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Design optimization of polarization volume gratings for full-color waveguide-based augmented reality displays

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Abstract

Reflective polarization volume gratings (PVGs) can be used as input and output couplers in a diffractive waveguide-based augmented reality (AR). To improve the stability and wearing comfort, a thin and lightweight full-color waveguide display is needed. In this paper, we propose a single full-color waveguide AR display based on PVGs. By analyzing the optical system, we derived the field of view limit by optimizing a three-layer PVG as an in-coupler. Pairing with a single-layer, thin PVG as an out-coupler, we can achieve a relatively uniform exit pupil of 8 mm at horizontal pupil expansion direction.

KEYWORDS

liquid crystal polarization volume grating, smart glass, waveguide display

1 | INTRODUCTION

With the rapid development of near-eye augmented reality (AR) displays, diffractive waveguide technology has received extensive attention due to its attractive thin form factor and exit pupil expansion (EPE) capability.[1] In diffractive waveguides, the current mainstream couplers are surface relief gratings (SRGs) and volume holographic gratings (VHGs). However, applying these diffractive optical elements as couplers in a waveguide still faces some challenges.[1] The manufacturing process of SRGs is complex, resulting in a low yield and high cost. Due to the small degree of index modulation, VHGs suffer from a narrow response bandwidth, which limits the achievable FoV and colors of waveguide displays. Recently, a novel liquid crystal reflective polarization volume grating (PVG) has been developed for the waveguide-based AR displays because of its high diffraction efficiency, large angular and spectral response, simple fabrication process, and high yield.[2–8] Many efforts have been made to improve its optical performance and employ it into waveguide displays, realizing a large field of view (FoV) and full color images.[9–12] In 2018, Weng et al.[10] designed and successfully fabricated a PVG-based full-color display with two waveguides. Subsequently, Gu et al.[11] further enlarged the FoV in the above two-waveguide structure by employing multilayer PVGs as couplers.

So far, the reported full-color waveguide designs require at least two glass plates due to the limited bandwidth of the in-coupler. It should be noted that the multi-waveguide structure suffers from the misalignment issue, which inevitably increases the volume and weight of the system. In contrast, a single waveguide structure eliminates the alignment issue while remaining in an ultra-compact form factor, thereby improving wearing comfort and stability of the entire system.

In this paper, we propose a single full-color waveguide display based on an optimized three-layer PVG as the in-coupler. We first analyze the theoretical FoV limit in single waveguide structure for full-color imaging. Then, following the guidance, a home-made rigorous coupled-wave analysis (RCWA) model is built to optimize the angular bandwidth of the in-coupling and out-coupling PVGs to reach the FoV limit. Finally, we perform a ray-tracing simulation and evaluate the imaging performance of the optimized PVGs integrated onto a waveguide. This work provides a comprehensive methodology for optimizing the design of a single full-color waveguide display based on PVGs.

2 | LIQUID CRYSTAL POLARIZATION VOLUME GRATINGS

Unlike intensity holography, such as holographic photopolymers, which records the intensity of interference beams, PVGs record the polarization state of an electric field based on photoinduced anisotropy.[13] PVGs are usually fabricated by a photo-alignment polarization holography technique, as shown in Figure 1A. When two circularly polarized (CP) beams with opposite handedness interfere, the electric field on the plane exhibits a sinusoidal linear polarization pattern. The photo-alignment materials, which tend to align perpendicular to the electric field direction, records the pattern. By spin-coating a liquid crystal polymer onto the patterned photo-alignment layer (PAL), the LC in contact with it replicates the pattern and forms a polarization volume grating.

As illustrated in Figure 1B, the PVG presents a slanted structure. In this figure, Λ_b is the Bragg period and φ is the slanted angle of the Bragg plane. The horizontal (Λ_x) and longitudinal (Λ_z) periods are related to Λ_b and φ by trigonometry, and the diffraction angle is determined by Λ_x through the grating equation. At normal incidence, the Bragg period Λ_b and incident wavelength λ_b should satisfy the Bragg condition:

$$2n_{eff}\Lambda_b\cos(\varphi)=\lambda_b, \tag{1}$$

where $n_{eff}=\sqrt{\left(n_e^2+2n_o^2\right)/3}$ is the effective refractive index of the anisotropic material, n_e is the extraordinary refractive index, and n_o is the ordinary refractive index.

