Proc. of SPIE Vol. 1044, Optomechanical Design of Laser Transmitters and Receivers, ed. B D Seery (Jun 1989) Copyright SPIE

Optomechanical design of a space-based diode-laser transmitter assembly*

Allen D. Pillsbury and John A. Taylor
Lincoln Laboratory
Massachusetts Institute of Technology
P.O. Box 73
Lexington, MA 02173

ABSTRACT

The advent of space-based coherent diode-laser communication systems requires development of transmitter assemblies capable of operating under harsh conditions after exposure to the launch environment. This paper presents the optomechanical design and expected performance of a transmitter for use in a heterodyne system.

1. INTRODUCTION

MIT Lincoln Laboratory is developing a heterodyne 4-ary frequency-shift-keyed satellite communications system to operate at 220 Mbit/sec using directly modulated GaAlAs laser diodes operating at wavelengths between 8630 and 8660 Å. [1, 2] The packaging of the laser diode and its supporting temperature control system, supporting electronics and optical conditioning components presents a challenge because of the harsh launch and operating conditions, stringent operating requirements and limitations on weight, volume, and power consumption. A design has been developed that allows four redundant diode assemblies to be housed in a common support structure capable of surviving typical Space Shuttle launch environments.

The transmitter assembly will be housed in a larger optical package (36x66x92 cm) which will include a 20-cm aperture telescope, beam-pointing equipment, acquisition and tracking hardware, and beam-diagnostics equipment.[3] This opto-mechanical subsystem (OMS) would be mounted on a nadir-facing panel of a geosynchronous satellite. A separate electronics subassembly would be remotely located on the satellite.

2. FUNCTIONAL REQUIREMENTS

Figure 1 shows the 5116-cm^3 volume within which the transmitter assembly must fit. It contains four independent laser diode assemblies, conditioning optics, and temperature-control hardware including a thermal radiator. The four available output beams are directed to a common point outside the transmitter envelope where a two-axis servo-driven source-select mirror (SSM) is located. By rotating the SSM, the activated source can be boresighted to one of three optical paths. The four output beams must be parallel to the mounting surface to within 0.005 radian to be within the available stroke of the SSM's elevation axis. To limit truncation losses in the telescope, the beam must be centered at the input of the telescope to within 100 μm.

The diode operating temperature requirements place significant demands on the transmitter's

----

*This work was sponsored by the Department of the Air Force. The views expressed are those of the authors and do not reflect the official policy or position of the U.S. Government.

thermal design. Diodes will be selected to operate in the range of 8630 to 8660 Å when the diode mounting flange is controlled to be in the 15 to 25°C range. To provide margin in diode selection and to accommodate diode aging, the transmitter is designed to allow operation at any temperature in the 10 to 30°C range. Once the operating temperature is established by measuring the wavelength with an independent diagnostics module,[4] the diode's temperature must be held stable to 0.001°C to limit frequency variations to 30 MHz. To prevent excessive loading of the transmitter temperature controller, good thermal isolation from the OMS must be provided. Also, the mounting arrangement must prevent large distorting forces from developing at the mechanical interface.

The complete transmitter assembly weighs 2.3 kg and consumes less than 4.2 W during normal operation.

3. SOURCE ASSEMBLY

The principle subassembly in the transmitter is the source assembly, as shown in Fig. 2.[5] It consists of the diode itself, part of a temperature controller, a collimating lens assembly, and a titanium support structure which includes a small electronics housing. This modular unit contains all of the difficult alignment features in the transmitter and is a self-contained unit. It can be fully aligned and functionally tested before it is integrated into the top-level transmitter assembly and may be readily replaced with a spare unit if necessary.

An Hitachi channeled-substrate planar GaAlAs laser diode is used in the source assembly. It is secured by way of its flange to the diode mounting plate with two studs, one of which is on a reed flexure. This flexure allows for the mismatch in coefficients of thermal expansion (CTE) between the diode's iron base and the titanium mounting plate. Thermal conductivity at the flange is enhanced by the use of an indium foil gasket.

