An Electronic-Calibration Scheme for Logarithmic CMOS Pixels

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***Abstract*—Logarithmic cameras have the wide dynamic range required to image natural scenes and encode the important contrast information within the scene. However, the images from these cameras are severely degraded by a fixed pattern noise (FPN). Previous attempts to improve the quality of the images from these cameras by removing an additive FPN have led to disappointing results. Using an existing model for the response of logarithmic pixels, it is concluded that the residual FPN in these images is caused by gain variations between pixels. In order to reduce the effects of these variations, a readout circuit, which is based upon a differential amplifier, has been used. However, even with this readout circuit, high-quality images will only be obtained if each image is corrected to remove the effects of both gain and offset variations. Measurement results are presented that show that the quality of the output from the logarithmic pixels is significantly improved if an electronic-calibration procedure is used to correct for both types of variations. In fact, with this procedure, the contrast sensitivity of the logarithmic pixels becomes comparable to that of the human eye over five decades of illumination intensity.**

***Index Terms*—CMOS imagers, contrast threshold, electronic calibration, fixed pattern noise (FPN), gain correction, logarithmic pixels, model-based calibration, subthreshold operation, wide dynamic-range pixels.**

I. Introduction

The human visual system has the ability to interpret scenes with illuminations varying from 10^{-3} lux to those as bright as 10^5 lux and with a contrast sensitivity of 1%–2% at high illuminations [1]. Typical real-world scenes have intrascene dynamic ranges that might extend five orders of magnitude, from 1 lux in shadows to 10^5 lux in bright sunlight. Unfortunately, charged coupled devices (CCD) and CMOS active pixel sensors (APS), which currently dominate the image-sensor market, have a dynamic range of less than three orders of magnitude. Consequently, when imaging a wide dynamic-range natural scene, the response of these sensors saturates in some regions of the scene. Several techniques including dual or multi-sampling stepped reset voltages and threshold comparison have been proposed to extend the dynamic range of these sensors [2]–[4]. Most of these techniques have complex pixel circuits leading to a reduced fill factor and, hence, low sensitivity. In addition, any linear sensor requires a large number of bits to encompass a wide dynamic range.

Logarithmic image sensors based upon the subthreshold region of the operation of a MOS are capable of capturing wide dynamic-range scenes with intensity variations of more than six decades [5], [6]. In addition, these sensors provide a random addressability and use a comparatively small number of bits per pixel while retaining a fill factor comparable to that of the CMOS APS. Another potential advantage of the logarithmic pixels is that they encode the contrast information from a scene that is critical to users. However, variations between devices within different pixels cause this type of sensor to suffer from the FPN, which severely degrades the quality of the resulting image.

The dominant form of the FPN is an additive offset contribution whose impact can be reduced using one of a variety of different techniques described in Section II. In Section III, the disappointing results obtained using these techniques are explained using a model for the response of these pixels [7]. This model suggests that the variations between the gains of pixels should be taken into account when correcting the FPN. A procedure to extract the gain and offset parameters of each pixel is, therefore, also proposed in Section III. A new pixel circuit is then described in Section IV, which has been designed both to reduce the effects of the gain variations and to allow the response of each pixel to be calibrated for different operating conditions. Finally, in Section V, results are presented that show the relative importance of the various types of variations between pixels, and that, it is possible to correct the FPN to create a sensor with a contrast sensitivity that is comparable to that of the human eye over an input range of five decades.

II. Previous Work

A typical logarithmic pixel is shown in Fig. 1. It contains a photodiode to convert an input light to a photocurrent. This photocurrent is converted to a voltage, which is proportional to the logarithm of the photocurrent by the load transistor M1 operating in its subthreshold region. This output voltage can be sensed by selectively connecting a transistor M2 to a shared output line using a row select switch M3. When it is connected to the shared output-line transistor, M2 forms a source follower (SF) with a constant current source, not shown in the figure.

