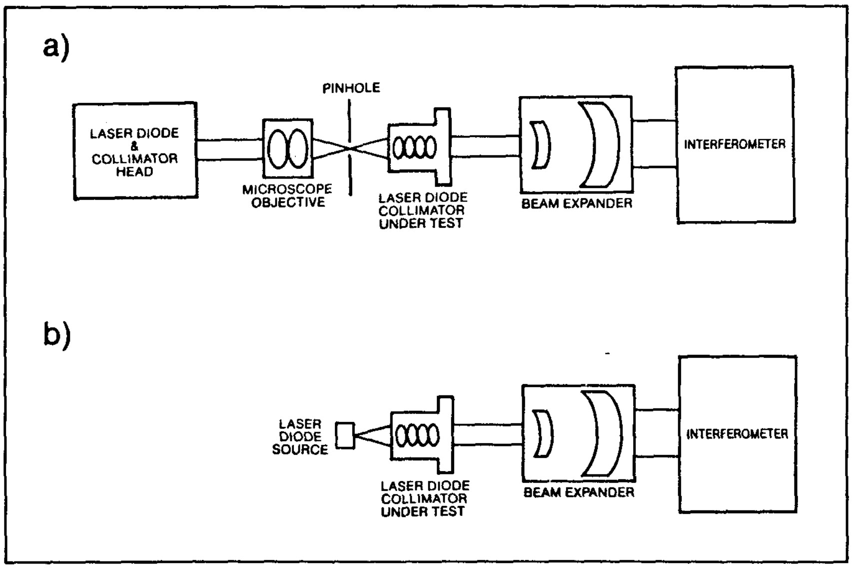

Figure 3. The schematics show the test fixture for the laser diode collimators. (A) The setup used during assembly, and (B) the modified setup used for final acceptance testing of assembled collimators.

The wavefront quality for all collimator assemblies was measured. This test data includes wavefront error contributions from the laser diode source and from the beam expander. To estimate the wavefront error of the collimators only, conservative estimates of these additional errors were assumed to be 0.010-wave rms error from the source and a 0.012-wave rms error from the beam expander. The distribution of the estimated rms wavefront error for the collimators is presented in Figure 4. Table 2 gives the results when the estimated error contributions are removed from the test data to characterize the performance data for the assembled LDCs alone.

