Proposal of Ultra-thin AR wearable display film using liquid crystal waveguide

Takao Tomono[1], **Rumiko Yamaguchi**[2]

takao.tomono@toppan.co.jp
[1] Digital Innovation Div., Toppan Inc., Tokyo 110-8560 JAPAN
[2] Graduated School of Engineering Science, Akita University, Akita 010-8502 JAPAN
Keywords: AR, wearable, waveguide, liquid crystal, film.

ABSTRACT

We propose an ultra-thin AR wearable display (WD) film (<1mm) using a liquid crystal waveguide. The principle is to outgoing light from waveguide by changing the refractive index of the clad when power-on. The device does not cause fatigue in the eye because of direct projection system onto the retina.

1 Introduction

Expectations for AR smart glasses have increased recently. See-through, high resolution, shape equivalent to glasses, etc. are required from the shape set on the head for AR glasses. Many researchers are developing AR smart glasses as waveguide wearable display since proposal of hologram thin light guide path [1]. Currently, the optical system of display represented by HOLO-lens is light guide path using a hologram [2]. Further miniaturization is desired since the shape is large, as things are. However, its size is impossible to exceed the configuration of small head mounted display as light guide path.

Our purpose is to implement ultra-thin AR wearable display film (AR WD film) on conventional glasses. Here, the AR WD film is within 1mm using a liquid crystal waveguide.

2 Proposal

Proposed optical system for Ultra-thin AR display film is shown in Fig.1. The light from light source is introduced into thin film waveguide. Using two grating 1 and 2 (lenses), the light is expanded and collimated. The advancing light in the waveguide is cut off when electric voltage is applied. The emitted light is oriented toward pupil by grating. After that, the Fresnel lens condenses the light and focus pupil. The device does not cause fatigue in the eye because of direct projection system onto the retina.

We explain light trace on the waveguide using fig.2. Fig (a) and (b) are cross section and plan view. Here, laser diode with gaussian mode is used. And the light is introduced direct coupling or using prism coupling. into waveguide. The light is expanded using grating lens 1 and the light is collimated using grating lens 2 after expanding till the width of display. As shown in fig (b), the refractive index of liquid crystal is changed, and the light is emitted when electric voltage is applied. The light is controlled toward vertical just after emitting using grating 3. After that, the light condenses on the point of pupil.

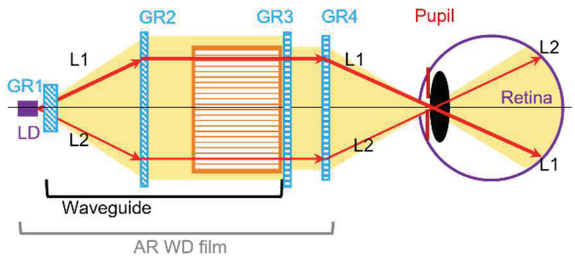


Figure1 Proposal optical system for Ultra-thin AR Wearable display waveguide film. Here, GR1 and GR2 stand for grating lenses. GR3 and GR4 stand for grating and Fresnel lens.AR WD film stand for AR wearable display film.

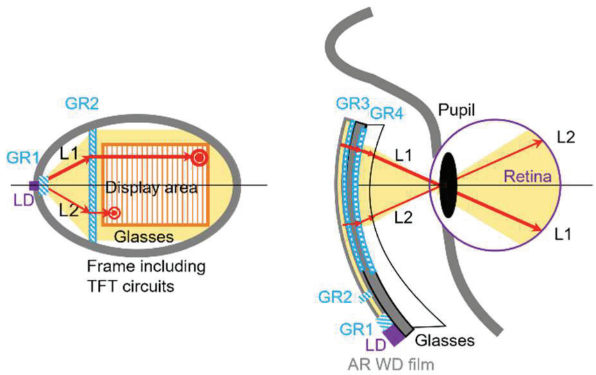


Figure2 Plain and cross section view of proposed configuration. Fig (a) and (b) show plain view of device image of eyeglasses and cross section view of light tracing to retina from eyeglasses.

