A Pixel-Level Color Image Sensor With Efficient Ambient Light Suppression Using Modulated RGB Flashlight and Application to TOF Range Finding

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Abstract

We present a pixel-level color image sensor with efficient ambient light suppression using a modulated RGB flashlight to support a recognition system. Bidirectional photo integrators realize in-pixel demodulation of a projected flashlight with suppressing an ambient light at short intervals during exposure time to avoid saturation from ambient illumination. Every pixel has a capability of depth and color capture. A prototype chip has been designed using 0.35 μm CMOS process and successfully tested.

Keyword: CMOS image sensor, modulated flashlight, color imaging, time-of-flight range finding, recognition system.

Introduction

In recent years a monitoring/recognition system becomes important for a security system, an intelligent transportation system (ITS), factory automation, robotics and so on. Object extraction from a captured scene is important for such a recognition system. Color information is also useful to identify a target object. However object extraction requires huge computational effort in general, and color information changes with ambient illumination. In this paper, we propose a CMOS image sensor supporting image processings of object extraction and color capture for a recognition system as shown in Fig.1. Target objects are desired to be extracted by flashlight decay or time-of-flight (TOF) range finding, which is called a depth-key technique[1]. Moreover ambient light suppression is important since a recognition system requires color information of a target object itself.

Some image sensors with demodulation have been presented for signal detection suppressing a constant light [2]–[4]. The conventional techniques [2, 3] have two photo integrators. One accumulates a signal light and an ambient light together, and the other accumulates only an ambient light. Therefore its dynamic range is limited by the ambient light intensity. The logarithmic-response position sensor [4] expands the dynamic range due to adaptive background suppression. The signal gain, however, changes with the incident light intensity, so it is not suitable for capturing a scene image.

The present photo detector has bidirectional photo integrators for in-pixel demodulation, which accumulate a signal light with an ambient light and then subtract the ambient light from the total level at short intervals during demodulation. It contributes to avoid saturation from ambient illumination for the applicability to non-ideal illumination conditions. Every pixel provides color information without false color and intensity loss of color filters by using a modulated RGB flashlight. The flashlight imaging also supports object extraction using flashlight decay. Moreover the demodulation function has a possibility of TOF range finding as presented in [5, 6] to achieve more efficient object extraction.

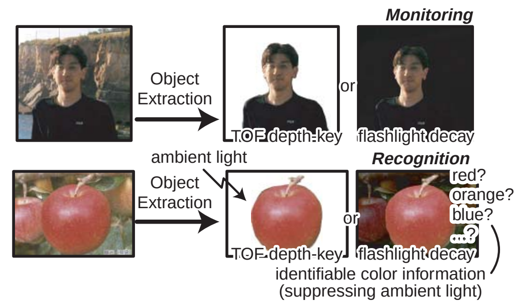


Fig. 1 Application Requirements of Recognition System.

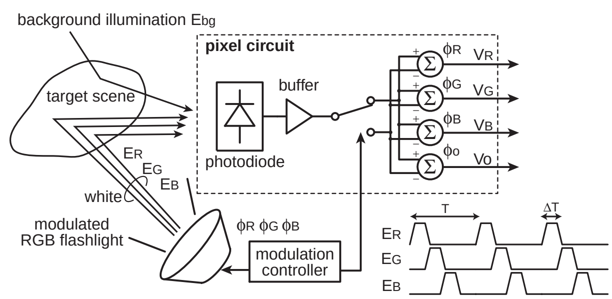


Fig. 2 System Configuration Using Modulated Flashlight.

