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A pixel array PSD with divide-by-M winner-take-all architecture

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Abstract: This paper presents a pixel array position sensitive detector (PSD) with analog winner-take-all (WTA) blocks. The pixels are divided into M-number of sub-groups and a WTA is assigned to each sub-group. The winner pixel of entire pixels is obtained from the sum of the sub-group's winner addresses. Detailed noise analysis shows that there is an optimal number of sub-groups for improved noise immunity.

Keywords: PSD, pixel array, WTA

Classification: Integrated circuits

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1 Introduction

The position sensitive detector (PSD) is an opto-electronic device that detects the brightest point of incident light and is widely used in triangulation-based range finding applications. The PSD can be implemented using either a lateral effect photodiode (LEP) [1] or a photodiode pixel array [2]. Recent progress of the CMOS image sensor technology makes the photodiode pixel array as a preferable choice for a PSD over the LEP since it provides better sensitivity and speed as well as the spatial resolution that is limited by pixel-pitch. Another advantage of CMOS process is that it allows integration of a pixel array and an analog winner-take-all (WTA) circuit [3] which finds the brightest pixel, i.e., the winner pixel. Measurement accuracy of the pixel

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array PSD is determined by noise from the pixels and the WTA circuit for the given pixel-pitch. A simple interpolation scheme for a pixel array PSD with two WTA blocks was presented for better resolution and measurement accuracy [4].

This paper presents a pixel array PSD with the M-number of WTA blocks that find the winners from the groups of every M-th pixel for improved accuracy.

2 Proposed PSD architecture

Figure 1 shows the architecture of the proposed pixel array PSD with the M-number of WTA blocks. Pixels are divided into sub-groups of every M-th pixel. A WTA is assigned to each corresponding sub-group and it finds the winner address n_m within the sub-group.

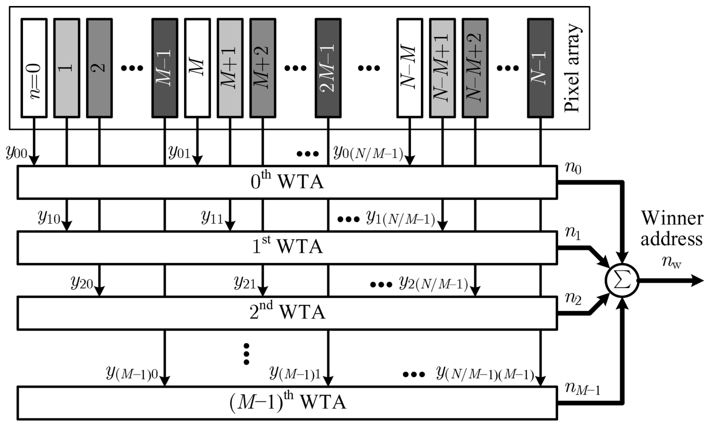

Fig. 1. Block diagram of the proposed pixel array PSD with divide-by-M WTA architecture.

Under the assumption that the incident light has a Gaussian-shaped light intensity profile over the pixel array, the winners from WTAs are adjacent to each other. Therefore, the winner address n_w of the entire pixel array is the sum of the winner addresses from WTAs as follows.

$$n_\mathrm{w} = \sum_{m=0}^{M-1} n_m. \tag{1}$$

The overhead to divide a WTA into M pieces is negligible because the total number of WTA cells is same with that of single WTA that finds the winner from entire pixels.

3 Noise analysis of the divide-by-M WTA architecture

Let us consider a situation that the incident light is exactly centered on the mid-point between two neighboring pixels 'a' and 'b' in the same sub-group as shown in Fig. 2 (a). The decision boundary of the WTA is affected by the pixel noise Δy_a and Δy_b, and results in the decision boundary fluctuation Δx as shown in Fig. 2 (b).

