Fourth Generation Optics:

Planar Optics Revolutionized by LCD Technology

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Patent Disclosure Form

1. Title of invention: (Brief, but comprehensive, technically accurate and descriptive) Devices for displaying visual information

2. Inventors: (Full name, title, nationality, address (work and home), phone of inventor or inventors)
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b. Nelson V. Tabirian, Ph.D., President and Director for Research, BEAM Corp., 686 Formosa Ave., Winter Park, FL, 32789, phone (407) 629-1282,

Disclosed on 16 pages
by Dr. Boris Zel'dovich,

B. Zeldovich

SSN [redacted] Professor, School of Optics/CREOL, UCF,

and by Dr. Nelson Tabirian,

SSN [redacted] President and Director of Research, BEAM Corp.
Orlando, FL, July 19, 2000.

STATE OF FLORIDA
COUNTY OF ORANGE

Drs. Patrick Likamwa, Boris Zel' dovich and Nelson Taririan affixed there signatures to this codument consisting of 16 pages this 21st day of July. The title of this document is Devices for displaying visual information.

Frederick J. Smith, Notary, Florida
My Commission expires August 12, 2003.

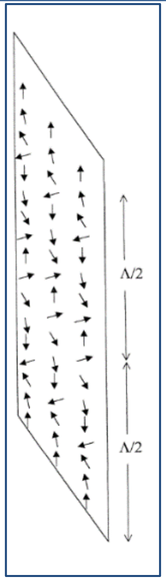
Frederick J Smith
My Commission CC851300
Expires August 12, 2003

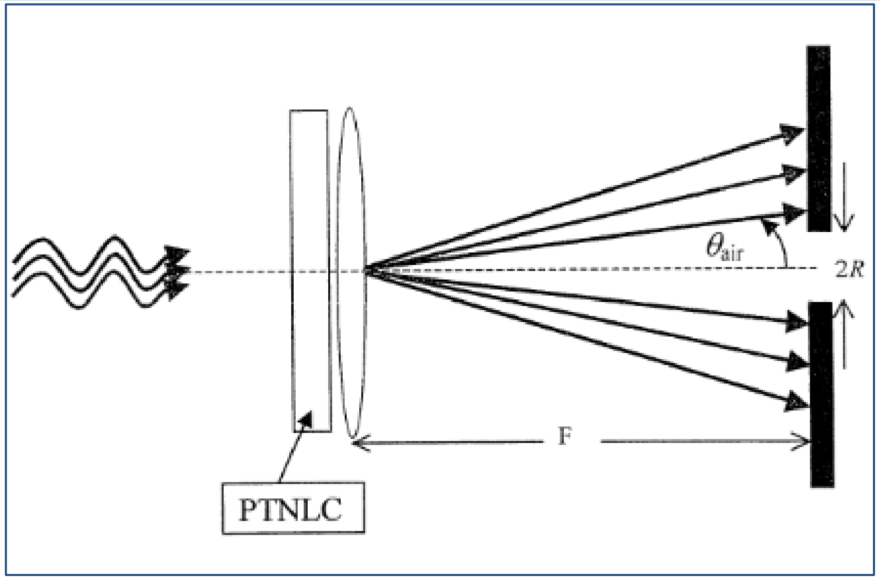
16

5. Concise description of the invention: Your disclosure should enable someone ... (whichever is most applicable), their relationship to one another, and their mode of operation. Include all essential elements (features, concepts, or new results of the invention, whichever is most applicable), their relationship to one another, and their mode of operation. Identify the elements which are considered novel. Also, if the invention is an apparatus or system, attach drawings or a sketch and indicate if it has ever been built or tested. Use additional pages if necessary, attach drawings, manuscripts, papers, or other supporting material to facilitate understanding of the invention.

Attached are pp. 1 through 16 of the Disclosure notarized at CREOL on July 21, 2000.

REV. 4/97





This design of the cell possesses several remarkable properties.

First of all, the **performance** of this cell **is achromatic**, in spite of the fact that phenomenon of diffraction is used for the deflection of the beam's power. In other words, light is stopped by the combination of the cell and the aperture stop for **any wavelength**, if the angular size of the limiting aperture satisfies the above condition for all the wavelengths under consideration.

Second, the **performance of this cell is polarization-independent**. Indeed, if we consider the incidence of the ordinary-type wave ($\mathbf{e}_y$-wave) upon the cell, the output wave will be, under the conditions of adiabatic following,

$$\mathbf{E}_{in} \equiv \mathbf{E}(z=0) = \mathbf{e}_y, \qquad \mathbf{E}_{out} \equiv \mathbf{E}(z=L,\ x,\ y) = [\mathbf{e}_x \sin\varphi(x,\ y) - \mathbf{e}_y \cos\varphi(x,\ y) +] \exp(i\gamma_{ord}),$$

Important property of the azimuthal angle distribution $\varphi(x,\ y)$ described above is that the spatially-averaged value of the field $\mathbf{E}_{out} \equiv \mathbf{E}(z=L,\ x,\ y)$ is zero for the ordinary wave as well! It means that the aperture will stop the other polarization as well.

Third, the **disclosed spatial light modulator is completely polarizer-free and absorption-free!** It will result in much better transmission for the "on" state of the cell. We would like to remind that the film-type polarizers/analyzers do absorb not only "forbidden" polarization.

Made possible due to support and close collaboration with:

BEAM

Brian R. Kimball, Diane M. Steeves
US Army Natick Soldier Systems Center
Natick, Massachussetts

Timothy J. Bunning, Michael McConney
Air Force Research Laboratories
Wright Patterson Air Force Base, Ohio

Eugene Serabyn
NASA Jet Propulsion Laboratory
California Institute of Technology

Liquid Crystals:

Great for displays, but not for optics?

Limitations due to Fluctuation / Dissipation Theorem

Large electro-optical coefficients ⇔ large fluctuations of molecular orientation

Control voltage $V_F \sim \sqrt{\dfrac{K}{\Delta\varepsilon}}$

Δε: dielectric anisotropy
K: elastic constant

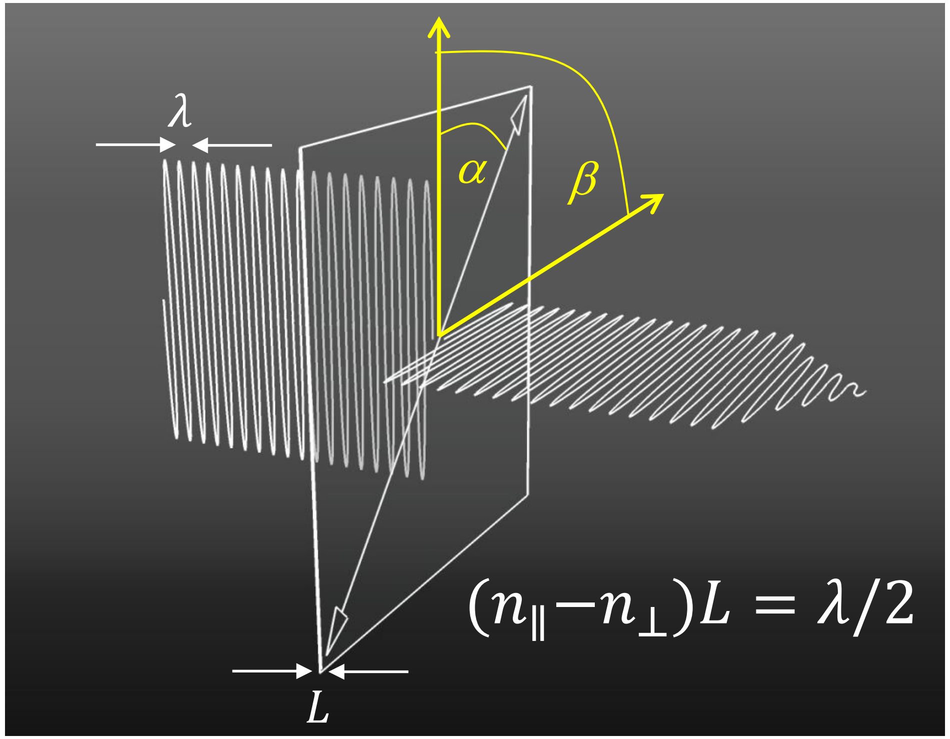
Light scattering cross-section $\sigma \sim \dfrac{(\Delta n)^2}{K}$

Relaxation time $\tau \sim \dfrac{\gamma L^2}{K}$

γ: orientational viscosity

Strong light scattering caused by fluctuations of molecular orientation limit the thickness of transparent LC layers to $L_c \sim 10\mu m$

LCDs: switchable half-wave phase retarder plates

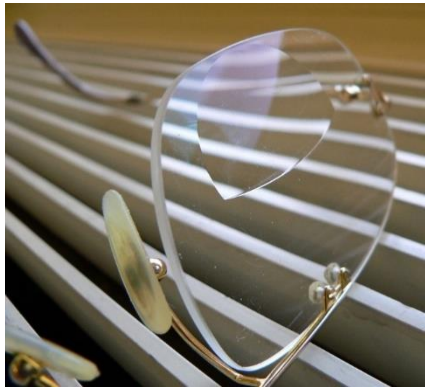


$\Rightarrow$ input linear polarization remains linear, and

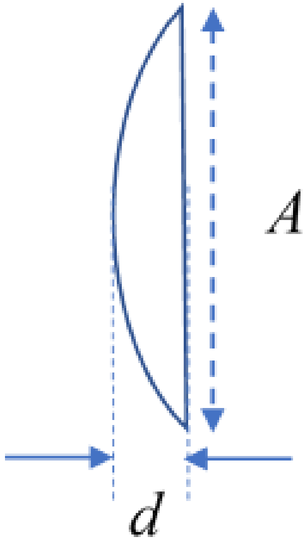
$\Rightarrow$ polarization is rotated at the output beam $\beta = 2\alpha$

$$\left.\begin{array}{l} \text{Optical anisotropy } (\Delta n) \sim 0.1 \\ \\ \text{Wavelength } (\lambda) \sim 0.550\ \mu\text{m} \end{array}\right\} \quad L \sim 2\ \mu\text{m} < L_c$$

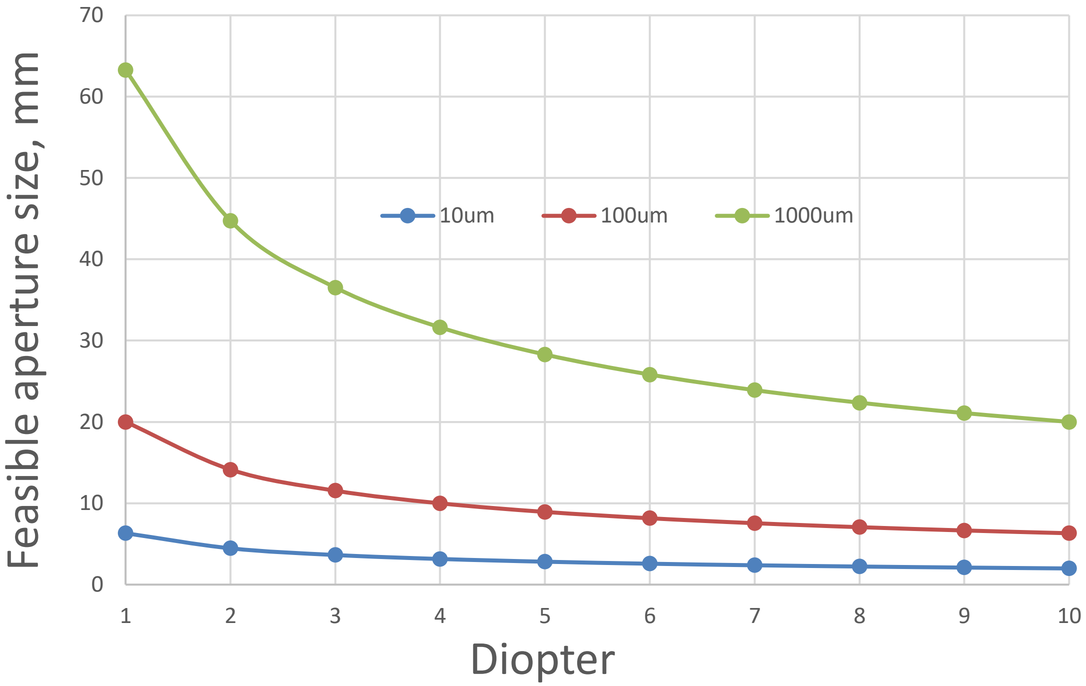
Large aperture refractive LC lenses?



