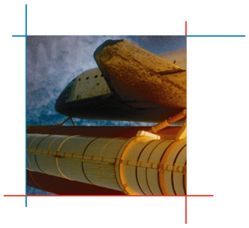
Application Note No. 8



LATERAL-EFFECT PHOTODIODES

MECHANICAL-ALIGNMENT APPLICATIONS of electro-optical instruments have expanded dramatically during the past three years in the construction, machinetool, aircraft and aerospace industries, increasing demands for new types of position-sensing detectors. One new type that may be unfamiliar to many optical designers is the lateral-effect photodiode, which provides direct readout of the displacement of a light spot across its active area; with the aid of optics and electronics such a detector can measure angle and distance.

They make remote measurements of angle and distance by Sensing lateral displacement of a light spot.

Deriving position information

Typically position information is extracted from nonuniform illumination of lateral-effect photodiodes by monitoring the photogenerated currents from each lateral contact. Based on the device characteristics shown in Figure 1, the current I, through the contact S for steadystate operation with terminating impedance-approaching zero have been calculated as

(eq-1)
$$I = L \left(\frac{\sinh\left[a(L-s)\right]}{\sinh\left(aL\right)} \right)$$

Where *I* is photoinduced current and *a*, the Lucovsky falloff parameter is given by

$$a = \left(\frac{QnJ_p q}{W_n KT} \right)$$

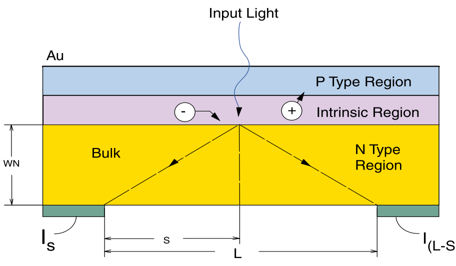


Fig-1 Crossection of lateral-effect position-sensing Photodiode showing some device charactristics used in calculation of equation 1

where Q_n is the resistivity of the *n*-type material J_d, is the current density of the diode, q is the electronic charge, W_H is the thickness of the undepleted *n*-type material, *K* is Boltzman's constant and *T* is absolute temperature.

Carriers produced by incoming photons are separated by the junction field, generating a localized photovoltage. The resulting photocurrent injected into the diode substrate is

(eq-2)
$$I_o = P_d R_d$$

where P_d is the monochromatic incident power and R_d the detector responsivity at that wavelength. For a PIN photodiode terminated in zero impedance most of this current flows through the lateral contacts to sustain the lateral field throughout the *n*-type material; however, some of the majority electrons must flow back across the junction and recombine at the diode surface.

To give good linearity, *a* must be minimized because, in the limit where *a* approaches zero, the current distribution in equation 1 becomes linear

(eq-3)
$$I = R_o \left(1 - \frac{S}{L} \right)$$

Another source of nonlinearity is in the derivation of equation 1 where it was implicitly assumed that $Q_n W_H$ the sheet resistance, is uniform throughout The device in order to calculate current distribution in terms of light spot position. In practice, however, this is a poor assumption, since sheet resistance is probably the most difficult device characteristic to control and is the dominant cause of nonlinearities in lateral-effect photodiodes.

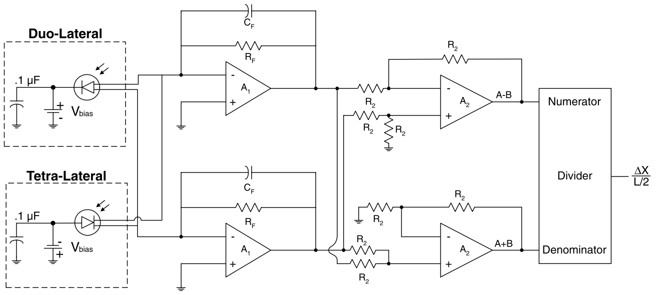


FIGURE-2

Lateral-effect tradeoffs

Equation 3 shows the advantages of lateral-effect position-sensing photodiodes compared with such other position sensors as bicell types. Lateral-effect devices[3] provide position information which is linear and independent of the intensity profile of the illumination, unlike bicell types which produce nonlinear position information with most intensity profiles. Furthermore the linearity properties shown in equation 3 are independent of the symmetrical defocusing that may occur in optical systems. Independence of light-spot intensity is obtained either by taking the ratio of the difference current output to the current sum or by using the sum signal for automatic gain control of the illumination. Both techniques normalize I_o thus avoiding influences from variations in incident power and responsivity within the device.

