DOI: 10.2352/ISSN.2470-1173.2016.12.IMSE-271

Development of an 8K full-resolution single-chip color image acquisition system

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Abstract

We have been researching compact 8K ultra-high definition television (UHDTV) camera systems for practical use. In this paper, we describe the world's first 8K “full-resolution” single-chip image acquisition system. This system can obtain an 8K full-resolution image at 60 frames-per-second, which has 33 megapixels for each color, using a 133-megapixel color CMOS image sensor. To reduce the size of the camera head, the signal processing is implemented in the separated camera control unit (CCU). The signal from the camera head to the CCU is transmitted using four 25-Gbps optical signals through one single-mode optical fiber by wavelength division multiplexing (WDM) technology. The signal processing unit can process all the 133-megapixel image data in real-time and can output an 8K video signal that is compliant with the ARIB STD-B58 and ITU-R BT. 2077 standards (U-SDI).

Introduction

8K Super Hi-Vision is a next-generation ultrahigh-definition television system (UHDTV), with a resolution of 7680 horizontal pixels and 4320 vertical lines. Its video parameters were standardized as Recommendation ITU-R BT.2020 [1] in 2012. The upmost specifications for 8K UHDTV, which we call “full-specification” 8K UHDTV, require 4320 lines of 7680 pixels with a RGB 4:4:4 sampling structure, 12-bit depth and 120 frames-per-second (fps) progressive scan. To meet the full-specification of the recommendation, NHK is accelerating the development of 8K equipment, including camera systems.

Previously, NHK developed 8K prototype cameras that use three 33-megapixel sensors with a large optical format [2]. Those cameras are generally large and heavy as they require an optical color separation prism. To reduce the size of large format cameras, single-chip color imaging without color separation prism is a promising approach. We have already developed single-chip 8K cameras using a 33-megapixel color CMOS image sensor with Bayer color filter array (CFA), and the smallest 8K single-chip camera [3] has a reduced weight of 2 kg at present. However, conventional single-chip cameras require demosicking tequniques [4][5] to reconstruct an 8K "full-resolution" (4320 lines of 7680 pixels) image from spatially incomplete color images.

To aquire an 8K full-resolution image by single-chip color imaging, we developed a 133-megapixel 60 fps CMOS image sensor [6], and performed basic imaging experiments [7]. However, the developed evaluation equipment could not carry all the 133-megapixel image data in real-time. In addition, 8K full-resolution images from the 133-megapixel image sensor had a sensitivity difference between the left and right sides of the imaging area that derived from different exposure in the sensor fabrication. When compensating for the difference, it was not enough to assign different gain settings to each of exposure areas simply due to the different sensitivity characteristics around the boundary of two exposure areas.

In this paper, we describe a newly developed 8K full-resolution single-chip image acquisition system that carry out all the 133-megapixel CMOS image sensor data in real-time. First, we describe the design of developed image acquisition system. Next, we have performed two imaging experiments. One of that is measurement of resolution and singal-to-noise ratio. The other is a method for the sensitivity difference in the 133-megapixel CMOS image sensor.

Overview of 133-meagapixel image sensor

Table 1 lists the specifications of the 133-megapixel CMOS image sensor, and Figure 1 shows the appearance of the sensor. The sensor can operate at 60-fps with resolution of 15360 × 8640 pixels (133-megapixels). The pixel size of the image sensor is 2.45 µm × 2.45µm. The output data consists of 112 channels of 1.15-Gbps current mode logic (CML) signals, for which the total data rate reaches about 128-Gbps. The active area is 37.632 × 21.168 mm (diag. 43.2 mm), corresponding to the 35-mm full-frame image format.

The sensor is fabricated with 1D-stitching technology, because it is difficult to compose the entire circuit of 35-mm full-frame image area using a single-shot exposure. Figure 2 shows the reticle patterns of the 133-megapixel image sensor. Two sets of reticle pattern A and B are used for 1D-stitching. The pixel area is made from two shots of reticle pattern B.

