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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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Abstract
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.

Author Keywords
Wide angle deflector; Color crosstalk; Polarization sensitive combiner.

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 Bragg reflector is a material that has a periodically modulated index of refraction). A more recent advance is the use of liquid crystal technology to produce volume holograms sensitive to the circular polarization state of light (CPVH), 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 a separate primary color image. This is a design problem with these types of devices.

The second approach to solve 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 making each layer's reflection bandwidth narrow enough only to reflect the light of the desired color.

But there is a problem with this solution. To design a PVH with a narrow bandwidth of reflection wavelengths, 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 deflect 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. 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 approach
Our approach is a synergistic combination of CPVH devices for red, green, and blue light(The respective layers are CPVH-R, CPVH-G, and CPVH-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 referred to as a Solc filter. This device, used as a sensitive wavelength selective filter for spectroscopy, consists of a stack of "half-wave retarders" (HWRs). These half-wave retarders are layers of a birefringent material partially characterized by the difference in the index of refraction measured using normally incident, linear polarized light for polarization states parallel and perpendicular to the optic axis of the material. This difference in the index of refraction, measured in this way, is called the birefringence(Δn). They are further characterized as having the property of the value of the product of their thickness (d) with Δn to be equal to the wavelength of the design vacuum wavelength (λo)divided by two. That is: $\Delta n * d = \lambda o/2$.

In the particular example, PIF used in the description of this example, a particular type of Solc filter is considered 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: $|p| = 180/(4*N)$

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 of that narrow range, light is passed without effect. We have found that these types of devices can be paired with CPVH 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 CPVH 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 CPVH. 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 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 the device is shown in Figure.1. It is seen that each of the three color layers of the device now consists of two sublayers: a CPVH and CPIF. In each layer, the CPIF and CPVH are designed to operate for either red, green, or blue light.

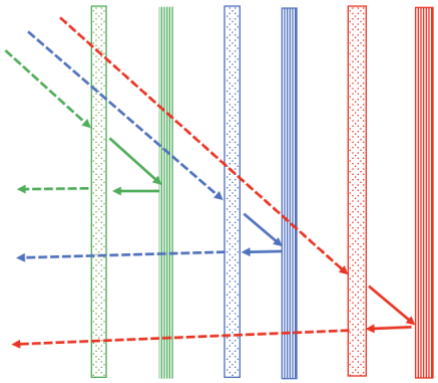

Figure. 1. An example wide-angle color reflector described in this work.

The device is a stack of 6 components. Following the incident light, they are CPIF-G, CPVH-G, CPIF-B, CPVH-B, CPIF-R, and CPVH-R. They are shown separately in Figure.1 for clarity. The dot-filed rectangles are CPIFs tuned to the color of the rectangle. The line-filled rectangles are CPVH 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 CPVH and CPIF layers could be replaced by PVH and PIF devices sensitive to linear polarization states of light.

3. An example case of CPVH and CPIF

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

In this example, the CPVHs have nx=1.7 and ny=nz=1.5. The CPVH-G director is shown in Figure.2. CPVH-R and CPVH-B have the same Bragg plane angle and grating vector angle as shown in Figure 2, but the pitch of the spiraling optic axis is changed, as shown in Table 1.

