A day and night MOS imager spectrally adjusted for a wide range of color temperatures

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ABSTRACT

We present a day and night MOS imager based on a single plate on-chip interference color filter. The filter comprises periodic multiple layers of TiO_2 and SiO_2, with an intermediate color selection layer (SiO_2) to disturb the period of the layers, analogous to a “defect” layer in the one-dimensional photonic crystal. A particular advantage of this filter is flexibility of designing a spectral profile of each color. Thus, one unit cell of the present MOS imager is designed to have three multi-spectral, i.e. R+IR, G+IR, B+IR, pixels and one IR dedicated pixel, which would never be realized by ordinary pigment materials. Daytime color image signals are obtained by subtracting the IR pixel signal, as a reference, from each signal of R+IR, G+IR and B+IR pixels. Nighttime black and white imaging is simply realized by using the IR components of all the pixels as brightness signals. This enables seamless switching between the day and night operations of a camera. Although the subtraction operation usually reduces the dynamic range (DR) and signal-to-ratio (SNR), in particular at low color temperatures, we overcome the issues by employing a new design scheme of the color filter comprising double defect layers for each visible pass band and narrow IR pass bands for common IR components. As a result, signal degradations in SNR and DR are suppressed even at low color temperatures enabling daytime imaging in a wide range of color temperatures from 2300 K to 6500 K.

Keywords: day and night imager, CMOS image sensor (CIS), color filter array (CFA), near infrared imager, automotive camera, interference filter, photonic crystal

1. INTRODUCTION

Day and night vision MOS imagers have a variety of applications such as network, security and automotive cameras. We have been developing a MOS imager with RGB and IR color filters integrated on a chip that is perfectly suitable for these uses [1-3]. The one-dimensional photonic crystal color filter (PCCF) technology plays a vital role in realizing the MOS imager. The PCCF consists of periodically alternating transparent multi-layers with high and low refractive indices, giving rise to a forbidden spectral band of light propagation. By incorporating a different-thick defect layer in the periodic multi-layers that disturbs the periodicity, transmission bands, e.g. R+IR, G+IR, B+IR, and IR bands, can be introduced into the bandgap [4]. Daytime imaging is realized by subtracting the common IR components, obtained from the IR pixel signal, from the R+IR, G+IR and B+IR pixel signals. Nighttime scenes are imaged by simply using the IR signals of all types of the pixels. With this technology, a mechanical IR cut filter in a camera system can be made unessential. This, in turn, enables seamless operation of the camera, which is crucial for continuous monitor applications. On the other hand, the major drawbacks of the system are reductions in dynamic range (DR) and signal-to-noise ratio (SNR), because the signal processing is based on the subtraction operation that inherently reduces the total amount of signals. This is particularly serious at low color temperatures (3000 K or less) corresponding to early evening or dawn. The DR and SNR reductions in these environments are as large as 5 dB, while these at high color temperatures (6500 K or more) are only 2 dB. In this work, we present a MOS imager with a newly developed PCCF that circumvents the above issue. The signal deteriorations are determined by the ratio of the common IR components in each color signal, which is also a function of the bandwidth of the IR pass band. The new PCCF improves the spectral characteristics of both in visible and IR regions. Firstly, to increase each visible color component, the new PCCF has two defect layers giving rise to broadening of the pass band of the RGB colors by twice or 6 dB. Secondly, in order to reduce the common IR components, the bandwidth of the IR band is reduced to one half of the original one by increasing the total number of

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the layers. Thus, the new PCCF significantly improves the SNR and DR of the RGB color images. Signal degradations of SNR and DR are suppressed to 2 dB even at low color temperatures, and at high color temperatures, these are as small as 1 dB. Thus, we demonstrated a day and night MOS imager with high SNR and wide DR in a wide range of color temperatures.

The organization of this paper is as follows. In Section 2, basic principles of the day and night MOS imager of the present work are described. In Section 3, the new design of a PCCF that realizes the broad visible and the narrow IR pass bands is introduced. In particular, the signal-to-noise ratio (SNR) and the dynamic range (DR) are estimated in detail both as functions of color temperatures. In Section 4, experimental results that demonstrate excellent color reproduction together with the SNR and DR performance estimation given above are presented. Finally, we give a brief discussion on the present results with regard to application aspects.

