Broadband Vector Vortices for High Contrast Coronagraphy

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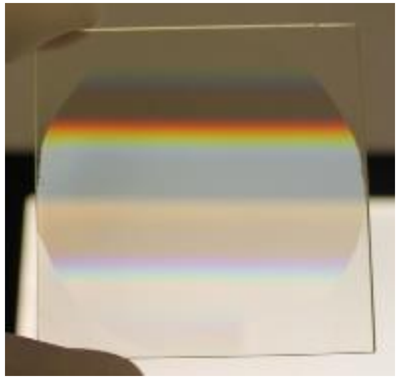
Acknowledgements

Michael Bottom (JPL) **Dimitri Mawet (CalTech)** **Eugene Serabyn (JPL)**

NASA SBIR Program

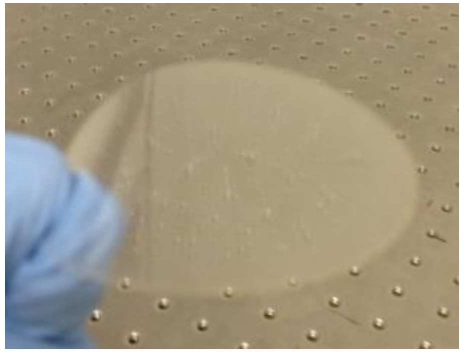
Planar Thin Film Optics and Electro-Optical Systems

Lenses

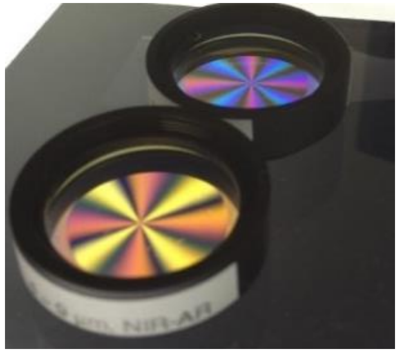


Prisms

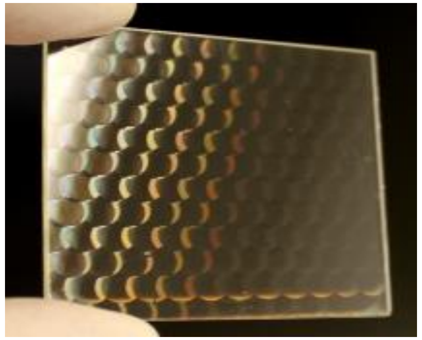
Beam shapers



Free-form/flexible



Vortex phase plates



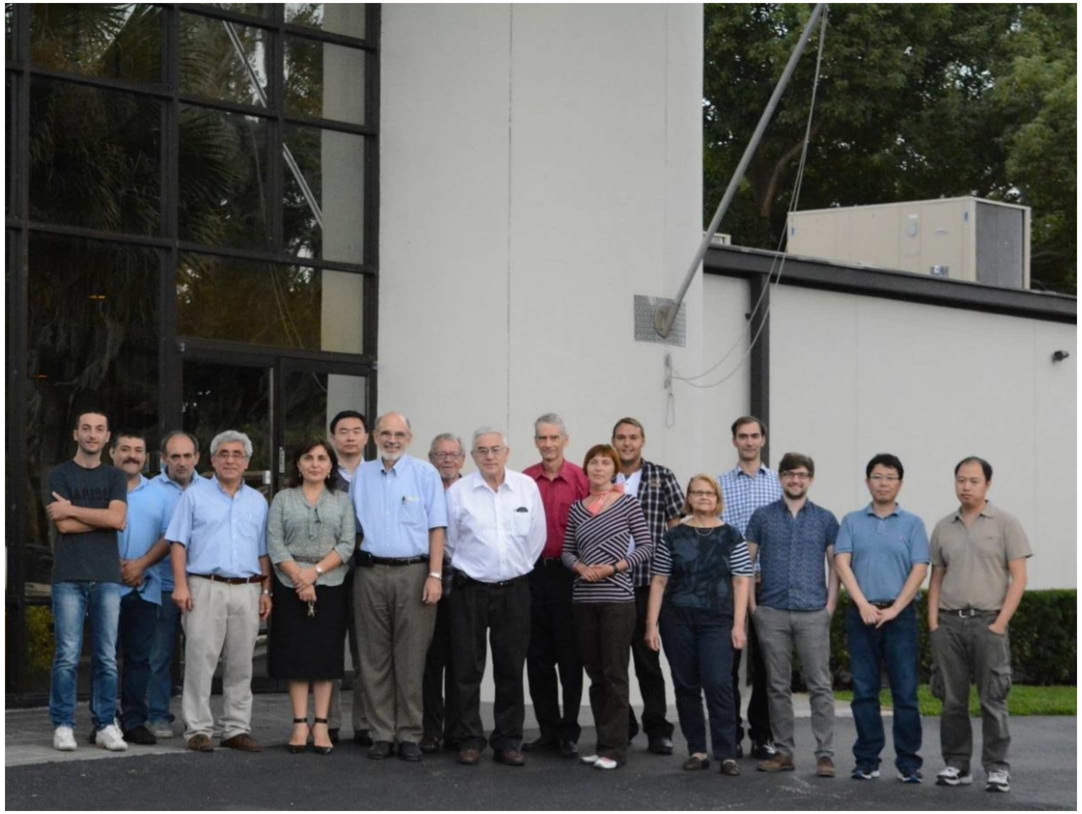
Arrays and microarrays

- ~100% efficient
- Micrometer Thin
- Broadband
- Fabricated as coatings and films
- Continuous structure
- Fast and inexpensive fabrication
- Scalable to very large sizes

BEAM Team

BEAM

Founded in 1996



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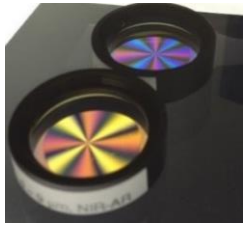
intel

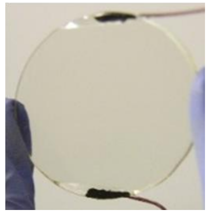
AIR FORCE RESEARCH LABORATORY

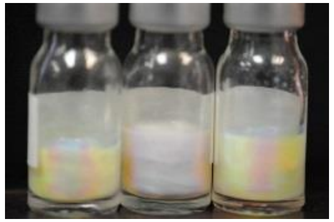
LG

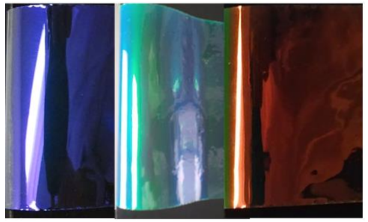
NASA

Johnson & Johnson Vision Care



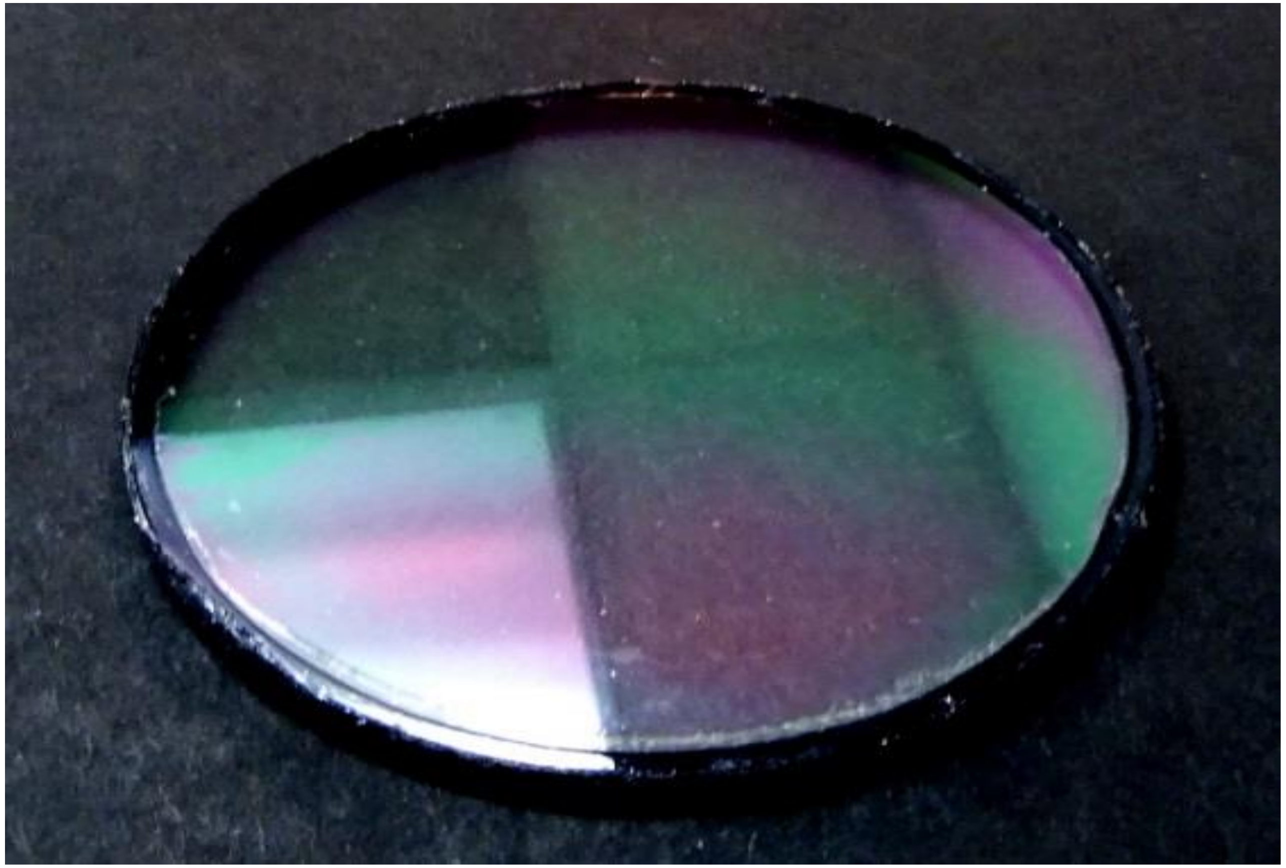






MADE IN THE U.S.A.

