Characterization and Simple Fixed Pattern Noise Correction in Wide Dynamic Range "Logarithmic" Imagers

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***Abstract*—Wide dynamic range logarithmic imagers can render naturally illuminated scenes while preserving detail and contrast information at a lower cost than high dynamic range linear sensors. However, the quality of the output is severely degraded by fixed pattern noise (FPN). Although previous FPN correction techniques can eliminate the dominant additive form of this noise, the contrast threshold of the imager over a wide illumination range is poor compared to the human visual system. In this paper, it is shown that a four-parameter model fits the measured characteristic response of wide dynamic range pixels over 11 decades of input current. A comparison of the responses of 200 pixels shows that there are significant variations in all four parameters. A procedure is described that allows the four pixel parameters to be obtained from the response of each pixel to five input currents. However, a much simpler procedure is shown to correct FPN, leading to a contrast threshold comparable to the human visual system over the five decades required to image wide-dynamic-range, naturally illuminated scenes.**

***Index Terms*—Enz–Krummenacher–Vittoz (EKV) model, fixed pattern noise (FPN), FPN correction, high dynamic range, logarithmic complimentary metal–oxide–semiconductor (CMOS) imagers.**

I. Introduction

NATURALLY illuminated external scenes can have an intrascene dynamic range of five orders of magnitude [1]. In contrast, the charge-coupled devices and active pixel sensors, which currently dominate the image sensor market [2], have a dynamic range of less than three orders of magnitude. Consequently, when imaging a naturally illuminated external scene, the response of these sensors saturates in some areas of the scene, resulting in loss of detail within these areas. To overcome this problem, several techniques have been proposed that can extend the sensor's dynamic range [3]–[6]. However, for a sensor with a linear response, these dynamic range improvements can only be achieved by significantly increasing the number of bits per pixel used to represent the image and multiple sampling techniques, which significantly adds to the cost of the final imager.

An alternative approach to capturing high dynamic range scenes is to design imagers containing pixels with a nonlinear response that compresses the dynamic range of the input signal. Usually, this nonlinear response is achieved by using an MOS load transistor operating in weak inversion to create an output voltage that is proportional to the logarithm of the photocurrent. This means that while the dynamic range of the input signal is compressed by these pixels, they preserve the contrast information in the scene, which is important in the human visual system [7]. The problem is that the relative small range of output voltages created by these pixels means that their output signal is susceptible to noise and interference. To overcome this problem, it was recently suggested that the photodiode used in most pixels should be replaced by a phototransistor [8]. The current gain of this bipolar transistor then increases the current flowing through the pixel. This, in turn, increases the output voltage range of the pixel by forcing the load transistor to operate in moderate inversion in the brighter areas of the scene.

As with all pixels, this new type of pixel suffers from fixed pattern noise (FPN), which is caused by variations between nominally identical devices in different pixels that limits the sensitivity of the pixel. Section II shows that even after correcting the dominant contribution to FPN, the contrast threshold of this type of pixel is still disappointing. The first stage in developing a more sophisticated FPN correction procedure is to develop a compact model of the complex nonlinear response of each pixel. In Section III, a four-parameter model [9] is shown to fit the measured response of a pixel over 11 decades. The analysis of the parameters of this model shows that, as expected, the dominant contribution to FPN is variations in an additive term. However, significant variations occur in all four parameters. A simple procedure to extract the four parameters for the model is therefore developed in Section IV, which shows that the four parameters for the model can be obtained from the response of a pixel to five currents. Finally, in Section V, a simple procedure is described that allows the measured output of each pixel to be corrected to remove FPN to achieve a contrast threshold comparable to the human visual system over five decades.

