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Opto Mechanical Design Aspects of High Power Laser Mirrors

Ashwani Mudgil, Rahul Bhatt & Ravindra Kumar Jain
LASTEC, Defence R&D Organization, Delhi, India
Tel: +91 11 23907623, Fax: +91 11 23811319, Email: ashwanimudgal@lastec.drdo.in

Abstract: Reflecting Optics is a critical component of any High Power Laser (HPL) based System. With the advancements in Laser Sources, power is continuously increasing with decrease in operating wavelength. This has lead to even more sophisticated mechanical design of HPL optics. A large portion of the incident power is reflected and the rest is absorbed and transmitted in various stages. This absorbed power is very detrimental which affects the system performance and may even lead to catastrophic system failure. The mechanism of laser reflection, absorption and transmission is explained in a simple way. General requirements and desired properties of substrate materials are listed. Various metallic and non metallic substrate materials are tabulated along with their physical and mechanical properties. The materials are compared on the basis of their Figure of Merit (ratio of thermal conductivity to coefficient of thermal expansion) and strength to weight ratio (E/ρ). Finally thermo structural analysis is carried out for specific design input and results are formulated.

Keywords: High Power Laser (HPL), Opto Mechanical, Mirror Substrate, Fiber Laser, Figure of Merit.

1. Introduction

High Power Laser (HPL) is an emerging field for possible military applications. The laser power ranging from a few watts to kW and MW level in CW and pulsed modes of operations has been reported for military applications. System concepts include shipboard devices for fleet defense as well as air borne, ground based and vehicle mounted HPL based Directed energy Systems. An essential element of High Power Laser System is the optical sub system including a number of reflective and refractive components subjected to very high heat loads. Because of the severity of the heating conditions, optical substrate materials and cooling mechanism are critical design requirements and controlling factors of the accepted performance of a military grade HPL system.

The earlier High Power Laser Sources viz. Gas Dynamic Laser (GDL) operated on 10.6 μm. GDL was scalable to hundreds of kWs but with some inherent drawbacks like poor beam quality and very bulky in size & weight. With the technological advancements, fiber laser sources are now available with very high beam quality and lower size & weight as compared to earlier sources. The fiber laser sources operate at a wavelength of approx 1 μm, which calls for sophisticated opto mechanical design because allowable distortion in optics is a function of the operational wavelength. Further, high beam quality creates higher power density on the optics in an exponential manner. In this study, we have primarily focused on reflective optics i.e. Mirrors for High Power Laser Systems.

2. Design Considerations of HPL Mirrors

In essence, a high power laser mirror consists of two parts: the reflecting surface (usually a single layer thin film or a multiple layer stack of dielectric or dielectric/metallic thin films) and a rigid substrate machined and polished to very high tolerances and surface finish of the order of λ/10 (approx 0.1 μm). Only very thin reflecting surface serves an optical purpose and the substrate serves primarily to hold the reflecting surface in place and in proper contour during all operational and storage conditions. The HPL, as it strikes the mirror, is primarily reflected and the rest is absorbed in the multiple layers of coating\cite{1, 2} and subsequently in the substrate material. Figure 1 illustrates the concept of laser reflection, absorption and transmission in various stages.
If the substrate material is transparent for incident wavelength of laser, the power absorbed in coating ($P_{ac}$) is dominant but if the substrate is opaque for incident laser, power absorbed in substrate ($P_{as}$) is significantly large in addition to $P_{ac}$. The material, which are suitable for actively/passively cooled mirror are usually opaque to incident laser wavelength (~1μm) whereas the transparent materials don’t offer the advantage of cooling due to very low thermal conductivity and non compatibility to fabrication of monolithic micro cooling channels. The designer can finalize the cooling mechanism and substrate material only after thermo structural analysis for the required operating conditions. In compact and space based laser systems, high strength to weight ratio is the critical design requirement of the optomechanical system.

3. General properties of HPL Substrate Material:

1. Smoothness:
   Practically all mirrors used in optical systems are required to be polished to a high degree of smoothness with very low surface figure errors\cite{3} and micro roughness. The mirror substrate material should be compatible to machining, grinding and polishing processes to achieve the required values.

