Application Note

Opto-Mechanics

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Fast Steering Mirror Technology: Active Beam Stabilization

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Fast Steering Mirror Technology: Active Beam Stabilization

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The laser is now a firmly established tool in a wide range of applications, including semiconductor manufacturing, QA/QC, industrial marking, materials processing, biomedical systems, reprographics, information display and telecommunications. In virtually every one of these disparate applications, it is critically important to avoid fluctuations and drifts in laser beam alignment, in order to achieve optimum system performance. Furthermore, there is continual pressure on optical engineers for higher resolution, finer features and greater stability in their designs. This is especially true in the rapidly expanding and technology-driven semiconductor and optical telecommunication equipment markets. It is routine in these markets to cut critical dimensions and alignment tolerances in half every few years. Failure to meet this road map can spell disaster for companies whose chip life cycles are measured in months. To help meet these demanding needs, Newport engineers have developed a number of approaches, such as active vibration isolation and dynamic beam stabilization, to improve optical alignment stability. With proper utilization of these techniques in next generation optical instrumentation, designers can improve system performance cost effectively while meeting tighter tolerances and increased throughput requirements.

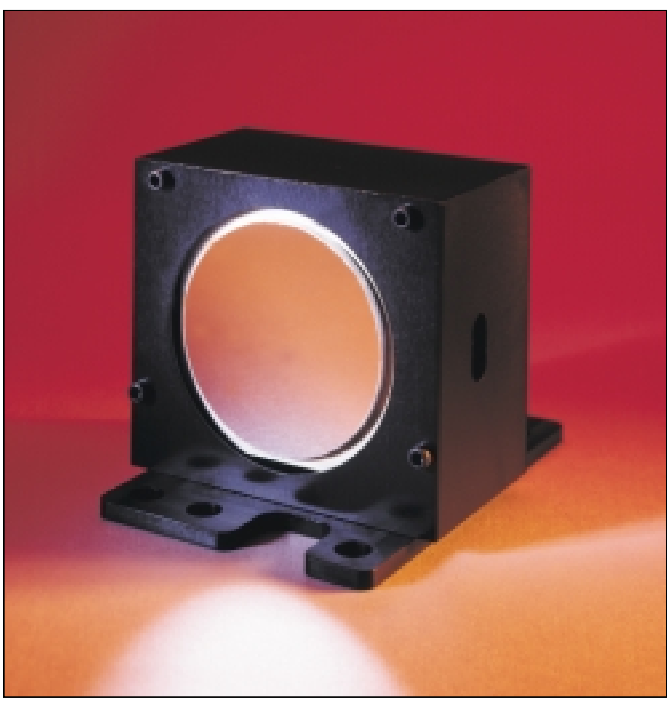

Figure 1 Fast steering mirrors come in an integrated and compact package.

This paper explores dynamic beam stabilization using a fast steering mirror (FSM), a technology originally developed for demanding aerospace pointing and tracking requirements. After reviewing the underlying concept of beam stabilization and comparing different beam steering technologies, the performance of a closed-loop beam stabilization system based on FSMs is described. Optical engineers will find that incorporation of active beam stabilization using FSM technology (Fig. 1) offers a unique and highly advantageous combination of performance and cost characteristics.

Sources of Beam Misalignment

Laser beam alignment can be characterized by essentially two parameters—lateral displacement and angular misalignment. Defining the beam direction as the z-axis, lateral displacement is the xy offset in beam position. Angular misalignment is the angle between the actual beam direction and the desired optical axis. A perfectly aligned beam would have no lateral displacement and no angular misalignment. The minimization and control of these dynamically varying parameters constitutes the fundamental definition of active beam stabilization.

Unfortunately, a number of real world factors conspire to disturb laser alignment. Virtually all gas and solid state lasers are subject to internal thermal effects that cause temporal changes in output beam position and pointing. Thermal drifts inevitably alter the position of various optical mounts and mechanical structures within the system. Also, adjustable mounts used to hold and position lenses, mirrors and other optical components, may experience long term mechanical creep as stresses and strains reach their equilibrium values. The combination of all of these sources slowly affects downstream beam alignment, requiring optical realignment to restore initial accuracy.

