Development of a fast position-sensitive laser beam detector

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We report the development of a fast position-sensitive laser beam detector. The detector uses a fiber-optic bundle that spatially splits the incident beam, followed by a fast balanced photodetector. The detector is applied to the study of Brownian motion of particles on fast time scales with 1 Å spatial resolution. Future applications include the study of molecule motors, protein folding, as well as cellular processes. © *2008 American Institute of Physics.* [DOI: 10.1063/1.3002422]

I. INTRODUCTION

The measurement and control of laser beam pointing finds many important applications in atomic force microscopy, spatial imaging with optical tweezers, and target acquisition.[1–6] The standard method of beam pointing detection is to focus the laser onto a split detector. A commercial realization of this concept is the quadrant detector that splits the beam into four parts, providing information about the laser pointing in two orthogonal directions.

Our interest in this technology was stimulated by the study of Brownian motion of nanometer size beads held by optical tweezers where a very fast time response is required. We report here a simple split detector design, which meets our design goals and provides an alternative and complementary approach to the commercial quadrant detector when that method is inconvenient or has more limited time response. Our detector measures motion in one transverse direction but can be easily generalized to detect the other transverse direction (two-dimensional). Information about the axial position of the particle is related to the total optical power reaching the detector thus true three dimensional tracking can be achieved.[4] Beyond the study of Brownian motion, this detector should find important scientific and technological applications.

II. DETECTOR DESIGN

Our guiding philosophy in developing a new device was to separate the functions of a position sensitive detector so that each can be independently optimized. The first function is the splitting of the beam and the second function is the balanced photodetection of each half. This was realized in practice with a fiber optic waveguide that was split into halves with the light from each end focused onto a fast photodiode. The two detectors were operated in a balanced subtraction mode, providing position information. A schematic of our setup is shown in Fig. 1 and we now describe each stage in detail.

A. Fiber optic wave-guide splitter

Our design utilized a fiber optic waveguide splitter to spatially split an incident laser beam in two equal halves. The front end of the bundle was sorted vertically, where two halves are separated at the back end of the bundle as shown in Fig. 2. The fiber splitter was assembled with 1000 multimode fibers (Model MM-S105/125–22A, 105 μm core, 125 μm cladding, Nufern Corporation, East Granby, CT) packed into a 4.4 mm diameter front end with two back ends composed of an equal number of fibers. The fibers were stripped of their coating to allow a higher packing efficiency, which reduces loss of the incident laser beam. Stripping the protective coating exposes the fragile glass core and cladding, so heat-shrink tubing was used to bind and protect the exposed fiber tips. To permanently seal the fibers, low viscosity glue (Acrylic 609, anaerobic cure, Henkel Loctite Corporation, Rocky Hill, CT) was applied between the fibers. Two aluminum rings were epoxied over the front end to help mount the bundle for cutting and polishing. We then used a diamond-edge blade to cut the fibers to the same length.

In order to polish the cut fiber bundle tips, we used a series of aluminum oxide lapping films of grits ranging from 30–0.3 μm (Model LFG, aluminum oxide lapping films:30, 5, 3, and 0.3 μm, ThorLabs Corporation, Newton, NJ). An aluminum holder kept the fiber bundle perpendicular to the lapping film surface to ensure the smoothest and flattest pol-

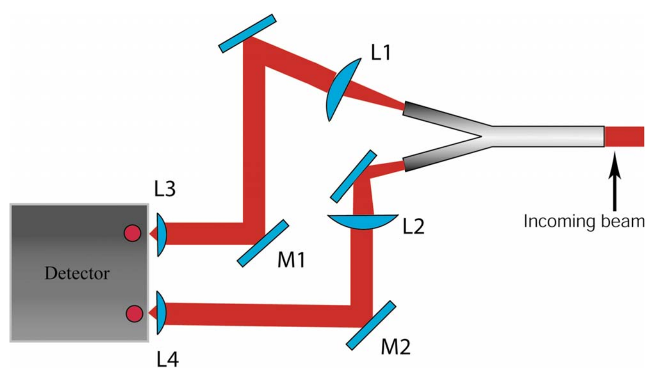

FIG. 1. (Color online) Schematic of the complete position-sensitive detector. The fiber optic waveguide splitter splits an incident beam into two equal parts. Lenses L1 and L2 serve to collimate the light. The light is directed with mirrors M1 and M2 and focused onto the balanced photodetector with lenses L3 and L4.

