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Abstract

A 64-inch swing, vertical spindle axis precision lathe has been constructed. The machine incorporates a multiple-path laser feedback system, capacitance gauges, a 32-bit computer and capstan drives to provide two axes of tool motion in a 32-inch radius by 20-inch length working volume. Dimensional stability of critical components is achieved through the use of low coefficient-of-thermal-expansion materials and temperature-controlled heat sinks. Projected accuracy of the machine is approximately one microinch rms.

Introduction

The Large Optics Diamond Turning Machine (LODTM) is a precision vertical axis lathe constructed at Lawrence Livermore National Laboratory. This machine, built under the sponsorship of the Defense Advanced Research Projects Agency and the direction of the Air Force Wright Aeronautical Laboratory, has been optimized for the single point diamond turning of annular resonator optics. The LODTM will accept a workpiece with maximum dimensions of 64 inch diameter and 20 inch length, and a maximum weight of 3000 pounds. The design goal for tool positioning accuracy within this work volume is 1.1 microinches rms. The goal for azimuthal error (excluding workpiece and fixture distortion) is 0.5 microinch. In order that the diamond turned optics might be usable in infrared applications without subsequent polishing, a goal of 42 Angstoms rms was specified for surface finish errors.

The requirement for azimuthal symmetry led to the adoption of a vertical spindle axis to minimize asymmetric gravity loading of the workpiece. The choice of a vertical spindle and the wide range of workpiece mass make it quite difficult to incorporate axial (z-axis) positioning by moving the spindle, as is commonly the case with existing diamond turning machines. As a result, tool positioning on the LODTM is accomplished with stacked slides; a vertical tool bar provides z-axis motion and is mounted on a carriage which provides radial (x-axis) motion. The remaining design features of the machine, as well as environmental controls have been coordinated with the use of a detailed error budget. In fact, the accuracy values quoted in the preceding paragraph are the result of the error budget summations based on the initial machine design.

Metrology Loop

The fundamental problem in the design of feedback-controlled machine tool is measuring the tool-to-workpiece relative position without intruding into the work volume, which may be occupied by the workpiece. We refer to the series of measured and a priori known distances which connect the tool tip to the workpiece base outside the work volume of the machine as the 'metrology loop'. The LODTM metrology loops are comprised of high-stability low coefficient of thermal expansion (CTE) passive components, laser interferometers and high-precision capacitance gauges. To avoid quantization error in the digital control system, measurements are made with a resolution of 0.025 microinch, although accuracy goals for measurement components are generally 0.1 microinch. The active measurements made by laser interferometers and capacitance gauges are referenced to a passive 'metrology frame'. This metrology frame is an unloaded structure which is kinematically mounted to the main machine frame.

Interferometers

All large-travel measurents are made with laser interferometers. Figure 2 depicts the arrangement of the seven laser interferometers used on the LODTM, while figure 3 shows the optical design of a single, typical, interferometer. The interferometers are Michelson type, with a polarizing beam splitter and corner cubes for reflectors. The use of corner cubes reduces the angular sensitivity of the interferometer, while the use of a polarizing beam splitter allows the application of optical heterodyning as a detection mechanism by supplying a different frequency beam to the measurement and reference arms of the interferometer. The two frequencies of source beam are separated by 1.75 MHz and occur in orthogonal linear polarization states. The two beams are recombined at the dectector with a polarizer oriented at 45°; the phase of the resulting 1.75 MHz modulation provides a measure of the difference in length of the measurement and reference arms. Subsequent processing by digital electronics provides a phase resolution of 1.4°, corresponding to path length resolution of approximately .025 microinch when a He-Ne laser is used as the source.