Large aperture refractive optics of any appreciable power needs to be mm thick.



$$d = \frac{A^2}{8(n-1)f}$$

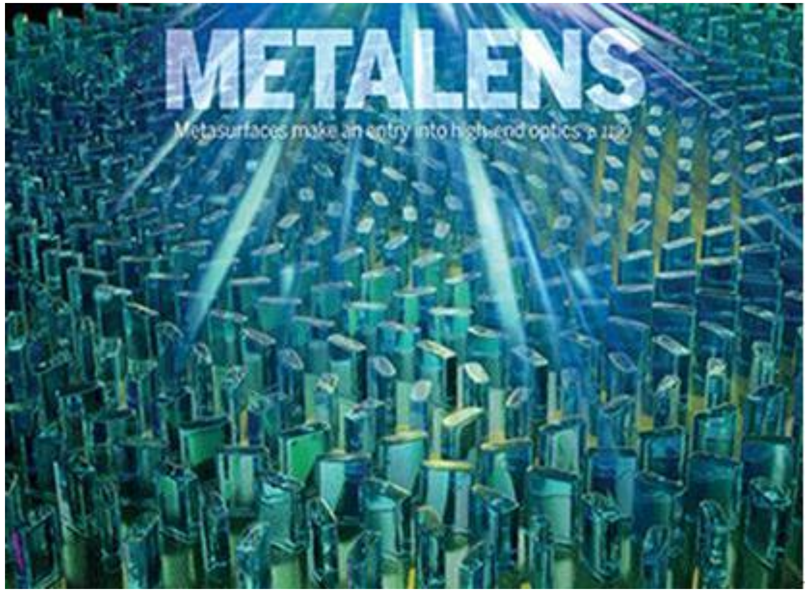


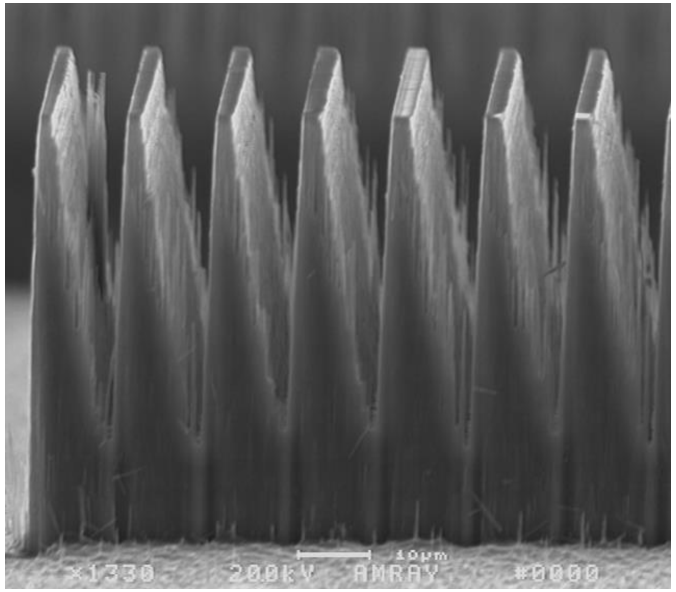
f = 1000 mm (1 Diopter)
A = 10 mm
n = 1.5

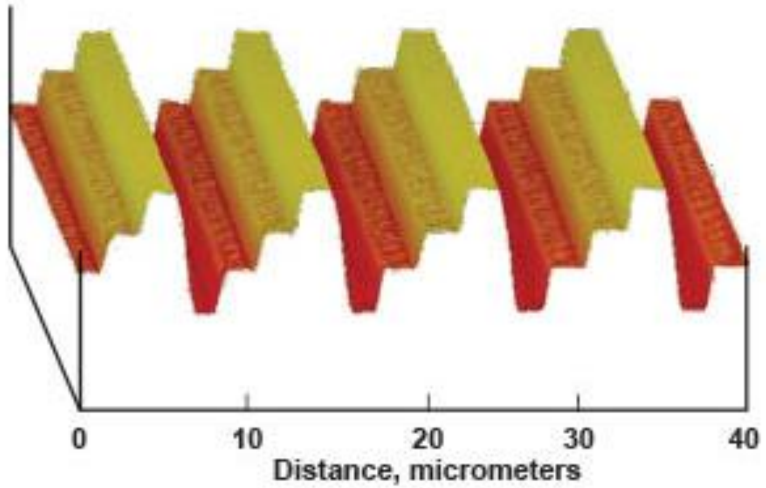
d = 25 um

Fresnel? Metamaterials?

Size? Cost? Transmission? Efficiency? Haze? - No good answers…







"…the only facility in the world that can make precision diffractive optics of more than a few centimeters in diameter."

LLNL Science and Technology Review, March 2003, pp. 12-18

No Moore's law in optics…

TUESDAY, JANUARY 30, 2018 | 25

Optics the key challenge for AR, VR and mixed reality evolution

A new conference incorporating interactive experience at Photonics West reveals the rapid growth of augmented and virtual realities. Its chair, Bernard Kress of Microsoft's Hololens division, tells Matthew Peach that optics remains the key challenge in developing the ultimate virtual experience.

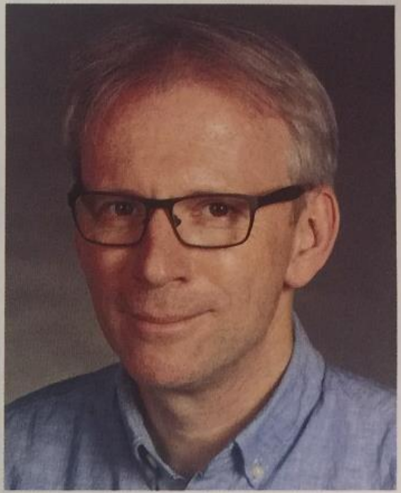
New types of optical and photonics technologies need to be implemented in next-generation virtual reality and augmented reality (VR/AR) systems in order to provide greater visual comfort for prolonged usage, and to achieve a better sense of display immersion for the user.

That is one of the main conclusions

Kress told *Show Daily*, "This conference at Photonics West is the first time we have in a single location all the major developers of VR, AR and MR headsets. These include large corporations such as Microsoft, Google, Facebook, Amazon, Intel and Huawei, but also exciting smaller start-ups such as DigiLens, Avegant,

Palmer Luckey, founder of Oculus).

Kress described his own personal highlights of the day: "I really enjoyed the various novel solutions described by the participants to solve main visual discomfits in AR systems, such as how to resolve Vergence Accommodation Conflict, and how to enable more comfortable arm's



Bernard Kress, Partner Optical Architect at Microsoft HoloLens and chair of the inaugural VR, AR, MR one-day industry conference at Photonics West this week.
Photo: Microsoft.

"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"

Photonics West Show Daily, Jan 30, 2018, pages 25-28

No Moore's law in optics…

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Photo: Microsoft.

"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"

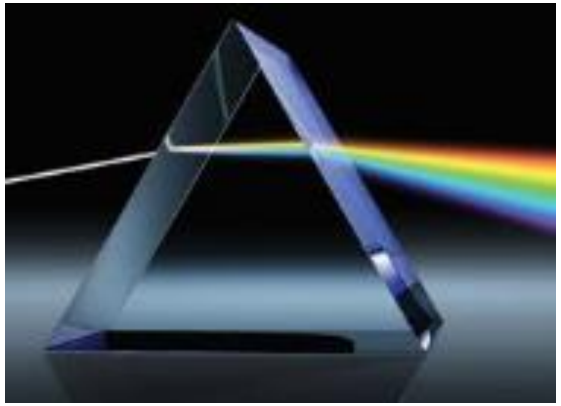
Photonics West Show Daily, Jan 30, 2018, pages 25-28

"Everybody complains about the weather, but nobody does anything about it."

Charles Dudley Warner / Mark Twain

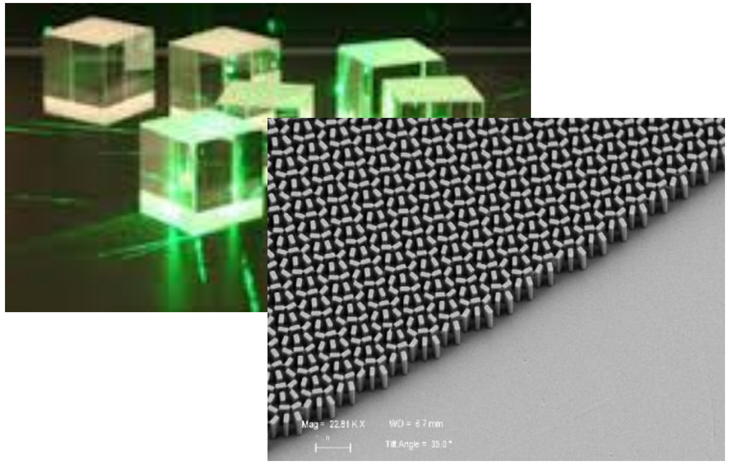
The only four ways of controlling light

Modulating shape



Modulating refractive index

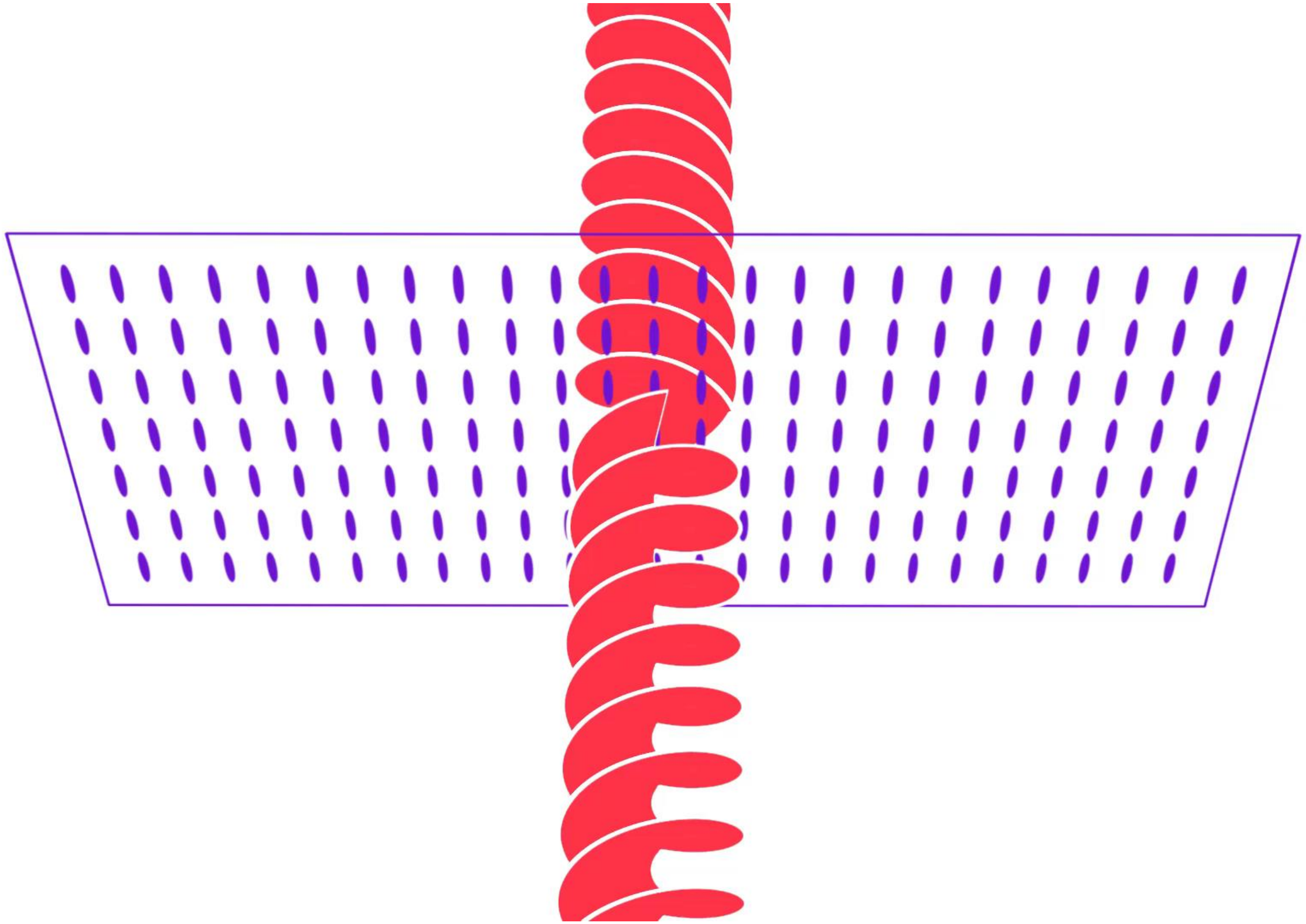
- Gradient index lenses
- Bragg gratings
- Metasurfaces