Static and dynamic beam misalignment may be introduced by various external sources (from the optical platform) of shock and vibration. This is especially true in industrial environments; vibration from production equipment can be transmitted through the floor to laser based instrumentation where it affects beam alignment. Mechanical shock may occur in an instrument when parts are loaded/unloaded, and when equipment covers or access doors are opened and shut. Internal sources can be some of the most difficult to accommodate since traditional vibration isolation is not as easily applied. Motorized stages and mirror mounts, active shutters, cooling water and circulating fans used in the system can impart relatively high frequency vibration to the otherwise static optomechanical components. This effect is particularly problematic if the vibration occurs at a resonant frequency of one of the mechanical supports or spring-loaded component mounts. Finally, circulating air combined with thermal gradients leads to dynamic index changes (air turbulence) that can produce rapid changes in beam pointing.

Conceptually, most of these effects could be eliminated or greatly reduced by constructing an extremely massive, rigid system, using proper damping, utilizing construction materials with negligible thermal expansion coefficients, and then totally isolating the entire assembly from all internal and external sources of vibration. Needless to say, this approach, even if feasible from an engineering perspective, is expensive to both design and build. Furthermore, even if all components could be held perfectly fixed relative to one another, it might still be necessary to compensate for the unstable pointing characteristics of the laser or surrounding air turbulence. Thus, there is virtually no escaping the need for internal alignment mechanisms in most laser-based systems.

Beam Alignment Techniques

The most common beam alignment method relies on the use of two mirrors (Figure 2), each of which can be rotated in both axes perpendicular to the optical axis. With the direction of beam propagation defined as the z-axis, each mirror provides both θ_x and θ_y adjustment. During the alignment process, the first mirror is used to set the beam to the desired point at the surface of the second mirror, which is placed some distance downstream. This point often determines the optical axis “height” and is the pivot point for setting the direction of beam propagation. The second mirror is then used to point the beam in the required direction.

Manual Alignment

Manual mirror mounts are the most basic and inexpensive way to implement the two-mirror alignment method just described. These mounts are adjusted by a technician to achieve the required alignment when the system is built, installed and/or serviced. Depending upon the characteristics of the system, and the level of alignment precision required, this adjustment may be performed by visually noting the position of the laser beam at one or more components, by referencing and aligning to precision cross hairs or apertures, or by noting the position electronically with position sensing photodetectors.

There are four serious limitations to using manual mirror mounts for beam realignment. First, they can only be used to fix long term drifts in alignment, and cannot correct for any transient errors. Second, they may require equipment downtime while realignment is being performed. Third, they necessitate having personnel trained in optical alignment available to perform the work. Finally, because there is no automatic correction to beam misalignment, the equipment can unintentionally be used when it is not performing properly. In a production environment, this can lead to the disastrous event of devices being certified by out-of-calibration or misaligned inspection equipment.

Slow Drift Compensation

A substantial improvement over the manual realignment method can be achieved by using motorized actuators on the two mirror mounts. These actuators can now be controlled by a feedback signal from position sensing photodetectors thus maintain alignment automatically (Figure 3). The primary advantage of feedback is that the equipment is continuously being realigned, so that there is no longer any performance degradation within the response bandwidth of the active control system. This eliminates the need to take equipment off line for routine realignment and check, as well as the need to have a technician available to perform the chore.

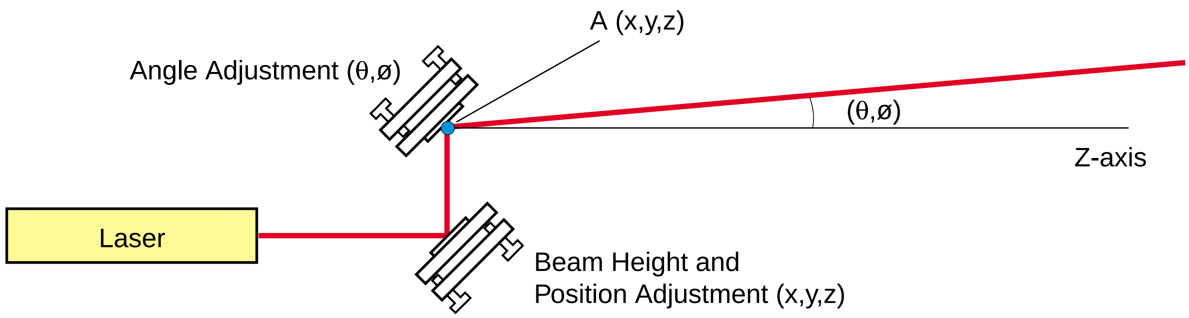

Figure 2 The two-mirror laser alignment layout uses the first mirror to set the beam height (position) on the second mirror. Tilt angles are subsequently adjusted by the second mirror using the pivot point determined by the first mirror.

