Full-Color AR Display Based on Thin Grating in Waveguide Element

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ABSTRACT

This study proposed the AR device composed of two diffractive waveguide combiners to achieve a 32.6° full-color display function. The first waveguide provides the red image and half of the green image. The other one provides the blue image and the other part of the green image.

1 Introduction

Augmented Reality (AR) is the technology that combines virtual and reality. It is often combined with Head Mounted Display (HMD) to transmit the required information to the human eyes. However, the traditional See-through HMD system made of geometric optical elements has a large volume and heavyweight. In recent years, HOEs have been used to replace the traditional geometric optical elements and combiner in the system. HOE has the advantages of simplifying and miniaturizing the system [1,2].

The common manufacturing methods of full-color holographic waveguide elements (HWEs) are using wavelength multiplexing, the method of recording each red light, green light and blue light grating in the same photosensitive material to achieve the full-color display. In the case of reconstructing the image with wavelength multiplexing, if full-wavelength light is coupled into the waveguide, the grating with wavelength multiplexing may cause crosstalk interference, or to avoid crosstalk resulting in a smaller full-color Field of View (FOV) [3]. In the case of being composed of multiple reflective HWEs, the overall volume will be increased, and to achieve a large FOV angle multiplexing is required [3].

In this study, to avoid these problems and inconvenience of the manufacturing process by wavelength multiplexing and angle multiplexing, and the problems of composing multiple waveguides to achieve full-color display leading to the large size of the whole system, etc. Finally, by simulation, analysis to determine the recording conditions, and using the photoresist to generate the thin grating to manufacture the DOE. It is further reduced to only composed of two diffractive waveguide elements (DWEs) to achieve a full-color FOV. The first DWE provides a larger red light FOV and a positive green light FOV, the other one provides a larger blue light FOV and a negative green light FOV. The aberration of this device can be compensated by symmetrical grating structure, and because the thin grating has low angular selectivity and low wavelength selectivity this device can achieve a larger full-color FOV display.

2 Experiment

The functional schematic diagram of the system is shown as Fig. 1. It is expected that only composed of two DWEs to achieve a full-color FOV, so each red light, green light and blue light FOV must be confirmed by simulation. First, the recorded parameter of the grating is simulated by MATLAB, using the grating formula Eq. 1, to change the diffractive angle parameters of the light diffractive coupling into the waveguide, and both must meet the condition of total internal reflection (TIR) in the waveguide. And find which condition that composing of two DWEs can achieve a larger full-color FOV. Where θ is the angle of incidence, φ is the angle of diffraction, m is the order of diffracted light, d is the grating period, λ is the wavelength of incident light, n_1 is the refractive index of the incident medium, and n_2 is the refractive index of the diffractive medium. The light source used in the simulation are the red, green and blue LED, the center wavelength of which is 633 nm, 530 nm, and 449 nm respectively.

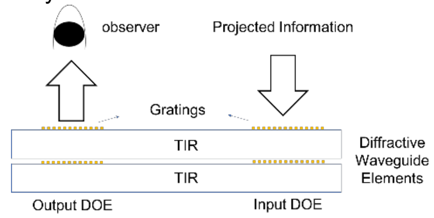
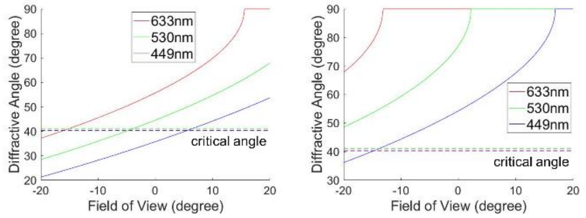


Fig. 1 The schematic diagram described the full-color AR display composed of two diffractive waveguide elements.