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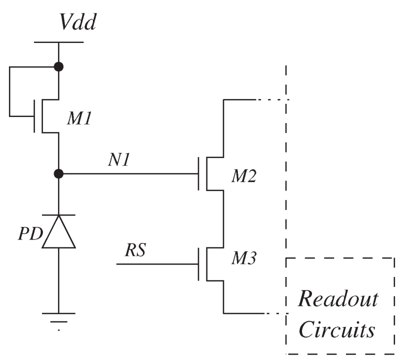

Fig. 1. Logarithmic pixel with a simple SF readout circuit.

If the pixel circuit is part of a two-dimensional array, another selectable SF readout circuit is required to connect this shared line to the single output.

By considering the characteristics of the devices within a logarithmic pixel, Joseph and Collins have shown that the response of a logarithmic pixel y to a photocurrent x can be written in the form [7]

$$y = a + b\ln(c + x). \tag{1}$$

Here, a is an additive offset, which depends on the threshold voltages of the various transistors as well as the offsets added in the readout chain. The parameter b represents the gain of the pixel, which depends on the load transistor and the gains of the readout circuits. Finally, parameter c represents the effects of leakage currents within the pixel. The most important effect of this third parameter is to limit the sensitivity of each pixel at low illumination levels. At higher photocurrents, the effects of this term are negligible, and the pixel output is proportional to the logarithm of the photocurrent.

The major contribution to the FPN arises from the variations between the threshold voltages of the various transistors in the different pixels. This has led to the development of various techniques to reduce the effects of the resulting additive FPN. The ideal approach to tackle this problem is to change each pixel so that their array has a more uniform response. One method of achieving this that has been investigated is the use of a hot-electron injection within each pixel to alter the threshold voltage of the load transistor [8]. This technique has been successfully applied to a small number of pixels. However, even when high-stressing voltages are employed to increase the number of available hot electrons, this proves to be a time-consuming process. In an alternative approach, Loose and co-workers [9] have used a feedback to adjust the gate voltage of each load transistor. This technique has the advantage that it avoids the slow process of adjusting the threshold voltage of the load transistor, and it can accommodate changes due to the temperature dependence of the threshold voltage of the various transistors. However, the additional circuitry required to use this technique increases the pixel area and reduces the fill factor. As a result, the reported pixel has a fill factor of 30% in a pixel of dimensions 24×24 μm.

The difficulties involved in creating pixels with more uniform responses have led to the development of techniques, in which each image is corrected after it has been acquired. In the case of correcting for the FPN, this means that the response of each pixel to a uniform input has to be measured. The most direct method of obtaining the data required to correct for the additive FPN is to image a uniform scene [10]–[12]. Unfortunately, the temperature dependence of the transistor threshold voltages means that this procedure must be undertaken whenever the operating temperature of the camera changes. This is inconvenient in a laboratory environment, and it might be impossible to implement in many applications. To avoid the need to provide a uniform input scene, an alternative scheme was proposed by Kavadias and co-workers [5]. In this scheme, the offset of each pixel is determined by forcing a large constant current through the load transistor using a MOSFET acting as a constant current source in parallel with the photodiode. Using the resulting data to correct for the offset variations leads to a residual FPN that is 2.5% rms of the dynamic range of the data. Since the dynamic range of the data is six decades, this corresponds to 15% of one decade. In a similar scheme, Lai and co-workers electronically generate the equivalent of a negligible photocurrent in each pixel to create a reference level for the FPN correction [13]. Although this significantly reduces the variations between pixels, the residual FPN after correction corresponds to a contrast change of more than 30%. Both of these schemes lead to disappointing results when compared to the human visual system.

III. Pixel Calibration

The high residual FPN in the images captured using an offset correction with bright- or dark-reference scenes can be understood by considering the model of the response of a logarithmic pixel. At higher photocurrents, when the bias term c is negligible, the response of the photocurrent can be accurately approximated by

$$y = a + b\ln(x). \tag{2}$$

Forcing a constant current x_c through the load transistor of a pixel will lead to a response y_c. Subtracting this from the pixel response at an unknown current, x_{in} will then lead to a corrected output y_{corr}

$$y_{\text{corr}} = y_{\text{in}} - y_c = b\ln(x_{\text{in}}/x_c). \tag{3}$$

When the input scene is uniform, the current through all the pixels will be the same. However, the corrected output will only be the same if all the pixels have the same gain. Unfortunately, the variations between the devices within each pixel lead to gain variations.