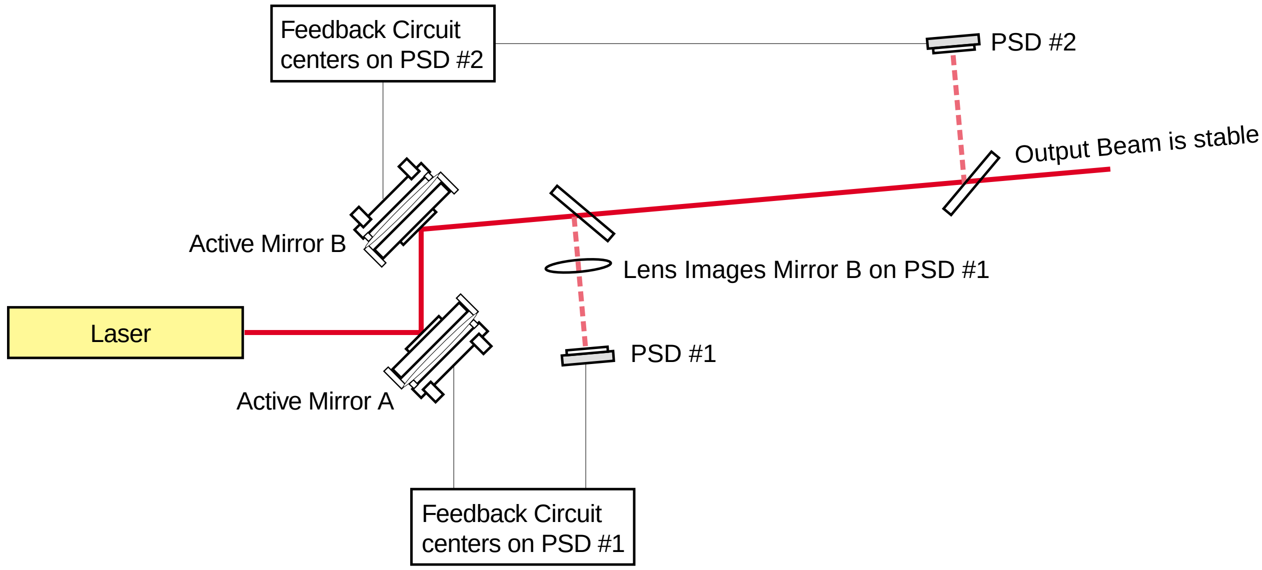

Figure 3 General active-mirror (high speed or motorized) beam stabilization system using two position sensing detectors (PSD) for feed back control.

However, because of the electromechanical characteristics of the motorized actuators typically used in mirror mounts, together with the mechanical properties of most mount bearings, the system bandwidth is limited to correcting for slow (<< 1 Hz.), long term drifts in laser beam pointing. Thus, it is not effective in eliminating the deleterious effects of many external and internal vibration sources. A more comprehensive solution is to use actuators and mirror mounts specifically constructed to respond at speeds sufficient to correct for all the transient effects that the system might encounter.

Dynamic Compensation

By replacing the motorized mounts just mentioned (Figure 3) with fast tip/tilt mirrors, all the benefits of the slow drift tracking are retained but the ability to compensate for internal and external vibration sources is now provided. It enables relatively delicate or sensitive systems to operate properly in more adverse environments, permitting instrumentation to be located directly on the factory floor for in-process inspection rather than in an isolated remote laboratory for statistical process control.

The combined ability to correct for both long-term drift and transient errors provides benefits to the system developer by simplifying the design and construction tolerances of many system components. For example, it may allow the use of lower cost optical mounts, with relaxed specifications regarding vibration resistance and long-term drift. In addition, less stringent attention can be paid to component thermal characteristics, and in some instances, the need for vibration isolation technology can be eliminated. The introduction of dynamic compensation might even enable an existing product to meet higher resolution or stability requirements, without any other redesign.

Thus, for system developers, the use of automated dynamic stabilization can reduce costs by decreasing component count and loosening component specifications. Just as important, it can shorten design cycle time by simplifying the system design and reducing the need for in-depth modeling and testing of vibration effects.

