Fourth Gen Optics - Planar Optics Revolutionized by LCD Technology

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Abstract

We will review the state-of-the-art of the Fourth Generation Optics – a planar optics rooted in LCD technology, – and the advance it has enabled in display, AR/VR, imaging, and other critical modern technologies beyond displays. The review will lead to the conclusion that the technology is mature for many applications offering the most versatile and efficient techniques for controlling light with truly flat, thin film, achromatic, and high quality optical systems produced at low manufacturing cost inherent to LCDs.

Author Keywords

Flat optics, AR/VR, LCDs, liquid crystals, liquid crystal polymers, photoalignment; switchable lenses; switchable optics.

1. Introduction: The reason why there is no Moore's Law in Optics

"Unlike electronics, optics does not follow Moore's law, and is proving to be one of the hardest challenges to solve in AR/VR hardware". This statement made by Microsoft's Bernard Kress on a number of occasions, for example, as a Visionary Speaker at the OSA's recent Frontiers in Optics [1], has a clear fundamental basics: there are only four ways for controlling propagation of light with transparent materials. They all involve spatial modulation of one of the optical properties of materials:

-shape (the 1st generation optics)

-refractive index (2nd Gen optics)

-birefringence (3rd Gen optics), and

-the orientation of optical anisotropy axis (the 4th Gen or 4G Optics).

Thus, a modern lens, for example, is different from Nimrud lens made 3000 years ago mostly by quality…

In contrast, there are numerous ways of generating light, hence, numerous revolutions in development of light sources.

2. PBOE? GP? Just Diffractive Waveplates!

Any of the optical parameters of a material when changing linearly in space results in prism action, and varying either shape or refractive index or birefringence or the orientation of optical anisotropy axis in a parabolic fashion results in a lens action, Figure 1.

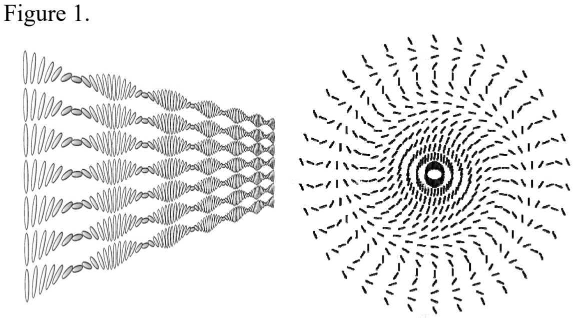

Figure 1. Molecular orientation in a 4G prism (left) rotates in the plane of the film as a linear function of a coordinate while it is a parabolic function in a 4G lens (right).

The mechanism of phase modulation in 4G Optics appears far less intuitive and more challenging for physical understanding than for any of the prior generation optics. It is often called Pancharatnam or Pancharatnam-Berry, or Geometrical phase. Most developers, our experience shows, cannot describe what is behind those names, and its complex definition (see, for example, Wikipedia) does not help.

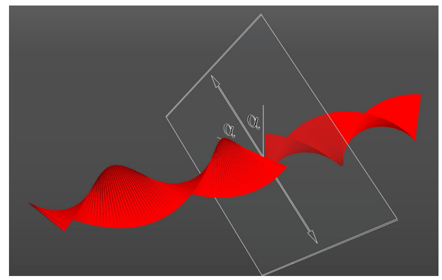

Figure 2. A half-wave retardation plate converts a circular polarized beam at its input into a orthogonally circular polarized beam at its output while also imparting a phase that depends on the orientation of the HWP axis.

Revealing their essence as half-wave-retardation films [2], see also the review articles [3,4], just like an LCD, demystified the simple origins of phase modulation in 4G Optics – the phase of a circular polarized light beam at the output of a half-wave retardation film (or, half-wave plate - HWP) varies with the orientation of the optical axis of the HWP, Figure 2: $\Delta\Phi = 2\alpha(\mathbf{r})$. This fact takes only a few minutes to verify mathematically, and it could be visualized in simple physical terms as HWPs with patterned axis of their optical anisotropy orientation – diffractive waveplates (DWs) [4].

