Precision absolute positional measurement of laser beams

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We describe an instrument which, coupled with a suitable coordinate measuring machine, facilitates the absolute measurement within the machine frame of the propagation direction of a millimeter-scale laser beam to an accuracy of around ±4 μm in position and ±20 μrad in angle. © 2013 Optical Society of America

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1. Introduction

In the construction of precision optical systems such as interferometers, the relative alignment of two laser beams to high accuracy is frequently important. In some specialized systems, the absolute alignment of a beam to a mechanical reference can also be crucial. In most situations, however, the absolute position is significantly harder to measure than a relative alignment. One such situation where the absolute alignment of a laser beam is crucial is in the construction of the optical benches for the planned spaceborne gravitational wave detector NGO/LISA [1] and its precursor mission LISA Pathfinder [2], the optical bench for which has recently been completed [3]. LISA and LISA Pathfinder will monitor the relative displacement of free floating centimeter scale test masses to an accuracy of a few tens of picometers. To minimize the coupling of various noise sources to this measurement, the laser beams launched from the interferometer subsystem toward the test masses must be incident on the geometric center of the test mass face to an accuracy of around ±25 μm. This requires that during the construction of the interferometer, at which time the test masses are not present, the measurement beams must probe a nominal reflection point to a precision of ±25 μm.

2. Design Concept

To achieve the required alignment, a means to relate an optical measurement of the axis of a beam to an intermediate mechanical reference is required. This intermediate reference, together with mechanical features of the interferometer, can then be measured with a suitably accurate coordinate measuring machine (CMM). Hence, the beam propagation direction and interferometer reference frames (or any other relevant frame) can be related using coordinate transformations.

To determine the optical axis of the beam, quadrant photodiodes (QPDs) are used. A QPD can be positioned in the center of the beam by equalizing the photocurrent produced in all four quadrants. This technique benefits from being easy to implement and can help average out local imperfections in the laser beam. If two measurements of the center of the beam are made using a QPD spatially separated by a sufficient amount, the resulting two center points give a line that will have an equation

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representing the propagation direction of the beam. By mounting the QPD into a mechanical structure, where the center of the QPD is known, one point along the beam propagation path can be determined.

Having a mechanical structure with a single QPD that is then translated along a beam would allow a beam propagation direction to be measured. If it is to be used as an active alignment tool, however, it is beneficial to make two spatially separated but simultaneous measurements, hence giving the position and direction of the beam in real time. To achieve this, the mechanical structure has a beam splitter mounted on it, with a QPD positioned at each of the output ports with different propagation distances to the detection point. We call this a calibrated quadrant photodiode pair (CQP). In this way, there is only a single incident beam vector on the beam splitter where the beam will be centered on both QPDs (Fig. 1).

This CQP structure can then be mounted onto a suitable actuator—in our case a Physik Instrumente M-842 hexapod—allowing it to be actuated in six degrees of freedom with submicron and microradian precision. There are then two possible ways to utilize the CQP. The first is to align the CQP to an existing beam (by centering the beam on both QPDs) and measuring the CQP with a CMM; this yields the equation of the beam being measured. The second method is to align the CQP to a theoretical beam (e.g., a beam that intersects a desired point in a reference frame). In this mode, the CQP can act as an alignment target. Any beam that is actuated such that it is centered on both QPDs will then have the same equation as the theoretical beam and will intersect the target point in the reference frame.

3. Implementation

A. System Design

As a result of the extremely tight accuracy requirement, the stability of the CQP is important and must be very resistant to both thermal expansion and mechanical vibration. The thermal expansion of aluminum over 200 mm (a reasonable size for this instrument given the available measurement volume and desire to have a compact device) is on the order of 4 μm/°C, for example, which could add significantly to the positional and angular error of the CQP. Invar, which will have submicron thermal expansion per degree Celsius over the same baseline, was therefore chosen as a suitable material. Invar is also strong and easily machinable, allowing for rigid construction to help with mechanical stability.

A further factor to consider is the effective distance between the photodiodes (i.e., the optical path from the beamsplitter to QPD2, minus the distance to QPD1), which is the optical baseline that determines how accurately the CQP can be angularly aligned to the beam. Since aligning a beam perfectly to the center of a QPD is not realistically possible (factors like air currents will always cause beam jitter at the level of a few milliradians, and actuators have resolution limits), some margin must be defined under which the beam can be considered centered on the diode. If this margin is taken to be ± 1 μm (a feasible number), then this defines an angular error of the beam centering over the optical baseline. It is desirable to keep this error as small as possible. Simply taking the optical baseline to be the same as the length scale of the CQP (~250 mm) gives an additional angular error of ~10 μrad. If the path is folded, however, the baseline can be increased to more than double this number, bringing the error down to a level where it can be regarded as negligible (in comparison to other errors in the measurements, predominantly the CMM angular measurement error, which is on the order of 20 μrad).