In order to quantify the effects of the gain variations, consider a pixel whose gain b differs from the mean pixel gain $\overline{b}$ by Δb. With the offset correction, this gain variation will lead to an error in the corrected output of

$$\Delta y_{\text{corr}} = \Delta b\ln(x_{\text{in}}/x_c). \tag{4}$$

The equivalent percentage error in the apparent contrast of this pixel compared to an average pixel K is then given by

$$K = \frac{100\Delta b}{\bar{b}} \ln(x_{\text{in}}/x_c). \tag{5}$$

This equation shows that since the contrast error depends on the ratio of the photocurrent to a calibration current, the effects of any gain variations can be limited using a typical photocurrent as the calibration current. Unfortunately, both Kavadias and co-workers [5] and Lai and co-workers [13] used typical calibration currents to generate the data for the FPN correction. Since these typical currents can be as much as six orders of the magnitude, which are larger or smaller than a photocurrent, these techniques can only match the contrast sensitivity of the eye if the gain variations between pixels are less than 0.07%. It is very unlikely, if not impossible that this level of matching will be achieved in the small area available for each pixel. This suggests that high-quality images will only be achieved over a wide dynamic range by correcting for both offset and gain variations.

When demonstrating the validity of the three-parameter model, Joseph and Collins [7] used data from 24 uniform images at different illumination levels and an iterative parameter-extraction technique. It is impractical to use this technique to obtain the data required to correct an image for the FPN. However, there are only three parameters in the model, and these parameters can therefore be estimated using three data points per pixel. Furthermore, one of the parameters simply determines the minimum illumination at which the pixel gives a logarithmic response. Only two data points per pixel are therefore required to correct for variations in both offset and gain. In particular, if the response of each pixel is measured at two currents that are large enough so that the contribution of c to the response of the pixel is negligible, then the gain and offset parameters for the pixel can be calculated using

$$b = \frac{y_1 - y_2}{\ln(x_1/x_2)} \tag{6}$$

$$a = y_1 - b\ln(x_1) \tag{7}$$

where y_1 is the pixel response at a reference current x_1, and y_2 is its response to another current x_2.

These equations can be used to determine the statistics for the variations between pixels for a particular circuit design. The data from each pixel could then be used to correct each image for the offset and gain variations. However, a more direct method of performing the offset and gain correction is simply to use the responses of the pixel at the two reference currents. In particular, substituting (6) and (7) into (2) gives

$$y = y_1 - b\ln(x_1) + \frac{y_1 - y_2}{\ln(x_1/x_2)} \ln x.$$

This can be rearranged to give a corrected output y_{corr}

$$y_{\text{corr}} = \ln\frac{x}{x_1} = \frac{y - y_1}{y_1 - y_2} \ln\left(\frac{x_1}{x_2}\right) \tag{8}$$

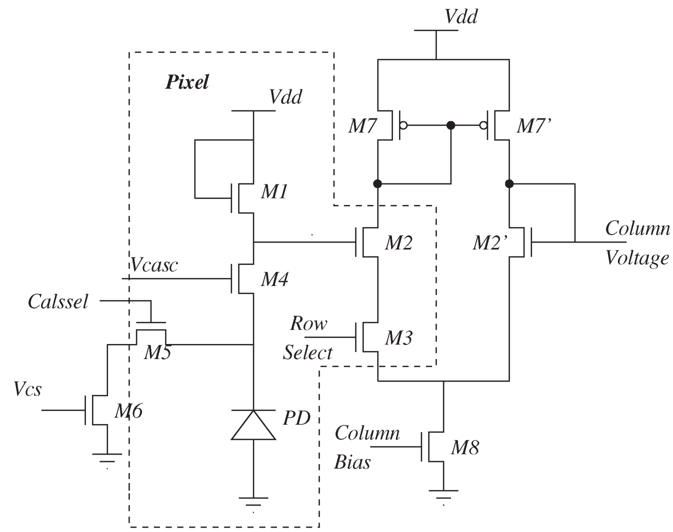

Fig. 2. Logarithmic pixel with one stage of a DIFF AMP readout and circuit for electronic calibration.

which shows that the ratio of the two reference currents is a common multiplication factor, while one of the reference currents becomes the scaling factor for the logarithmic response. The pixel output can therefore be corrected to compensate for the offset and gain variations without any knowledge of the actual currents used to obtain the calibration data needed.

