Journal of Applied Sciences

ISSN 1812-5654

Journal of Applied Sciences 8 (9): 1781-1785, 2008
ISSN 1812-5654

Modeling and Simulation of Lateral Effect Position-Sensitive Detector Responsivity to Optical Stimulators

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Abstract: Lateral effect position-sensitive detector is one of the detectors commonly used in laser trackers, particularly in out-door areas. In this study, we analyze behavior and simulation of this detector to different optical stimulators such as impulse, step and sinusoidal optical sources. For this purpose, typical parameters and equations are used in order to analyze the detector response to different optical stimulators. Finally, relative position of the incident light beam on the surface of the detector will be calculated with regards to the related photocurrents.

Key words: Position-sensitive detector, lateral photo-effect, optical stimulators, position detection error

INTRODUCTION

A Lateral Effect Photodetector (LEP) can be widely used as a position sensing device in many applications. In the seekers, trackers and micro-robotic systems, it is necessary to obtain the accurate position (Abdulhalim, 2004; Kim *et al.*, 1997; Wang *et al.*, 1990; Nicholas *et al.*, 2002). A dual-axis Position Sensing Detector (PSD) such as a LEP or four-quadrant photodetector is used in order to monitor the position of the micro-beams in telecommunication and guidance systems. The PSDs are widely used in environments where several other light sources also coexist (Iqbal *et al.*, 2008).

A LEP can be used for dynamic testing to determine the centroid of all light in the field of view (FOV) as non-imaging sensor. However, in compared to four-quadrant detectors, LEPs have many advantages, especially in out-door areas.

Lateral effect position-sensitive detectors include a uniform resistance layer. This layer is formed on one side or both sides of a high conductance coefficient layer (Makynen, 2000). LEPs can be also implemented based on the CMOS technology.

In one dimensional detector, one pair of contacts is provided at the edges resistance layer to obtain the position signals. The structure of this detector is similar to a PIN photodetector (Wallmark, 1957; Lucovsky, 1960).

When light spot is incident on a p-n junction, some optical energy will be stored through each of junction layers. Now, if the junction is under reverse bias, the optical energy moves toward the junction, that is called Lateral Photo-effect (Lucovsky, 1960). A model of one dimensional lateral effect position-sensitive detector is shown in Fig. 1.

A general model of the lateral effect detector was first presented by Lucovsky (1960) for the steady and transient states of a small signal. Permittivity, recombination and electrical load transfer steps were described in this model. Other different models have been also introduced to describe the behavior and characteristics of a lateral effect photodetector (Connors, 1971; Narayanan, 1993).

In this study, the Lucovsky's equation is used to study the behavior of LEP to impulse, step and sinusoidal signals. Subsequently, according to the output photocurrent density of two contacts, the position and its error are calculated.

LEP RESPONSIVITY TO OPTICAL STIMULATORS

The behavior of a lateral effect can be described as:

$$\phi_{uu} - \frac{RC}{L^2}\phi_t = -j_{pn}\frac{\rho}{D} \qquad (1)$$

Where:

ϕ = The potential difference between the position sensitive layer and substrate

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C = The capacitor of the detector
R = The resistance of the detector
L = The length
j_{pn} = The input current density of the position-sensitive layer when ω = 0.

Impulse stimulus: The first optical stimulus to be described here is impulse function. The Lucovsky's equation can describe the behavior of the detector. The boundary conditions are assumed as $\phi|_{x=0,L} = V_R$ and $t \rangle 0$, where V_R is the reverse bias. If phrase $j_p \delta(t-t_0)\,\delta(x-x_p)$ is replaced by j_{pn}, Lucovsky's equation can be written as:

$$\phi'_{xx} - \frac{RC}{L^2}\phi'_t = -\frac{\rho}{D} j_p \delta(t-t_0)\delta(x-x_p) \quad (2)$$

Where:

$$\phi' = \phi - V_R$$

The new boundary conditions will be $\phi'|_{x=0,L} = 0$.