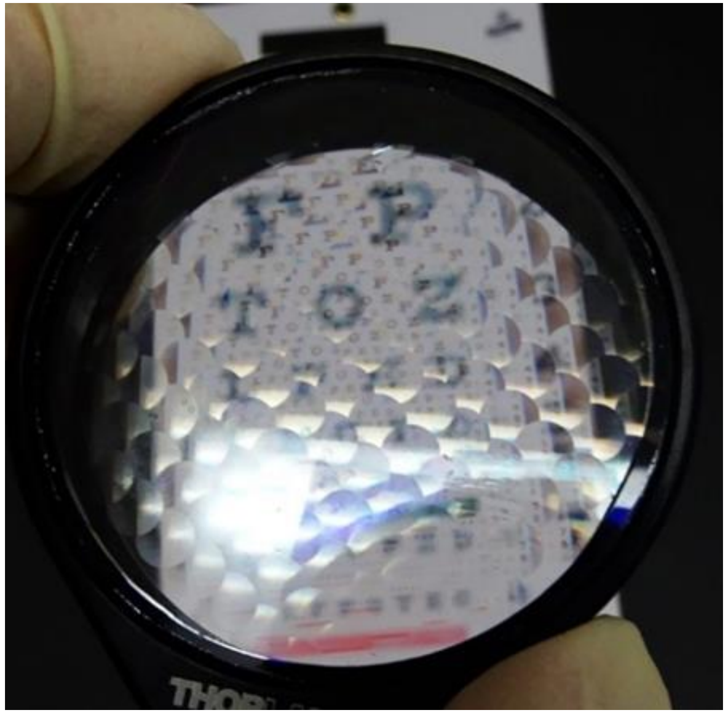
Thinnest optics



Lens

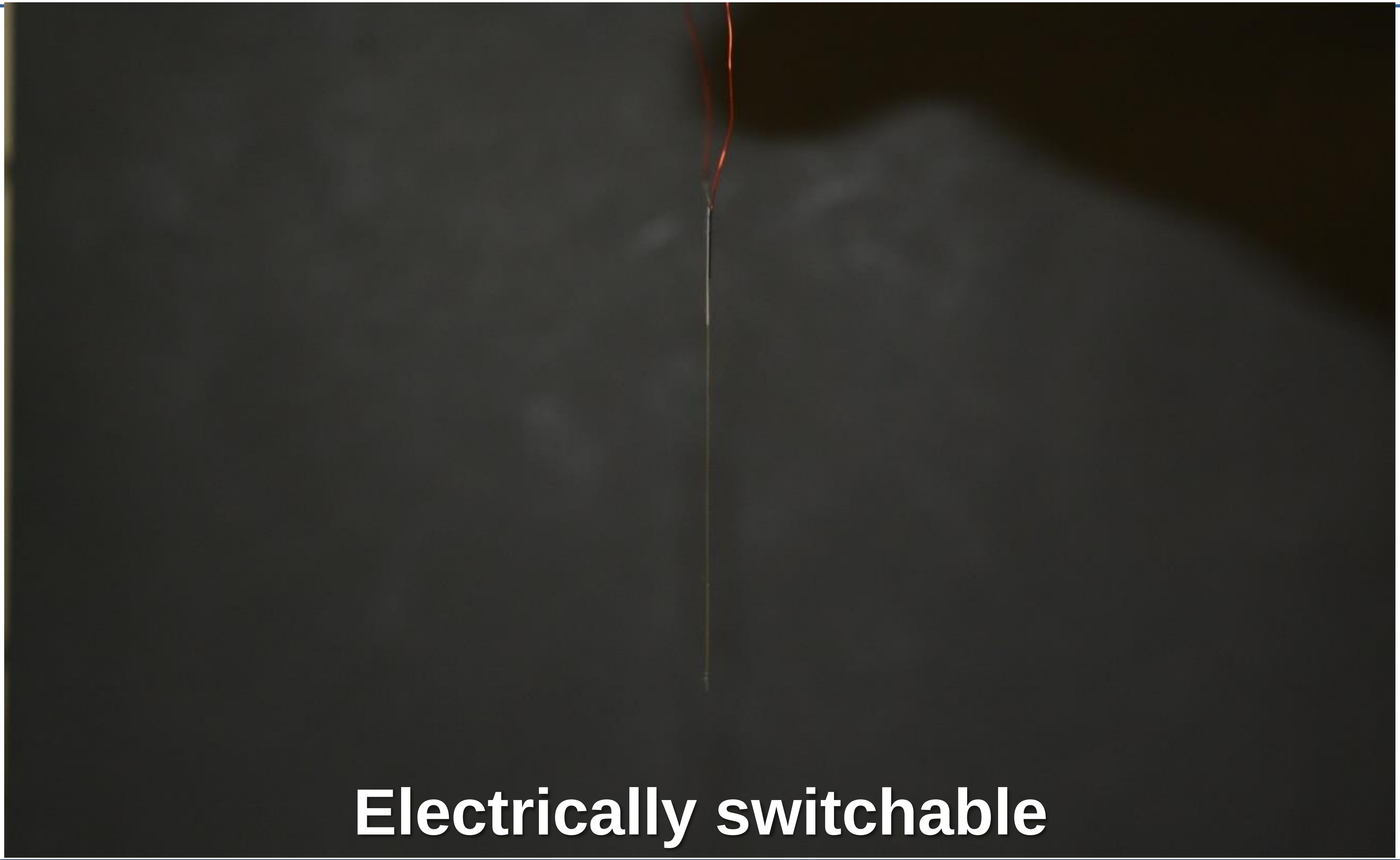
∅38 mm, F = 460 mm @ 442 nm, L = 1.3 μm

Thinnest optics



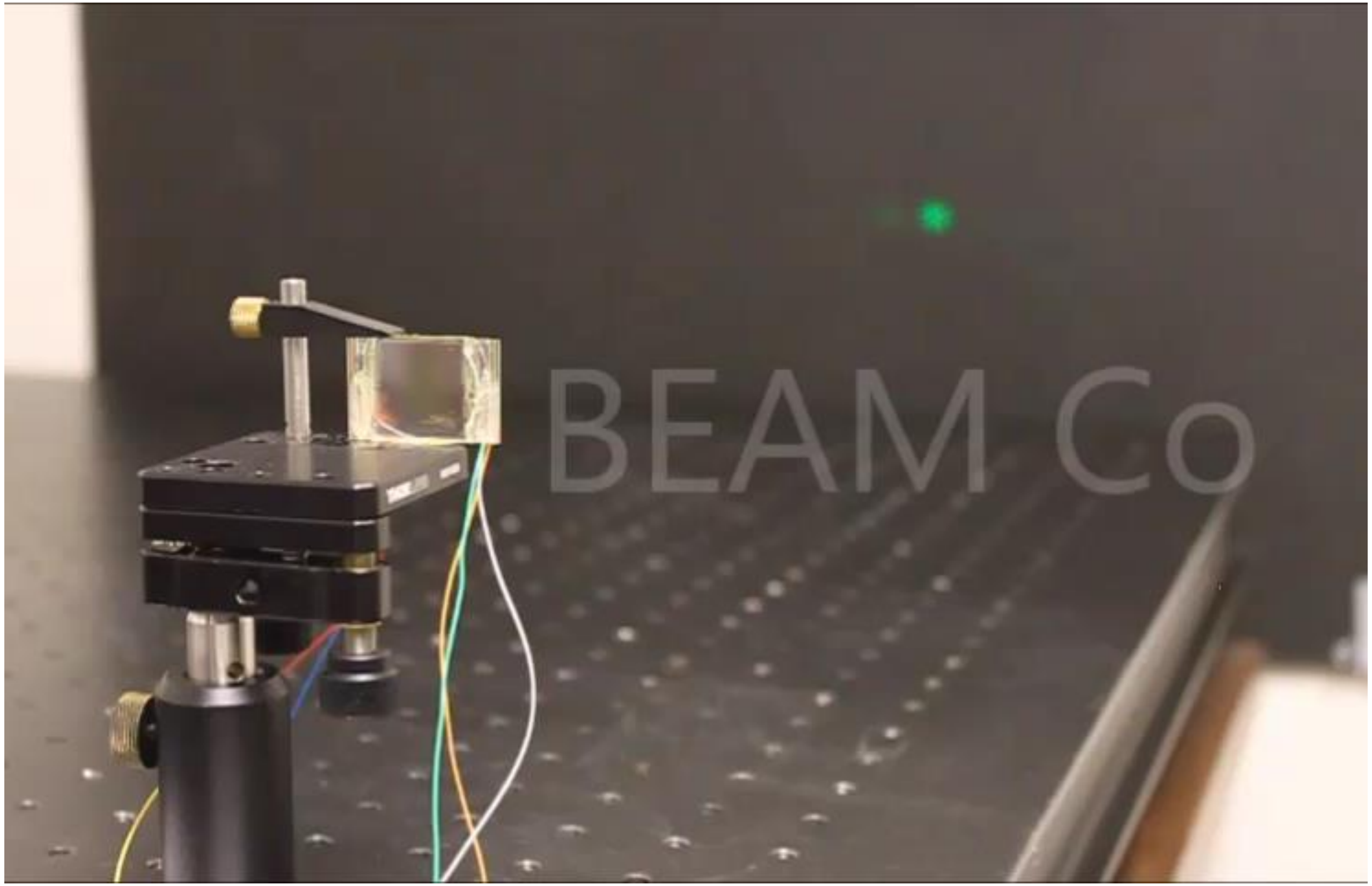
“Prism”

Lens arrays

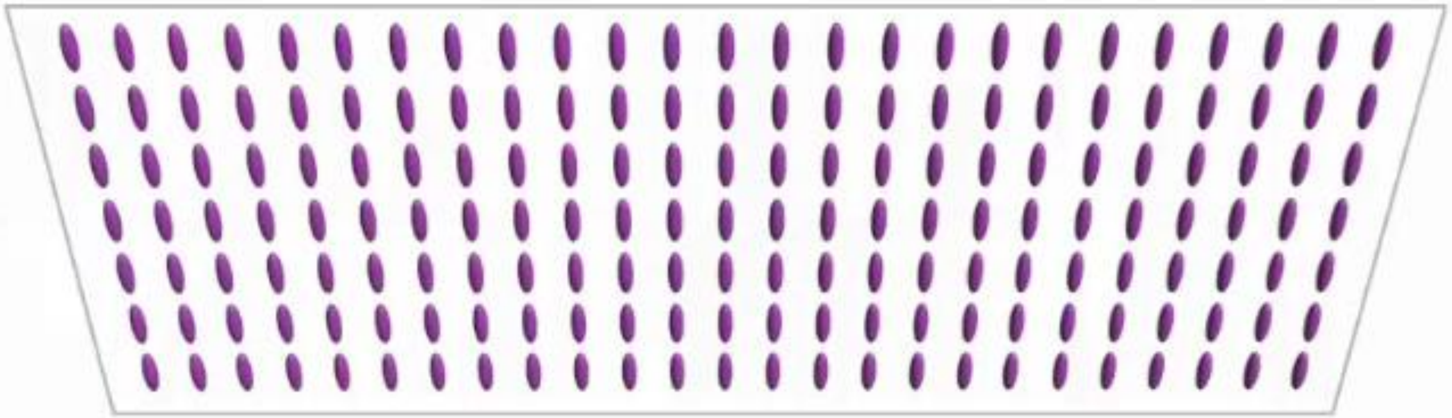

Electrically switchable

Switchable planar lenses

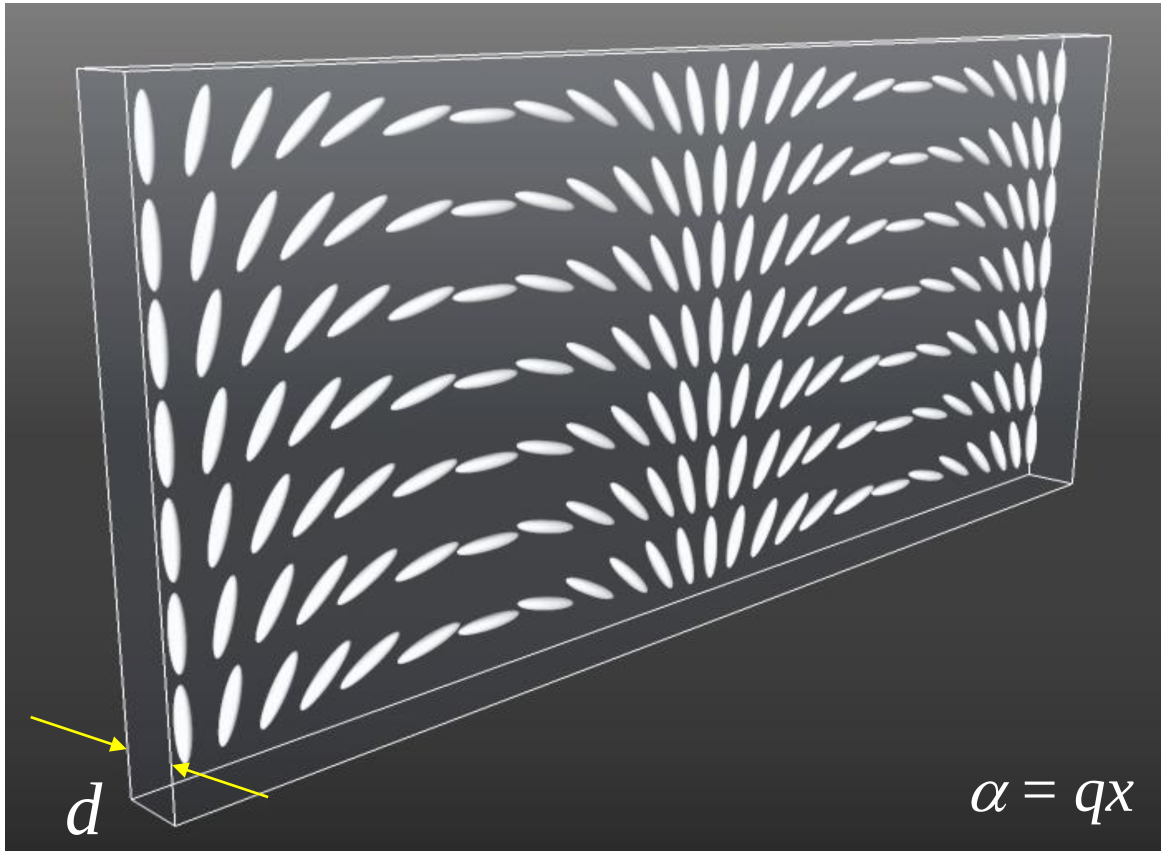
Non-mechanical beam steering



The concept of diffractive waveplates



Optics of Diffractive Waveplates



Max efficiency (~ 100%)

$$\lambda_{max} = 2\Delta n d$$

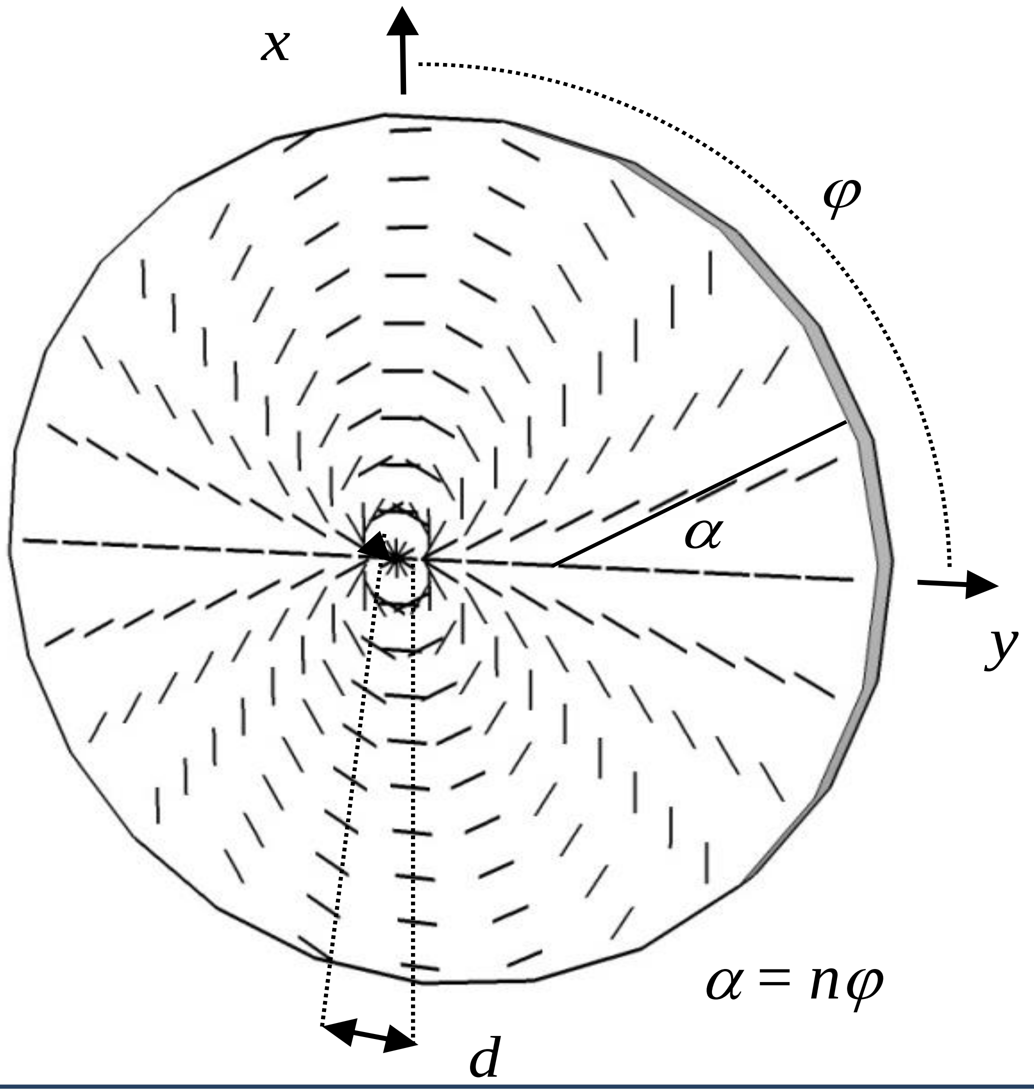
Δn: optical birefringence
d: layer thickness

Δn ~ 0.1-1
(liquid crystals and LC polymers)

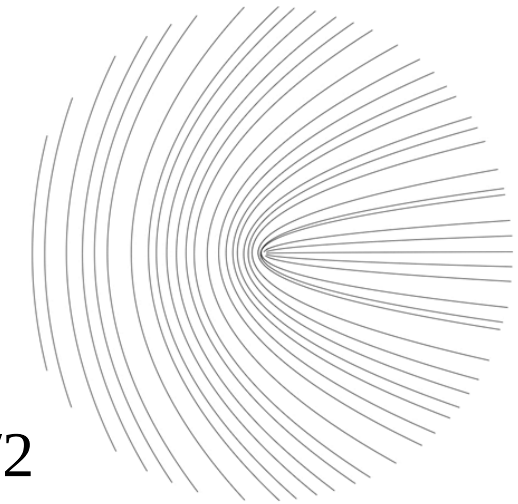
d ~ 1 μm
(for visible wavelengths)

