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Large Aperture, Tip Tilt Mirror for Beam Jitter Correction in High Power Lasers

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ABSTRACT

This paper describes a large aperture tip-tilt mirror (TTM) assembly for correction of beam jitter in high power lasers. The design intricacies and trade-offs among various parameters of TTM to meet the desired goals are discussed. The TTM assembly uses a 180 mm diameter and 5 mm thick silicon mirror glued onto the movable ring of a solid flexure. Four stacked piezo-ceramic based actuators have been used to incorporate angular tilts of the mirror along two orthogonal directions. Simulation studies have been carried out to study the dynamics of the TTM. The performance of the TTM assembly in both static and dynamic condition is provided. An experimental set-up is described to test the TTM performance in closed loop conditions. A tilt correction of ±200 micro-radians along two orthogonal directions with a closed loop bandwidth of 20 Hz has been achieved.

Keywords: Tip-tilt mirror, beam jitter, high power lasers, adaptive optics

1. INTRODUCTION

Tip-tilt mirrors are the key components in a wide variety of systems which find applications in diverse fields such as defence, laser communication, astronomy, material processing, medical diagnostics and various research and development projects. Tip-tilt mirrors perform a variety of functions that include scanning, beam pointing and tracking, beam stabilization[1-5] and so on. In the directed energy weapon (DEW) systems, besides beam pointing and tracking, TTMs are used to correct beam jitter inherently present in high power lasers or the one introduced by the atmospheric turbulence.

Most high power lasers used for DEW applications suffer from wavefront distortions in their beam profiles. A high power gas dynamic laser (GDL) involves large mass flow rate of gases expanding through short throat, short length nozzles into the cavity to achieve laser action with required power level. Non-laminar flow of gases in the laser cavity brings in-homogeneities in lasing medium resulting in degradation of wavefront quality of output laser beam. Moreover, mechanical and acoustical vibrations of the optical components and the platform supporting these components generate high frequency beam jitter. An adaptive optical system is, in general, used to correct the localized wavefront errors and the beam drift/jitter[6-8]. Wavefront errors are compensated using a segmented or continuous face-sheet deformable mirror while the beam jitter is corrected with a tip-tilt mirror[9-11]. The global tilt error (jitter) correction can also be accomplished with a deformable mirror but its use drastically reduces overall bandwidth of the adaptive optical system. Most adaptive optical systems, therefore, use a separate tip-tilt mirror for correction of beam jitter.

In this paper, authors described a large aperture, tip-tilt mirror assembly for correction of beam jitter in a CO_2 gas dynamic laser. Simulation studies have been carried out to optimize various response parameters of the TTM. Dynamics of TTM have been studied experimentally and results are presented. The TTM assembly has been used to correct tilt error up to ±200 micro-radians with a closed loop bandwidth of 20 Hz.

2. MIRROR DESIGN

A Mirror is the key component of any TTM assembly. Controlled angular displacements of the mirror along two orthogonal directions are responsible for closed loop correction of beam jitter. Clear aperture of the mirror, maximum tilt range and first mechanical resonance (open loop bandwidth) are some of the important considerations in the design of a tip-tilt mirror. Clear aperture of the mirror is governed by initial beam size of the laser source, inherent tilt errors, beam divergence and the distance of tip-tilt mirror from laser exit plane. For our application, where laser beam has an annular shape (150 mm x 88 mm), the required clear aperture of the mirror is 170 mm. For mirror substrate of this size, maintaining surface flatness over the entire aperture is a real challenge. For reasonable surface flatness of the mirror, thickness to diameter ratio must be at least 1/10. However, thick mirror substrates adversely affect closed loop bandwidth requirements of TTMs. A design trade-off is required between these two conflicting parameters. The selection of material for the mirror substrate is another important factor which decides crucial parameters of TTM such as its first mechanical resonance, surface flatness, machinability, and capability to withstand high thermal loads. Copper, Aluminum,