Table 1: Specifications of the 133-megapixel sensor

Optical Format	35-mm Full-Frame	
Pixel Count	Total	15488 (H) ×8766 (V)
	Active	15360 (H) ×8640 (V)
Pixel Size	2.45 µm ×2.45 µm	
Active Area	37.632 mm × 21.168 mm (diag. 43.2 mm)	
Frame Rate	60 fps, Progressive	
Bit Depth	12 bits	
Output	112 ch. CML 1.15 Gbps / ch @ 60 fps	
Color Filter	Bayer CFA	
Package	1125-pin PGA	

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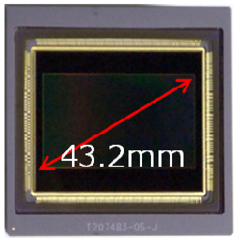

Figure 1. Visual appearance of the 133-megapixel sensor

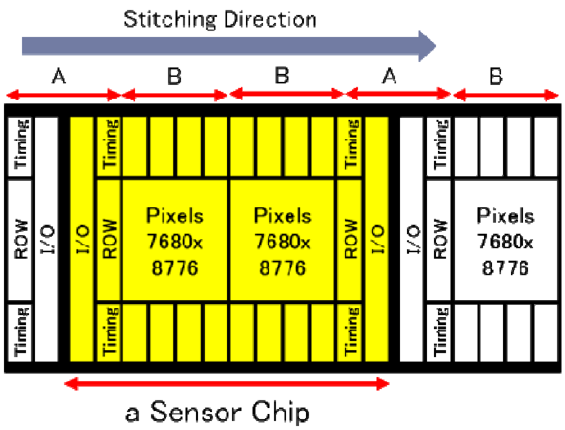

Figure 2. Fabrication of the 133-megapixel sensor

Image Acquisition System

Table 2 lists specifications of the developed image acquisition system. The weight of the camera head without a lens is 10 kg less than one fifth the weight of conventional 8K full-resolution camera system [2]. The height of the CCU is 5U (222 mm), in reference to the Electronic Industries Alliance (EIA) standard. The total power consumption of the camera head and CCU is 350 W: quarter that of a conventional 8K full-resolution camera system.

Figure 3 shows a block diagram of the image acquisition system. The system is composed of camera head and camera contorol unit (CCU). 35 mm full-frame lenses that are widely used in digital single-lens reflex camera (DSLR) can be used. The signals between camera head and CCU can be transmitted using a common optical camera cable used in HDTV cameras. The CCU outputs 8K, 60-fps and RGB 4:4:4 format signal from UHDTV Signal/Data Interface (U-SDI) that compliant with Association of Radio Industries and Businesses (ARIB) and ITU-R standards [8][9].

Table 2: Specifications of the image acquisition system

System	7680 pixels (H) × 4320 pixels (V) 60 fps Progressive Scan
Sensor	133-megapixel CMOS image sensor
Sensitivity	F2.8 @ 2000 lx
Dynamic Range	200%
SNR	49 dB
Weight	Camera Head: 10 kg CCU: 15 kg
Power Consumption	120 W (camera head) 230 W (CCU)