Optics of Diffractive Waveplates

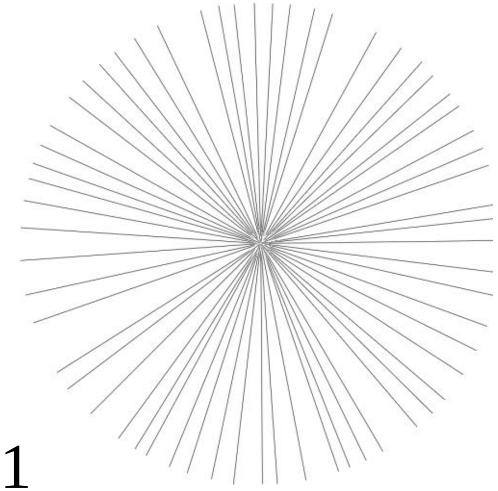
Vector Vortex Waveplates (VVW)



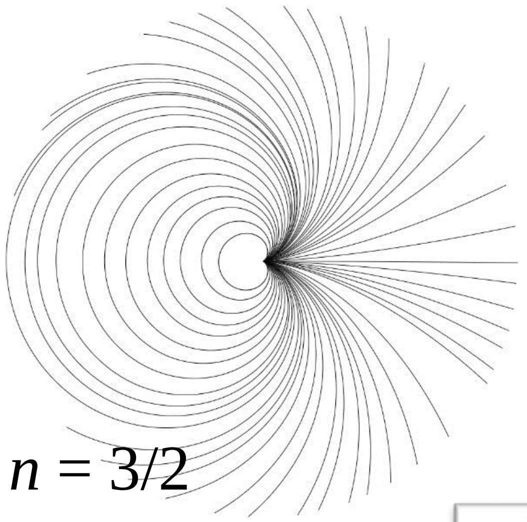
Vector Vortex Waveplates (VVW)



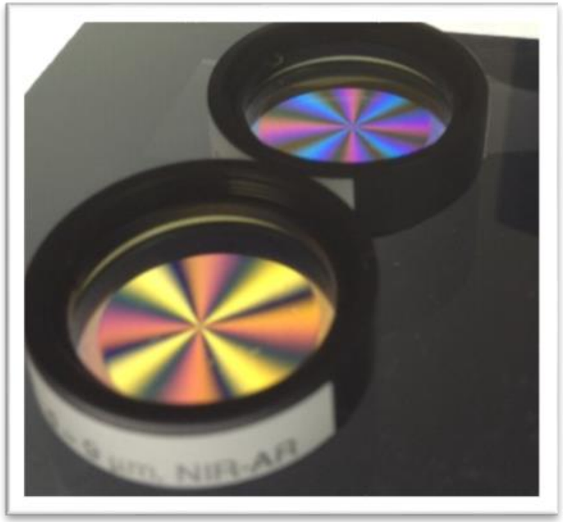
$n = 1/2$

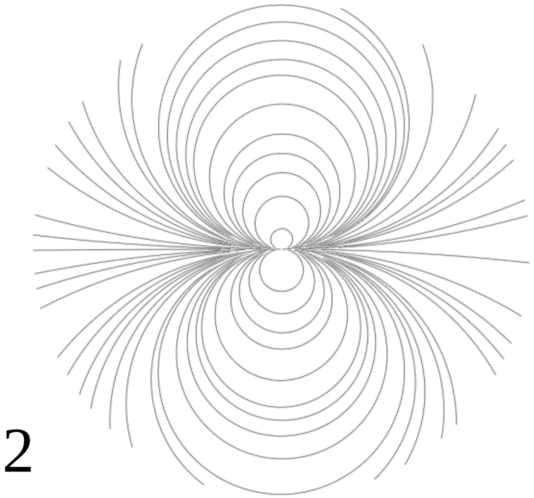


$n = 1$

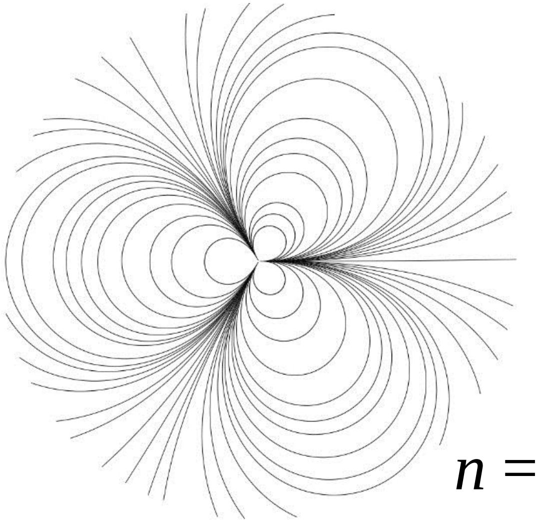


$n = 3/2$





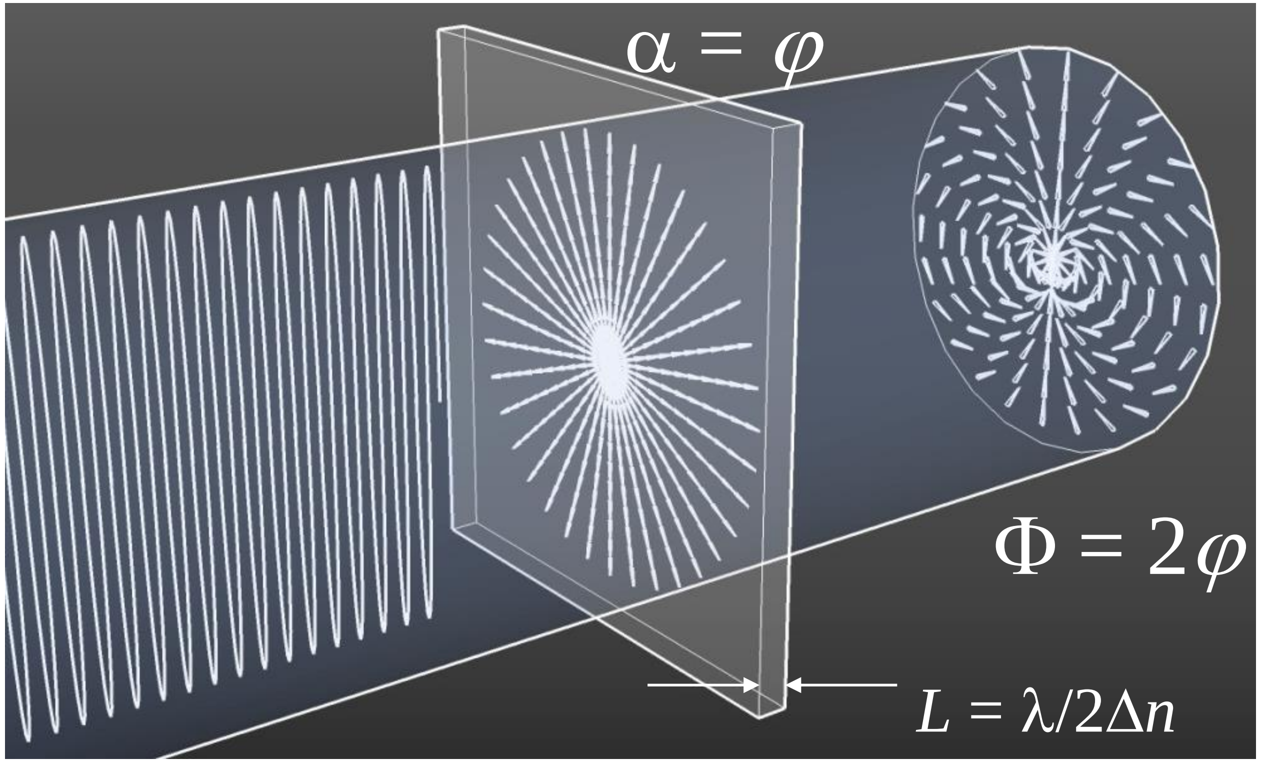
$n = 2$



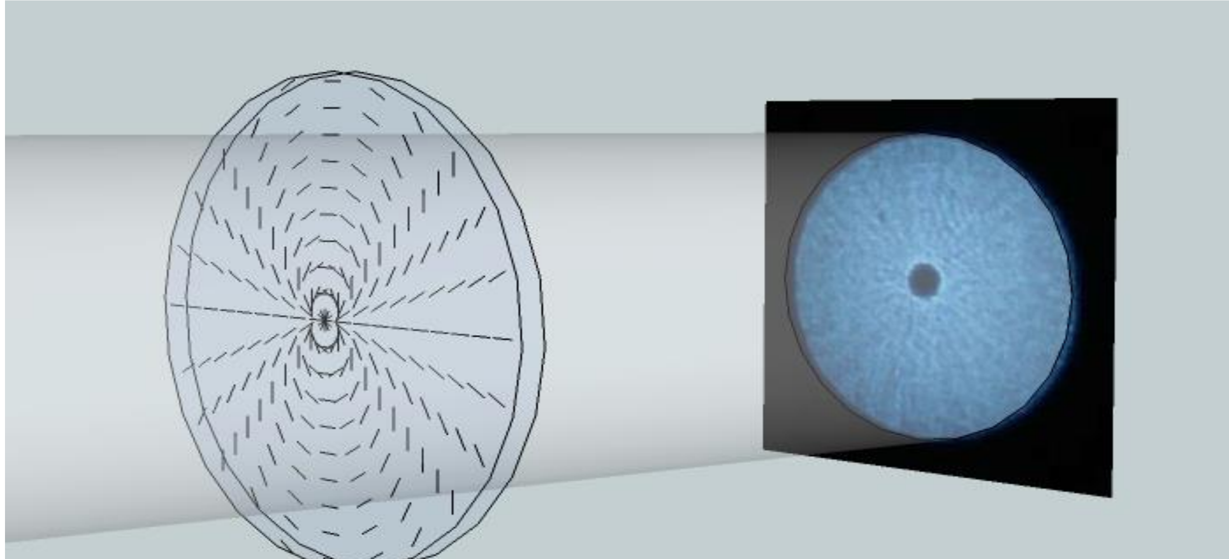
$n = 5/2$

$\alpha = n\varphi$ $\quad$ $n = \pm 1/2, \pm 1, \pm 3/2 \ldots$

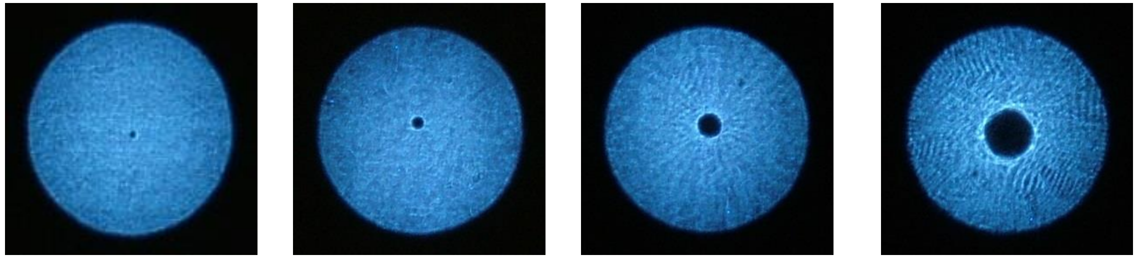
Cancelling light on the axis of VVWs



Light propagation through a VVW



$$\mathbf{E}_{out} = \mathbf{E}_{in} e^{\pm 2i\alpha(x,y)} = \mathbf{E}_{in} e^{\pm 2in\varphi}$$



q =1 q =64

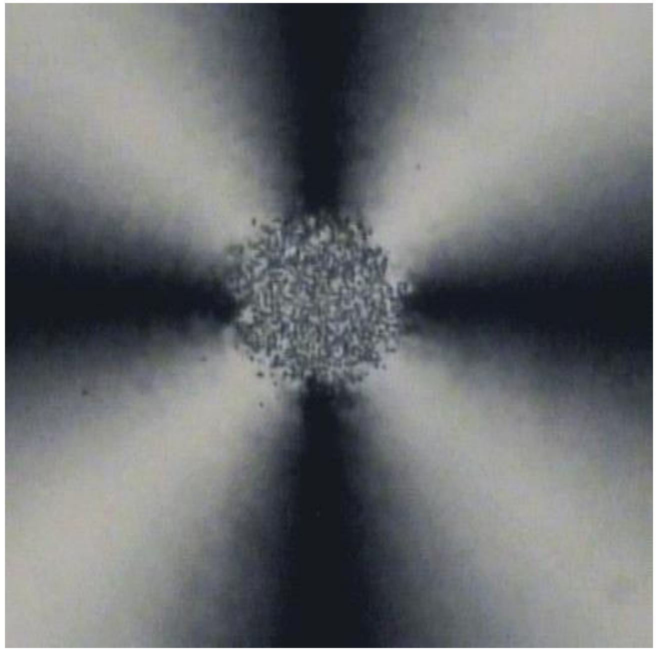
Intensity on axis

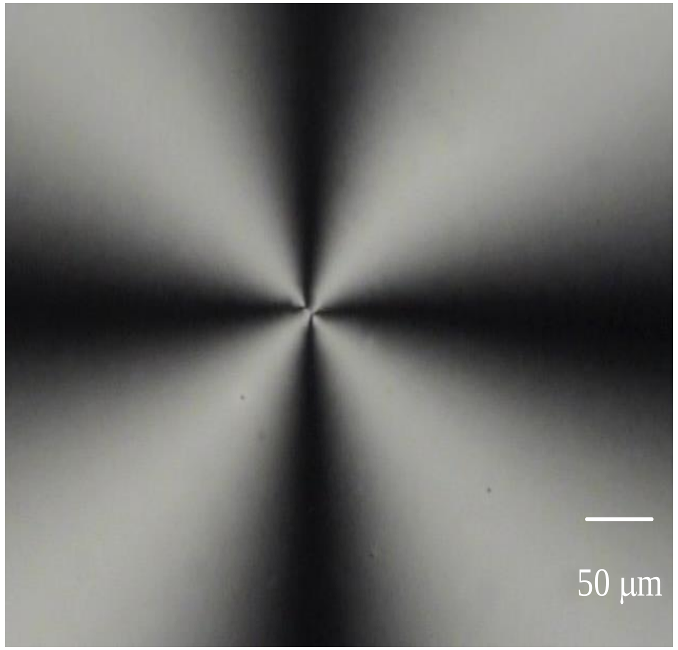
$$I_n \sim \left(\frac{\rho^2}{z}\right)^n$$

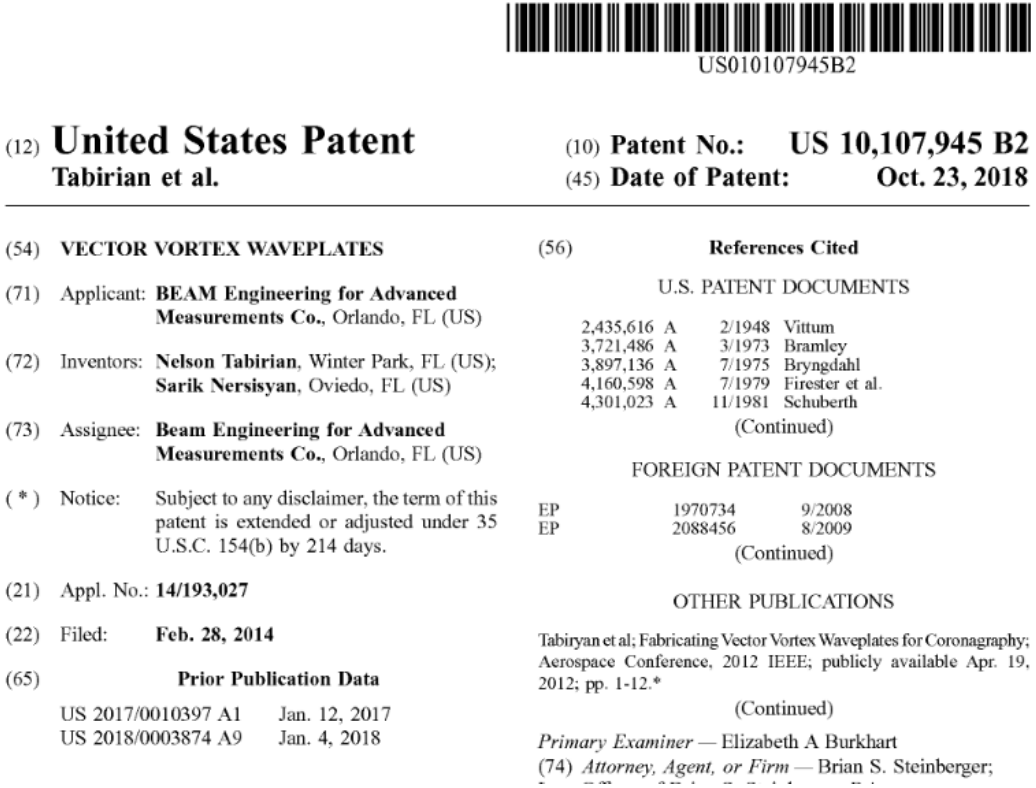
Vortex core size

$$\rho_n \approx \sqrt{\lambda z(1 + 0.54n)}$$

Challenges: reducing defect size







US010107945B2

(12) **United States Patent**
Tabirian et al.