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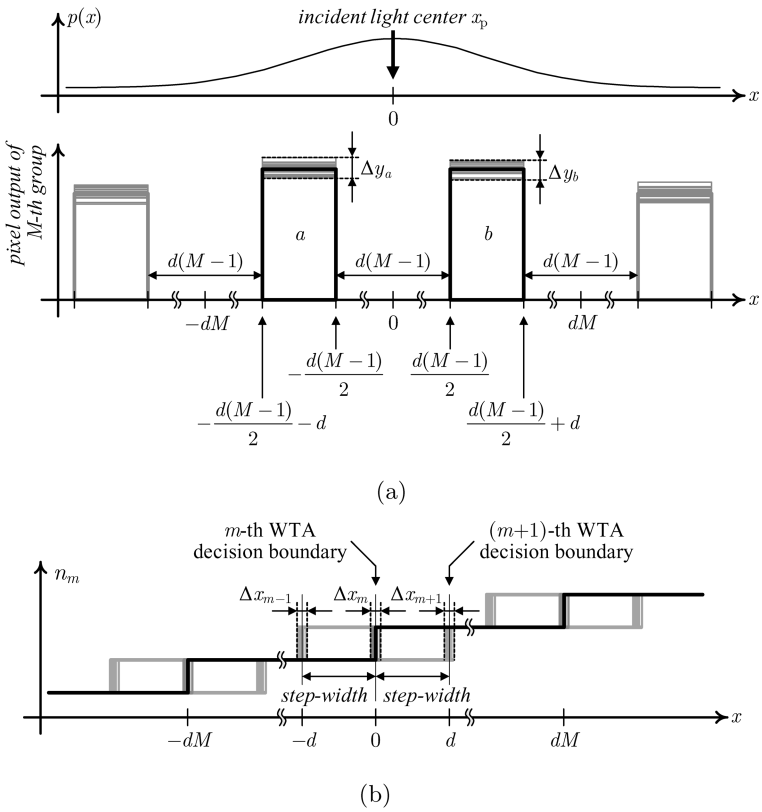

Fig. 2. Illustration of an incident light, pixel outputs and the decision boundary; (a) the incident light intensity profile and corresponding pixel outputs of M-th pixel group and (b) outputs of WTAs.

Assume that the intensity profile of the incident light is Gaussian-shaped as

$$p(x - x_{\mathrm{p}}) = p_0 e^{-\frac{(x-x_{\mathrm{p}})^2}{2w^2}} \qquad [\mathrm{W/m}] \tag{2}$$

where x_{p} is the incident light center, p_0 is the peak light power density at $x = x_{\mathrm{p}}$, and w corresponds to the width of the incident light. Two neighboring pixels in the same group are apart from each other by $d(M-1)$ where d is the pixel pitch as shown in Fig. 2 (a). The output of each pixel is obtained by integrating (2) within the corresponding pixel dimension. As there exist noises in the pixel outputs, the output of pixel 'a' and 'b' in Fig. 2 (a) can be obtained as follows.

$$y_a = S \cdot p_0 \int_{-\frac{d(M-1)}{2}-d}^{-\frac{d(M-1)}{2}} e^{-\frac{x^2}{2w^2}} dx + \Delta y_a \tag{3}$$

$$y_b = S \cdot p_0 \int_{\frac{d(M-1)}{2}}^{\frac{d(M-1)}{2}+d} e^{-\frac{x^2}{2w^2}} dx + \Delta y_b \tag{4}$$

where S is the sensitivity of the pixel, Δy_a and Δy_b are noises of each pixel. The winner is decided by the sign of difference between y_a and y_b as follows.

$$\mathrm{sgn}(y_a - y_b). \tag{5}$$

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The pixel noise causes the decision boundary fluctuation that corresponds to the shift of incident light center by Δx which can be expressed as follows.

$$y'_a = S \cdot p_0 \int_{-\frac{d(M-1)}{2}-d}^{-\frac{d(M-1)}{2}} e^{-\frac{(x-\Delta x)^2}{2w^2}} dx \tag{6}$$

$$y'_b = S \cdot p_0 \int_{\frac{d(M-1)}{2}}^{\frac{d(M-1)}{2}+d} e^{-\frac{(x-\Delta x)^2}{2w^2}} dx. \tag{7}$$

Then, the relationship between the pixel noise and the decision boundary fluctuation can be obtained from following equality.

$$y_a - y_b = y'_a - y'_b. \tag{8}$$

Substitution of (3), (4) and (6), (7) into (8) leads to following equality.

$$\frac{\Delta y_a - \Delta y_b}{S \cdot p_0} = \int_{-\frac{d(M-1)}{2}-d}^{-\frac{d(M-1)}{2}} e^{-\frac{(x-\Delta x)^2}{2w^2}} dx - \int_{\frac{d(M-1)}{2}}^{\frac{d(M-1)}{2}+d} e^{-\frac{(x-\Delta x)^2}{2w^2}} dx. \tag{9}$$

Here, the integral can be expressed with an error function as follows.

