Analysis of the optimized low-nonlinearity lateral effect sensing detector

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Abstract- In this paper, the current time delay (TD) and the voltage difference (VD) modes for some practical lateral effect position sensing detectors are investigated, simulated, and compared. Some advantages of the current time delay mode are more linear response, independent position from magnitude and frequency, background illumination-independent response, and no need to signal normalization.

Key words: Lateral effect position sensing detectors, voltage delay, time delay.

1. Introduction
Position-sensing detectors are known as simple photodiodes capable of detecting centroid of light beam position. There is an important feature for PSDs due to no need to have contact with specimen being inspected. Position information is calculated from photocurrent signal magnitude by these detectors. For designing these detectors with high resolution, the most effective method is to create Schottky barrier with surface diffusion method [1].

When an optical spot incidents on the detector surface, electric charge is generated proportional to the light intensity at the collision region. Electric charge passes from resistive layer and collected as the photocurrent by electrodes. It is divided between two terminals with an inverse relation to the distance of optical spot from electrodes.

Applying full reverse bias to LEP, the thickness of depletion region increases, diffusion current decreases to zero and surface regeneration is stopped. To achieve best performance quality, the photodiode should be able to absorb maximum photons in depletion region. It means photons should not be absorbed anywhere except depletion region before passing it.

So, when a p-n junction is illuminated by the optical spot, little energy is saved in space charge region. Under reverse bias, this light energy will move horizontally to the electrodes mounted next to the junction. This phenomenon is called lateral effect first presented by Schottky in 1930, but has not been developed much [2]. In 1959, Wallmark used this theory practically [3]. He designed a device including a p-n junction. By illuminating light beam to the surface, a position-dependent voltage difference is generated between the contacts [3].

The position sensing detectors have many applications in distance measurement, machine vision, atomic force microscope, surface shaping, robots, tracking laser beam, etc. They are classified into
two types: lateral effect position sensing detectors and four-quadrant position sensing detectors [4], with some similarities and differences to each others, physically and practically [1].

Voltage delay mode has been widely used to determine the position of optical spot until now. As shown in Figure 1, if optical spot incidents on the detector surface, \( I_1 \) and \( I_2 \) photocurrents are generated at electrodes and then convert to voltage, so the optical spot position can be obtained by calculating voltage difference between two electrodes. The disadvantage of this method is diameter-dependent voltage in optical spot led to detector nonlinearity. In this paper, current time delay mode is proposed to make detector more linear.

In this method, as the optical spot incidents on the detector surface, a current has been generated. The current reaching time, for each electrode is different, depending on the optical spot position. So, there is a time difference between two signals reached to terminals. Here, the diameter of optical spot has no effect on signals arrival time. For example, if reaching signals oscillate synchronous, the optical spot will mount at the center of detector surface.

The rest of the paper is organized as follows. In section 2, a brief investigation is presented about LEPs, their dynamic equations and electronic circuit based on the [7]. The simulation results for three practical LEPs are discussed in section 3 and the conclusions are drawn in the final section.

![Figure 1](image1.png)

**Figure 1.** One-dimensional detector structure.

2. Lateral effect position sensing detectors (LEPSDs)

Lateral effect position sensing detectors include a uniform resistive layer mounted in one or two sides of semiconductor sub-layer with high resistivity (Figure 2).

![Figure 2](image2.png)

**Figure 2.** Schematic of lateral effect position sensing detectors (LEPs) [5].
In one-dimensional case, there is a pair of electrodes to obtain position signals at the two ends of resistive layer, and in two-dimensional case, two pairs of electrodes mount on the edge of the detectors mutually. The active area (or resistive layer) includes a p-n junction generated photocurrent due to light collision to the surface (photovoltaic effect).

LEPs have uniform big structures with an anode and a cathode. Because these detectors do not depend on optical spot diameter magnitude, detectivity quality is independence of their distance from the object. There are two models for LEPs: one-dimensional and two-dimensional models, i.e. the ability to detect 1-D or 2-D positions. Usually in detector analysis, first 1-D case is investigated and then it can be generalized to 2-D case. When an optical spot mounts on the detector surface, photocurrent is generated by each electrode, depending on the distance of beam centroid from electrodes. So, with measuring output, the beam position can be also measured [6]. The equation of 1-D position detectivity, based on Figure 1 is given as [7]:

\[ \Delta X = S \frac{I_2 - I_1}{I_2 + I_1} \]  

(1)

where \( I_1 \) and \( I_2 \) are the output currents of electrodes. After calculating currents, we can write them in the form of voltage difference between two electrodes. As shown in Figure 3, Eq. 1 can be rewritten as:

\[ \Delta X = S \frac{V_2 - V_1}{V_2 + V_1} \]  

(2)

and the time delay between two signals can be obtained by Eq. 3:

\[ \Delta X = S \Delta t \]  

(3)

where \( \Delta t \) is the time delay between the two signals.