2. Dimensional Stability:
   Once an optical surface has been ground and polished in to a mirror substrate, it is important for the surface figure not to change due to environmental exposure, temperature changes, release of internal stresses and most importantly due to thermal effects of High Power Laser irradiations (in case of HPL Mirrors).

3. Rigidity:
   The inherent stiffness of the substrate material has significant effects on the suitability of the finished and installed mirror. A more rigid material with low density tends to resist deformations due to polishing, mounting, gravity and vibrations during operation. The mirror substrate materials are usually light weighted in suitably designed mechanical configurations to achieve higher strength to weight ratios. Stress free Holding and mounting of the mirror and design for
athermalization is a critical opto mechanical design process which is beyond the scope of this paper.

4. Material Selection for High Power Laser Mirror Substrate:
Ranging from metals to non metals, the mirror substrate can be selected depending on the operating conditions. A detailed opto mechanical and thermo structural analysis is usually required to be carried out to arrive at the optimal mirror design. Manufacturability and cost aspects also play an important role in substrate selection. There are usually two configurations for High Power Mirrors viz. Cooled and Un-Cooled. Cooled mirrors have built in micro cooling channels in a monolithic structure. A coolant flow circuit is required additionally which is usually not desired for military grade systems. On the other hand un-cooled mirrors rely on heat dissipation through natural convection.

HPL mirrors are required to have a very high rate of heat dissipation alongwith minimal distortion. Substrates must have a good thermal conductivity alongwith very low coefficient of thermal expansion. Metallic substrates viz. copper, Aluminum etc, have good thermal conductivity but a very high coefficient of thermal expansion also. Non metallic substrates viz. Fused Silica, Glass etc. have low coefficient of thermal expansion but poor thermal conductivity. Semi Conductor Materials like Silicon etc have moderate thermal conductivity and thermal expansion. A comprehensive and comparative thermo structural analysis will lead to optimal substrate selection for given operating conditions. Table 1 lists a few suitable materials for HPL mirror applications.

| Sr. No. | Material          | Density (ρ) Kg/m³ | Young’s Modulus (E) GPa | Thermal Conductivity (k) W/m.K | Linear CTE (α) 10⁻⁶/°C | Specific Modulus (E/ρ) | Figure of Merit (k/α) |
|---------|-------------------|-------------------|-------------------------|-------------------------------|-------------------------|------------------------|------------------------|
| 1       | Fused Silica      | 2,200             | 71                      | 1.35                          | 0.41                    | 32.3                   | 3.3                    |
| 2       | Zerodur           | 2,530             | 91                      | 1.43                          | 0.05                    | 35.9                   | 32.8                   |
| 3       | Silicon           | 2,330             | 190                     | 153                           | 2.1                     | 81.5                   | 72.8                   |
| 4       | Silicon Carbide   | 2,900             | 450                     | 145                           | 2.1                     | 155.2                  | 69.1                   |
| 5       | Copper            | 8,920             | 126                     | 391                           | 17.7                    | 14.12                  | 22.1                   |
| 6       | Beryllium         | 1,850             | 290                     | 200                           | 11.6                    | 156.7                  | 17.2                   |
| 7       | Nickel            | 8,900             | 220                     | 75                            | 13.3                    | 24.7                   | 5.6                    |
| 8       | Molybdenum        | 10,200            | 350                     | 145                           | 5.0                     | 34.3                   | 29                     |
| 9       | Aluminum 6061     | 2,690             | 69                      | 167                           | 23.6                    | 25.6                   | 7.1                    |
| 10      | Carbon/carbon     | 2,000             | 16                      | 0.23                          | 0.27                    | 8                      | 0.8                    |

Materials at Sr. No 1 & 2 are highly brittle and have a very low thermal conductivity. They are not suitable for cooled mirror applications. Materials from Sr. No 3 to 9 offer the advantage of cooled configurations.

5. Thermo Structural Analysis:
The opto mechanical design approach for a High Power Laser Mirror is presented here. Necessary design inputs are given below.