IV. Circuit Implementation

A. Pixel Circuit

The two data points per pixel needed to either determine the offset and gain of each pixel or compensate for the offset and gain variations can be obtained using uniform scenes at two different illumination levels or one scene at different aperture settings. However, it is more convenient to obtain the data electronically. Another advantage of an electronic calibration is that the reference currents used to obtain the data can be selected by the circuit designer to ensure the best possible results.

The logarithmic pixel, which is shown in Fig. 2, has been designed to be calibrated electronically if necessary. In this circuit transistor, M1 is the load device that converts the photocurrent to a voltage. Transistor M4 was included in the pixel to limit the voltage across the photodiode, while transistor M5 acts as a switch. This switch can be used during the calibration to selectively connect the pixel to the drain of transistor M6, which acts as the voltage-controlled current source. In order to save an area and to ensure uniformity of the current flowing in different pixels, this device is shared by all the pixels in the same column.

In a conventional logarithmic pixel, which is shown in Fig. 1, an SF is used as the readout circuit. The problem with this simple circuit is that it has a relatively low gain. This can be a problem for the logarithmic pixels that typically have a sensitivity of less than 70 mV/decade. In order to minimize any attenuation of the resulting small signals by the readout circuit, the SF has been replaced by a differential amplifier (DIFF AMP) [14]. In this circuit, the two pMOS transistors form a current mirror, and the transistor M8 acts as a constant current source. Assuming that the ON-resistance of the transistor M3 is zero, and that the current mirror is ideal, then the gate-source voltages of the transistors M2 and M2′ will be equal. The circuit then acts as a voltage follower with a higher gain than the alternative SF circuit. In addition, since only the transistors M2 and M3 are actually within each pixel, this increased gain can be achieved without increasing either the area of each pixel or their variability. When the pixel circuit is connected into a two-dimensional array, a second DIFF AMP is used to selectively connect each column output to the global output pin.

B. Calibration Circuit

In addition to the readout circuits, every pixel in a column shares a common calibration current source. Although the FPN correction takes into account the variations in the complete readout chain, these shared current sources introduce a source of the FPN between the different columns of pixels. To allow the variability of these current sources to be quantified, and to allow for correction for this type of FPN if required, the pixel array is designed so that the current sources can be selectively connected to a reference pixel circuit. This reference circuit is the same as a logarithmic pixel except that it does not have a photodiode.

To characterize the variability of the current source, a constant calibration voltage is applied to the gates of all current sources. Each of these current sources is then connected to the reference circuit in turn, and the response of this circuit is measured. The response of the reference circuit to the different current sources gives a measure of variability of these sources.

To complete the calibration circuit, the calibration select switch of every pixel is activated by an "AND" combination of the row select and the calibration signals. The switch to feed the calibration current source to the reference circuit is activated by an "AND" combination of the column select and calibration-enable signals with a row-select signal for the last row. This ensures that at any particular time, a current source can only supply current to either one pixel in the column or the reference circuit.

C. Test Chip

An integrated circuit has been designed and manufactured that contains an array of 200 $\times$ 100 electronically calibratable pixels with the various column circuits as described above. This circuit was fabricated in a 0.35-μm standard CMOS process from Austria Microsystems. Each pixel has an area of 10 by 10 μm with a fill factor of 49%. In addition to the pixel array, a single large photodiode, 100 by 100 μm, was also fabricated, which was designed to have a large enough photocurrent at a typical illumination level to be measured with a picoammeter, so that the photocurrent in a pixel can be estimated accurately. Finally, to quantify the gain improvement obtained by using a DIFF AMP rather than an SF readout circuit, two small arrays of 100 $\times$ 10 pixels having either the conventional SF or DIFF AMP readout circuits were also fabricated.