System Configuration and Sensing Scheme

Fig.2 shows a system configuration using a modulated RGB flashlight. The flashlight is modulated in RGB respectively by ϕ_R, ϕ_G and ϕ_B, and projected on a target scene together. A photo detector receives the modulated lights E_R, E_G and E_B with an ambient light E_{bg}. A photo current I_{pd} is generated in proportion to the incident intensity E_{total} as follows:

$$I_{pd} \propto E_{total} = \begin{cases} E_R + E_{bg} & if \quad t = nT \sim nT + \Delta T, \\ E_G + E_{bg} & if \quad t = nT + \Delta T \sim nT + 2\Delta T, \\ E_B + E_{bg} & if \quad t = nT + 2\Delta T \sim nT + 3\Delta T, \\ E_{bg} & otherwise, \end{cases} \tag{1}$$

where T is cycle time of modulation, ΔT is a pulse width of each flashlight, and n is the number of cycles in exposure time. I_{pd} is accumulated in each integrator synchronized with ϕ_R, ϕ_G and ϕ_B respectively. Then all integrators subtract E_{bg} from the total level in a modulation cycle T. The short-interval subtraction contributes to suppress background illumination with keeping the dynamic range.

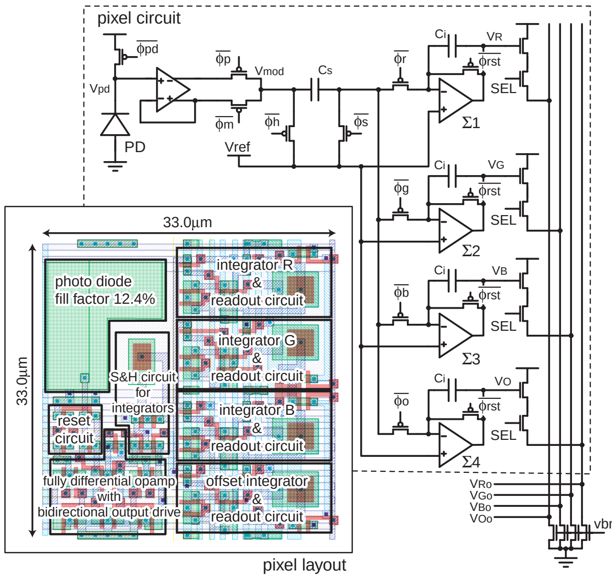


Fig. 3 Pixel Circuit Configuration and Layout in 0.35μm Process.

In the conventional demodulation sensor [2, 3], the signal level V_{sig} is calculated from the accumulation results V_{sig+bg} and V_{bg} after an exposure period.

$$V_{sig} = V_{sig+bg} - V_{bg} \tag{2}$$

$$= \sum_{i=0}^{n} \frac{(I_{sig} + I_{bg}) \cdot \Delta T}{C_{pd}} - \sum_{i=0}^{n} \frac{I_{bg} \cdot \Delta T}{C_{pd}} \tag{3}$$

where C_{pd} is a parasitic capacitance of a photo diode. I_{sig} and I_{bg} are photo currents generated by a modulated flashlight and an ambient light respectively. Therefore the dynamic range of [2, 3] is limited by a saturation level V_{sat} as follows:

$$V_{sig+bg} < V_{sat}. \tag{4}$$

On the other hand, the present image sensor suppresses an ambient light at short intervals during an exposure period. The signal level V_{sig} is provided directly from a pixel output as follows:

$$V_{sig} = \sum_{i=0}^{n} \left(\frac{(I_{sig} + I_{bg}) \cdot \Delta T}{C_{pd}} - \frac{I_{bg} \cdot \Delta T}{C_{pd}} \right). \tag{5}$$

Thus the dynamic range is given by

$$V_{sig} < V_{sat}. \tag{6}$$

In the present sensing scheme, a short interval time of demodulation makes the dynamic range higher. The fourth integrator provides V_O as the offset level to cancel asymmetry of bidirectional integration. The color sensing has no intensity loss caused by color filters. Furthermore a reconstructed image has no false color because of pixel-level color imaging.