Temperature control is achieved by use of a foil-type heater bonded between the diode mounting plate and heater block. By bonding a chip thermistor next to the diode, a control loop can be established with the actual control-loop circuitry remotely located. To maintain active temperature control while holding a constant temperature, some heat must constantly be bled off, thereby allowing the controller to servo some positive amount of heat. To this end, the source is attached to a thermal radiator by way of a flexible thermal strap.

The source assembly printed-circuit board must handle DC, RF and logic signals. Modulation and DC bias signals are mixed in the electronics housing using a bias T circuit. In addition, an enable circuit consisting of a Darlington transistor pair is located on the source printed-circuit board. Finally, a signal from the diode's internal power monitor is passed to the transmitter controller.

Collimation is accomplished with a custom-built f/1.1 lens assembly housed in a titanium barrel.[6] To maintain good wavefront quality, the diode must be centered on the collimator's optical axis to within 25 μm and focused to within 0.7 μm. Once the radial position is established, it must be stable to 1.0 μm to prevent excessive beam walk at the SSM. Figure 3 illustrates how focus is maintained despite large temperature changes. Changes in the lens assembly back focal length (BFL) with temperature were calculated by use of the CODE V optical simulation program[7] which includes the effects of lens de-space due to housing thermal growth, lens curvature changes due to glass thermal growth, and changes in the glass's index of refraction with temperature. Similarly, by knowing the geometry and materials used in the diode construction, the diode's change in length relative to the mounting flange can be estimated. By optimizing the length of the spacer placed between the collimator and the diode along with the material used, the combined de-focus with temperature changes can be made zero, as shown in Table 1. For our system, Invar spacers 0.71 cm long are used.

4. TRANSMITTER ASSEMBLY

An overall view of the transmitter assembly is shown in Fig. 4. The four source assemblies are supported by a titanium structure consisting of the housing, the support struts and the prism mounting tray. Two sources are loaded in from the top with each elliptical beam directed towards a fold flat that diverts the beam to an anamorphic prism pair which circularizes the beam. The prisms are located by integral tabs and are bonded in place. Wedge angles were selected such that each output beam is directed to the SSM. A similar beam path is used for the two sources loaded in from the bottom.

The support struts must provide a rigid attachment of the transmitter housing to the OMS without allowing excessive thermal coupling. To minimize the pitch and yaw reaction caused by operational disturbances, it is desirable to have the center-of-reaction of the support struts located at the center-of-mass of the transmitter assembly. To this end, symmetry is employed along the Y axis. The Z-axis center-of-reaction location is optimized by balancing the cross sectional areas of the diagonal support strut and the front support strut and by selecting the front support "V" angle. The low cross section of the support struts and the poor thermal conductivity of the 6A1-4V titanium alloy used for the support structure provide good thermal isolation of the housing from the mounting surface.

A 161-cm^2 aluminum thermal radiator covered with optical solar reflectors (OSR) eliminates waste heat and allows active temperature control of the source assemblies. It is supported from the housing by means of three flexures to allow for differences in temperature and coefficients of thermal expansion between the radiator and the housing. The radiator is coupled to the sources by means of four flexible thermal straps. The transmitter's location in the OMS will provide the radiator an unobstructed, south-facing view of deep space.

5. TEMPERATURE CONTROL

To minimize thermal gradients within the sources and throughout the support structure, all four sources receive heater power, regardless of which source is active with the thermistor in the active source selected for feedback purposes. This provides the important side benefit of eliminating the need to switch a high current heater line. Gradients in the source are reduced because only one quarter as much heat is dissipated within each source while frame gradients are reduced because the heat is being introduced over a larger area. In addition to the four source heaters, two heater elements are attached to the frame directly (near the top of each side support strut) and receive a fixed portion of the total heater power.

The wiring harness design received special attention to minimize its impact on the thermal isolation of the transmitter assembly. The semirigid coaxial cables used for the modulation signals are 0.21-cm-diameter stainless steel which is 8 percent as thermally conductive as the equivalent copper cable. The DC harness has the fewest possible wires passing over the interface. The -15V supply line and the heater power are divided on a small printed-circuit board mounted under the prism mounting tray. The splitter board can be seen in a photograph taken during the preliminary fit check (Fig. 5).

