Highly Sensitive Image Sensors Using Micro Color Splitters

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Abstract

We developed unique micro color splitters, which can disperse light incident upon image sensors by exploiting property of light as a light-wave behavior, and has succeeded in achieving highly-sensitive color photograph by applying them to actual image sensors. Color alignment avoiding the use of color filters is permitted using the micro color splitters which control diffraction phenomena of light in microscopic area, approximately 2-fold higher sensitivity in color photograph in comparison with a conventional method using color filters has been achieved.

Keywords: image sensor**,** micro color splitter, deflector, diffraction, highly-sensitive, color filter, Bayer array

1. Introduction

Image sensors are used in devices like smartphones, digital cameras and video cameras, as well as for security use, vehicle, offices, and healthcare applications —anywhere, in fact, that digital imaging is needed. Progress is being made in increasing the resolution of image sensors used in mobile and other devices by reducing pixel size, but demand for higher-sensitivity cameras is also increasing. The pixel size in state-of-the-art image sensors is now approaching 1 μm, and this is placing a practical limit with respect to the signal-to-noise ratio of detected signals. The mainly possible strategy for overcoming this limit is to retain the maximum amount of light received at the pixels by optimizing micro-lenses or using a light-guiding structure or a back-illuminated structure (BSI, Back Side Illuminated image sensor) [1-3]. All of these approaches use a Bayer array, in which a red, green, or blue light-transmitting filter is placed above each sensor. These filters block 50 - 70% of the incoming light before it even reaches the sensor. We have proposed a new method (a MiCS, or MIcro Color Splitter) [4] to split colors without absorption by using a miniature plate-like structure (a deflector). Here we show that the application of this method to an image sensor allows a dramatic improvement of the sensor's light-receiving efficiency.

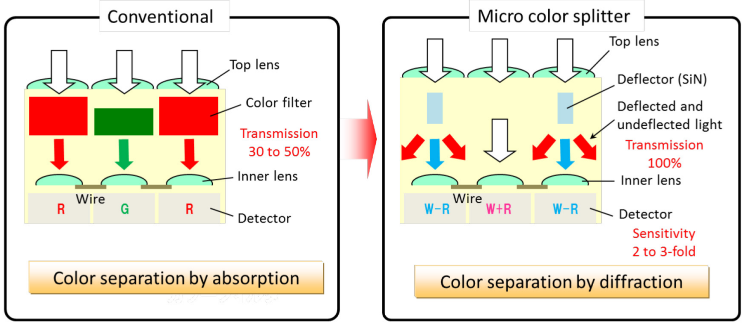

Fig. 1 Constitution and feature compared with the conventional method

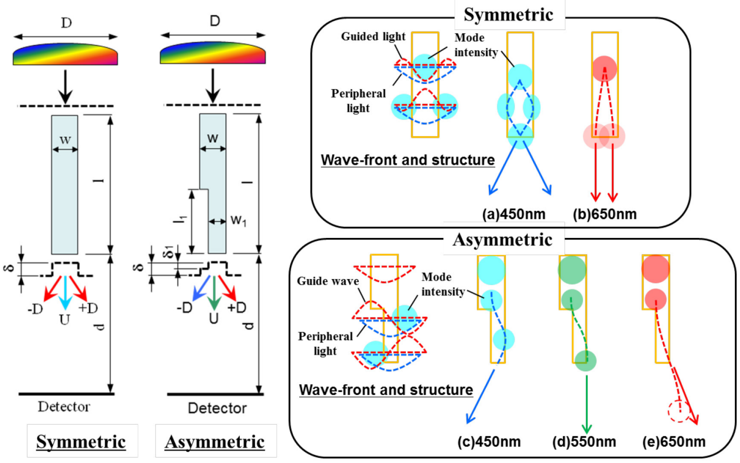

Fig. 2 Principle of deflectors

2. Operational principles

There are two structures within a MiCS: a symmetric deflector and an asymmetric deflector. The symmetric deflector has a plate-like structure and comprises a transparent medium that has a higher refractive index than the surrounding material, and light is separated into a primary color and its complementary color. As shown in Fig. 2, when light enters a symmetric deflector, a phase difference δ develops between the light (or the guided light) propagated through the deflector and the light (or the peripheral light) propagated through the surrounding volume. If δ is an even multiple of π, the transmitted light becomes undeflected light (U), and if δ is an odd multiple of π, the transmitted light becomes deflected light (+D and –D). The phase difference δ rises and falls as a function of wavelength λ, so the ratio between the amount of the undeflected light and that of the deflected light varies depending on λ. In contrast, the asymmetric deflector has a structure whose side surface has a step that distinguishes it from the shape of a symmetric deflector, and light is separated into red-green-blue. When light enters an asymmetric deflector, phase differences δ and δ_1 develop between the guided light and the peripheral light. These phase differences closely approximate a slanted wave-front. As the phase differences δ and δ_1 rise and fall as a function of wavelength λ, their polarity may change. In short, the direction of propagation of the deflected light varies as a function of wavelength. These phenomena can also be explained by the transformation of a guided-mode. The mixed mode produced by the interference of the guided light and the peripheral light is (a) joined together (and light deflects after radiation from the edge of the deflector), or (b) separated into either side (and light undeflects after radiation), or snakes and deflects to (c) the left side, (d) the center, or (e) the right side. The status of the mixed mode at the guided edge determines the direction of deflected light.