Pixel Circuit Configuration

Fig.3 shows a pixel circuit configuration and layout in 0.35 μm process. It consists of a photo diode (PD), a fully differential amplifier with gain = 1, four integrators (Σ_i) with a demodulation function, and four source follower circuits. The pixel size is 33.0 μm × 33.0 μm with 12.4% fill factor in 0.35 μm CMOS

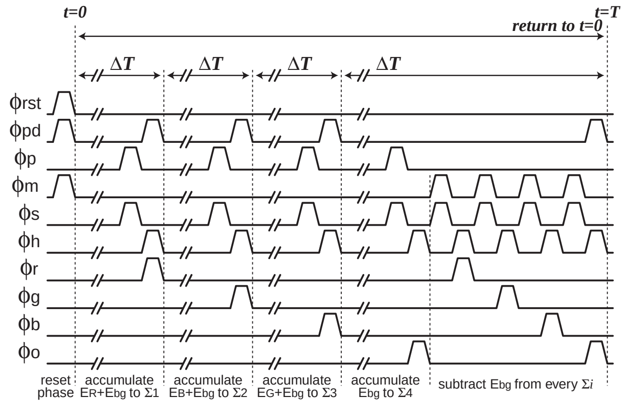


Fig. 4 Timing Diagram.

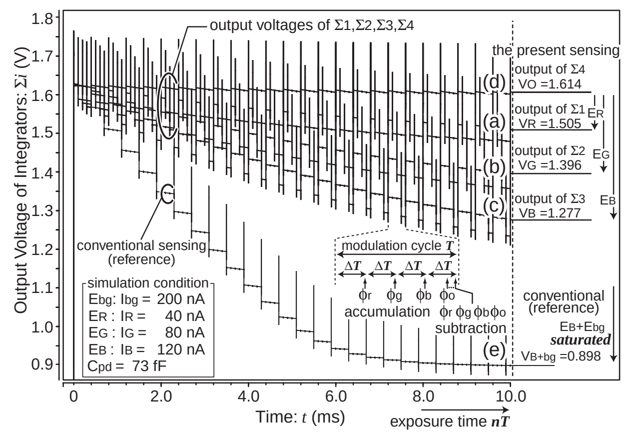


Fig. 5 Simulation Waveforms of In-Pixel Demodulation.

process. Fig.4 shows a timing diagram of the pixel circuit. In the reset period, all integrators are initialized by ϕ_{rst}, and also V_{pd} at a photo diode is reset by ϕ_{pd}. In the first ΔT, the photo detector accumulates E_R with E_{bg} in Σ_1 since a projected flashlight has a red light E_R. Then the photo detector accumulates E_G and E_B with E_{bg} in Σ_2 and Σ_3 in the second and third ΔT respectively after V_{pd} has been reset again. Finally E_{bg} is accumulated in Σ_4 and subtracted from all integrators in the fourth ΔT. The modulation cycle T is iterated in exposure time.

Fig.5 shows simulation waveforms of the in-pixel demodulation. In the simulation condition, a photo current I_{bg} generated by an ambient light E_{bg} is set to 200 nA. Photo currents I_R, I_G and I_B generated by a modulated RGB flashlight are set to 40 nA, 80 nA, and 120 nA respectively. A parasitic capacitance C_{pd} of a photo diode is 73 fF. A sampling capacitance C_s is 12 fF. An integration capacitance C_i is 17 fF. ΔT is set to 0.1 ms. A modulation cycle T of 0.4 ms is iterated 25 times in exposure time of 10 ms. The photo currents by a modulated flashlight are accumulated as $|V_R - V_O|$, $|V_G - V_O|$ and $|V_B - V_O|$ with suppressing an ambient light E_{bg} as shown by (a)–(c) in Fig.5, where V_O represents $E_{bg} - E_{bg}$ as an offset level of bidirectional integration. Therefore the present sensing scheme can avoid saturation from ambient light intensity E_{bg} as shown in eqn.(5). In the conventional sensing as shown by (e) in Fig.5, the signal level can be saturated since the integrator accumulates E_B and E_{bg} together without suppressing E_{bg} in an exposure period as shown in eqn.(3).

