Dual-phase synchronous light detection with 64 × 64 CMOS modulated light camera

M.C. Pitter, R.A. Light, M.G. Somekh, M. Clark and B.R. Hayes-Gill

A scalable sensor for wide field detection (imaging) of low contrast amplitude-modulated light has been fabricated in a standard CMOS process. The sensor has a randomly addressable array of 64 × 64 feedback buffered photodiodes. Any row of the photodiode array can be connected to 64 independent dual-phase lock-in detection channels allowing two-dimensional phase sensitive imaging without mechanical scanning.

Introduction: Synchronous (lock-in) detection of intensity or phase-modulated light is an essential component of many optical imaging techniques. The ability to sharply bandpass filter at the optical modulation frequency is particularly useful when a small change must be detected in the presence of a large DC background. The need for lock-in detection circuitry means that synchronous optical detection has traditionally been a point measurement technique. Typical applications of modulated light detection include thermoreflectance measurement and other optical pump/probe techniques. When there is a need for two-dimensional image acquisition, as in thermoreflectance microscopy for the measurement of thermal conduction and thermal diffusivity, optical scanning is usually used in conjunction with point detection. However, fast optical scanning requires complex and delicate equipment. The sensor described here is an example of a robust solid-state modulated light camera suitable for modulated light imaging in the presence of high levels of background light. Modulated light cameras have been previously fabricated [1, 2], but the camera described here is distinct in that, unlike [1], which performs envelope detection of the AC signal, the camera uses phase-sensitive detection techniques, and unlike [2], the camera is designed to work in the presence of high levels of background light (AC:DC ratio of 2% or less) and occupies a far smaller die.

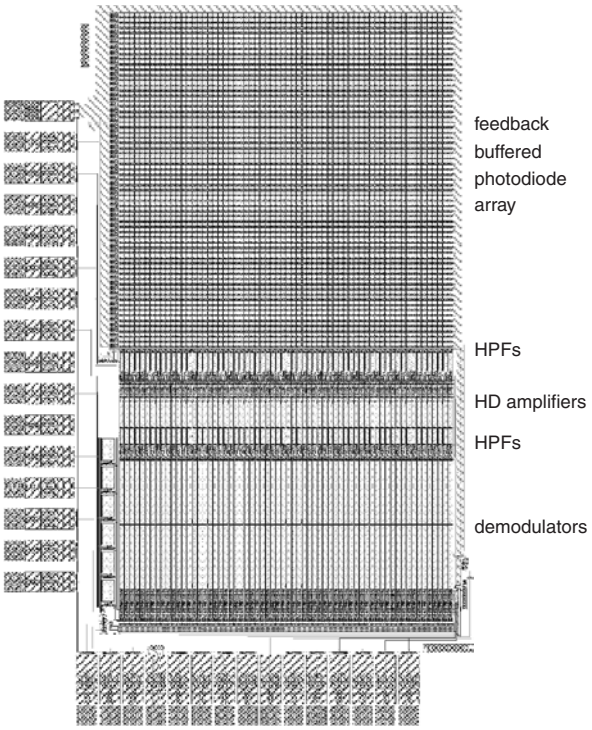

Fig. 1 *Layout of modulated light camera showing buffered photodiode array and synchronous detection circuitry*

Overview of the sensor: Dual-phase synchronous optical detection is performed in 64 independent channels. Each channel contains highpass filters, an amplifier and two switched capacitor boxcar averagers, which act as demodulators [3]. Two demodulators are used so that measurement of AC phase and AC amplitude can be performed simultaneously. A 64 × 64 photodiode array adjacent to the synchronous detection circuitry can be electronically scanned to capture a two-dimensional image without mechanical aids. The sensor pixels have a pitch of 25 μm and a fill factor (ratio of light sensitive area to total pixel area) of 56% and are integrated with the synchronous detection circuitry on a 3.3 × 2.5 mm die using an AMS 0.35 μm standard digital CMOS process with poly-poly linear capacitors. Additional circuitry decodes a 6-bit column and a 6-bit row address to allow random addressing. The top metal layer is used to shield all of the circuitry except for the photodiodes to minimise the effect of stray photoelectrons. The chip layout can be seen in Fig. 1. The dark square area at the top of the layout is the array of feedback buffered photodiodes. The synchronous detection circuitry is below the array.

Photodiode array: The light-sensitive area of the sensor comprises an array of 64 × 64 pixels. Each pixel contains a 'deep' (ntub to *p*-substrate) photodiode of 22 × 16 μm, a transimpedance circuit with buffered feedback [4] and a row selection switch, which connects the voltage output to column lines. This circuit is a type of 'log pixel' as it outputs a continuous voltage, which is logarithmically related to the photocurrent flowing in the photodiode, rather than an 'active pixel', which integrates the photocurrent onto a capacitance. The log pixel benefits from a continuous voltage output and a large dynamic range but has low contrast. For large values of AC amplitude (relative to the DC background), the log response causes unacceptable distortion. However, the sensor is designed for measuring small values of AC amplitude superimposed on a large DC background where the logarithmic response is not a problem.