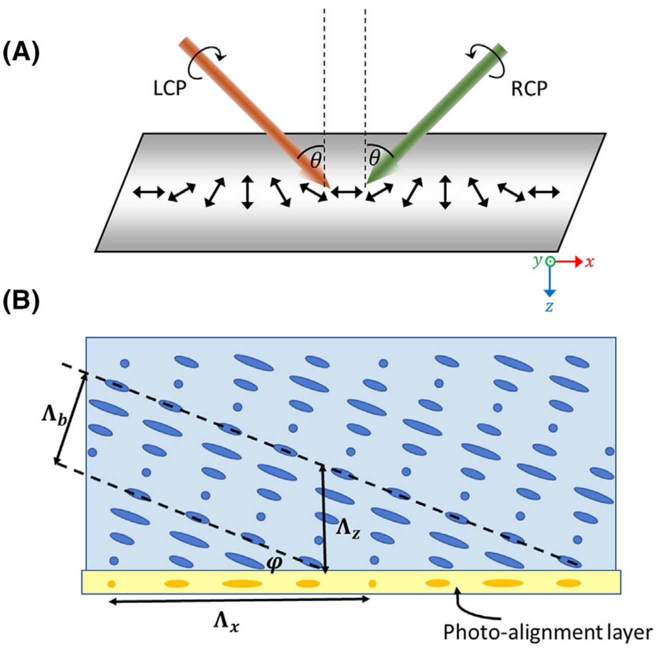

FIGURE 1 (A) Sinusoidal linearly polarized pattern expoured by the interference of left-handed circularly polarized (LCP) and right-handed circularly polarized (RCP) lights. (B) The slanted configuration of PVG.

3 | ANALYSIS OF THEORETICAL FOV LIMIT IN A SINGLE FULL-COLOR WAVEGUIDE

In a single full-color waveguide, as shown in Figure 2, the RGB lights are coupled into the same waveguide by in-coupling grating and then propagate inside the waveguide through total internal reflection (TIR). When they encounter the out-coupling grating, the lights are duplicated and diffracted into human eyes.

To provide a comprehensive understanding, we theoretically analyze the limit of horizontal FoV in this configuration. For a PVG, the first-order grating equation can be described as

$$n_{\text{in}}sin\theta_{\text{in}}+\frac{\lambda}{\Lambda_x}=n_{\text{out}}sin\theta_{\text{out}}, \tag{2}$$

where θ_{in} and θ_{out} represent the incident angle and diffracted angle in the incident medium and output medium with refractive index n_{in} and n_{out}, respectively, λ is the wavelength in vacuum, and Λ_x is the horizontal grating period for PVG. With this governing equation, if we assume the FoV in air is centrosymmetric, then the incident angle in air (θ_{air}) is related to the minimum/maximum diffraction angles ($\theta_{\min}/\theta_{\max}$) in the waveguide as

$$n_{\text{air}}sin(-\theta_{\text{air}})+\frac{\lambda_{\min}}{\Lambda_x}=n_g sin\theta_{\min}, \tag{3}$$

$$n_{\text{air}}sin\theta_{\text{air}}+\frac{\lambda_{\max}}{\Lambda_x}=n_g sin\theta_{\max}, \tag{4}$$

where n_g and n_{air} are the refractive index of a waveguide and air, respectively, and $\lambda_{\min}$ and $\lambda_{\max}$ represent the minimum and maximum wavelength guided in the waveguide. Thus, the maximum horizontal FoV ($2\theta_{\text{air}}$) in air is

$$FoV=2\arcsin\left(n_g sin\theta_{\max}-\frac{n_g\lambda_{\max}}{\lambda_{\min}+\lambda_{\max}}\left(sin\theta_{\max}+sin\theta_{\min}\right)\right). \tag{5}$$