Practical Beam Stabilization Technologies

There are three technologies that are routinely used for dynamic beam stabilization—dual xy galvanometer scanners, piezo-actuated mirrors, and fast steering mirrors. Since each of these technologies have very different operating characteristics, it is useful to briefly review them for comparison and contrast.

Dual XY Galvanometer Scanners

In a galvanometer scanner, a mirror is attached to the rotation shaft of a galvanometer actuator. Consequently, a galvanometer scanner provides only a single axis of rotation; and, a pair of scanners, positioned to scan in perpendicular axes, is required to replace each fast steering mirror in the beam-steering scheme previously described. Unfortunately, this means that each pair, which should ideally only produce an angular displacement, can also produce a linear displacement since the rotation axes are not coplanar. This so called “displacement jitter” can be minimized by keeping the scanner separation in each pair as small as possible, or using optics to image the surface of the first scanner on to the second. Thus a complete compensation system requires dual xy scanners, or a total of four galvanometer units.

One major advantage of galvanometer technology is that it is established and widely used in a number of other types of scanning applications; hence it is well understood and relatively inexpensive due to the quantities manufactured. In terms of performance, the most outstanding advantage of galvanometer actuators is their large angular range (commonly 40 deg.). For dynamic beam stabilization applications, this large range is largely irrelevant and extraneous since the optical system probably only has a few milliradians of tilt error at most. Galvanometer scanners can offer very fast response, which is very useful for stabilizing dynamic tilts. However, there is a tradeoff with mirror mass. Because the galvanometer does not produce a high torque, obtaining high bandwidth (fast response) performance requires the use of a fairly lightweight mirror. Reducing the component's diameter can minimize mirror weight, but this limits the maximum beam size and displacement that can be input into the system. Alternately, utilizing a thin mirror can reduce mirror weight. Unfortunately, this approach has two pitfalls. First, it is virtually impossible to manufacture thin mirrors to a high degree of optical flatness, and second, thin mirrors are more easily deformed under rapid acceleration (necessary for high bandwidth operation). Both these conditions can introduce wavefront distortions, such as focusing errors, into the reflected laser beam. The severity of this problem is compounded by the increase from two to four mirrors that are required for a dual xy galvanometer scanning system.

Piezoelectric Actuated Mirrors

The singular outstanding feature of piezo-actuated mirrors is their high resolution; they are capable of producing extremely small and precise motions. Furthermore, they offer high response speeds, and are capable of moving fairly large optics. It is also possible to construct piezo-actuated mirror mounts offering two degrees of motion, thus avoiding the displacement jitter inherent in galvanometer scanners.

The major limitation of piezo-actuated mirrors is their severely restricted angular range, typically on the order of a milliradian. Thus, a transient impulse or shock that puts the beam out of the actuator's angular range will cause the system to lose its alignment lock. As a result, piezo-based beam stabilization systems are best suited to systems that are substantially limited in the range of tilt errors that can be encountered so that there is no possibility of single event shock ever exceeding the capture range.

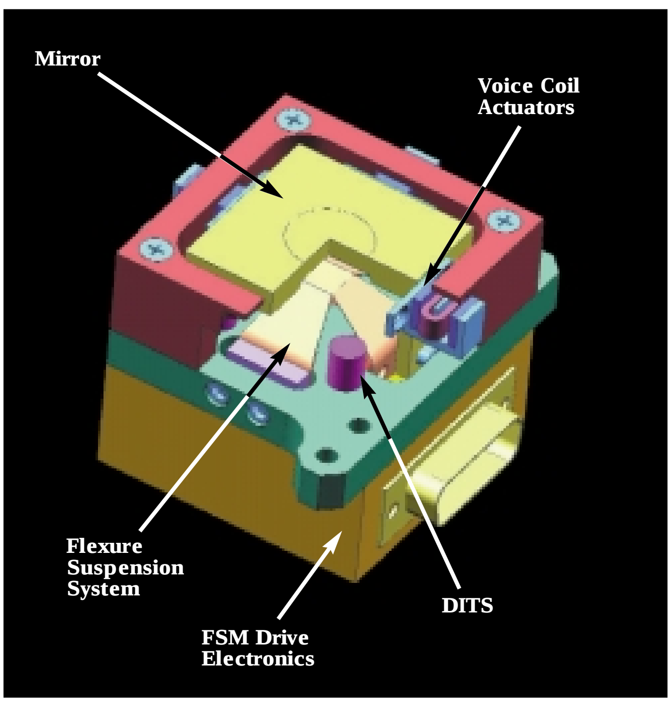

Figure 4 Typical FSM assembly showing the five key subsystems that determine performance.

