To be published in Applied Optics:

Title: A full-color optical combiner with good imaging quality and a wide angle of incident light acceptance

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Accepted: 30 October 23

Posted 31 October 23

DOI: https://doi.org/10.1364/AO.501094

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Author-accepted manuscript

Applied Optics 62(33), 8918-8923 (2023)

Journal abstract and version of record

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A full-color optical combiner with good imaging quality and a wide angle of incident light acceptance

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Received XX Month XXXX; revised XX Month, XXXX; accepted XX Month XXXX; posted XX Month XXXX (Doc. ID XXXXX); published XX Month XXXX

This work demonstrates a full-color optical image combiner for AR and heads-up displays. The novel feature of the device is that the angle of incident light of the computer-generated image reflected by it, can vary over a large range. It achieves improved performance by using a combination of polarization interference filters (PIF), quarter wave retarders (QWR), and polarization volume holograms (PVH). Details of an example design and its performance are presented. © 2023 Optica Publishing Group

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1. Introduction

In augmented reality (AR), mixed reality (MR), and heads-up displays (HUDs) devices, there is a need for an optical combiner that allows the viewer to see a computer-generated image overlayed on the image of the real world. This device needs to be transparent for light coming through it but is a reflector for the light coming from a projector on the viewer side of the device.

This need has been met by holographic devices typically made from surface relief gratings (SRGs) or volume holograms. In the case of volume holograms, the optical effect is based on the well-known Bragg reflector idea. A more recent advance is the use of liquid crystal technology to produce volume holograms sensitive to the circular polarization state of light (PVH), which adds versatility to the system design. However, all of these devices are wavelength-sensitive, unlike a mirror. The wavelength sensitivity reflects the light of different wavelengths to different angles for the same angle of incidence. In this case, the user will see a white image produced by the projector as separate primary color images. This is a design problem with these types of devices.

The approach to solving this problem is to design a three-layer polarization volume hologram (PVH) combiner. A PVH layer is intended to reflect red light to the desired angle. Another PVH layer is intended to reflect green light to the same desired angle. Another PVH layer is intended to reflect blue light to the same desired angle. This approach works if a particular color of light only interacts with its designated layer. For example, the green light should reflect from the green PVH but pass unaffected through the red and blue layers. If the green light were to be reflected by the red or blue layers, it would be reflected to an undesired angle and cause image blurring or a chromatic aberration. This problem can be solved by narrowing each layer's reflection bandwidth only to reflect the light of the desired color.

But there is a problem with this solution. To design a PVH with a narrow spectral bandwidth, the main parameter that is adjusted to obtain this is to lower the degree of index modulation. It has been shown analytically [1][2] and experimentally [2] that lowering the degree of index modulation has the effect of reducing the reflection bandwidth of both incident angle and incident wavelength.

In [1], using Kogelnik's coupled wave theory, it is shown that both wavelength and incident angle affect the deflected light efficiency by changing the off-Bragg factor ϑ, which is used to quantify how much the Bragg condition is violated either in terms of incident wavelength or incident angle of light. In [2], transmissive and reflective Bragg polarization grating with Px=400nm and n=1.65 is simulated using RCWA [3]. The paper shows that, with increasing birefringence, a monotonic increase of both spectrum and angular bandwidth is observed, regardless of the type of grating being transmissive or reflective.

This leads to a fundamental problem related to the physics of these devices; they cannot simultaneously be designed to have a narrow enough reflection spectral bandwidth AND be able to have high efficiency over a wide range of incident light angles.

2. The basic approach

Our approach is a synergistic combination of PVH devices for red, green, and blue light (The respective layers are PVH-R, PVH-G, and PVH-B); and devices designed for astronomical spectrometers called polarization interference filters (PIFs). Polarization interference filters (PIFs) are wavelength-selective filters based on the filter's effect on polarized light. A particular type of PIF, used as an example device, is a Solc filter that consists of a stack of "half-wave retarders" (HWRs). These half-wave retarders use a birefringent material characterized by their birefringence(Δn). The HWRs are further characterized by their retardation value ΔΓ,

$$\Delta\Gamma = \frac{\Delta n \cdot d}{\lambda o} \qquad (1)$$

d is the thickness of the HWR, and λ_o is the wavelength in vacuum. For HWR, ΔΓ=1/2.