2. BASIC PRINCIPLES OF THE PCCF BASED DAY AND NIGHT MOS IMAGER

In Fig.1, the basic principles of the daytime and nighttime imaging modes of the present imager are described [4]. The imager should have a single color filter with transmission colors of R+IR, G+IR, B+IR and IR for each unit cell. As shown in Fig. 1(a), color imaging during the daytime is realized by subtracting the IR components common to all pixels. On the other hand, black and white imaging during the nighttime is simply obtained by using the IR signals available from all the pixels (Fig. 1(b)). Because signals due to IR radiation are removed by signal processing, IR cut filters used in ordinary day and night cameras are unnecessary for this type of the MOS imager. It is noted that there may be adjusting parameters of multiplicative coefficients (described as K_R, K_G, and K_B in Fig. 1 (a)) of subtracted IR components possibly different for different colors. This, in turn, brings about an issue of white balancing or spectral adjustment for different color temperature environments as described in Section 4.

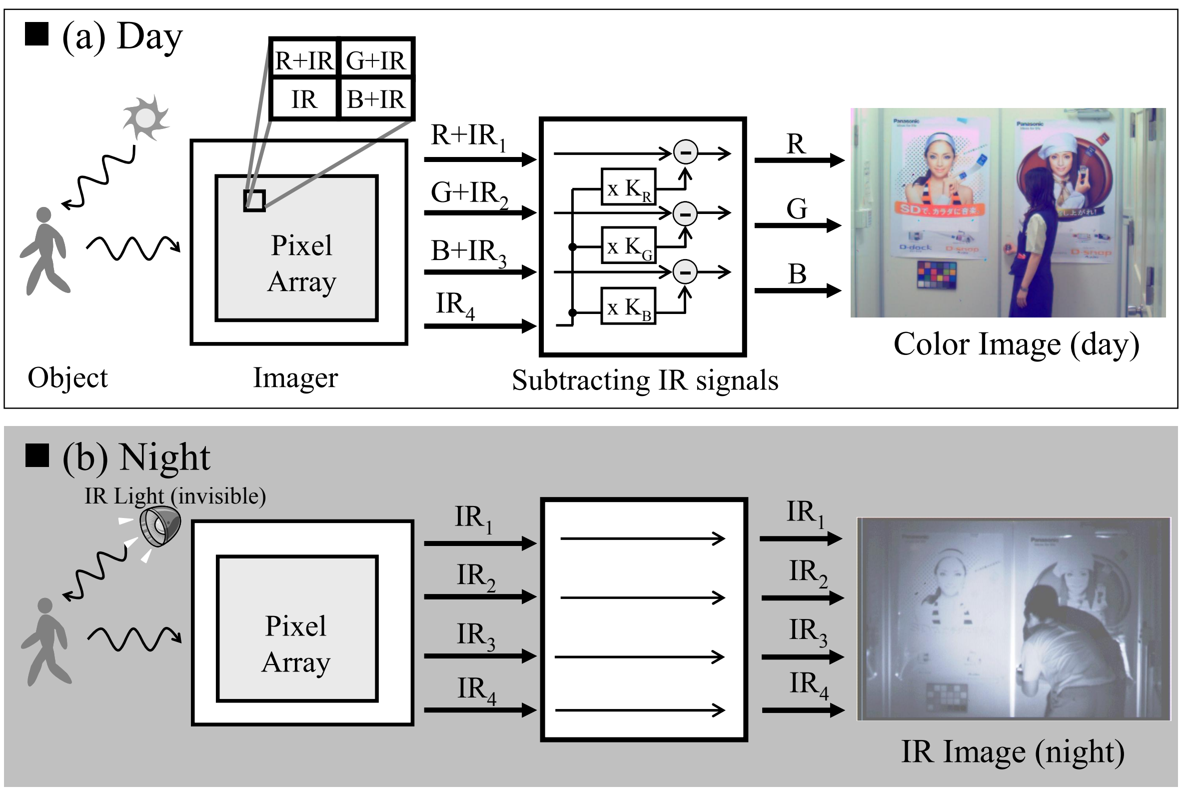


Fig. 1. Basic principles of daytime imaging (a) and nighttime imaging (b) with the present MOS imager comprising a single plate color filter with R+IR, G+IR, B+IR and IR color pixels. Daytime imaging is based on common IR components subtraction from visible-IR compound pixel signals while the nighttime imaging simply realized by using the IR signals obtained from all the pixels as the brightness signals.