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Beryllium and Silicon are some of the potential materials that can be used for TTMs. Copper substrates provide large stiffness required to resist surface deformation under both static and dynamic conditions. In addition, large thermal conductivity of copper helps in diffusing the heat generated during irradiation by high power laser source. However, use of copper limits the bandwidth of TTM. Aluminum is highly cost effective solution for moderate bandwidth requirements. It is cheap, light weight and possesses good thermal conductivity. However, for large thermal load the mirror is more likely to get deformed. Beryllium with high stiffness-to-weight ratio is the best solution in terms of both surface figure and bandwidth requirements. It can be easily machined and hence light-weighted so as to meet large bandwidth requirements of DEW applications. Because of its toxicity, Beryllium is not always a preferred choice. Silicon is a light weight material which possesses moderately high stiffness-to-weight ratio. Moreover, Silicon can be easily and effectively polished to optical quality and thus Silicon mirrors provide very high reflectivity. The thermal conductivity of Silicon is also reasonably high to resist thermal deformation due to high power laser beam. We have chosen a 5 mm thick Silicon substrate of diameter 180 mm for the TTM assembly. The initial flatness of the mirror is $\lambda/10$ @10.6 µm. One of the two sides of the mirror has high reflection coating with a protective layer of SiO_2. The non- reflective side of the mirror is glued to the inner ring of solid flexure mechanism.

3. STACKED PZT ACTUATORS

Actuators in a TTM assembly are used for driving/ steering the mirror for required closed loop correction of tilt errors. Voice coil actuators and stacked piezo-ceramic based actuators are used for most of TTM assemblies[12-14]. In a voice coil actuator, the driving force is generated by the motion of a multi-turn coil in fixed magnetic field. The voice coil actuators provide large linear excursion resulting in large angular displacement in a given tip tilt mirror. However, the bandwidth of these actuators is limited which restricts their use to only low frequency applications. A stacked piezo-ceramic based actuator comprises a large number of piezo-ceramic disks stacked together. In general, the discs are made of $Pb(Zr,Ti)0_3$, commonly referred to as Lead-Zirconium-Titanate or PZT. The randomly oriented electric domains of the piezo-ceramics are aligned in the preferred direction by applying high voltages, a process called poling of piezo-ceramics. In order to form the stacked PZT actuator, multiple discs are stacked together in such a way that the discs are mechanically in series but electrically in parallel. Although stacking of PZT discs can be done manually, this is actually achieved using tape casting technique wherein stacking of discs, electroding and provision of electrical connections are done automatically in a pre-planned process control. The method allows more number of PZT discs of lesser thickness to be stacked for obtaining the same total length of actuator. This ensures lesser voltage to be given to stacked PZT actuator for a given stroke length. Moreover, the approach allows simultaneous fabrication of large number of actuators of same specifications.

Stacked PZT actuators are compact, rugged, generate large forces and provide high bandwidths. Moreover, these actuators draw negligible power for holding the TTM in a given static position. The linear excursions of these actuators are, however, comparatively less than those of voice coil actuators. For our application, we have used PZT stacked actuator from Piezomechanik GmbH with linear stroke of 80 microns @ 150 V excitation voltage. These actuators generate a maximum mechanical force of 1800 N with a 300 N preload. The maximum frequency of operation of these actuators under no-load conditions is 1.5 kHz.