3 Simulation

We calculated the possibility of designing this device.

Grating lenses are an already established technique. Therefore, it was examined whether the light could be confined in the waveguide 1), whether the light could be emitted by applying a voltage 2), and whether the light could be controlled in the direction perpendicular to the film by the grating 3). In addition, 4) was examined as to whether color display is possible.

3.1 Film device structure for AR

We thought this device structure. Grating lenses are an already established technique. Therefore, it was examined whether the light could advance in the waveguide 1), whether the light could be emitted when voltage is applied 2), and whether the light could be controlled in the vertical direction to the film using the grating 3). In any case, we examined whether color display is possible.

3.2 waveguide design

The cross-sectional figure of AR WD film is shown in Fig.3. The clad1 is formed on the TFT substrate. Although not shown here, it is assumed that the core layer has GR1 and GR2, and that the laser bee has already been expanded and collimated. Sub1 and sub2 stand for substrate that controlled applied voltage for liquid crystal and is formed on Fresnel lens. The candidates for clad1, core and clad2 are PMMA, polycarbonate (PC), and LC layer (5PCH) of liquid crystal.

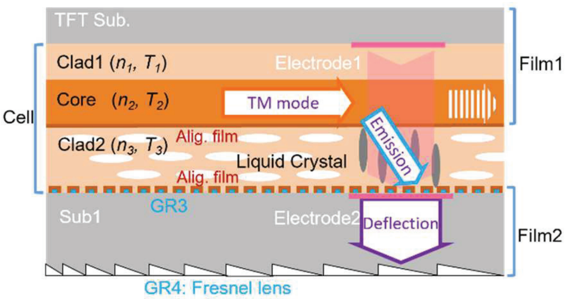


Figure3 Cross section view of AR WD film that consists of film1, film2 and liquid crystal. The clad1 is formed on the TFT substrate. Sub1 and sub2 stand for substrate that controlled applied voltage for liquid crystal and is formed on Fresnel lens.

TABLE1 Optical properties of candidate materials. PMMA and PC stand for Poly Methyl Methacrylate and polycarbonate.

Candidate Material	refractive Index	wavelength(μm) 0.45	0.55	0.65
Clad1: PMMA	n_{PMMA}	1.5006	1.4926	1.4881
Core: PC	n_{PC}	1.6079	1.5893	1.5792
Clad2: 5PCH	$n_{o,\,5PCH}$	1.5009	1.4902	1.4845
	$n_{e,\,5PCH}$	1.6235	1.6075	1.5991

As the waveguide structure, we selected PMMA as clad1, PC as Core, and 5PCH as clad2. We selected TM0 mode in waveguide as the refractive index of liquid crystal is on ordinary light when voltage is not applied. When the film thickness of polycarbonate is less than 0.65 μm, we cannot be guided the light in the range of red region. We decided that the thickness of Polycarbonate is 0.7μm. We find that it is possible to use waveguide from 450nm to 650nm if the core thickness is set on 0.7μm. The field distribution and optical power on clad1, core and clad2 is shown in figure 4.

Fig (a), (b) and (c) is field distribution on wavelength of 450nm, 550nm and 650nm. The band width of electric field distribution become wide as the wavelength increase. However, the band width of optical power is within about 3 μm. we confirmed that the thickness of each Clad is more than 1μm as the clad is 0.7μm.