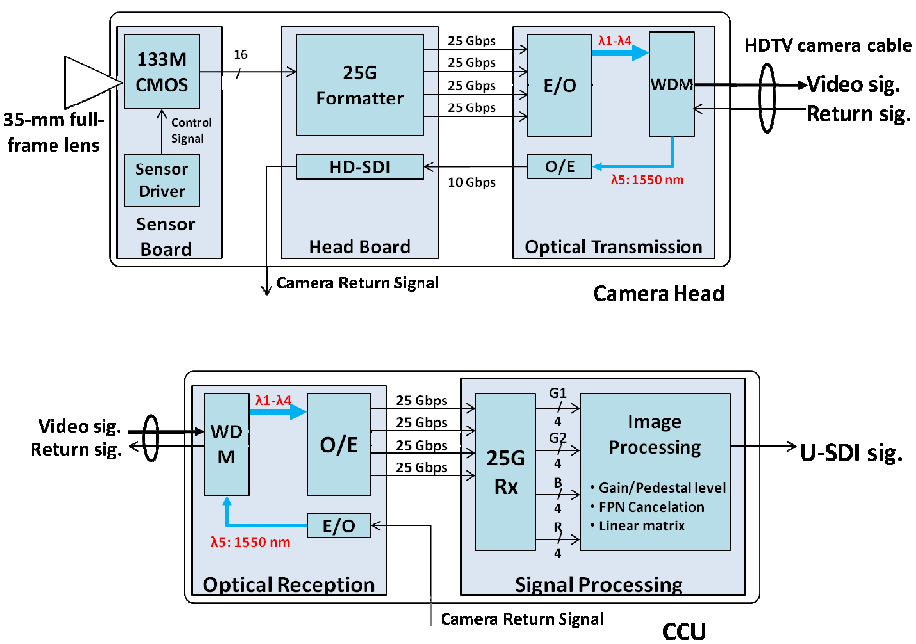

Figure 3.Block diagram of the developed image acquisition system

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Camera Head

Figure 4 shows the visual appearance of the developed camera head that can support various mounts of 35-mm full-frame lenses. Figure 5 shows the flange back (FB) of this camera head. In order to deal with various mounts of 35-mm full-frame lenses, the camera head can attach lens mount adapters as the base mount of the camera head is designed with a 22-mm (in air) FB distance. The lens adaptor is designed so that the FB distance of the camera head is corresponding with that of each lens.

The developed camera can also embed neutral density (ND) filters and color-compensating (CC) filters in the base mount. These filters are built into a filter turret as is the case with conventional HDTV broadcast cameras. The developed camera has three types of ND and CC filters that can be selected by operators.

Figure 4. Visual appearance of the camera head

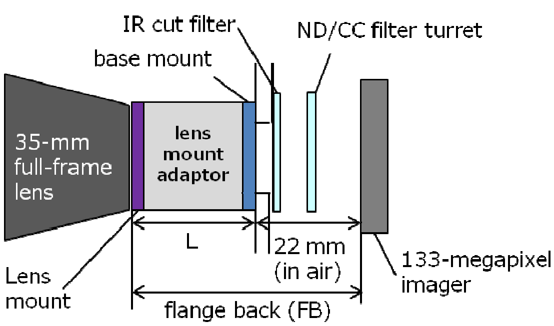

Figure 5. Flange back of the developed camera head

Camera Control Unit

Figure 6 shows the appearance of the signal processing unit (CCU). The signal processing unit (CCU) receives four 25-Gbps data streams, converts them into an 8K full-resolution signal, and performs the minimum required signal processing, including fixed-pattern noise (FPN) cancellation, black-level adjustment, gain control, gamma-correction, and color correction circuit. After this signal processing, addition of G1 and G2 is processed to improve the sensitivity of the system. Finally, the CCU outputs an 8K full-resolution signal as 12 channels of 10.692-Gbps multi-mode optical signal that is compliant with the ARIB STD-B58 and ITU-R BT.2077 standard formats.

The CCU also transmits a camera return signal to the camera head. The return video signal is converted into a 10-Gbps signal and, in the camera head, the camera return signal is separated from the 8K full-resolution signal, and is sent as output as an HD-SDI signal.

Figure 6. Appearance of the signal processing unit (CCU)

Bi-Directional Optical Transceiver

We developed a wavelength division multiplexing (WDM) transmission system that consists of a 100-Gbps optical transceiver (CFP2 [10]), a 1310 nm/1550 nm WDM filter, and a 10-Gbps optical transceiver (SFP+). The CFP2 transceiver can transmit four 25.78-Gbps data streams and multiplex them into one optical fiber. This leads to downsizing of the camera head. Furthermore, power consumption is less than that of WDM interfaces used in conventional 8K cameras [2].

To satisfy the CFP2 input format, the data formatter converts output signals from the 133-megapixel image sensor into four 25.78-Gbps data streams. Each stream is a single color of 8K full resolution, 12-bit, 60-fps signal. Figure 7 shows transformation scheme from single color channel of 8K full-resolution signal to a 25-Gbps data stream. The data formatter serializes the 8K full-resolution signal in increments of four lines (including the start of active video and horizontal optical black pixels). Next, by performing 64B/66B encoding on the serialized data stream, the 25.78-Gbps data stream is obtained. Finally, the CFP2 transceiver generates four 25.78-Gbps optical signals (1295 nm, 1300 nm, 1305 nm, and 1309 nm) and multiplexes them into one optical fiber of a standard camera cable.In the CCU, the CFP2 receiver restores four 25.78-Gbps optical signals into an 8K full-resolution signal.