TABLE I
COMPARISON OF THE STATISTICAL PARAMETERS OF THE SF AND DIFF AMP READOUTS

Parameter	Mean/SD	SF	Diff.Amp.
Offset	Mean	0.552	1.743
(V)	SD	0.017	0.018
Gain	Mean	-56.9	-66.7
(mV/decade)	SD	0.335	0.340
Bias	Mean	28.2	26.2
(fA)	SD	4.5	6.3

V. TEST RESULTS

A. Experimental Setup for Calibration of Array

All the clock and other digital signals needed to test the pixel arrays were generated using a Xilinx Spartan-3 FPGA. The analog output voltages from the pixel arrays were then digitized using an external 2MSPS 16-bit analog-to-digital converter (ADC). To reduce the temporal noise between the data points introduced by the connection between the pixel-array output and the ADC, to less than the signal corresponding to the target sensitivity of a 1% change in contrast, each data point corresponds to eight measurements from a pixel under the same operating conditions, which were averaged.

When necessary, the uniform optical scenes were generated by a combination of a DC-powered stable light source working at 12 V and 100 W and an integrating sphere of diameter 100 mm with an output port of diameter 10 mm. The intensity of the resulting uniform output beam was then altered by using neutral-density filters and by varying the input power of the light source. At each different beam intensity, the photocurrent from the large photodiode on the integrated circuit was used to determine the photocurrent through a typical pixel. The bias voltage applied to the column current sources could then be used to ensure that two typical currents were used to calibrate the pixel array.

B. Performance Comparison of Readout Circuits

To compare the performance of the pixels with the SF and DIFF AMP readout circuits, the responses of the small arrays of the two types of pixels were measured at two typical photocurrents and in the dark. The resulting three data points per pixel were then used to determine the three parameters needed to model the response of each pixel using (1). The measured mean and standard deviation of each of the three pixel parameters for the two types of pixels are tabulated in Table I. These results show that as expected, there is a significant difference in the mean offset voltage of the two designs arising from the voltage drop across the SF. In addition, there appears to be very little difference in the bias parameter in the two types of pixels. The most important difference in the mean parameter values is an increase in the pixel gain from 56.9 mV/decade with an SF to 66.7 mV/decade when a DIFF AMP readout circuit is used. This latter value is very close to the gain parameter at the pixel without a readout circuit as determined by a circuit simulation. In addition, the variability of the gains of the two types of the readout circuits are comparable. The larger gain of the DIFF AMP readout circuit means that the gain variations in these pixels will give rise to a smaller contribution to the FPN. Significantly, because only two of the transistors within the DIFF AMP circuit are within each pixel, this improvement has been achieved without increasing the area of the pixel. However, since the gain variations are approximately 0.5% of the mean pixel gain, the discussion in Section III shows that it will be impossible to obtain good-quality high-dynamic-range images without correcting for gain variations.

C. Calibration Results

To correct images for both offset and gain variations, the response of each pixel to the two different input currents needs to be measured. The two currents used to perform the FPN correction need to be chosen carefully. In particular, the procedures used to correct the image are based upon the assumption that the response of a pixel is represented by (2). Since this model assumes that the effects of the leakage currents are negligible, the smaller of the two calibration currents should be chosen to be significantly larger than the leakage current in a pixel. Since our aim is to achieve a contrast sensitivity of approximately 1%, the smaller current was set to at least 100 times the largest expected leakage current. The choice of the second calibration current is more difficult. Since the correction procedure relies upon the difference between the response of each pixel to the two input currents, it can be expected that the accuracy of the correction will be improved by using two very different input currents. However, the minimum value that can be used is fixed, and it has been pointed out previously using a simulation data [15] that the larger of the two currents must be small enough for the load transistor to remain operating in weak inversion rather than a moderate inversion. Even with a pixel model that includes the effects of the load transistor operating in either weak or moderate inversion, it is difficult to quantify the limit that this places on the maximum current that should be used to calibrate each pixel [15]. The effect of varying the larger of the two calibration currents has therefore been investigated empirically.