B. Construction

The CQP, as built, is shown in Fig. 2. The optical baseline is on the order of 44 cm, which gives good angular resolution of the incoming beam. Due to the extreme sensitivity to mechanical deformation (which would change the calibration parameters), a single-point mount is used: a single bolt affixes the CQP to a hexapod through a large washer. To further increase the mechanical rigidity of the CQP, the various components are secured with epoxy in addition to mechanical fasteners.

The mounts for the mirrors and the beamsplitter were designed to be isostatic three-point mounts

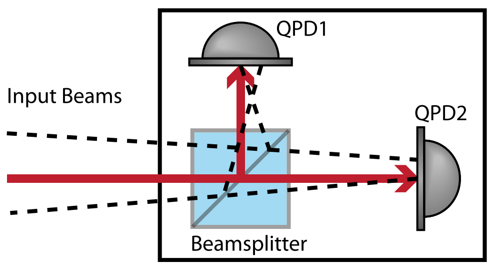

Fig. 1. (Color online) Diagram illustrating the CQP measurement principle. There is only one incident beam, shown as a solid arrow, which is centered on both QPDs. Other beams that are centered on one of the QPDs are possible, shown as dashed lines, but they will always be off center on the other QPD.

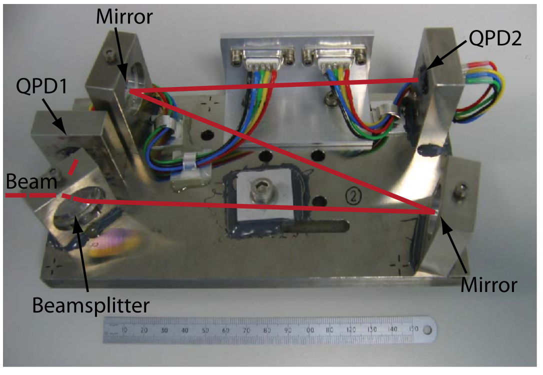

Fig. 2. (Color online) Illustrated photograph of the CQP showing the beam path and the main components. The small cross shapes visible are the CMM measurement points.

(similar to a commercial mirror mount). Given the extreme sensitivity of the mechanical frame to any movement of the mirrors (which would invalidate the calibration), glue was added at the three points to ensure rigidity to the mount. The QPDs, which are 2 mm in active diameter, are located in counterbored holes and are glued from the front and back to minimize the possibility of movement.

The QPDs are reverse-biased with 15 V and read out through an eight-channel transimpedance amplifier into a simultaneously sampled eight-channel National Instruments 16 bit analog-to-digital convertor at a sample frequency of 92 kHz. A LabVIEW program calculates the positions of the beam on each photodiode in microns using the equations

$$x = -\beta[(A + C) - (B + D)]/[A + B + C + D], \quad (1)$$

$$y = \beta[(A + B) - (C + D)]/[A + B + C + D], \quad (2)$$

where x and y are the Cartesian coordinates of the beam center on the QPD; A, B, C, and D are the voltages measured on each of the four quadrants; and β is a calibration factor that gives an output in micrometers, determined by translating the CQP a small amount and using the CMM to measure the relative displacement. To improve accuracy, the measurement beam is typically amplitude-modulated at a frequency of a few hundred hertz; A, B, C, and D are then the amplitudes of the modulated signals that are extracted using a single bin discrete Fourier transform technique. This modulation scheme minimizes the influence of DC offsets, particularly those caused by background lighting, which can be significant with Si photodiodes.

4. Calibration

A crucial step in making the CQP into a useful tool is the calibration, which defines the relationship between the physically measured frame and the laser beam. When the CQP mechanical structure is measured with the CMM, a fully defined reference frame is established. Importantly, the measurement points used to define the reference frame are fixed such that each time the CQP is measured, exactly the same measurement frame is constructed (within the measurement uncertainty of the CMM). Under the assumption that the optical components and QPDs are fixed and unmoving with time, we can define a set of calibration parameters that describe the position and direction of the incident-centered laser beam in the mechanical reference frame (Fig. 3).