The major disadvantages of the lateral-effect detector are slow speed and high noise. In bicell detectors, series resistance can be made much smaller than in lateral-effect types, permitting higher speeds for bicell types with comparable junction capacitance. Because linearity considerations require a small impedance between lateral contacts, the lateral-effect photodiode typically is noisier than a bicell type. Since this impedance exhibits full Johnson noise and normally is the dominant noise source in the device, detector-noise current in amperes per root hertz is

(eq-4)
$$I_d = (4\,KT/R)^{1/2}$$

where R is the resistance between back contacts.
Other noise sources in a circuit such as that in Fig. 2 are shot noise of the dark and signal currents and effective input-noise current of the preamplifiers. Shot-noise current is

(eq-5)
$$Is\ = (2L\,q)^{1/2} \quad a/hz^{1/2}$$

For a field-effect-transistor input amplifier effective input-noise current is

(eq-6)
$$I_a = (E^2/R^2)^{1/2} \quad a/hz^{1/2}$$

Where E_n is amplifier input-noise voltage. Total noise is obtained by adding these uncorrelated noise sources in quadrature, giving

(eq-7)
$${}_t = \left(\frac{4KT}{R} + \frac{E^2}{R^2} + 2\,I\,q \right) \quad a/hz^{1/2}$$

This assumes that all sources produce white noise with equivalent noise bandwidths and that amplifier-feedback impedance's are much larger than R; assumptions which fit a range of applications but not those at high frequencies.

Resolving displacement

To calculate minimum resolvable displacement we must first calculate signal current produced by an incremental change in position ΔL.

(eq-8)
$$\Delta I = \frac{2\,I\,\Delta L}{L} = \frac{2\,R\,P\,\Delta L}{L}$$

The signal-to-noise ratio is unity when the displacement current of equation 8 equals I in equation 7; this gives minimum resolvable displacement ΔR.

(eq-9)
$$\Delta R = \frac{\left(\frac{4KT}{R_2} + \frac{E_2}{R^2} + 2R\,P\,q \right)^{1/8}}{\sqrt{2}\quad P\,R} \quad x\,L$$

To obtain an order-of-magnitude estimate of ΔR, equation 9 can be solved assuming typical values for the parameters. For example, a 0.2-inch-long detector with a back-contact resistance of 10 kilohms illuminated with a 20-microwatt light spot at 900nm in a circuit with amplifier input-noise voltage of 12 nanovolts per root hertz has minimum resolvable displacement of $4\text{x}10^{-6}$ inch per root hertz. Experimental resolution agrees with this theoretical prediction.

While even a rigorous characterization of the device suggests that position measurements should be independent of temperature, a large temperature dependence can be caused by inhomogeneities in the recombination current across the junction boundary or sheet resistance. Careful optimization of photodiode parameters permits variation in measured position to be held within 0.02% when

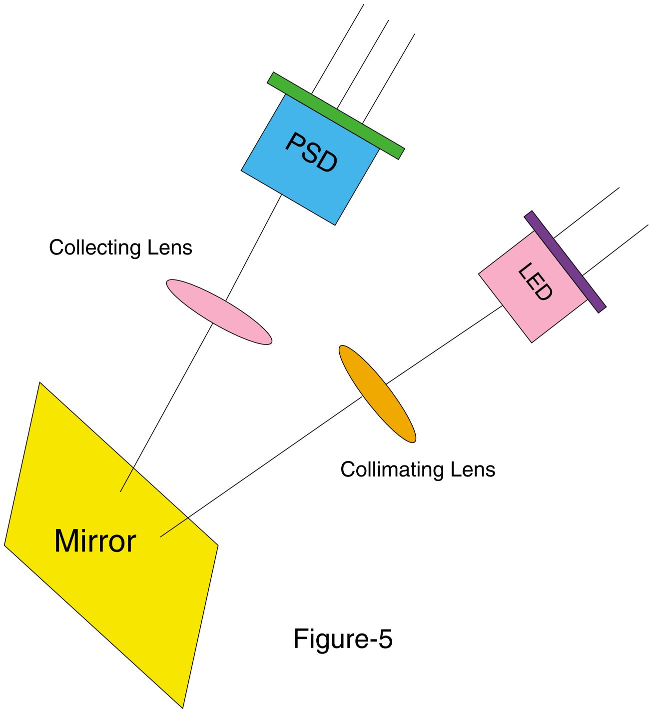


Figure-5

Temperature changes from -25° to 125°F.