(10) **Patent No.: US 10,107,945 B2**
(45) **Date of Patent: Oct. 23, 2018**

(54) **VECTOR VORTEX WAVEPLATES**

(71) Applicant: **BEAM Engineering for Advanced Measurements Co.**, Orlando, FL (US)

(72) Inventors: **Nelson Tabirian**, Winter Park, FL (US); **Sarik Nersisyan**, Oviedo, FL (US)

(73) Assignee: **Beam Engineering for Advanced Measurements Co.**, Orlando, FL (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 214 days.

(21) Appl. No.: **14/193,027**

(22) Filed: **Feb. 28, 2014**

(65) **Prior Publication Data**

US 2017/0010397 A1	Jan. 12, 2017
US 2018/0003874 A9	Jan. 4, 2018

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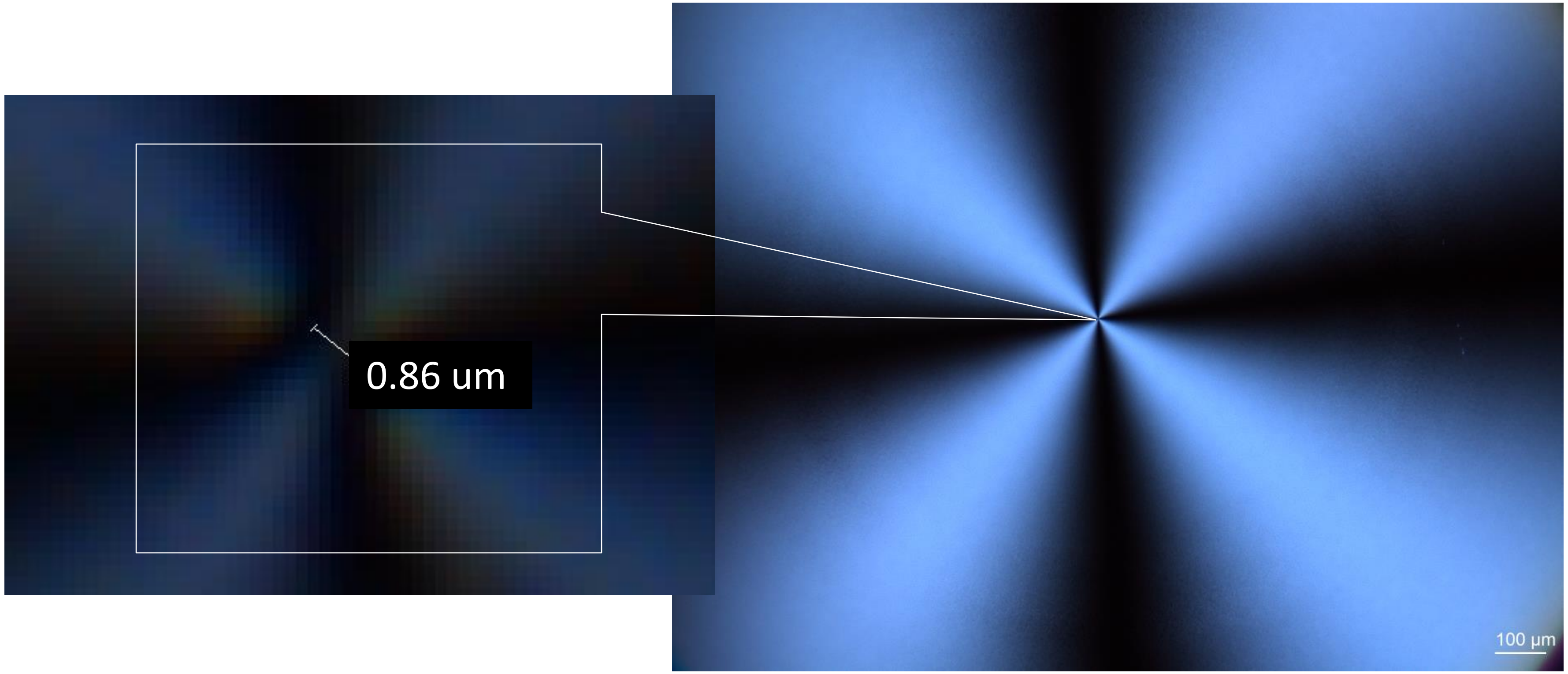
(Continued)

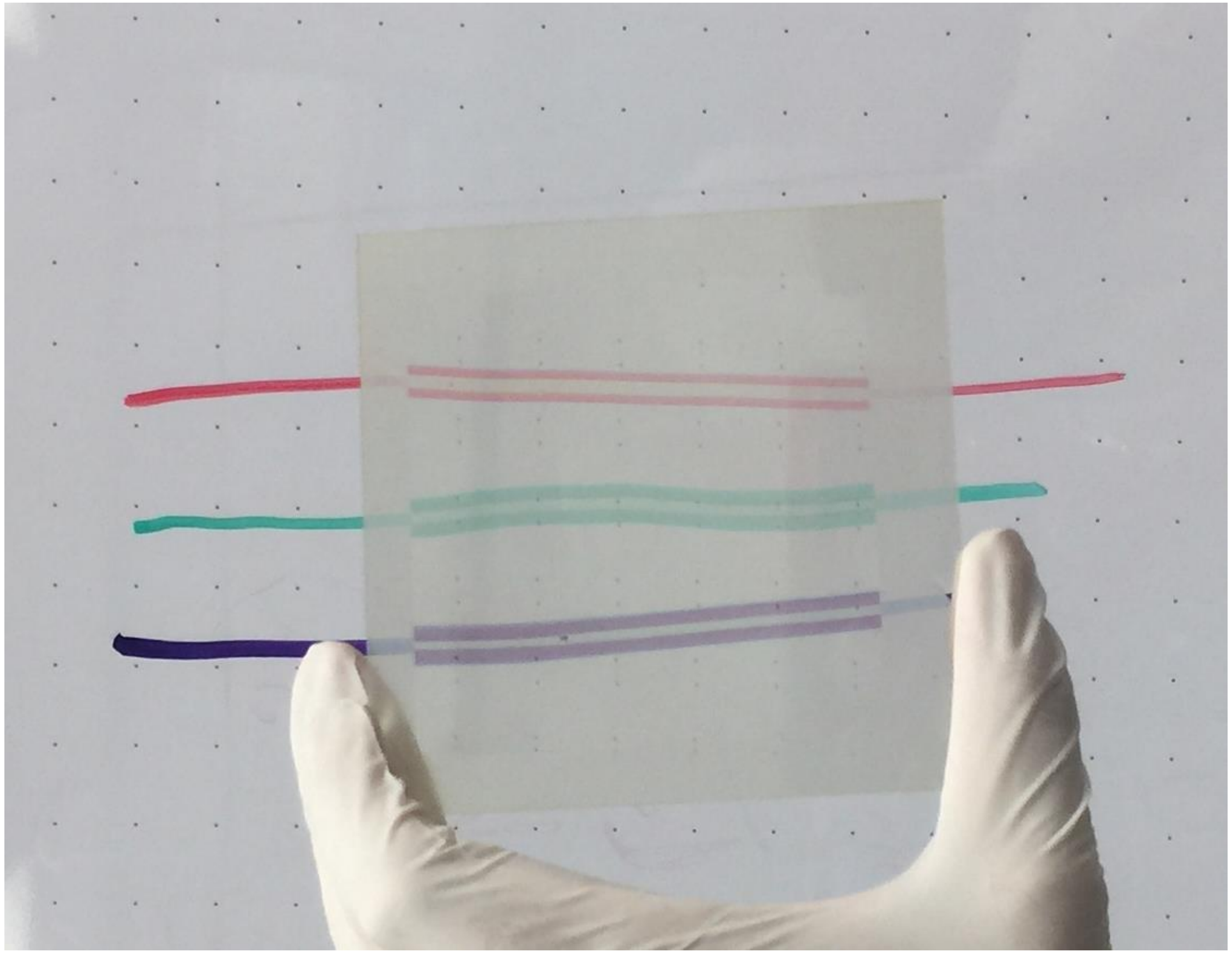
Primary Examiner — Elizabeth A Burkhart

(74) *Attorney, Agent, or Firm* — Brian S. Steinberger;

VVW with submicron defect size



Challenges: bandwidth



Multilayer achromatic half-wave plates

JOURNAL OF THE OPTICAL SOCIETY OF AMERICA VOLUME 49, NUMBER 4 APRIL, 1959

Achromatic Combinations of Half-Wave Plates

CHARLES J. KOESTER
Research Center, American Optical Company, Southbridge, Massachusetts

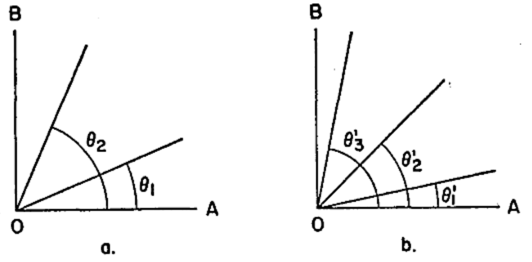


FIG. 1. (a) The two-element achromatic rotator. θ_1 and θ_2 are the azimuths of the slow axes of the two half-wave plates. (b) The three-element achromatic rotator. θ_1', θ_2', and θ_3' are defined as θ_1 and θ_2 above. OA is the azimuth of the plane of polarization of the incident light, OB is that of the emerging light.

In Fig. 1(a) it is easily seen that if $\theta_1=22.5$ and $\theta_2=67.5°$ then for the wavelength λ_0 the plane of polarization is rotated 45° by the first plate, another 45° by the second plate. This arrangement is not achromatic. If the angles are changed to

$$\theta_1=22.5°+\delta \quad (1a)$$

and

$$\theta_2=67.5°-\delta, \quad (1b)$$

For the three-element rotator, the configuration of slow (or fast) axes is shown in Fig. 1(b). It can be seen that if $\theta_1'=11.25°$, $\theta_2'=45°$, and $\theta_3'=78.75°$, then for the wavelength λ_0 the plane of polarization is rotated 22.5° by the first plate, an additional 45° by the second plate, and 22.5° by the third plate, a total of 90°. If the angles are changed to

$$\theta_1'=11.25°+\delta \quad (2a)$$

$$\theta_2'=45° \quad (2b)$$

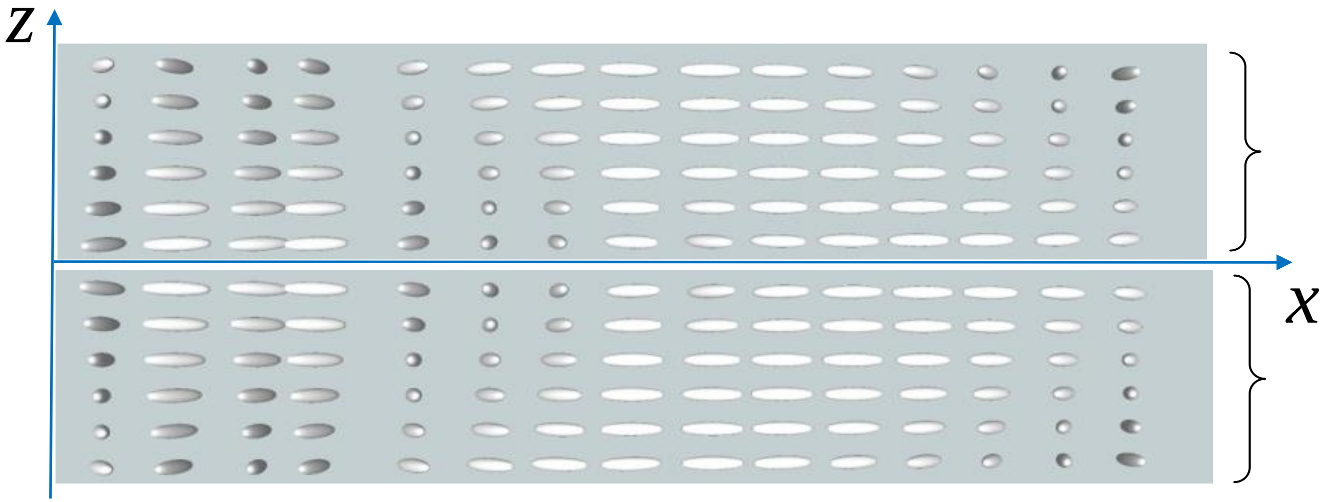
$$\theta_3'=78.75°-\delta \quad (2c)$$

the total rotation for wavelength λ_0 remains 90°. But in addition two other wavelengths, λ_1 and λ_2 are also rotated 90°. For $\delta=0.75°$ and 0.25° the values of Δ_1, Δ_2, λ_1, and λ_2 are given in Table I(b).

As with the two-element system, the smaller the value of δ the narrower the range of achromatization, but the greater the degree of achromatization within that range. In practice the value of δ is selected by turning the plates relative to each other until the best achromatization is obtained for the particular situation.