Fast Steering Mirrors

Fast steering mirror technology was originally conceived for military/aerospace applications such as high-speed target tracking and secure satellite-to-satellite communication. Recently it has been developed to the point where it is economically viable for widespread use in commercial dynamic mirror alignment applications.

To create a practical fast steering mirror, voice coil actuators[1] are used to tilt the mirror substrate (Figure 4). Four actuators are mounted behind or to the side of the mirror, one in each quadrant. Two voice coils connected by the diameter of the mirror operate as a push/pull pair, rotating about the axis that bisects them. Therefore two actuator pairs (four coils) are used to produce two orthogonal rotations (θ_x, θ_y). A unique flexure suspension system is used to support the mirror. This flexure allows free rotation about orthogonal axes while constraining side-to-side motion and rotation about the normal (z) axis. In most implementations, the mirror pivots about its front surface, making it a true gimbal mount.

Depending upon the application, differential impedance transducers (DITS) can be included in the assembly to provide absolute position feedback at the 0.1 µrad level (referencing the FSM support structure). Additionally, a reaction-torque cancellation mass can be incorporated into the design of an FSM. This mass moves in the opposite direction from the mirror and is designed to cancel base structure recoil motion. While this increases the cost of the FSM assembly, it substantially reduces the net vibration caused by rapid mirror motion and thus simplifies the design of surrounding companion structures.

The high force generated by four FSM actuators (versus one in galvanometer scanners) enables them to move relatively massive optics at high speed, while still maintaining excellent positional resolution and large angular range. This ability to use more massive (thicker) mirrors than galvanometer scanners largely eliminates wavefront distortion problems due to poor flatness or dynamic deformation. Furthermore, the coil portion of the actuators is placed within the support structure and contacted to a heat sink. This enables heat produced in the actuator to be dissipated far from the mirror surface, thus minimizing thermal distortions.

1 Historically, voice coils were first used in loudspeakers, from which they derive their name. A linear voice coil consists of a tubular coil of wire situated within the radially oriented magnetic field of a permanent magnet. When current flows through the coil, a force is generated that causes axial (linear) motion. This linear motion is then used to move the mirror.

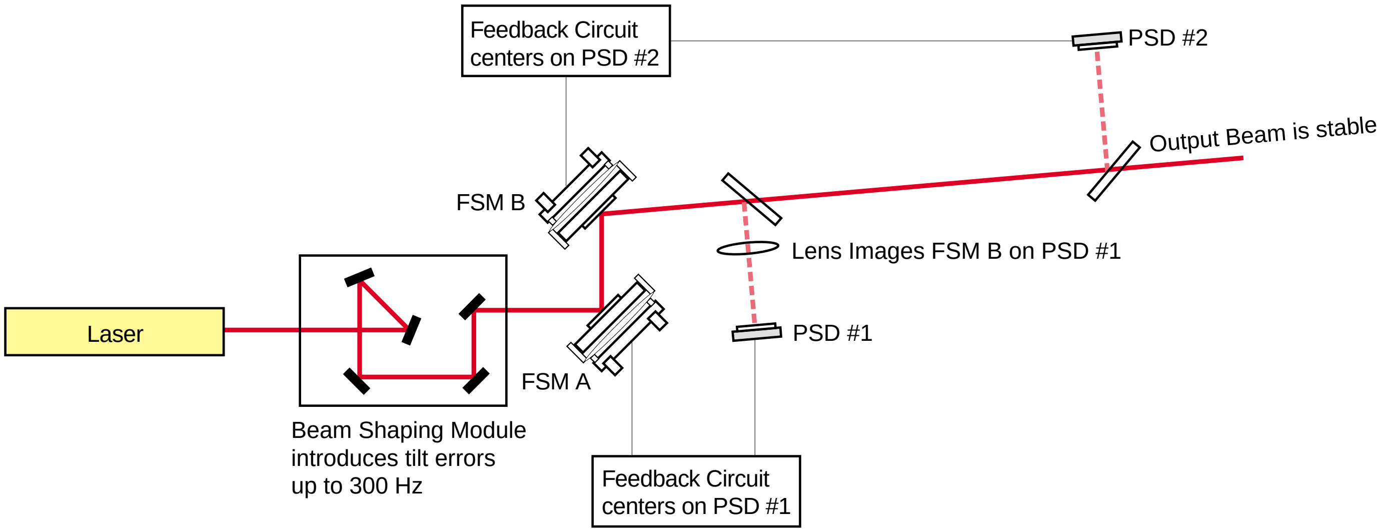

Figure 5 FSM-based beam stabilization system used in simulation run. The beam shaping module is the source of the dynamic tilt errors. Sinusoidal errors up to 300 Hz were used in the simulation.