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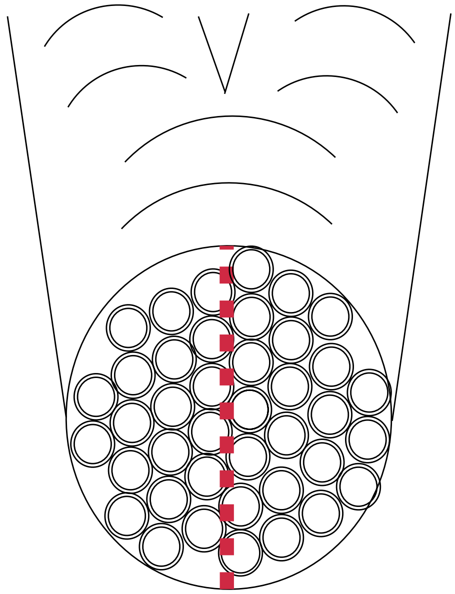

FIG. 2. (Color online) Schematic of the front end of the fiber optic waveguide splitter. Fibers on the left side of the red dashed line were sorted into one bundle on the back end while fibers on the right side were sorted on the other end. A laser and knife edge was used to split the waveguide into two nearly equal parts.

ish, see Fig. 3. The aluminum rings were matched to the holder and the entire bundle was locked in place with set screws. These same aluminum rings were used for mounting the fiber bundle in the final experimental setup. The lapping films were placed on a glass surface and polishing lubricant was added (BlueLube polishing lubricant, isopropyl and denatured alcohol, Allied High Tech Products Inc.). We started with the coarsest lapping film (30 μm) and stepped with various lapping film grits ending the finest lapping film of 0.3 μm. Between each lapping film polish, the bundle was inspected under a microscope to ensure that the fibers were being polished evenly. The front end of the bundle was sorted after the polishing stage.

Sorting of the front end of the fiber optic waveguide was accomplished by mounting a flat-edge mask (razor blade) vertically on a translation stage in front of the waveguide and illuminating with a laser. The mask blocked exactly half of the fiber waveguide so sorting can be accomplished. At the other end, fibers that emitted light were manually moved to one side while the dark fibers were moved to the other side. Fibers partially covered by the knife edge (center fibers) were divided up by relative intensity. Sorting fibers in this manner naturally divides the center fibers equally between both sides. Operating our balanced detector in subtraction mode greatly reduces crosstalk of the two halves due to the overlap of the fibers in the center region. Once the sorting was completed, the two back ends were bound and polished in the same fashion as the front end. A photograph of the completed waveguide is shown in Fig. 4. In the experimental setup, the waveguide is mounted on an x-y-z translation stage to enable alignment with respect to the incident beam.

FIG. 3. (Color online) Photographs of the top (left) and bottom (right) view of the aluminum holder. The aluminum rings on the fiber bundle fit tightly into the holder. The set screws lock the bundle in place for polishing.

FIG. 4. (Color online) Photograph of completed split fiber bundle. The bundle is 8 in. in length and the two back ends are split about 2 in.

B. Optics and detector

After the waveguide splitter, the rest of the position detector consists of a balanced photodetector and optics. Due to the numerical aperture of the fibers (NA=0.22), light coming out of the waveguide must be collimated and focused onto the balanced photodetector. In our experimental setup, we used a 1064 nm laser with a maximum power of 700 mW [NPRO model 126–1063–700, Lightwave Electronics (now JDSU), Milpitas, CA].

We collimated the light from the back end of each bundle using two-inch diameter, 37 mm focal length aspheric lenses (lenses L1 and L2 in Fig. 1). The collimation serves to redirect the light toward the balanced detector without any loss due to the divergence of the light coming out of the fibers. Two mirrors (M1 and M2) directed the collimated light toward the balanced detector. Finally two smaller aspheric lenses, (one-inch diameter 12 mm focal length, lenses L3 and L4), focused the light onto the detector. Each of these lenses and the detector were mounted on translation stages for alignment and balancing.

We used a balanced photodetector sensitive in the range of 800–1700 nm (PDB120C, dc to 75 MHz bandwidth, photodiode diameter 0.3 mm, ThorLabs, Newton, NJ). The detector was chosen for its high transimpedance gain (1.8×10^5 V/A) and high-frequency bandwidth. The subtracted photocurrent provided the baseline for our measurements. As an optically trapped particle moves within the incident beam, the fraction of light impinging on each detector changes, and the resulting voltage of the balanced detector is proportional to the particle excursion as long as the displacement remains small (typically up to a few hundred nanometers).[4]

III. RESULTS

A. Waveguide splitter efficiency

To determine the efficiency of the waveguide we measured the fraction of light that was transmitted by the bundle. We mounted the waveguide on an x-y-z translation stage and set up two power meters to measure the intensity coming out each back end. A neodymium doped yttrium aluminum garnet (YAG) 1064 nm laser (beam waist of 4 mm), illuminated the front end of the waveguide. We adjusted the waveguide until the beam was centered on the front end and the