Equation 2 can be calculated by one finite Fourier sinusoidal transfer (FFST) for x (Brown and Churchill, 1987). The result of the dual transfer is given by:

$$-\left[(\frac{n\pi}{L})^2 + \frac{RC}{L^2}S\right]\Phi(n,s) = -\frac{\rho}{D} j_p \sin(\frac{n\pi x_p}{L})\exp(-st_0) \quad (3)$$

Therefore, ϕ' will be calculated by a two dimensional reverse transfer as:

$$\frac{\phi'}{j_p} = \sum_{n=1}^{\infty} \frac{2\rho}{D}\frac{L}{(n\pi)^2}\sin(\frac{n\pi x_p}{L})\sin(\frac{n\pi x}{L}) g_n(t-t_0) \quad (4)$$

Where:

$$g_n(t) = \lambda_n^2 e^{-\lambda_n^2 t} S(t)$$
$$\lambda_n^2 = \frac{(n\pi)^2}{RC} \quad (5)$$

Also, S(t) is the unit step function. Lateral current density at the left side contact (x = 0), as shown in Fig. 1, is given by ($\phi_x' = \phi_x$),

$$j_{left}^{pulse}(x_p,t) = -\frac{\phi_x(0,t)}{\rho} = -\frac{j_p}{D}\sum_{n=1}^{\infty}\frac{2}{n\pi}\sin(\frac{n\pi x_p}{L}) g(t-t_0) \quad (6)$$

Here, a new coordinate system is used that its center corresponds to the center of detector. Therefore, sin $(n\pi x_p/L)$ in Eq. 6 must be replaced by:

$$S_n(x_p) = \sin n\pi(\frac{x_p}{L} + \frac{1}{2}) \quad (7)$$

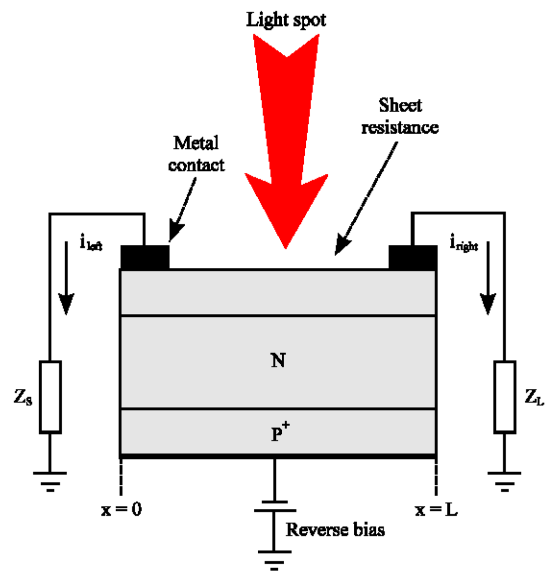

Fig. 1: Lateral photo-effect position-sensitive detector layout

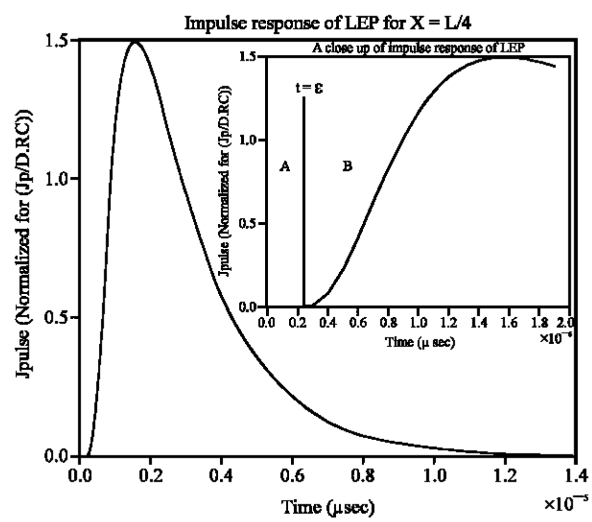

Fig. 2: The LEP response to impulse stimulus

As a result, the impulse responses for the left and right signals in the new coordinate system are respectively given by:

$$j_{left}^{pulse}(x_p,t) = -\frac{j_p}{D}\sum_{n=1}^{\infty}\frac{2}{n\pi}S_n(x_p) g(t-t_0) \quad (8a)$$

$$j_{right}^{pulse}(x_p,t) = +\frac{j_p}{D}\sum_{n=1}^{\infty}\frac{2}{n\pi}S_n(-x_p) g(t-t_0) \quad (8b)$$