$$d(n_1 \sin\theta - n_2 \sin\varphi) = m\lambda \tag{1}$$

$$n_1 \sin\theta_1 = n_2 \sin\theta_2 \tag{2}$$

The interference fringes are recorded on a photoresist layer on the glass substrate to generate a thin grating, and this photoresist material (AR–P7400) is sensitive to 405 nm LASER, so selecting 405 nm LASER to form a grating. In order to simplify the manufacturing process, the experiment chose to interfere in free space. Eq. 2 Snell's Law is brought into Eq. 1, Eq. 1 can be changed to $d(\sin\theta - \sin\theta_{air}) = -405$, where the $m = -1, n_1 = 1$ and $\lambda = 405$. It is expected that the period of DWE 1 made can provide a larger red light FOV and a positive green light FOV, as shown in Fig. 2(a). The vertical axis is the diffractive angle of light in the waveguide, and the horizontal axis is the FOV. The element is directly vertically facing the observer and the projected information, so the FOV is equal to the incident angle, and the diffractive angle is the angle propagated in the waveguide. The final available DWE 1 needs to use $0°$ and $54.6°$ for recording, as shown in Fig. 3, which θ is $0°$. And we can get $d_1 = 497\ nm$. Similarly, the period of DWE 2 made can provide a larger blue light FOV and a negative green light FOV, as shown in Fig. 2(b). The DWE 2 needs to use $-18.49°$ and $54.6°$ for recording, as shown in Fig. 3, which θ is $-18.49°$. And we can get $d_2 = 358\ nm$. As a result of the simulation, we can achieve a $31°$ full-color FOV when two DWEs are composed.



(a) (b)

Fig. 2 The relationship between incident angle and propagating angle of (a) DWE 1 and (b) DWE 2 was utilized to expect the FOV with different wavelengths backlight.

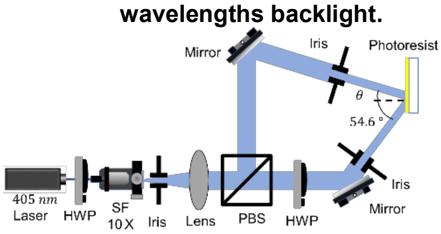


Fig. 3 The recording system for DWE. HWP: half-wave plate; PBS: polarized beam splitter; SF: spatial filter.

The interference area is a circle with a diameter of 2 cm, and the input DOE and output DOE are recorded on the same side of the photoresist to form the symmetrical grating structure. The photoresist is used AR–P7400, and the developer is AR 300–26.

Because the photoresist layers on the glass substrate, there will be parameters refractive index n of glass in simulation. In experiment, we use the red light, green light and blue light LASER to measure each Brewster's angle, the wavelengths of which are 640 nm, 532 nm, and 473 nm respectively. Take each Brewster's angle to change to refractive index and critical angle, by using Eq. 3. Taking the range of wavelengths of 400 nm to 500nm as an example, only one value of n is used in the simulation. It is obtained from Brewster's angle of the 473 nm LASER. There we ignore the dispersion caused by other wavelengths in the waveguide. Similarly, being used only one value of n in the simulation ranges of 501 nm to 600 nm and 601 nm to 700 nm, respectively.

$$\tan\theta_p \frac{n_{glass}}{1}, \sin^{-1}\frac{1}{n_{glass}} = \theta_c \qquad (3)$$

Table 1. n_{glass} and θ_c of each wavelength

Wavelength(nm)	n_{glass}	θ_c
640	1.542	40.43°
532	1.520	41.12°
473	1.546	40.30°

3 Results

In order to measure the vertical and horizontal FOV, the 5 cm lens images the pattern at infinity, and the camera focuses at infinity. Then the half FOV can be described as

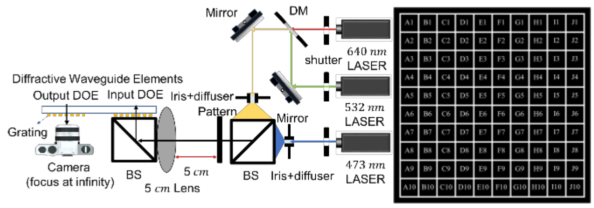
$$\theta = \tan^{-1}(w/f) \qquad (4)$$

where w represents the half-height or half-width of the pattern, f represents the focal length of lens.

When input a 10×10 square grid image with an input light source, and its theoretical horizontal and vertical FOV is 3.4° per grid.

3.1 LASER Backlight

First taking the LASER to confirm that whether the experiment is matching with the simulation, because using a single wavelength by simulation. Use the LASER as the light source to input image information where is imaged at infinity by lens to the DWE. The observation system and the input pattern information are shown as Fig. 4(a)(b), the pattern size of each small square is 3 mm by 3 mm.

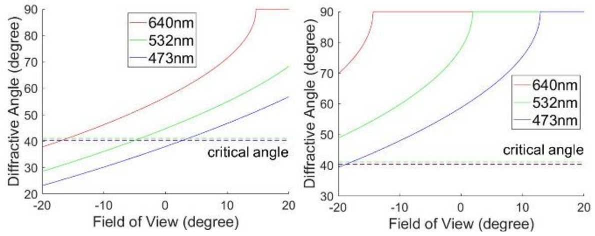


(a) (b)

Fig. 4 The final image with LASER backlight was recorded by (a) the experimental setup with (b) the target pattern. BS: beam splitter; DM: dichroic mirror.