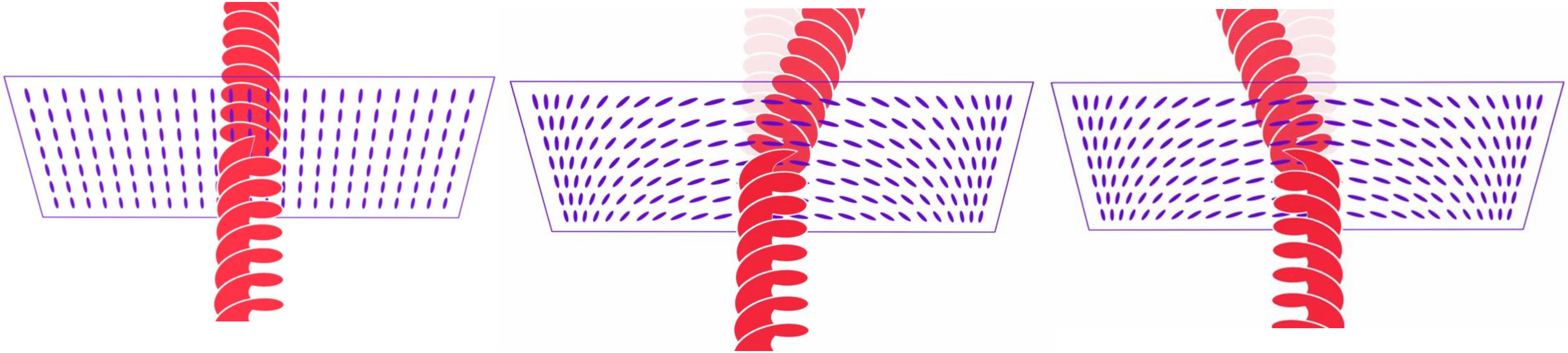
Modulating birefringence

LCDs, LC-SLMs

Modulating orientation of half-wave plate axis



Modulating orientation of half-wave plate axis



Circular polarized light propagating through a HWP…

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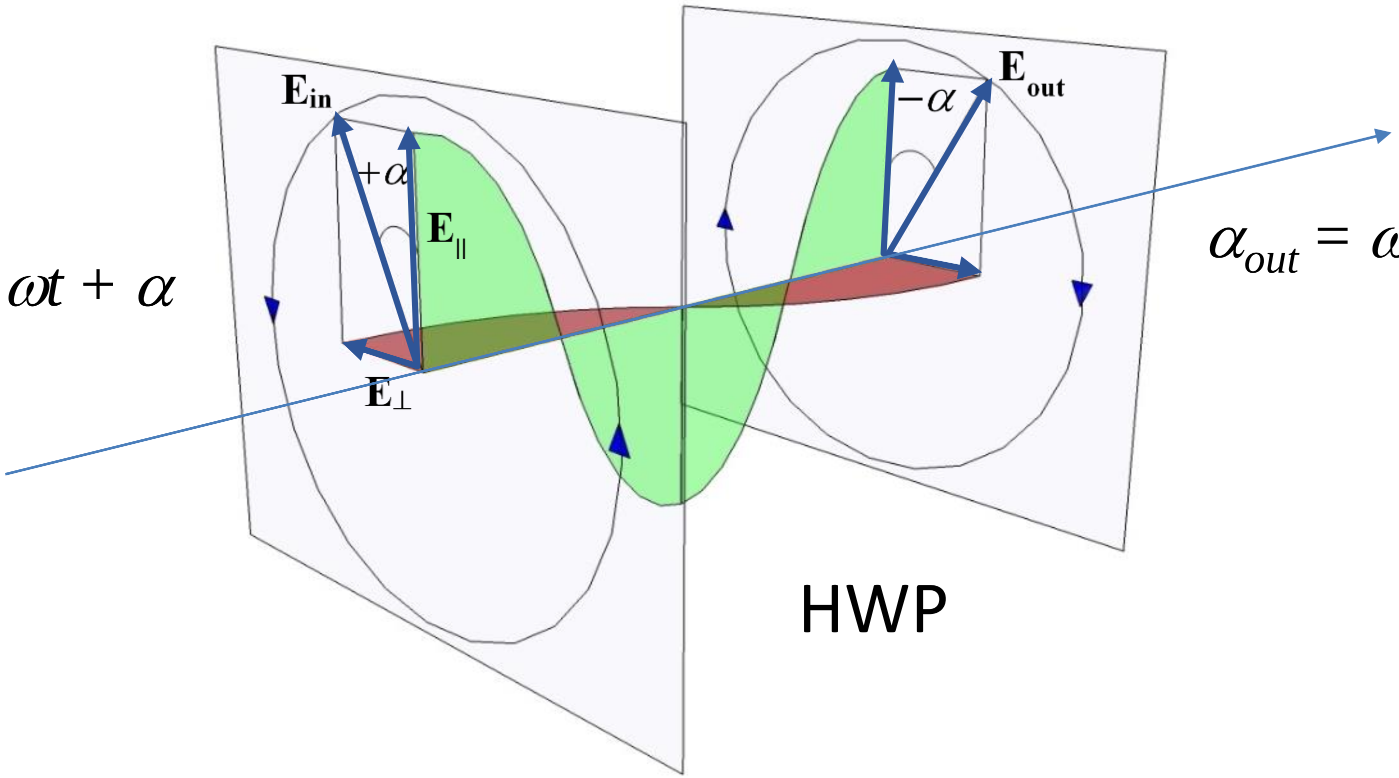
…undergoes phase change dependent on optical axis orientation of the HWP

$$\alpha_{in} = \omega t + \alpha$$



$$\alpha_{out} = \omega t - \alpha$$

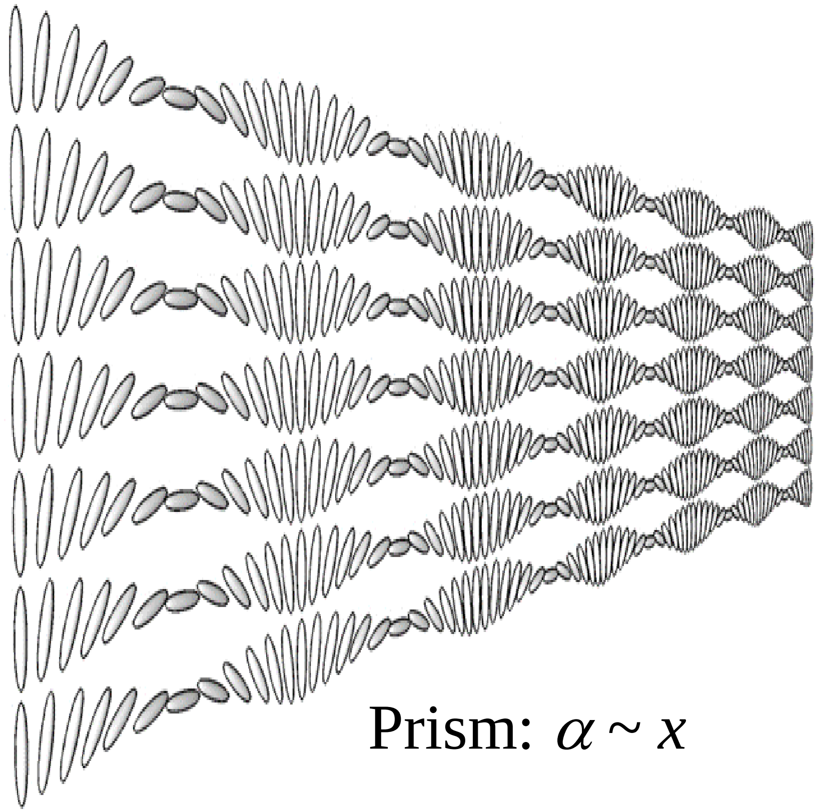
Left-hand circular polarized input beam

$$\mathbf{R}_{out} = \mathbf{L}_{in}\exp(2i\alpha(\mathbf{r}))$$

Right-hand circular polarized output beam

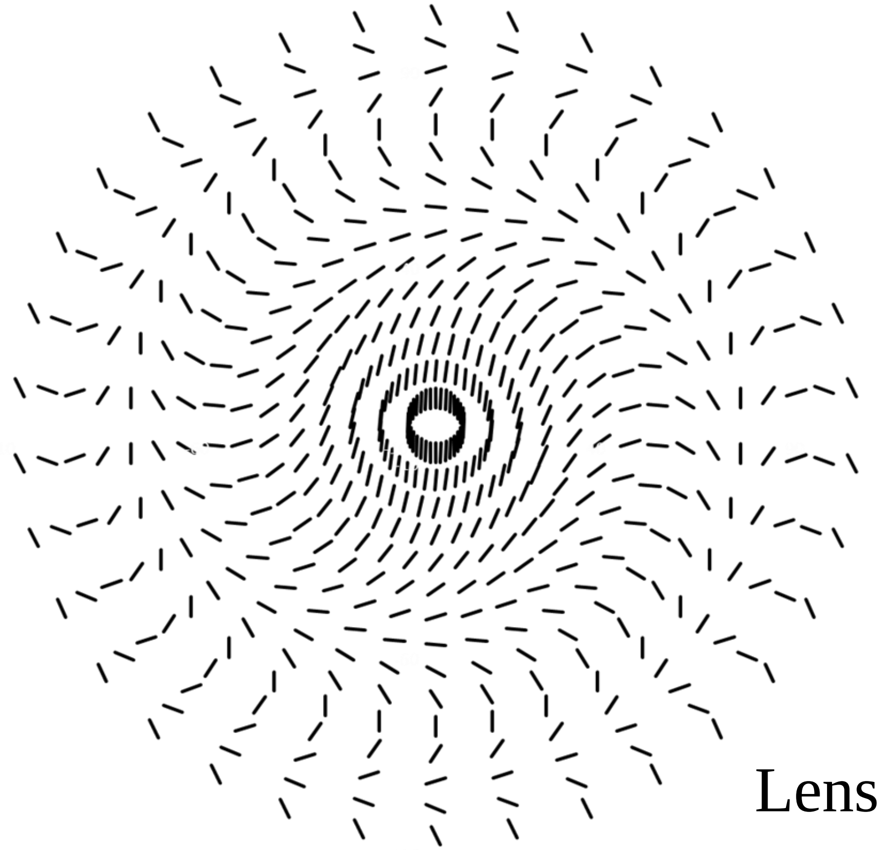
$$\mathbf{L}_{out} = \mathbf{R}_{in}\exp(-2i\alpha(\mathbf{r}))$$

Diffractive Waveplates



Prism: $\alpha \sim x$

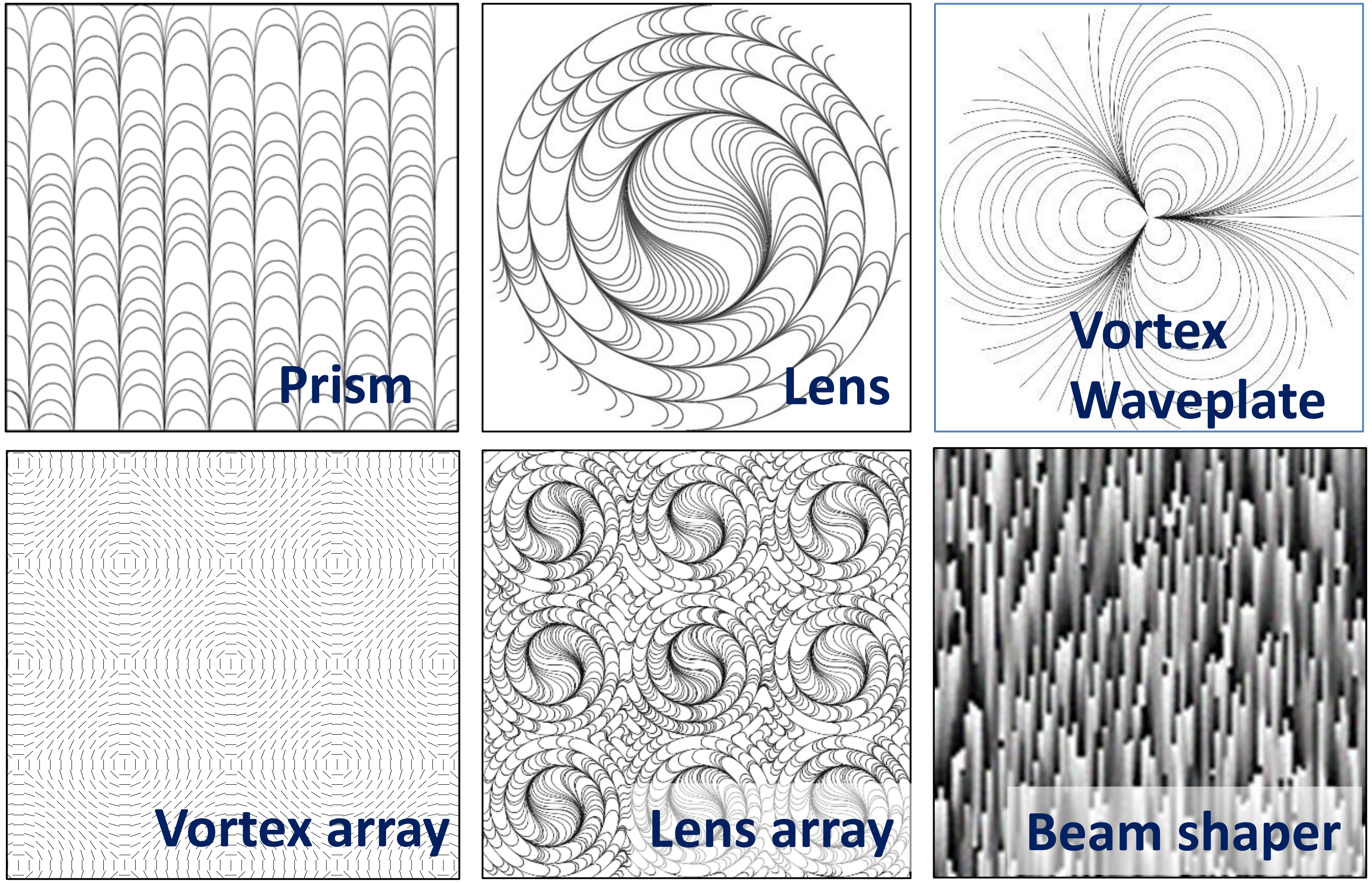
$$\mathbf{E}_{out} = \mathbf{E}_{in}\exp(\pm 2iqx)$$