The PIF used in this example is a particular type of Solc filter where the optic axis of the HWRs in the Solc filter stack is "rocking" between + and – values of a defined angle. The defined angle is related to the number of HWRs in the stack and is given by:

$$|p| = \frac{180}{(4 * N)} \qquad (2)$$

p is the angle, and N is the number of HWRs. The narrowness of the range of wavelengths of light affected by the Solc PIF is affected by N: the larger the value of N, the narrower the range of affected wavelengths.

PIFs have the property of changing the polarization state of light from one state of linear polarization to an orthogonal state for a narrow range of wavelengths. Outside that narrow range, light is passed without change in the polarization state. We have found that these types of devices can be paired with PVH devices to provide an optical combiner that simultaneously reflects red, green, and blue light to the same angle and can do this for a wide range of incident angles.

However, there was an issue with implementing this combination. A PVH reflects light of one circular polarization state and transmits (unaffected) light of the orthogonal circular polarization state. Therefore, a PIF that affects the state of linear polarization is not directly applicable to act with the PVH. To solve that issue, we modified the design of a typical PIF to operate with circularly polarized light. The modified PIF (we designate it as a CPIF) changes the circular polarization state of a narrow range of incident wavelengths to the orthogonal circular polarization state while not affecting the polarization state of light outside the wavelength range. The respective CPIF layers for red, green, and blue are named CPIF-R, CPIF-G, and CPIF-B.

The outline of our full-color, wide angle reflector is shown in Fig.1. It is seen that each of the three color layers of the device now consists of two sublayers: a PVH and CPIF. In each layer, the CPIF and PVH are designed to operate for either red, green, or blue light.

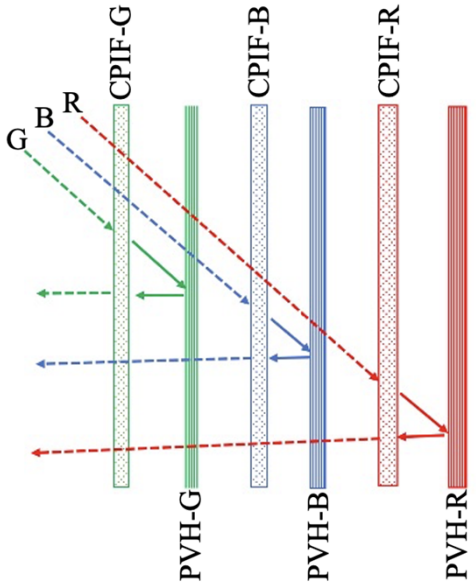

Fig. 1*. An example wide-angle color reflector is described in this work.*

The device is a stack of 6 components. Following the incident light, they are CPIF-G, PVH-G, CPIF-B, PVH-B, CPIF-R, and PVH-R. They are shown separately in Fig.1 for clarity. The dot-filed rectangles are CPIFs tuned to the color of the rectangle. The line-filled rectangles are PVH films tuned to the rectangle's color. The dotted lines represent the right-hand circularly polarized (RCP) light with wavelength designated by their color. The solid lines represent the left-hand circularly polarized light(LCP) with wavelength designated by their color. It is understood that the PVH and CPIF layers could be replaced by PVH and PIF devices sensitive to linear polarization states of light.

In this approach, the required incident polarization state is RCP for red, green, and blue incident light. The CPIF is used to change the circular polarization to the orthogonal circular polarization state for the designated color. The polarization selectivity of the PVH is utilized to avoid color crosstalk in a full-color combiner.

3. PVH and CPIF in this work

A specific example of PVH-R, PVH-G, PVH-B, CPIF-R, CPIF-G, and PVH-B used in this work is given in this section.

In this example, the PVHs use uniaxial liquid crystal material of extraordinary and ordinary index of 1.7 and 1.5. The PVH-G director orientation is shown in Fig.2. PVH-R and PVH-B have the same Bragg plane angle and grating vector angle as shown in Fig.2, but the pitch of the spiraling

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optic axis is changed, as shown in Table 1.