4. SOLID FLEXURE SUSPENSION

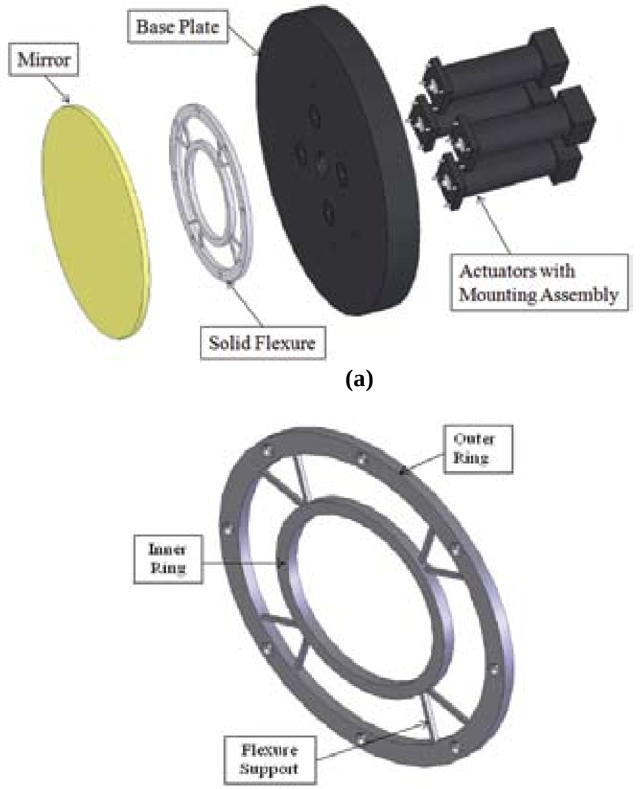
The purpose of flexure suspension is to allow smooth movement of the mirror in the compliant direction and resist all movements in the constrained directions[15]. The flexure suspension determines the tilt correction capability and open loop bandwidth of the TTM assembly. The flexure mechanism of large aperture TTM assembly, described here, uses a flexure ring made of special spring-steel alloy (EN47) to provide high dimensional stability, material uniformity, ease of machinability and high fatigue strength. Because of complex geometry, tight tolerances and symmetry consideration, the flexure ring was cut out of a single piece using electric discharge machine/ wire cutting. Another ring also made of spring-steel alloy with high axial stiffness is used to prevent any kind of axial motion of the mirror. The flexure mechanism ensures smooth angular tilt displacements of the mirror, while restricting any kind of radial or axial displacement.

5. TTM ASSEMBLY

The TTM assembly comprises large aperture Silicon mirror, solid flexure, stacked PZT actuators and a base plate. The mirror is bonded to the central ring of the flexure mechanism using a special adhesive. Four stacked PZT actuators are mounted on the base plate with the actuator tips touching the central ring of solid flexure. The four PZT stacked actuators are located 90^o apart along azimuthal direction. Each pair of oppositely located actuators operates in push-pull mode to provide angular tilt displacement along one of the two orthogonal directions. The flexure supports i.e. ‘V’ shaped fins between the outer ring and the central ring of the solid flexure provide required restoring force to the tip-tilt mirror. CAD model of the exploded view of TTM assembly and flexure details are shown in Figs. 1(a) and 1(b). The TTM assembly is held inside a motorized mount to provide tilt displacements to TTM assembly for initial alignment of the laser beam. Photographs of front and back views of mounted TTM assembly are shown in Fig. 2.

6. SIMULATION STUDIES

Simulation studies were performed to optimize the performance of large aperture tip-tilt mirror. The closed loop bandwidth of the jitter correction system depends upon first mechanical resonance of TTM which is a function of inertia of mirror substrate, stiffness of flexure and flexure design. The mirror inertia is dictated by the dimensions of mirror and material selection. These parameters are selected on the basis of beam size, mirror flatness requirements and thermal load of high power laser source and hence cannot be altered. Thus, open-loop bandwidth of TTM can be increased only by



(a)

(b)

Figure 1. CAD model of TTM assembly (a) Exploded view (b) Flexure ring.

(a) (b)

Figure 2. Photographs of mounted TTM assembly (a) Front view (b) Back view.