Here we apply a method to reproduce colors by combining the outputs of the R- and B- symmetric deflectors using a 2-dimensional CCD (Charged-Coupled Device). As shown in Fig. 3, the R- and B-deflectors are located on alternate detectors along adjacent lines in the vertical transfer direction. Light entering the R- or B- deflector is undeflected or deflected respectively. Undeflected light impinges on the detector below the deflector and deflected light enters the closest detector on the right and the closest detector on the left. Light entering the space between neighboring R-deflectors or neighboring B-deflectors impinges on the detector located midway between them. Detectors are classified as being in four areas: between neighboring R-deflectors, just beneath the R-deflectors, between neighboring B-deflectors, and just beneath the B-deflectors. These respectively detect the colors of W+R, W-R, W+B, and W-B. Red, green, and blue are obtained from the equation (1) using this color combination.

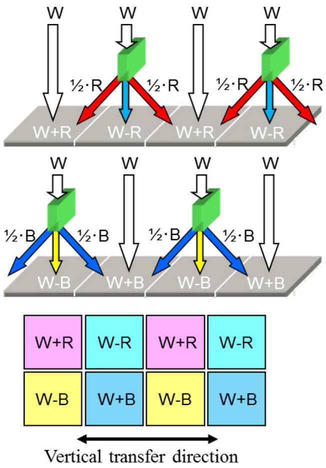

Fig.3 Two deflector layout

$$\begin{pmatrix} 2R \\ 2G \\ 2B \end{pmatrix} = \begin{pmatrix} 1 & -1 & 0 & 0 \\ -1/2 & 3/2 & -1/2 & 3/2 \\ 0 & 0 & 1 & -1 \end{pmatrix} \begin{pmatrix} W+R \\ W-R \\ W+B \\ W-B \end{pmatrix} \quad (Eq.1)$$

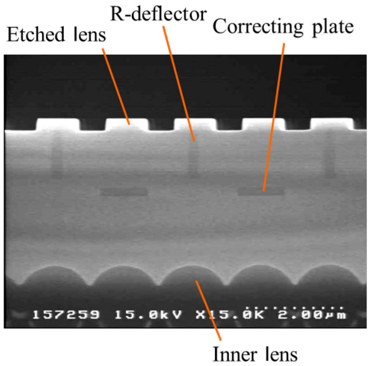

Fig.4 Cross-sectional SEM

3. Fabrication and imaging characteristics

R- and B-deflectors were formed on conventional CCDs (MN34570, Panasonic) with a 1.43 µm-square pixel (14 million pixels) in which inner lenses had been fabricated. Figure 4 shows a cross-sectional SEM photograph of the MiCS image sensor (MiCS-IS). The symmetric deflectors (silicon nitride) were designed to take account of the fact that the cross-sectional shape is trapezoidal. Instead of a reflow process, an etching process was adopted for forming the micro-lens (silicon oxide). Furthermore, a correcting plate (silicon nitride) with a higher refractive index than the surrounding material (silicon oxide) is positioned on the path for the light beam (white light shown in Fig. 3) transmitted between two neighboring deflectors. The correcting plate has the effect of collecting the transmitted light, giving it the same function as an inner lens.

We installed a fabricated MiCS-IS in an experimental camera and succeeded in displaying color images using the above arithmetic process. Figure 5 shows a comparison of a picture image after color correction using the MiCS-IS with that using the color filter method. From comparisons of their experimental spectroscopic characteristics, we confirmed the amount of light received to be 1.85-fold that of the color filter method using the Bayer array. We also confirmed the resolution to be closely comparable to that obtained using the color filter method.

4. Conclusion

We demonstrated a unique principle that a microscopic plate-like structure caused color-splitting. Conventional diffractive gratings [5] are based on the principle of interference by phase-matching of periodic wave surfaces of diffracted light, and so they split colors in the far field. In contrast, the color-splitting principle of our structure is based on self-interference along the deflector, so the color-splitting occurs in the near field and this allows the application to high pixel-density image sensors. We also demonstrated the potential for abolishing color filters and replacing them with color-splitting using two symmetric-deflectors. The data demonstrate that our MiCS-IS color splitters dramatically improve the amount of light received compared with conventional image sensors, while maintaining the same level of resolution. On the other hand, the color purity of our method might be of concern, since the area ratio responsible for color separation (that is, the R- and B- deflector area) is half of the entire area. We are considering some improved methods

Micro color splitter　　Conventional method (color filter)

Fig.5 Comparison of images

other than the two-deflector scheme. For example, other than B- and R- deflectors, we have discovered the potential for Green-, Magenta-, and Yellow- deflectors. Employing a combined G- and M- deflector and a B- and Y- deflector instead of the combination of an R-deflector and white, white and B-deflector, the area ratio responsible for color separation would rise 100%, making it possible to improve the color purity.

We believe that the MiCS-IS shows promise as a new method for creating high-sensitivity next-generation detectors. We plan next to examine the drawbacks of MiCS-IS, with the intention of expediting its practical use.

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