Radiation coupling to the environment is limited by a multilayer thermal insulation blanket which is supported by a lightweight cover, as shown in Fig. 6. Thermal-vacuum testing will be used to confirm the required radiator size. If adjustments must be made to the active area of the radiator, the blanket can be modified to expose the proper amount of OSR. There is a 25 percent contingency in the available area. The cover and blanket will also provide some protection from contamination and mishaps.

The total thermal resistance from the active source assembly to the OMS is expected to be 30°C /W. This includes conduction through the support struts, DC and RF wiring harnesses, and radiation coupling.

6. STRUCTURAL ANALYSIS

A detailed finite element model (FEM) employing 395 elements and 1860 degrees of freedom was used during the development of the transmitter design. The beam path is modeled by multiplying the optical sensitivity of each component along the path by the local displacements. In this way beam deflections at the SSM were found.

The qualification random vibration specification was derived by applying the expected OMS qualification test levels to the FEM of the OMS and finding the response at the transmitter location. This response was then banded to become the qualification specification for the transmitter as a subassembly. Figure 7 shows the three power spectral density (PSD) levels for the X direction which is the most demanding. The same process was performed for the other two directions yielding RMS levels of 20.8 g's rms for the Y direction and 26.4 g's rms for the Z direction.

These banded responses were played into the transmitter FEM to find the structural stresses during qualification level testing. The peak 3σ stress is 48,000 PSI and occurs in the diagonal support strut during Y loading. Fatique analysis indicates that there will be an adequate factor of safety for the titanium alloy selected.

The primary operating disturbances are due to the host spacecraft's momentum wheel which generates disturbances nominally at 100 Hz and its harmonics, as shown in Table 2. A dynamic analysis of the transmitter model indicates that the first three modes will be at 281, 394 and 550 Hz and are primarily translation modes in the X, Y, and Z directions, respectively. Having the first structural modes this high limits excitations of the transmitter line-of-sight (LOS) pointing. The operational disturbance response at the transmitter location has been played into the transmitter model to find the LOS jitter expected during operation. Table 3 shows the results of this analysis. Note that the SSM has rejection in the elevation axis while having some gain in azimuth.

A separate thermal model of the transmitter was used to determine gradients in the structure for various operating scenarios. These temperature distributions were then entered into the structural model to find the resulting deformations and beam-pointing errors. Table 4 shows the result of this analysis for the two cases which bound the operating scenarios. Case 1 has the smallest amount of heater power while case 2 has the maximum amount of power dissipation. In both cases the expected beam walk at the SSM produces negligible throughput losses in the optical train.

7. RESULTS

Components for twelve source assemblies have been fabricated and several have been assembled and tested to date. These tests include wavefront quality, optical throughput of the collimators, optical feedback to the diode, modulation port input impedance, temperature control loop performance, and operational demonstations at 110 Mbit/sec in a binary-frequency-shift-keyed breadboard system. Acceptable results were found during all of the tests with the results having been reported previously.[2] One source assembly has been subjected to qualification random vibration and thermal cycling (-20°C to +66°C) without significant changes to its performance.

The transmitter assembly has been subjected to modal analysis which indicates that the FEM estimates of resonant frequencies and mode shapes are accurate. Future plans call for environmental testing of the entire unit once assembly is complete.

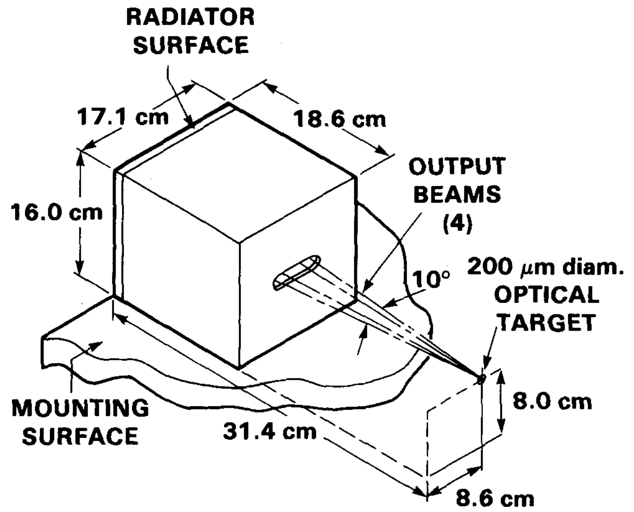

Figure 1. Transmitter envelope constraints. The SSM axes of rotation are located at the optical target.