To quantify the effects of the different choices of the calibration current, the response of 200 pixels in a column was measured over a wide range of different currents generated by the current source at the end of the column. One of these responses corresponding to a photocurrent significantly above the leakage current was then chosen as one of the calibration points. The impact of various different choices of the second calibration current on the level of the FPN is shown in Fig. 3. These results show that for all the combinations of the calibration currents, the quality of the final image is degraded at low currents when the leakage current becomes significant, and at high currents when the load transistor operates in a moderate inversion. More importantly, these results show that when appropriate calibration currents are selected, the FPN is reduced to less than the equivalent of a 2% change in contrast for currents corresponding to six decades of the light intensity. This shows that by performing the offset and gain correction, it should be possible to create a sensor that matches the dynamic range and contract sensitivity of the human eye.

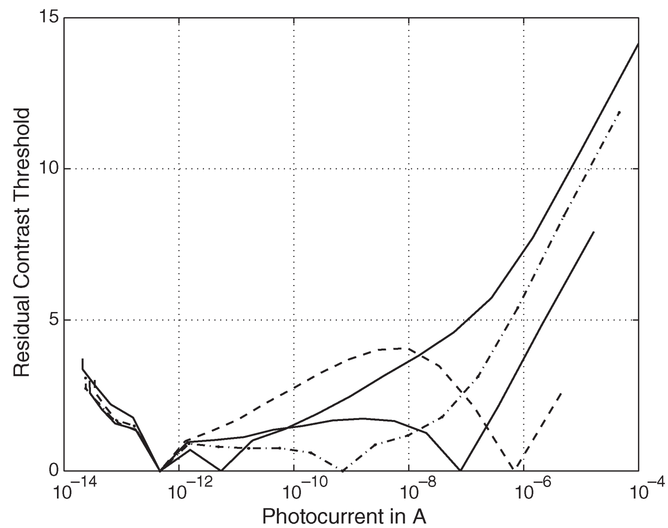

Fig. 3. Residual FPN expressed as a contrast threshold % at different photocurrents with one calibration current fixed, and a second calibration current that is 1, 3, 5.5, and 6 orders of magnitude larger than the first.

D. Optical Stimulation

The one source of variability between the pixels that will not be corrected using the responses of pixels to the currents flowing through the voltage-controlled current sources in each column are variations in the responses of the photodiodes. To quantify the impact of these uncorrected variations, the response of a column of 200 pixels to varying levels of a uniform illumination were measured. The resulting data was then corrected using the responses of the same pixels to the two similar currents flowing through the voltage-controlled current sources. The results in Fig. 4 show that after the correction with this data, the residual FPN corresponds to a contrast change of less than 2%. A comparison with the corresponding results obtained from the responses of the pixel to the same currents flowing through the voltage-controlled current sources, which are also shown in Fig. 4, suggests that the variations between the photodiodes are equivalent to a contrast of approximately 1%. Variations between photodiodes are therefore expected to make a significant but not dominant contribution to the residual FPN remaining once an image has been corrected to compensate for variations in the gain and offset of pixels.

E. Uniformity of Calibration Current Sources

Ideally, a single current source would be used to calibrate all the pixels in an array. However, the relatively long time required for the response of each pixel to settle would make this a lengthy process. To reduce the time needed to calibrate the pixels, a voltage-controlled current source has been included at the end of each column. Although this will reduce the time needed to gather the data from each pixel, using the different current sources introduces a source of nonuniformity that could cause the FPN between columns rather than between pixels.

To study the uniformity of the column current sources, a constant gate voltage was applied to the current sources, and their outputs were selectively connected to the reference pixel.