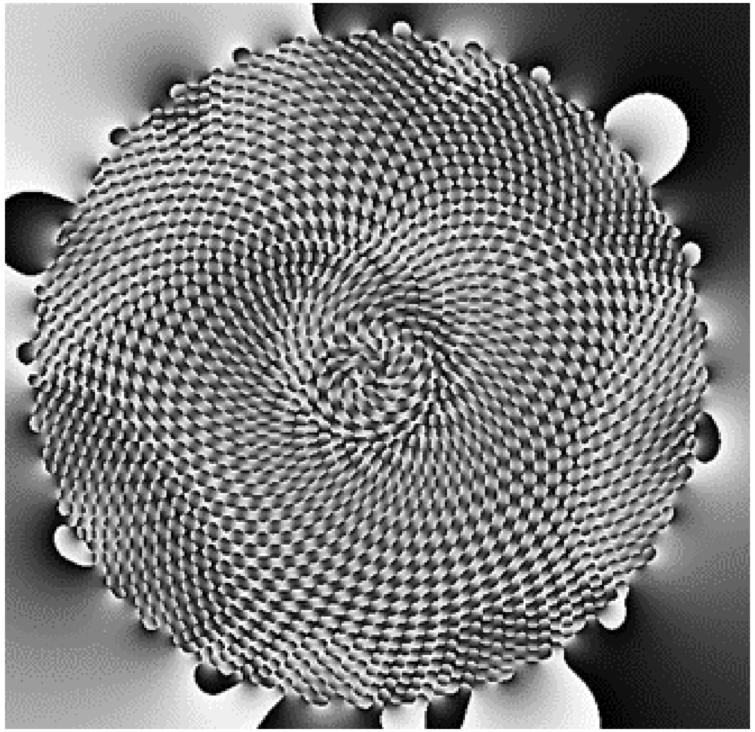


Lens: $\alpha \sim r^2$

$$\mathbf{E}_{out} = \mathbf{E}_{in}\exp(\pm 2i\pi r^2/\lambda f)$$

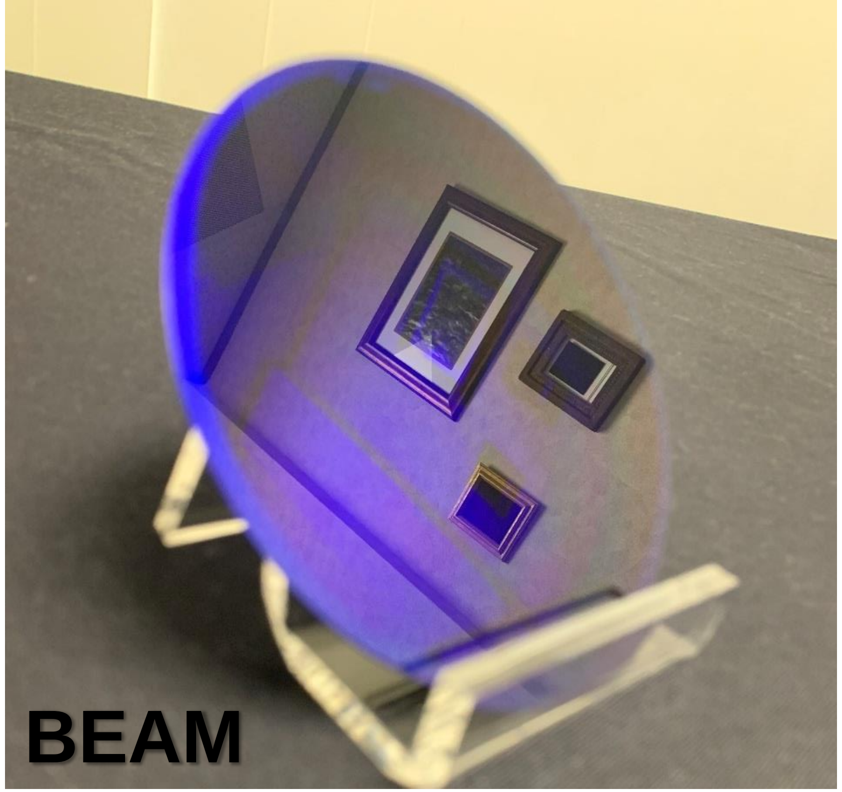
Any optical function and their combinations…

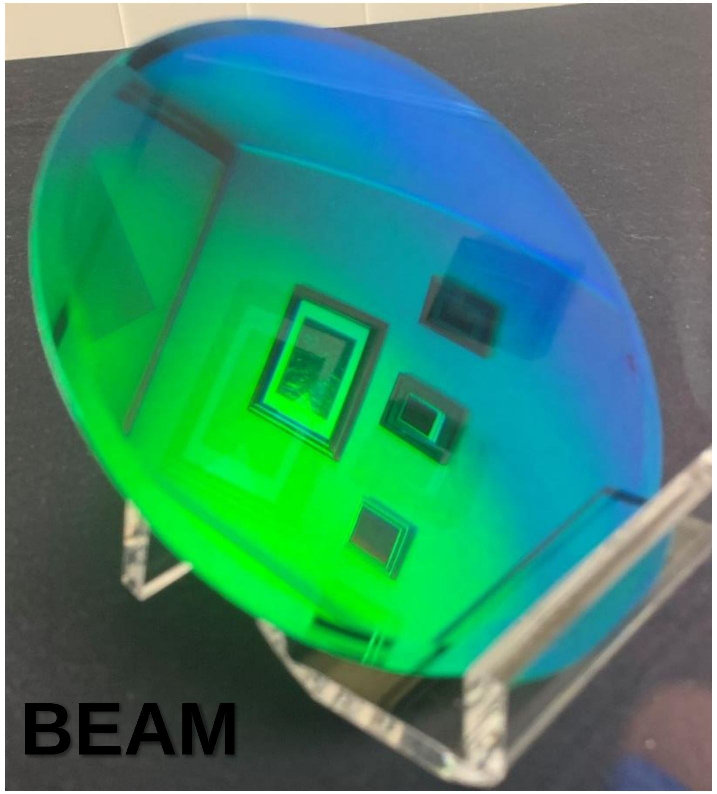




$$\alpha(\mathbf{r}) = \Delta\Phi(\mathbf{r})/2$$

Also reflective optics

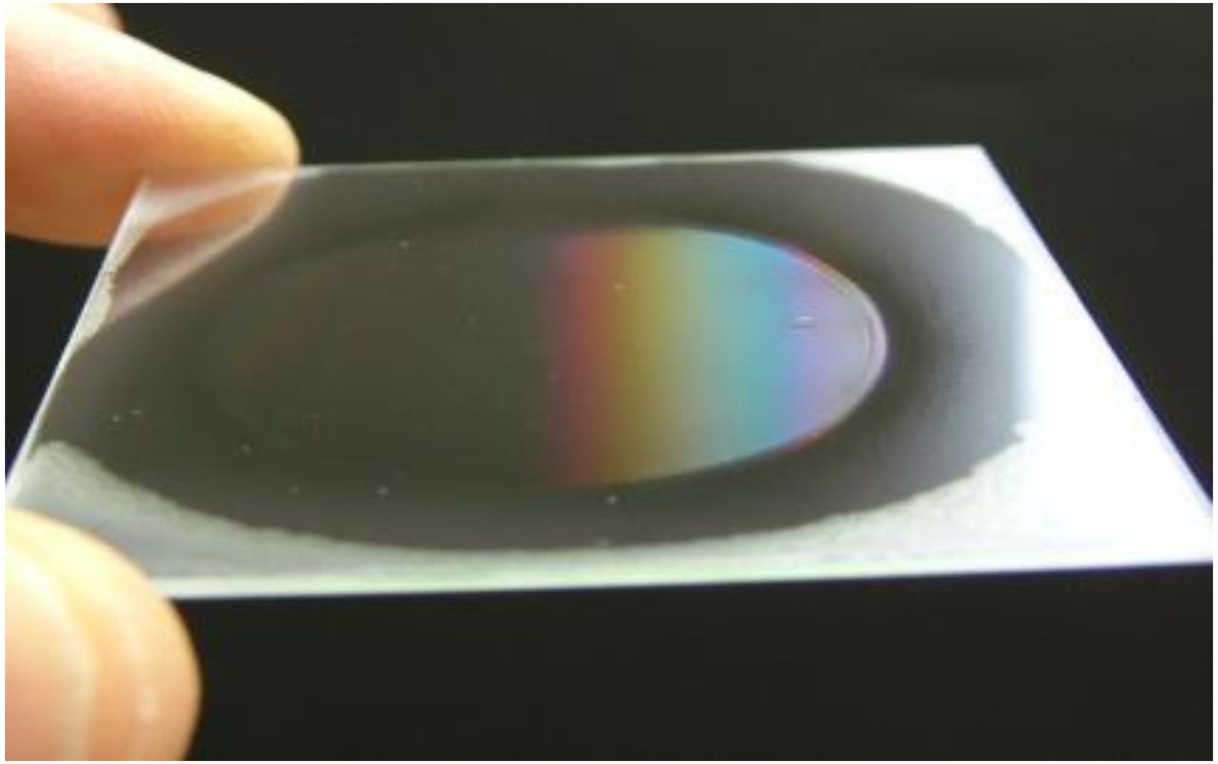


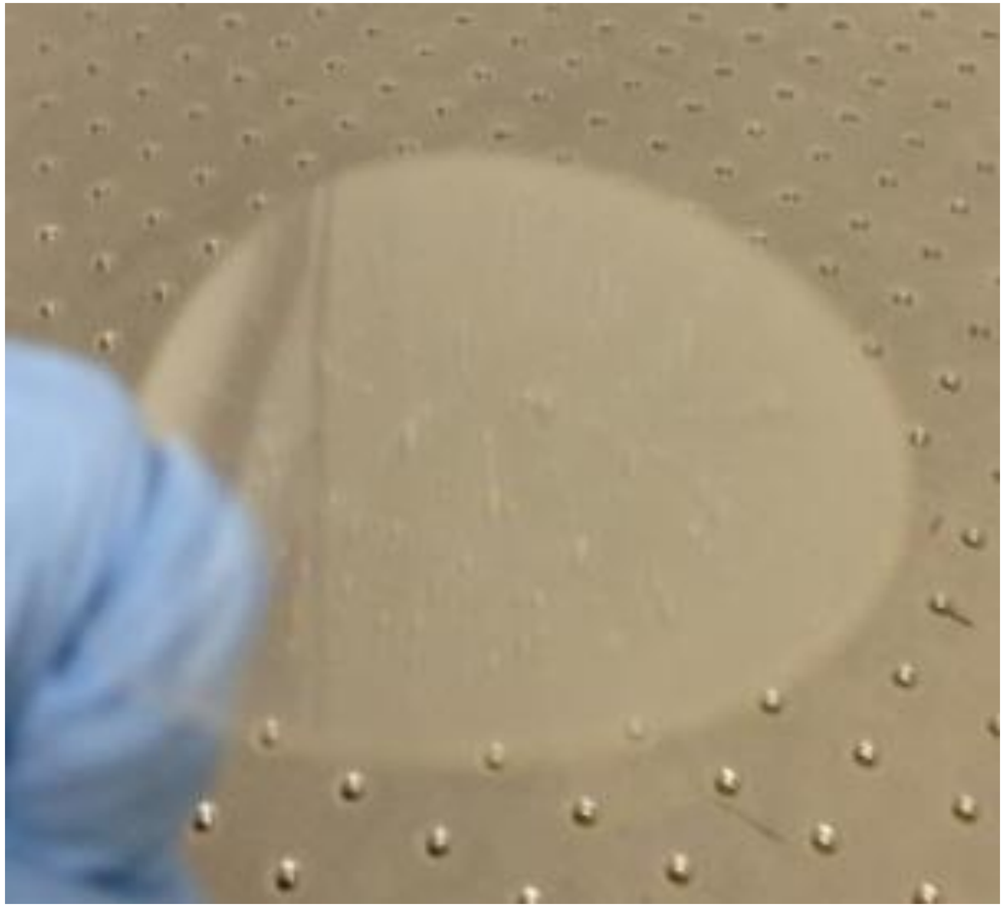


BEAM Co. reflective lenses of 4” diameter made with cholesteric LC polymer bandgaps

J. Kobashi, H. Yoshida, and M. Ozaki, “Planar optics with patterned chiral liquid crystals,” Nat. Photonics 10, 389–392 (2016).