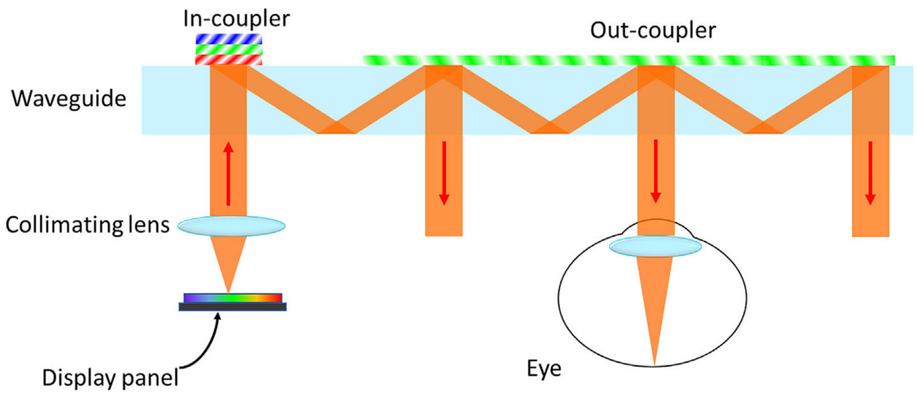

FIGURE 2 Schematic diagrams of a single full-color waveguide based on PVGs.

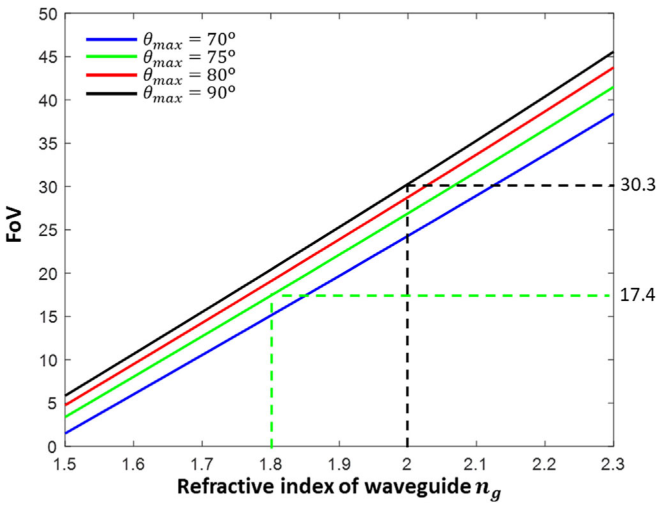

FIGURE 3 Theoretical limit of FoV as a function of waveguide refractive index n_g and maximum TIR angles $\theta_{\max}$.

Figure 3 shows the FoV limit as a function of n_g and $\theta_{\max}$, assuming $\lambda_{\max} = 630\,\text{nm}$ and $\lambda_{\min} = 457\,\text{nm}$. The FoV in a single full-color waveguide increases as the refractive index of waveguide medium increases. In an ideal case where $\theta_{\max} = 90°$ and $n_g = 2$ (the waveguide medium used in Magic Leap 2),[14] the FoV can reach 30.3° in air. In a practical design, a higher refractive index would be challenging to achieve, and $\theta_{\max}$ should be kept smaller than 90° due to the image quality and pupil expansion consideration.

4 | OPTIMIZATION OF IN-COUPLING AND OUT-COUPLING PVGS

Based on the analysis of horizontal FoV in a single full-color waveguide, if we set the refractive index of waveguide $n_g = 1.8$, the maximum TIR angle $\theta_{\max} = 75°$ and center wavelength of R, G, and B as $\lambda_r = 630\,\text{nm}, \lambda_g = 532\,\text{nm}, \lambda_b = 457\,\text{nm}$, the horizontal period is then 396.9 nm and FoV can reach 17.4° in air.