The calibration is performed by making multiple measurements of the CQP when aligned to a reference beam, the pointing vector of which is unknown but unimportant, provided it is stable during the calibration. These measurements are made at multiple locations along the beam (i.e., translating the CQP in x) and with the CQP rotated in multiple orientations around the beam (i.e., rotated about the x axis). Since

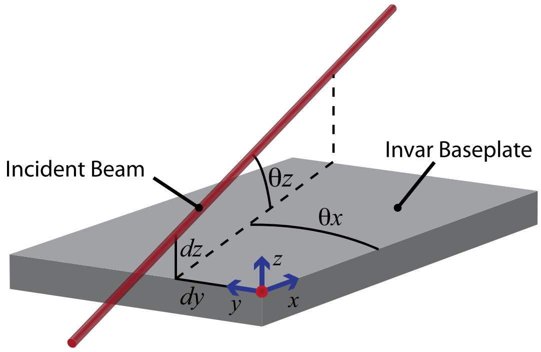

Fig. 3. (Color online) Coordinate system of the CQP and the four calibration parameters required to define a beam relative to it: dy, dz, θx, and θz.

the beam (when centered) always intersects the y–z plane of the CQP at the same point (dy, dz), the distance from the origin point in each measurement to the beam is always constant. The set of measured origin points will then lie on the surface of a cylinder, the axis of which is collinear with the measured reference beam. For each measurement of the CQP, we then reconstruct the full measurement frame and calculate the values dy, dz, θx, and θz with respect to the best-fit axis of the cylinder. These values can then be averaged to give a set of calibration parameters for the CQP.

5. Accuracy Achieved

The first indicator of accuracy is gained by examination of the CQP calibration results. The minimum number of measurement points required to fit a cylinder is five, however, typically around 20 measurements are made. These measurements are taken over as large a baseline in x as possible (typically around 600 mm) and over as large a range of CQP rotation angles as possible, usually 0°, ±45°, and ±90° around x. By averaging over this many measurements, the residuals can give an estimation of the accuracy. Typically, the residuals of the displacement parameters $|dy, dz|$ are <3 μm and the residuals of the angular parameters θx and θz are <20 μrad. These numbers are consistent with the accuracy of the CMM used for the measurements, which over a baseline of L mm, has a measurement error of $(1.5 + L/1000)$ μm.

The second indicator of accuracy is to perform a verification measurement. Typically, this involves making two (or more) measurements of the stable reference beam at multiple angles about the x axis, akin to a part-calibration. By rotating the CQP about the beam, any error in the calibration parameters will rotate with the CQP when comparing the measured beam equations in each orientation. An example set of results from a measurement of this type is shown in Fig. 4.

The measurement shown in Fig. 4 is typical of the results seen when the CQP is well calibrated, with no strong dependence on CQP orientation visible. In this state, we can draw reasonable estimates for

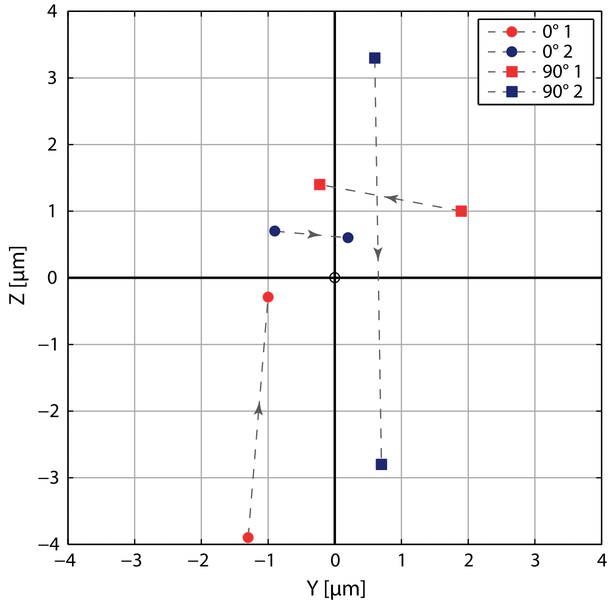

Fig. 4. (Color online) Plot showing the results of a check of the CQP accuracy. Here, two measurements were made with the CQP in its nominal orientation (0°) and two measurements in an orthogonal orientation (90°). For each measurement, two points are shown with an arrow indicating a direction between them. These points are spatially separated on the x axis by 300 mm, with the arrow indicating the propagation direction of the beam.

the typical accuracy of the CQP of around ±4 µm and ±20 µrad.

6. Conclusion and Lessons Learned

A method for performing an absolute measurement of the position and propagation direction of millimeter-scale laser beam in a reference frame to an accuracy of a few millimeters and ~20 µrad has been presented. This system was successfully used to align the optical bench for the LISA Pathfinder, ensuring that the measurement beams are incident on the nominal test mass reflection points to <25 µm [4,5].

While the system presented was sufficiently precise for the required alignment tasks, improvements are possible. Some potential modifications being considered for a second generation CQP include: substituting the Invar structure for a hydroxide-catalysis bonded Zerodur one [3,6], which would further minimize the probability of the calibration parameters varying over time due to structural deformation; utilizing larger diameter QPDs to increase the range of beam sizes that can be accurately measured; and optimizing the size and shape of the device to help improve the angular accuracy of the CMM measurements.

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