

Nanometric Positioning Technology

In an optics laboratory, the need to align optical components with nanometric precision, as well as to maintain this alignment once it is achieved, is increasingly crucial. For example, since a typical single fiber has a core diameter of from 2 to 10 μm , a precision of $<0.1 \mu\text{m}$ (100 nm) may be required when aligning such a fiber with another fiber or optical system.

Traditionally, resolutions of 0.1 μm can be achieved with differential micrometers and, in many applications, this resolution is perfectly adequate, particularly if the system design employs mechanical gain or leverage.

However, it is not sufficient just to have high-resolution adjusters. They must be coupled with optical holders or stages to facilitate the desired linear or angular motion of the optical component such as an optical fiber. Three linear (translational) and three angular (rotational) motions must be achievable in order to fully describe the motion and position of a solid body in free space (see figure 8.22), and these six degrees of freedom are the basis for describing the alignment of an optical component.

FIBER ALIGNMENT

Greater performance and functionality are being asked of fiber-positioning systems. For example, a fiber-to-waveguide alignment workstation may use up to 12 axes of motion, each requiring nanometric resolution. The workstation should be quick to set up, easy to use, and ergonomic. Once set up it should work reliably even under harsh, prolonged, and continuous use.

As the commercial demand grows for fiber-pigtailed optoelectronic components, so does the production requirement for automated, semi-automated, and operator-assisted fiber-optic alignment operations. With the cost-effectiveness of implementing these operations an increasingly important factor, it is clear that there is a demand for a new class of tools for fiber-optic alignment.

Component designers typically use two main positioning technologies: Crossed-roller bearings and flexures. Crossed-roller bearings offer long travel

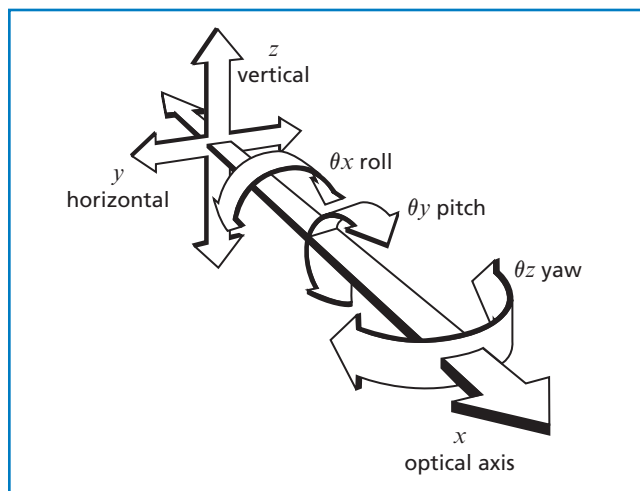


Figure 8.22 Degrees of freedom or motion using the Cartesian frame of reference

and high load capacity. For example, some of the motorized stages use crossed-roller bearings to give travel up to 150 mm and load capacity up to 50 kg. The positioning resolution of bearing stages relies heavily on the accuracy of the component parts. Flexures derive high resolution from their basic geometry and the elastic properties of solid materials. Because they are extremely reliable and repeatedly achieve very fine resolution, CVI Melles Griot selected flexures as a preferred technology for fiber alignment.

In the past, multi-axis systems were built by connecting together a series of single-axis mechanisms (whether bearing or flexure). When the number of axes involved is large, the designs grow in complexity and become cumbersome. This initiated the creation of multi-axis, parallel flexure designs which exhibit a remarkable combination of performance and functionality.

FLEXURE DESIGNS FOR MULTIAXIS SYSTEMS

Stability and simplicity make the parallel flexure design ideal for fiber alignment and other types of nanometric positioning. Because a rigid body naturally has six degrees of freedom, each actuator in the parallel flexure design should subtract one degree of freedom from the body, so that, with six actuators, the body becomes fully constrained. This contrasts with serial designs which, as shown in figure 8.23, use a stack of single-degree-of-freedom mechanisms.

The positioning errors of each element in a stacked system are additive, ultimately degrading the performance of the final multi-axis system. To transmit motion accurately, it is preferable to have as few moving parts acting in series as possible. Parallel flexure stages, by effectively combining positioning mechanisms, can transmit motion very precisely.