The simulation of impulse response of LEP is illustrated in Fig. 2. As shown in the figure, the impulse response can be divided into two regions; A: t ∈ [0, ε] and

B: $t \in [\varepsilon, \infty]$. In the region A, sum of n phrases should be done for $n \to \infty$ and in the region B ($t > \varepsilon$), the summation is converged for n = N.

In calculation of Eq. 8, the determination of proper values for summation limit (N) and time boundary (ε) that are dependant to C, R and the position of light spot is important. When the light source gets closer to the contact, ε is decreased and therefore summation limit will be increased. Required values of ε and N for near the contact position are sufficient for every position of detector. Here, N and ε are considered as 100 and 200 ns, respectively.

Step and sinusoidal stimulus: In this section, the response to a variable optical source including the step and sinusoidal responses are calculated. First, $x_p(t)$ is introduced as the position of incident light spot and is assumed intensity to be constant for t > 0. The current density of the left contact can be obtained by applying the convolution of $j_{left}^{pulse}(x_p(t),t) * S(t)$,

$$j_{left}(t) = j_{left}^{pulse}(x_p(t),t) * S(t) = -\frac{j_p}{D}\sum_{n=1}^{\infty}\frac{2}{n\pi}\int_0^t S_n(x_p(t_0))g_n(t-t_0)d_{t_0} \quad (9)$$

Then, a special state of an optical source will be discussed that has been modulated by a sinusoidal function. We assume the oscillation range in compared to the detector length (L) is small.

$$x_p(t) = x_c + \Delta x \sin(\omega t) \quad (10)$$

Where:
x_c = The central position
Δx = The amplitude of oscillation
ω = The frequency of oscillation

Based on this special state, the equation of $j_{left}(t)$ will be rewritten as:

$$j_{left}(t) = -\frac{j_p}{D}\int_0^t \sum_{n=1}^{\infty}\frac{2}{n\pi}[S_n(x_c)\cos\left(n\pi\frac{\Delta x}{L}\sin\omega t_0\right) + C_n(x_c)\sin\left(n\pi\frac{\Delta x}{L}\sin\omega t_0\right)g(t-t_0)\, d_{t_0} \quad (11)$$

Similar to Eq. 7, the $C_n(x)$ is given by:

$$C_n(x) = \cos n\pi\left(\frac{x_p}{L}+\frac{1}{2}\right) \quad (12)$$

Now, sinusoidal functions can be linear as:

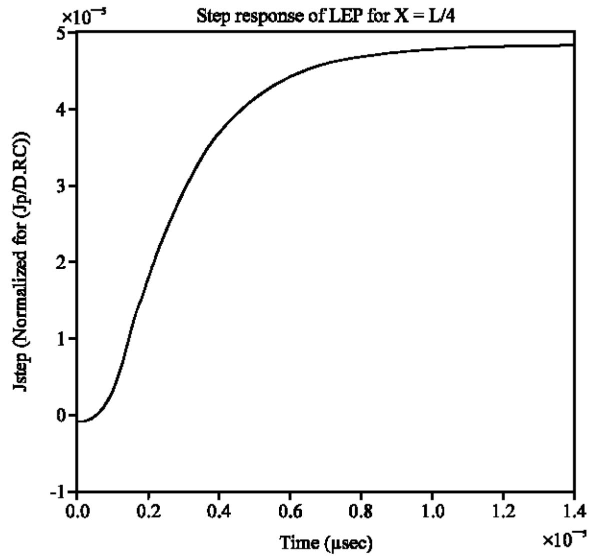

Fig. 3: Step response of LEP

$$j_{left}(t) = \frac{-j_p}{D}\sum_{n=1D}^{\infty}\left[\left(\frac{2}{n\pi}S_n(x_c)\int_0^t g_n(t-t_0)d_{t_0}\right) - \left(\frac{j_p}{D}\sum_{n=1}^{\infty}\frac{2}{n\pi}C_n(x_c)n\pi\frac{\Delta x}{L}\int_0^t g_n(t-t_0)\sin\omega t_0\, d_{t_0}\right)\right] \quad (13)$$

