Toward Mass Production of Polarization Volume Hologram Waveguides

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Abstract

Polarization Volume Hologram (PVH) waveguides are an outstanding alternative to other currently widespread Augmented Reality technologies. Some advantages of this technology include higher efficiency, light weight, and lower rainbow effect. The careful formulation of our materials to allow for high refractive index, adequate birefringence and good reliability is a clear enabler for this technology. Additionally, establishing reproducible and high-throughput deposition and patterning processes helps clearing the way for mass production.

Author Keywords

Polarization Volume Hologram; Reactive Mesogens; Augmented Reality.

1. Introduction

Polarization Volume Hologram (PVH) waveguides (WG) are an outstanding alternative to other currently widespread Augmented Reality (AR) technologies such as geometric WGs, or other diffractive WGs such as surface relief gratings (SRG) or volume holographic gratings (PVGs) [1]. PVH WGs are comprised of liquid crystal molecules that are oriented forming periodic patterns defined by a photo-alignment material (PAM) layer, as shown in Fig. 1. After polymerization, the molecules are locked in place giving rise to optical layers able to diffract light very efficiently. Due to their unique nature, PVH WGs offer an effective combination of performance and ease of fabrication, making them well-suited for mass production [2]. PVH has been shown to achieve improved WG efficiencies when using LCOS or LBS projectors as compared to other technologies as SRG, with 1500 to 3000 nits/lm for 30° field of view (FoV) RGB full color using newly developed reactive mesogens (RMs) materials with n_e ~2.0 [3]. Additionally, the incorporation of large slant angles and the stacking of multiple layers allow for minimizing world-side leakage, enhances color and brightness uniformity, and reduces the rainbow effects associated with the waveguide polarization selectivity.

From a fabrication standpoint, PVH WGs also offer some advantages. PVH's periodic structure is formed through light manipulation rather than etching or nano-imprinting methods used, for example, in SRGs. Instead, PVH establishes its periodic structure in mere seconds using polarization holography, photo-alignment, and the self-assembly of reactive mesogens[4]. While PVH WGs have been demonstrated at an R&D level, some challenges remain to demonstrate the path for mass production. In this presentation, we will show our work aimed at modifying both materials and processes to enable the fabrication of PVH waveguide components. The careful formulation of our materials to allow for high refractive index (RI), tuned birefringence and reliability is a clear enabler for this technology. Also, establishing reproducible and high-throughput deposition and patterning processes clears the way for mass production of PVH-based AR components.

2. Results

High-performance PVH WGs require optimized materials to achieve the above-mentioned performance metrics. RMs consist of liquid crystal building blocks that can be polymerized under UV curing conditions, typically using acrylic-based active groups. They have been widely used to enhance the image quality of LCD and OLED displays, and have also been more recently applied in virtual reality (VR) lenses [5],[6]. RMs will also play an important role in PVH fabrication for AR applications due to their versatility. Fig. 1 shows a PVH structure comprised of RM twisted planar layers. This application pushes the requirements for RM materials since lower periodicities are required to properly guide light through the WG as compared to previous VR applications. Also, high RI is needed to enhance FoV, and multiple layers with different slant angles are required to maximize diffraction efficiency. Wettability and alignment quality are crucial factors in designing such formulations. We have developed a novel type of RMs with high RI (n_e >2) for these applications that allows for the synthesis of PVH WGs with high performance.

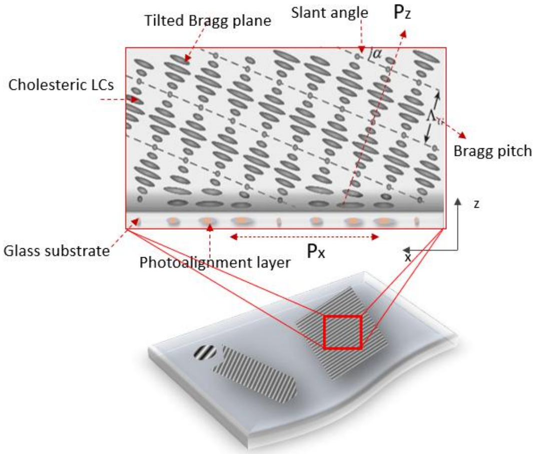

Figure 1. PVH WGs are comprised of twisted planar layers of RMs that are polymerized following the PAM layer pattern.