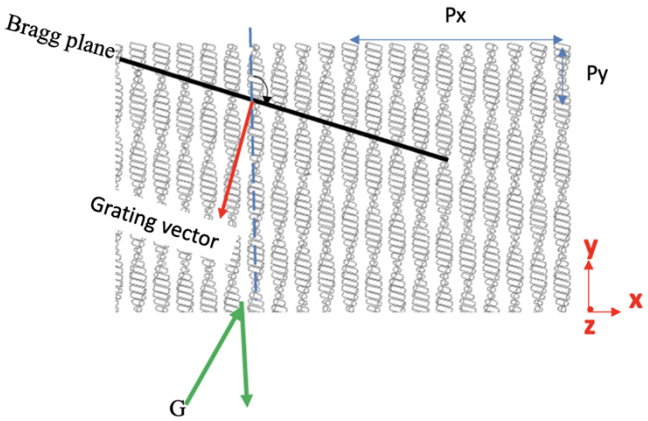

Fig. 2*. Director picture for PVH-G. The coordinate system in this work: +x is pointing right, +y is pointing up(cell normal direction), and +z is pointing out of the page towards the reader. The black line is the Bragg plane; it makes 104.125 degrees with the +y direction. The red arrow is the grating vector at 194.125 degrees with the +y direction. The green arrows indicate the incident and reflected beams at 50.87 with +y direction and 178.8 degrees with +y direction in the air, which is 29 and 179.25degree in the medium with an average index of 1.6.*

Table 1. The horizontal and vertical pitch of the PVH used in this work. The length unit for pitch is micron.

	Px(horizontal pitch)	Py(pitch along the thickness direction)
PVH-R	0.8413	0.2117
PVH-G	0.6956	0.1750
PVH-B	0.5962	0.1500

The property of the PIF to inappropriately operate with linear polarized light is modified by adding two "quarter wave retarders" (QWRs that convert light from being linearly polarized to circularly polarized for a particular design wavelength. The design wavelength of the QWRs is fixed by the equation: $\Delta\Gamma=1/4$. The rotation angle of the optic axis of the QWRs is +- 45 degrees to the +x axis in the xz plane. The sign of the angle determines if the incident linear polarized light will be converted to LCP or RCP, or conversely, if incident LCP (for example) will be converted to linearly polarized light with polarization axis at + or – 45 degrees. These retarders are specified by their retardation value $\Delta\Gamma$, and the angle ϕ their optic axis in the xz plane makes with respect to the +x axis. Table 2 gives the values of each of the 14 retarders in an example CPIF stack.

Table 2. Definition of an example CPIF

Retarder number	$\Delta\Gamma$	ϕ
1	¼	+45
2	½	+3.75
3	½	-3.75
4	½	+3.75
6	½	-3.75
7	½	+3.75
8	½	-3.75
9	½	+3.75
10	½	-3.75
11	½	+3.75
12	½	-3.75
13	½	+3.75
14	¼	-45

The property of the CPIF to inappropriately shift its range of affected wavelengths as a function of angle is modified by substituting typical uniaxial HWRs with biaxial versions[4]. While there are several designs for "wide angle" retarders, in the example system considered here, Nz type retarders are modeled. Nz type retarders in this work have the value of the index of refraction for light polarized along the thickness direction of 1.6, which is the average value of the retarder extraordinary index of 1.65 and retarder ordinary index of 1.55. A possible candidate is to use a stretched polycarbonate retarder with a birefringence close to what we used in this paper [5][6]. With the birefringence being 0.1, using (1), the thicknesses of the HWRs for red, green, and blue are 3.175, 2.625, and 2.25 microns. The thickness of the QWR is half of the HWR thickness. The CPIF&CPVH stack thicknesses are 41.275, 34.125, and 29.25 microns for red, green, and blue. This makes the total thickness in Fig.1 to be 104.65 microns. The actual thickness depends on the manufacturing process. A possibility is to laminate retarders on the opposite side of the holographic exposed PVH-R,G,B glass substrate.

Note the number of the HWR layers can be reduced to reduce the device complexity and overall thickness. An example is studied in supplemental material 4 that uses less number of HWR without decreasing the overall performance.

4. Method of modeling

The method of finding the efficiency of this example case can be found in supplemental document.1.