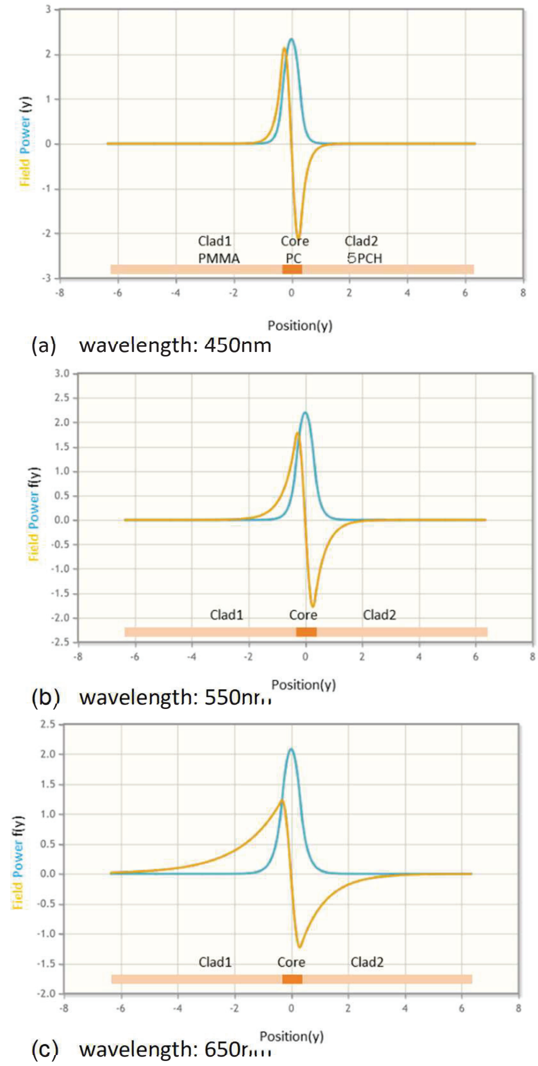


Figure 4 Position vs electric field distribution in TM mode slab waveguide. ■: Core position (thickness: 0.7μm), ■: clad1 and clad2 position (thickness: 6μm).

3.3 Liquid Crystal Design

Next, we decided device structure for liquid crystal. As shown in fig.3, we have multilayers. To be estimated appropriate applied voltage, we changed the thickness of PMMA and PC.

We need enough electric filed for liquid crystal reorientation. The threshold voltage of the LC of 5PCH is about 0.9 V. However, the applied voltage across the liquid crystal layer decreases with thickness of polymer layers. Therefore, threshold voltage of the LC in the multilayer cell increases to 1.1 V, when the thickness of PMMA, PC and LC layers are respectively 1, 0.7 and 10 µm. Relative permittivities of PMMA, Polycarbonate and LC of 5PCH are respectively 4.3, 2.9, 17.7 (ε//) and 5.0 (ε⊥). We estimate the effective refractive index of the LC layer as a function of applied voltage to the multilayer cell, as shown in Fig.5. Refractive index of the LC increases to n_{pc} by applying the voltage of 6 V and reaches to 1.6 by 14 V. This voltage is about 2 times higher than that in the mono layer LC.

Next, we estimate the refractive index distribution in the multilayer cell when the applied voltage is 10 V, as shown in Fig. 6. Most of the liquid crystal in the bulk is reoriented perpendicular to the substrate, except the region of 2 µm thickness from each substrate. Therefore, refractive index of 1.6075 can be obtained around the inner 6 µm thickness.

We will use field sequential driving circuits for liquid crystal to use image pixel effectively. It is possible to drive LC for displaying image if we use the circuit.

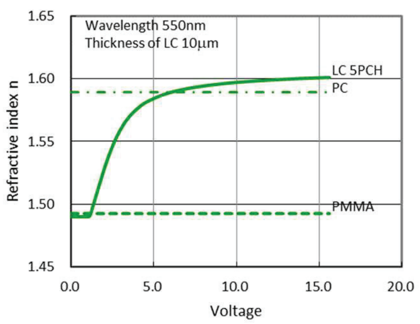


Figure 5. The relationship between applied voltage and effective refractive index of LC layer.

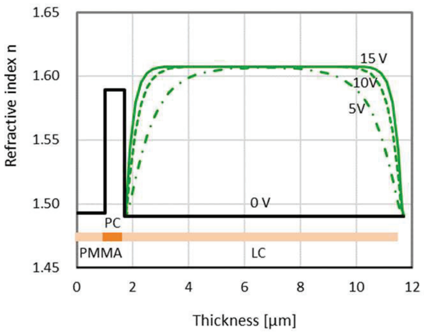


Figure 6 The relationship between LC film thickness in the cell and refractive index when voltage is 10V.

