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A Linear-Response, High-Dynamic Range CMOS Imager Suitable for Spectroscopic Applications

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I. Introduction

Linear charge-coupled devices (CCD's) and photodiode arrays are commonly used sensors in the conventional UV/VIS spectrometers. Typical requirements of these sensors are linearity for spectrum calibration and high sensitivity for weak input light. The systems are usually bulky and fragile. A conventional spectrometer as shown in Fig.1 is a precision scientific instrument. It is widely used in sample analysis, light calibration and other spectroscopy applications. A typical spectrometer consists of a sample chamber, a light source with lenses, an entrance slit, several mirrors to fold the light path, a reflective diffraction grating, blocking filters to eliminate high-order diffraction, an exit slit and a beam collimator. A calibrated detector is often used as a reference of measured signals to get absolute power density reading at each wavelength.

With the development of CMOS active pixel image sensors, more circuits can be integrated on chip. Thus, most functions of the board can be moved onto chip. Furthermore, these circuits can also be designed to enhance the photon-sensing capability of the pixel arrays. More circuits integration also results in reduced size of the spectrometer, lower cost and ease of use. These miniature spectrometers have enabled many new applications in different areas [1].

Current research in very high dynamic range sensors is mostly concentrated in 3 kinds of architectures: compression at bright scene, adaptive integration time, and pulsed output with reset feedback. Compression sensors, such as logarithmic sensors and discrete potential barrier sensors, cannot provide linear response which is required by spectrometer. The linearity cannot be reconstructed because the information has been lost. Adaptive integration time sensors have different integration time for different portions of the sensor. Different portions of the sensor can be turned on or off at different time to form a relayed readout. However, this creates a dark current offset mismatch problem due to the drastically different integration time and requires significant offline signal processing to reduce this mismatch.

The pulsed output sensor [2] has linear response, high dynamic range and simple implementation. With controllable high dynamic range, linear response and inherent digital output, pulsed mode sensor is more suitable for spectroscopic applications.

Most of the pulsed output sensors presented in the literature use a light-to-frequency method [2][3]. Although

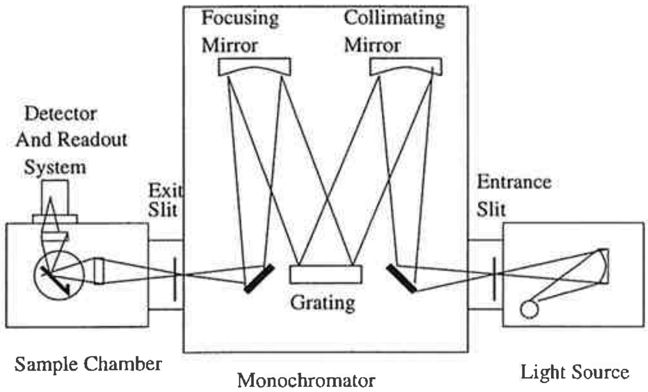

Fig. 1. Conventional spectrometer for sample analysis.

this approach is simple to implement and can work reliably, there are a few limitations. First, the counter resolution is very low for small input signals, i.e. low-light conditions. Also, Correlated Double Sampling (CDS) is not implemented to reduce reset noise.

For spectroscopic applications, linear sensors are most commonly used. Thus, more circuits can be built into the pixel. In this paper, design and simulation of a 1-D sensor array with very high dynamic range and linear response is presented. In our proposed design, pulsed output (coarse) is combined with regular A/D output (fine output) to guarantee high-resolution output at any point of the light curve. A second architecture is also proposed to use a high-speed accumulator to replace the counter. By using this mixed signal architecture at the pixel level, we can shift the complexity in the analog circuits to digital circuits to avoid many noise, matching and special process problems.

II. Sensor Chip Design

Sensor chip for the spectrometer includes the design of pixel, the readout circuits and the optics. All three components are tailored to fit spectroscopic applications

A. Photo-Sensitive Element Design

Since the total power of incident light is spread over the wavelength region of 380nm to 700nm, the light intensity at each wavelength is very small. Thus, a high-sensitivity detector is needed to ensure enough signal-to-noise ratio. With controlled light of medium-to-high light level, silicon photodiode can be used. In most of the spectrometers with