The order of the stack is determined to be green, blue, and red, which is based on both human eye sensitivity, and the polarization state change when the light transmit through the CPIF. More details can be found in supplemental document.2.

The design parameters are chosen to give maximum efficiency at an incident angle of 50.87 degrees. This angle is chosen as the incident angle for an unrotated eye in a Maxwellian view combiner using system parameters in [7]. The combiner is illuminated by a point source and to accommodate the eye rotation the point source moves to change the incident angle. From the system parameters, the required reflection angle is found to be 1.2 degrees. When the eye rotates 18 degrees away from the object horizontally, the required reflection angle is 9.3 degrees. Using the grating

equation, we find that the incident angle is 50.87 and 66.6 degrees for the 1.2 and 9.3 degrees reflections.

To design a full-color combiner that works for RGB, the approach of using PVH stack and using PVH with the inclusion of CPIF are both simulated for the incident angle of 50.87 and 66.6 degrees.

While the 66.6 degree is about 15 degrees larger than 50.87 degrees, we are also interested in what if the incident angle is smaller than 50.87 degrees. Because the PVH has a wide bandwidth, the efficiency is mainly limited by the angular performance of PIF. From supplemental material 3, we can see the performance of PIF is better at (optimal angle-15 degrees) than (optimal angle+15 degrees). Thus, we can expect that the device's overall performance is also better at (optimal angle+15 degrees) than (optimal angle-15 degrees). Thus, if we simulated 50.87 and 66.6 degrees and showed good performance, we expect the device will work well for a 30-degree angle range in the air.

The structure shown in Fig.1 is simulated, with parameters of PVH and CPIF described in section 3. The red, green, and blue wavelengths used in the simulation are 0.635,0.525, and 0.45 microns.

5. Thickness optimization of the PVH layers

The effect of PVH layer thickness is studied in this section using RCWA. To increase the reflection efficiency of the PVH for the design wavelength, a larger PVH layer thickness is preferred. However, because the light of different wavelengths needs to transmit through the PVH with minimum polarization state change, a smaller PVH layer thickness is preferred.

4.1 Determine PVH-G thickness

As the first layer, the red and blue light must transmit through the layer to reach its PVH layers. We will focus on the transmitted red light since our eye is much more sensitive to green and red than blue.

Thus, we are interested in two parameters for different thicknesses:

Parameter 1(P1): The reflection efficiency of the PVH-G of incident green light, which favors a larger thickness.

Parameter 2(P2): The transmitted S3 of the incident red light, which favors a smaller thickness.

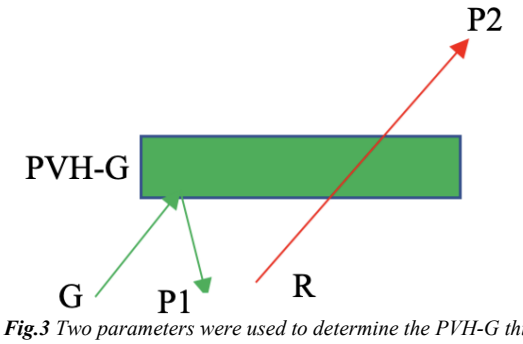

Fig.3 *Two parameters were used to determine the PVH-G thickness.*

For the two parameters, 1,2,4,10 micron thickness is simulated using RCWA.

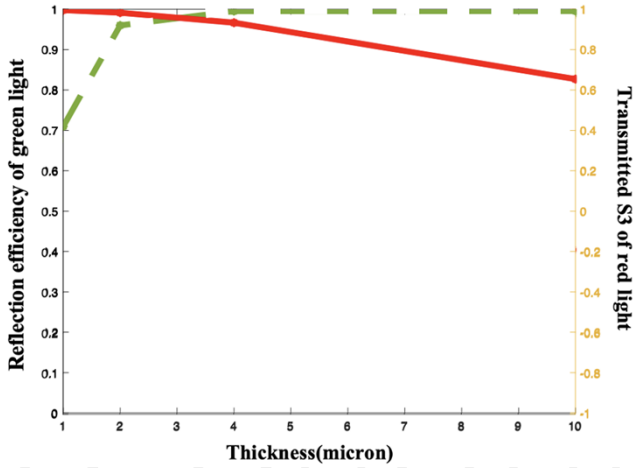

Fig.4. *Thickness(x-axis, in microns) dependence of green light reflection efficiency(parameter 1, left y-axis) and red light transmitted S3(parameter 2, right y-axis). Green dash line are green light reflection efficiency with 50.87 degrees incident angle. Red solid line are red transmitted S3 with 50.87 degrees incident angle.*

PVH-G is set to 2 microns with 0.2 birefringence, so the efficiency of the green light is> 95% and the transmitted S3>0.98.