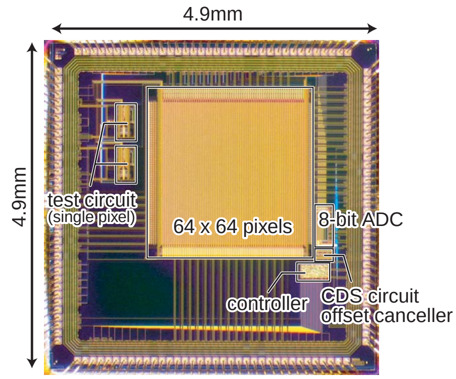


Fig. 6 Chip Microphotograph.

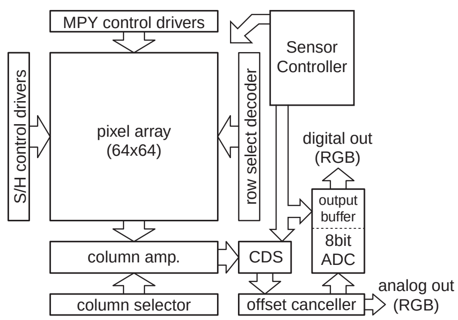


Fig. 7 Sensor Block Diagram.

Table 1 Specifications of the Designed Sensor.

Process	0.35 μm CMOS 3-metal 2-poly-Si
Die size	4.9 mm $\times$ 4.9 mm
# of pixels	64 $\times$ 64 pixels
Pixel size	33.0 μm $\times$ 33.0 μm
Pixel config.	1 PD, 57 FETs and 5 capacitors
Fill factor	12.4 %

Chip Implementation

We have designed and fabricated a 64 $\times$ 64 image sensor using the present sensing scheme and circuits in 0.35 μm CMOS process[1]. Fig.6 and Fig.7 show the chip microphotograph and its components. The sensor consists of a 64 $\times$ 64 pixel array, a row select decoder, control signal drivers, a correlation double sampling (CDS) circuit, an offset canceller, an 8-bit ADC, and a sensor controller. Specifications of the designed sensor are shown in Table 1. A CDS circuit suppresses a fixed pattern noise from the output voltages V_{Ro}, V_{Go}, V_{Bo} and V_{Oo} respectively. And then the offset canceller, which is shown in Fig.8, subtracts a demodulation offset level V_{Oo} from the other output voltages. The fabricated chip also has a charge-distributed 8-bit ADC as shown in Fig.9. All components are operated by an on-chip sensor controller.

Measurement Results

A. *Efficient Ambient Light Suppression*

Fig.10 shows measurement results of a differential output voltage $|V_{Ro} - V_{Oo}|$ as a function of modulated light intensity E_R. Red LEDs of 630 nm wavelength project a modulated light and a constant light simultaneously on the sensor plane directly.

[1]The sensor in this study has been fabricated through VLSI Design and Education Center (VDEC), University of Tokyo in collaboration with Rohm Corp. and Toppan Printing Corp.

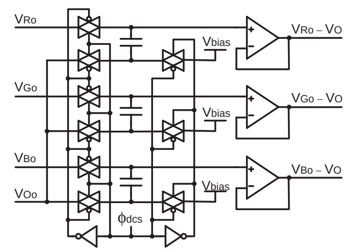


Fig. 8 Schematic of Offset Canceller.

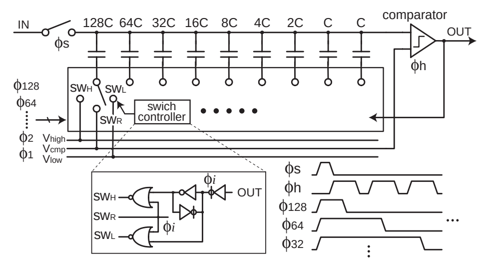


Fig. 9 Implemented Charge-Distributed 8-bit A/D Converter.