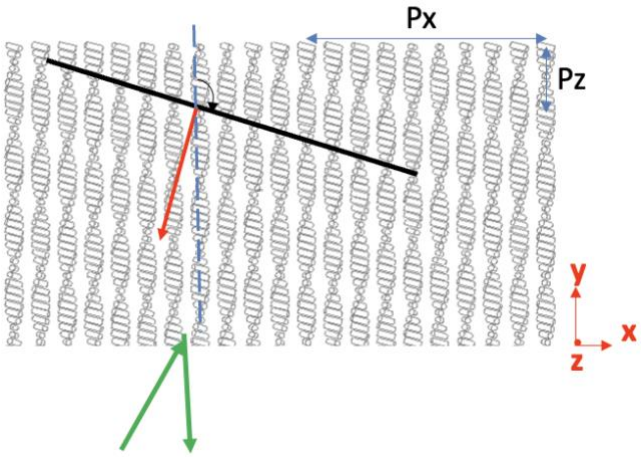

Figure. 2. Director picture for CPVH-G. The coordinate system in this work: +x is pointing right, +y is pointing up(cell normal direction), and +z is pointing out of the page towards the reader. The black line is the Bragg plane; it makes 104.125 degrees with the +y direction. The red arrow is the grating vector at 194.125 degrees with the +y direction. The green arrows indicate the incident and deflected beams at 50.87 with +y direction and 178.8 degrees with +y direction in the air.

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

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

The property of the PIF to inappropriately operate in linear polarized light is modified by adding two "quarter wave retarders" (QWRs). QWRs are known to be able to 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: $\Delta n^*d = \lambda o/4$. The rotation angle of the optic axis of the QWRs is +- 45 degrees to +z 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 $\Delta\Gamma = \Delta n^* d / \lambda$, and by the angle ϕ their optic axis in the xz plane makes with respect to +z 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

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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[3]. While there are several designs for "wide angle" retarders, in the example system considered here, Nz type retarders are modeled. Nz type retarders have the value of the index of refraction for light polarized along +y to be the average value of the two indices of refraction measured for light polarized along +x and +z.

4. FDTD simulation of a wide-angle reflector

The designed device's optical properties were calculated using the finite-difference time-domain (FDTD) method. Tables 3 and 4 show the percentage of light deflected to the desired angle (main deflection) and the percentage of light deflected to incorrect angles (crosstalk). This is shown for the case in Figure 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

Case Name	Main deflection	Largest crosstalk	2nd largest crosstalk	Main/ cross ratio	Transmitted beam
635nm with no CPIF	89.9%	2.5%	1.9%	20.4	3.7%
635nm with CPIF	96.0%	0.006%	0.03%	2666.7	4.1%
450nm with no CPIF	76%	21.1%	N/A	3.6	2.0%
450nm with CPIF	94.2%	0.1%	N/A	942.0	4.5%
525nm with no CPIF	98.0%	N/A	N/A	---	2.6%
525nm with CPIF	96.0%	N/A	N/A	---	4.5%

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

Case Name	Main deflection	Largest crosstalk	2nd largest crosstalk	Main/ cross ratio	Transmitted beam
635nm with no CPIF	78.0%	3.0%	1.2%	18.6	15.0%
635nm with CPIF	95.1%	0.04%	0.01%	1902.0	4.3%
450nm with no CPIF	63.0%	20.4%	4.7%	2.5	9.8%
450nm with CPIF	83.7%	0.02%	0.8%	102.1	13.3%
525nm with no CPIF	96.2%	N/A	N/A	---	4.1%
525nm with CPIF	90.8%	N/A	N/A	---	8.2%

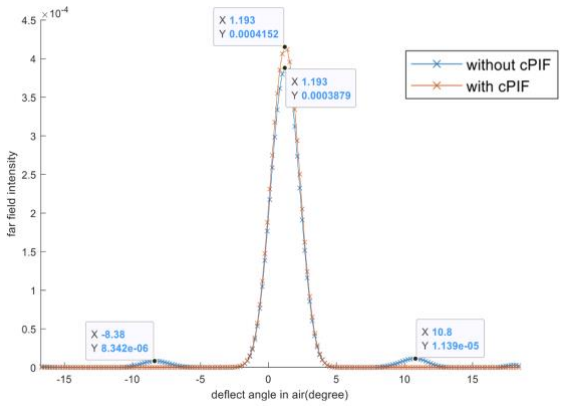
In Table 3, the main deflection is integrated from the [-3.8,5.4] degree range. The transmitted beam is integrated from the [40,90] degree range. In Table 4, the main deflection is integrated from the [5.4,13.8] degree range. The transmitted beam is integrated from the [54.6,90] degree range.