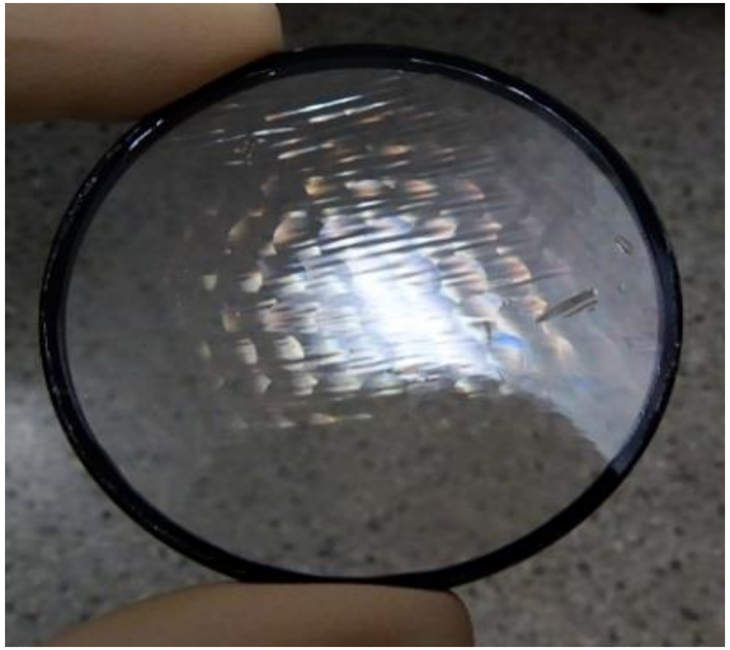
Any substrate



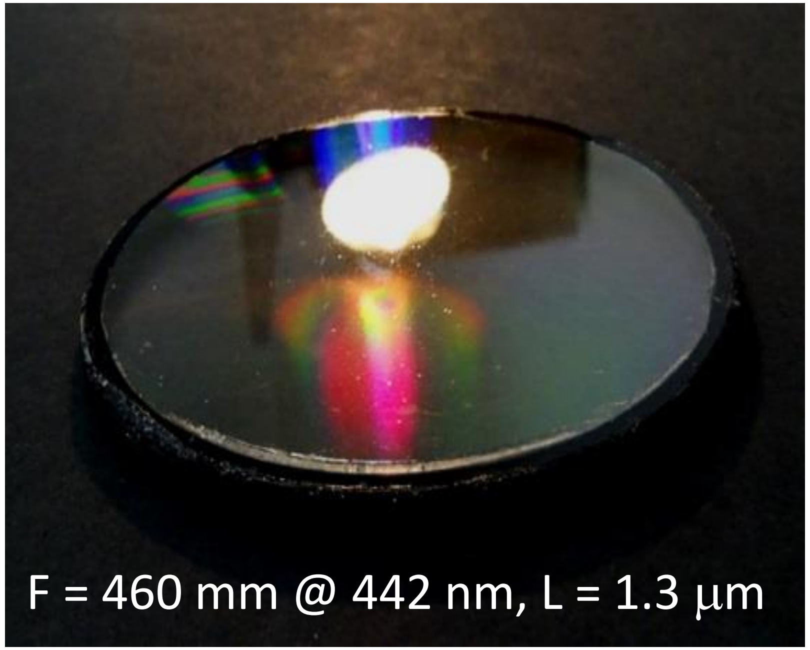


…or no substrate

Liquid Crystal Polymer Pellicle Optics



Pellicle lens array stressed
to reveal thinness



Pellicle lens

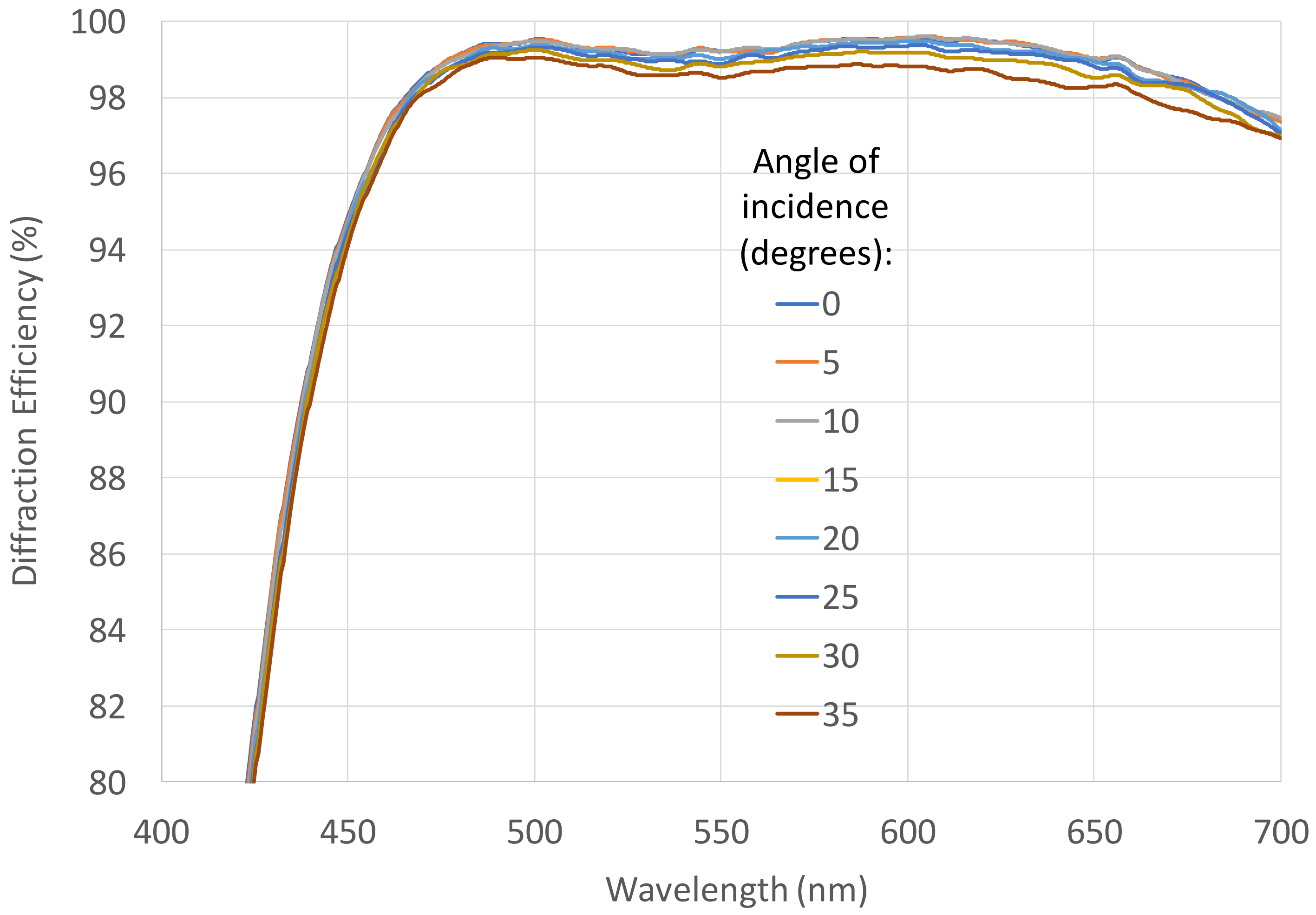
Original

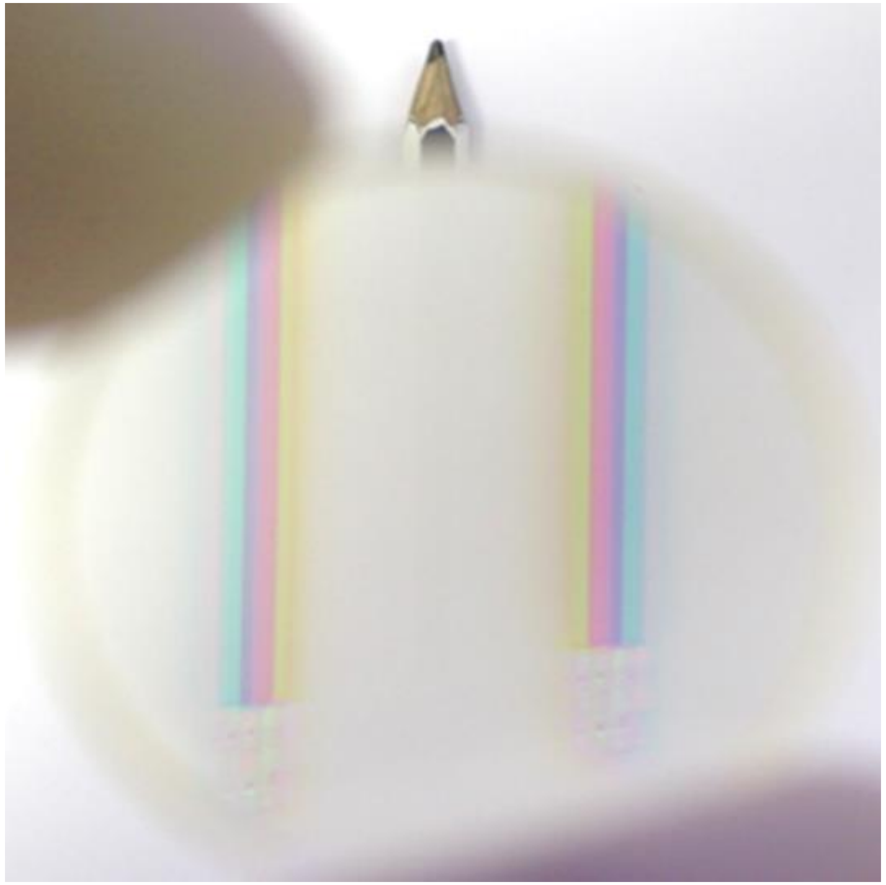
Focused

Defocused

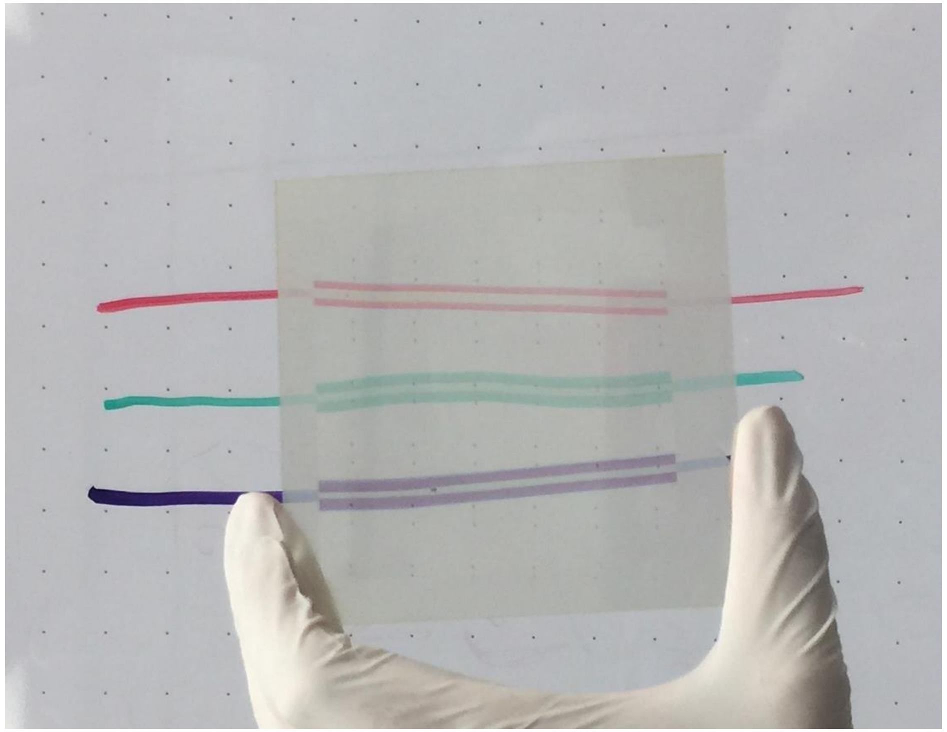
Green pellicle lens

Broadband high efficiency, even at large angles





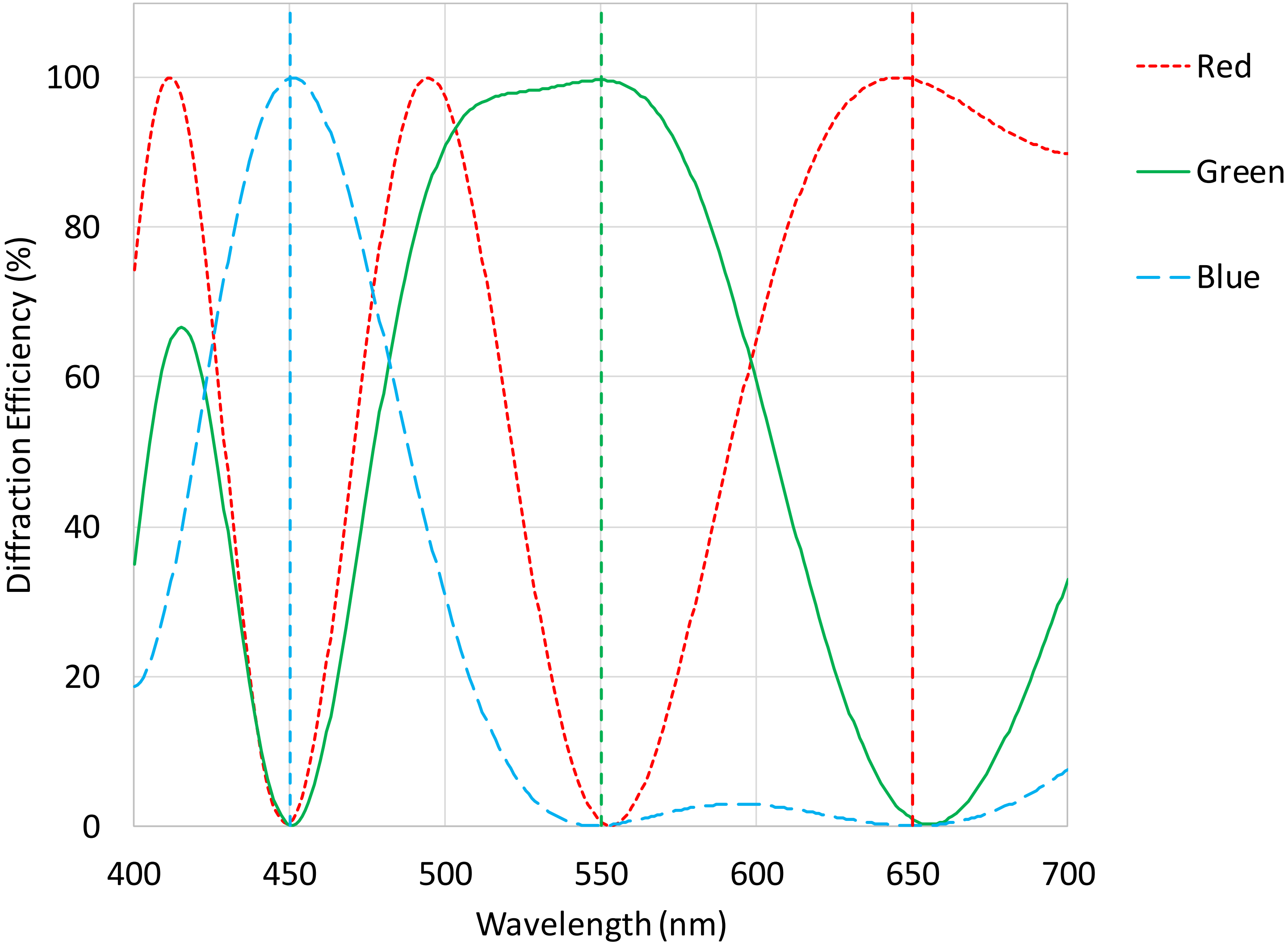
Feasibility of large aperture – like LCDs