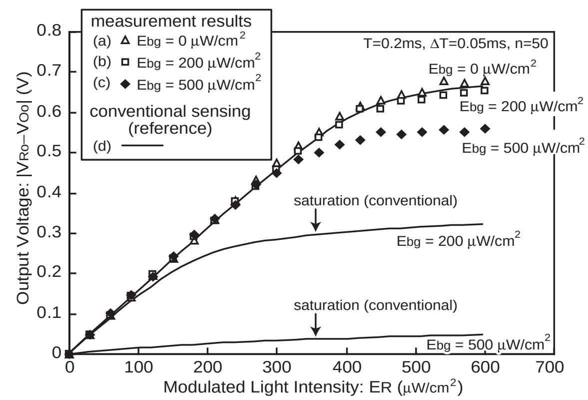


Fig. 10 Output Voltage versus Modulated Light Intensity E_R: (a) $E_{bg} = 0\mu W/cm^2$, (b) $E_{bg} = 200\mu W/cm^2$, (c) $E_{bg} = 500\mu W/cm^2$, (d) conventional demodulation without efficient ambient light suppression.

The modulated light has a modulation cycle T of 0.2 ms and a pulse width ΔT of 0.05 ms. The exposure time is 10 ms. The noise level of the present sensor is 3.4 mVrms, which is measured by $|V_{Ro} - V_{Oo}|$ under a constant light. As shown by (a)–(c) in Fig.10, the present sensing scheme has high linearity regardless of an ambient light E_{bg}. Moreover it can avoid saturation from an ambient light efficiently in comparison with the conventional demodulation sensing scheme (d) in Fig.10.

Fig.11 shows a saturation level of modulated light intensity E_R versus ambient light intensity E_{bg}. The conventional scheme is not suitable for various conditions since the saturation level is limited by the total level of E_R and E_{bg} as shown by (b) in Fig.11. On the other hand, the saturation level of the present scheme is not limited by the total intensity as shown in Fig.11 though it is slightly affected by an offset level V_O caused by asymmetry of bidirectional integration. Therefore the present sensor keeps high SNR and has a capability of various measurement situations.

B. *Pixel-Level Color Imaging*

We have demonstrated color imaging using the present image sensor and a modulated RGB flash light as shown in Fig.12. A prototype flashlight has 8 red LEDs, 8 green LEDs and 16 blue LEDs, whose wavelengths are 630 nm, 520 nm and 470

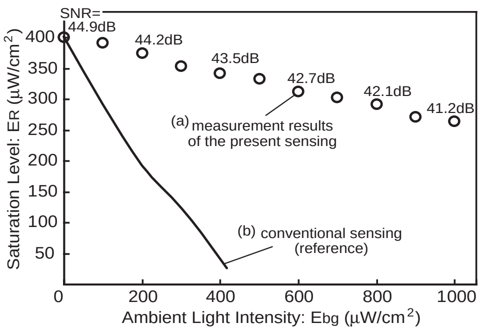
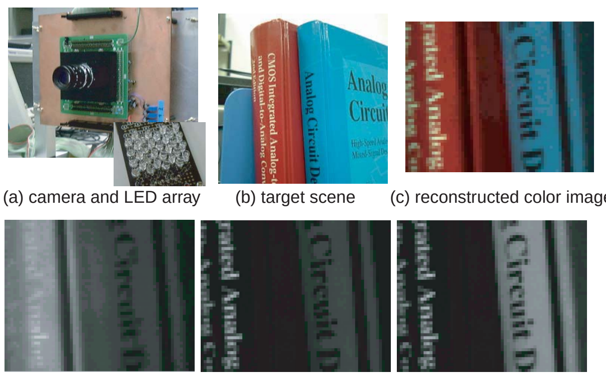


Fig. 11 Saturation Level of E_R versus Ambient Light Intensity E_{bg}: (a) measurement results of the present sensing scheme, (b) reference of the conventional sensing scheme.