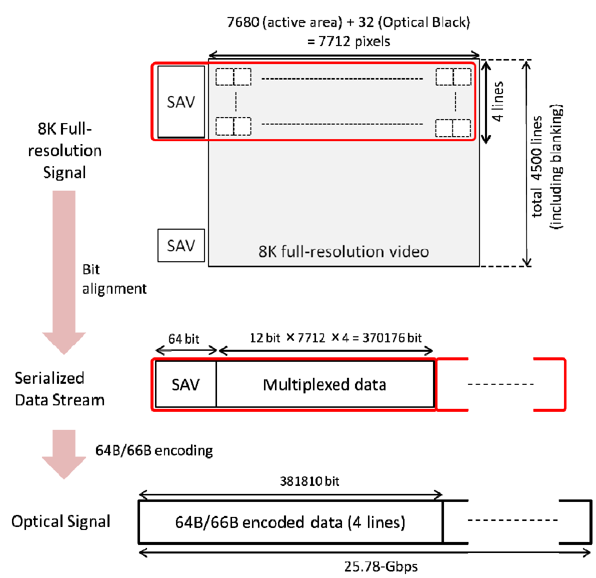

Figure 7. CFP2 input data format used in the developed system

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In addition, the camera return signal can also be bi-directionally transmitted in the same single-mode optical fiber using a 1550-nm wavelength SFP+ transceiver. This will enable-easy double-rate (e.g. 120 fps) transmission in the future because a standard optical camera cable has only two single-mode optical fibers. The 1310-nm-and 1550-nm- wavelength signals are multiplexed by a WDM filter in the CCU, and separated by a WDM filter in the camera head, respectively.

Image Acquisition Experiments

We performed image-capturing experiments using the developed image acquisition system to evaluate the characteristics of the 8K full-resolution video signal.

Figure 8 shows MTF characteristics using a 35-mm full-frame cinema lens (f=70 mm, T5.6, vertical direction) for the developed image acquisition system and for a conventional three sensor pick-up camera system [2]. The MTF of the image acquisition system exceeds 35% at 3200 TV lines, and 20% at the Nyquist frequency (4320 TV lines). Figure 9 shows a resolution chart image captured by the image acquisition system. We confirmed over 4000 TV lines from the magnified view of the center portion in the resolution chart.

We also measured the signal-to-noise ratio (SNR) of the image acquisition system. The SNR is 49 dB at a sensitivity of F2.8 for 2000 lx illuminance. The dynamic range of the system is 200%. These values are approximately equivalent to those of a conventional three pick-up camera system [2].

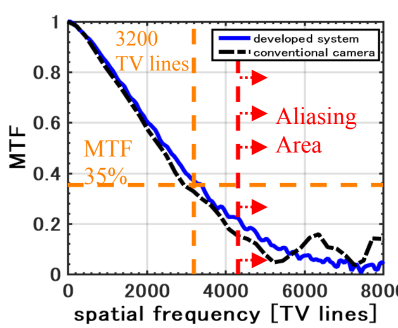

Figure 8. MTF characteristics of the image acquisition system

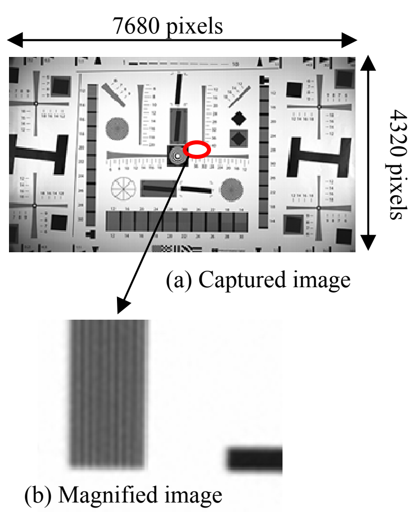

Figure 9. A captured 8K full-resolution image

Correction Method for Sensitivity Difference

Sensitivity characteristics of exposure areas

Since the sensitivity difference between two exposure areas in the 133-megapixel image sensor degrades the image quality of the produced 8K video, sensitivity correction is necessary. However, a simple correction technique multiplying the individual gain values for each exposure area is incomplete especially close to the exposure boundary. To improve the correction technique, we examined the sensitivity characteristics of exposure areas.

Figure 10 shows the measured horizontal pixel values near the boundary between two exposure areas when flat uniform light enters to the active area of the sensor. In order to avoid the influence of lens shading, we measured the center 80 (H) × 200 (V) pixels and calculated the vertically-averaged horizontal pixel values to suppress randam noise. Pixel values on the exposure border (between the 3840th and 3841th horizontal pixel positions) are slightly different from other pixel values in the same exposure area.

