POSITION SENSING WITH PHOTODIODES

Two complementary technologies allow system optimization for optical beam centering and/or quantitative measurement of lateral beam displacement.

Introduction

Position sensing photodiodes are detectors that provide quantitative information about the position of an incident light beam or spot image. There are currently two technologies that offer this functionality: multi-element photodiodes and position sensing (or lateral displacement) photodiodes. This article reviews the construction and operation of both types, discusses key considerations for optimizing their performance, and briefly examines some representative applications.

Multi-Element Photodiodes

Multi-element photodiodes are detectors that consist of several separate active areas. The most common formats are the bi-cell and four-element quadrant detector (or quad cell). The principles of operation are very simple. Incoming light is focused or imaged on to the detector as a spot. In the case of the quad cell, the position of the centroid of this spot is determined by comparison of the signals from the four quadrants (referred to here as A, B, C and D). Specifically, x and y displacements can be calculated using the following simple relationships.

$$x = [(B+D) - (A+C)] / [A+B+C+D]$$

$$y = [(A+B) - (C+D)] / [A+B+C+D]$$

The optics in front of the detector can be arranged so that the xy measurements of spot displacement can then be correlated with angular or lateral displacement of the incoming light.

There are several factors that must be considered when designing a position sensing system based on a quad cell or other type of multi-element detector. The most important is the relationship between the diameter of the light spot and the dimensions of the detector. If the light spot is smaller than the spaces between the detector elements, these will represent a dead zone, where beam tracking will be lost completely. This can be an issue in diffraction-limited applications such as data storage. Conversely, the light spot must be smaller than the overall detector dimensions or the signal will be truncated by the edges of the detector, resulting in erroneous position feedback.

The relationship between spot size and detector dimensions is often determined by the trade-off between spatial resolution and range. Tracking range increases with spot size, because once the spot is entirely located within one quadrant, further tracking is impossible. However, positional resolution is inversely proportional to the spot size. This is because a given displacement of a small spot produces a much bigger differential signal than the same movement in a larger spot.

To summarize these design/operational rules:

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Detector gap< spot size < detector size
Positional range $\leq$ spot size or detector size
Positional range α spot size
Positional resolution α 1/spot size

Keep in mind, however, that the equations and linear relationships just outlined are based on the simplistic assumption that the beam has the same straight edges and (square or rectangular) shape as the detector elements. Of course, this is rarely the case. In reality, the light spot is most often circular, or a circular approximation. As a result, the quad cell, for example, can only produce linear (± 5% error) over the central half of the beam, which results in tighter design constraints. The situation is even worse for laser beams, which often have a gaussian cross-section. Here the linear range only applies over the central 10% of the beam diameter. Of course, software can be used to extend the linear range, but that adds to system cost and complexity.

Avalanche photodiode (APD's) bi and quad cells have recently become commercially available. APD's offers similar positional information to conventional multi-element photodiodes, but Advanced Photonix patented Large Area APD's have an internal gain of up to several hundred, making them well-suited to applications involving very low light levels.

Although multi-element detectors offer the advantages of high positional sensitivity, low cost and operational simplicity, their range limitation means that they are mostly used in centering/alignment applications. Here the goal is maintain or monitor optical alignment by keeping a balanced or null signal, rather than to quantitatively measure beam displacement.

Position Sensing Photodiodes

The position sensing photodiode (PSD) typically offers less positional sensitivity, but much greater range, than the multi-element photodiode. The basic structure of a PSD, which has a single active area, is shown in Figure 3. As in any photodiode, the active sensing region is formed by a p-n junction. Electrodes are arranged on both the anode and cathode of the photodiode so that the photodiode internal resistance forms a series resistance for current between the electrodes.

The PSD is ideally operated under an applied reverse bias. When absorbed photons produce charge carriers (electrons and holes) in the depletion layer, this bias causes the charge carriers to move to the appropriate electrode (anode or cathode). However, this means the carriers have to first pass through the resistive silicon. Because the P and N layers are produced with high spatial uniformity, the photocurrent at each electrode is inversely proportional to the distance between that electrode and the centroid of the incoming light beam. Thus the location of the beam centroid can be accurately located by using the ratio of the signals from the different electrodes.

Several factors affect the spatial resolution that can be obtained in practice. First, resolution is proportional to the detector size (length). Because achieving high resolution requires measuring microscopic differences in individual photocurrents, low noise is critical. This includes using a low noise

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signal amplification and processing setup. In addition, the light level is very important in these applications, since this impacts the ratio of signal to shot noise.

As with multielement detectors, both one and two-dimensional devices are available. For example, a one-dimensional PSD may have just two bonded contacts along one axis, but 5 or more along the measurement axis. The response linearity – measured dX versus true dX – is a function of device uniformity. Typical commercial PSDs yield position linearity of better than 4%. If superior linearity is required, values of 0.5% can be achieved in custom devices, but software correction/calibration is usually preferred as a lower cost option.

The main advantage of the PSD versus the quad cell is measurement range. The device response performance is uniform across the detector aperture, with no dead space, and no problem of having the beam in a single detector segment. For this reason, PSDs are preferred in applications where continuous or fine displacements must be measured in real time.

Applications

The applications for multi-element detectors usually involve nulling or centering, i.e. to attain, maintain or confirm optical alignment or to optically maintain physical/mechanical alignment. A very simple example is the bi-cell used in some faxes and printers. Light from a LED is directed across the paper path at a bi-cell. Until paper is fed in the machine, both halves of the bi-cell are fully illuminated. As the paper sheet is fed across this optical path, cell it reaches a point at which one side of the bi-cell is illuminated and the other element is receiving no signal, because of the paper edge. This is used as the reference position for commencing printing.

There are many diverse applications for quad cells and bi-cells in the aerospace industry. For example, these are used to align the motion axis of a laser gyro to a mechanical reference axis that is ultimately reference to the airframe of the aircraft. They are also used for bore-sighting in an autocollimator used in the F-18 fighter and will be used for similar purposes in a Lockheed Martin system to be used in the new “SuperFighter” aircraft. In addition, quad cells and more exotic multi-element detectors are widely used in “smart” bombs and missiles, to align the trajectory to some optical reference such as a laser-designated target.

Position sensing photodiodes are used mainly to monitor position and track fine motion. A typical example is the latest automated equipment for wheel alignment on cars and small trucks. Every car has optimum angles for camber and toe settings that are specified by the manufacturer, for a car mounted on a lift or jack. Camber is the vertical tilt on the wheels and toe refers to the front to back tilt on the wheel. (The weight and motion of the car causes these values to correct to zero during normal operation.)

In practice the car is raised on a platform and a jig is mounted on the wheel to be aligned. This jig includes a mirror. A low-cost laser beam (usually a HeNe) is directed at the mirror and the reflection then strikes a PSD. The machine uses simple geometric algorithms to convert the observed displacement into an angular measurement. This application formerly used bi-cells, one for camber and one for toe. However, the use of a PSD provides more accurate information and allows measurements to be made rapidly over a wide angular range without having to adjust the machine between measurements.

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There are also several potential applications for PSDs in drive by wire schemes being developed for future use in automobiles. For example, these types of devices may be used in lightweight steering columns to provide information to the steering computer, obviating the need for a heavy direct mechanical linkage to the wheels.

Conclusion

Position sensing photodiodes have been in use for many years. As optical technology continues to find increasing application in areas as diverse as telecommunications, biomedicine, data storage, manufacturing, test and measurement, and aerospace/military, the need for these workhorse devices will undoubtedly continue to thrive.

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