In order to ideally realize such operational principles as described above, the targeted spectral profiles of each pixel are shown in Fig. 2. An important point is that the common IR components should line up perfectly each other. Otherwise, on subtraction, a false color can be easily made. Such false color production is particularly serious for objects with high IR reflectance such as plants, flowers, and textile materials and for illumination environments with high amount of IR radiation, that is, at low color temperatures.

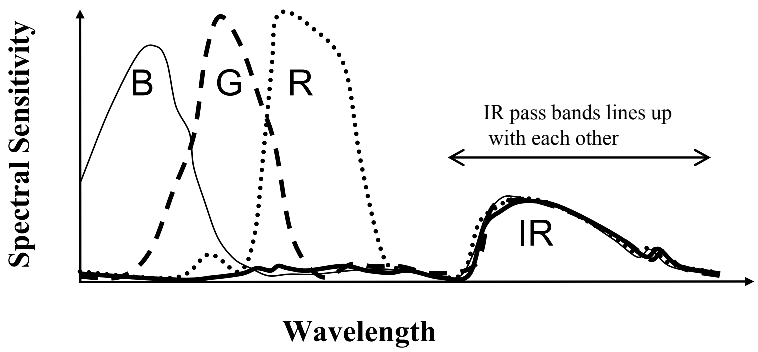


Fig.2. Targeted spectral profiles of the day and night MOS imager that realize IR signal removal by signal processing.

3. DESIGN OF THE PHOTONIC CRYSTAL COLOR FILTER WITH BROAD VISIBLE AND NARROW IR BANDS

3.1 Spectral Design

We previously reported a single plate color filter based on one-dimensional photonic crystal concept [5]. In that scheme, the core structure of the filter comprises periodic multiple pairs of materials with two different refractive indices and a period disturbing "defect" layer inserted into the pairs. The core is responsible for production of a band gap for light propagation while the "defect" layer enables formation of a pass band of each color at any position in the band gap [5]. The basic methodology originates from the well established design methodology of the Fabry-Perot interference filter [6,7]. However, the present color filter requires two additional spectral characteristics; (1) broader pass bands of visible range of radiation. (2) narrower pass band of IR associated with all the pixels.

In Fig. 3, the designed filter structure (a) and a cross sectional image of scanning electron microscope of a fabricated MOS imager (b) are shown. For specification (1), we employ "double defect layers" approach in which the visible pass band is created by two identical defect layers. The mechanism that leads to effective broadening of the original pass band is "level splitting "of the original pass band levels. Note that the coupling layer of the present filter consists only of one quarter-wave layer of the low refractive index material in contrast to the conventional coupling approach where at least two simple stacks are used in addition to a coupling layer [6].

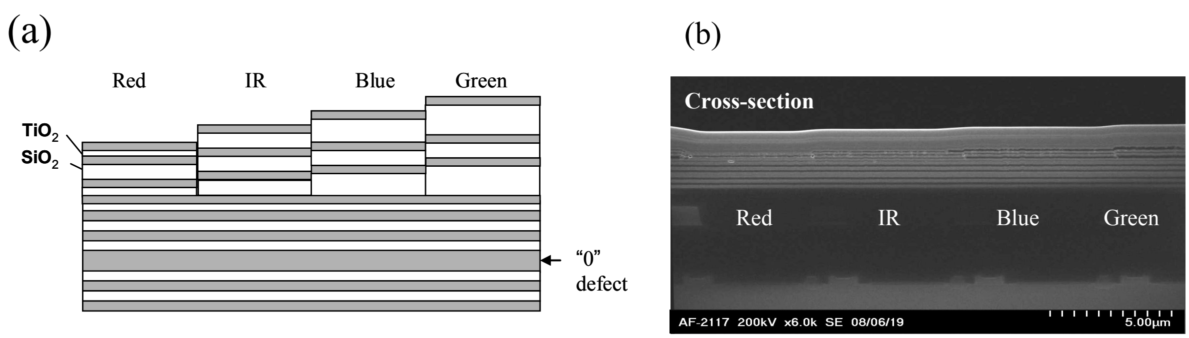


Fig. 3 The basic structure of the new PCCF (a) and a cross sectional SEM image (b) of a fabricated device. The specification of film thickness is summarized on Table 1.

Our approach dramatically reduces the total number of layers, at most 6 for each visible color, which is essential to applications to image sensors. The simulated spectra of the structure of Fig. 3 (a) are shown in Fig. 4 (a) for all the colors.