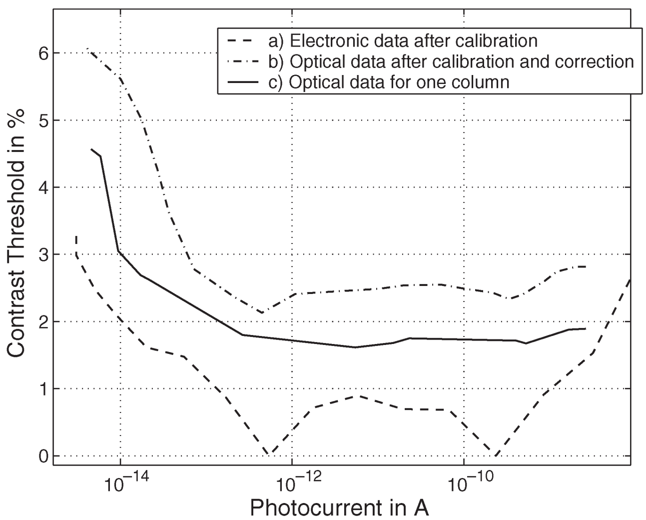

Fig. 4. Residual FPN at different illumination levels. Curve (c) shows the residual FPN after the correction of the responses of a column of the pixels stimulated by a uniform scene. For comparison, curve (a) shows the residual FPN in the same pixels stimulated electronically and corrected using the same data as the responses to the optical stimulus. Curve (b) shows the residual FPN in an array of sensors after the calibration and correction for calibration sources.

A marked variation in the reference pixel's response was observed when it was connected to the different column current sources. From the reference pixel's response, it was found that the calibration currents generated by these sources had a variation of approximately 8%. This variation is too large to be ignored. A procedure is therefore required to compensate for the variations between the calibration currents in each column of pixels.

In order to remove the effects of the offset and gain variations, the response of each pixel in a column and the reference pixel must be measured at two input currents. If the response of a particular pixel and the reference pixel at one input current are y_1 and $y_{1\mathrm{r}}$, while their responses at a second current are y_2 and $y_{2\mathrm{r}}$, then a subsequent output from this pixel y_{outr} can be transformed to the equivalent output from the reference pixel y_{outr} using the equation

$$y_{\mathrm{outr}} = y_{1\mathrm{r}} - \frac{y_{1\mathrm{r}} - y_{2\mathrm{r}}}{y_1 - y_2} \cdot (y_1 - y_{\mathrm{out}}). \tag{9}$$

This expression then generates an image that is equivalent to the one that would be obtained if the reference pixel occupied each position in the two-dimensional array. Ideally, this means that there will be no FPN in the final output image.

A worst-case contrast threshold of 2.5% was obtained for about five decades of illumination for the complete array after the calibration of pixels and correction for the calibration sources, as shown in Fig. 4. The residual FPN for the whole array after the correction is higher than that of a single column by about 1%. The source of this error lies in the correction procedure for the calibration currents, which has an accuracy of about 1%. To make the calibration procedure easier and more accurate, larger current sources will be used in any future design to minimize the effects of this source of variability.

TABLE II
CHIP SPECIFICATIONS

Technology	Austrian Microsystems 0.35μ
Array	200×100
Pixel	5-Transistor
Size	$10\mu\times10\mu$
Fill Factor	49%
Readout	2 stage differential
Dynamic Range	6 decades
Average FPN	3% contrast threshold

VI. CONCLUSION

Logarithmic pixel arrays can image wide dynamic-range scenes and encode important contrast information. However, the images from these arrays are degraded by the FPN. Previous approaches to reduce this FPN have concentrated on compensating for an additive contribution to the FPN. However, using a three-parameter model of the logarithmic pixel described previously, it can be established that the variations between the gains of individual pixels will limit the effectiveness of these approaches when imaging a wide dynamic-range scene.

A new type of readout circuit has been designed and tested that reduces the significance of the gain variations (see Table II). However, high-quality images will still only be obtained if each image is corrected for both gain and offset variations. An electronic-calibration scheme involving the use of the calibration current sources in every column of an array has been investigated. Measurement results have been presented, which show that correcting for both types of variations will significantly improve the quality of an output image. In particular, despite the 1% variations between the responses of the photodiodes that remain uncorrected by this procedure, it will be possible to create images with a contrast sensitivity comparable to that of the eye over five decades of an input illumination intensity. Further work is now required to improve the design of the camera in order to simplify the FPN correction procedure and reduce the effects of a temporal noise. In particular, a larger voltage-controlled calibration current sources are needed to reduce their variability, and an ADC should be integrated onto the same substrate as the pixel array to reduce the temporal noise.

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