Ultimate Planar Optics for AR/VR and Next Generation Displays

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ABSTRACT

Only one planar optics technology – diffractive waveplates – has shown capability to match large sizes and low-cost of Fresnel optics and the bandwidth of refractive optics. Electrically switchable and tunable with low-power controls, the thinnest lenses, prisms, and holograms make diffractive waveplate optics best suitable for AR/VR applications.

1 INTRODUCTION

"An optic, thinner in size than ever seen before" was the main subject of a presentation by BEAM Co. at the recent conference on New Optical Materials and Applications. The title was adapted from Franz Kafka's The Schoolmaster: "A mole, larger in size than ever seen before". The thinnest lenses ever demonstrated took years of development of special materials and processes. They make use of phase modulation imparted on a circularly polarized beam by half-wave retardation films due to spatial modulation of the orientation of their optical anisotropy axis in the plane of the film. The existence of this so-called Pancharatnam, Pancharatnam-Berry, or just geometrical phase, was known since the 1950's, first discussed by S. Pancharatnam [1], then placed in a wider physics context by M. Berry [2]. It remained however as a barely known science artefact until the demonstration of an efficient technology for patterning the optical axis orientation in half-wave retardation films with a high spatial resolution over a large area [3,4]. Currently, all versatility of optical functions is obtained by patterning optical anisotropy axis orientation in liquid crystal (LC) and liquid crystal polymer (LCP) films [5].

2 DIFFRACTIVE WAVEPLATE LENSES VS ALTERNATIVE FLAT LENS TECHNOLOGIES

The interest in planar optics dates back to about two centuries driven by the need to replace large lenses in lighthouses. Fresnel lenses proved not only lighter but optically superior to rather thick refractive lenses used at the time. While well meeting the needs of lighthouses and, later on, the needs for light collectors in solar power plants, and while allowing dramatic cost reduction, the optical quality of Fresnel lenses was never good enough for demanding imaging systems due to light scattering on structural discontinuities, related haze and compromise in efficiency, aberrations, and limitations related with manufacturing of fine lens structures for fast lenses.

All these limitations apply to multilevel diffractive Fresnel lenses that, additionally, require fabrication systems that are prohibitively complex and expensive for most applications; see, for example, a statement concerning the Lawrence Livermore National Laboratory having "…the only facility in the world that can make precision diffractive optics of more than a few centimeters in diameter" [6].

Notwithstanding the titles of research papers, metamaterial lenses, or metalenses, show even lower efficiency and smaller bandwidth, while requiring even higher levels of fabrication complexity and cost even for millimeter aperture sizes, with no practical pathway in sight for scaling up the technology [7,8].

Refractive LC planar lenses, gradient index lenses in essence, have proven good for imaging, and they even are being used for developing computer cameras and ophthalmic lenses. However, while making it possible to obtain strong gradients of effective refractive index in a plane, their functionality is limited to sizes of only a few millimeters small sizes since LC layers thicker than 100 μm are opaque due to strong spontaneous light scattering.

Diffractive waveplate (DW) optics overcome those drawbacks. BEAM Co. has been able to demonstrate micrometer-thin lenses in large area exceeding 2" in diameter and efficiency near 100% for circular polarized components of light over the whole visible spectrum, using simple low-cost equipment, materials, and processes (Figs 1-3).

The DW technology is revolutionizing optics and photonics by making it possible to design any desired optical function in thin films produced as coatings on any substrate relevant to the spectral range of operation, as well as with no substrate at all, in the form of a pellicle. The design and manufacturing process is mere minutes even for large area components. Technology allows not only to obtain achromatic performance for visible or infrared parts of the spectrum, but customizing the diffraction spectrum for selectively focusing light in a certain spectral range while having no optical power for other parts of spectrum [9,10]. Due to thinness, multiple lenses and components of different functionalities can be combined in a single thin and light-weight system.

Thus, DW lens technology is currently the only technology that can compete with glass in bandwidth, efficiency, transparency, and quality. DW lens technology is far superior compared to Fresnel, metamaterial and essentially any other diffractive technique due to its continuous texture smooth at nanometer scale (Fig. 4). A demonstrated function of DW devices is non-mechanical beam steering or switching the focal length of the system between multiple values (Fig. 5).

3 DISCUSSION

For isotropic materials, a lens can be made by spatially modulating its shape or refractive index. There are two more opportunities in anisotropic materials: the optical anisotropy (as in liquid crystal lenses), and the optical axis orientation. Pancharatnam revealed the phase related to the optical axis orientation still in 1950s, however, a constant phase change did not present much value or interest. In the year 2000, we suggested the opportunity of modulating the optical axis orientation to particularly produce an achromatic prismatic action. Relating it to waveplates cleared the path to fabrication of broadband components following principles well-developed for waveplates.

DWs are made broadband/achromatic by stacking multiple layers with certain retardation and angle between their optical axis orientation. Moreover, LCPs provide additional controls due to possibility of twist within the layers. We have shown, for example, that a hybrid, Twist/Uniform/Twist, architecture yields 99% and higher efficiency over a wide bandwidth, requiring moderate tolerances.

In practice, even a three-layer structure requires more layers due to the instabilities in LC orientation pattern when its layer thickness becomes comparable to the modulation period. Namely the prediction of stability of LC continuous modulation patterns in [11] enabled using of LC polymers in fabrication of DW optics! Thus, the coating process should allow deposition of multiple layers without degradation of alignment, and with well controlled retardation condition. The number of layers increases indeed with increasing resolution needs – larger diffraction angles, faster lenses.