Figure 11 shows the sensitivity characteristics for four different horizontal pixel positions. Figures 11 (a), (b), (c), and (d) show results for each color channel. These results show two points: first, the sensitivity properties are different not only for each color channel but also for each exposure area. Second, the pixels just on the exposure boundary have singular characteristics compared with other pixels. Thus, sensitivity characteristics including non-linearity should be corrected by considering pixel color and horizontal position.

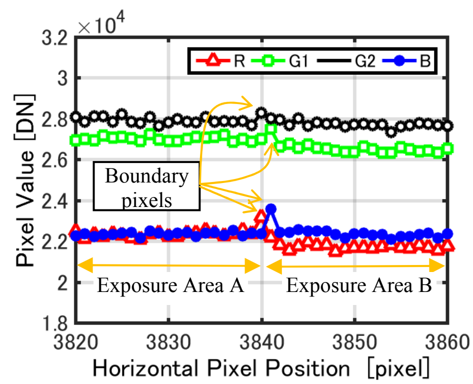

Figure 10. An example of digital values near the boundary between two exposure areas

Proposed Correction Method

In order to correct the sensitivity difference between two exposure areas including the boundary pixels, the active area is divided into four areas as shown in Figure 12. The four areas are composed of the left exposure area ($x < 3840$), left boundary ($x = 3840$), right boundary ($x = 3841$) and the right exposure area ($x > 3841$). The non-linear characteristics of each area are corrected by the following equations:

$$I_C(x,s) = L_C(x,s) \times s \tag{7}$$

$$L_C(x,s) = \begin{cases} f_{C,1}(s) & 1 \le x \le 3839 \\ f_{C,2}(s) & x = 3840 \\ f_{C,3}(s) & x = 3841 \\ f_{C,4}(s) & 3842 \le x \le 7680 \end{cases} \tag{8}$$

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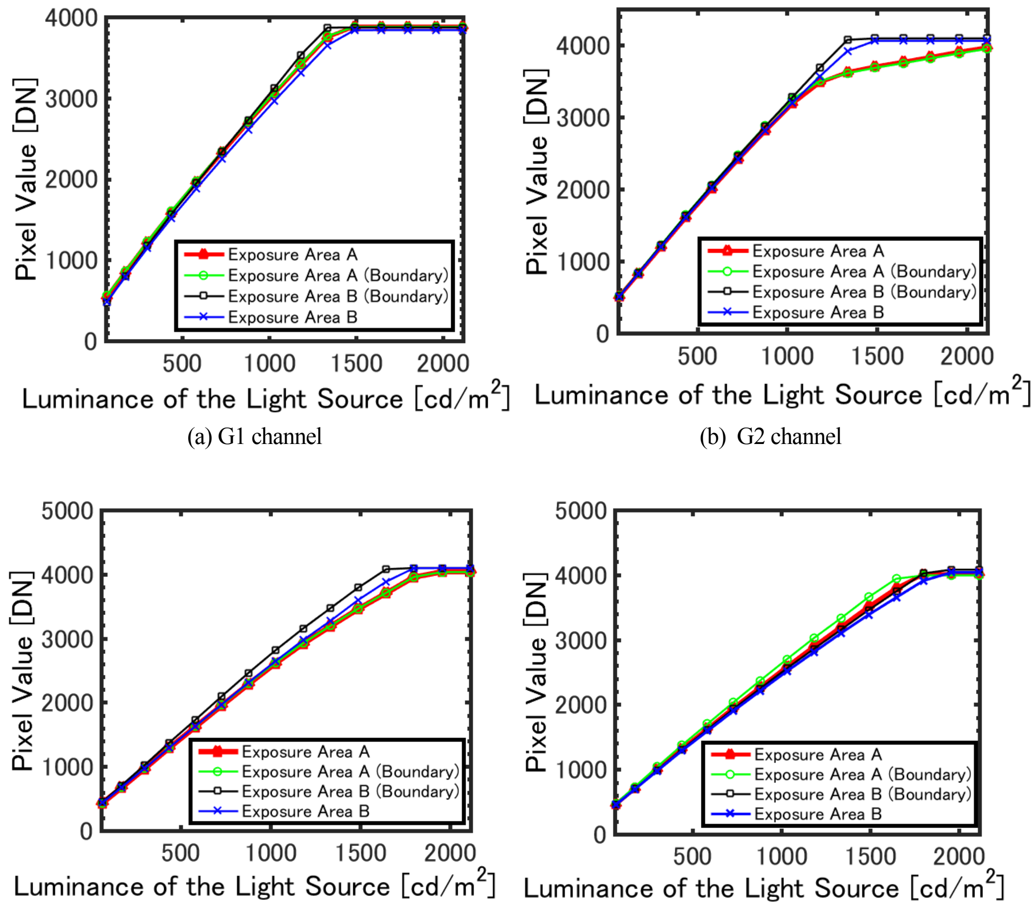
where s is the original pixel value with the sensitivity difference, $I_C(x,s)$ is the corrected pixel value after compensating the sensitivity difference, C denotes the color channels of G1, G2, B or R, x is the horizontal position of the pixel and $f_{C,i}(s)$ (i =1, …, 4) is a linearity correction function.