(a) camera and LED array (b) target scene (c) reconstructed color image

(d) captured red image (e) captured green image (f) captured blue image

Fig. 12 Measurement Results of Color Imaging with Ambient Light Suppression.

nm. Total power consumption is 474 mW. The flashlight and an ambient light of a fluorescent lamp provide around 500 lux and 120 lux on a target scene at a distance of 30 cm from the sensor. Color image reconstruction requires each modulated light intensity, each distribution on a target scene, and spectral-response characteristics of the sensor. In this measurement, we acquired sensitivity of all pixels for the prototype flashlight projector using a white board. It can provide calibration parameters for non-uniformity of a modulated light, spectral-response characteristics and sensitivity fluctuation caused by each integration capacitance C_i. Fig.12(c) is a color image of a target scene (b) reconstructed from the sensor outputs (d)–(f). It has color information corresponding to 64 × 64 × 3 pixels of a standard color imager since every pixel provides RGB colors.

C. Time-of-Flight Range Finding

Fig.13 shows a timing diagram and an expected output voltage of TOF range finding. A pulsed light is reflected from a target object with a delay time T_d. The delay T_d resulting from a target distance L_o changes demodulation outputs V_1 and V_2. The target distance L_o is given by

$$L_o = \frac{cT_p}{2}\left(1 - \frac{V_1}{V_1 + V_2}\right), \tag{7}$$

where c is a light velocity and T_p is a pulse width. Fig.14 shows measurement results of TOF range finding using a 5-MHz pulsed laser beam. It has 10 mW and 665 nm wavelength. The measured target range is between 60 cm and 120 cm from the sensor. The measured range error is within ±15 cm. A standard deviation of error is 7.3 cm.

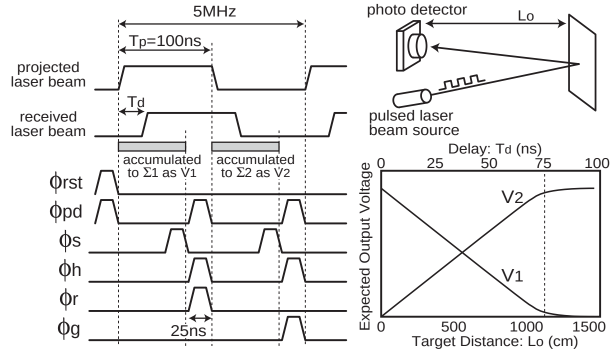


Fig. 13 Timing Diagram and Expected Output Voltage of Time-of-Flight Range Finding.

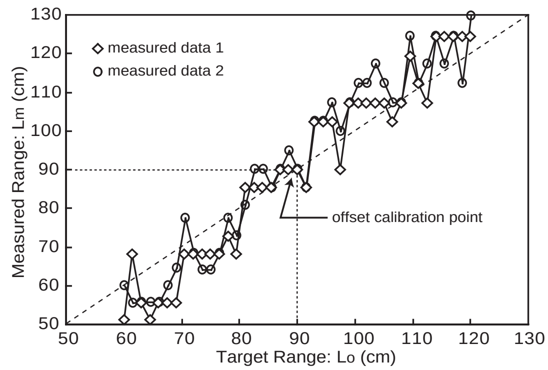


Fig. 14 Measured Range Accuracy of Time-of-Flight Range Finding.

Conclusions

A pixel-level color image sensor with efficient ambient light suppression has been presented. Bidirectional photo integrators realize in-pixel demodulation of a modulated RGB flashlight with suppressing an ambient light at short intervals during exposure time. Therefore it avoids saturation from ambient illumination to realize the applicability to non-ideal illumination conditions. Every pixel provides color information without false color and intensity loss of color filters. The flashlight imaging also supports object extraction based on flashlight decay. We have demonstrated the efficient ambient light suppression and the pixel-level color imaging using a 64 × 64 prototype sensor in 0.35 μm CMOS process. Moreover TOF range finding with ±15 cm range accuracy has been performed to achieve more efficient object extraction. The present image sensor supports object extraction and identifiable color caputre for a recognition system in various measurement situations.

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