The most common circuit configuration used with lateral-effect photodiodes is shown in Fig. 2. The preamplifiers operate in transconductance mode to provide high sensitivity while presenting the low impedance boundary condition necessary for linear photodiode operation. Since this circuit normally provides significant amplification of input offset voltage, which can make output strongly temperature dependent for high-accuracy or low-light-level dc applications best results are obtained with a source modulated at audio frequencies. One problem with modulated input, however, is that preamplifier phase differences produce a temperature-sensitive quadrature error at the difference-amplifier output.

Measuring angular rotation

A system for measuring angular rotation of a mirrored surface is shown schematically in Fig. 3. Collimated light from an incoherent gallium-arsenide diode is projected onto the mirror whose angular rotation is to be measured: a collecting lens refocuses the return beam onto a position-sensing diode. Because the optics provide unitary magnification,the size of the light spot on the detector equals the 0.036-inch diameter of the LED's active area. Focal length of each lens is 2.5 inches, producing lateral displacement of about 24 microinches on the detector for each aresecond of mirror rotation.

One-kilohertz modulation was superimposed to the direct-current bias to the LED, with modulation level set so peak-to-peak alternating-current power at the detector is about 20 microwatts. The photodiode is operated unbiased with *p* region grounded and outputs from the lateral contacts fed to the noninverting inputs of two transconductance amplifiers as in Fig. 2. The amplifier outputs are summed and differenced, with the sum signal used as feedback for control of modulation depth of the LED drive signal to normalize collected ac photocurrent. The difference signal is demodulated and smoothed to have 100-hertz bandwidth.

For 0.1 aresecond mirror rotation, the ratio of signal to peak-to-peak noise was about two, in exact agreement with the solution of equation 9 for lateral-contact resistance of 10 kΩ and E of 12 nanovolts per root hertz. Linearity of the system was calculated by measuring maximum deviation from a straight line on a curve of demodulator output plotted against theodolite readings of mirror rotation angle, giving mean linearity 0.3% of dynamic range; only part of the nonlinearity probably was due to the detector.

Diffuse-surface displacement

The system shown in Fig. 5 measures z-axis displacement of a diffuse surface. Light from an LED is focused onto a diffuse surface, and the diffuse reflectance from the surface is reimaged onto a lateral-effect photodiode. When the surface is moved toward or away from the emitting lens lateral displacement of the light spot on the diode is proportional to the surface displacement. Because the transfer function of the vertical motion to linear motion on the detector is linear only across a small range, applications of this technique are limited: in the system shown in Fig. 5 the geometrical deviation from linearity is about 1% for a 0.1 inch travel of the surface.

The same photodetector was used as in the previous system and the electronics were similar although circuit gains were different because of the large optical losses inherent in reimaging of a diffuse source. The 2 µw power measured at the detector permitted displacements of 0.0001 inch to be measured with adequate signal-to-noise ratios. Linearity of the system limited by geometrical nonlinearities averages 1.2% for a 0.1 inch surface displacement. Such a system is a good example of the lateral-effect photodiode's independence of symetrical defocusing of an image at the detector plane.

For such applications, lateral-effect position-sensing photodiodes provide high resolution of position together with wide dynamic range and good linearity. Further efforts to characterize the semiconductor processes in such devices should lead to devices with better linearity and smaller dependence on temperature.

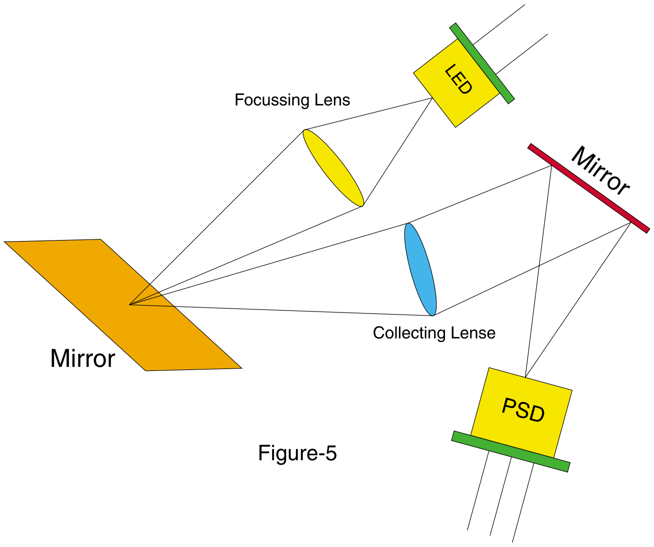


Figure-5