A single laser source supplies the beam used by all seven laser interferometers. This source (figure 4) consists of Spectra-Physics model 125 He-Ne laser which is frequency-offset locked to a second laser which is stabilized to an atomic iodine absorption line using an internal iodine cell.[1] The model 125 laser is modified for this application by the addition of a longitudinal mode selection etalon and the replacement of the front cavity mirror mount with a piezzoelectric mount. The output from this system is approximately 15 milliwatts of collimated 6328 Angstrom light with a coherence length greater than ten meters and line center stability better than one part in 10^9. This beam is directed to a Mach-Zehnder interferometer constructed with polarizing beam splitters and incorporating accousto-optic modulators in the legs. The two states of polarization are shifted either 60 or 61.75 MHz in frequency to obtain the 1.75 frequency split for the heterodyne interferometers. Any beam retroreflected from the interferometer system will traverse the modulators twice, and will enter the model 125 laser cavity at a frequency of minimum gain, hence minimizing the pertubations resulting from downstream optics.

Four horizontal interferometric measurements are made from the metrology frame to Zerodur straightedges mounted to the tool bar. The difference between upper and lower measurements yields the pitch angle of the straightedge, allowing extrapolation of the measurement to its lower end. Averaging measurements from each side rejects symmetric expansion of the metrology frame, while comparing them provides an assessment of error. The two straightedges are kinematically mounted to the tool bar at their lower ends and at points approximately one quarter of their length from the upper end, calculated to minimize bowing distortion from the lateral body forces resulting from x-axis acceleration and machine tilting. The use of these straightedges permits the measurement of the horizontal position of the lower end of the tool bar independent of distortion which may occur in the bar itself do to the effects of its drive, bearings or tool force during cutting.

Three measurements are used to establish the vertical position of the lower end of the tool bar. The interferometers used for these measurements are mounted on a stable, rigid platform which is kinematically mounted to the main machine frame. Two of the interferometers measure the distance to Zerodur straightedges mounted on the metrology frame, while the third measures distance from the platform to a mirror mounted on the lower end of the tool bar. The two straightedges, equidistant from the centerline of the machine, are used to create a virtual reference in the plane of the tool so that carriage or platform rotation about the x-axis does not introduce an Abbe offset error.

The primary errors to which the interferometers are subject are index of refraction variations along the path and spurious mixing of the two frequencies used for heterodyne detection. The former is primarily due to temperature changes in the glass optics and atmospheric index changes along the measurement path, while the latter results from errors in the source or polarization mixing in the interferometer system. Both reference and measurement beams traverse the same optical path length in the polarizing beam splitter and corner cubes, thus minimizing the effect of temperature changes in these components. The use of left-right symmetry in the horizontal measurements and parallel references in the vertical measurement result in gross cancellation of path length changes due to temperature drift in the quarter wave plates and vacuum windows; only differences between interferometer temperatures cause apparent motion.

The interferometric measurements are isolated from atmospheric effects by enclosing the interferometer and all but a small gap of the measurement path in vacuum. The two vertical reference measurement paths are enclosed in solid tubes, while all other interferometer measurement paths are enclosed in welded metal bellows to permit the required travel. The horizontal metal bellows are self-supporting because of the external atmospheric pressure; therefore no sliding contact elements or dynamic seals are present to influence the axis drives.

Capacitance Gauges

The interferometer system provides sufficient information to determine the position of the tool with respect to the metrology frame. Position of the workpiece relative to the metrology frame is determined by capacitive sensors mounted to metrology frame extensions which measure drift of the outer edge of the spindle faceplate. Two capacitance gauges are used at each edge of the faceplate to provide measures of axial, radial and tilt motion; the fourth independent signal combination of the four sensors should remain constant, and provides a check on system stability.

Each capacitance gauge consists of a differential air gap pair of electrodes that use the spindle faceplate as a common ground electrode. The electrodes are thin film chromium deposits on a Zerodur plate which is positioned in slot machined into the spindle faceplate. A nominal air gap of .004 inch was chosen as a compromise between considerations of sensitivity, hydrodynamic force from the sheared air film, and ease of assembly. The total plate area of the gauge is approxiately one square inch; isolation from parasitic capacity in the leads is provided by an equipotential shield. The capacitance gauges exhibit an output noise equivalent of 5 Angstroms rms in a bandwidth of 500 Hz, quite sufficient for the intended operation. Attempts to measure the linearity and stability of the gauges have resulted in instrumentation limited values indicating the gauges exceed 0.1% linearity and 0.1 microinch stability.