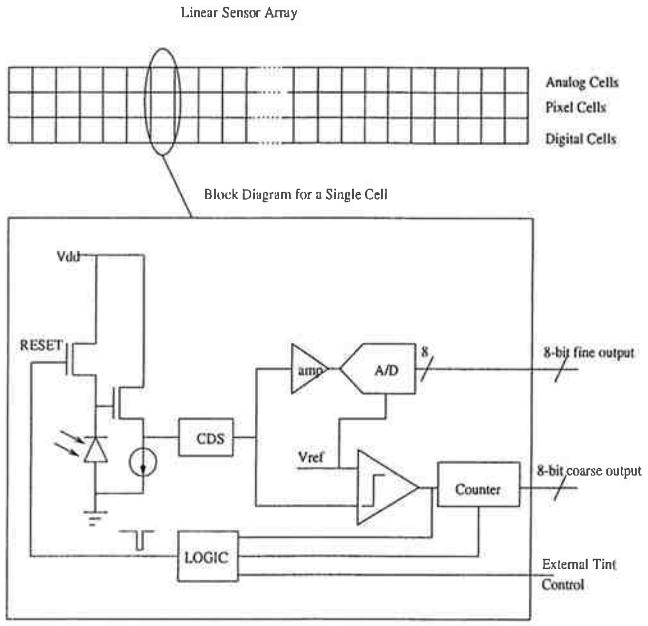

Fig. 2. Architecture of a folded output high-dynamic range sensor with linear response.

light sources, CCD's (charged-coupled devices) and photodiode arrays are widely used. However, at low light levels, detector with enhanced sensitivity has been used, such as photomultiplier tube (PMT).

Using standard CMOS processes, the only way to increase total sensitivity is to increase the area of the photodiode. The photodiode in this chip has an area of 30um × 500um in 1um process. Increasing the absolute photodiode area increases the absolute amount of photo charge collected by one pixel. However, this will also increase the capacitance of the junction and in turn reduce the charge-to-voltage conversion gain. Increasing integration time increases both dark current and signal. Large dynamic range also needs to be guaranteed to prevent blooming. For spectrometer automatic calibration and alignment tolerance, a large photodiode can be split into multiple photodiodes. However, the total dark current will increase and total sensitivity will decrease.

Several other techniques can be employed to achieve higher sensitivity, such as avalanche photodiode array and optic fiber-coupled light input.

B. Linear Sensor Chip Design

Conventional image sensors only collect photo charge over one integration cycle for each output. Thus, the requirement for this single cycle is very high. Not only does the pixel well capacity have to meet specifications, the signal processing circuits including amplifier and analog-to-digital conversion also have to meet certain requirements to match the output of the pixel. 12-16 bit ADC is typically used in many CCD frontends in order to achieve high dynamic range. For the linear CMOS imager presented here, a mixed signal folded output technique is adopted to achieve the necessary dynamic range and linear response.

In Fig.2, one readout cycle consists of multiple integration cycles. The maximum charge in the pixel can be kept well below saturation voltage, thus the output linearity is ensured. V_{ref} is adjustable externally. After CDS stage, the output of the pixel goes into a switch capacitor comparator with V_{ref} adjustable at about half of V_{sat}. Once the pixel output reaches V_{ref}, it triggers the pixel reset control circuit in the reset feedback loop. Then, the pixel is reset and a new integration cycle for that particular pixel starts again. In the mean time, the output of the comparator also advances the counter by one. At the end of light input (controlled by an external integration time control signal), the residual analog values of all the pixels are converted by the low-resolution A/D converter with full range equals to V_{ref}, and the results are combined with the counter outputs in the digital signal processing circuits.

This design effectively folds the output curve into small linear pieces which are combined at the last output stage with some additional digital and auto calibration circuitry. High-resolution output can be obtained at any time interval controlled externally. Using an 8-bit counter and 8-bit A/D provides a full 16-bit output sensor. The design target for dark current is less than 400pA/cm2, and sensitivity is 1V/lux-second, similar as that of CCD's, and the dynamic range of linear response is over 90dB. Multiple rows can be used for pixel averaging and automatic calibration for optics misalignment.

The folded design also provides a complexity leverage between the analog circuits and digital circuits. The traditional circuit design barrier at ADC is minimized. A low-resolution and low-speed ADC can be used to satisfy the requirement for a high-resolution sensor. However, digital circuits may occupy more area. A 8-bit counter consist of at least 40 transistors although most of them can be of minimum sizes. Capacitor matching in ADC requires linear capacitors which can occupy a large area if a double poly process is not used.

The amplifiers used in the comparator and CDS block are slightly modified folded cascode op amps to provide high bandwidth and rail-to-rail swing. A simple single-slope ADC is implemented to minimize area, and its performance easily meets the requirement.

The output errors of pulsed output image sensor arise from several sources: Dark current offset, reset noise and reset feedback loop delay. Since all pixels have the same integration time, the dark current mismatch is assumed to be small, and the dark current offset can be compensated by using a single dark line clamp. Reset noise is reduced by correlated double sampling right after the pixel.