3.4 Emission of light

When the voltage is applied to liquid crystal, the refractive index of liquid crystal is changed from $n_{o,\,5PCH}$ of ordinary light $L1_{core}$ to $n_{e,\,5PCH}$ of extraordinary light $L1_{clad}$ as shown in fig.7. We can obtain light out of waveguide. and the value is larger than that of polycarbonate.

Here, we will estimate θ$_1$. In a normal waveguide, light satisfies the total internal reflection condition. The angle of the total reflection condition of the light was set to θ_1.

Using this θ_1, θ_2 was obtained from the law of refraction on the interface between core and clad2.

$$\theta_1 = \sin^{-1}\left(\frac{n_{o,5PCH}}{n_{pc}}\right) \quad (1)$$

$$\theta_2 = \sin^{-1}\left(\frac{n_{pc}}{n_{e,5PCH}}\sin\left(\sin^{-1}\frac{n_{o,5PCH}}{n_{pc}}\right)\right) \quad (2)$$

The results of emitting angle are shown in Table 2. and the emitting angles are 69 to 70 degrees on the wavelength of 450nm, 550nm and 650nm. Though emitting angle is very large, we can confirm that the light advance to clad2. This result affects the shape of the diffraction grating. Next, we will find out if there was a manufacturing potential for its grating.

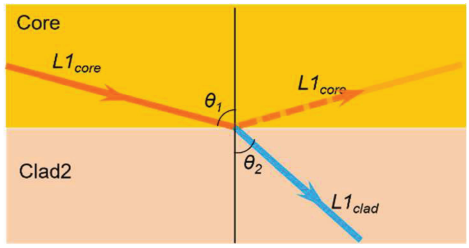


Figure 7. Emitting out of waveguide. The light trace of L1 advance toward dotted arrow when n of clad2 is n_o of liquid crystal 5PCH. The light trace of L1 advance toward $L1_{clad}$ when voltage is applied between electrodes.

TABLE2 Wavelength, Refractive index n_{pc}, n_o, n_e, θ_2 obtained by equation (1)

Wavelength (µm)	n_{pc}	$n_{o,\,5PCH}$	$n_{e,\,5PCH}$	ϑ_2
0.45	1.6079	1.5009	1.6235	68.98
0.55	1.5893	1.4902	1.6075	69.66
0.65	1.5792	1.4845	1.5991	70.06

3.5 Grating 3

We must control light direction using this θ_2. We decide to use grating as we are considering thin film as shown in Fig. 8 (a). Using Ewald Sphere as shown in Fig.8 (b), We used the wave vector to determine the shape of the diffraction grating.

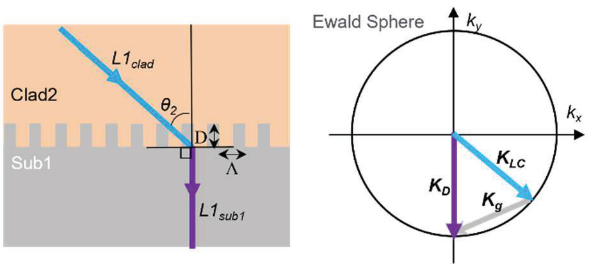
In the direction of k_x, wave vector is satisfied with,

$$\frac{2\pi n_{e,5PCH}}{\lambda_0}\sin\theta_2 + \frac{2\pi}{\Lambda} = 0 \quad (3)$$

In the direction of k_y, wave vector is satisfied with,

$$\frac{2\pi n_{e,5PCH}}{\lambda_0}\cos\theta_2 + \frac{2\pi}{D} = \frac{2\pi n_{sub1}}{\lambda_0} \quad (4)$$

Simulation results is listed in Table 3. The period is 360±60 nm, and the depth is 500±100 nm between 450nm and 650nm. We will focus on the case of 550nm. The period and depth are 360nm and 500nm.



(a) Grating structure (b) Ewald Sphere

Figure 8. Grating configuration for light deflection. (a) is grating structure. (b) is Ewald sphere for grating design.