The first term of the Eq. 13 is the light intensity step response. In the second part, the integral of the left side current density is calculated by integration to $t-\varepsilon$ as:

$$\int_0^{t-\varepsilon} g_n(t-t_0)\sin\omega t_0 dt_0 \approx e^{-\lambda_n^2\varepsilon}g_n(t) * \sin\omega t \quad (14)$$

However, due to $\varepsilon << \omega^{-1}$, the equation of current density will be changed and it can be rewritten by:

$$j_{left}(t) = j_{left}^{step}(x_c,t) + j_{left}^{Sine}(x_c,t) \quad (15)$$

where, $j_{left}^{step}(x_c,t)$ is the intensity of the step response for $x = x_c$ and it indicates that the light source is incident in t = 0 (Fig. 3).

$$j_{left}^{step}(t) = -\frac{j_p}{D}\sum_{n=1}^{\infty}\frac{2}{n\pi}S_n(x_c)e^{-\lambda_n^2 t}(1-e^{-\lambda_n^2 t}) \quad (16)$$

On the other hand, $j_{left}^{Sine}(x_c,t)$ illustrates the responsivity to the sinusoidal beam. This term can be determined by:

$$j_{left}^{Sine}(x_c,t) = 2\frac{j_p}{D}\frac{\Delta x}{L}\sum_{n=1}^{N}C_n(x_c)e^{-\lambda_n^2\varepsilon}g_n(t) * \sin\omega t \quad (17)$$

According to the Eq. 17, $j_{left}^{Sine}(t)$ is considered as the sum of linear filters $g_n(t)$. The filters are applied on the

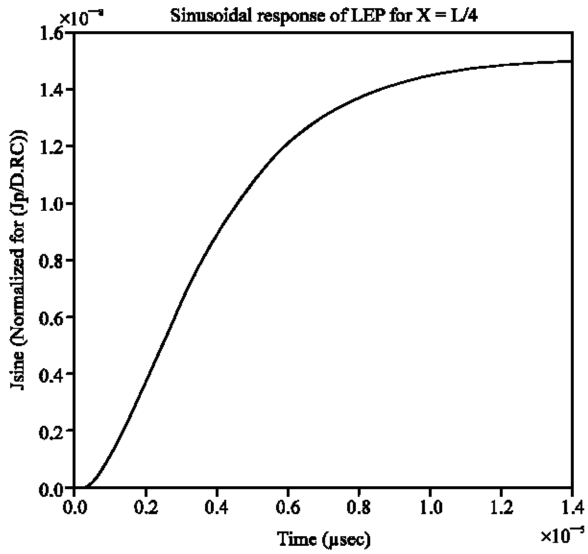

Fig. 4: Sinusoidal response of LEP

sinusoidal movements of the light source $\Delta x \sin\omega t$. The sinusoidal response of LEP is shown in Fig. 4.

POSITION DETECTION BY LEP

Using a uniform resistance layer, the position of incident light on the detector can be easily calculated by the density of the output photocurrents. One dimensional position x is determined by two output photocurrents, $i_{right}(t)$ and $i_{left}(t)$ as:

$$x = \frac{L}{2} \frac{i_{right}(t) - i_{left}(t)}{i_{right}(t) + i_{left}(t)} \tag{18}$$

where, L is the active length of detector. The LEP detector is operated in reverse bias mode and the beam intensity is so small that it can not produce the lateral photovoltaic effect. Therefore, re-injection of carrier through the junction is assumed equal to zero. By measuring the output photocurrents, the position of x is estimated. The photocurrents are obtained in different points by Eq. 16-18.