In Fig.3, t_{update} is the integration cycle time, and t_{fix} is the dead time due to the finite reset pulse width. $t_{update} - t_{fix}$ will vary with light intensity as shown in Eq.3.

$$t_{update} - t_{fix} = \frac{Q}{I_{ph}} = \frac{C_j V}{I_{ph}} \quad (1)$$

Fig.4 shows the major error source of this scheme. Since the photodiode is being constantly reset during integration, the finite reset pulse width and reset noise results in

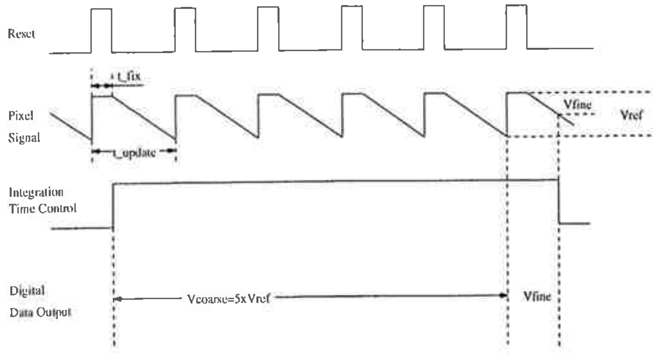

Fig. 3. Timing diagram of linear sensor operation.

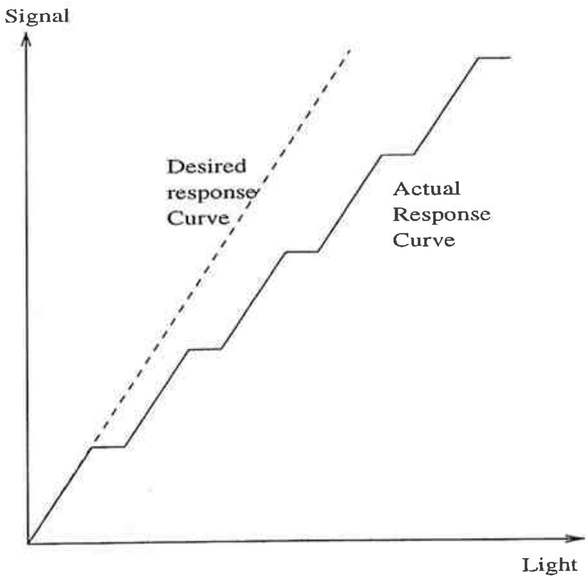

Fig. 4. Illustration of one source of inaccuracy.

an error between the measured and actual signals. As an example, if the reset time is 100ps and integration time is 10ms, the error due to finite reset pulse width will be 0.01ppm. However, the largest source of error is still reset noise. Further investigation of the optimum reset signal to minimize errors due to image smearing, reset noise and reset pulse width is required.

Fig.5 shows an alternative scheme. Instead of a simple counter, the actual signal is AD converted every cycle. The output of the A/D converter is summed by the 16-bit accumulator. This design is more tolerant of comparator offset. For comparison, in the counter output design shown in Fig.2, the offset voltage of every integration cycle is accumulated, and the final output has a larger accumulated error. However, accumulator-type output poses high requirement on the A/D converter in terms of speed because A/D output is needed for every integration cycle. Also, the acumulator has to run at the same speed as the pixel rate.

III. Options for Optics

Optics for color separation can be divided into two categories: External off-chip and on-chip. If external off-chip optics is used, existing housing and optics for any commer-

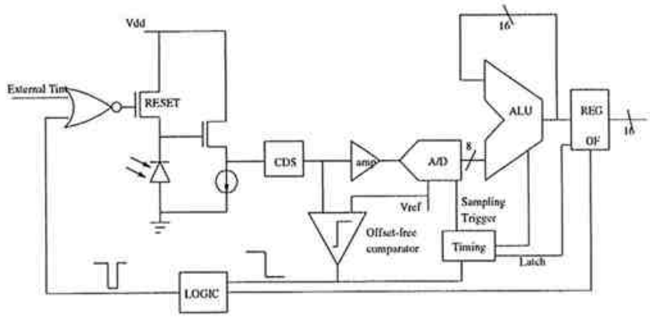

Fig. 5. Output with an accumulator - An alternative design.

cial miniature spectrometers can be used. The CMOS sensor will be used as a direct replacement of the linear CCD used in the spectrometer and its data acquisition circuits. Conventional spectrometers most commonly use reflective concave diffraction grating. Several companies have tried to reduce the size of this box to the size of match box. However, certain requirements of reflective gratings with optics pose difficulties to further shrink the size of such spectrometers. Also, reflective grating spectrometers have accuracy problems in alignment and strayed light.

