Camera pixel for coherent detection of modulated light

P.R. Dmochowski, B.R. Hayes-Gill, M. Clark,
J.A. Crowe, M.G. Somekh and S.P. Morgan

A CMOS pixel with local processing suitable for use in a modulated light camera is described. The pixel was designed to detect sinusoidally modulated light within the frequency range of 500 kHz–25 MHz. It consists of a photodiode, a transimpedance amplifier, a mixer and an active 150 Hz bandpass filter. It is a prototype design capable of further size reduction suitable for tiling into an array for imaging purposes. This allows the modulated light component of a frequency far in excess of the frame rate to be detected at the pixel level.

Introduction: In many situations in optics the detected light consists of a large constant background with a small modulated component superimposed. In this Letter we discuss a pixel suitable for tiling into an imaging array, which is sensitive to this modulated light component. Moreover, conventional image sensors cannot detect frequencies in excess of the frame rate and are restricted to a maximum of a few kHz. It is for these two reasons that there is a pressing need for the development of imaging technologies for the detection of modulated light. Work previously reported centres around designs operating in the 1–200 kHz region [1, 2] and up to 1 MHz [3]. This latter work employs lower selectivity at the output via a 35 kHz bandwidth filter whilst the system reported in this Letter uses a bandwidth of 150 Hz.

Designing a pixel suitable for tiling into an array is not an easy task. Power consumption, maximum detectable frequency, bandwidth, fill factor, pixel pitch, pixel complexity are very often conflicting requirements. The work presented here is an approach to build a full field camera with local pixel processing capable of detecting modulated light with frequencies far in excess of the frame rate. Moreover, the detected frequency is independent of this frame rate. The pixel has been designed to detect amplitude of modulated light at frequencies up to 25 MHz and all signal processing circuits were integrated at a pixel level making it suitable for a full field modulated light camera.

Chip description: The prototype modulated light camera (MLC) pixel was designed and fabricated in the AMS 0.35 μm (CSI) CMOS process. A block diagram of the presented MLC pixel sensor is shown in Fig. 1. The pixel integrates a logarithmic light sensor (50 × 50 μm) photodiode followed by a logarithmic transimpedance amplifier (TIA), single ended to a differential amplifier, a mixer and a lowpass filter having a bandwidth of 150 Hz. The output of the front-end and logarithmic TIA is first converted to a differential signal and amplified before being fed to the input of a mixer where it is multiplied with a reference local oscillator (LO). This forms a phase sensitive signal path. A bandpass filter at the output of the mixer provides lock-in detection. As can be seen the signal is processed continuously using analogue processing circuits, and hence there is no 'dead time' as found in conventional image sensors during CMOS pixel resetting or CCD charge shifting. In addition no signal is lost and no noise is added by switching or reset circuits.

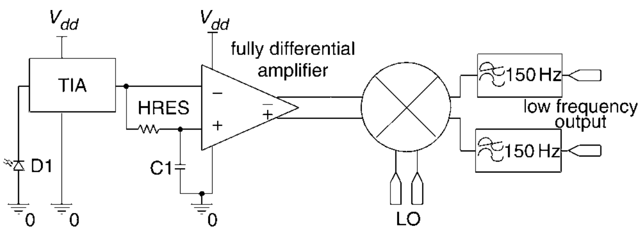

Fig. 1 *Block diagram of modulated light camera pixel*

The front-end transimpedance amplifier determines the speed, sensitivity, and signal-to-noise ratio (SNR) characteristics of the whole lock-in pixel. Furthermore, the design of the TIA leads to a number of trade-offs between gain, bandwidth, noise and power consumption. The bandwidth and sensitivity characteristics of the TIA are primarily determined by the total input capacitance, which is dominated by the junction capacitance of the photodiode used. The front-end is shown in Fig. 2 and consists of an *n*-well/*p*-substrate photodiode, transimpedance amplifier consisting of two NMOS transistors arranged in a feedback configuration and a diode connected PMOS transistor [1]. The advantage of this design is that it reduces the voltage swing at the cathode of the photodiode thereby extending the bandwidth compared to a simple diode-connected transistor load. The bias current I_1 is provided by a standard regulated cascode current source.

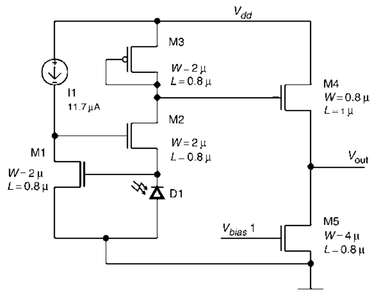

Fig. 2 *Front-end transimpedance amplifier and source follower*

The single-ended output of the TIA is converted to a differential signal using an R-C filter and a fully differential amplifier (see Fig. 1). As a capacitor we use the gate capacitance of a MOS transistor operating in strong inversion. The resistor is implemented using a 'horizontal resistor' (HRES) circuit [4]. With this circuit arrangement the unmodulated background light is therefore rejected by the differential amplifier.