![Figure 3. Converting output currents to voltage.](image)

When the optical spot incidents on the LEP surface, there will be a carrier distribution led to a gradient in excess carrier concentration. The optical spot will start to spread in a Gaussian manner controlled by the diffusion coefficient and the recombination lifetime without any lateral or transverse external electric fields. So, the obtained current difference can be in the form of voltage difference between electrodes. This idea was presented first by Walmark. In this method, current difference led to voltage difference mode while time delay causes time difference and more linear response. To simulate LEP, we used Lucovsky Equation [6-7]:

\[ \text{Equation} \]
where \( V \) is the lateral photo-voltage, \( J_s \) is the transverse saturation current density, \( \rho_p \) is the resistivity of the p-doped region and \( w_p \) is the thickness of the p-doped region.

In small signal analysis, because \( q_s V \ll k_B \), it can be ignored and the Eq. 4 can be rewritten as:

\[
\frac{\partial^2 V}{\partial x^2} - \frac{J_s \rho_p}{w_p} \left[ \exp \left( \frac{q_s V}{k_B T} \right) - 1 \right] - \frac{\rho_p c}{w_p} \frac{\partial V}{\partial t} = -\frac{q_s \rho_p}{w_p} g(x,t)
\]  

With normalizing relation 5 (to the \( V_{\text{max}} \) and by the time constant RC) it can be written [7]:

\[
\frac{\partial V}{\partial t} = \frac{\partial^2 V}{\partial x^2} - \frac{R_{se}}{R_{sh}} V_r + g_r(x',t')
\]

where \( V_r = \frac{V}{V_G} \) is normalized to \( V_{\text{max}} \) (represented by \( V_G(x',t') \)) and \( g_r(x',t') = \frac{V_G(x',t')}{V_{G_{\text{max}}}} \) is normalized photon flux distribution in the detector surface [5]. Equation 5 is valid for any LEPs with a similar ratio \( \frac{R_{se}}{R_{sh}} \). We can replace a similar relation for current distribution not voltage instead of Eq. 5. For this reason, the initial and boundary conditions should be considered as:

\[
V_r(x',0) = V_r(0,t') = V_r(1,t') = 0
\]

And for generated photocurrent in two electrodes, we have:

\[
i_{1,2} = \frac{\partial V_r}{\partial x'} \quad x' = 0, x' = 1
\]

By expanding Eq. 5 in Fourier series form and by converting voltage to current, the currents will be:

\[
i_r = I \left( 1 - x'_p \right) \sin(\omega t' + \phi_0)
\]

\[
i_1 = -I \left( x'_p \right) \sin(\omega t' + \phi_1)
\]

\( x' \) is the normalized position for detector length and \( \phi_0 \) and \( \phi_1 \) denote phase delays for signals.

By expanding Fourier series around mid point, the slope of linear region is given [7]:

\[
S_2 = \frac{\omega L}{2} \left\{ \cosh(e_r) - \cos(e_r) \right\}
\]

\[
S_1 = L \left\{ \cosh(e_r) - \cos(e_r) \right\}
\]

\[
S_1 \approx \frac{L}{2} \left\{ \cosh(e_r) - \cos(e_r) \right\}
\]

\[
S_2 \approx \frac{L}{2} \left\{ \cosh(e_r) - \cos(e_r) \right\}
\]

\( S_1 \) and \( S_2 \) are the slopes of time delay and voltage difference modes [7].

3. Simulation results

The functions resulted from Eqs. 11 and 12 are shown in Figure 4. The linearity of time delay mode can be easily inferred in comparison to voltage difference mode. With \( R_{se} \) and \( R_{sh} \), we can use these relations for any photodetectors. We know when an optical spot approaches to detector terminals,
voltage difference decreases. As shown in Figure 4, over a dynamic frequency range, time delay mode is more linear than voltage difference mode. Figure 5 shows the simulation results for S3931 detector. This detector is more linear in time delay mode than S3979 detector over a larger frequency range. The simulation results for S3932 detector are also shown in Figure 6. It can be concluded that this detector has better performance comparing two other detectors.

Figure 7 is a 3-dimensional graph for voltage difference and time delay mode signals. As shown in this figure, in voltage difference mode, signals will saturate at the edges.

**Figure 4.** Normalized slope with respect to the normalized frequency for (a) VD and (b) TD modes in S3979 detector.

**Figure 5.** Normalized slope with respect to the normalized frequency for (a) VD and (b) TD modes in S3931 detector.
Figure 6. Normalized slope with respect to the normalized frequency for (a) VD and (b) TD modes in S3932 detector.

Figure 7. The error of position detection in X- and Y-axes for (a) VD and (b) TD modes in S3931 detector.

4. Conclusion
In this paper we have compared three practical LEPsDs based on the analysis reported by Abdullhalim in 2004 [7]. According to the obtained results, time delay mode has more advantages comparing to the voltage difference mode. Also with having the ratio $R_w/R_{in}$, for any lateral effect position sensing detectors, TD and VD modes relations can be written and investigated. Here, S3932 has more linearity in the response comparing to the S3931 and S3979.
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