In Tables 3 and 4 elements, "main/cross ratio" in the second-to-last column refers to the ratio of the main deflection peak over the crosstalk peak. "N/A" indicates "Not clearly observed." In the design, as shown in Figure.1, the CPVH-G is the first CPVH in the stack, so the "Main/cross ratio" is not applicable, as indicated by "---."

The calculated results presented in Tables 3 and 4 indicate that the inclusion of the CPIFs provides the same deflected angle for the three considered colors of light (red, green, and blue), with very little crosstalk between the colors.

Table 4 shows that the light angle is varied by positive 16 degrees from the optimized angle. However, calculations over a negative 16 degrees also provided a good result, indicating the range of incident angles usable when incorporating the CPIFs is greater than 30 degrees.

The FDTD simulated far field intensity picture is given for 50.87 and 66.6 degree incident angle, 635 and 450nm incident wavelength. The 525nm incident wavelength is omitted because no clear crosstalk is observed in the FDTD result.



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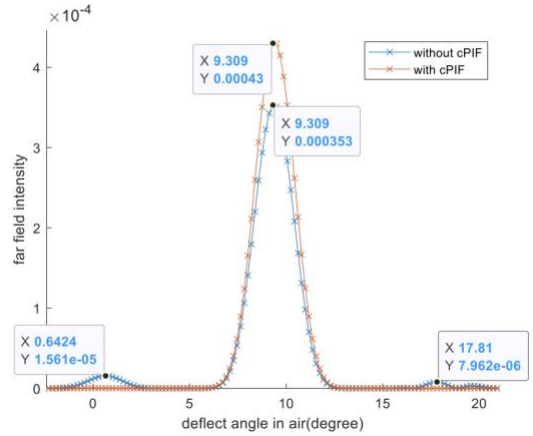

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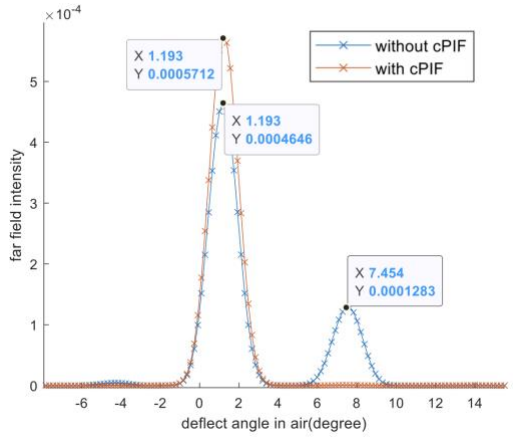

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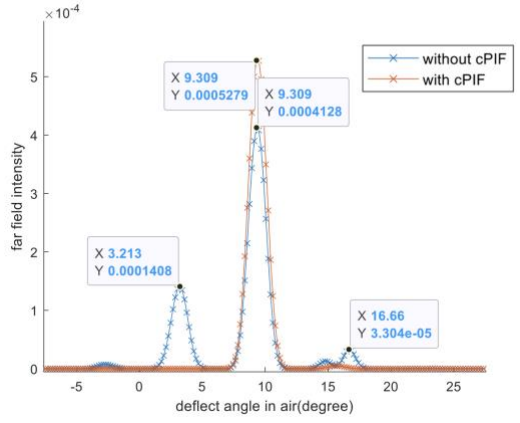

(d)

Figure. 3. Far field intensity of 635nm,50.87 degree (a) 635nm,66.6 degree (b),450nm,50.87 degree (c) 450nm,66.6 degree (d) incidence in air.

5. Conclusion and discussion

In this work, using CPIF and CPVH, a wide-angle CPVH reflector is proposed with high deflect efficiency and negligible crosstalk.

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

1. The CPVH 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 optimized. The number of the half wave retarders in the CPIF(12 in this work) can be modified based on different design goals and wavelengths of the R, G, and B used. In future studies, a reduced number of half-wave retarders can be studied to reduce the complexity of manufacturing.
4. To increase the deflect efficiency, a compensator can be added to the CPVH to compensate for the polarization change at the CPVH.

6. Acknowledgements

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7. References

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