II. Background

The schematic circuit diagram for a nonlinear pixel is shown in Fig. 1. Within the pixel, the incident light is converted to

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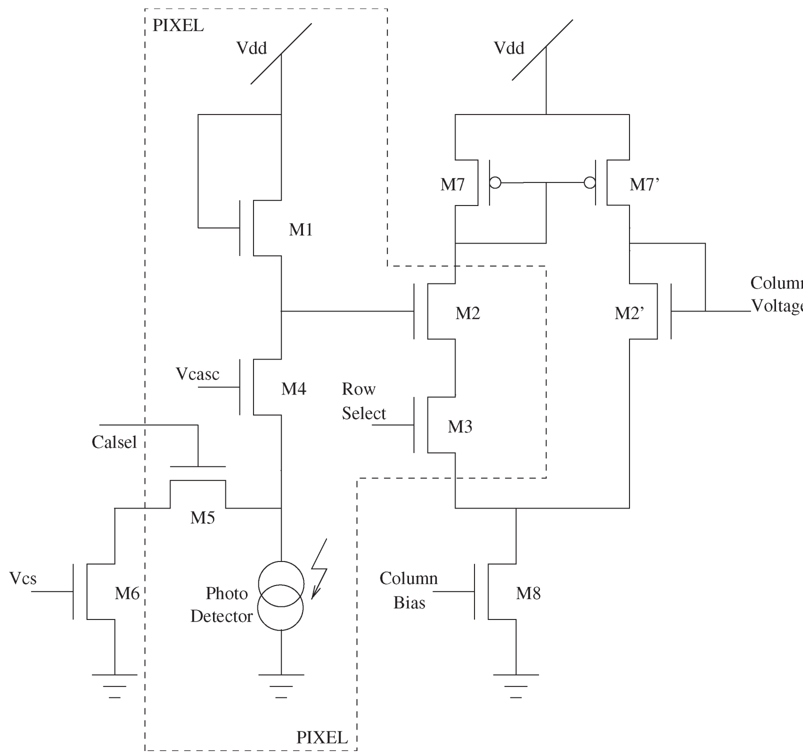

Fig. 1. Schematic diagram of a pixel with a differential readout circuit and devices used to characterize the circuit electronically.

a photocurrent by a photodetector. The resulting photocurrent then flows through the load device M1, which converts the photocurrent into a corresponding voltage. In a conventional pixel, this output voltage is connected to a shared output line via a source-follower circuit [10]. However, the source follower attenuates an already small signal. To reduce any signal attenuation, the source follower has therefore been replaced by a differential amplifier in the circuit in Fig. 1. Although the differential amplifier contains significantly more transistors than the simpler source-follower circuit, only two of these transistors are actually within the pixel. A differential amplifier readout circuit can therefore be used without increasing the number of transistors within each pixel and affecting the fill factor [11]. The other unconventional aspect of the circuit in Fig. 1 is that for convenience, the pixel has been designed so that it can be characterized using a metal–oxide–semiconductor field-effect transistor acting as a voltage-controlled current source in parallel with the photodetector. To ensure that pixels in the same column are characterized at the same current, the voltage-controlled current source, i.e., transistor M6 in Fig. 1, is shared by all the pixels in a column. The output current from this device can then be selectively steered through a pixel using the selectable switch device M5. Ideally, employing this voltage-controlled current source for the entire array would eliminate the effects of mismatches in these sources but would slow imager performance. As a tradeoff, a separate study revealed how a single current source can be used at calibration to reduce mismatch rather than in the actual frame capture, hence, maintaining the performance speed [11].

In most logarithmic pixels, a photodiode is used as the photodetector, and the load device is designed to ensure that it operates in weak inversion. However, with a bipolar transistor