Achromatic combinations of four and even more plates are possible. The azimuth angles of the slow axes

Internally twisted layers

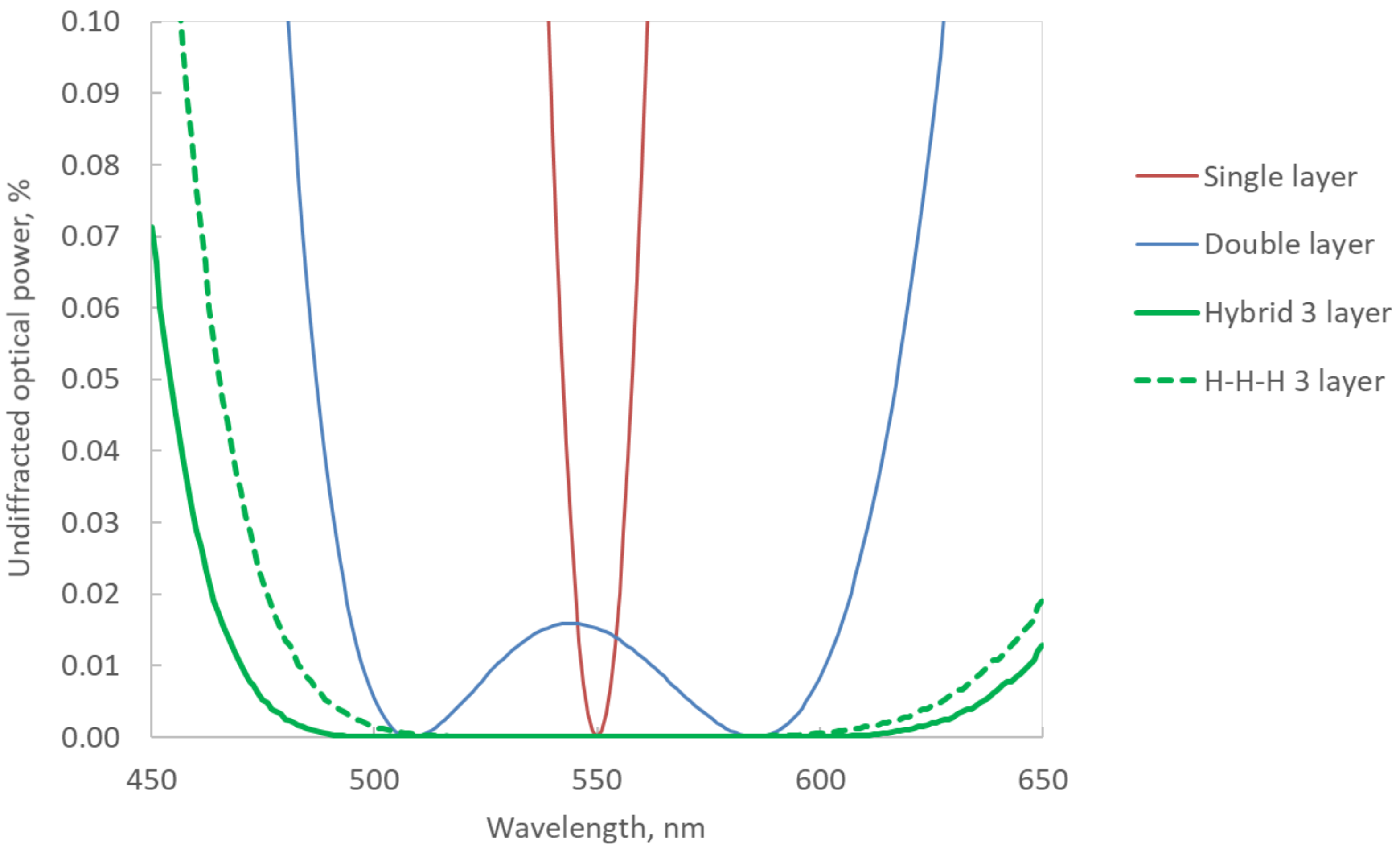


$\alpha = qx + Qz$

$\alpha = qx - Qz$

$$\eta = 4\eta_S(1 - \eta_S) \qquad \eta_S = G^2\left[\frac{sinX}{X}\right]^2 \qquad G = \pi\Delta nL/\lambda \qquad X = \sqrt{\phi^2 + G^2}$$

Architectures of broadband DWs



Theory vs practice

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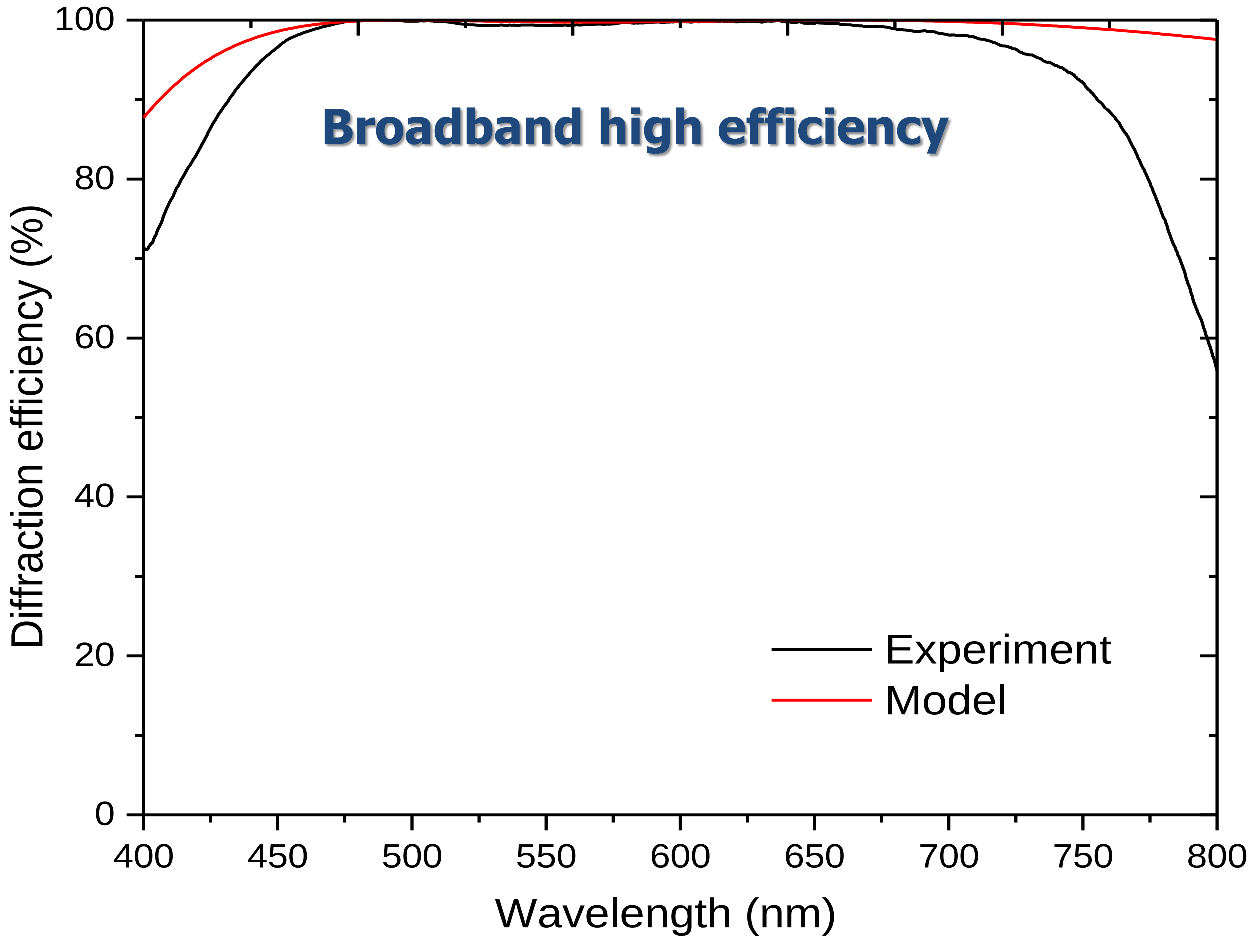
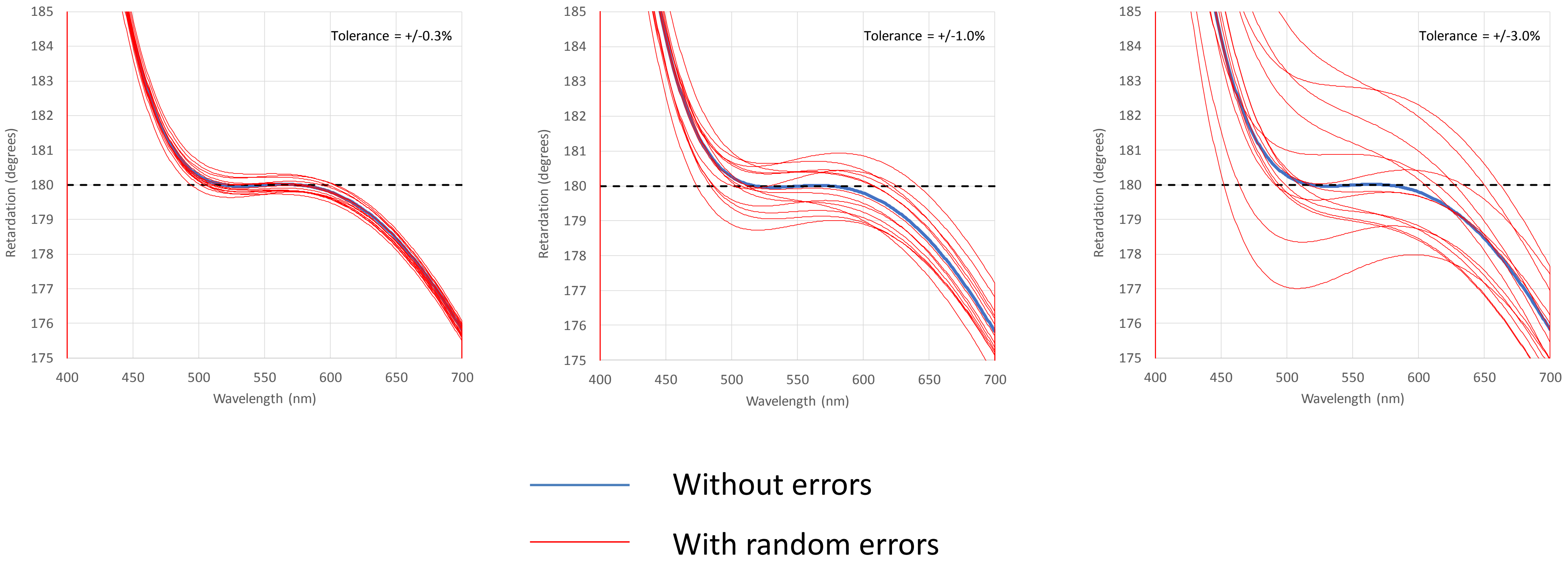
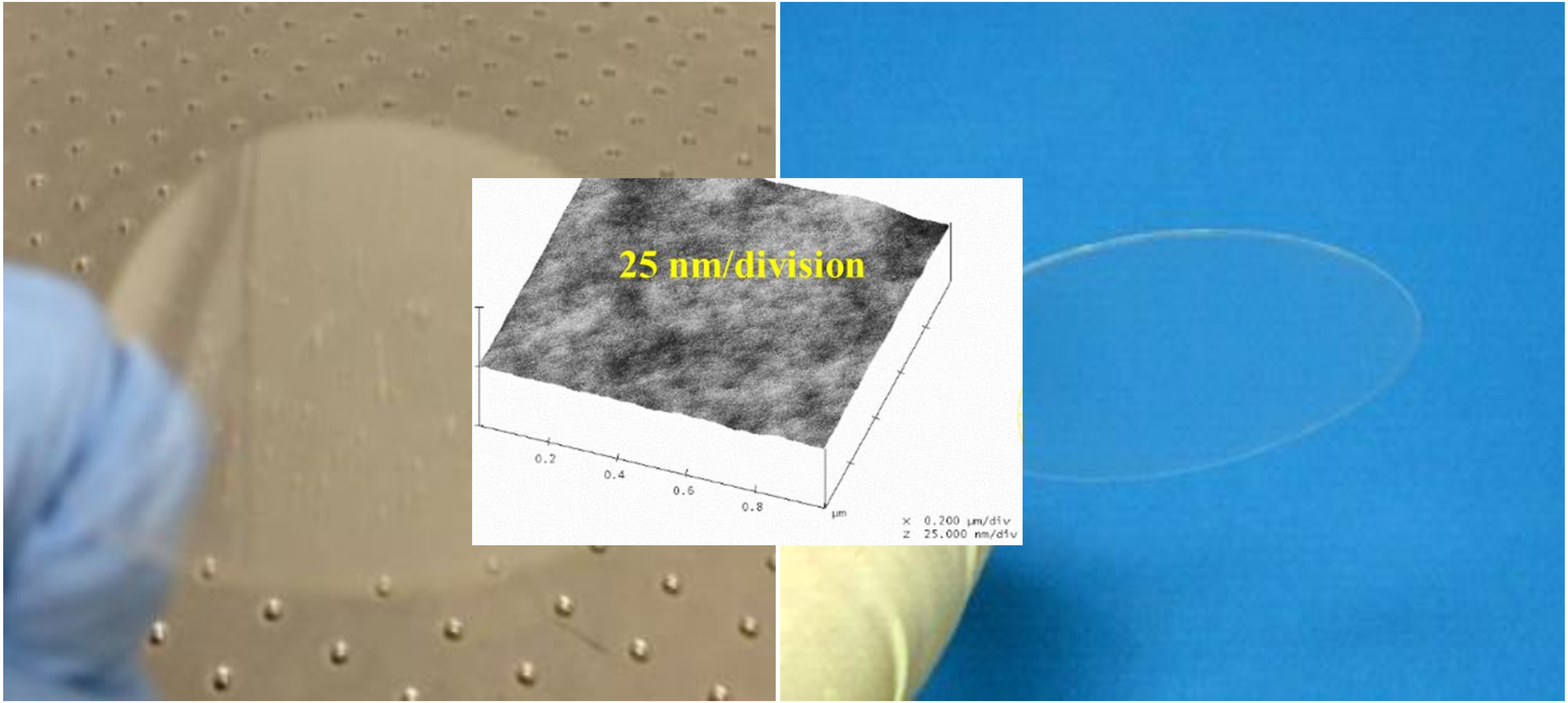


