190-1100 nm waveband multispectral imaging system using high UV-light resistance 94dB dynamic range CMOS image sensor

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Abstract A 190-1100nm waveband multispectral imaging system is developed utilizing a highly UV-light sensitive and robust, wide dynamic range CMOS image sensor. A time-sharing LED illumination optical system with small chromatic aberration using achromatic lens is introduced to the multispectral imaging system. With the developed system, a 60fps real-time multispectral imaging using LEDs with eight different wavelengths from UV-Visible-Near IR was successfully conducted.

Keywords: Spectral imaging, UV-Visible-Near IR light waveband, CMOS image sensor

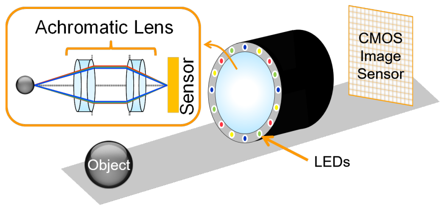
1. Introduction

Spectral imaging has been utilized in many application fields. Several spectral imaging technologies have been reported so far; a multispectral image sensor approach with on-chip Fabry-Perot spectral filters with multiple center wavelengths within visible to near-IR (NIR) waveband [1], a time sharing optical filtering approach using band-pass filter wheel or liquid crystal spectral filter [2], a selective light wavelength illumination approach [3], and so on. Recently, demands have been increasing for the development of spectral imaging system using a wide light waveband including UV-light range especially in the environmental monitoring and food inspection fields in order to accurately detect and analyze chemical substances that cause harmful effects to human body. Among the selective light wavelength illumination approach, light emission diodes (LED) have come to be utilized as light source more widely since the availability of LEDs with various specific wavelength from UV-Visible-NIR waveband has become higher.

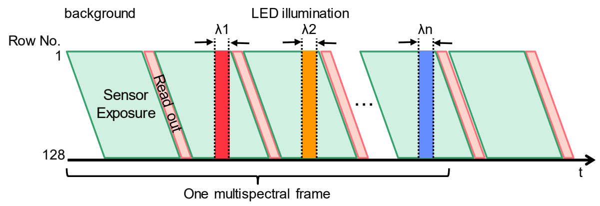
The goal of this work is to develop a compact UV-Visible-NIR waveband spectral imaging system highly adaptive to various applications. This paper presents a 190-1100nm waveband multispectral imaging system developed by combining a newly designed wide spectral response, especially in UV-light region, high light resistance and wide dynamic range CMOS image sensor and a time-sharing LED illumination optical system with small chromatic aberration using achromatic lens. The design of the developed multispectral imaging system and the measured performances of the prototype CMOS image sensor specially designed for this usage are summarized in the following sections. In addition, a 60fps real-time multispectral imaging result using LEDs with eight different wavelengths from 370nm to 1022nm is demonstrated.

2. Multispectral imaging system design

Fig.1(a) shows a schematic illustration of the wide light waveband multispectral imaging system developed in this work utilizing a high light resistance and wide dynamic range CMOS image sensor technology [4-7] and a time-sharing LED illumination optical system. In this system, multispectral image is captured by time-sharing illuminations of LEDs with different center wavelengths placed around the optical lens. The illumination timing of LEDs is synchronized to the image sensor's exposure periods. In order to minimize the effect of focal length errors, an achromatic lens system is introduced to suppress the chromatic aberration for a wide waveband light which is consisted of two infinite conjugate lenses placed back-to-back as shown in Fig. 1(a). Fig. 1(b) shows the schematic timing diagram of the employed CMOS image sensor and the time-sharing LED illumination optical system. A multispectral frame is composed of multiple frames of the CMOS image sensor's operation, each with different LED's illumination during the exposure period. In order to improve the accuracy of spectral imaging analysis, the duty ratio of LED illumination and exposure periods were set small. By doing so, variations of light wavelength and emission intensity of LED are suppressed. In addition, in order to achieve a robust spectral imaging analysis, in each multispectral frame, a designated image sensor's frame was introduced to compensate the temporal variation of the imaging system's characteristics and captured objects.



(a) Concept of spectral imaging system.



(b) Timing diagram of the time-sharing LED illumination optical system.
Fig. 1. Conceptual diagram of spectral imaging system.

3. Results

Fig. 2 shows the pixel circuit schematic of the CMOS image sensor specially designed for the developed multispectral imaging system in this work. The lateral overflow integration capacitor (LOFIC) is employed in the pixel circuit [4-5]. With the LOFIC technology, a high sensitivity and a high full well capacity photo-signals are simultaneously obtained. This technology is suitable to the multispectral imaging application because high quality images are to be obtained even when the variation of light

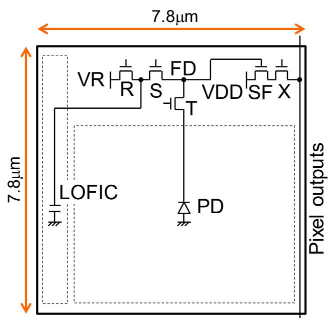


Fig. 2. Pixel circuit schematic.