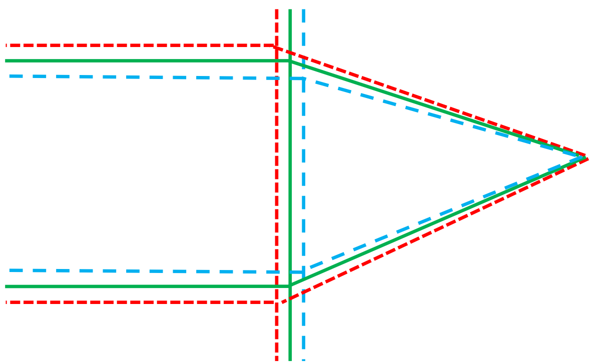
4” DW prism

6” DW lens

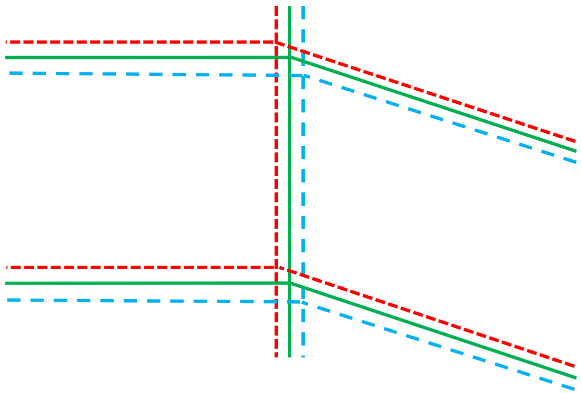
Custom Bandwidths



RGB lens

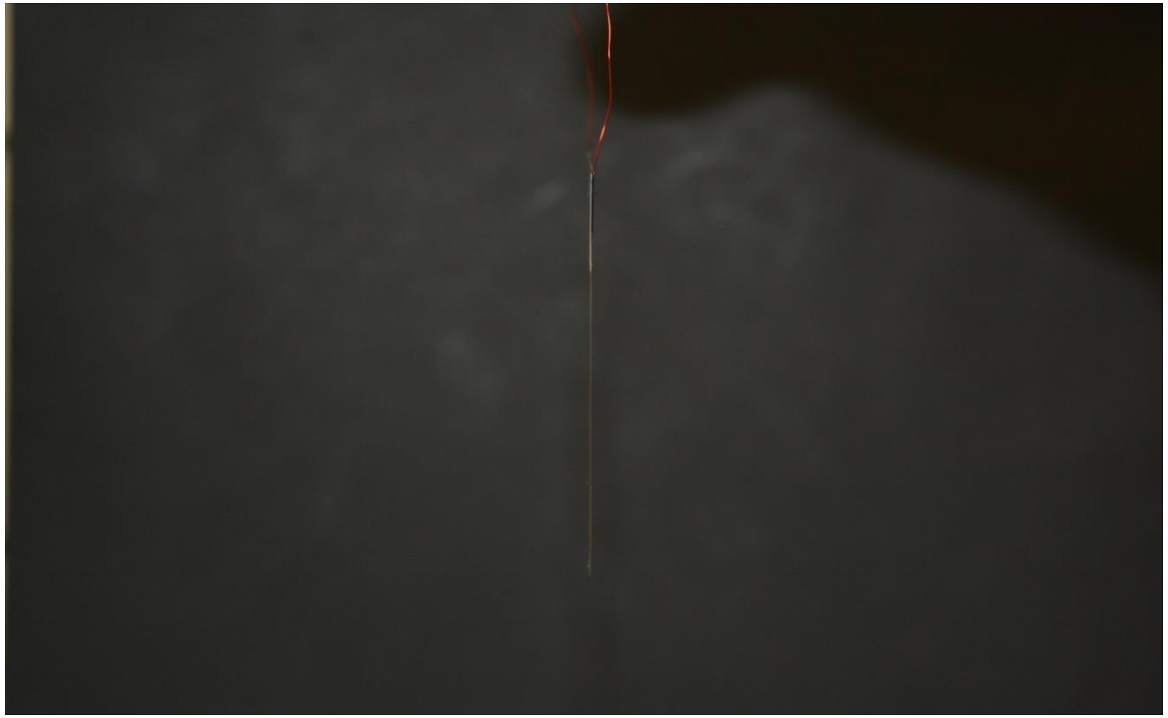


RGB beam deflector



Three layers allow achromatic focusing, deflection...

Electrically switchable – Just Like LCDs



Electrically-switchable optics, 200 μm thick including substrates.
Combination of N = 10 lenses (as an example) would provide 2^N = 1024 focal points (steering angles) still in 2 mm thick packaging.

2248 OPTICS LETTERS / Vol. 31, No. 15 / August 1, 2006

BEAM

Polarization-controlled switching between diffraction orders in transverse-periodically aligned nematic liquid crystals

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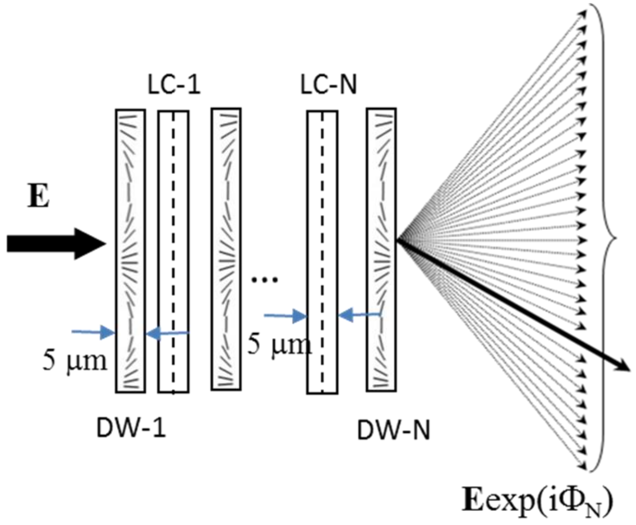
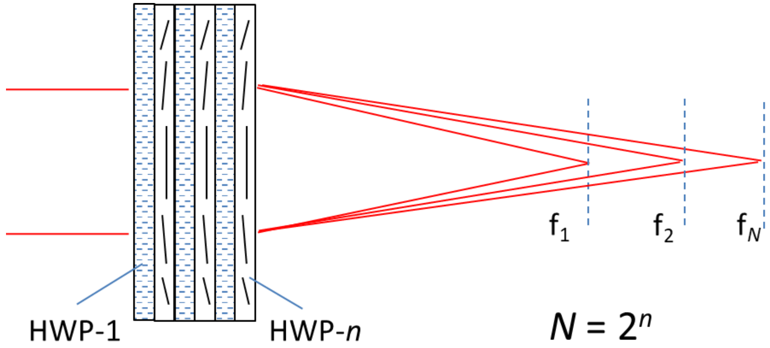
Beam Engineering for Advanced Measurements Co., 809 South Orlando Avenue, Suite I, Winter Park, Florida 32789

Leon B. Glebov, Vasile Rotar, and Boris Ya. Zeldovich
College of Optics and Photonics/CREOL, University of Central Florida 4000 Central Florida Boulevard, Orlando, Florida 32816-2700

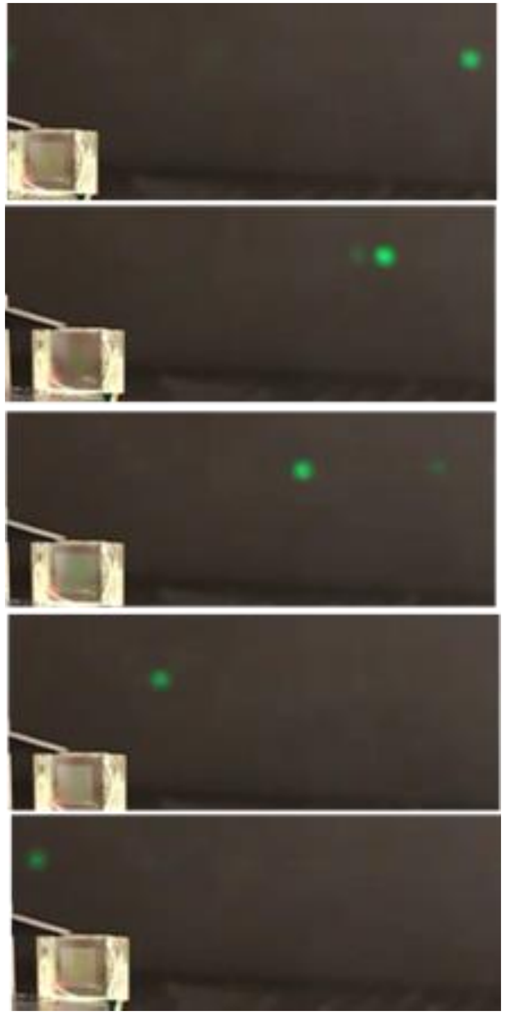


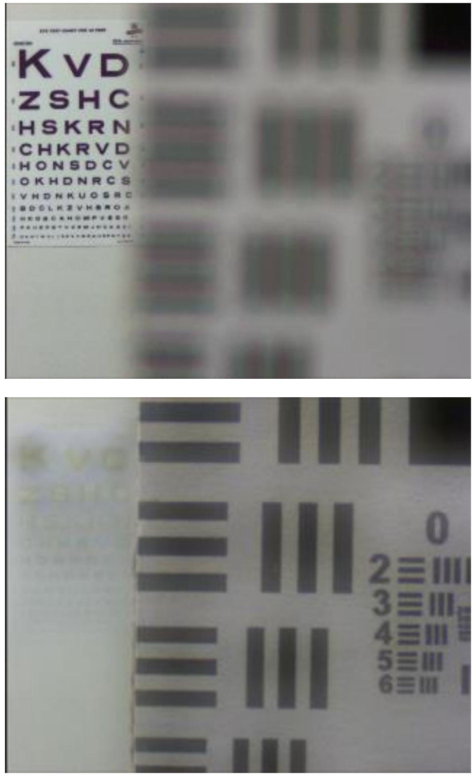


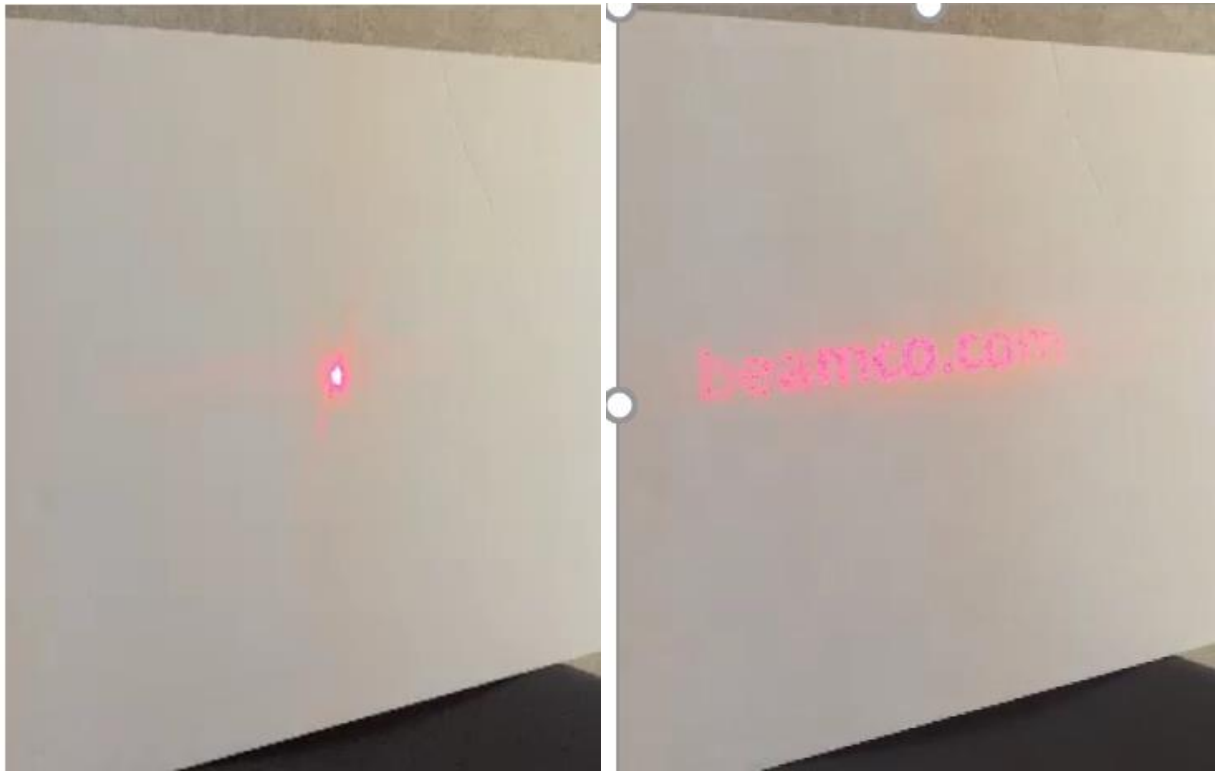
8x8 positions, 1.2 mm

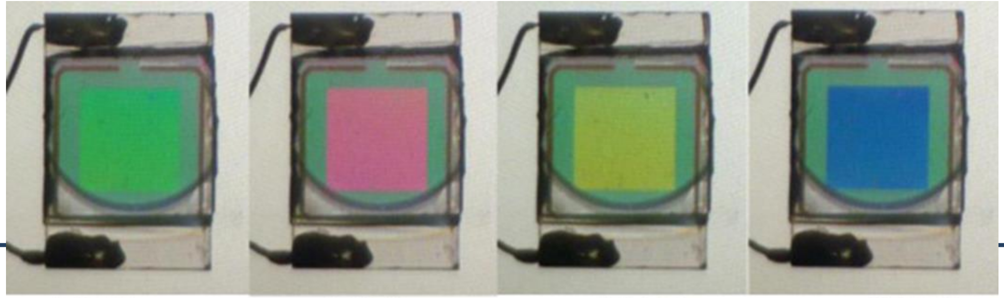
Low-power/low-voltage controls - like LCDs