A wide variety of DW structures requiring multiple layers are feasible, have been identified, fabricated, and tested [12]. They may be characterized by twist not only in the plane but also across the thickness of the film. An important distinguishing feature is having 100% efficiency for a given circular polarization handedness while not diffracting light of the orthogonal polarization. This makes possible combining two films for polarization-independent function [12]. The second interesting feature of such multitwist/multilayer material systems is the feasibility of obtaining fast optics without sacrificing efficiency.

Finally, diffractive waveplate optics, as other thin liquid crystal devices (most LCDs are in essence switchable waveplates) are switched with voltages as small as 5-10V, which is almost three orders of magnitude less than, for example, metalens-based systems [13]. Due to thinness of the layer of DW lenses of practically any focal length, millisecond switching times typical to LCDs and even faster are readily obtained [14].

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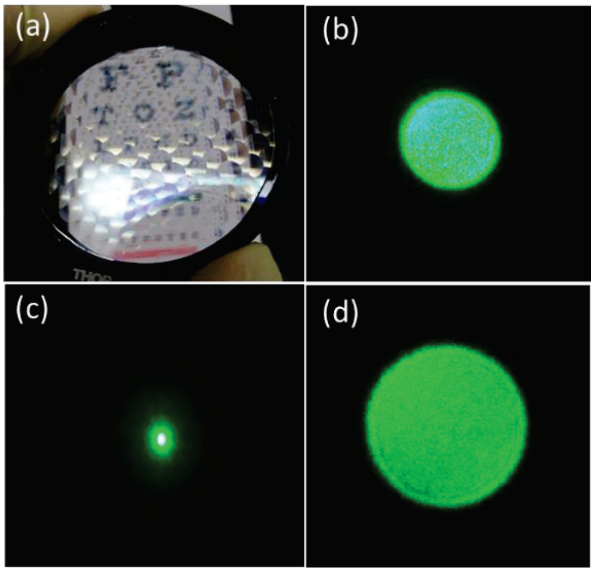

Fig. 1. (a) Photo of a pellicle lens array (with no substrates), and (b) the laser beam spot (c) focused and (d) defocusing by a pellicle diffractive waveplate lens (1.4 μm thick, 38 mm diameter).

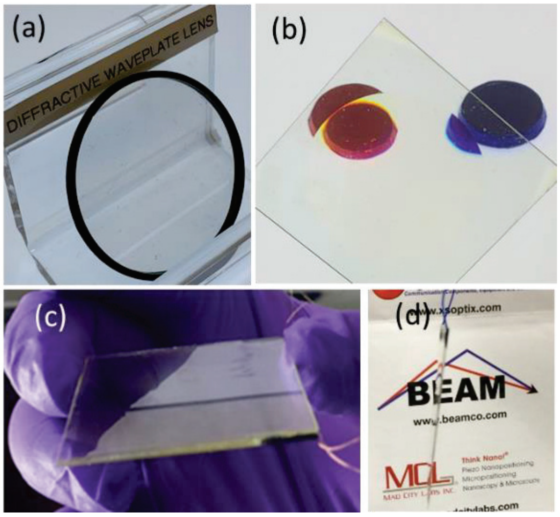

Fig. 2. Photos of diffractive waveplate lenses: (a) ring-mounted pellicle lens; (b) a broadband lens of 2” in diameter created as a coating on glass; (c) and (d) electrically switchable lenses with glass (c) and 100 μm-thick polymer substrates (d).

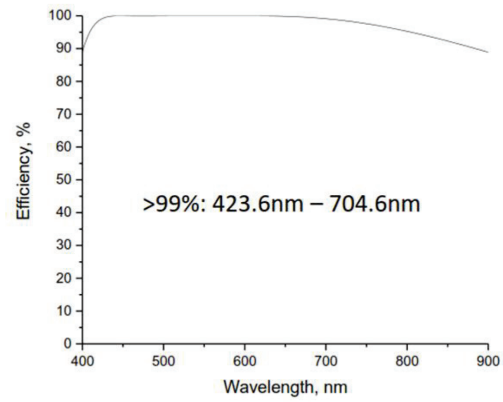

Fig. 3. Spectrum of a high efficiency broadband diffractive waveplate.

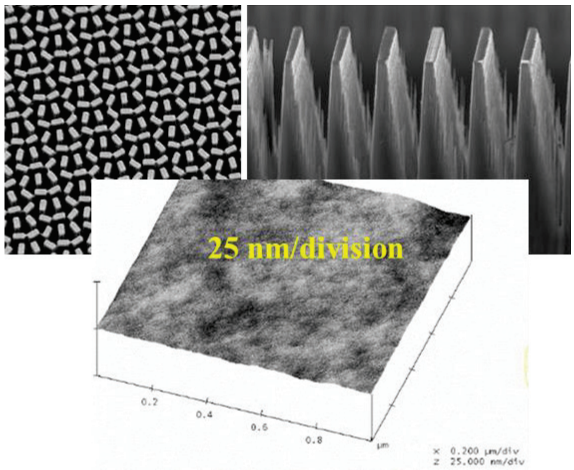

Fig. 4. DW films are coatings with smooth continuous texture even at nanoscale as opposed to discontinuous structure of Fresnel

or nanomaterial optics (generic examples in the background).

Fig. 5. Non-mechanical beam steering and multifocal systems based on diffractive waveplate lenses and prisms can be assembled into thin devices.