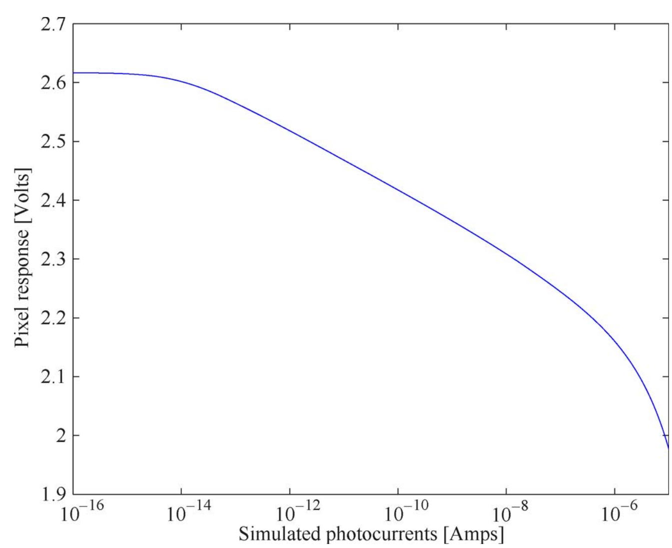

Fig. 2. Response of a "logarithmic" pixel over a wide range of input photocurrents.

being used as the photodetector, Lai *et al.* [8] suggested that the advantage over a photodiode would be that for a particular incident photon flux, the gain of the transistor will increase the current flowing through the load transistor. As shown in Fig. 2, increasing the photocurrent flowing through the pixel has the advantage that it increases the output voltage swing from the pixel in the brighter regions of the scene and, therefore, reduces the susceptibility of the pixel to noise.

One of the problems with any pixel design is the FPN caused by variations between nominally identical devices in individual pixels. The impact of this FPN has been assessed from the responses of 200 pixels, such as the one shown in

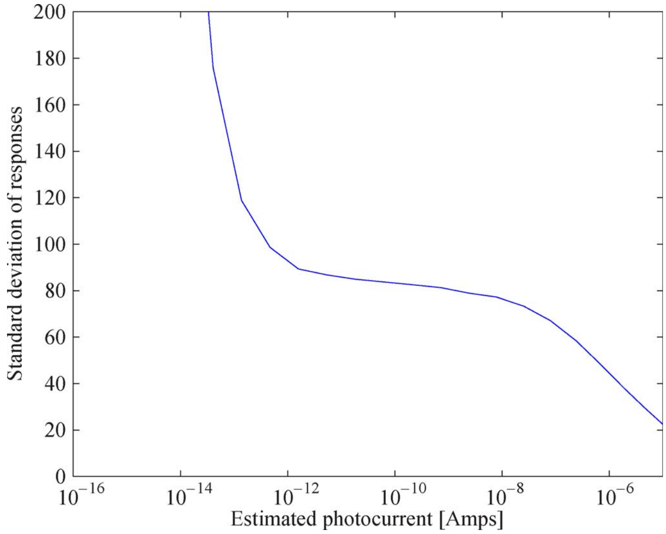

Fig. 3. Limit of the contrast threshold of 200 pixels arising from FPN. The y-axis represents the ratio of the standard deviation in the responses of the pixels to the change in output voltage caused by a 1% change in input current.

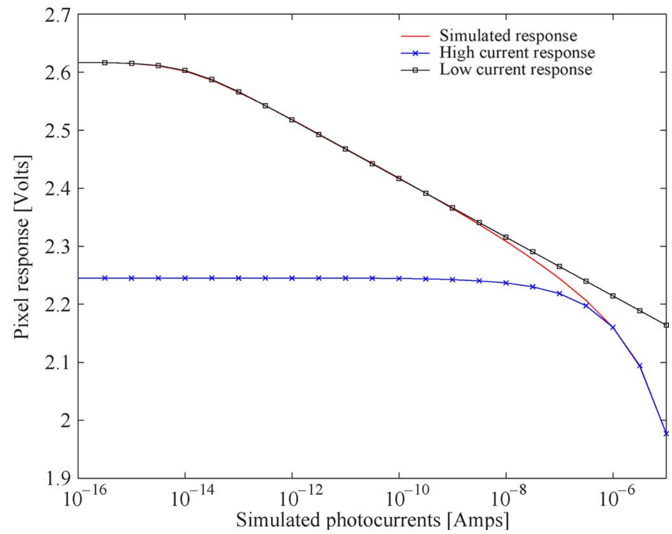

Fig. 4. Comparison between the responses of a pixel and the models for high and low photocurrents.