Tolerance analysis for hybrid three layer design



Fabrication cycle

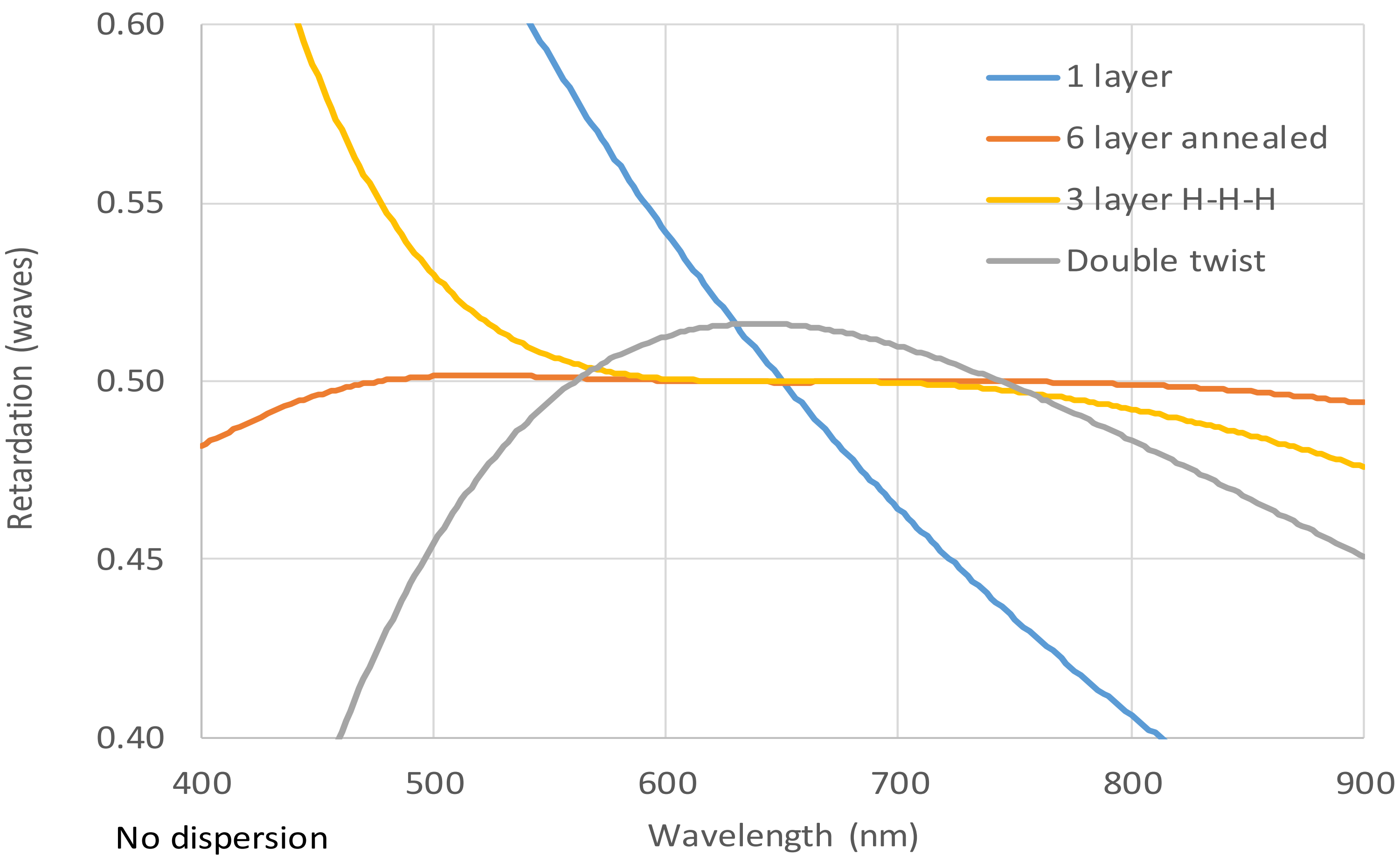
Coatings on polymer films



Future Tasks

Optimize vortex structure

Architectures for better tolerance



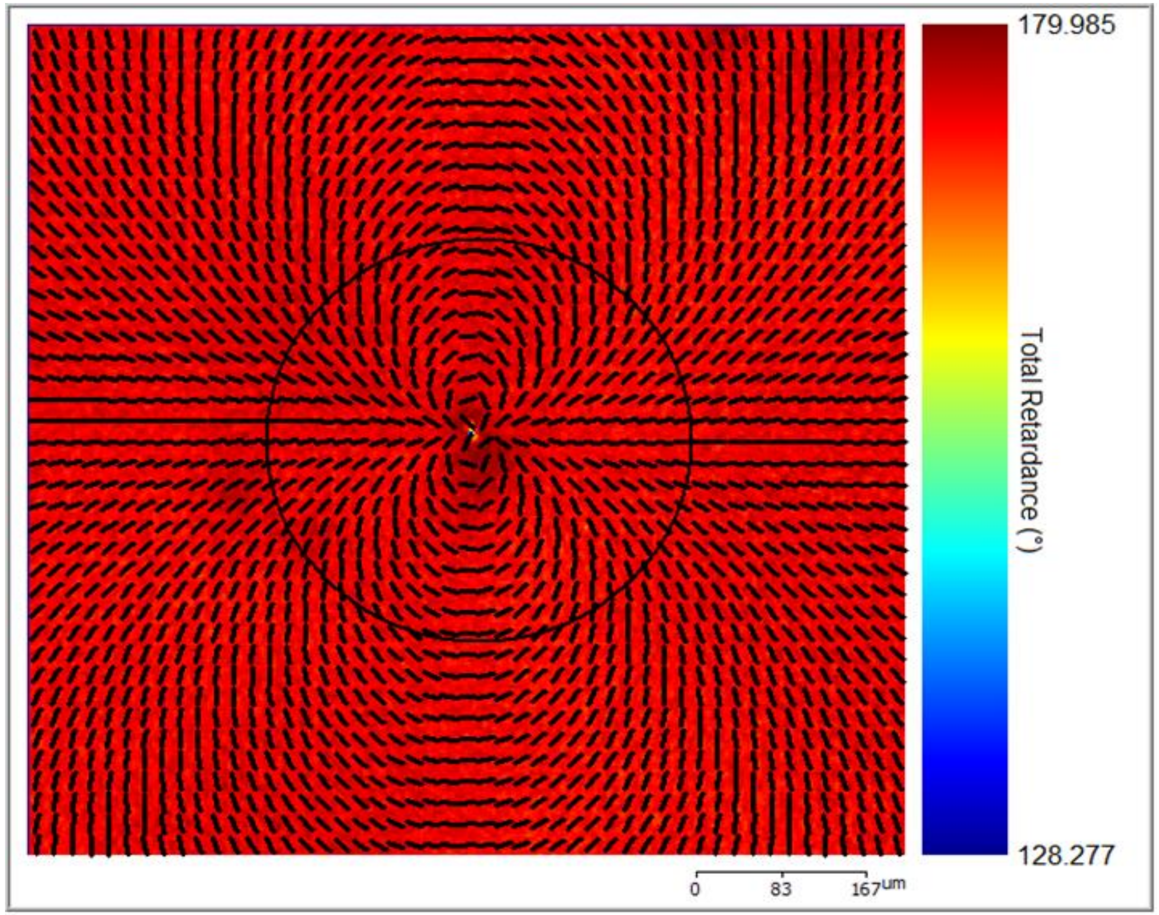
No dispersion

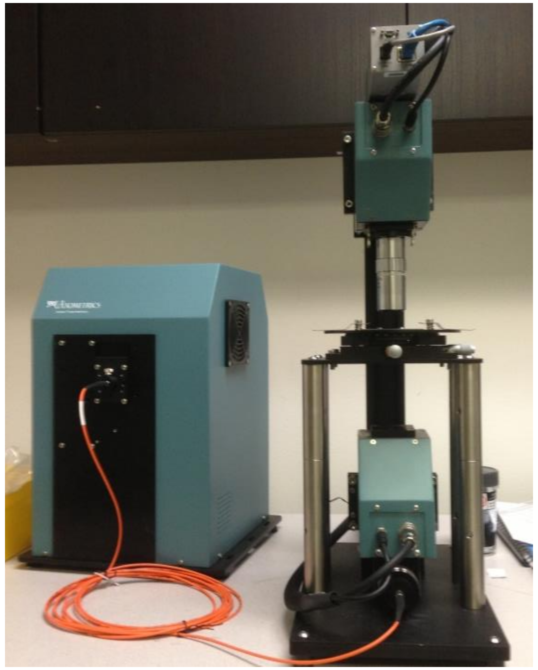
Architectures for better tolerance

BEAM

	Double twist 2 layer	Hybrid 3 layer	Quad twist 4 layer
First layer retardation (nm)	256.2	182.6	323.9
First layer twist (degrees)	72.3	84.9	111.2
Second layer retardation (nm)	256.2	323.9	170.6
Second layer twist (degrees)	-72.3	0	-72.5
Third layer retardation (nm)	N/A	182.6	170.6
Third layer twist (degrees)	N/A	-84.9	72.5
Fourth layer retardation (nm)	N/A	N/A	323.9
Fourth layer twist (degrees)	N/A	N/A	-111.2
Maximum deviation of total retardation from half wave over operating wavelengths (degrees)	0.44	0.04	0.03

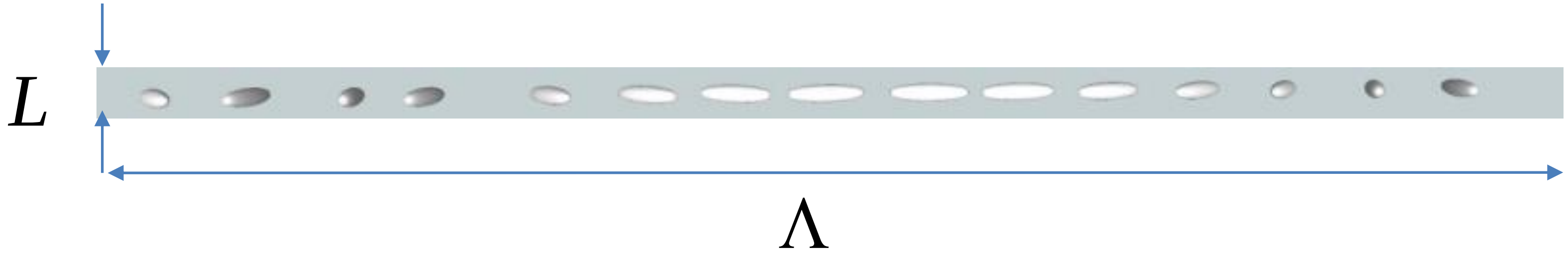
High precision characterization techniques





Mueller Matrix Spectro-polarimeter

Fabrication technology improvement



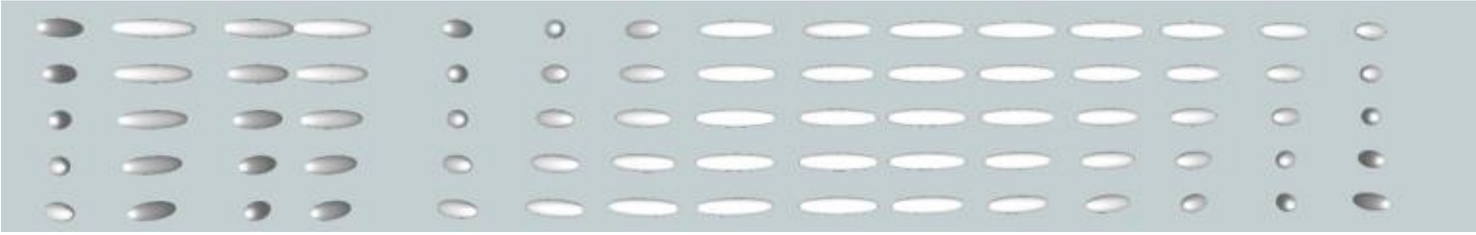
$$L < 0.4\,\Lambda$$

Fabrication technology improvement

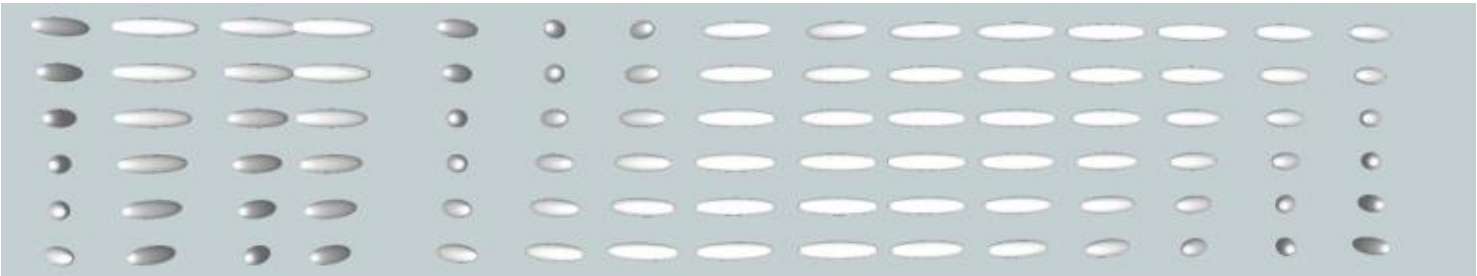
Fabrication technology improvement

Fabrication technology improvement

Fabrication technology improvement

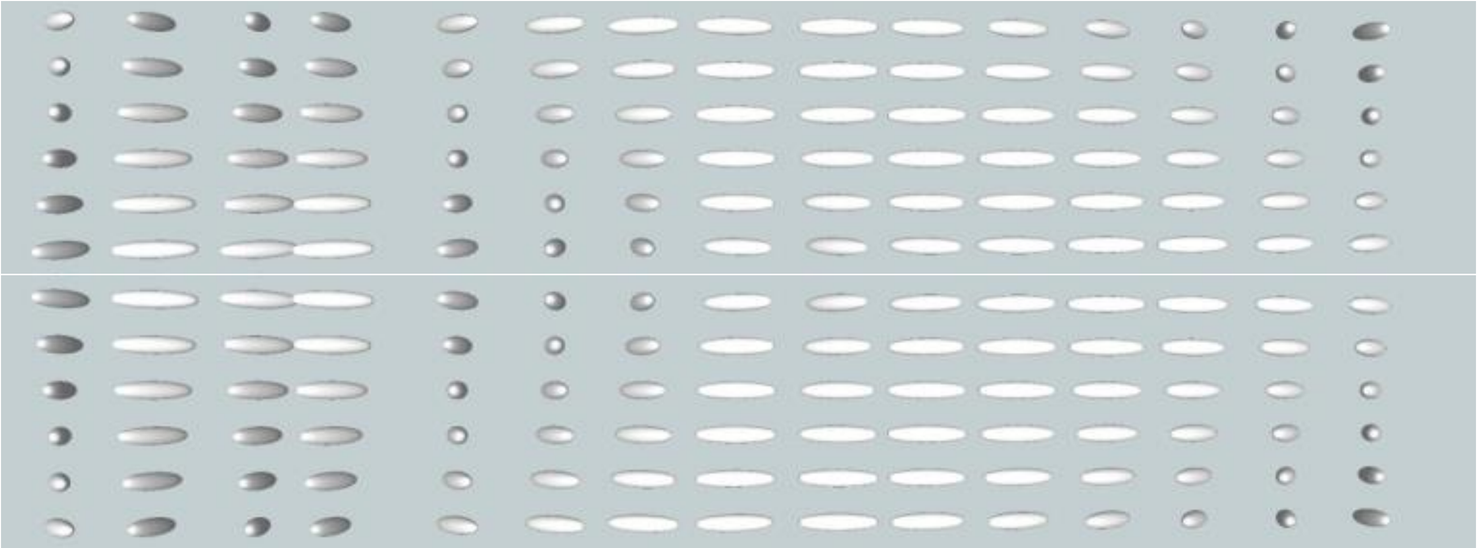


Fabrication technology improvement



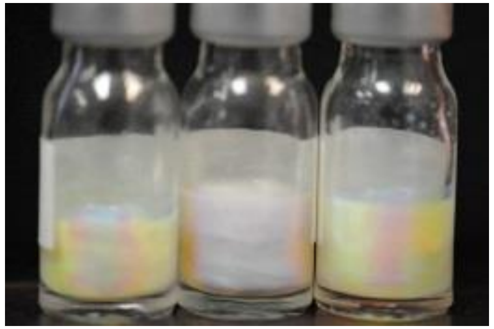
$$L = \frac{\lambda}{2(n_{\parallel} - n_{\perp})}$$