3. The thinnest of all lenses

Given high optical anisotropy of LCs, both low-molecular weight and polymer, $\Delta n = n_{par} - n_{perp} \sim 0.1$ for commercial LCs, and even $\Delta n \sim 1$ [5], the half-wave retardation can be obtained in micrometer thin films, $L \sim \lambda/2(n_{par} - n_{perp})$ as in LCDs. If made with a LC polymer (LCP), the film proved to be strong enough to be produced in the form of a pellicle with no support substrate whatsoever. Thus, we have the thinnest optics ever demonstrated, Figure 3.

Most importantly, the film is smooth at nanometer scale which allows formation of multilayer systems for advanced functionality and customization, and it allows deposition of antireflection coatings that is not feasible for Fresnel, metasurface, or similar optics. Smoothness prevents haze typical to those other technologies.

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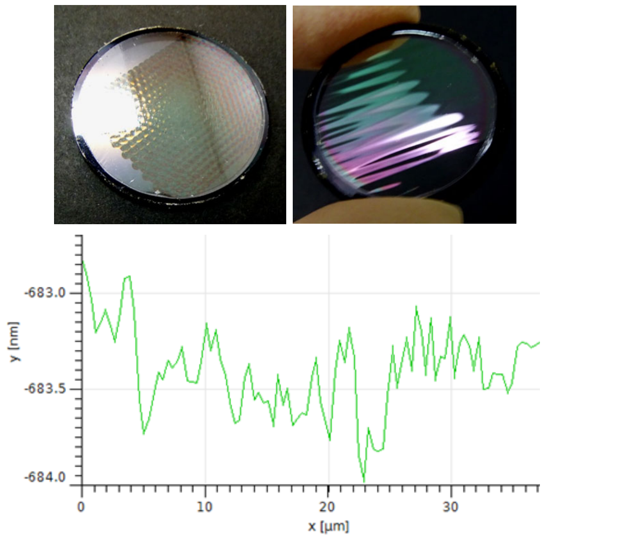

Figure 3. The thinnest optics: Top – a photo of a micrometer thin LCP 4G lens array as a pellicle with no substrates, and the film stressed to exhibit its robustness – maintaining mechanical integrity even with severe deformations; bottom – AFM of the film demonstrating smoothness in nanometer level.

4. Highest efficiency in broadest bandwidth

4G Optics can be made broadband using multilayer techniques well-known for HWPs, see, e.g. [6]. LCs allow additional opportunity of incorporating twist in individual layers [7-9]. The Twist-Uniform-Twist (TUT) structure is capable of providing essentially 100% diffraction efficiency over all visible, Figure 4 [10].

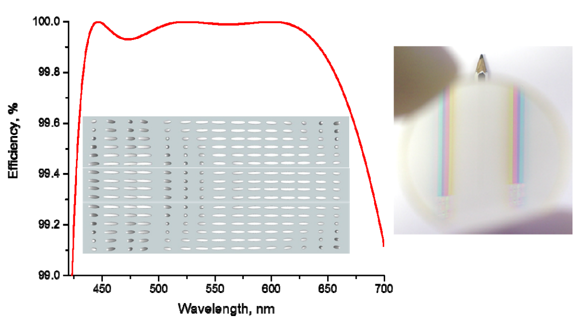

Figure 4. Diffraction efficiency of TUT 4G structures is >99% for wavelengths 423.6nm – 704.6nm. The photo inserts show the architecture of TUT structure and a pencil looked at through a 4G prism to demonstrate the lack of leakage/undiffracted light throughout the visible spectrum.

Moreover, due to their waveplate nature, the diffraction spectrum can be customized, for example, to provide near 100% efficiency in certain wavelengths and have near 0% efficiency at certain other wavelengths or spectral range [11]. The TUT structure also dramatically extends the angular bandwidth [11] and Figure 5.