Coating techniques are also essential in enhancing the functionality, durability, and aesthetics of surfaces in AR/VR applications. Various methods exist, each with unique characteristics and applications in the liquid crystal thin film coating industry. Slot-die coating is a well-established deposition technique known for its high throughput and uniform coatings in industries like liquid crystal displays (LCDs) and solar panels. The principle of slot-die coating is illustrated in Fig. 2, which depicts the continuous coating of RMs onto a moving glass substrate to produce a uniform and consistent thin film. This method excels in producing large-scale uniform coatings. Still, it can lead to the formation of dead zones on substrates, necessitating specific meniscus formation to mitigate them and enhance coating repeatability. Moreover, slot-die coating is primarily suited for uniform techniques and operates effectively only within narrow viscosity and solvent ranges, limiting its flexibility in addressing the diverse needs of AR technologies [7].

Inkjet printing (IJP) offers a more suitable alternative for PVH WG fabrication due to the requirement for multilayer stacking of high RI RMs, with specific slant and thickness variations. These complexities can be effectively addressed through the IJP simplified fabrication processes. The IJP coating method generates a stream of droplets, as illustrated in Fig. 2, allowing for precise control over film thickness and the deposition of specific patterns on the substrate. This method allows for exceptional control over film thickness and the ability to deposit specific patterns directly onto substrates with higher resolution. This capability not only minimizes material waste but also significantly reduces costs. The versatility to accommodate various substrate types and sizes, positions IJP technology as a game-changer for the evolving AR smart glasses technologies. As AR continues to grow and diversify, adopting IJP will enable us to meet its complex demands effectively, making it the clear choice over traditional slot-die coating methods [8].

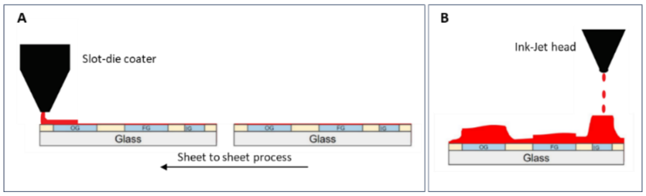

Figure 2. While slot-die coating technique allows for constant thickness coatings (left), inkjet printing offers significantly more flexibility for AR technology designs.

When it comes to patterning, the fabrication of PVH-based WGs has been demonstrated using R&D-level techniques [4]. Two-beam interference has been initially used to produce cyclonic patterns on PAMs [9]. With this technique, two orthogonal circularly polarized beams interfere to produce a linearly rotating polarization modulation pattern on the PAM. Its advantage is that it allows for the writing of the entire grating in a single exposure by expanding the beam to the desired size. However, because this process relies on interference recording, the patterning quality is highly sensitive to the stability and coherence of the laser source as well as to any ambient vibrations. Direct laser writing has also been demonstrated [10]. In this case, a focused laser beam passes through a polarization modulator and scans across the sample that is placed on a high-precision motorized translation stage. The advantage of this technique is that it provides greater flexibility in writing arbitrary polarization patterns on the PAM. However, this is generally a low-throughput process because of the time required to write large patterns.

While these patterning methods have been critical to demonstrate the value of this technology, high throughput techniques will be required to enable mass production. An alternative path is to use a phase mask to duplicate the polarization patterns [11, 12]. There are primarily two different configurations for a proximity mask duplication setup: on-axis mask duplication [13] and off-axis mask duplication. In an on-axis mask duplication setup, collimated input light with linear polarization is normally incident on the mask. The two diffracted beams, which have opposite handedness, interfere to duplicate the polarization modulation pattern on the PAM layer with a grating pitch that is halved from the master mask. The main challenge in this configuration lies in the fabrication of the master mask, which must be a multi-twist retarder stack to achieve the half-wave condition at the writing wavelength. In contrast, in an off-axis duplication setup, the input collimated beam with circular polarization is incident on the mask at an oblique angle. In this case, the direct 0th-order leakage and the 1st-order diffracted beam interfere to duplicate the polarization pattern on the PAM layer at a 1:1 ratio, with no pitch-halving in this case.

The combination of RM material development, deposition technique optimization, and use of high throughput patterning techniques will pave the way to enable mass production of high-performance, cost-effective PVH-based AR devices.

3. Conclusion

While previous works have demonstrated PVH WG proof of concept using R&D level methods, we reviewed how the combined optimization of RM formulations, the application of IJP as a versatile method to obtain varying thickness coatings and the use of high-throughput friendly master duplication patterning methods will open the path for PVH waveguide mass production. These high-performance and cost-effective devices are expected to heavily impact the adoption of AR technology.

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