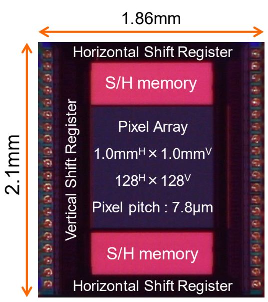


Fig. 3. Sensor chip.

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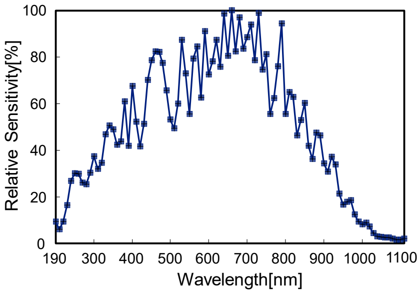

Fig. 4. Spectral sensitivity characteristic.

Table 1. Summary of the CMOS image sensor performances.

Process technology	1-Poly 5-Metal CMOS with pinned PD
Power supply voltage	3.3V
Die size	1860μm^H × 2100μm^V
# of pixels	128^H × 128^V
Pixel size	7.8μm^H × 7.8μm^V
Aperture ratio	51.8%
Maximum frame rate	1200fps
Multispectral frame rate with 8 light wavebands	60fps
Dark random noise	～1.6e$^-$
Full well capacity	87000e$^-$
Dynamic range	～94dB
Spectral sensitive range	190nm－1100nm

intensity of different wavelengths is large. The relatively large pixel pitch of 7.8μm is advantageous to achieve a high light sensitivity, also it makes good combinations with the employed achromatic lens system with intermediate resolution and with the thick p-type epitaxial layer of Si substrate while not causing crosstalk between pixels. Regarding the UV imaging, with the conventional technology, achieving high sensitivity and high light resistance to UV-light simultaneously is difficult. For the developed CMOS image sensor in this work, a high concentration surface p^+ layer with steep dopant concentration profile was employed to photodiode (PD) [6-8]. Due to the introduced PD profile, the high sensitivity and high light resistance to UV-light are simultaneously achieved. Fig. 3 shows the micrograph of the fabricated CMOS image sensor chip. A quartz glass was used as package lid in order to transmit UV-light to the sensor. The developed CMOS image sensor exhibited 1.6e^-_{rms} dark random noise, 87ke^- full well capacity and 94dB dynamic range. Fig. 4 shows the measured spectral sensitivity of the developed CMOS image sensor. A high sensitivity performance for a wide light waveband of 190-1100nm was obtained. Table 1 summarizes the image sensor performances.

Fig. 5 shows the developed 190-1100nm waveband multispectral imaging system [9]. Its camera system, named "McKinley(RM6170-T2)", was developed jointly with Regulus Co. Ltd. and INNOTECH CORPORATION. Fig. 6 shows a 3 ×3mm^2 color printed paper as image shooting object and captured images using eight LED light sources with different wavelengths from UV to NIR. Each set of eight images, for the respective wavebands, composes one multispectral frame, and the sensor achieved a multispectral frame rate of 60fps. For each wavelength employed, a different image was obtained due to the difference of reflectance of the color printed paper parts, showing that the eight wavebands multispectral imaging was successfully achieved. By changing the set of LEDs, the multispectral imaging system is easily adopted to various applications.

4. Conclusion

A 190-1100nm waveband multispectral imaging system was developed by using the CMOS image sensor and captured an eight light wavelength multispectral image. The developed system is highly adoptive to many applications with various sets of wavelength measurements.

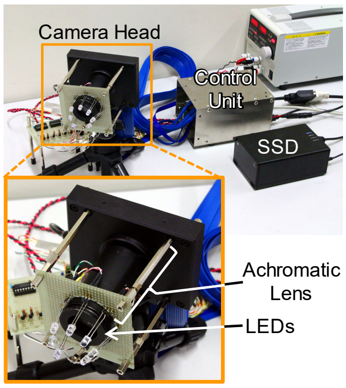

Fig. 5. Developed multispectral imaging system.

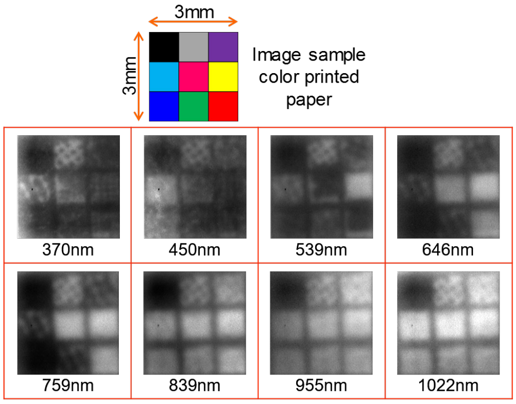

Fig. 6. Spectral imaging sample image. (top) Sample images captured by eight light wavelength multispectral imaging. (bottom)

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