Fig. 1, fabricated on an unmodified 0.35-μm complimentary metal–oxide–semiconductor process (Austria Microsystems). To quantify the effect of FPN, the contrast threshold of the 200 pixels has been determined by calculating the ratio of the standard deviation of the responses of the pixels to a variety of uniform stimuli to the change in the output voltage caused by a 1% change in stimulus under the same input conditions. The dramatic impact of FPN on contrast threshold is shown in Fig. 3. In particular, these results show that for most of the operating range of the pixels, the FPN is more than 80 times larger than the signal created by a 1% change in the photocurrent. Although this ratio is decreased at high current levels by the increased effective gain of the pixel, the standard deviation of FPN is never less than 20 times the voltage signal caused by a 1% change in photocurrent.

The dominant source of FPN in most pixels is an additive fixed pattern [9]. Various techniques have been proposed to compensate for the additive FPN caused by variations between pixel offsets by either modifying the pixel circuit itself [12] or subtracting the response of each pixel from its response to a uniform input current generated either optically [13] or electronically [8], [14], [15]. The ability to steer the output from a voltage-controlled current source through each pixel, as in Fig. 1, means that it was possible to investigate the effectiveness of correcting offset variations by measuring the response of each pixel to a uniform input current. The effectiveness of correcting for offset FPN has been assessed using the responses of a sample of 200 pixels from the same substrate. The first two techniques that were tested replicated the approaches adopted by Kavadias *et al.* [14], [15] and Lai *et al.* [8]. These results showed that using either a very high current [14], [15] or a very low one [8] to calibrate each pixel to compensate for FPN leads to disappointing results [9]. One problem with both these techniques is that they use calibration data from outside the range in which the pixel output is proportional to the logarithm of the photocurrent. Results are significantly improved when the input current used to calibrate each pixel to compensate for additive FPN is well within the region in which the pixel exhibits a logarithmic response. However, even using a better calibration point, the contrast threshold of the pixels rapidly degrades if the input photocurrent deviates from the calibration point and a contrast threshold of 2% is only maintained over a range of approximately two decades [9]. This may be acceptable for some applications. However, the human visual system has an optimum contrast threshold of about 1% [7], [16] and renders naturally illuminated scenes with a five-decade dynamic range at a time. This suggests that to achieve a performance comparable to the human visual system, it is necessary to use a more sophisticated form of FPN correction.

III. Four-Parameter Model

The first stage in developing an efficient strategy for compensating for variations between pixels is to create a compact model for the response of each pixel [10]. To explain the operation of a procedure to remove additive FPN, Lai *et al.* assumed that the load transistor in the pixel operated in one of two regimes [8]. In particular, using simple models of the current–voltage characteristics of a MOS transistor, they assumed that at high currents, the output voltage from the pixel is proportional to the square root of the current flowing through the load transistor, whereas at low currents, it is proportional to the logarithm of the same current. The comparison between the response of a pixel and these two forms of behavior in Fig. 4 shows that the pixel exhibits these two behaviors in the expected current ranges. However, these results also show that this simple approach to modeling the response of the pixel fails for the critical range of currents between 1 μA and 1 nA. A new model is therefore required for this new type of pixel.

A model that represents the complex relationship between current and the pixel output voltage must avoid any assumption concerning the operating region of the load transistor. An expression for the current–voltage characteristics of an MOS transistor that represents all the operating regions of the transistor from weak to strong inversion is the