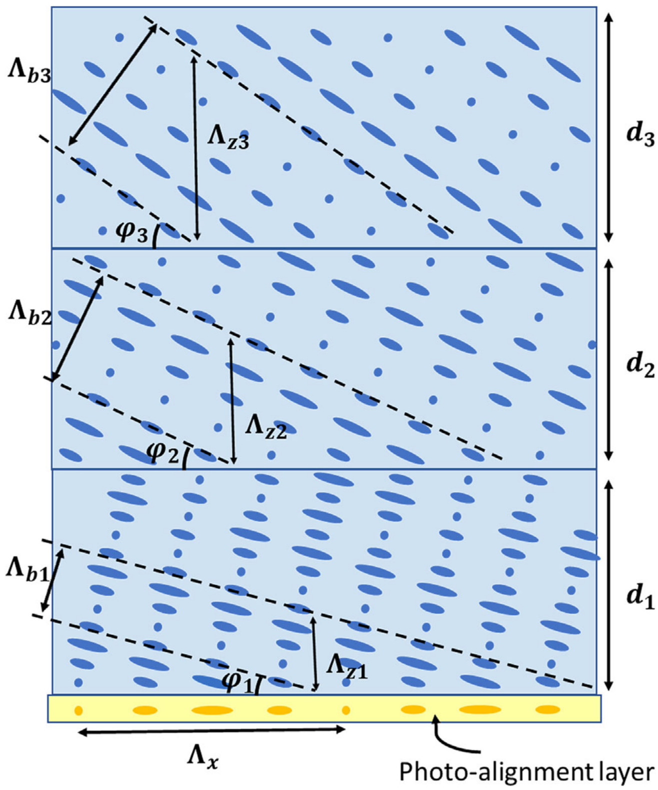

FIGURE 4 Sketch of the three-layer PVG structure. Λ_x is the horizontal period; Λ_b is the Bragg period; Λ_z is the longitudinal period; φ is the slanted angle; d is the thickness of each layer.

Although PVGs have a large angular bandwidth, it is challenging for a single-layer PVG to meet the large FoV requirement. So, we propose a three-layer in-coupling grating as shown in Figure 4, where three layers are combined at the same horizontal period.

In order to realize a full-color display in this FoV with uniform image quality, a small variance and high efficiency of angular response bandwidth for three different colors can be reached by varying the slanted angles φ_1,

φ_2, φ_3 and thickness of each grating layer d_1, d_2, d_3 in Figure 4. To realize this characteristic, RCWA method is implemented to simulate and optimize the following objective function:

$$\min \sigma^2(E_r) + \sigma^2(E_g) + \sigma^2(E_b),$$
$$s.t.\ E_r > 60\%, E_g > 60\%, E_b > 60\%;$$

where $\sigma^2(E_r)$,$\sigma^2(E_g)$, and $\sigma^2(E_b)$ are the variance of the first-order diffraction efficiency of a three-layer in-coupling grating in red, green, and blue colors. These variances are measured at an incident angle of $[-8.7°, 8.7°]$ in air. To reach this goal, a relatively large birefringence ($n_e = 1.9, n_o = 1.6$) liquid crystal material is used in our optimization. The optimized result is shown in Figure 5A, which is achieved at following slanted angles $\varphi_1 = 35.1°$, $\varphi_2 = 24.9°$, $\varphi_3 = 20.8°$ and thickness of each grating layer $d_1 = 1050$ nm, $d_2 = 700$ nm, $d_3 = 1150$ nm. It shows a relatively uniform diffraction efficiency at different incident angles for each color.

Besides, to realize pupil expansion in waveguide displays, the out-coupler should also be designed properly. Here, we design a broadband grating with a relatively low efficiency to make each pupil expansion as uniform as possible. Such grating can be realized in a thin, single-layer PVG. A relatively uniform and low efficiency response of the out-coupling grating (Figure 5B) is achieved at thickness $d = 180$ nm and slanted angle $\varphi = 24.5°$.