The mixer is based on a double balanced four-quadrant Gilbert cell topology. The difference frequency is filtered from the output of the mixer by a bandpass filter. The bandpass filter is designed as an OTA-C circuit [4] with cutoff frequency of 150 Hz chosen so as to achieve a compromise between good signal averaging, the silicon area used and a typical camera frame rate of 100 Hz. All parts of the chip (except the photodiode) are protected from light using the third metal layer.

Experimental results: Tests were performed on the full MLC pixel using a laser diode (670 nm), which was modulated by an external signal generator. The laser beam was focused on the photodiode giving a maximum light power on the photodiode of 330 nW. The laser was modulated at 1 MHz with an initial modulation depth of 7%. The frequency of the laser and the LO were simultaneously swept and it was observed that the DC output was sensitive to frequencies ranging from 500 kHz to 50 MHz. The lower frequency is limited by the laser cutoff while the high frequency is limited by the upper cutoff of the pixel amplifier. The frequency selectivity was investigated by maintaining the source modulating the laser at a fixed frequency of 1 MHz while the frequency of the local oscillator reference was swept from 500 kHz to 4.5 MHz. The measured normalised spectral response from the MLC output is shown in Fig. 3. The signals with frequencies different to that of the lock-in frequency are rejected, whilst the circuit shows some response to harmonics of the fundamental carrier. This is due to distortions of the TIA, the non-idealities of the mixer, as well as other harmonics present in the modulated light source. The pixel covers an area of 250 × 250 μm and draws 180 μA from a 3.3 V power supply.

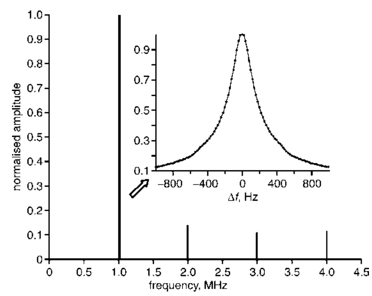

Fig. 3 *Bandpass filter output voltage against local oscillator frequency*

Conclusions: A lock-in pixel for a CMOS modulated light camera has been presented. This device has been demonstrated to be capable of detecting modulated light in the frequency range of 500 kHz to 25 MHz. This design can detect sinusoidal frequencies much higher than active pixel sensors presented in the literature to date. The architecture of the pixel is flexible and can be adapted to any particular requirements. Thus this design enables a whole range of new applications and it can be successfully used in existing laser assisted applications [5] such as light detection and ranging (LIDAR), full field heterodyne interferometry and ultrasound tomography [6]. It must be noted that this pixel is not yet optimal and can be made considerably more compact (at the time of writing we have designed a lock-in pixel array with quadrature mixer and two bandpass filters integrated at a pixel level for proof of scaling principle. Here each pixel has a size of 86×86 µm. The bandpass filter width was set to 1.5 kHz to match the 1 kHz frame rate of the proposed camera resulting in a space saving. The cutoff frequency of the bandpass filter was increased to match the array size and required frame rate).

Acknowledgments: The authors are grateful for the financial support of the Engineering and Physical Sciences Research Council (UK) and the University of Nottingham.

8 August 2004
Electronics Letters online no: 20046534
doi: 10.1049/el:20046534

P.R. Dmochowski, B.R. Hayes-Gill, M. Clark, J.A. Crowe, M.G. Somekh and S.P. Morgan (*School of Electrical and Electronic Engineering, University of Nottingham, University Park, Nottingham, NG7 2RD, United Kingdom*)

E-mail: eexprd@nottingham.ac.uk

References

1 Perelman, Y., and Ginosar, R.: 'A low-light level sensor for medical diagnostic applications', *IEEE J. Solid-State Circuits*, 2001, **36**, (10), pp. 1553–1558

2 Pitter, M.C., Goh, J.Y.L., Somekh, M.G., Hayes-Gill, B.R., Clark, M., and Morgan, S.P.: 'Phase-sensitive CMOS photo-circuit array for modulated thermoreflectance measurements', *Electron. Lett.*, 2003, **39**, (18), pp. 1339–1340

3 Bourquin, S., Seitz, P., and Salathé, R.P.: 'Two-dimensional smart detector array for interferometric applications', *Electron. Lett.*, 2001, **37**, (15), pp. 975–976

4 Mead, C.: 'Analog VLSI and neural systems' (Addison-Wesley, New York, 1989)

5 Pui, B.H., Hayes-Gill, B., Clark, M., Somekh, M.G., See, C., Piéri, J.F., Morgan, S., and Ng, A.: 'The design and characterisation of an optical VLSI processor for real time centroid detection', *Analog Integr. Circuits Signal Process.*, 2002, **32**, (1), pp. 67–75

6 Yao, G., and Wang, L.V.: 'Theoretical and experimental studies of ultrasound-modulated optical tomography in biological tissue', *Appl. Opt.*, 2000, **39**, (4), pp. 659–664