Enz–Krummenacher–Vittoz MOS transistor model [17]. In this model, the drain–source current I_{DS} at a gate–source bias voltage V_{GS} flowing in a transistor of width W and length L with an effective capacitance per unit area C'_{ox} is written in the following form [18]:

$$I_{\mathrm{DS}} = \frac{W}{L}\mu C'_{\mathrm{ox}} 2n\phi_t^2 \left[\ln\left(1+\exp\left((V_{\mathrm{GS}}-V_t)/2n\phi_t\right)\right)\right]^2 \quad (1)$$

where μ is the effective surface mobility, V_t is the transistor's threshold voltage, ϕ_t is the thermal voltage, and n is the subthreshold slope parameter. Within the pixel, the drain–source current of the load transistor M1 is the sum of the photocurrent I_p and the leakage current I_s [10]. The predicted response of the pixel is therefore given as follows:

$$V_{\mathrm{out}} = V_t + 2n\phi_t \ln\left[\exp\left(L(I_p+I_s)\left(W\mu C'_{\mathrm{ox}}2n\phi_t^2\right)\right)^{\frac{1}{2}} - 1\right]. \quad (2)$$

If the parameter

$$d = \frac{L}{W\mu C'_{\mathrm{ox}} 2n\phi_t^2} \quad (3)$$

is introduced for convenience, then the equation for the output of the pixel, i.e., y, can be written in the following form:

$$y = a + b\ln\left(\exp(\sqrt{c+dx}) - 1\right) \quad (4)$$

where a represents an additive contribution or offset in the output voltage, b represents the pixel gain, and $c = dx$ represents the effects of the leakage current in the pixel. Comparing the equation for d, to the simple model of a transistor operating in saturation, with a source–gate voltage greater than the threshold voltage

$$I_{\mathrm{DS}} = \frac{W}{2L}\mu C'_{\mathrm{ox}}(V_{\mathrm{GS}} - V_t)^2 \quad (5)$$

suggests that d is the inverse of the current that will flow through the load transistor when it is biased just above its threshold voltage by a gate–source voltage of

$$V_{\mathrm{GS}} = V_t + 2\phi_t n^{1/2}. \quad (6)$$

Since n is approximately unity and at room temperature $\phi_t \approx$ 25 mV, this is a gate–source voltage of approximately 50 mV larger than the threshold voltage of the device.

The four-parameter model (4) has been compared to the simulated response of a pixel. For this comparison, the parameters for this nonlinear model were obtained using a functional minimization regression technique [10]. The results in Fig. 5 confirm the validity of the four-parameter model over 11 decades. Comparison of the mean and standard deviation of the four parameters for 200 pixels (Table I), which were obtained after temporal noise averaging from a single column of an array, show that, as expected, the dominant source of error is the 16.6 mV variation in the additive offset parameter. However, this table also shows significant variations in the other parameters. To create a sensor that matches the contrast threshold of the human visual system, it is necessary to correct for these other variations.

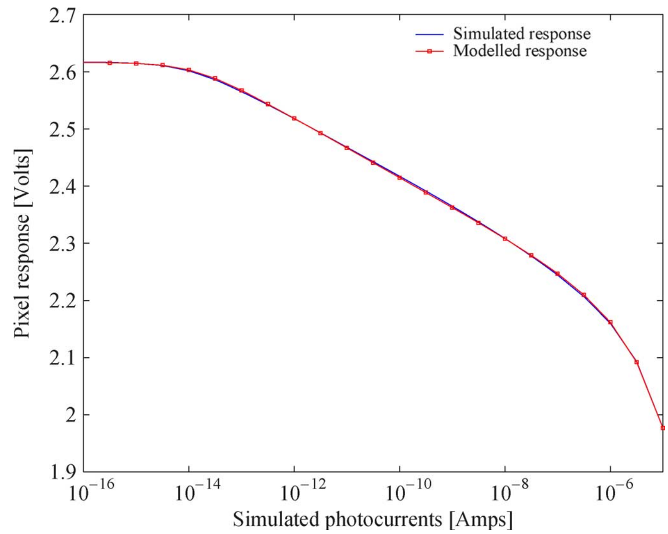

Fig. 5. Comparison between the simulated responses of a pixel and the model response after the model parameters were obtained using a regressive function minimization technique on the four-parameter model.