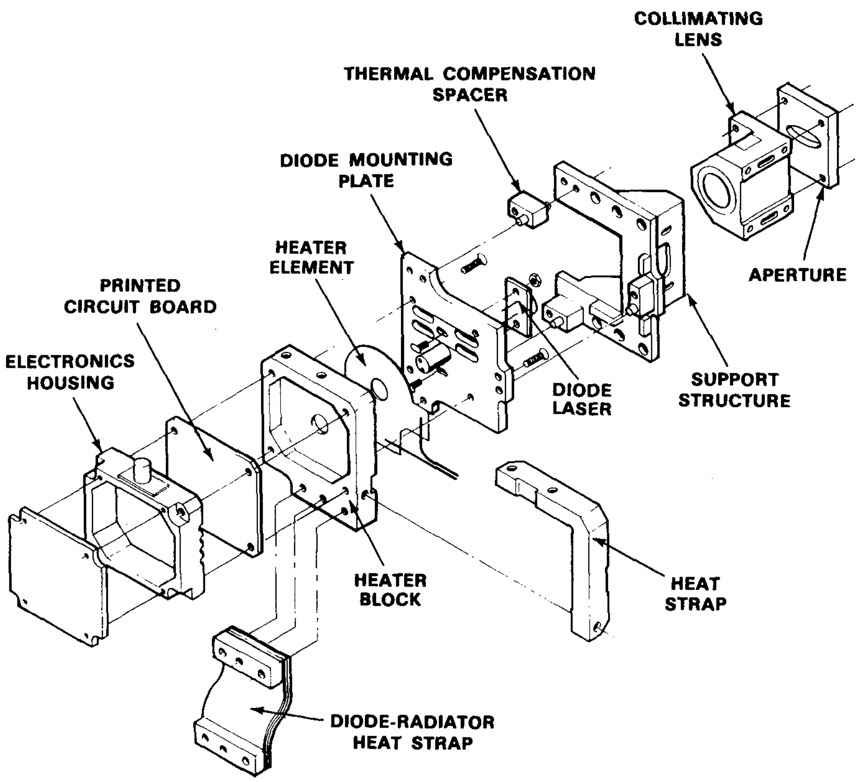

Figure 2. Exploded view of a source assembly.

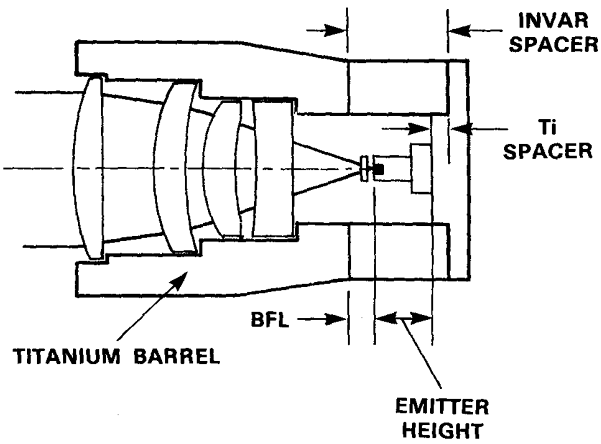

Figure 3. Focus compensation components
in a source assembly.