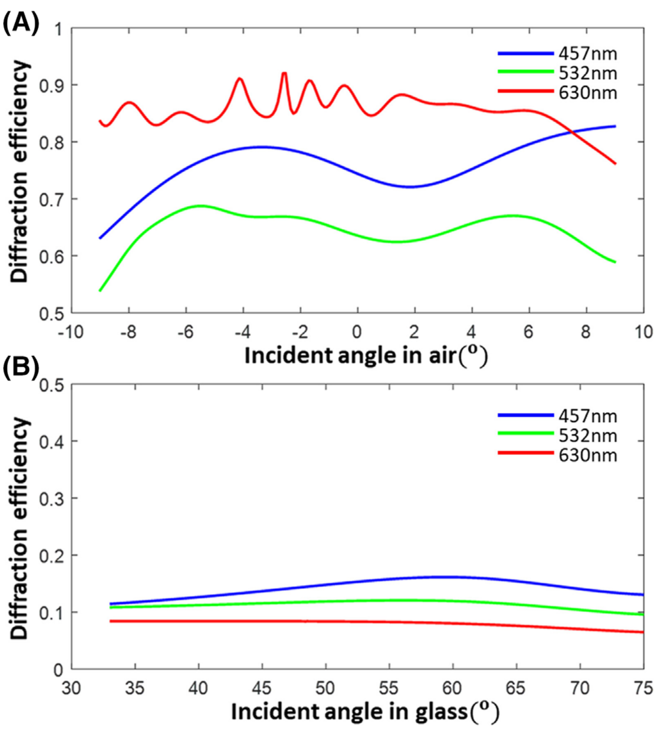

FIGURE 5 Diffraction efficiency of the optimized (A) in-coupling PVG and (B) out-coupling PVG at different incident angles and wavelengths 457, 532, and 630 nm.

5 | IMAGING SIMULATION OF A FULL-COLOR WAVEGUIDE DISPLAY WITH OPTIMIZED IN-COUPLING AND OUT-COUPLING PVGS

In this section, we evaluate the imaging performance of the optimized PVGs integrated on a waveguide. The simulation is performed using a commercial ray-tracing package OpticStudio (Ansys Zemax). The RCWA model of PVGs is compiled into a dynamic-link library (DLL) file and linked to OpticStudio, operating in non-sequential mode.

Based on the setting reported before,[15] the optimized PVGs are attached to the lower surface of the waveguide. As shown in Figure 6A, the in-coupling and out-coupling PVGs are designed based on desired exit pupil 8 mm (H) at eye relief 18 mm. The image used for the simulation is shown in Figure 6B. For simplicity, an ideal projection system that projects an image source to infinity is adopted in the simulation. The projection system provides a 17.4° horizontal FoV, which consists of a rectangular Lambertian source, a slide object, and an ideal collimating lens as illustrated in Figure 6C. To simulate the image received by the user's retina, an ideal lens with 2-mm radius and a color detector are used to imitate an ideal imaging system of the user's eye. Eventually, the output images at different exit pupil positions are obtained in Figure 7A–D when the wavelengths of the incident light are 630, 532, and 457 nm.

Nevertheless, there are several important points to be noticed. First, the input illuminance among three wavelengths should be different because the effective efficiency at each color is not identical and the pupil expansion is considered. Thus, we set the weight ratio for 630, 532, and 457 nm to be 2.3:1:0.8. Second, the brightness uniformity in different exit pupil positions is still not perfect. A cascaded out-couplers or a polarization management layer in the out-coupling region[16] could be applied to improve the uniformity at different exit pupils. Finally, since the polarization changes during TIR inside the waveguide, the output images in the whole FoV are not so uniform as the input image. Polarization maintainer[17] is required to maintain the desired circular polarization when light hits the out-coupling PVG.

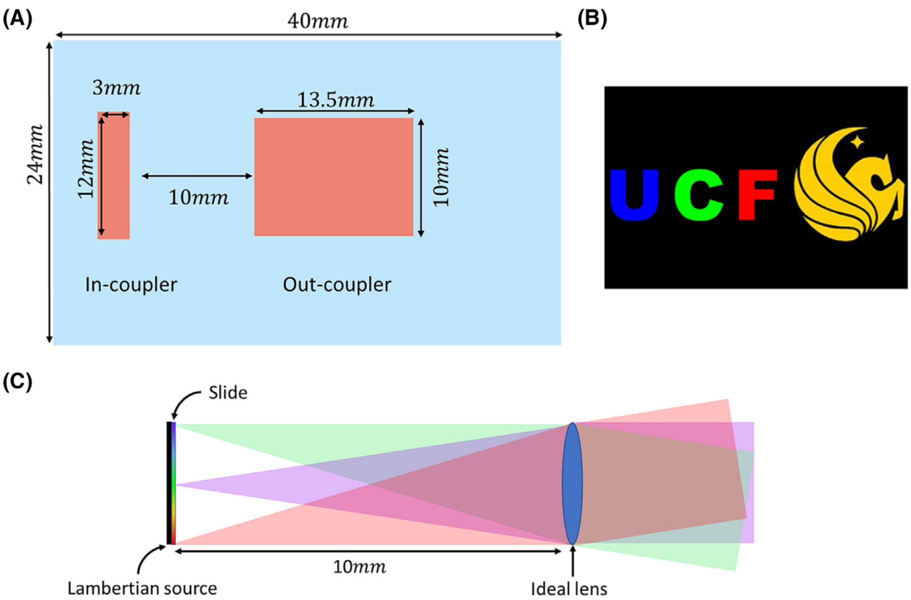

FIGURE 6 (A) Top view of PVGs-based waveguide structure diagram; (B) the input image used for simulation. (C) Device configuration of the projection system. It is composed of an Lambertian source with width 3.06 mm, a slide with width 3.06 mm, and an ideal lens with focal length 10 mm.