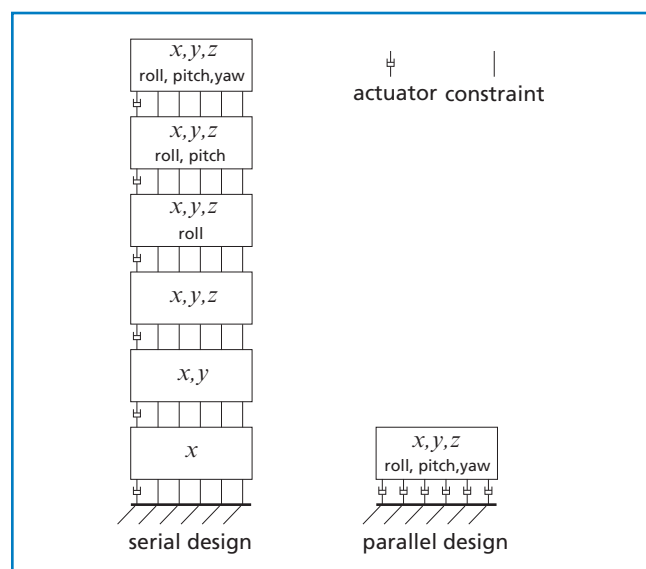


Figure 8.23 Comparison of six-axis serial and parallel stage designs

The graph in figure 8.24 shows the bidirectional repeatability of a six-axis flexure stage. The scan was made over 30 mm in 1-mm steps. Root-mean-square repeatability was 15 nm, or 0.05 percent of full range.

It is worth remembering that parallel flexures, like serial flexures, have arcuate motion. These secondary motions do not occur in the main axis of motion. As a stage is moved either side of its central position, transverse arcuate displacements of the order of tens of microns occur. If several axes are moved at once, the combined effect can be greater.

Although these arcuate displacements are sometimes of concern, they rarely hinder aligning fibers or other optical components since optical beams rarely propagate colinearly with the axes of any stage to better than the scale of the arcuate motion.

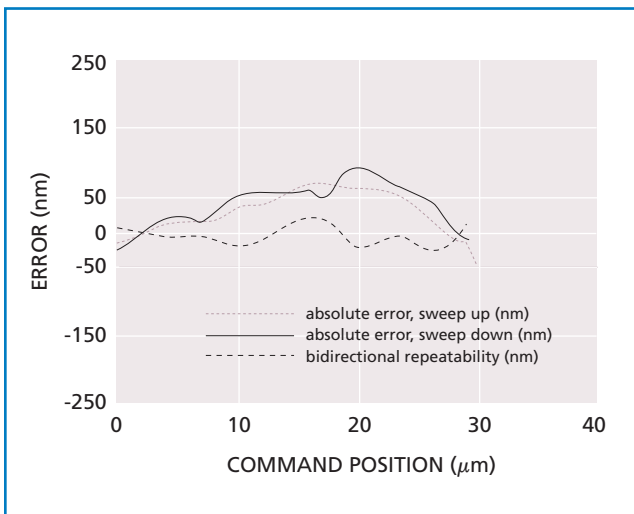


Figure 8.24 Bidirectional accuracy and repeatability of six-axis parallel flexure stage

STABILITY

Ambient vibrations and temperature changes are forces that can easily interfere with a fiber-alignment procedure; therefore, nanometric positioning stages should be designed to be as resistant as possible in the face of such detrimental disturbances.

If a mechanical system has many linkages in series, the stiffness of the whole system is less than the stiffness of each individual linkage. In a parallel flexure design, on the other hand, the stiffness of the linkages is additive. This makes parallel flexure designs very stiff, and there is little movement in response to any external disturbing force.

Due to the low friction among the small number of moving parts, small disturbances are of an elastic nature. When a transient load or shock is applied to the stage, it will quickly resettle into its original position, as shown in the figure 8.25.

To be immune to vibrations, the resonant frequency of a stage should be as high as possible above the range of ambient vibrations. The resonant frequency f can be estimated by using the formula

$$f = \frac{1}{2\pi} \sqrt{\frac{k}{m}} \quad (8.1)$$

where k is the stiffness of the stage and m is the mass of moving parts. It is therefore desirable that the stiffness be high and the mass of moving parts be low. Parallel flexure design stages optimize both of these parameters. These advantages of the parallel flexure design increase with the number of axes of motion.

We mentioned earlier that friction in the parallel flexure system is extremely low. A possible side effect is a prolonged ringing of the stage at its resonant frequency whenever a shock is applied. This is very effectively controlled, however, by a secondary damper fixed to certain moving parts. The damper quickly absorbs the energy of these vibrations without having any effect on the accuracy of the stage.

Thermal drift occurs when differential expansions occur among materials in a mechanical system. To minimize thermal drift of the parallel flexure stages, athermal design techniques may be used. Where possible, similar materials are used; otherwise, materials are chosen that compensate for differential expansions. Other elements in an alignment system, such as the mounting table surface and fixturing accessories, contribute to thermal drift. The system must be viewed as a whole to assess total thermal drift.