Linearity correction functions are implemented using the broken line approximation derived from the measured values of sensitivity. If a pixel value does not correspond with a measured point, the value of the linearity correction function is calculated from neighboring measurement points.



(a) G1 channel
(b) G2 channel
(c) B channel
(d) R channel

Figure 11. Sensitivity characteristics for each color channel

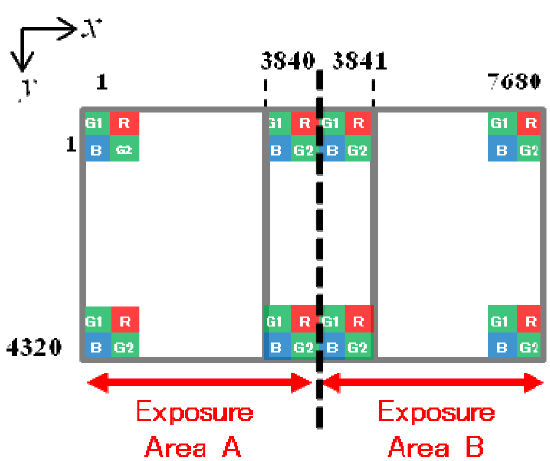


Figure 12. A method of dividing the imaging area into four regions

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Capturing Experiment Using the Proposed Correction Method

We performed a capturing experiment using the developed image acquisition system with an off-line process. Figure 13 compares the sensitivity difference before and after correction. The linearity correction function is derived from 15 measurement points. Comparing figure 13 to figure 11, it can be seen that the sensitivity difference is reduced after correction. In paricular, the maximum difference in pixel values between regions is suppressed from 463 DN to 114 DN at 1300 cd/m^2 in the G2 channel. Furthermore, figure 14 shows the reproducted images of capturing the grayscale chart before and after correction. Compared to figure 14 (a) and (b), it can be seen that the proposed method reduces the sensitivity difference to an extent that is almost invisible.