For specification (2) above, we introduced a new IR canonical filter of which spectral profile shown in Fig 4 (b) comprises visible pass band and a narrow IR pass band. The IR canonical filter constitutes the lower part of the new filter shown in Fig. 3 (a). This part is essentially regarded as a one-defect-layer cavity with "0" (zero) thickness defect structure as indicated by an arrow in the figure. Such an approach of adding another type of PCCF to the original visible filters is the consequence of impossibility of forming two transmission bands "apart" with two defect layers.

The final spectra are obtained by multiplication of the two sets of the spectra of Fig. 4 (a) and (b) for each color and shown in Fig. 4(c).

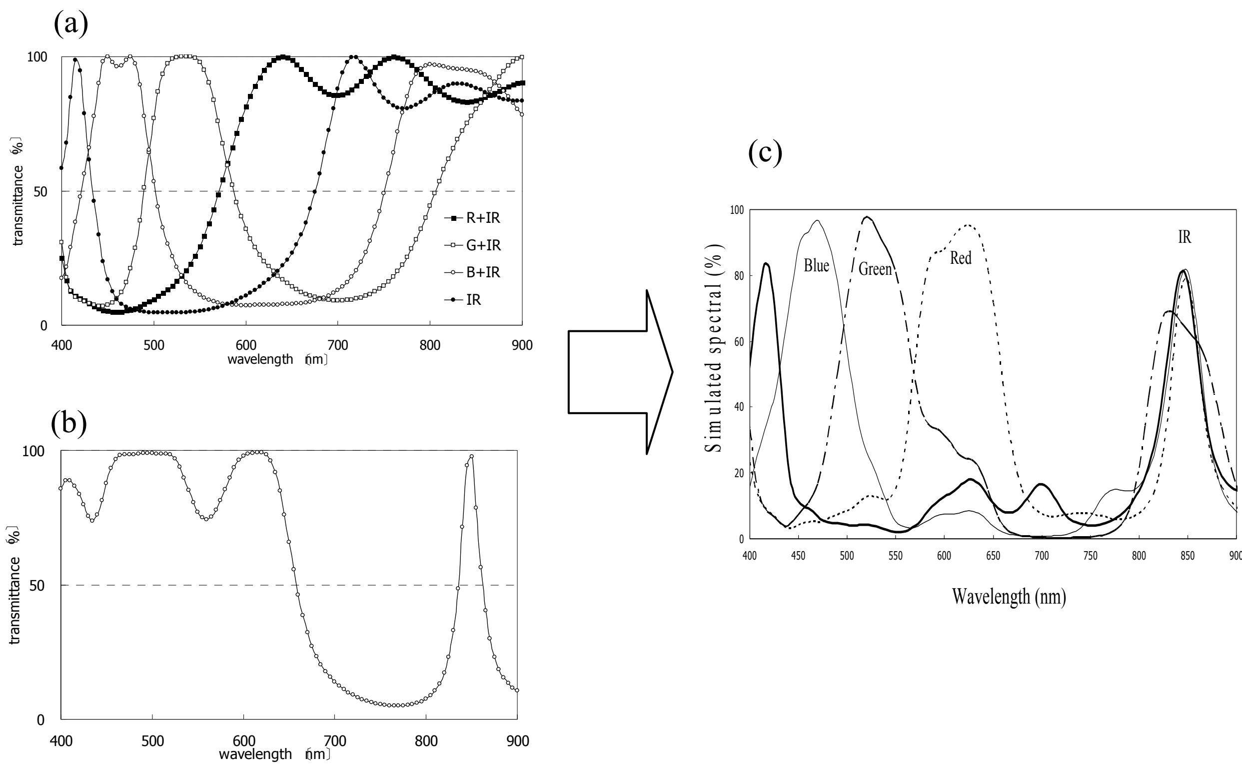


Fig. 4 Spectral profiles of the color transmission part of all the pixels (a) and the IR pass band part that narrows only the IR band of each color (b). The total profiles of each color are shown in Fig. 4(c).