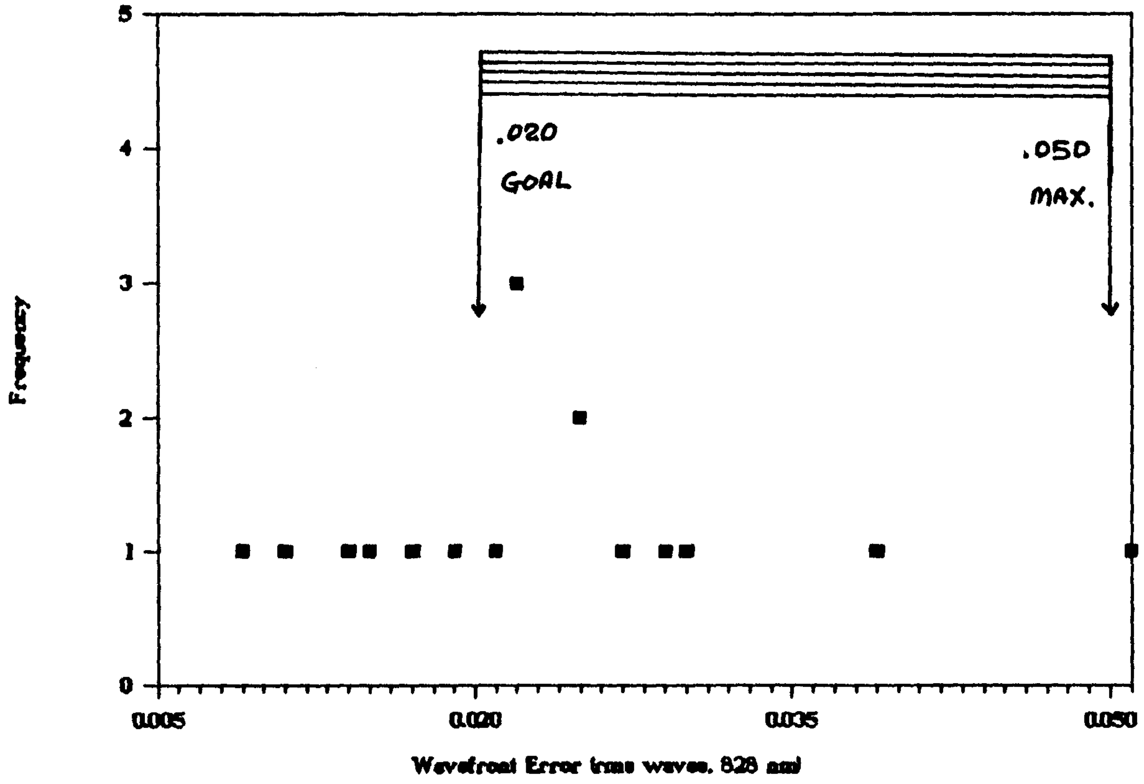

Figure 4. The measured wavefront error of the assembled LDCs after removal of error contributions for the laser diode source and the beam expander.

Operational test results reported for these conventional LDCs demonstrate excellent optical quality. Of significant interest, the laser diode sources exhibited no instabilities with these collimators, unlike others under evaluation. This implies the optical feedback was controlled and below the 0.001% goal.

Table 2. Wavefront Error Estimates for the Assembled LDCs (four-element design using conventional optics).

	Smallest measurement	**Average measurement**	**Largest measurement**
	(wave rms at 828 nm)		
Diode-laser collimator plus source and expander	0.021	0.033	0.051
Estimated wavefront error of diode-laser collimator	0.009	0.028	0.039

ADVANCED ASPHERIC LDC DESIGNS

Lens molding technology has three capabilities that make improved LDC design feasible: reproducible aspherics, integral mounting surfaces, and optical spacers.

Several collimator designs that utilize the capabilities and benefits of the finished lens molding (FLM) technique have been developed. Examples of one- and two-element aspheric designs are shown in Figure 5. Each design meets the requirements of the four-element conventional design. The single element design in Figure 5A has integral mounting surfaces; the two-element design in Figure 5B employs an optical spacer.

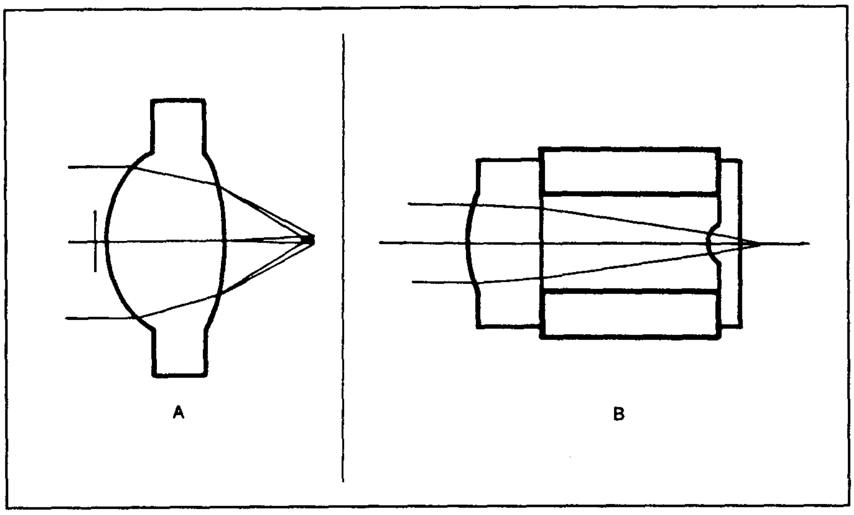

Figure 5. Aspheric designs which can achieve LDC performance requirements utilizing FLM technology include (A) a single, dual-asphere design and (B) a two-element, two asphere design separated by an optical spacer.

The FLM technology is currently producing infinite and finite conjugate aspheric singlets for optical data storage and digital audio disk applications. A 0.3 NA LDC is also being manufactured with as a single, dual-aspheric FLM element.

Radiation-hardened glass materials which are doped with additives such as cerium oxide are compatible with FLM processing.

CONCLUSION

Space qualified laser diode collimators capable of 1/50-wave wavefront errors and insignificant optical feedback have been manufactured successfully in quantity. Collimators based on FLM technology can provide equivalent performance and lower costs by incorporating aspheres, optical alignment features and optical spacers in the design.

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