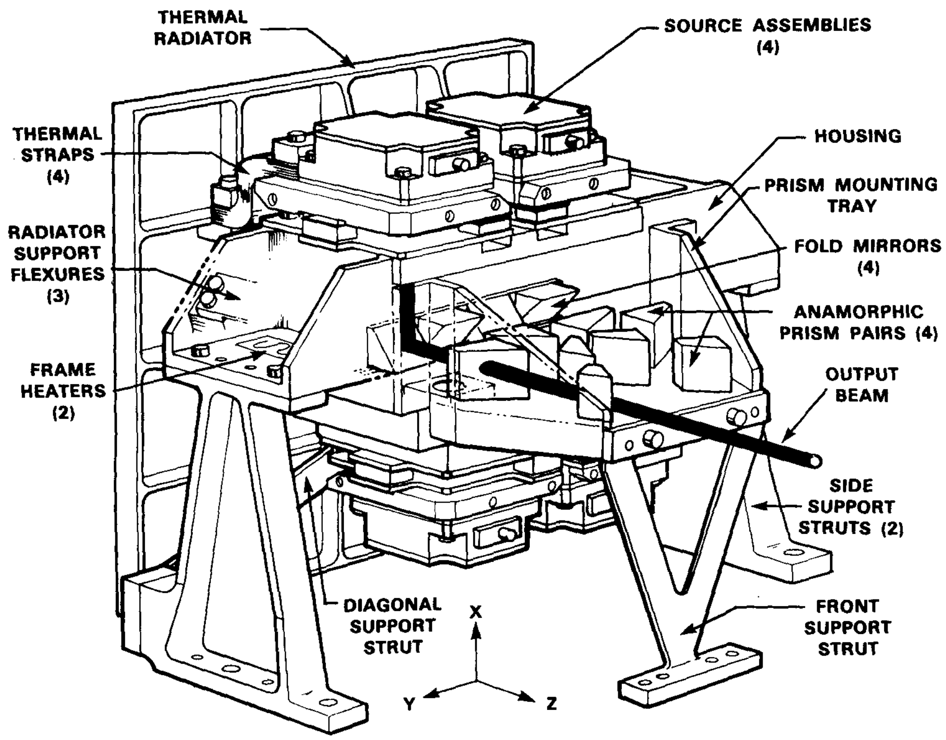

Figure 4. Transmitter configuration shown without
environmental cover or wiring harness.

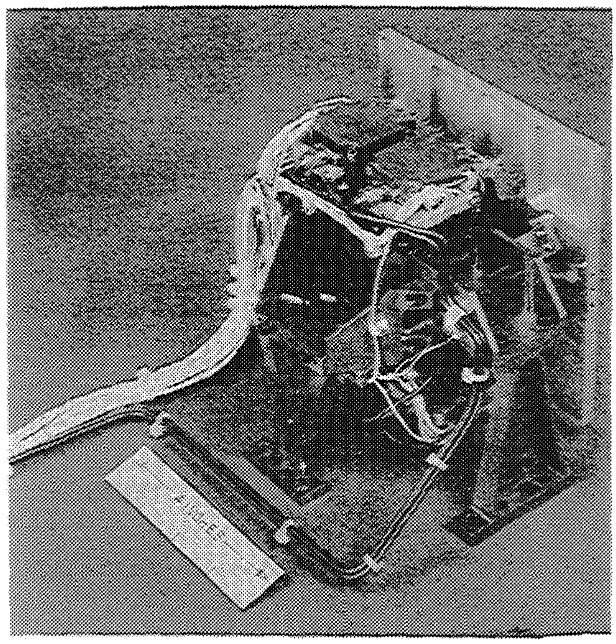

Figure 5. Transmitter assembly without environmental cover or anamorphic prisms.

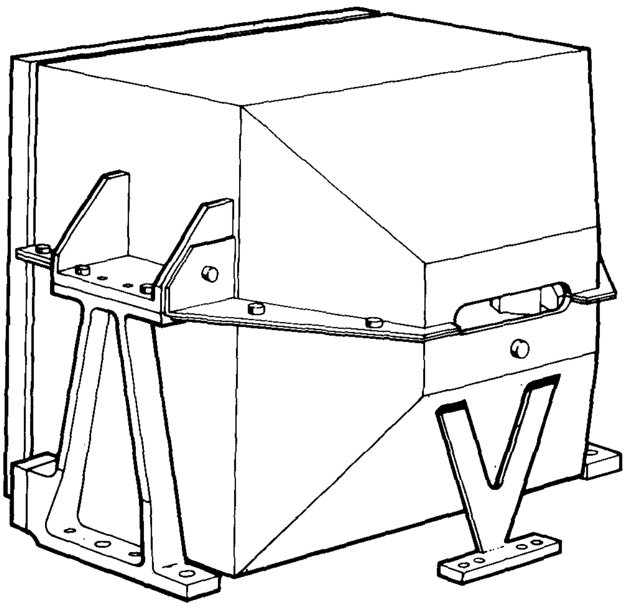

Figure 6. Transmitter with environmental cover.