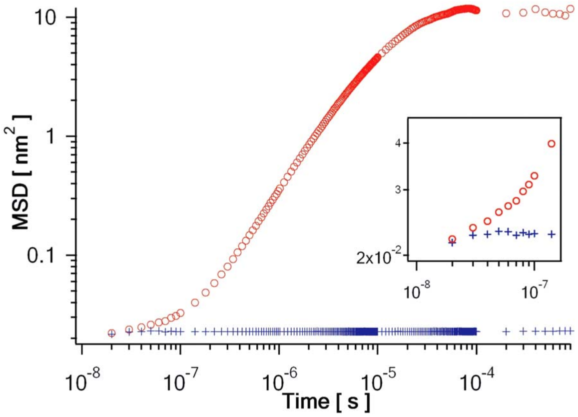

FIG. 5. (Color online) Mean square displacement of a 1 μm polystyrene bead in an optical trap (red circles) with the noise background shown (blue crosses). The temporal resolution of the detector is around 30 ns with spatial resolution of about 1 Å.

intensity coming out each back end was equal. The "balanced power" was determined to be 30% of the initial power of the incident laser beam. The fiber can only transmit light if the light impinges on the core of the fiber therefore light entering the cladding region of the fiber is lost. A loss of 29% is accounted for by the ratio of the cross-sectional area of the core to that of the total cross section of the fiber. The rest of the 41% is lost due to packing efficiency and broken fibers (five fibers were known to have broken out of 1000).

B. Temporal and spatial resolution

To test the temporal response of our detector, we recorded Brownian motion of a single particle. The experimental setup consisted of a focused 1064 nm YAG laser beam, creating a harmonic potential for a small bead in the center of the focus (optical tweezer[7]). When a particle is within the optical tweezer, the scattered light from the particle interferes with the nonscattered light of the incident laser beam creating an interference pattern.[3,4] As the particle moves the interference pattern changes creating an intensity difference between the two halves of the detector. This interference pattern was captured by the condenser lens, collimated by a 25 mm focal length lens, and projected onto our split fiber bundle and detector. We used attenuators between the 25 mm focal length collimating lens and the waveguide splitter to control the power impinging on our detector. We tested both polystyrene and silica beads of diameter of 0.5 and 1 μm in water. We used a high resolution high speed digitizer (14-Bit, DC to 100 MHz, National Instruments model PXI-5122) to record data. All data was taken at a sample rate of 100 MS/s over a sampling time of 40 ms. The data was collected on the digitizer and transferred to the computer for analysis.

Figure 5 shows the mean square displacement of a 1 μm polystyrene bead in water. For this curve, the y-axis shows the mean square displacement in units of nm^2 and the measurement background is given to show both the temporal and spatial resolution range of the detector. The background signal is recorded when a particle is not present within the optical trap. The signal from the particle drops into the measurement background at 30 ns, which corresponds to a mean square displacement below 0.03 nm^2, providing a spatial resolution in the 1 Å range. This result is confirmed by measuring different sized polystyrene and silica beads where we find similar spatial resolution.

The mean square displacement shown in Fig. 5 agrees well with the current theory of Brownian motion on fast time scales.[8] Further work is currently being conducted in this direction using our detector.

IV. DISCUSSION AND CONCLUSION

We report the development of a position-sensitive detector by converting a balanced photodetector into a position-sensitive detector using a fiber optic waveguide splitter. We are able to observe particle displacements on time scales of 30 ns with 1 Å spatial resolution. This is an improvement over previous measurements of Brownian motion[8] and will enable the exploration of Brownian motion on much faster time scales where new phenomena may emerge. A 1 μm polystyrene particle in water moves about an average of 1 nm in 1 μs intervals and therefore fast detection is required not only for high-frequency events but also to achieve high spatial resolution.

The combination of high temporal and spatial resolution has many applications in the study of biological processes. One example is protein folding, where fast events occur on tens of nanosecond time and angstrom length scales. Another example is the study of Brownian motion in confined geometries, such as motion of particles in a living cell, which will help us understand how transport occurs within the crowded cytoplasm of living cells. Finally, thermal motion of a particle bounded to a single molecular motor has been used to investigate its mechanical properties.[9] Using our detector, one can study motion of molecular motors on much faster time scales with higher spatial resolution which may reveal details about the conformational changes that take place when chemical energy is converted into mechanical work. The versatility of our design can accommodate a wide range of available balanced detectors and we expect a broad range of applications beyond the discussed examples.

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