BEAM





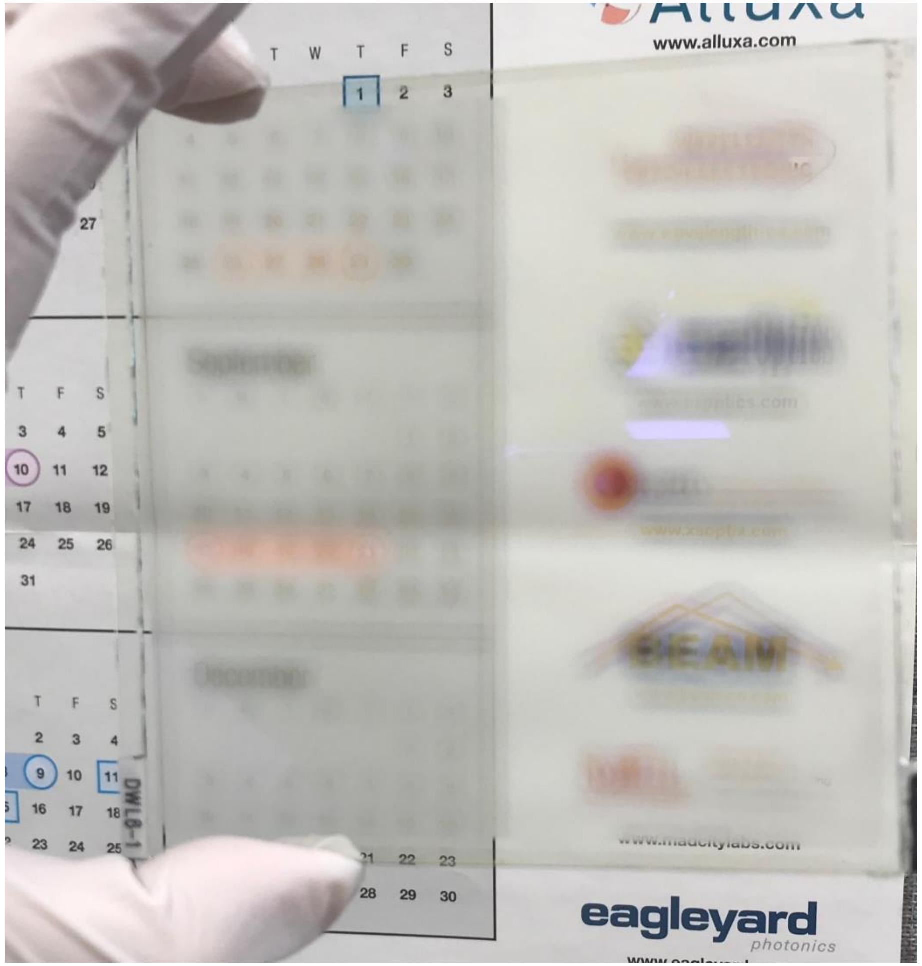




1.86 V 2.12 V 2.24 V 2.81 V

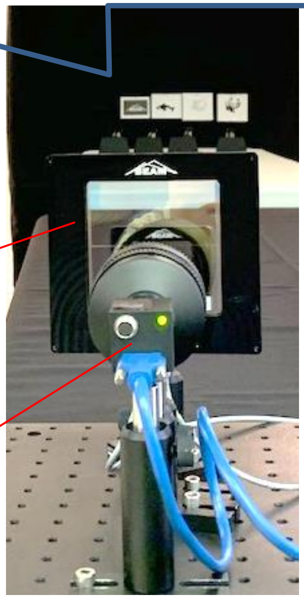
(a)

4”x4” array of ~100,000 switchable microlenses



Non-mechanical line-of-sight switching

Non-mechanical field of view steering system



Camera

AIP ADVANCES 1, 022153 (2011)

Transparent thin film polarizing and optical control systems

Nelson V. Tabiryan,[1,a] Sarik R. Nersisyan,[1] Timothy J. White,[2] Timothy J. Bunning,[2] Diane M. Steeves,[3] and Brian R. Kimball[3]
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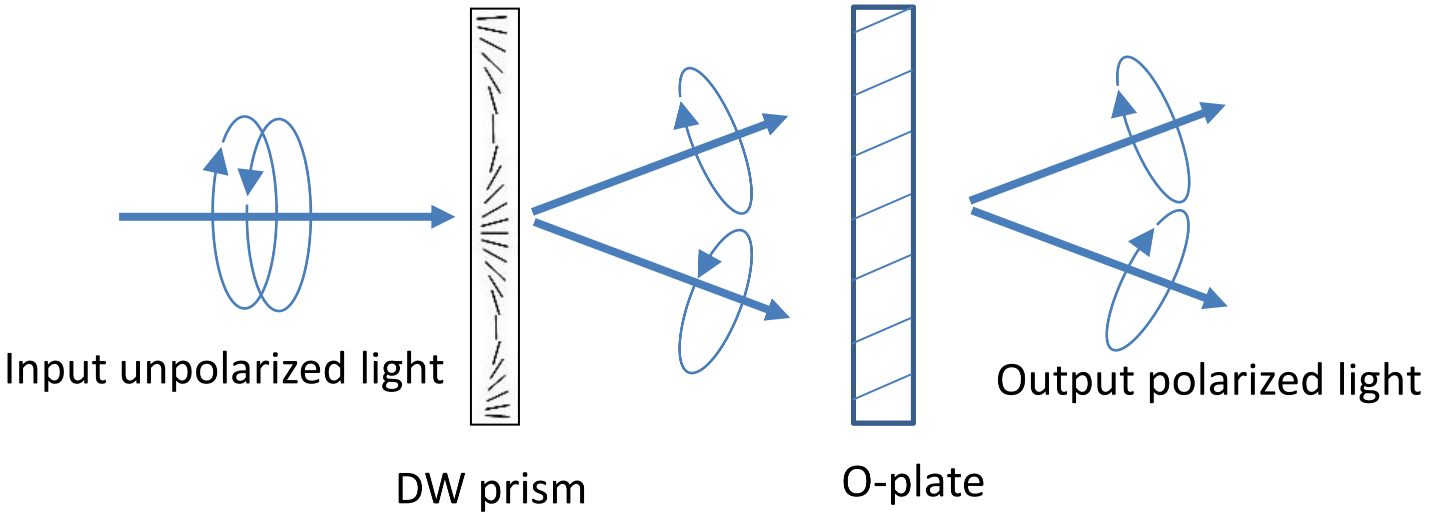
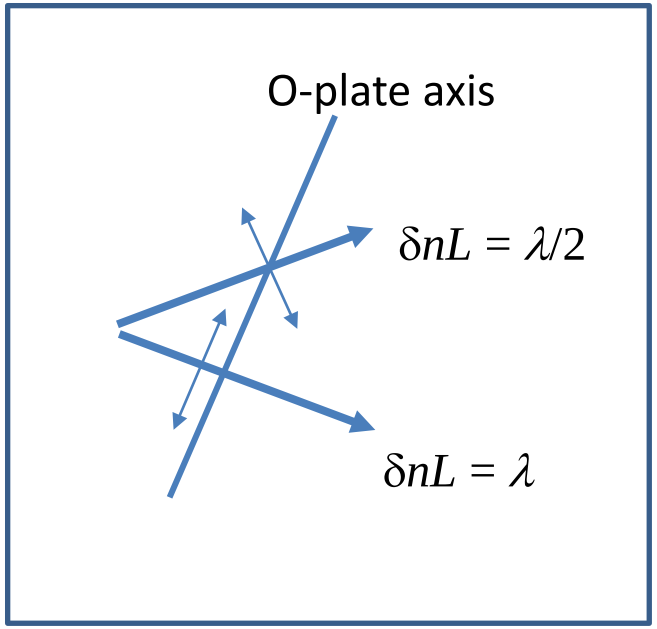
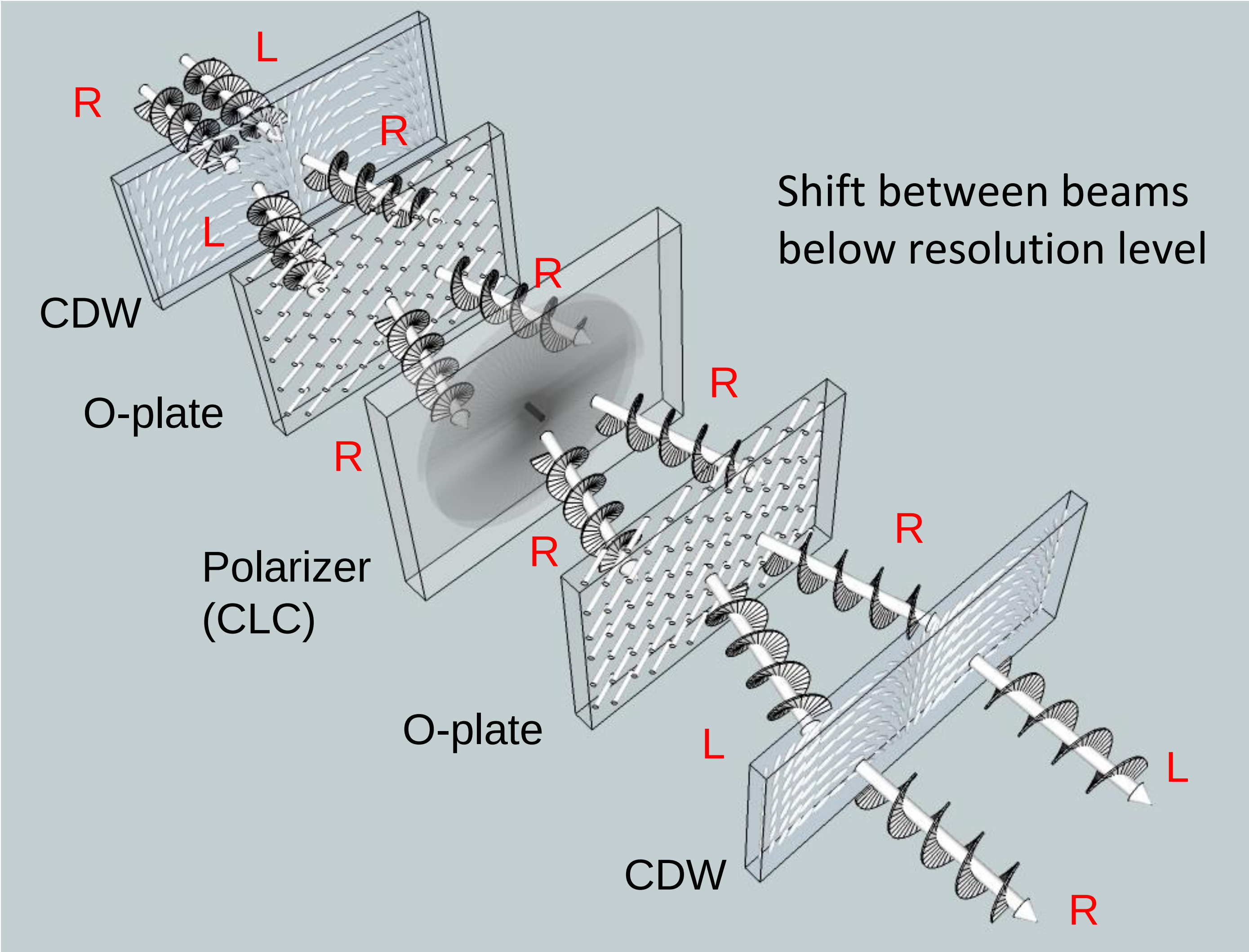
[2]*Air Force Research Laboratory, Wright-Patterson Air Force Base, Ohio 45433, USA*
[3]*US Army Natick Soldier Research, Development & Engineering Center, Natick, Massachusetts 01760, USA*

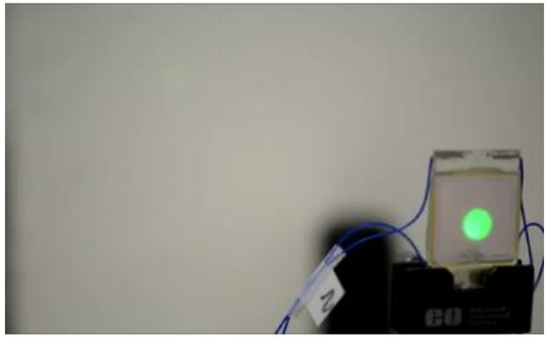


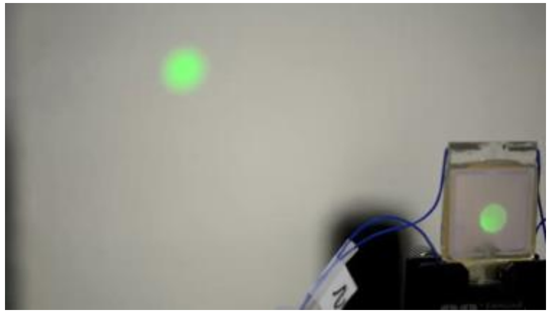


Unpolarized-to-polarized polarization conversion

“High-contrast, low-voltage variable reflector for unpolarized light”