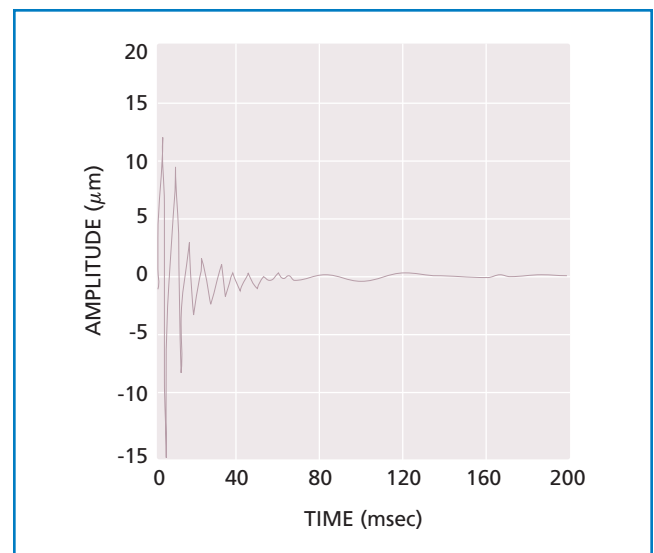


Figure 8.25 Response to a transient load

EASE OF USE

Those involved in the day-to-day manufacture of fiber-optic devices understand the complexities involved. Skill and training are required to achieve very fine alignments repeatedly. A key feature of parallel flexure designs is that the actuators, whether manual or motorized, always remain stationary. They are literally bolted onto the outside of a solid case.

When adjusting a micrometer, torque and sideways force will always be applied. The exact amount of these forces depends on the skill of the user. In a serial design, whether bearing or flexure, this force is transmitted through the moving parts of the stage and will disturb its position. In a parallel design, however, very little disturbance occurs even if the micrometers are handled less cautiously. It is therefore easier to achieve a given resolution, making parallel flexure devices ideal for production environments.

The simplicity of the parallel flexure design has been applied to a new class of nanometric positioning stages offered by CVI Melles Griot. These three-axis and six-axis products offer all the benefits of parallel flexure design, including accuracy, resolution, stiffness, immunity to vibration, dynamic response, ease of use, functionality, modularity, and upgradability.

METHODS OF FIBER LAUNCH AND COUPLING

The vast majority of fiber launch and coupling applications can be incorporated into five general categories: fiber to fiber, fiber to lens, fiber to waveguide to fiber, fiber to multiwaveguide, and fiber to multi-waveguide to fiber.

Fiber-to-Fiber Coupling

After initially launching light into a fiber, researchers in optoelectronics laboratories often obtain a temporary link between fibers by butt-coupling them. Single-mode fiber-to-fiber coupling is extremely sensitive to lateral misalignment of the fiber cores and to the end separation. For example, a lateral offset of one third of the fiber core diameter or an end separation of five times the core radius results in a 1-dB loss in transmission.

For efficient coupling, the two single-mode fibers must be aligned to within a few microns. As a starting point for the alignment, the tip of the fibers are placed at a separation of approximately 1 mm and as near to the optical axis as possible. It is often necessary to use a sensitive power meter for this process. Typically the experimentalist uses a set of transverse horizontal (y) and vertical (z) micrometer drives to alternately scan the tip of the fiber on the moving platform in two axes in order to couple light into the fiber on the fixed platform. At some point in this scan, the power meter will detect a slight increase in power. When this occurs, the user adjusts y and z to maximize the power. Finally, the fibers are brought together using the x micrometer until it is only just possible to see the separation between the fibers. While doing this, one must make fine lateral (y and z) adjustments to maintain maximum power throughput. This is done in a step-wise fashion, so that, with each x movement, both y and z are optimized again.

When butt-coupling polarization-maintaining fibers, it is necessary to rotate the fibers to match the birefringent axes, in addition to aligning the fibers laterally.

The above process can be significantly enhanced with the addition of an automated optical alignment system. One such device, an automatic alignment controller from CVI Melles Griot, can automatically perform the fiber-to-fiber alignment process in less than one second. It can dramatically simplify characterization and pigtailing procedures and can ensure drift-free positioning and accurate data acquisition. The automatic alignment controller performs three functions: searching, aligning, and maintaining optical coupling. More is said about this technology in the following sections.

Fiber-to-Lens Coupling

Sometimes it is necessary to couple light from a focused (lensed) laser source into a single-mode optical fiber. Aligning a fiber to a lens requires the accurate manipulation of the fiber in a minimum of three axes (x , y , z). Depending on the manufacturing and fixturing tolerances of the components, adjustment in roll (θ_x), pitch (θ_y), and yaw (θ_z) may also be needed (see figure 8.26). Typically the laboratory setup that is used for this purpose is equipped with precision stages with stepper-motor drives on all axes and piezoelectric actuators on the y and z axes.