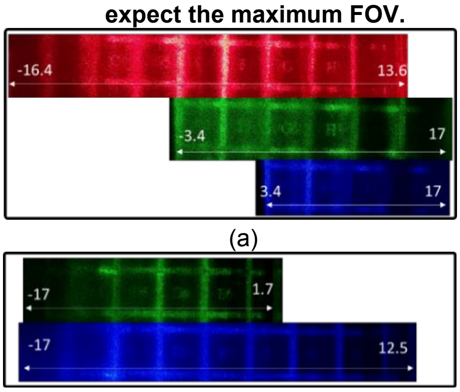
Select the wavelengths of which are 640 nm, 532 nm, and 473 nm LASER s as the backlight which is only a single wavelength. When the ideal DWEs use the LASER as the backlight, the simulated FOV are shown as Fig. 5(a)(b). For the DWE 1, it is expected that the red image FOV is $-16.7°{\sim}14.7°$, and the green image FOV is $-4°{\sim}17°$, and the blue image FOV is $2.8°{\sim}17°$. And for the DWE 2, it is expected that the red image FOV is $-17°{\sim}-14.3°$, and the green image FOV is $-17°{\sim}1.9°$, and the blue image FOV is $-17°{\sim}13°$.

It can be seen from Fig. 6 that experiment match the simulation, but also can be seen there don't have the red image for DWE 2. The reason is that the diffractive angles of red light for DWE 2 are too close to $90°$, so the low efficiency lets the camera cannot record a clear image.



(a) (b)

Fig. 5 The diffractive angle simulations of (a) DWE 1 (b) DWE 2 with each LASER were utilized to expect the maximum FOV.



(a)

(b)

Fig. 6 The experiment FOV of each color image with the LASER backlight provided by (a) DWE 1 (b) DWE 2.

Because the LASER has high coherence, they interfere with each other when propagated in the waveguide. And other noise caused by interference such as the Fabry-Pérot effect. The phenomenons all make the image blurry and have bright and dark faults.

3.2 LED Backlight

The LASER has been used to confirm that the experiment and simulation will be matched. For LED with a wider spectrum, we take the LED spectrum to add to the simulation. The spectrum of LED is shown as Fig. 7 respectively.

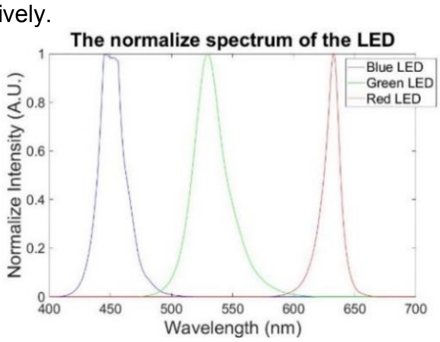


Fig. 7 The spectrum of the red, green and blue LED.

Due to adding the spectrum to the simulation, the simulated FOV increase, as shown in Fig. 8. The vertical axis is the wavelength of visible light, the horizontal axis is the FOV, the color bar is the diffractive angle. The wavelength of one-tenth of the maximum intensity is marked by a dashed line. The simulations are matched with the experiment. For the red, green and blue images FOV are superimposed, the device can achieve a $32.6°$ full-color FOV display. The blue area is indicated that the diffraction angle is less than the critical angle or greater than $90°$, which both don't meet the TIR.

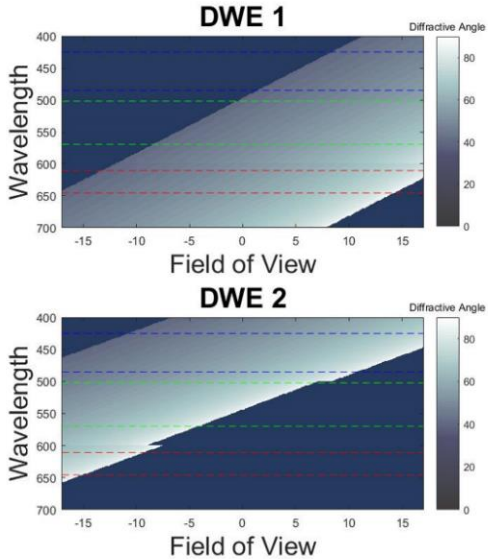
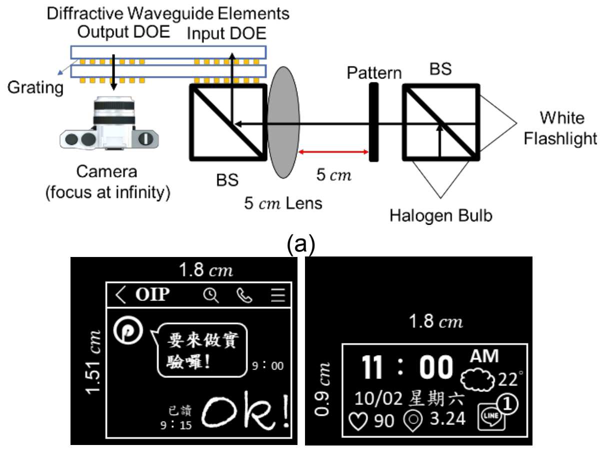