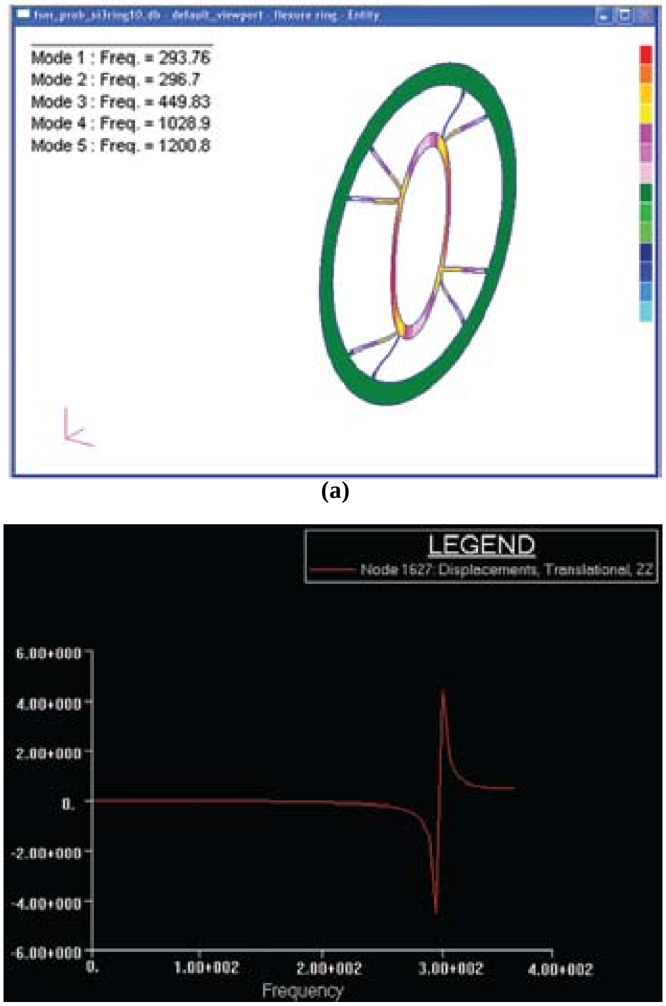
optimization of solid flexure. The optimization of solid flexure was aimed at achieving 1.5 mrad tilt range and more than 300 Hz as the first mechanical resonance of tip-tilt mirror. The material for flexure was selected as spring steel (EN47) which offers high modulus of rigidity and good wear resistance. Important optimized parameters of solid flexure are as follows:

Flexure outer ring: Outer dia: 152 mm; Inner dia: 132 mm; Thickness: 5 mm

Flexure inner ring: Outer dia: 90 mm; Inner dia: 78 mm; Thickness: 4 mm

Flexure Supports (Fins): Width: 2 mm; Thickness: 2 mm; Angle between flexure supports ~ 60°; Flexure stiffness: 9 N/μm

The results of simulation study for the optimization of TTM are depicted in Fig. 3.



(a)

(b)

Figure 3. Simulation Results of TTM (a) Normal mode analysis (b) Frequency response analysis.

7. STATIC AND DYNAMIC RESPONSE OF TTM

The tip-tilt mirror was evaluated experimentally for its various static and dynamic response parameters. For the measurement of tilt range, a laser beam (5mW, He-Ne) after reflection from the TTM was incident on a graph sheet placed at a known distance from the TTM. The tilt range of TTM was then determined by measuring the maximum linear displacement (for maximum permissible excitation voltage) of laser spot on the graph sheet and the distance between TTM and graph sheet. The maximum tilt of TTM was 1 mrad for 150 V excitation voltage.

In order to test the open-loop bandwidth and inter-axes coupling of the TTM, the laser light reflected from TTM was incident on a position sensing detector (PSD), the output of which was measured on a digital storage oscilloscope (DSO). The mirror was given small excitation voltage along one of the axes, say X-axis. Keeping the excitation voltage same, the frequency of excitation signal was increased in steps and output of PSD was monitored. A graph between the excitation frequency and PSD output was plotted. The open loop bandwidth of TTM was determined from its first mechanical resonance. The first mechanical resonance of TTM along the other axis (Y-axis) was determined in the same manner. The open loop bandwidth of the TTM along X- and Y- axes was 280 Hz and 285 Hz, respectively. The frequency response of large aperture tip-tilt mirror along X- axis is shown in Fig. 4.

For measurement of inter-axes coupling, tip-tilt mirror was given excitation voltage along X-axis and the PSD output along both X- and Y- axes was monitored. The ratio of the tilt amplitudes along Y- and X- axes provides the value of inter-axis coupling. The measurements were repeated by giving excitation signal to Y-axis. The inter-axes coupling of the TTM was found to be less than 2 per cent.

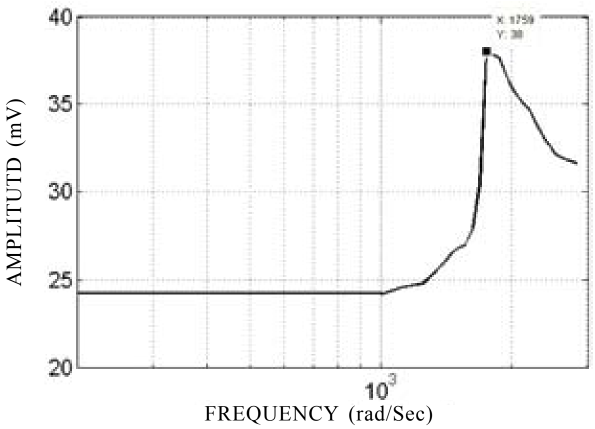


Figure 4. Response function of tip-tilt mirror.