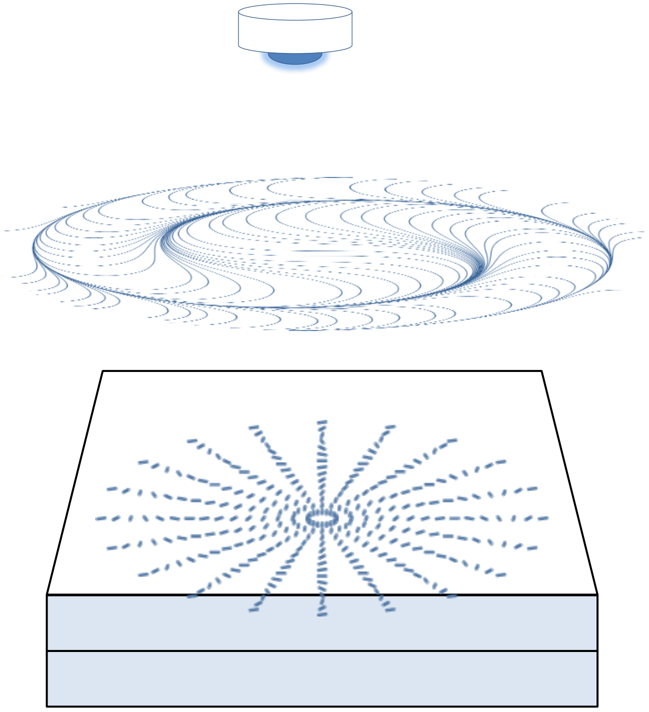
Transmission change: 3% - 80%
(polarization-independent)

Control voltages: 3 Vpp @ 1kHz

Clear normal state feasible

Fabrication – similar to LCDs except…

Photoalignment performed with light with spatially patterned polarization



- Fast and scalable as LCDs
- Affordable as LCDs
- Standard equipment and processes developed for LCDs

crystals

Article

Ultrafast Photoalignment: Recording a Lens in a Nanosecond

Svetlana V. Serak [1], Timothy J. Bunning [2] and Nelson V. Tabiryan [1,*]

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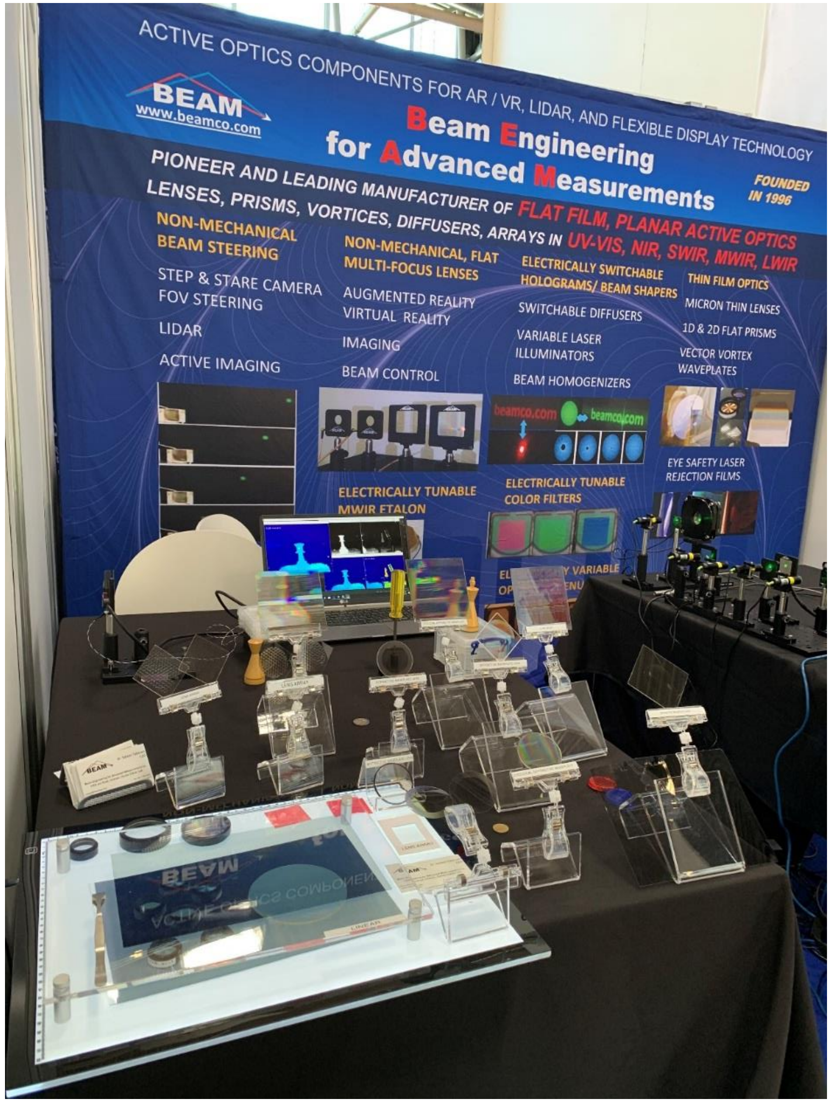
[*] Correspondence: info@beamco.com

Academic Editor: Vladimir Chigrinov

The technology is mature and widely exhibited…



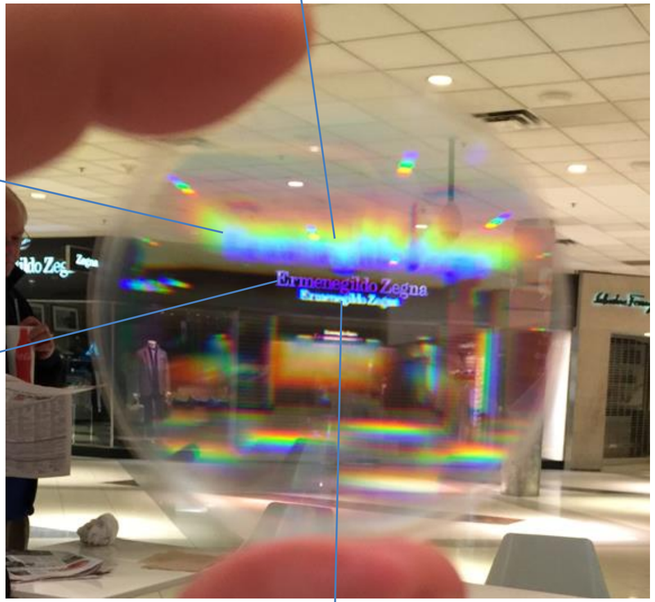
- Photonics West
- Defense and Security
- Munich Laser Show
- DoD events
- OPIE
- Eurodisplay
- ICALEO
- Display Week -2020 - Cancelled
- …..

Issues and solutions

I. Polarization dependence

defocused beam

II. Chromatic aberration



0^{th} order

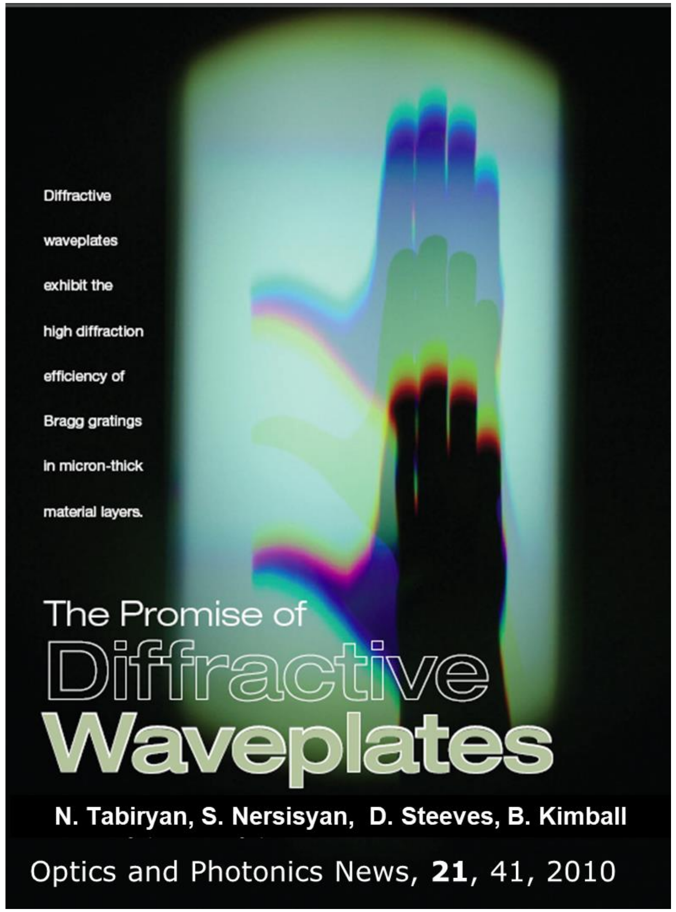
focused beam

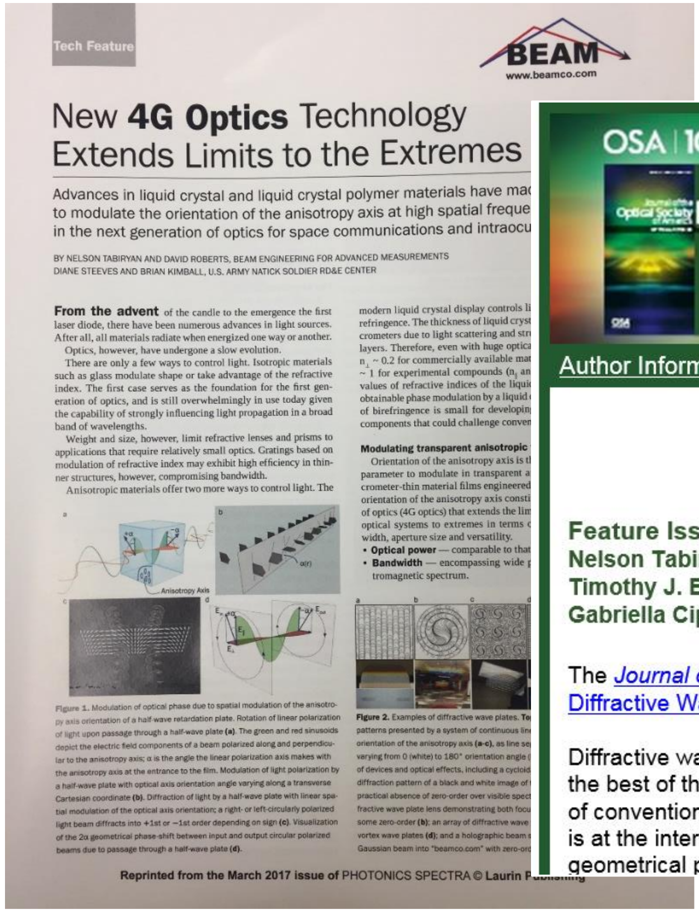
"Chromatic aberration corrected switchable optical systems", Proc. SPIE 10735, Liquid Crystals XXII, 107350Q

“Polarization-Independent Diffractive Waveplate Optics,” 2018 IEEE Aerospace Conference, 10.1109/AERO.2018.8396781

"Optimization of diffractive waveplate optics for visual perception," in Digital Holography and Three-Dimensional Imaging 2019, OSA Technical Digest, paper W1A.8

D. Roberts, et al. (BEAM Co.)





Tech Feature

BEAM www.beamco.com

New **4G Optics** Technology Extends Limits to the Extremes

Advances in liquid crystal and liquid crystal polymer materials have mad[e] ... to modulate the orientation of the anisotropy axis at high spatial freque[ncies] ... in the next generation of optics for space communications and intraocu[lar] ...

BY NELSON TABIRYAN AND DAVID ROBERTS, BEAM ENGINEERING FOR ADVANCED MEASUREMENTS
DIANE STEEVES AND BRIAN KIMBALL, U.S. ARMY NATICK SOLDIER RD&E CENTER

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OSA | 100

Journal of the Optical Society of America B

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Newly Published in JOSA B:
Diffractive Waveplates Feature Issue

Feature Issue Editors
Nelson Tabiryan, *Beam Engineering for Advanced Measurements Co., USA* (Lead Editor)
Timothy J. Bunning, *AFRL, USA*
Gabriella Cipparrone, *University of Calabria, Italy*

The *Journal of the Optical Society of America B (JOSA B)* has published a new Feature Issue—Diffractive Waveplates.

Diffractive waveplate technology has enabled a breakthrough in planar and thin-film optics. It combines the best of three aspects—the thinness of diffraction gratings, the broad bandwidth and high-efficiency of conventional refractive optics, and the low-cost fast manufacture of polymer optics. The technology is at the intersection of polarization holography and polarization gratings, Pancharatnam–Berry or geometrical phase optics, waveplates, metasurfaces, and planar optics.

Marrucci (Univ. Naples, Italy) Cipparronne (Univ. Calabria, Italy) Escuti (NCU) Kwok, Chigrinov (HKUST), Bos (LCI)…

Conclusion

Diffractive Waveplates Make Liquid Crystals Great Again!

Armenian symbol of eternity