The response of LEP is simulated by parameters of one dimensional lateral effect detector (Manufactured by Hamamatsu Company). Table 1 shows the specifications of this LEP.

The result of simulation is shown in Fig. 5. As shown in the figure, in steady state, the relation between the responsivity and the position of incident optical spot is linear. Near the steady state region, the position can be accurately determined. But in transient region, the result of simulation presents that non-accurate position is obtained unless in the center of surface. In addition, there is a small dead-time before forming the current in the contacts. The dead-time is related to spot position. As the light spot moves towards the contacts, this time gap is increased.

Table 1: The parameters used in simulation (http://www.hamamatsu.com, Position sensitive detectors, accessed December 2007)

Parameters	Typical value
R	315 Ω mm^{-1}
C	330 pF mm^{-1}
R_S	1 MΩ mm^{-1}
L	20 mm

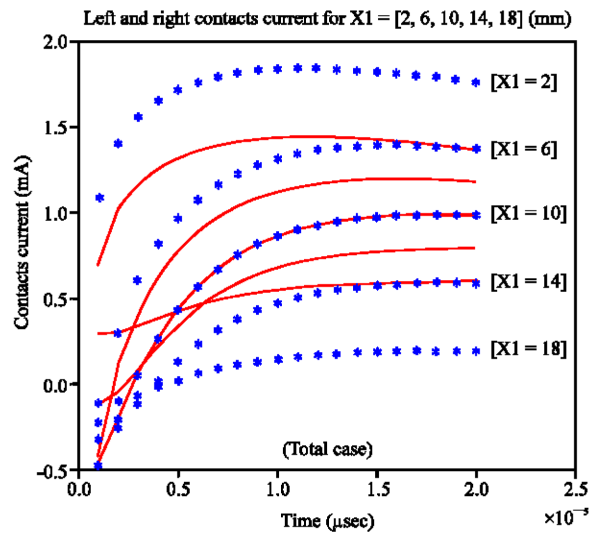

Fig. 5: Output photocurrents for different position of incident light spots. (The lines illustrate the photocurrent of right contact and the stars illustrate the photocurrent of left contact)

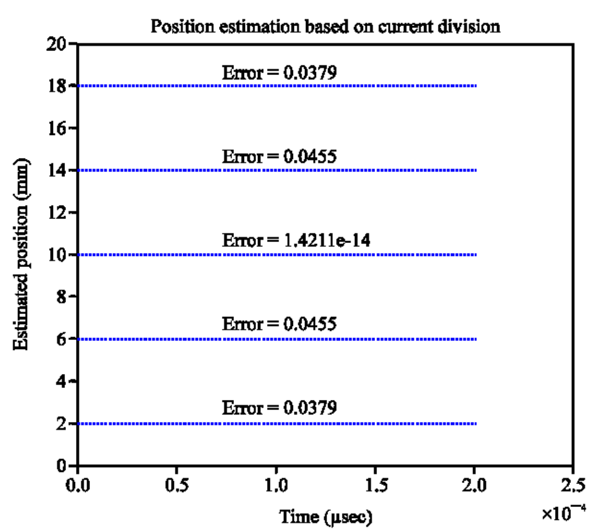

Fig. 6: Simulated position of incident light spot and related error for different positions

However, measured position is slightly different of actual position due to noise, dark current (Mohammad Nejad *et al*., 2008) and uncertainty in the determination of photocurrents. Therefore, the LEP model must be containing these deviations. Figure 6 shows the errors of position determination. As shown in Fig. 6, minimum error appears in the center of detector. Because nonlinearities and noise in two contacts are similar, the error is constant in overall surface. In addition, the error in compared to center of surface is symmetry.

CONCLUSION

In this study, the responsivity of a lateral effect position-sensitive to different stimulators such as impulse, step and sinusoidal has been calculated and presented. The response has two region; transient and steady state. The transient part of the response can not able to present correct information from the position. But the steady state region of the response can be applied for the position calculation.

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