IV. Parameter Estimation

Using the parameter values obtained by function minimization, it is possible to confirm the validity of the four-parameter model. However, function minimization is too complex to be used to characterize pixels to compensate for the FPN. A simpler procedure is therefore required to determine the parameters of each pixel. One approach to simplifying parameter estimation is based upon exploiting the fact that the pixel can be characterized using calibration currents that ensure that the load transistor is biased into one of three different regions of the complex response shown in Fig. 2.

First, assume that the current flowing through the load transistor is significantly less than the current that will flow through this device when it is biased just above its threshold voltage. In this situation, dx is less than unity. Similarly, the current flowing through a device biased near its threshold voltage is much larger than the leakage current through the pixel, and hence, c is much less than unity. Under these conditions

$$\exp(\sqrt{c+dx}) \approx 1 + (\sqrt{c+dx})$$

and therefore, (4) can be rewritten as

$$y = a + \frac{b}{2}\ln(c+dx). \quad (7)$$

As expected, the new four-parameter model reduces to the simpler three-parameter model proposed by Joseph and Collins in the low current conditions that ensures that the load transistor is operating in weak inversion [10]. This model can be further simplified by assuming that the current in the load transistor is small enough to ensure that the load transistor is operating in weak inversion and the contribution of the leakage current is

TABLE I
CHARACTERISTICS OF THE PARAMETERS EXTRACTED FROM REAL DATA OF 200 PIXELS

Parameter	**a**$(Volts)$	**b**$(Volts/Neper)$	**c**	**d**$(Amps^{-1})$
Mean	2.2424×10^{0}	-4.0028×10^{-2}	8.4839×10^{-8}	2.6477×10^{6}
Standard deviation	1.6623×10^{-2}	$+1.9048 \times 10^{-4}$	1.0352×10^{-8}	2.0734×10^{5}

negligible. The model for the response of the pixel then further simplifies to

$$y = a + \frac{b}{2}\ln(dx).$$

Under these conditions, the pixel output voltage is proportional to the logarithm of the current in the load transistor. If the responses y_1 and y_2 of the pixel at two currents x_1 and x_2 in this operating region are known, then the gain parameter can be determined using the following equation:

$$b = \frac{2(y_1 - y_2)}{\ln(x_1/x_2)}. \tag{8}$$

To determine the next parameter, consider the situation when the current through the load transistor is large enough so that dx is greater than 1; then, the effects of the leakage current will be negligible, and

$$\exp(\sqrt{c + dx}) - 1 \approx \exp(\sqrt{dx})$$

which means that the pixel output will be

$$y = a + b\sqrt{dx}.$$

As expected, in this high current condition, the output voltage is proportional to the square root of the current flowing through the pixel. More importantly, it is then possible to determine the value of parameter d from the value of b (8) and the responses of the pixel to two high currents x_3 and x_4, i.e.,

$$d = \left(\frac{y_3 - y_4}{b(\sqrt{x_3} - \sqrt{x_4})}\right)^2$$

where y_3 and y_4 are the responses of the pixel to currents x_3 and x_4, respectively. Once the values of b and d are known, it is then possible to determine the value of parameter a from (7) using

$$a = y_1 - \frac{b}{2}\ln(dx_1).$$

The value of the final parameter can be determined from the response of the pixel when only the leakage current flows through the load transistor. This is the dark response, and in this operating condition, $c > dx$; therefore

$$y = a + \frac{b}{2}\ln(c).$$

The value of parameter c can then be determined from the response of the pixel under these conditions, i.e., y_5, using the following equation:

$$c = \exp\left[2(y_5 - a)/b\right].$$

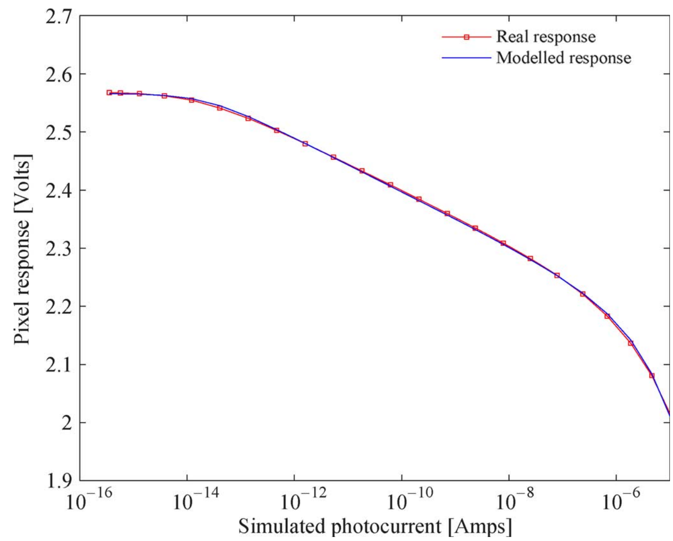

Fig. 6. Comparison between the model and the measured response of a pixel.

Thus, using the response of the pixel to five specific currents, it is possible to estimate the four parameters required to model the pixel.

Results such as those shown in Fig. 6 show that this simpler parameter extraction procedure can be effectively used to determine the parameters needed to model the response of a real pixel. In principle, the output from each pixel could be corrected for variations in all four parameters. However, the sensitivity of each pixel is degraded when the leakage current becomes significant. The pixel should therefore always be operated in the regime in which the leakage current is negligible and pixel performance is truly logarithmic. A simple procedure can then be described to correct FPN in an image.

V. FPN CORRECTION

When the load transistor in the pixel is operating in weak inversion and the leakage current is negligible, the response of the pixel can be modeled using the simple two-parameter model, i.e.,

$$y = a + \frac{b}{2}\ln(dx).$$

Under these operating conditions, the output from each pixel can be corrected to compensate for variations in both the offset a and the gain b using the pixel responses y_1 and y_2 at two different currents x_1 and x_2 using the following equation:

$$y_{\mathrm{corr}} = \frac{y - y_1}{y_1 - y_2} = \frac{(\ln x - \ln x_1)}{\ln(x_1/x_2)}.$$

The right-hand side of this equation shows that the corrected output y_{corr} is proportional to the logarithm of the photocurrent scaled by a constant $[\ln(x_1/x_2)]^{-1}$ and shifted by

$-\ln x_1/[\ln(x_1/x_2)]$. Both the scaling factor and the shift are determined only by the two currents at which the pixel response was measured. The corrected output y_{corr} from all pixels will therefore be the same for any current x. Thus, using the measured responses of the pixel at two input currents, it is possible to correct for variations in both offset and gain. A key factor in determining the final quality of FPN correction is the selection of these two calibration currents x_1 and x_2.

To reduce the effects of quantization and temporal noise when calculating y_{corr}, the two calibration currents should be chosen to ensure that y_1 and y_2 are as different as possible. However, the two-parameter model is based upon the assumption that the load transistor is operating in weak inversion and that the leakage current is negligible. This means that the smaller calibration current must be significantly larger than the leakage current. Similarly, the larger calibration current should not be so large that it drives the load transistor out of weak inversion. The values of parameter d in Table I suggest that the larger current must be significantly smaller than 500 nA. However, it is difficult to determine a simple relationship between the two calibration currents and the quality of FPN correction.

The relationship between the two calibration currents and the quality of a corrected image has therefore been empirically investigated. For this investigation, the output from each pixel has been quantized to represent the effects of the analog-to-digital converter required to create the digital signal that can be corrected. The sensitivity of the typical pixel (Fig. 1) in the array when the load transistor is operating in weak inversion is 46 mV per decade change in input current. This means that a 1% change in the current corresponds to a change of approximately 0.2 mV in the output voltage. The digitization of an analog signal introduces a maximum error, which is equal to one half of the change equivalent to at least a significant bit in the resulting digital output. This suggests that it should be possible to maintain a contrast threshold of 1% if the response of each pixel is represented as an integer multiple of 0.4 mV.