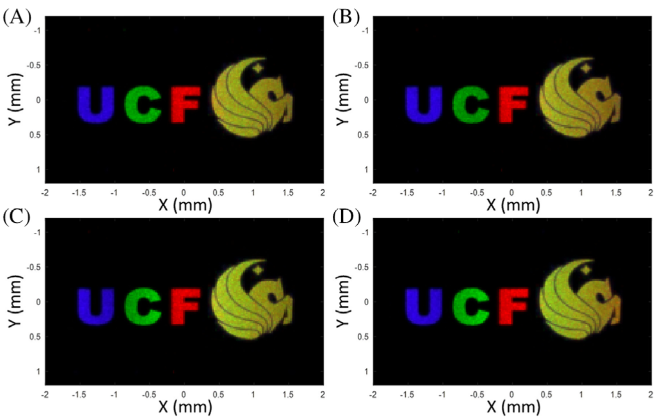

FIGURE 7 Output images (A) at the left edge of horizontal exit pupil, (B) 2-mm away from the left edge of horizontal exit pupil, (C) 4-mm away from the left edge of horizontal exit pupil, and (D) 6-mm away from the left edge of horizontal exit pupil.

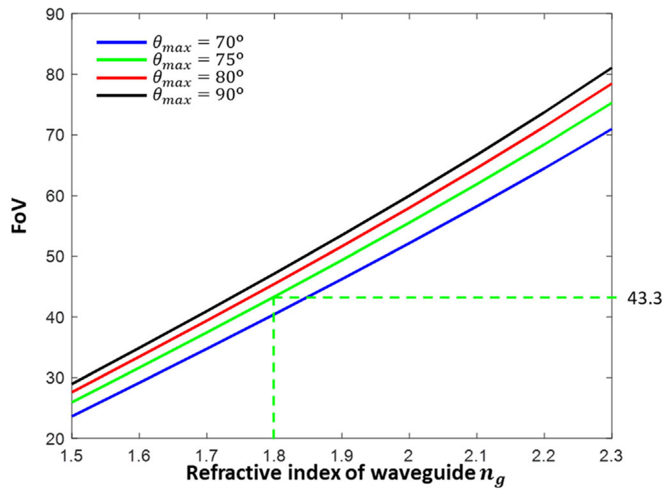

FIGURE 8 Theoretical limit of FoV as a function of waveguide refractive index n_g and maximum TIR angle $\theta_{\max}$ in the three-waveguide configuration.

6 | DISCUSSION

To decrease the form factor of light engine in an AR waveguide display, 2D EPE scheme should be developed. The single waveguide AR design presented here can be easily extended to 2D EPE by adding an extra folded grating or replacing the out-coupler with a pair of crossed gratings.[18] Besides, the FoV analysis can still apply to 2D EPE design.

Although in this paper we mainly focus on the single waveguide, the analysis and optimization could also be applied to a full-color display in two or three waveguides. In the three-waveguide scheme, R, G, and B lights are guided by three different waveguides, respectively. In this structure, with the governing Equations (2)–(4), the theoretical limit of FoV can be expressed as

$$FoV = 2\arcsin\left(n_g sin\theta_{\max} - \frac{n_g}{2}\left(sin\theta_{\max} + sin\theta_{\min}\right)\right). \quad (6)$$

Figure 8 shows the FoV limit as a function of n_g and $\theta_{\max}$ in the three-waveguide configuration. In this structure, the horizontal FoV can reach 43.3° if the same condition as in Section 4 is considered, where the refractive index of waveguide is $n_g = 1.8$ and maximum TIR angle is $\theta_{\max} = 75°$.