TABLE3 Wavelength, period Λ and Depth of Grating.

Wavelength (μm)	Λ (μm)	D (μm)
0.45	0.2969	0.4388
0.55	0.3649	0.5337
0.65	0.4324	0.6288

The period of 360 nm stand for Installing the wall (distance of 180nm and Hight of 500nm) with a period of 360 nm wall if we set aspect ratio is 1 vs 1. We found that it is possible to make the grating in the manufacturing process.

4 Discussion

Our proposal consists of light source such as laser, two grating lenses (GR1, GR2) to collimate laser beam, waveguide and grating for controlling beam deflection (GR3), and Fresnel lens (GR4). We focus waveguide and grating for controlling beam deflection as we are thinking that we can make GR1, GR2 and GR4 using existing manufacturing equipment.

The AR WD film consists of film1 and film2 and the liquid crystal inserted between them. Here, the beads or pillars are inserted to keep the space of liquid crystal layer. The film1 is formed in a core layer with GR1 and GR2, and further consists of a clad layer and a substrate on which a TFT drive electronic circuit is printed. film2 consists of GR3 and GR4 which is a Fresnel lens.

We could show that the red (650 nm), green (550 nm), and blue (450 nm) laser beams proceed according to the proposed light trace L1 and L2. When we make a production, we had better select design on 550 nm green.

With the GR3 diffraction grating design, the film travels almost vertically, and then a Fresnel lens forms an image on the pupil. The pupil diameter is several mm, and the chromatic aberration due to the diffraction grating corresponding to each color cannot be known unless it is manufactured. However, since the optical system initially considered is an illumination optical system that is directly projected onto the retina, it is considered to have a smaller effect than the imaging optical system.

Many spectacle lens companies are manufactured with 6 curves and an objective surface with a radius of curvature of 87 mm. This means that the curvature of the anti-pupil surface is determined according to each power. Therefore, it is preferable to attach this AR WD film to the objective surface as shown in fig.2.

5 Conclusions

As the first step, we propose ultra-thin AR Wearable Display film attached to eyeglasses. Except for conventional grating design, we focus the liquid crystal waveguide and grating design for deflection of light direction as key. We chose these materials from dozens of material candidates.

As the waveguide structure, the core of 0.7μm is PC(Polycarbonate), clad1 of 6μm is PMMA (Poly Methyl Methacrylate), and clad2 of 6μm is 5PCH of liquid crystal. The grating for beam deflection is the period of 0.365μm and the depth of 0.534μm as grating 3. The proposed structure of AR wearable display film is shown in TABLE4. We estimate that the thickness of AR glasses is less than 1 μm even if the film includes TFT circuits.

We have only presented the potential of AR WD film. In the future, we would like to start from the verification of beam extraction using the liquid crystal waveguide and the diffraction grating 3. After that, I would like to check the structure one by one and lead to the completion of the proposed device.

TABLE4 Proposal AR glasses using liquid crystal waveguide.

Proposal spec.	Numerical Data
Screen size on Glaases	41.0 mm×27.2 mm
Resolution on Glasses	1024×768
Pixel size on Glasses	40μm×40μm
Distance to pupil	12 mm
Viewing angle	above 120°×90°
Waveguide thickness PMMA/PC/5PCH	1μm/0.7μm/10μm
Thickness of grating	<1μm
AR wearable display film	Thickness≦1mm

References

[1] T. Tomono, Spectacle-type wearable display, Optics Communications 180 (2000) 205–210.

[2] Doughty, M., Singh, K., Ghugre, N.R. et al. Surgeon Assist-Net: Towards Context-Aware Head-Mounted Display-Based Augmented Reality for Surgical Guidance. In Medical Image Computing and Computer Assisted Intervention – MICCAI 2021. Lecture Notes in Computer Science, 12904.

[3] R. Yamaguchi and K. Inoue, “*Electrical and Optical Model of Reverse Mode Liquid Crystal Cells with Low Driving Voltage*”, J. Photopolym. Sci. and Technol., 34, (2021) .p.315-320