3.2 Estimation of signal-to-noise ratio (SNR) and dynamic range (DR)

Compared to the conventional method of IR component cut by a mechanical IR cut filter, the signal-to-noise-ratio (SNR) and the dynamic range (DR) of the present imager are reduced because of the subtraction operation that reduces the signal power and the dynamic range and increases the noise power. Therefore, in the following, we estimate the two variables of the present filter based on a simple model in which the signal components are assumed to arise from a black body radiator and the noise is assumed to be entirely due to shot noise giving rise to square-root dependence of both SNR and noise amplitude. In Fig. 5, the basic procedure to calculate SNR and DR for a visible color pixel is illustrated.

Firstly, the noise components (amplitudes) of the visible color (N_{VIS}) and IR (N_{IR}) are described as

$$N_{VIS} = \sqrt{S_{VIS}} \tag{1}$$

and

$$N_{IR} = \sqrt{S_{IR}}\ , \tag{2}$$

where S_{VIS} and S_{IR} are signal power of visible and IR components, respectively. The noise amplitude of the signal before the IR subtraction is,

$$N_{p1} = \sqrt{S_{VIS} + S_{IR}}\ . \tag{3}$$

When a signal component is subtracted from another signal component, the noise powers are summed up. Therefore, the total noise after subtraction of the IR component is

$$N_{p2} = \sqrt{N_{p1}{}^2 + N_{IR}{}^2} = \sqrt{(S_{VIS} + S_{IR}) + S_{IR}}\ , \tag{4}$$

which leads to the total SNR after subtraction as

$$SNR = \frac{S_{VIS}}{N_{p2}} = \frac{S_{VIS}}{\sqrt{(S_{VIS} + S_{IR}) + S_{IR}}}\ . \tag{5}$$

Plugging into the expression for the black body radiator into the signal terms, we estimated SNR as functions of color temperature. The results are plotted in Fig. 6 (a), (b), and (c), corresponding to the red, the green, and the blue pixels, respectively. Because of increase of S_{IR} with the fall-off of the color temperature, in general, SNR decreases with respect to fall of color temperature. It should also be noted that the SNR reduction is more serious with the blue pixel than those of green or red pixels due to reduced silicon spectral sensitivity in the short wave length region. We note that the newly designed filter improves both SNR of red, green, and blue signal by 3.2 dB, 4.2 dB, and 8.0 dB at a temperature of 2800 K. This is the consequence of the present design method in which pass band broadening of each color and narrowing of the IR pass band are simultaneously achieved.

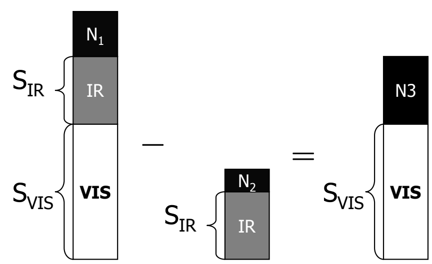
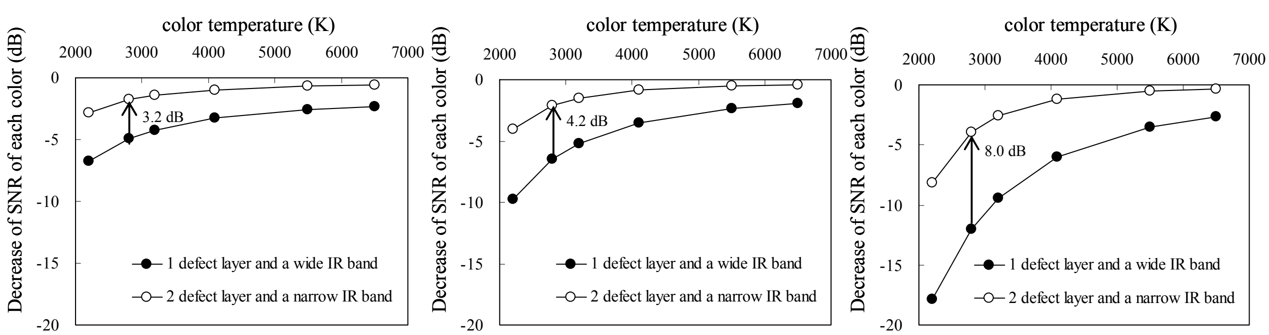


Fig. 5 Basic principle of the SNR calculation.



(a) Red (b) Green (c) Blue

Fig. 6 Calculated SNR of single and double defect layer configurations for red (a), green (b), and blue (c) pixels as functions of color temperature. Note for all the colors, the SNR are significantly improved with the present double-defect-layers configuration with the narrow IR pass band.