On-chip optics has several options. A transmission diffraction grating can be directly mounted on top of the sensor. This scheme can not only reduce the size of the optics part of a spectrometer, the strayed light inside the spectrometer is also minimized.

A simplified grating equation can be written as:

$$d \sin \phi = m\lambda \tag{2}$$

Where d is the grating density in number/mm, ϕ is the blaze angle, λ is wavelength , and m is an integer. And, from Snell's Law, we have:

$$n \sin \phi = \sin(\phi + \beta) \tag{3}$$

Where n is refractive index, and β is the dispersion angle at the output of the grating. From Eq.2 and Eq.3, the blaze angle ϕ can be obtained as:

$$\tan \phi = \frac{m\lambda}{dn - \sqrt{d^2 - m^2\lambda^2}} \tag{4}$$

If the working distance is L, and the dispersion at the sensor plan is x shown in Fig.6(a), we have:

$$\frac{\Delta x}{\Delta \lambda} = \frac{Ld^2}{\sqrt{d^2 - \lambda^2}} \tag{5}$$

Assume the resolution of the grating is 1000 $groves/mm$, pixel size is 8 μm, and the spectral resolution desired is 1 nm, we can find that the working distance needs to be over 1 cm which makes fabricating the grating and sensor on the same wafer using standard CMOS process is very difficult. However, standard IC process technology can be used to fabricate blazed type diffraction gratings on a quartz wafer [9]. Eight-step etch can create a simulated blaze which has over 90% efficiency. The quartz wafer with micro-gratings and imager wafer can be aligned and

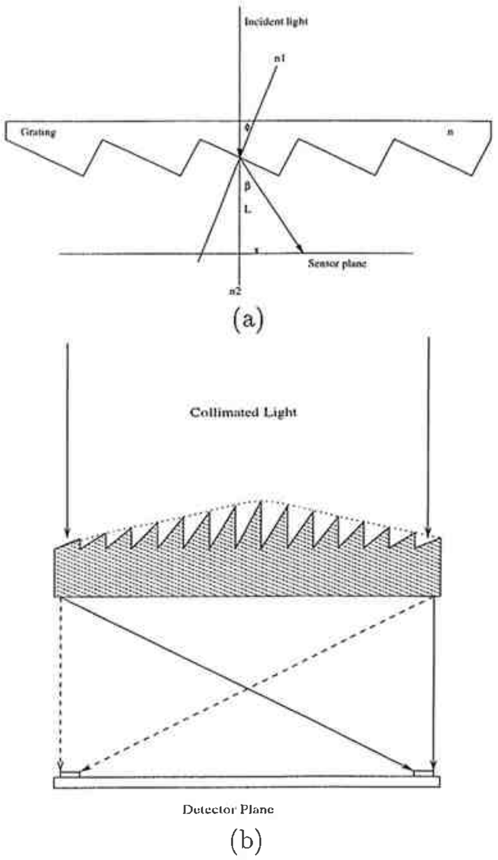

Fig. 6. Integrated transmission gratings. (a) Transmission diffraction grating. (b) Curved grating with focusing.

bonded together. Then the bonded wafer will go through assembly and packaging.

On-chip transmission gratings have been fabricated to combine with the sensor to form a single-chip spectrometer [4][7]. However, it is almost impossible to insert a focusing lens between the grating and the sensor chip to focus the spectrum line to achieve better accuracy. Thus, a new transmission grating which has the focusing function is shown in Fig.6(b). By curving the surface of the grating, the separated single spectral light can be focus onto the sensor plane [8].

Another option for on-chip optics is thin-film interference filter. The thickness of the coating is controlled when depositing using standard CMOS processes. Constructive and destructive interference causes narrow spectrum light transmitted through certain location of the coating. This process fits very well with the single chip spectrometer as shown in [3][6]. However, the spectral resolution achieved is not very high (over 10nm).

Electrical-biased piezo-crytal can form a grating (Bragg Cell). The advantage is that the grating spacing can be controlled [5]. However, typical acousto-optic crystal is made from T_eO_2 or G_aP which is not compatible with standard IC processes.

IV. Conclusion

A linear-response, high-dynamic range CMOS linear sensor for spectrometers has been designed and simulated. By combining digital and analog readout and folding the output into multiple linear pieces, linear-response and high dynamic range can be achieved. Different options for on-chip color separation optics have also been explored with emphasis in focusing transmission diffraction grating.

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