$$\int e^{-\frac{(x-\Delta x)^2}{2w^2}} dx = \sqrt{2}w \int_0^{\frac{x-\Delta x}{\sqrt{2}w}} e^{-t^2} dt = w\sqrt{\frac{\pi}{2}} \operatorname{erf}\left[\frac{x-\Delta x}{\sqrt{2}w}\right]. \tag{10}$$

Then, (9) can be rewritten as follows.

$$\begin{aligned} &\operatorname{erf}\left[\frac{d(M-1)+2\Delta x}{2\sqrt{2}w}\right] - \operatorname{erf}\left[\frac{d(M+1)+2\Delta x}{2\sqrt{2}w}\right] \\ &\qquad - \operatorname{erf}\left[\frac{d(M-1)-2\Delta x}{2\sqrt{2}w}\right] + \operatorname{erf}\left[\frac{d(M+1)-2\Delta x}{2\sqrt{2}w}\right] \\ &\qquad\qquad = \sqrt{\frac{2}{\pi}} \frac{1}{w} \frac{\Delta y_b - \Delta y_a}{S \cdot p_0}. \end{aligned} \tag{11}$$

Since $|\Delta x| \approx 0$, we can expand the error functions in (11) into Taylor series with respect to Δx around $\Delta x = 0$ as follows.

$$\operatorname{erf}\left[\frac{d(M \pm 1)+2\Delta x}{2\sqrt{2}w}\right] \approx \operatorname{erf}\left[\frac{d(M \pm 1)}{2\sqrt{2}w}\right] + \sqrt{\frac{2}{\pi}} \frac{1}{w} e^{-\frac{d^2(M\pm1)^2}{8w^2}} \Delta x. \tag{12}$$

Then, (11) can be approximated as follows.

$$\Delta x \approx \frac{1}{2} \frac{e^{\frac{(1+M)^2}{8W^2}}}{\left(e^{\frac{M}{2W^2}} - 1\right)} \frac{\Delta y_b - \Delta y_a}{S \cdot p_0} \tag{13}$$

where $W = w/d$ which denotes the normalized width of the incident light by the pixel-pitch.

If we assume that Δy_a and Δy_b are uncorrelated to each other, and $\sigma_{ya} = \sigma_{yb} = \sigma_y$ where σ_{ya} and σ_{yb} represent the standard-deviation of Δy_a and Δy_b respectively, then the standard-deviation of Δx, σ_x at the WTA decision boundary is found as follows.

$$\sigma_x = \frac{1}{2} \frac{e^{\frac{(1+M)^2}{8W^2}}}{\left(e^{\frac{M}{2W^2}} - 1\right)} \frac{\sqrt{\sigma_{ya}^2 + \sigma_{yb}^2}}{S \cdot p_0} = \frac{1}{\sqrt{2}} \frac{e^{\frac{(1+M)^2}{8W^2}}}{\left(e^{\frac{M}{2W^2}} - 1\right)} \frac{\sigma_y}{S \cdot p_0}. \tag{14}$$

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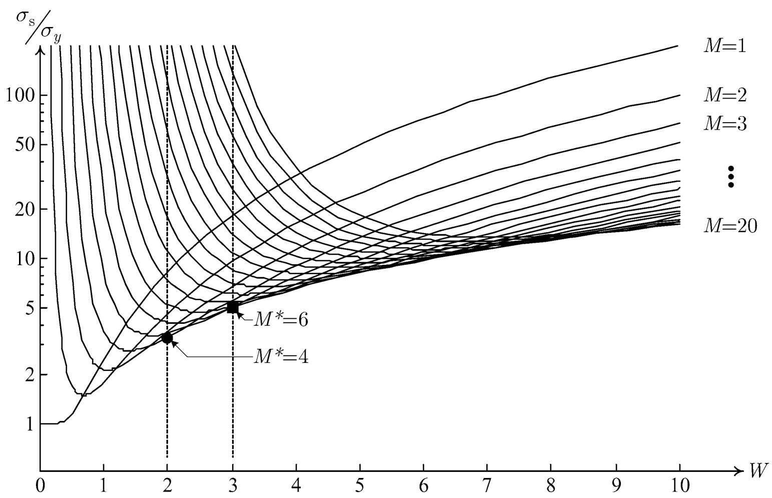
As shown in Fig. 2 (b), the step-width is defined as the distance along x-axis between two adjacent decision boundaries made by two neighboring WTAs. Assuming that the standard-deviations of all WTA's decision boundary are equal, that is $\sigma_{x:m} = \sigma_{x:m+1} = \sigma_x$, the standard-deviation of step-width, σ_s can be found as follows.