Table 1. Summary of the specification of the present MOS imager

Pixel size		5.6 μm x 5.6 μm
Photonic color filter	Pixel color	Red, Green, Blue, Near Infrared
	Principle	Photonic Crystal
	Material	TiO_2, SiO_2
	Layers	7
	Thickness of defect SiO_2 layer	45 nm (Red), 185 nm (Green), 140 nm (Blue), 90 nm (Near Infrared)
	Thickness of SiO_2 layer	91 nm
	Thickness of TiO_2 layer	52 nm
	Color lifetime	> 200,000 hours
	Heat resistance	> 300 °C
IR canonical filter	Layers	10
	Thickness of defect SiO_2 layer	0 nm
	Thickness of SiO_2 layer	146 nm
	Thickness of TiO_2 layer	84 nm
Dynamic range of nighttime imaging		65 dB
The number of pixels		750 (H) x 500 (V)
Saturation signal of a photodiode		45,000 electrons
Dynamic range of daytime imaging @6500K		63 dB
Dynamic range of nighttime imaging		65 dB
Frame rate		30 fps
Power supply voltage		3.3 V

4. EXPERIMENTAL RESULTS

We fabricate a MOS imager with the newly developed single plate color filter array via a 0.35 μm CMOS process. The cell size is 5.6 μm × 5.6 μm and the pixel arrangement is the panorama VGA format (750 (H) × 500 (V)). Primary parameters of the present MOS imager are summarized in Table 1.

In order to confirm the above, experiments for daytime color imaging were performed under different color temperature environments. In Fig. 7, the results are shown. Figures 7(a), 7(b), 7(c), and 7(d) are, respectively, the images taken at color temperatures of 6500K, 4150K, 2850K, 2300K.

Excellent color reproduction is demonstrated for all the color temperature settings. The constancy of the greenish color of the leaves of the plants is particularly emphasized. The IR reflectance of the leaves is extremely high, so that it is easy to result in false color with insufficient subtraction or complete elimination of the IR components which often occurs with conventional imagers without IR cut filters. The trees with, for example, “pink leaves” are typical experiences.

Another point to be made is the constancy of “black” for the textile object posted on the top raw of the board on the right side. Above the small color chart at the center, there exists a black object that is invisible due to perfect black reproduction in all the color images. As mentioned before, textile objects also reflect IR radiation significantly, false color would have been caused for this object unless IR components were properly subtracted.

As a reference, we took an IR image of the same objects under an LED illuminated condition (Fig. 7(e)). The wave length and the irradiance power of the scene are, 850 nm and 200 μW/cm^2. Once again, the leaves of the plant and the textile object on the top raw of the board are seen to be extremely bright demonstrating their high reflectivity in the IR region. We therefore conclude that splendid color reproduction immune to color temperature variation is the demonstration of successful operation of the new design, i.e. the combination of the broadening of the visible color bands and the narrowing of the IR pass band with perfect lining up of the band profiles between different colors.

Fig. 7 Color images obtained after IR subtraction operation taken at different color temperatures. (a) 6500K. (b) 4150K. (c) 2850K. (d) 2300K. Image (e) is an IR image taken under LED illumination condition. The wavelength and the power of the LED source are 850 nm and 200 μW/cm^2.

5. DISCUSSIONS

The results presented in the previous section are entirely due to the optimized design of the spectral profiles of the new color filter. Without the perfect line-up of the IR pass band, there could have been significant false color production especially at low color temperatures. As noted already, the lower the color temperature, the more the relative content of the IR power in the illumination source, which, in turn, could be mixed into the visible signal components. As for the total IR sensitivity, because the signals are obtained from all the pixels, reduction of the total IR power is practically insignificant for ordinary applications. For the applications that require high sensitivity such as a night-viewer of an automotive system, the trade-off between the IR sensitivity and the bandwidth of the IR pass band needs to be carefully considered. It is also noted that the daytime SNR of the present MOS imager is improved by 2 dB compared with the previous one with the narrow visible pass bands confirming the design strategy of the present device.

6. CONCLUSION

We have demonstrated excellent color reproduction capability of a day and night MOS imager based on a single plate color filter with broad visible- and narrow IR-pass bands. The perfect line-up of the IR pass bands with each others guaranteed such performance. This owes much to the flexibility in spectral profile design with the one-dimensional photonic color filter engineering methodology. Such a day and night imager is believed to play a vital role in automotive, network and security camera systems.

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