Fabrication technology improvement

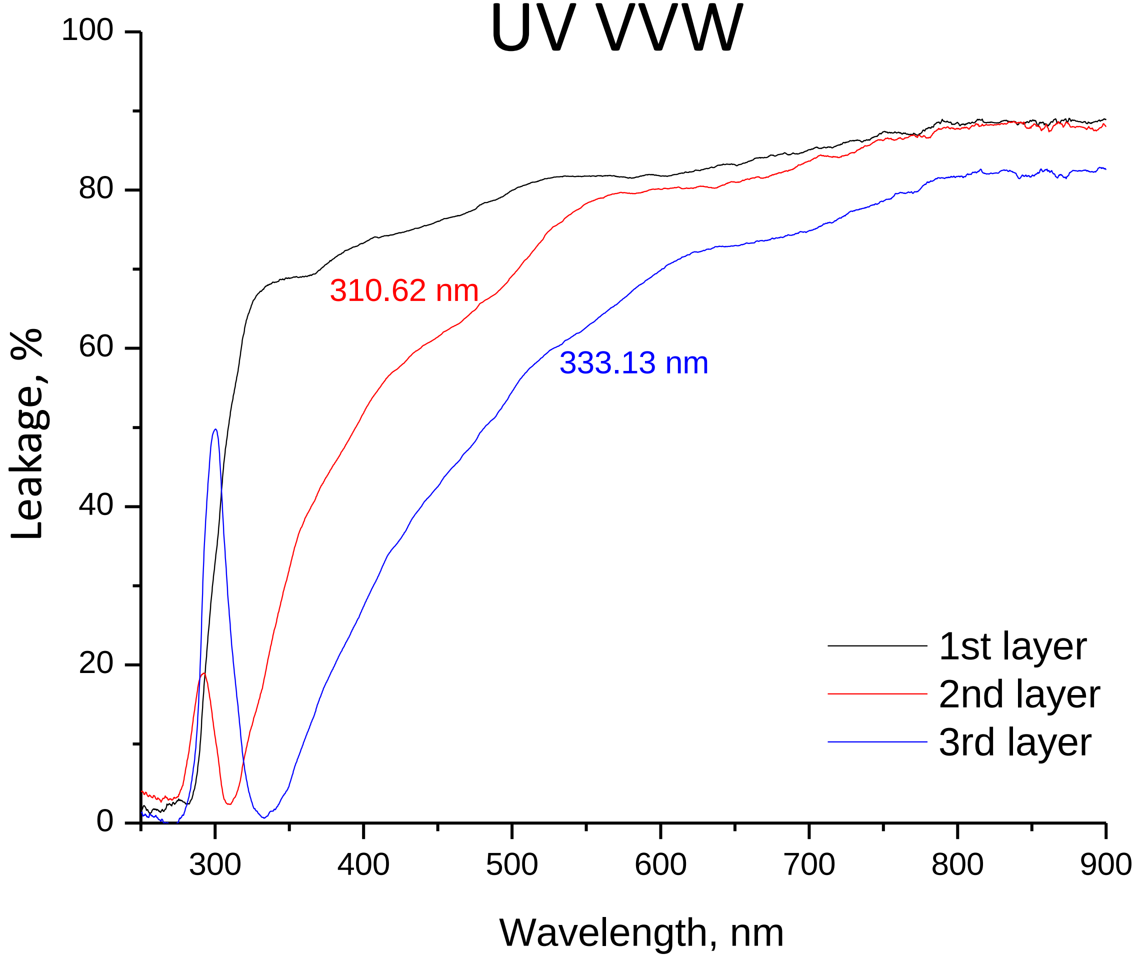


- On-site recording
- On-site curing
- Compatibility between layers
- Recording with no mechanically moving parts

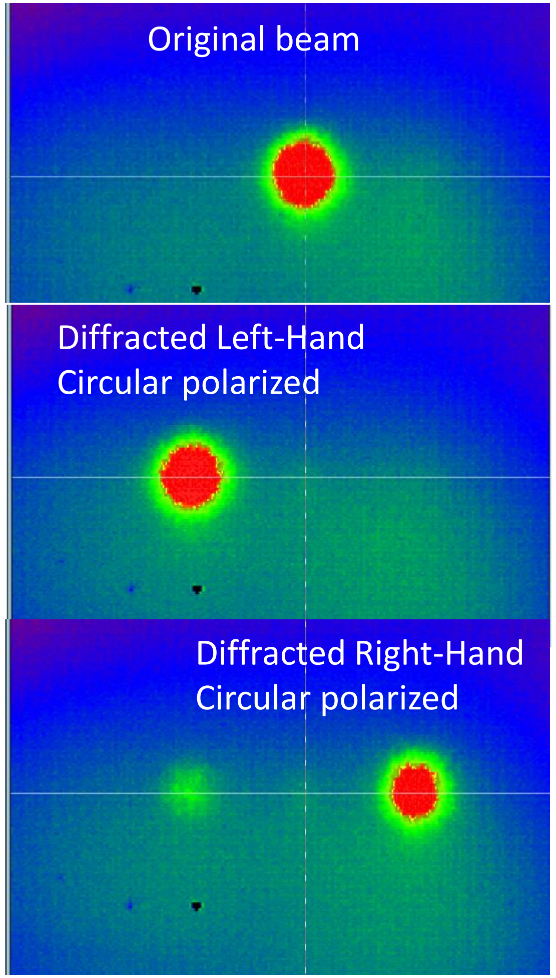
Improving materials, adapting to UV and other spectral ranges