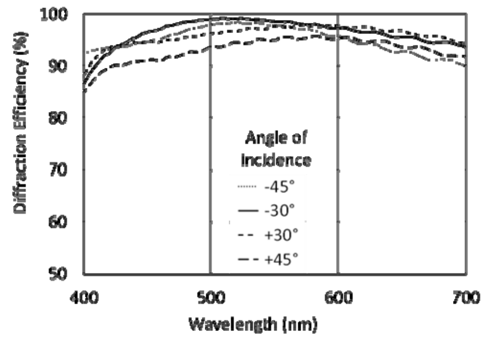

Figure 5. The thinnest optics: Top – a photo of a micrometer thin LCP 4G lens array as a pellicle with no substrates, and the film stressed to exhibit its robustness – maintaining mechanical integrity even with severe

5. Switchable like LCDs

Voltage and electrical power requirements of 4G Optics made switchable by using LCs are similar to those of LCDs. Note though that the modulation of molecular orientation in the plane of the film reduces the switching threshold [12]. Typically switching upon application of an electric field eliminates the diffraction, however, smooth tuning of the diffraction spectra is also possible. The 4G Optics can be made in full-phase retardation condition to have no diffraction without an electric field.

Switching speeds are also similar to the switching speeds of LCDs [13]. The most efficient technique for controlling with light propagation with the diffractive waveplates is indeed switching the state of polarization of the input beam which results in switching the sign of the diffraction order equivalent, for example, of reversing the sign of the focal length of the 4G lens [14]. Some ultrafast switching modes that are not required or are hard to use for large LCD sizes, can then be well adapted for smaller sizes of photonics components.

6. Low fabrication cost

Fabrication of 4G Optics involves many of the LCD manufacturing processes and materials. The photoalignment process can seamlessly be incorporated in the production line to replace conventional alignment processes used for LCDs. Thus the manufacturing can be done in batches or even on roll-to-roll basis as shown schematically in Figure 6.

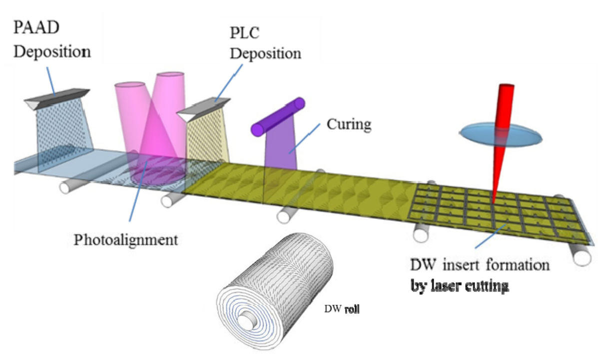

Figure 6. A schematic of roll-to-roll 4G Optics manufacturing process.

7. Sizes

There are no fundamental or technological limitations for sizes of 4G Optics. All application requirements can be met starting from microscopic sizes and all the way to huge area films required for solar sails or space telescopes [15]. Very large sizes can be obtained, for example, by tiled recording and release/transfer processes developed at BEAM Co.

8. Discussion

Due to LCDs industry, 4G Optics technology is currently at a high level of maturity; BEAM Co. has been exhibiting 4G Optics at all levels – components, devices, and systems – in all major photonics industry events for many years. Notwithstanding current research activities in many universities and companies, small and large, the unique capabilities of 4G Optics still come as a surprise to many.

One of the foci of the ongoing research relate to chromaticity, polarization dependence and, particularly, imaging capabilities of 4G lenses. These issues are overcome due to the multitude of opportunities of customizing the performance features of 4G Optics [11,16], with optimum solutions for different application needs.

The discussion above related to transmissive systems. 4G Optics makes possible highly efficient reflective systems as well either based on volume polarization gratings [17] or controlling the phase of light Bragg-reflected off the helical photonics bandgaps [18,19]. Reflective systems have been obtained also by deposition of 4G Optics as coatings on dielectric mirrors in combination with quarter-waveplates [19]. Very interesting for applications is the polarization-independent transmission-to-reflection low-voltage switchable system based on thin film unpolarized-to-polarized polarization converter utilizing combinations of 4G prisms with switchable o-plates [20].

9. Impact

4G Optics enables critical modern applications. Indeed, there still may be problems to overcome and specifications to meet in each particular case, but there is no alternative in most cases. For example, there is no alternative to using 4G lenses for augmented reality displays since no other technology can fundamentally make possible large area lenses that are still thin and lightweight and switchable between multiple vastly different focal states. Similarly irreplaceable is 4G Optics for non-mechanical random-access large angle beam steering applications for LiDARs, optical communication systems and non-mechanical steering of camera field-of-view.

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