4.2 Determine PVH-B thickness

As the second layer, the red light must transmit through PVH-B to reach its PVH-R.

The same step is used to determine the PVH-B thickness. The result is very similar to Fig.4. Thus, use 2 microns for the PVH-B thickness for the same reason that a 2-micron thickness is used for the PVH-G.

4.3 Determine PVH-R thickness

Since the PVH-R is the last layer, the green and blue light has already been reflected from the PVH-G and PVH-B. We do not need to worry about the polarization state change when green and blue light transmitted through PVH-R. However, we will need the reflection efficiency of the red light to be high, so a thicker PVH is preferred.

Here the PVH-R is chosen to be 8 microns; the RCWA simulated efficiency is above 99.5% when the incident angle is 50.87 degrees in the air.

The thickness optimization of the CPIF is also looked at in supplemental document 3, but the effect on the polarization state is minor compared with the PVH thickness optimization.

6. FDTD simulation of a wide-angle reflector

The incident angles in this simulation are 50.87 and 66.6 degrees in the air, and the corresponding reflection angles are 1.19 and 9.31 degrees in the air.

The designed device's optical properties were calculated using the finite-difference time-domain (FDTD) method. The resulting far field intensity for the two incident angles and wavelengths considered is shown in Fig.5. Tables 3 and 4 show the percentage of light reflected to the desired angle (main reflection) and the percentage of light reflected to incorrect angles (crosstalk). This is shown for the case in Fig. 1 with CPIF-G, CPIF-B, and CPIF-R and for the case in which the CPIFs are omitted.

Table 3: Efficiencies of the simulated cases with/without CPIF for 50.87-degree incidence

Inclusion of CPIFs	Incident wavelength	Reflection efficiency at 1.2 degrees	Efficiency of crosstalk from PVH-G	Efficiency ratio of desired reflection/ crosstalk from PVH-G
No	635nm	89.9%	2.5%	36.0
Yes	635nm	96.0%	0.006%	160000.0
No	450nm	76%	21.1%	3.6
Yes	450nm	94.2%	0.1%	942.0
No	525nm	98.0%	---	---
Yes	525nm	96.0%	---	---

Table 4: Efficiencies of the simulated cases with/without CPIF for 66.6-degree incidence

Inclusion of CPIFs	Incident wavelength	Reflection Efficiency at 9.3 degrees	Efficiency of crosstalk from PVH-G	Efficiency ratio of desired reflection/ crosstalk from PVH-G
No	635nm	78.0%	3.0%	26.0
Yes	635nm	95.1%	0.04%	2377.5
No	450nm	63.0%	20.4%	3.1
Yes	450nm	83.7%	0.02%	4185.0
No	525nm	96.2%	---	---
Yes	525nm	90.8%	---	---

When light is incident at 50.87 degrees or 66.6 degrees, from grating equation, we expect the reflection angle to be 1.2 and 9.3 degrees. Without the inclusion of PIFs, not all efficiency is at the reflection angle. After including PIFs, we see a major improvement in efficiency at the expected reflection angle.

The exact efficiency is calculated by integration around the deflection peaks. In the last column, we took the efficiency ratio of the expected reflection over the crosstalk to show that the approach of combining PVH and CPIF reduces the crosstalk and improves the efficiency of the overall device.

In the design, as shown in Fig.1, the PVH-G is the first PVH in the stack. Because of the high reflection efficiency of the PVH layers, >95% of the green light is reflected at the PVH-G, and does not reach PVH-B and PVH-R layers. Thus, there is no crosstalk problem for green incident light.