Fiber-to-Waveguide Coupling

Many optical devices have the form of a rectangular waveguide. For example, laser diodes are in the form of a rectangular waveguide, and the light beam that they emit is propagated from the edge of the waveguide in a highly divergent fashion. In fiber-optic applications, particularly those related to telecommunications, it is often necessary to couple the light from these waveguides into the optical fiber (see figure 8.27). This requires a high degree of precision, comparable and often higher than, the degree of precision required in fiber-to-fiber applications. However, the alignment processes and techniques described in the above section associated with the fiber-to-fiber alignment application, to a great extent, applies in the case of the fiber-to-waveguide alignment process as well.

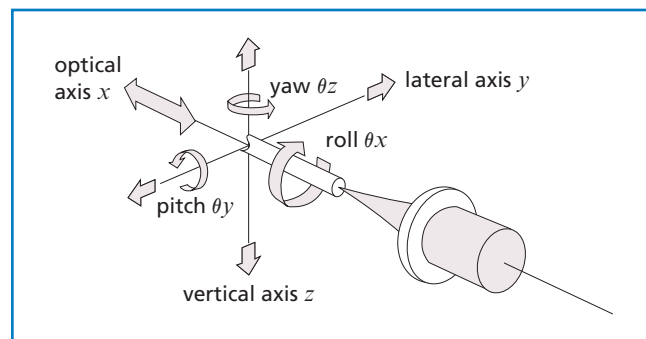


Figure 8.26 Fiber-to-lens alignment process

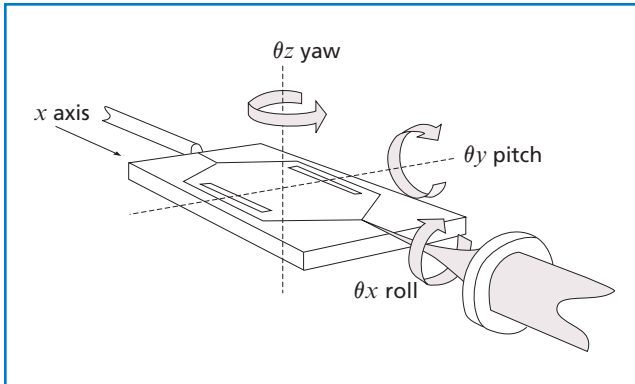


Figure 8.27 Fiber-to-waveguide alignment process



Various fiber-optic holders

Fiber Launch with Microscope Objective

It is common to launch a collimated beam of light into an optical fiber using a microscope objective as the focusing element (see figure 8.28). The collimated light, typically from a diode laser source, is collected and focused by the microscope objective directly into the fiber. For optimal coupling efficiency, the numerical aperture of the optical fiber must be compatible with that of the microscope objective. Aligning this system is very similar to aligning a simple fiber-launch application. However, lateral misalignments are less critical than in direct fiber-to-fiber coupling, but angular misalignments are more so. To compensate for the angular sensitivity, the standard microscope objective holders can be replaced with adjustable mounts equipped with specially threaded mounting adaptors that can provide ± 3 degrees of angular tilt in θ_y and θ_z (yaw and pitch) and provide a sensitivity (or resolution) of 10 arc seconds.

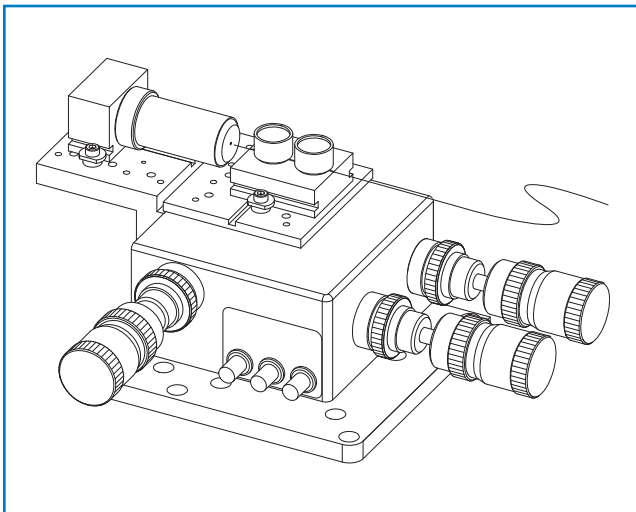


Figure 8.28 Three-axis fiber-launch system using microscope objective