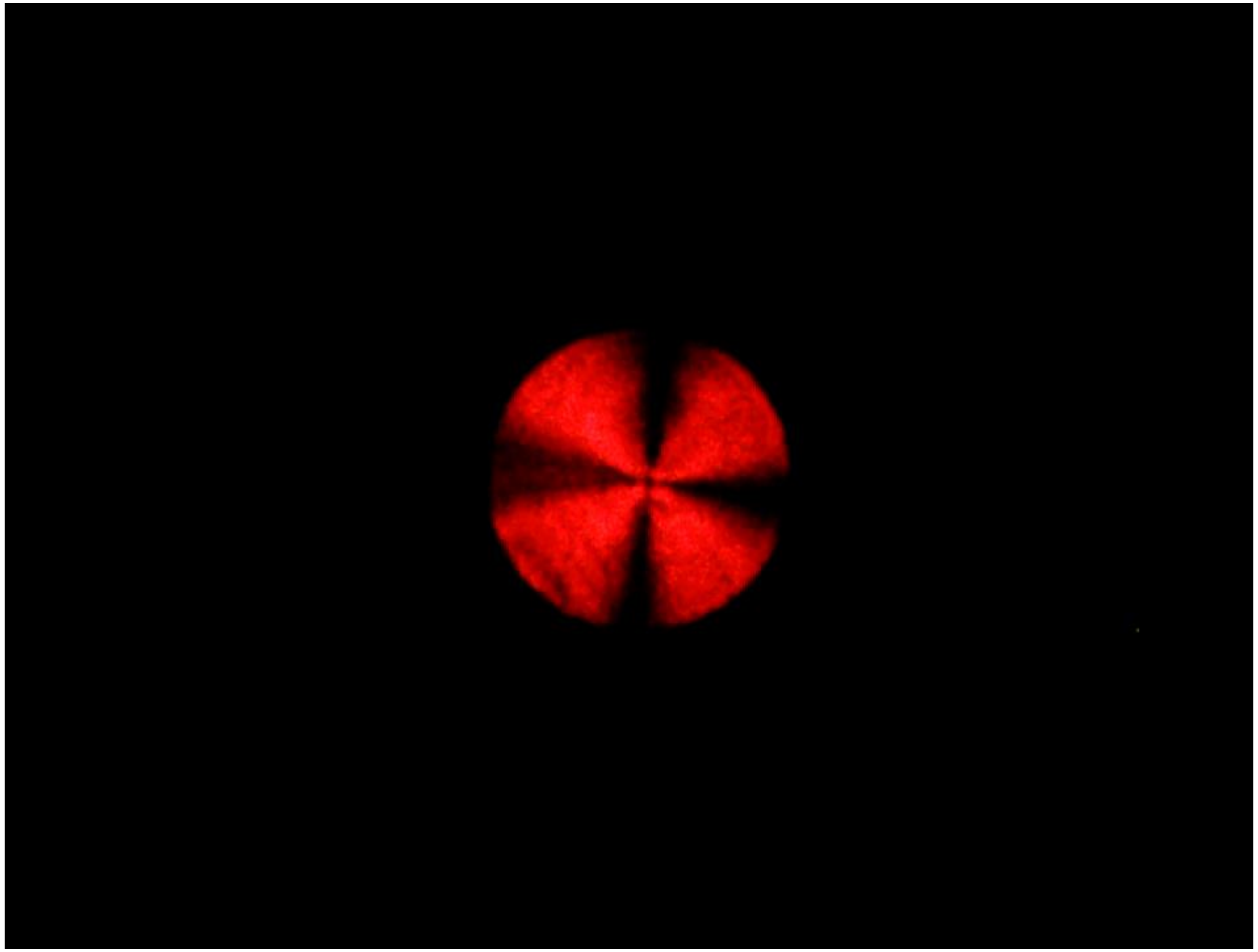
UV VVW



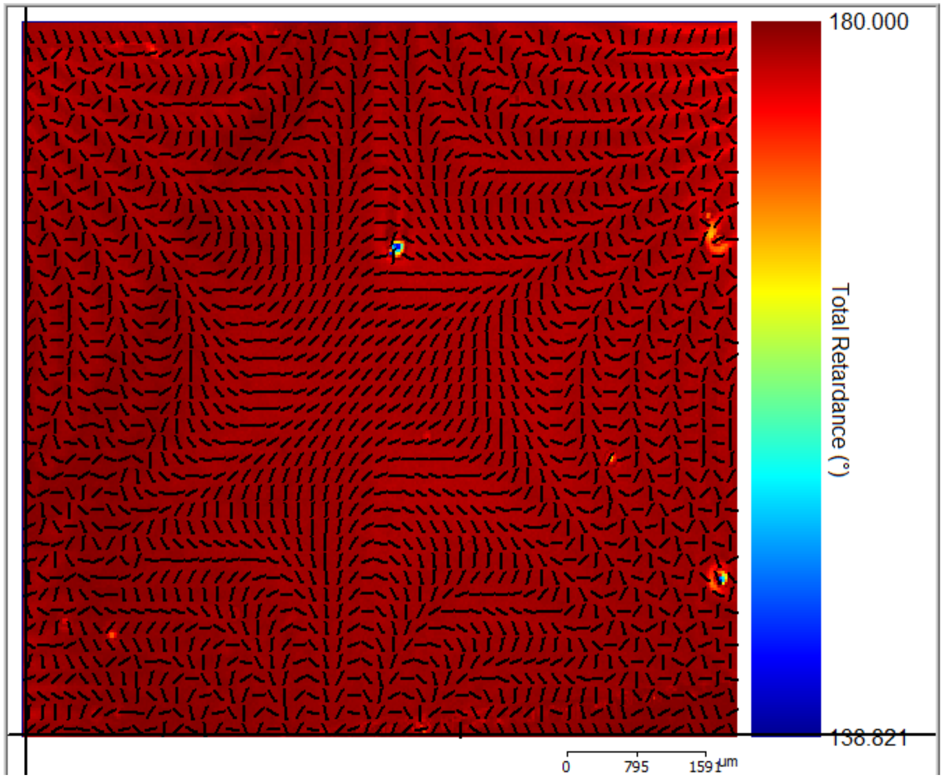
LWIR CDW



Exploring multifunctionality

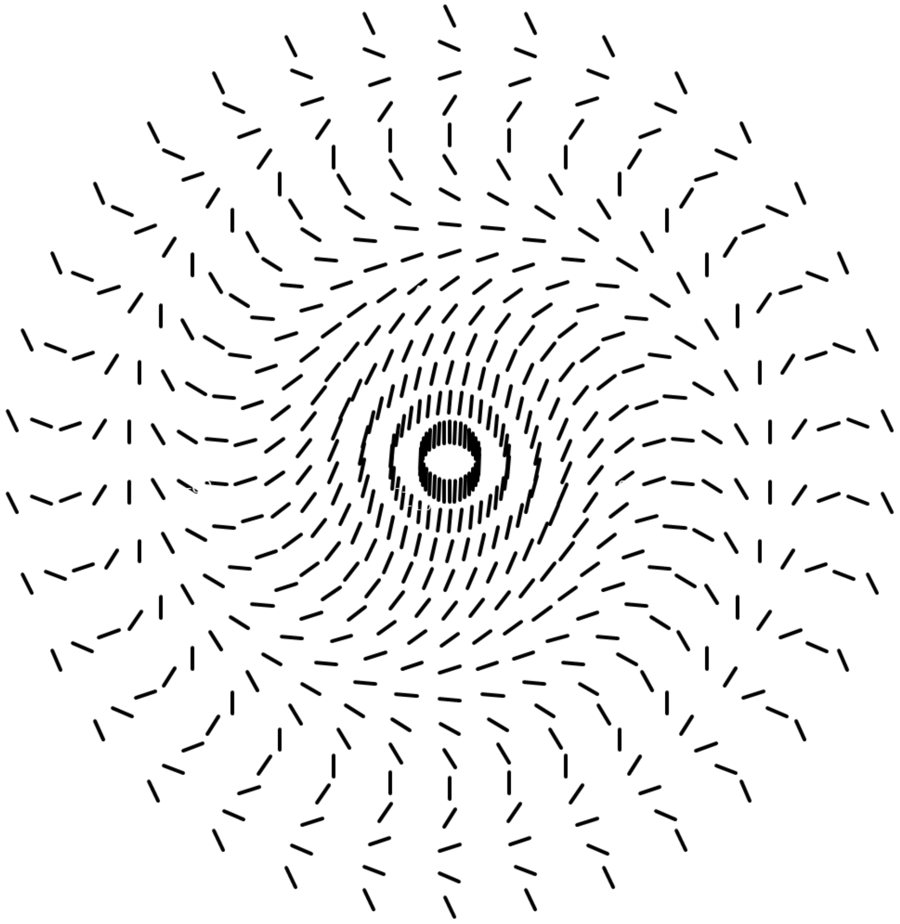


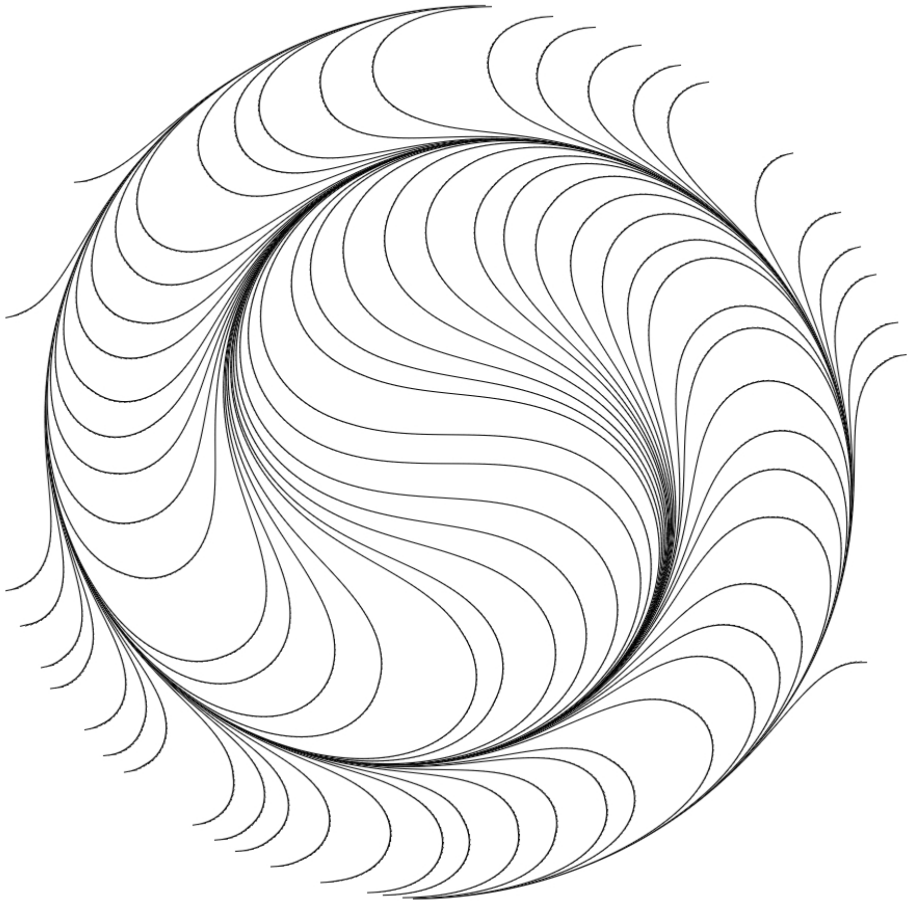
Vortices + Lenses + …



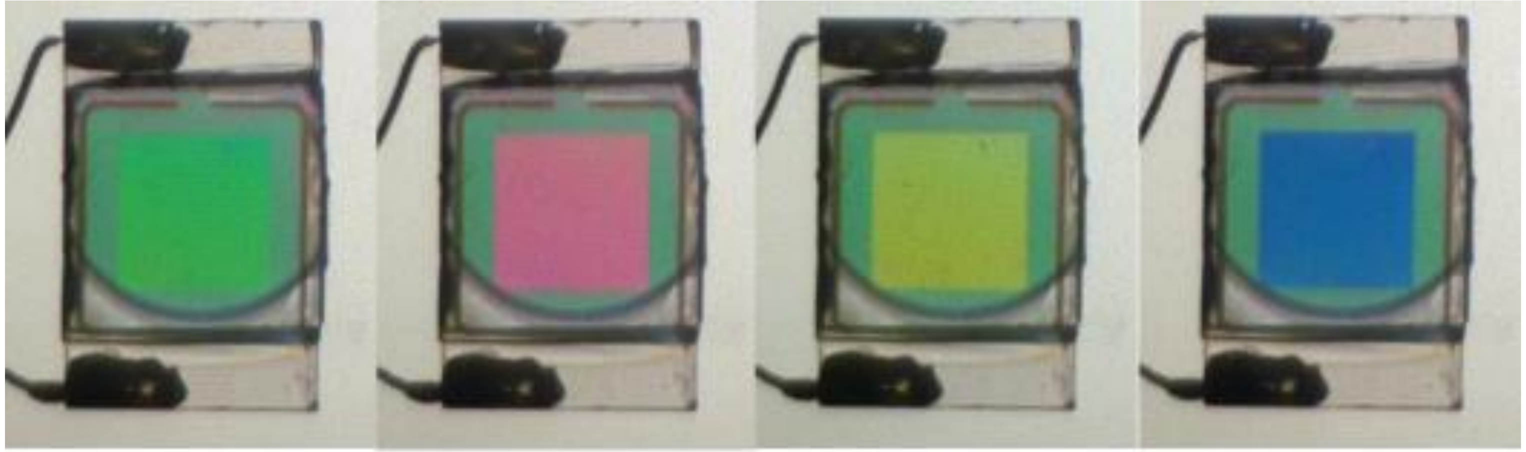
Diffractive Waveplate Lens

$$\alpha \sim r^2$$





Tunable filters and shutters



1.86 V 2.12 V 2.24 V 2.81 V

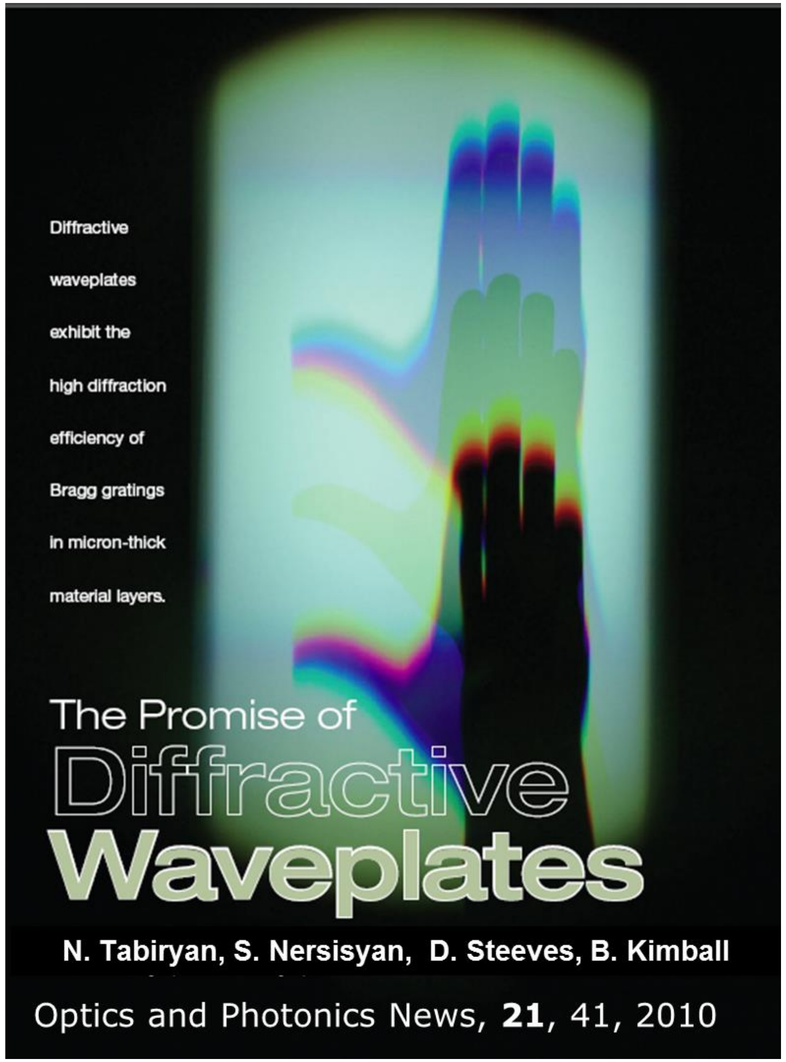
Tunable spectral filter

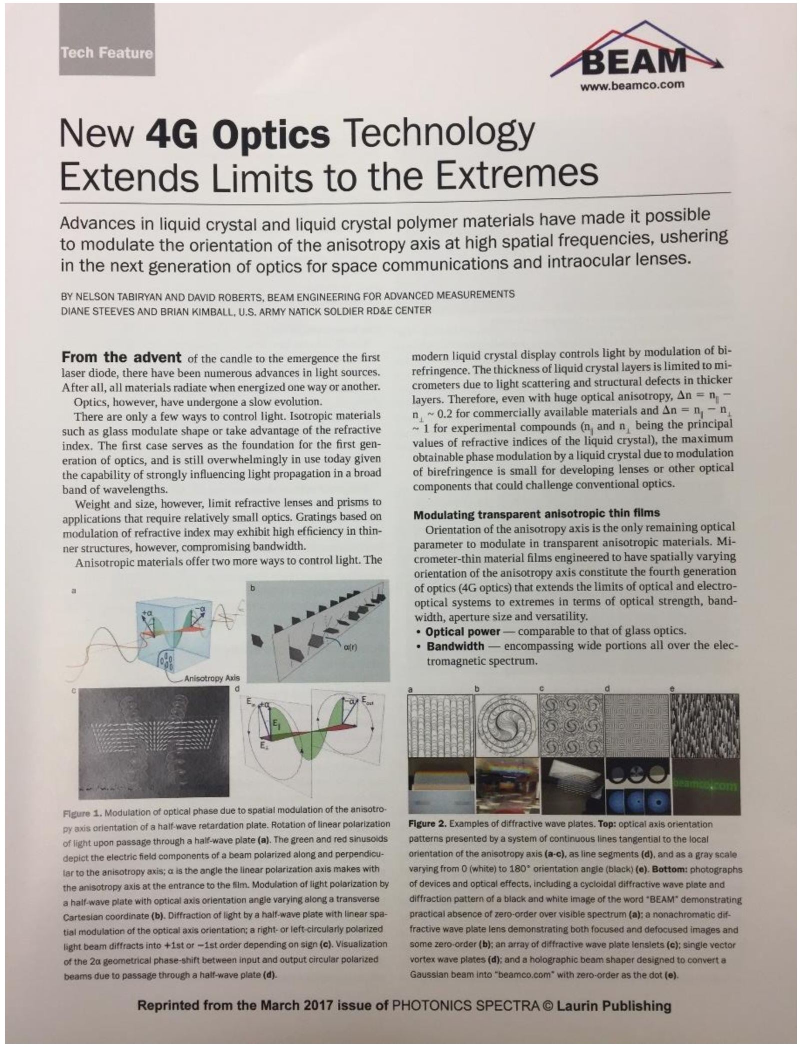
Non-mechanical shutter

DW lens converting a flat into a concave (convex) Mirror

Non-mechanical line-of-sight switch

References





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 made it possible to modulate the orientation of the anisotropy axis at high spatial frequencies, ushering in the next generation of optics for space communications and intraocular lenses.

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

From the advent of the candle to the emergence the first laser diode, there have been numerous advances in light sources. After all, all materials radiate when energized one way or another.

Optics, however, have undergone a slow evolution.

There are only a few ways to control light. Isotropic materials such as glass modulate shape or take advantage of the refractive index. The first case serves as the foundation for the first generation of optics, and is still overwhelmingly in use today given the capability of strongly influencing light propagation in a broad band of wavelengths.

Weight and size, however, limit refractive lenses and prisms to applications that require relatively small optics. Gratings based on modulation of refractive index may exhibit high efficiency in thinner structures, however, compromising bandwidth.

Anisotropic materials offer two more ways to control light. The modern liquid crystal display controls light by modulation of birefringence. The thickness of liquid crystal layers is limited to micrometers due to light scattering and structural defects in thicker layers. Therefore, even with huge optical anisotropy, $\Delta n = n_{\parallel} - n_{\perp} \sim 0.2$ for commercially available materials and $\Delta n = n_{\parallel} - n_{\perp} \sim 1$ for experimental compounds ($n_{\parallel}$ and $n_{\perp}$ being the principal values of refractive indices of the liquid crystal), the maximum obtainable phase modulation by a liquid crystal due to modulation of birefringence is small for developing lenses or other optical components that could challenge conventional optics.

Modulating transparent anisotropic thin films

Orientation of the anisotropy axis is the only remaining optical parameter to modulate in transparent anisotropic materials. Micrometer-thin material films engineered to have spatially varying orientation of the anisotropy axis constitute the fourth generation of optics (4G optics) that extends the limits of optical and electro-optical systems to extremes in terms of optical strength, bandwidth, aperture size and versatility.

- **Optical power** — comparable to that of glass optics.
- **Bandwidth** — encompassing wide portions all over the electromagnetic spectrum.

Figure 1. Modulation of optical phase due to spatial modulation of the anisotropy axis orientation of a half-wave retardation plate. Rotation of linear polarization of light upon passage through a half-wave plate **(a)**. The green and red sinusoids depict the electric field components of a beam polarized along and perpendicular to the anisotropy axis; α is the angle the linear polarization axis makes with the anisotropy axis at the entrance to the film. Modulation of light polarization by a half-wave plate with optical axis orientation angle varying along a transverse Cartesian coordinate **(b)**. Diffraction of light by a half-wave plate with linear spatial modulation of the optical axis orientation; a right- or left-circularly polarized light beam diffracts into +1st or −1st order depending on sign **(c)**. Visualization of the 2α geometrical phase-shift between input and output circular polarized beams due to passage through a half-wave plate **(d)**.

Figure 2. Examples of diffractive wave plates. **Top:** optical axis orientation patterns presented by a system of continuous lines tangential to the local orientation of the anisotropy axis **(a-c)**, as line segments **(d)**, and as a gray scale varying from 0 (white) to 180° orientation angle (black) **(e)**. **Bottom:** photographs of devices and optical effects, including a cycloidal diffractive wave plate and diffraction pattern of a black and white image of the word "BEAM" demonstrating practical absence of zero-order over visible spectrum **(a)**; a nonachromatic diffractive wave plate lens demonstrating both focused and defocused images and some zero-order **(b)**; an array of diffractive wave plate lenslets **(c)**; single vector vortex wave plates **(d)**; and a holographic beam shaper designed to convert a Gaussian beam into "beamco.com" with zero-order as the dot **(e)**.

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