The FDTD simulated far field intensity is given for 50.87 and 66.6 degree incident angle, for 635, 450, and 525 nm incident wavelength, in Figure 5. It is seen that the large birefringence of the PVH allows the angular bandwidth to be large enough to accommodate the change of incident angles. On the other hand, the large birefringence causes the blue and red light to be reflected to different angles by different PVH layers, as shown in Fig.5(a)-(d) for the design without the inclusion of CPIF. With the inclusion of CPIF, the spectral bandwidth is reduced effectively, so almost all of the light is reflected to only the desired angle. These results show that in this design high angular bandwidth is possible (requiring a high birefringence LC material), while at the same time eliminating crosstalk between R, G and B reflectors.

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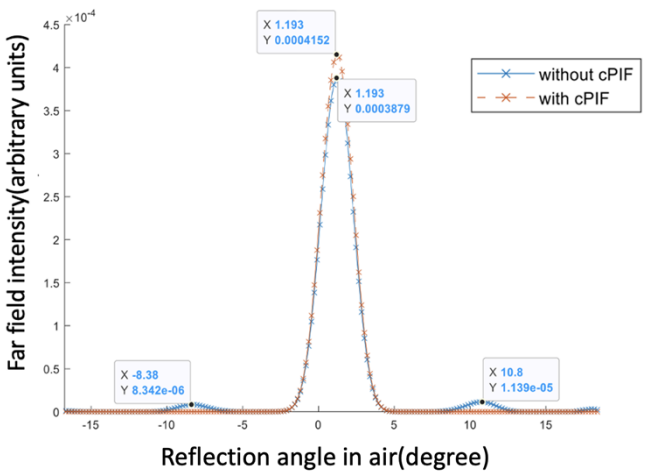
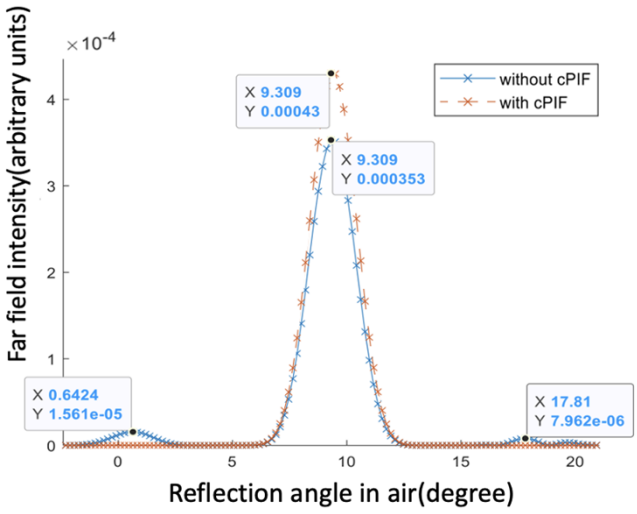


(a)



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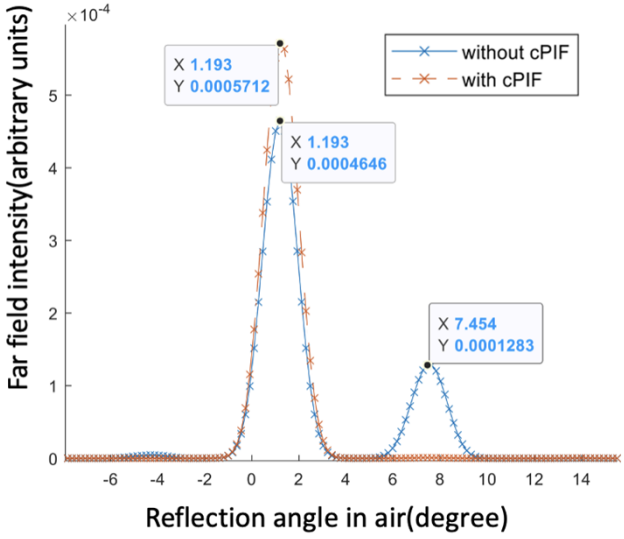