Passive Components

Three regions of the metrology loop must be completed with passive components: connection of the interferometer bases (or horizontal straightedge) to the capacitance gauges, connection of the spindle faceplate edge to the workpiece, and connection of the lower end of the tool bar to the tool tip. In all three areas, super invar is used to provide a stable, low CTE mechanical connection, while Zerodur is used exclusively for optical references. The initial selection of super invar for structural use was prompted by the CTE and temporal stability data reported by Berthold, Jacobs and Norton[2]. Subsequent measurements at LLNL, while not identical, confirmed the suitability of the material. In particular, the ability of properly welded joints to retain the desirable properties of the parent material was verified.

The major passive component of the metrology loop is the metrology frame. This is a 3,000 pound welded box-beam type structure connecting the interferometers and capacitance gauges and surrounding the machine work zone. The metrology frame is mounted to the LODTM mainframe in three places using blade-type flexure supports. As a result, the metrology frame suffers only rigid body rotation and translation during machine operation, while the mainframe deforms up to 250 microinches.

The spindle faceplate is also a 3,000 pound super invar structure. It consists of two 1.5 inch thick plates separated by a 9 inch layer of super invar honeycomb. The honeycomb layer is spiral wound, so that there is not a preferred angular orientation for radial elastic deformation. Capacitance gauge reference grooves are machined into the upper plate, while the lower plate is lapped to provide a flat surface for the spindle thrust bearing.

Drive System

Bearings

The design of LODTM moving parts relies heavily on the use of fluid film bearings. In all, there are 26 externally pressurized bearings in the LODTM, using either air or one of three oils as a working fluid. The tool bar is supported on a system of 14 identical air bearings, each with four separate film quadrants and feed systems. Each of these feeds incorporates two restricters and an intermediate damping chamber to provide enhanced stability and act as a damper for resonances in the main machine weldments. Indeed, impact testing confirms that these bearings reduce the resonant response to tool bar loading in the vicinity of 100 Hz by 10 dB.

The tool bar motion assembly is in turn mounted on a 3,700 pound carriage which provides x-axis motion. This carriage is supported on fluid bearings riding on a flat way on one side and a 90° vee way on the other. Two bearings are provided on the vee way to constrain rotation about the z-axis. All of these bearings are externally compensated bearings using very high viscosity silicone based oil as operating fluid. This oil was chosen to provide maximum shear damping for the drive servo loops, and has the additional advantage of high squeeze film damping and low flow rates. The latter characteristic makes practical the use of a non-cycling blow-down oil supply.

The LODTM spindle is supported by separate radial and thrust bearings. The radial journal bearing is a 3.5 inch diameter step bearing 3.5 inches long. A light oil is used as the working fluid in this bearing and gaps of 300 and 600 microinches are used to supply stability. This bearing is also supplied with water cooling passages on both the inside of the rotor and the outside of the stator to prevent heat generated from shearing the oil film during operation from reaching other parts of the spindle assembly.

The thrust bearing is a 42 inch diameter 2 inch wide annular step bearing which utilizes the flat lower surface of the super invar spindle rotor as the rotating element. This bearing uses a low viscosity oil as lubricant and has gaps of 500 and 800 microinches. The bearing stator is constructed of brass and has an integrally machined water heat exchanger to dissipate heat resulting from oil film shear. To insure the stability of the spindle rotor and the axial and angular error motion of the spindle, it is necessary to maintain the figure of the thrust bearing stator regardless of workpiece weight. This is accomplished with a combination of three-point mounting of the thrust bearing stator support and a pressurized trapped-volume oil film weight relief which maintains constant load on the three mounting points. Squeeze film damping in the trapped oil film provides dynamic stiffness in excess of that present due to the kinematic mounts.