Logically, the FoV will decrease if we use two waveguides. However, the FoV limit in three waveguides can also be realized in two waveguides when we use the scheme shown in Figure 9. Specifically, waveguide 1 supports the whole FoV of blue light and half FoV of green light with range $[-21.65, 0]$. Waveguide 2 supports the

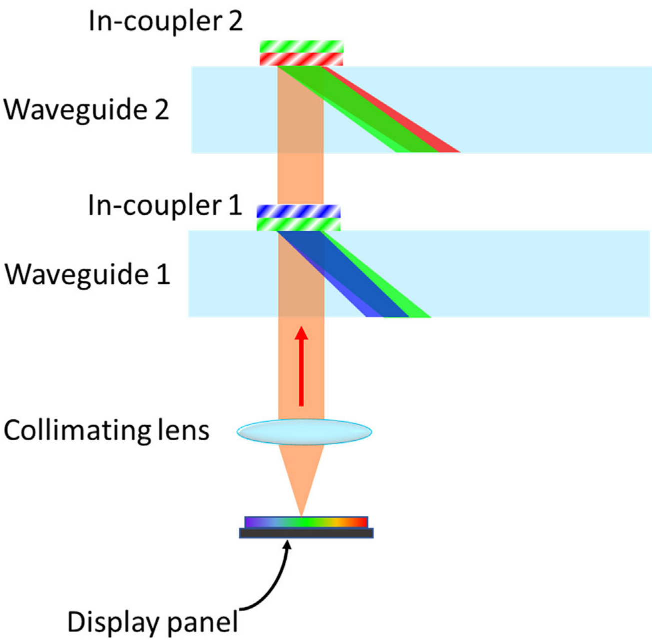

FIGURE 9 Schematic diagrams of a full-color display in two-waveguide structure.

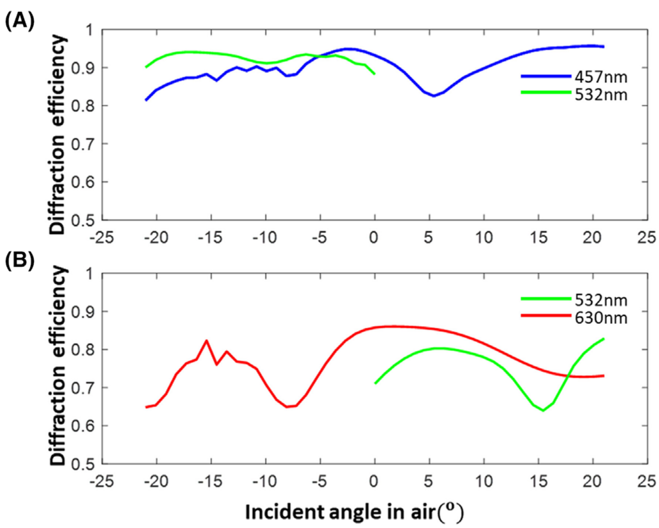

FIGURE 10 (A) Angular response of optimized in-coupler 1 at $\lambda = 457$ nm and 532 nm. (B) Angular response of optimized in-coupler 2 at $\lambda = 630$ nm and 532 nm.

whole FoV of red light and remaining FoV of green light with range [0,21.65]. To reach this FoV, double-layer PVGs are used in each waveguide as in-couplers. According to Equations (3) and (4), horizontal periods of two in-couplers are $\Lambda_{x1} = 333.7$ nm and $\Lambda_{x2} = 460$ nm, respectively. Following the optimization method described in Section 4, the optimized in-coupler 1 is achieved at following slanted angles $\varphi_1 = 30.2°$ and $\varphi_2 = 25°$, and thickness of each grating layer $d_1 = 1050$ nm and $d_2 = 1100$ nm. The optimized in-coupler 2 is realized at slanted angles $\varphi_1 = 30.1°$ and $\varphi_2 = 23°$ and thickness of each grating layer $d_1 = 900$ nm and $d_2 = 800$ nm. The uniform angular responses for two in-couplers are shown in Figure 10A,B.

7 | CONCLUSION

In this paper, we analyzed the theoretical FoV limit for a full-color display in a single waveguide. Based on the analysis, the optimization of a three-layer PVG is implemented to achieve the FoV limit. Pairing with a single-layer, thin PVG, we realized a relatively uniform exit pupil of 8 mm (H) in our designed AR waveguide system.

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