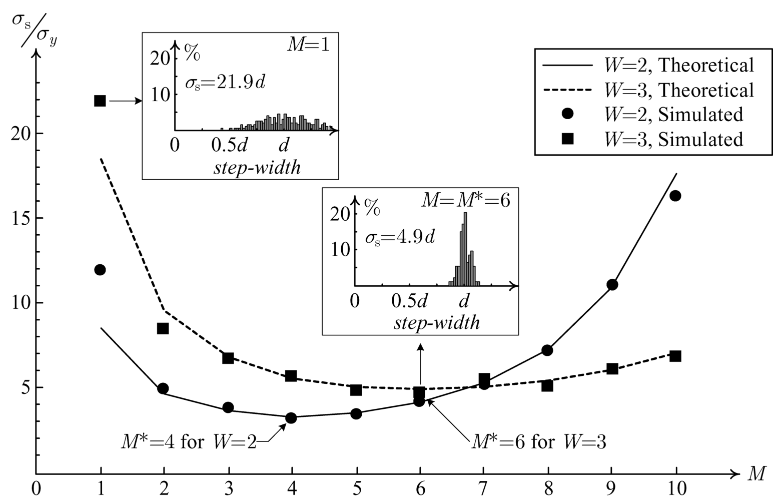
$$\sigma_s = \sqrt{\sigma_{x:m}^2 + \sigma_{x:m+1}^2} = \sqrt{2}\sigma_x = \frac{e^{\frac{(1+M)^2}{8W^2}}}{\left(e^{\frac{M}{2W^2}} - 1\right)} \frac{\sigma_y}{S \cdot p_0}. \tag{15}$$

4 Simulation Results

Figure 3 (a) plots the noise sensitivity σ_s/σ_y obtained from (15). For a given width of the incident light W, there exists an optimal number of the WTAs, M^* for minimum σ_s/σ_y which means the maximum noise immunity. For example, $M^* = 4$ for $W = 2$ and $M^* = 6$ for $W = 3$, respectively. The



(a)



(b)

Fig. 3. Step-width noise sensitivity plot for $S \cdot p_0 = 1\,\mathrm{V/m}$; (a) with respect to W (theoretical) and (b) with respect to M.

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relationship between the incident light width W and the optimal number of WTA division M^* is approximately given as follows in general.

$$M^* \approx 2 \cdot W. \tag{16}$$

The noise sensitivity reduction ratio (NSRR) of the divide-by-M architecture over the conventional single WTA architecture can be defined as follows.

$$\begin{aligned} \mathrm{NSRR} = 1 - \frac{\sigma_{\mathrm{s}}(W, M^*)}{\sigma_{\mathrm{s}}(W, 1)} &\approx 1 - \frac{\sigma_{\mathrm{s}}(W, 2W)}{\sigma_{\mathrm{s}}(W, 1)} \\ \approx 1 - \frac{0.7}{W} \approx 1 - \frac{1.4}{M^*} &\quad \text{for } M^* \geq 2. \end{aligned} \tag{17}$$

This means that 76.7% of the noise sensitivity reduction when $W = 3$ and $M = 6$ as an example, resulting in 1/4 of the standard-deviation compared to a single WTA architecture.

The pixel array PSD with divide-by-M WTA is simulated using a incident light model described in (2). The peak pixel output $S \cdot p_0$ is set to 1 V/m and the random noise of $\sigma_y = 1\,\mathrm{mV}$ is added to pixel outputs. Figure 3 (b) shows the simulated results of $\sigma_{\mathrm{s}}/\sigma_y$ for various M when $W = 2$ and 3. It is clear that the optimal number of the WTAs corresponds with the theoretical results from Fig. 3 (a).

The step-width histograms with $M = 1$ are compared with that with $M = 6$ for $W = 3$ in Fig. 3 (b) as an example. The step-width standard-deviation with the optimal M is reduced by 77.6% of that of the single WTA architecture. The simulated noise sensitivity is well agree with the theoretical estimation in (17).

5 Conclusion

This paper presented a pixel array PSD with divide-by-M WTA blocks. The analysis and simulation results showed that the divide-by-M WTA architecture provides improved noise immunity over the single WTA architecture. Optimal number of division is obtained theoretically and verified by the simulation. Although a Gaussian-shaped light intensity profile is assumed in this paper, the proposed procedure to find the relationship between the incident light width and the optimal number of division is valid without loss of generality.

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