Axis Drives

The primary actuators for both x- and z-axis motion are capstan drives, each consisting of a two inch diameter smooth steel roller driving against a flat steel bar approximately one inch wide. A slight barrel has been ground onto each roller, so that the actual Hertzian contact is an elipse with a large aspect ratio. The rollers are supported on both ends by 3.5 inch diameter step-type oil bearings, while the x and z drive bars are continuously mounted to the main frame and to the tool bar, respectively. Each roller is directly coupled to the rotor of a D.C. torque motor, eliminating the backlash typical of gear reduction or leadscrew drives. The only source of apparent 'friction' in the mechanical part of a drive is elastic hysteresis in the contact zone and geometrical imperfections of the bar and roller. In practice, with approximately 100 pounds of normal force on the contact zone, these effects are much smaller than the internal brush friction and magnetic torque of the drive motor and tachometer.

While these drives have proven to have very high resolution, their maximum driving force is limited by the normal pressure in the contact zone and the coefficient of friction between hard metal surfaces with oil present. This limits the drives to a force of about ten pounds. As this force is insufficient to overcome the spring force due to the numerous welded metal bellows used for vacuum optical paths, another actuator had to be provided to supply biasing force without exhibiting stiffness which would interfere with the action of the capstan drives. An additional set of welded metal bellows enclosing a servo-controlled pressure ranging from vacuum to several psi below atmospheric pressure serves this purpose. In the z-axis motion control system, these auxiliary bellows also support the static weight of the tool bar. The pressure in these bellows is maintained below atmospheric so that they, like the horizontal optical path bellows, will be self-supporting. Each servo-control loop senses the average current to a capstan drive motor, attempting to maintain it at zero.

Environmental Controls

It is critical that the LODTM be effectively isolated from vibration and maintained at constant temperature. The former requirement has been met by use of isolated mounting and accoustic shielding. The LODTM mainframe rests on four air isolators, two of which have been interconnected to provide a three-point kinematic support. These four isolators are mounted to concrete piers which are independent of the concrete structures of the surrounding building. In addition, all major vibration sources such as air compressors and air conditioning equipment in the surrounding facility are mounted on independent concrete slabs. Accoustic vibration isolation is achieved by surrounding the machine with a heavy-walled enclosure covered with sound-absorbing panels. This enclosure is contained within a high-bay experimental area whose walls are double-studded and filled with insulation. All support equipment such as cooling liquid systems and the control computers are housed outside the high-bay area.

The ambient temperature in the enclosure is maintained by a recirculating-flow air conditioning system based on a variable flow water-air heat exchanger. This air conditioning system maintains a constant air temperature within 0.01°F. Critical LODTM systems are temperature controlled directly by water flow. Channels constructed in the spindle journal and thrust bearings serve this purpose, as do double-walled panels surrounding the metrology frame. The water supplied to these systems is conditioned to constant temperature within 0.001°F through the use of variable-flow water-water heat exchangers. All temperature control water entering the machine enclosure is gravity-fed to avoid exciting the machine with pump vibrations.

References

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2. J. W. Berthold, S. F. Jacobs, M. A. Norton, "Dimensional Stability of Fused Silica, Invar, and Several Ultra-low Thermal Expansion Materials"; Metrologia 13, 9-16 (1977).