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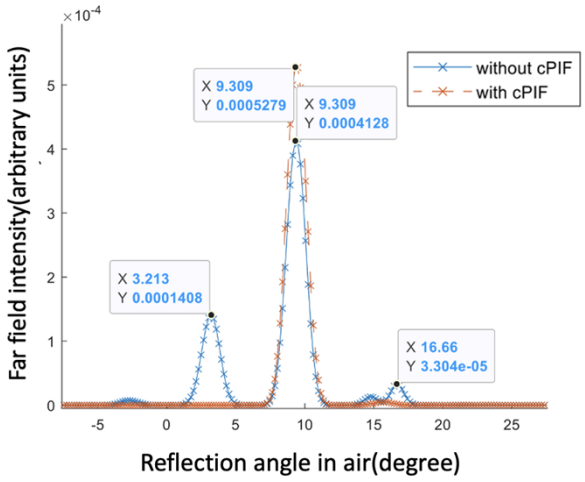

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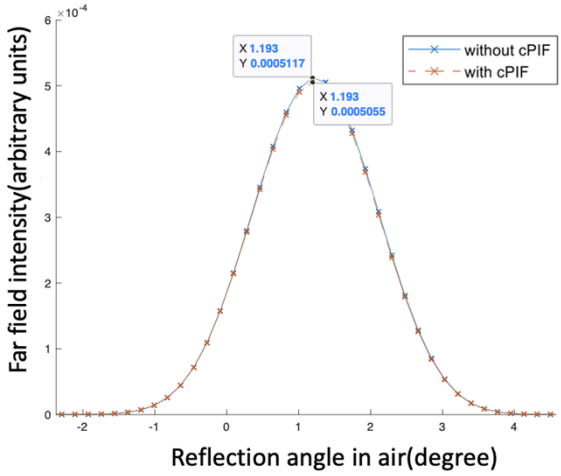

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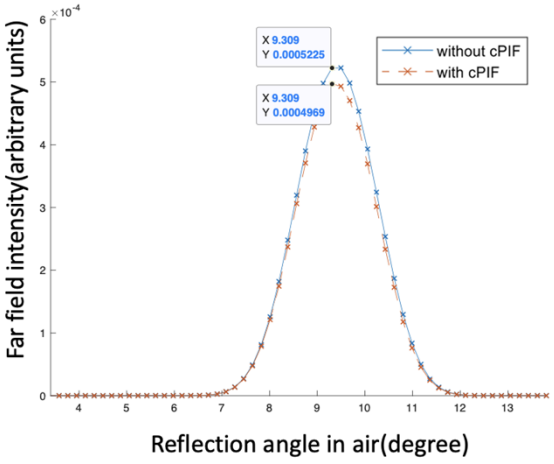

(f)

Fig. 5*. Far field intensity when the incident wavelength and incident angle are (a) 635nm,50.87 degrees, (b)635nm,66.6 degrees, (c) 450nm,50.87 degrees, (d) 450nm,66.6 degrees, (e) 525nm,50.87 degrees, (f) 525nm,66.6 degrees. The incident wavelengths are defined in vacuum, and the angle is defined in air.*

7. Conclusion and discussion

In this work, we showed that combining CPIF with PVH, compared with using PVH alone, shows improved efficiency and negligible crosstalk for an angle range of 30 degrees in the air for red, green, and blue incident light.

In future studies, the design can be modified/optimized in many ways, including:

1. The PVH is an example of a polarization-dependent reflector. It thus can be replaced by any general Reflective Polarization Volume Hologram(R-PVH) or transmissive polarization volume hologram(T-PVH) to deflect different wavelengths of light to the same deflection angle.
2. It is also possible to design PVH and PIF devices(without the QWRs) acting on linearly polarized light or any common polarization state.
3. The CPIF can be further optimized for lowered complexity. In supplemental document.4, an example is shown that reducing the number of HWRs with no decrease in performance.
4. To increase the reflection efficiency, a compensator can be added to the PVH to compensate for the polarization change at the PVH. The effect of this added compensator on all incident wavelengths and possible incident angles can be considered.
5. The proposed design can possibly be used as a full-color combiner in a Maxwellian view system.

Funding

This work was funded by Reality Labs Research, Meta Platforms.

Disclosures

The authors declare no conflicts of interest.

Data availability

Data underlying the results presented in this paper are available in Ref. [8].

Supplemental document

See Supplement 1 for supporting content.

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