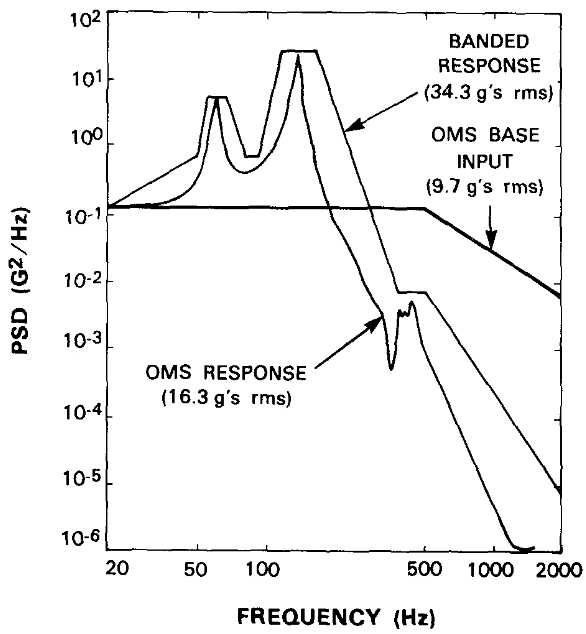

Figure 7. Qualification level random disturbances for the X-direction.

REFERENCES

1. V.W.S. Chan, "Space coherent optical communication systems-an introduction," IEEE Journal of Lightwave Technology, vol. LT-5, pp. 633-637 (1987).

2. J. A. Taylor, A. D. Pillsbury, M. F. Richardson and D. Welford, "Diode-laser transmitter for space-based heterodyne communication," in High Data Rate Atmospheric and Space Communications, Proc. SPIE 996, pp. 77-83 (1988).

3. R. S. Bondurant, et al., "An opto-mechanical subsystem for space-based coherent optical communication," in High Data Rate Atmospheric and Space Communications, Proc. SPIE 996, pp. 92-100 (1988).

4. V. Jayaraman, E. S. Kintzer, J. Garcia and A. Pillsbury, "Design and performance of an on-satellite laser diagnostic system for a free space optical heterodyne frequency-shift-keyed communications system," in High Data Rate Atmospheric and Space Communications, Proc. SPIE 996, pp. 84-91 (1988).

5. MIT has applied for patent protection for the source assembly.

6. Michael F. Richardson, "Optical design for laser diode based communication utilizing heterodyne communication," in International Lens Design Conference, W.H. Taylor and D.T.Moore, eds., Proc. SPIE 554, pp. 327-330 (1985).

7. Code V, Version 7 software, Optical Research Associates, Pasadena, CA.

ACKNOWLEDGMENTS

The authors wish to thank Gregory Loney, Eui In Lee, and Ronald Efromson of Lincoln Laboratory for their assistance with the design analysis and Roy Archibald, also of Lincoln Laboratory, for his contributions to the design of the transmitter.

Table 1. Focus Change Compensation in Source Assembly

Component	Displacement (µm/10°C)
BFL	+0.457
Stalk	-0.533
Ti	-0.013
Invar	+0.088
Total	+0.000

Table 2. Expected Momentum Wheel Disturbances in Host Spacecraft

Nominal Frequency (Hz)	Acceleration (g's)		
	X	Y	Z
100	0.040	0.036	0.036
200	0.006	0.002	0.002
300	0.016	0.030	0.018

Table 3. Transmitter LOS Jitter (µrad) with SSM Position Loop Open and Closed

	Budget	Expected	
		Open Loop	Closed Loop
Local Space			
Elevation	1.90	2.73	0.26
Azimuth	1.90	0.44	0.57
Radial	2.70	2.77	0.62
Object Space*			
Elevation	0.048	0.068	0.007
Azimuth	0.048	0.007	0.014
Radial	0.068	0.069	0.016

*Object space values include the 40X telescope.

Table 4. Expected Transmitter Thermal Beam Walk at SSM

	Case 1	Case 2
Diode Temperature	10°C	30°C
OMS Bench	14°C	0.5°C
Sun on Radiator	Yes	No
Age	EOL	BOL
Power		
- Heater	0.25 W	3.70 W
- Electronics	0.71 W	0.49 W
- Total	0.96 W	4.19 W
Beam Walk (µm)	14	30