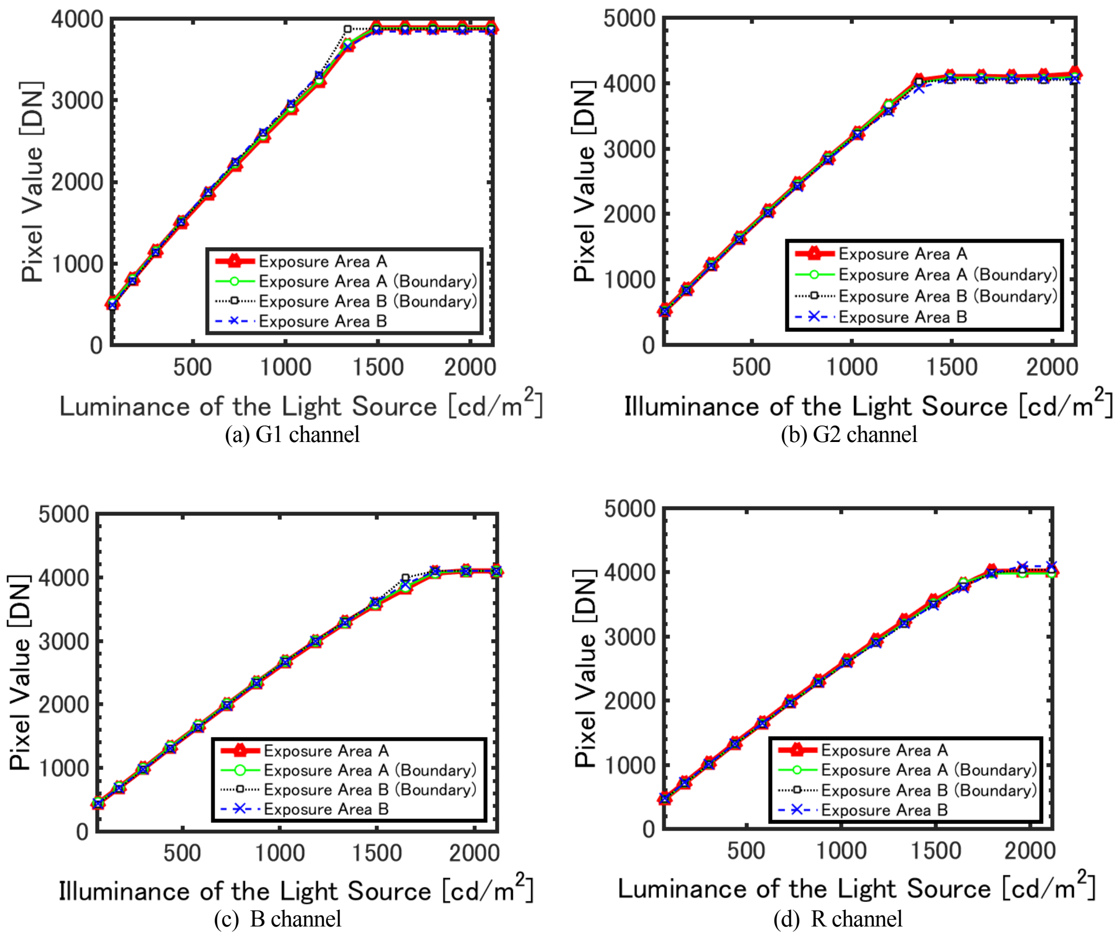

Figure 13. Results of correcting sensitivity characteristics

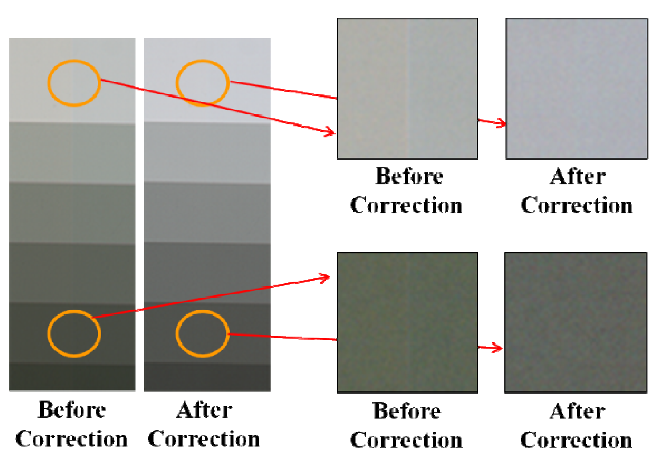

Figure 14. The result of a correction experiment in shooting grayscale

DOI: 10.2352/ISSN.2470-1173.2016.12.IMSE-271

Conclusion

We have developed the world's-first 8K full-resolution image acquisition system using a 133-megapixel CMOS image sensor. Using this system, an 8K full-resolution video signal can be obtained in real-time. The size of the camera head is drastically reduced compared with conventional 8K full-resolution cameras. In addition, measurement results for sensitvity characteristics of the 133-megapixel CMOS image sensor reveal that the sensitivity difference is seen not only in each exposure area but also in the pixels just on the exposure boundary. The off-line correction results indicate that the proposed method reduces the sensitivity difference.

From the results for the developed 8K full-resolution image acquisition system using a 133-megapixel single-chip CMOS image sensor, it can be seen that the system resolves the trade-off between size and resolution performance. In the future, we plan to develop a prototype camera system for practical-use, including signal processing circuits based on the proposed method. Furthermore, we plan to develop imaging equipment that achieves a broad color gamut and high dynamic range.

Acknowledgements

The authors would like to thank Mr. Taku Tsukamoto and Mr. Kazuki Endo of Astrodesign Inc. for their help in developing the 8K full-resolution single-chip color image acquisition system.

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Author Biography

Tomohiro Nakamura received BS and MS in electrical engineering from Waseda University (2006 and 2008, respectively). Since then he has joined in Japan Broadcasting Corporation (NHK). Since 2012, he has been engaged in research of UHDTV2 camera systems at NHK Science and Technology Laboratories. He is a member of the Institute of Image Information and Television Engineers of Japan (ITE)