- Incident Laser Power : 5 kW CW
- Operating Wavelength (λ) : 1 μm
- Mirror Type : Plane Circular
- Mechanical Size : φ 50 mm x thickness 5 mm
- Clear Optical Dia : φ 45 mm
- Incident Spot Size : φ 10 mm
- Exposure Time : 30 min
Reflectivity : 99.5 % @ 1μm
P_{ac} (Power absorbed in coating) : 1000 ppm
Ambient Temperature (T_0) : 20°C
Max Allowable Deflection : \lambda/6 = 1/6 \mu m

Boundary Conditions:
   i) Volumetric Heat Generation in Multi Layer Coating and Substrate Material due to Laser Absorption.
   ii) Convective Heat Dissipation at open surfaces.
      Un-cooled - Convective Heat Transfer Coeff (h) =5 W/m²K
      Air Cooled – Forced Convection (h) = 200 W/ m²K
   iii) Structural Mode: Temperature Load from thermal analysis at t= 30 min. DOF constraints at Back Surface of the Mirror

These inputs are based on the specific application requirement. Fused Silica and Silicon are used as substrate materials in this analysis. 3D modeling and FE tools (CREO, ANSYS) have been used for coupled field thermo structural analysis. Radiation heat losses are negligible and not included in this simulation study.

**Case 1:** Un-cooled Fused Silica (h = 5 W/m²K)

![Temperature Contours for Fused Silica un-cooled](image)
Max Temp. Rise: 17.2°C

![Deflection Contours (Thermo Structural)](image)
Max Deflection: 0.15 μm
Fig No. 2 & 3 shows the temperature and deflection contours respectively after 30 min of CW HPL exposure on un-cooled Fused Silica substrate. The absorption coefficient of Fused Silica is taken as $5 \times 10^{-5}/\text{cm} @ 1\mu\text{m}$. The Max Temperature rise observed is $17.2^\circ \text{C}$ whereas max deflection in mirror surface is $0.15 \mu\text{m}$ which is within the tolerable limit.

**Case 2:** Un-cooled Mirror Configuration, Substrate Material: Silicon

![Temperature Contours for Silicon Un-cooled](image1)

**Fig 4.** Temperature Contours for Silicon Un-cooled  
Max Temp. Rise: $110.6^\circ \text{C}$

![Deflection Contours (Thermo Structural)](image2)

**Fig 5.** Deflection Contours (Thermo Structural)  
Max Deflection: $15.4 \mu\text{m}$

Fig No 4 & 5 shows the temperature and deflection contours respectively after 30 min of CW HPL exposure on un-cooled Silicon substrate. The Max Temperature rise observed is $110.6^\circ \text{C}$ whereas max deflection in mirror surface is $15.4 \mu\text{m}$. The temperature rise and deflection in this case is very high and not acceptable to design requirements.
Case 3: Air Cooled Mirror, Substrate Material: Silicon

Fig 6. Temperature Contours for Silicon Air cooled
Max Temp. Rise: 21.6°C

Fig 7. Deflection Contours (Thermo Structural)
Max Deflection: 2.5 μm

Fig No 6&7 shows the temperature and deflection contours respectively after 30 min of CW HPL exposure on cooled Silicon substrate. The Max Temperature rise observed in 21.6°C whereas max deflection in mirror surface is 2.5 μm. The temperature rise is moderate but deflection is not acceptable to design requirements.

6. Conclusion
The results of thermo structural analysis are summarized in table 2.

| Sr. No. | Material   | Configuration | Max Temp @ 30 min | Max Deflection @ 30 min |
|---------|------------|---------------|-------------------|------------------------|
| 1       | Fused Silica | Un Cooled    | 17.2 °C          | 0.15 μm (λ/6)         |
| 2       | Silicon    | Un Cooled    | 110.6 °C         | 15.4 μm               |
| 3       | Silicon    | Air Cooled   | 21.6 °C          | 2.5 μm                |

It can be easily concluded that Fused Silica presents a better option for the given operating conditions in spite of its low Figure of Merit than Silicon. This is due to the fact that Fused Silica is Transparent (very low coefficient of absorption) for Lasers @ 1μm whereas Silicon absorbs all of the
residual power transmitted by multi layer coating. As explained earlier also, future of lasers is fiber laser @ 1μm. Most of the substrate materials which offer the advantage of cooled configuration absorb significantly higher powers than fused silica and Zerodur. The optimal, efficient and cost effective opto mechanical design of a HPL mirror can be realized through precise thermo structural analysis.

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