In this investigation, the performance of the pixels when the pixel responses were digitized was therefore tested by representing all the pixel responses as integer multiples of 0.4 mV. Results such as those in Fig. 7 show that it is possible to correct the outputs of logarithmic pixels so that they have a contrast threshold of better than 2% for input currents between 2×10^{-13} and 50×10^{-8} A. These results therefore show that by using a simple procedure, it is possible to correct the responses of pixels to achieve a contrast threshold of better than 2%, which is comparable to that of the human visual system, over a dynamic range of more than five decades. For any application that requires a higher dynamic range, there are two possible approaches. The most direct approach is to correct for variations in parameter d. Alternatively, reducing the leakage current will extend the dynamic range over which the simple FPN procedure works effectively and will increase the pixel sensitivity in low light.

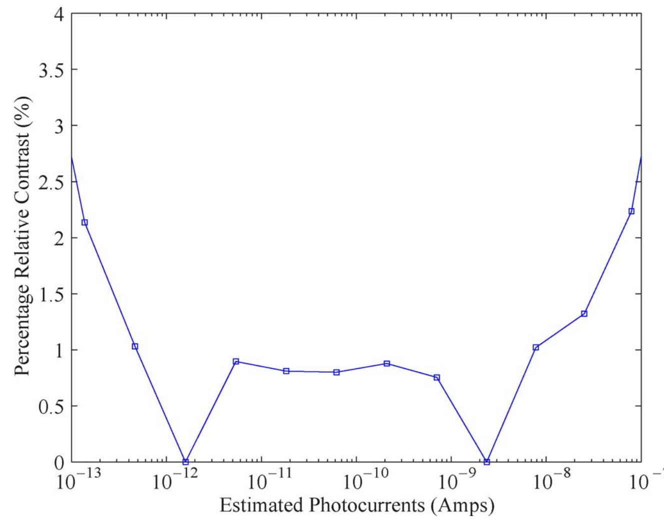

Fig. 7. Contrast threshold of the pixel array after all data have been represented as integer multiples of 0.4 mV to represent the effects of an analog-to-digital converter.

VI. Conclusion

The continuously available output and very high dynamic range of logarithmic pixels make them attractive for a range of applications. Recently, it has been proposed that the photodiode used in most pixels should be replaced by a phototransistor to increase the current flowing through the pixel and, hence, increase the output voltage swing from the pixel in the brighter regions of the scene. This has the advantage that it reduces the susceptibility of the pixel to temporal noise and electrical interference. However, like all pixels, the sensitivity of an array of these new pixels is limited by FPN, which is caused by variations between nominally identical devices in different pixels. Results from an array of pixels, which was presented in Section II, show that even after correcting the dominant contribution to FPN, the contrast threshold of this type of pixel is limited. In particular, a 2% change in photocurrent can only be reliably detected over an input range of two decades. A more sophisticated form of FPN correction is therefore required to match the contrast threshold of the human visual system. As a first stage in developing a better FPN correction procedure, a compact model of the complex nonlinear response of each pixel has been developed. Using function minimization to determine the value of the four parameters in the nonlinear model, it is possible to show that the model fits the response of a pixel over 11 decades, covering three different modes of behavior. Furthermore, the analysis of the parameters of this model for 200 pixels shows that significant variations occur in all four parameters. A simple procedure to extract the four parameters of the model has therefore been developed, which shows that the four parameters for the model can be obtained from the response of a pixel to five currents. Finally, in Section V, a simple procedure based upon the response of each pixel to only two currents is sufficient to allow the output of each pixel to be corrected to remove FPN to achieve a contrast threshold comparable to the human visual system over five decades. This simple procedure is therefore adequate for most applications. The remaining challenge when designing logarithmic pixels is to ensure that pixel sensitivity is not limited by circuit temporal noise.

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