Fig. 8 The relationship between incident angle and propagating angle of DWEs was utilized to expect the FOV with each spectrum of the LED backlight.

3.3 Full-Color Images

In order to improve the color uniformity, we use the existing light source of the continuous spectrum as the backlight. Due to the low precision and flatness made at present, the DOE is inhomogeneous. Therefore, input the pattern with a smaller FOV and do the full-color display.

By composed of the two DWEs. The observation system is shown as Fig. 9(a), which using the white flashlight and the halogen bulb as the backlight. The spectrum of the white flashlight and the halogen bulb is shown as Fig.10. The input pattern information is shown as Fig. 9(b), the pattern size is $1.8\ cm$ by $1.51\ cm$, and the full-color image is shown as Fig. 11, among the horizontal FOV is about $20.4°$, the vertical FOV is about $17.2°$, and the diagonal FOV is about $26.4°$. It was needed to use the bottom of DWE to observe the bottom information of the pattern. But the bottom of the DWE 1 has low efficiency. In order to display full-color images with better color uniformity, so making the information of the pattern its vertical size is reduced, only the range where the efficiency of the DWE 1 is better, as shown in Fig. 9(c), the smaller pattern size is $1.8\ cm$ by $0.9\ cm$. The smaller full-color image is shown as Fig. 12, among the horizontal FOV is about $20.4°$, the vertical FOV is about $10.3°$, and the diagonal FOV is about $22.8°$.



(b) (c)

Fig. 9 The (a) full-color display system employed the (b) pattern 1; (c) pattern 2 to confirm the full-color FOV that this system can display.

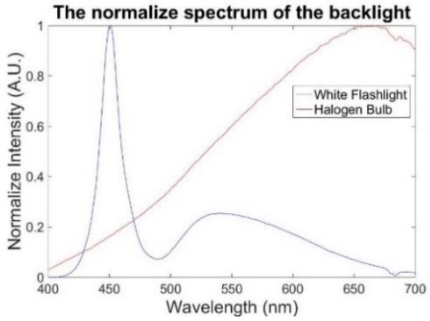


Fig. 10 The spectrum of the full-color displat based the white flashlight and the halogen bulb.


(a) (b)

Fig. 11 The full-color image for the larger pattern was recorded in (a) dark room; (b) bright room.


(a) (b)

Fig. 12 The full-color image for the smaller was recorded in (a) dark room; (b) bright room.

Due to the thin grating has low angular selectivity and low wavelength selectivity, when any wavelength is incident on the grating at any angle, the diffraction efficiency of the grating isn't much different, so that this device can be used for wide-wavelength and multi-angle incident light source. On the other hand, the aberration caused by a single linear grating can be compensated by the symmetrical structure.

4 Discussion

In the experiment, it is confirmed that the large horizontal full-color FOV DWEs are feasible. Due to the low precision and flatness made at present, the DOE is inhomogeneous. Except for improving the manufacturing process, we also hope to use a light source of a continuous spectrum that has the equal spectrum as the LED as the backlight, so as to have a larger full-color FOV display. And it is further display the dynamic information.

Finally, in order to improve color uniformity, uniform grating and glass etching are necessary.

5 Conclusions

In this study, a 405 nm LASER was successfully used to generate a linear grating and record it on a photoresist to generate a thin grating, and using the LED, LASER, and the white flashlight and the halogen bulb to display image information.

One of the common manufacturing methods of full-color HWE, that composed of multiple reflective HWEs. This device is reduced to only composed of two DWEs to achieve a larger full-color FOV. The first DWE provides the red image and half of the green image. The other one provides the blue image and the other part of the green image. Among them, the thin grating has the characteristics of low angular selectivity and low wavelength selectivity, so this device can achieve the 32.6° of horizontal full-color FOV with LED backlight, and also can reach the 20.4° of horizontal full-color FOV with the white flashlight and the halogen bulb as the backlight. The aberration of this device is compensated by the symmetrical grating structure.

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