Another advantage of FSM technology over galvanometer scanners derives from the flexure mounting. The use of a flexure eliminates bearing surfaces and their resulting wear and stiction. Galvanometer scanners that incorporate a shaft bearing are subject to stiction, which interrupts smooth motion of the actuator, and can limit its ability to accurately correct for fast, transient beam movements. Stiction also limits the smallest incremental movement that can be made. Finally, because each FSM delivers motion in two axes, this technology does not suffer from the displacement jitter present in galvanometer scanners.

Simulation Results

To test the performance of an FSM-based dynamic beam stabilization system, simulations were run to find the residual tilt error from a family of sinusoidal input errors of varying amplitudes. The optical layout was imagined as in Figure 5 where a laser passes through a beam conditioning unit (i.e. an optical layout in a test instrument) that has an internal dynamic error source. The raw output from the beam conditioning unit suffers from a dynamic tilt error. This tilt error creates a problem for the hypothetical instrument since the beam must pass through a final aperture. Now the transmitted power of the beam is modulated by the tilt-error produced clipping at the aperture edges.

A pair of FSMs[2] is used to stabilize the beam before entering the aperture. Quad-cell position sensitive detectors provide the feedback signals to the FSMs, forcing the beam to be centered on the detector. The amount of residual error is shown in Figure 6. For error frequencies up to 100 Hz, a reduction in error amplitude of at least one order of magnitude is expected. Even for frequencies as high as 250 Hz, there is at least a reduction of a factor of two.

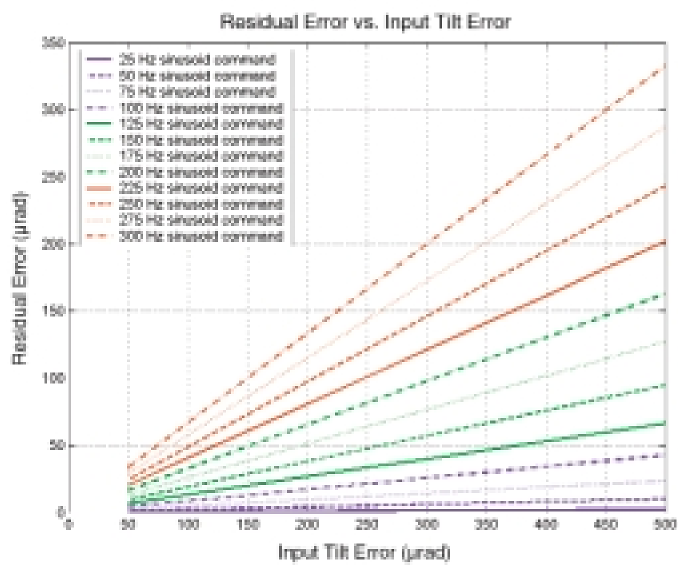

Figure 6 Predicted beam stabilization improvement for a 1 kHz bandwidth FSM-based system. Notice that there is at least a 10X reduction in tilt error amplitude for frequencies under 100 Hz.

Conclusions

The use of active beam stabilization in laser-based instruments offers the potential to simplify system design and construction, and also results in an end product that is extremely robust and reliable. Fast steering mirror technology in particular offers a practical method for implementing active beam stabilization. Simulations have shown greater than an order magnitude improvement in stability from a simple closed-loop compensation system. Delivering a superior combination of response speed, load capacity and angular resolution in a cost competitive package, FSMs are an enabling technology for next generation optical instruments needing stable and drift free laser beams.

2 Each FSM is configured for 1000 Hz closed-loop bandwidth operation and a ±10 mrad operating range of motion. An angular resolution of 0.07 mrad was set by the amplifier noise floor.

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DS-01012 (01-01)
Printed in the USA