The choice of logarithmic detection was dictated by the need for a continuous time output and a very large transimpedance gain in a small area. The photodiode load and buffering have to be integrated into the light sensitive region of the sensor so using a large value linear resistor would reduce the fill factor by an unacceptable amount and add considerable capacitance. The sensor is designed to operate with typical mean photocurrents in the range of pA to nA per pixel, so tens of MΩ are required. The buffered feedback circuitry improves the response time of the circuit by suppressing the effect of the photodiode capacitance from the overall time constant [4]. The logarithmic response causes the transimpedance to vary with mean photocurrent, such that the pixel bandwidth is inversely proportional to the photocurrent and varies from a few hundred Hz at the dimmest acceptable illumination to a few hundred kHz in stronger light.

An externally generated 6-bit row address can be used to randomly select a row of the pixel array by setting its row select line high. This connects the output of the selected row of pixels to the filters, amplifiers and boxcar averaging circuits that comprise the synchronous detection circuitry.

Synchronous detection circuitry: There are 64 independent dual-phase synchronous detection channels that share clock and bias lines. Each circuit is laid out in a strip of 25 × 1200 μm. In each channel, the small AC signal from the pixel is highpass filtered and then amplified with a hysteretic differentiator circuit (HD) [5]. The HD is an amplifier with a lowpass feedback network and has a signal frequency gain of around 40 dB but unity gain for DC. The bias current and consequently the high frequency cutoff of all 64 HDs can be set and tuned with a single external resistor. The HD is a very useful circuit in scalable arrays as it combines a stable DC operating point with a useful amount of single-stage gain while requiring no offset compensation or external connections other than power and a shared bias voltage. The HD is a low power circuit (<1 mW) and the gain can be set with accuracy and repeatability by a capacitance ratio.

After amplification and filtering the signal is demodulated with a simple switched capacitor circuit [3]. Each detection channel has two demodulators to allow independent measurement of phase and amplitude as required. Each demodulator samples the signal onto a small capacitor then, on a non-overlapping clock cycle, it integrates the small sampled charge onto a much larger capacitor. The circuit performs an exponentially weighted time average of the synchronously sampled input voltage. The ratio of sampling to integration capacitance can be selected from a bank of four giving ratios from 120:1 up to 6000:1 (neglecting the effects of parasitic capacitance and charge injection from the simple FET switches).

If the demodulators are clocked at the optical modulation frequency then they act as a pair of boxcar averaging circuits. The pair of modulators are clocked independently so many clocking schemes are possible, the most generally useful being a 90° phase difference for IQ demodulation of sinusoidally modulated light, a 180° phase difference for measurement of small amplitude square wave modulation, or with a very small time difference for high-speed time-averaged double exposure.

Modulated light imaging with sensor: Acquisition of modulated light images is performed row by row. A 6-bit row address is applied to the external pins to connect a row of pixels to the synchronous detection channels. Integration now occurs as the demodulators are clocked. After the required number of clock cycles to allow settling of the demodulators a 6-bit column address is used to sequentially read in the pairs of voltages from each synchronous detection channel. The sensor is controlled by a PC via a multifunction IO card equipped with 16-bit ADC and digital IO.

The sensor can also be used for conventional (DC) imaging. No integration is available or required when DC imaging with log pixels. The voltage output is continuous in time and can be randomly accessed. However, the lack of integration causes a noisy DC image when compared to active pixel sensors or CCD cameras. The noise sources are both temporal and fixed pattern, but the fixed pattern noise is easily removed. Direct access to the log pixel output is provided by the camera, primarily to allow fast DC imaging for alignment purposes. Each pixel on the sensor can therefore output three useful and independent measurements for example the DC, the in-phase AC amplitude and the quadrature AC amplitude.

An example of DC light imaging using the sensor is shown in Fig. 2. A chrome-on-glass USAF resolution target was back illuminated with unmodulated light and imaged onto the sensor with a lens. The DC image is clearly seen. As expected, there is no AC image. Next the back illumination of the resolution target was mechanically chopped at 2 kHz and, in addition, a stronger DC light source was shone onto the camera from a separate source. The ratio of DC to AC amplitude was 200:1 with around 100 nW of DC light per pixel. In Fig. 3 it can be seen that the DC image is completely obscured by the background light. However, the AC image has good contrast despite the high DC background.

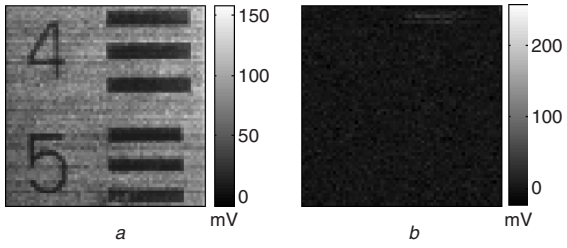

Fig. 2 *Image in unmodulated (DC) light*
a DC channel records clear image
b There is no AC image

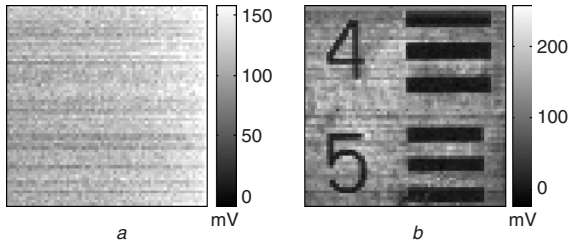

Fig. 3 *Image in modulated light on large DC background*
a DC channel has no contrast
b AC image has good contrast despite high background light levels

Conclusions: A 64 × 64 array of feedback buffered photodiodes has been integrated onto a single die with 64 channels of synchronous detection circuitry to create a modulated light camera. The camera can acquire two-dimensional images without any mechanical scanning. Modulated light cameras such as this should find application in thermoreflectance microscopy, fast medical imaging and machine vision.

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