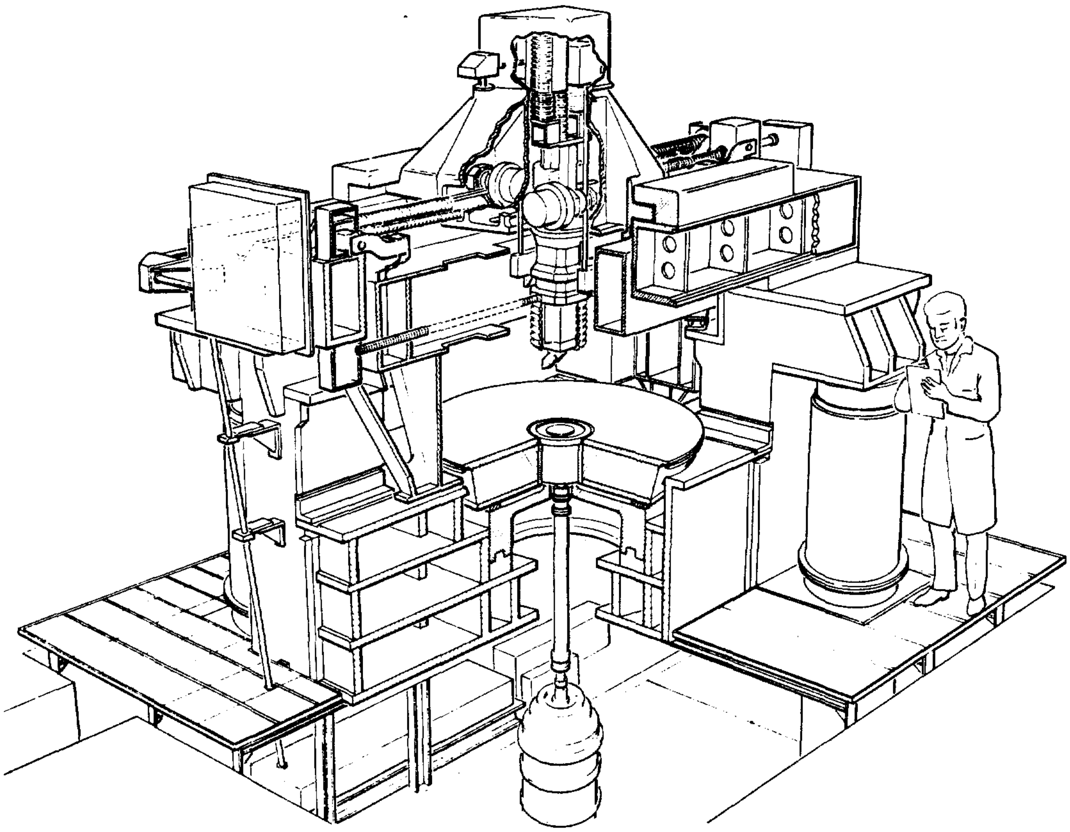


Fig. 1. Large Optics Diamond Turning Machine

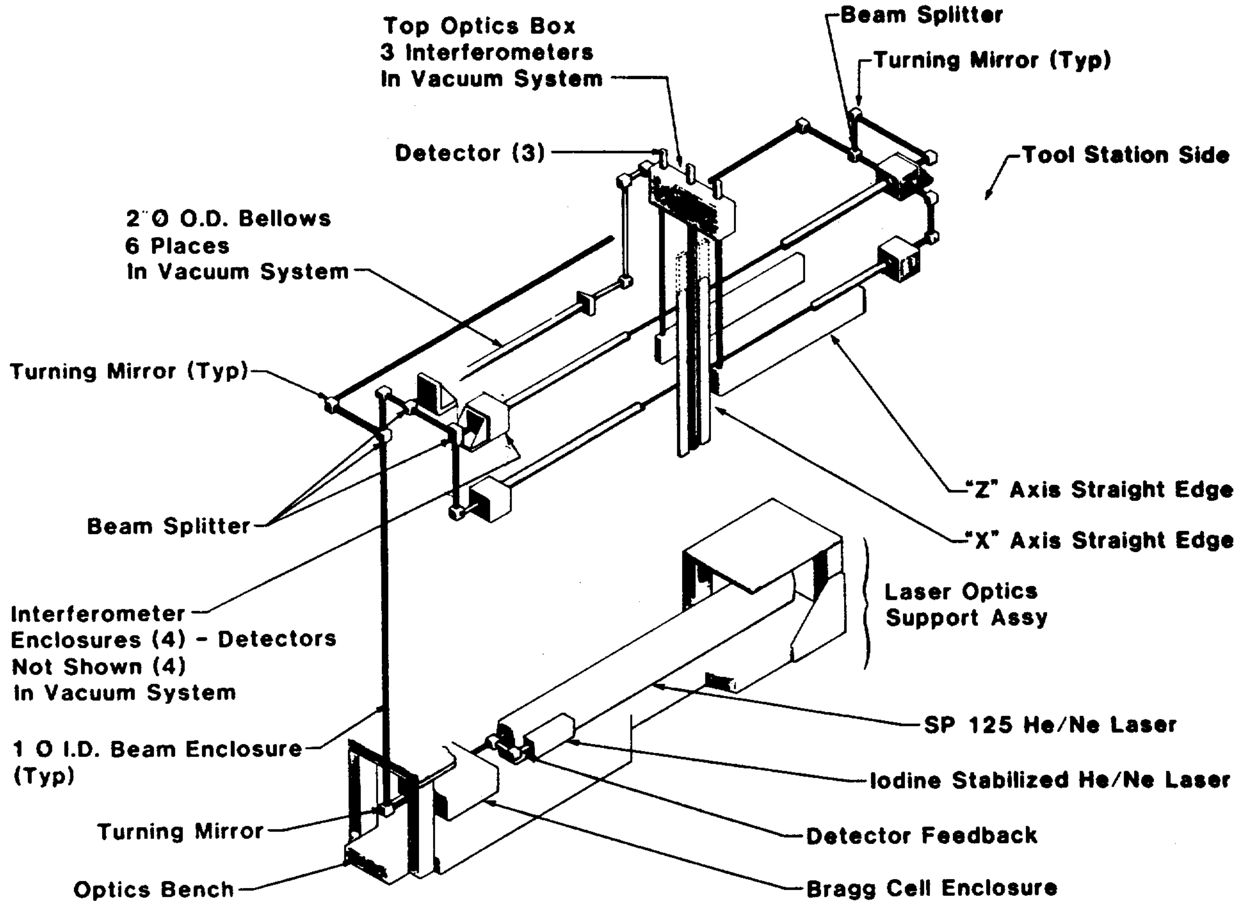


Fig. 2. LODTM Interferometer System

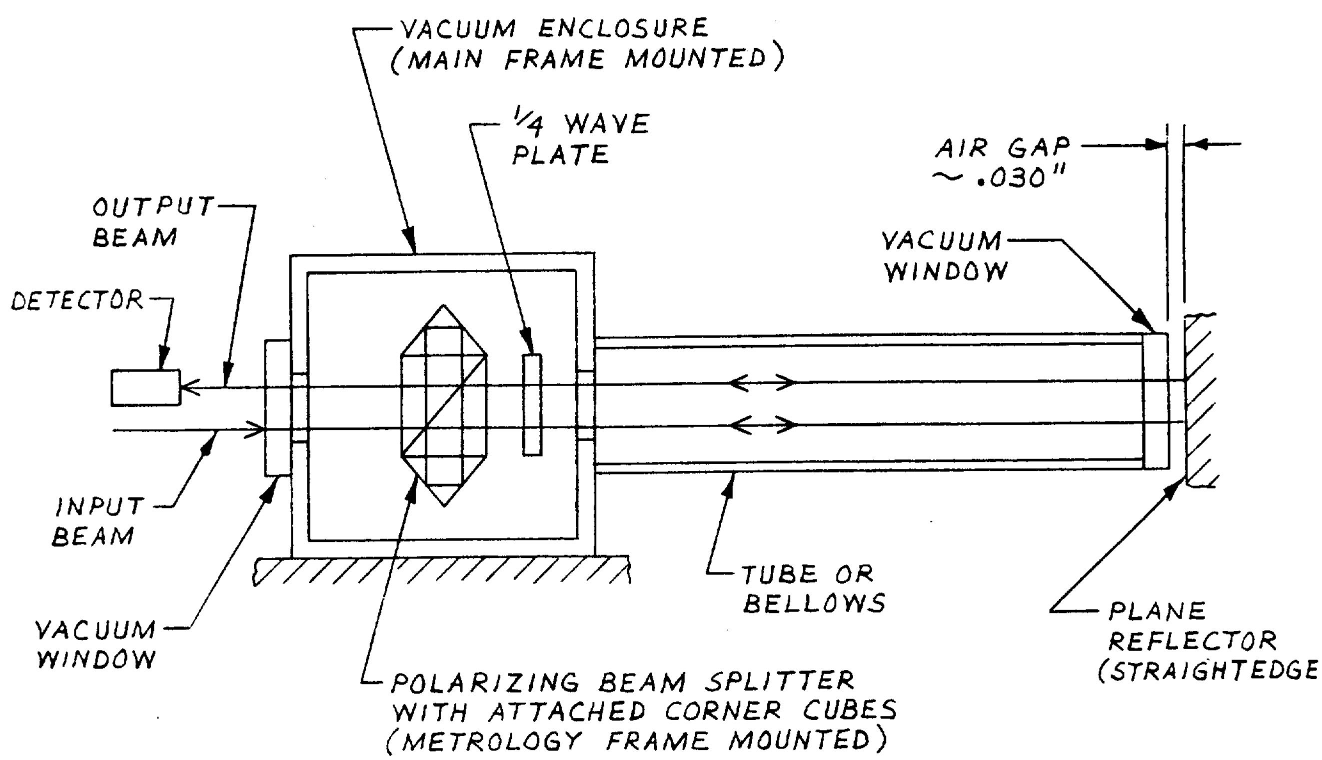
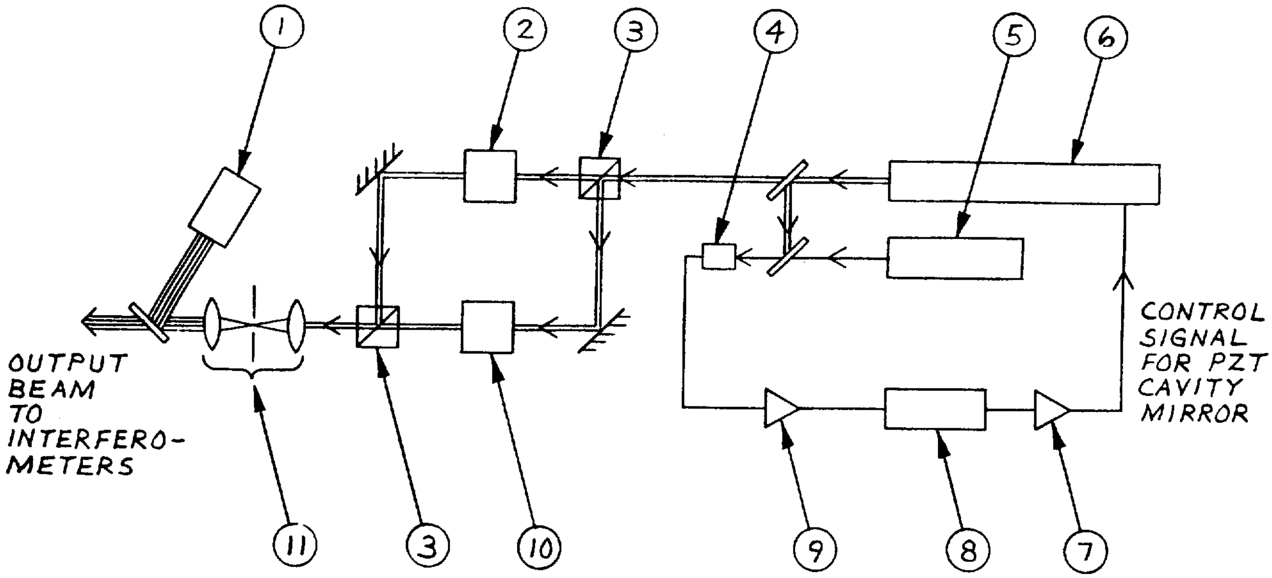


Fig. 3. Typical LODTM Interferometer



(1) Interferometer Reference Phase Detector
(2) Accousto-Optic Modulators, 60.0 MH_z
(3) Polarizing Beamsplitter
(4) Fast Photodiode
(5) I_2 - Stabilized Laser
(6) SP 125 He-Ne Laser
(7) H_1V_1 Amplifier
(8) Discriminator-Detector
(9) Preamplifier
(10) Accousto-Optic Modulators, 61.75 MH_z
(11) Spatial Filter

Fig. 4. LODTM Interferometer Laser Source

Auspices

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