8. JITTER CORRECTION USING TIP TILT MIRROR

The experimental arrangement for closed-loop correction of laser beam jitter is shown in Fig. 5. Simulated jitter in a 100 W CO_2 laser along two orthogonal axes was produced using a high bandwidth fast steering mirror (CO_2 laser and FSM not shown in Fig. 4). Two similar tip-tilt mirrors (TTMs) move in tandem to correct the beam jitter while maintaining the optical axis of the beam. The beam sampler has a special multi-layer dielectric coating such that it reflects more than 99.5 per cent of the laser beam incident on it. The small fraction of laser power entering the tilt sensing unit was reduced in size by a factor of ten using a beam reducer (an on-axis Cassegrain telescope working in reverse order). A 50:50 beam splitter is used to split the beam in two parts which are incident on two pyro-electric quadrant detectors, placed at unequal distances from the beam splitter. The quad detectors generate tilt errors which are fed to a controller to generate correction signals for closed loop correction of beam jitter. A multichannel high voltage amplifier is used to boost the correction signals generated by the controller before applying them to the TTMs. Results of closed loop jitter correction are depicted in Fig. 6.

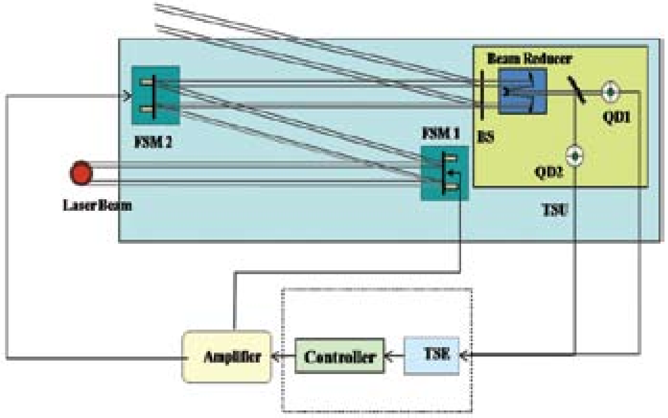
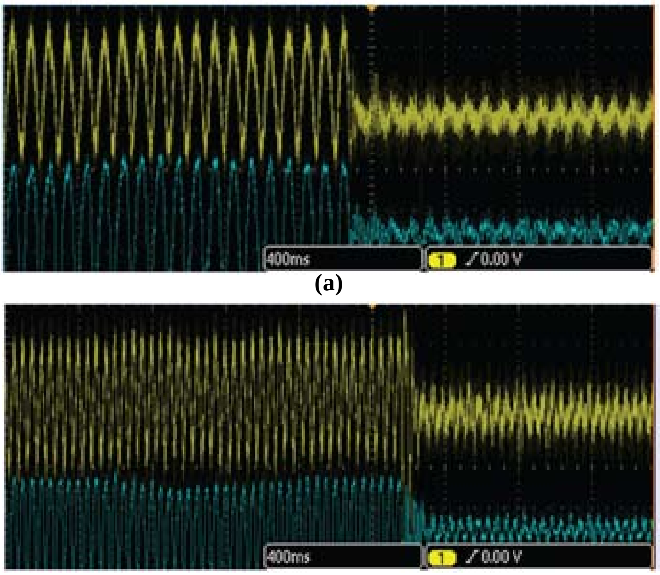


Figure 5. Experimental arrangement for closed loop correction of beam jitter.



(a)

(b)

Figure 6. Results of closed loop beam jitter correction.

9. CONCLUSION

A solid flexure based large aperture tip-tilt mirror for correction of beam jitter in high power laser source is described. Design details of TTM assembly are discussed in detail. Design of solid flexure of the TTM is optimized keeping in view the trade-offs between various conflicting parameters of TTM. A closed loop jitter correction in a 100 W CO_2 laser is demonstrated using a pair of tip-tilt mirrors.

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