NC STATE UNIVERSITY Electrical & Computer Engineering

Creating Arbitrary Optical Axis Patterns Via Direct-Write Lithography for Geometric Phase Holograms and Patterned Retarders

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Associate Professor, ECE

27 March 2014

National Science Foundation
WHERE DISCOVERIES BEGIN
2011 PECASE award, and prior

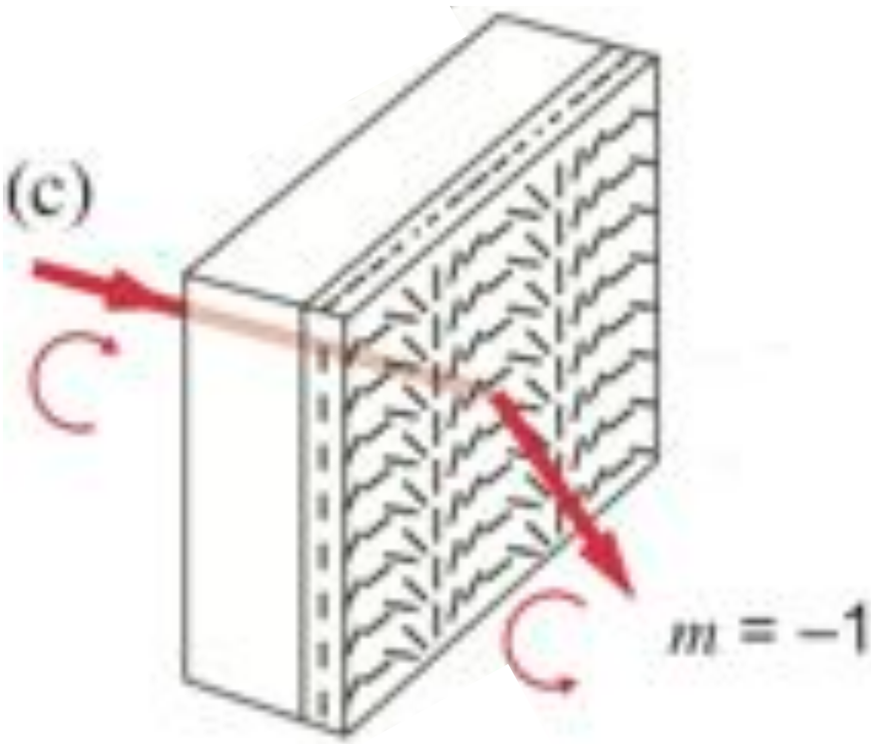
imagineOptix™

Making Impossible Optics Possible.

Optoelectronics & Lightwave Engineering Group (OLEG @ NCSU)

POLARIZATION GRATINGS

Polarization Gratings Act Differently



$$I(\pm 1) = \frac{1}{2}\left(S_0 \mp S_3\right)\sin^2\left(\frac{\pi \Delta n d}{\lambda}\right)$$

Polarization Gratings (narrowband)

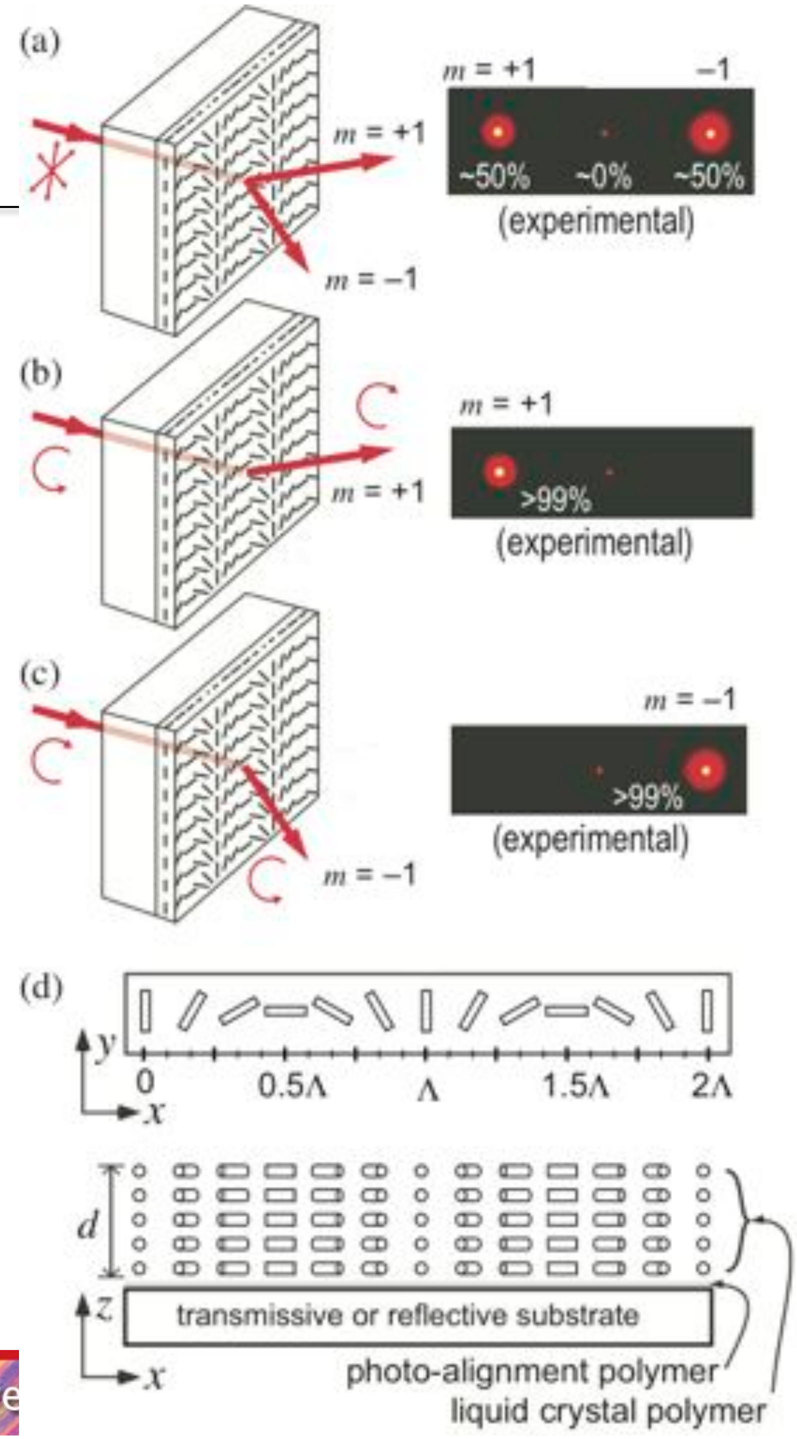
Features:

- Periodic Optical Axis formed in LCs
- Affects the Geometric Phase
  (not conventional phase or Bragg)
- Polarizing Beam Splitter
  (with excellent LCP/RCP)

Theory Predicts, Exp Confirmed:

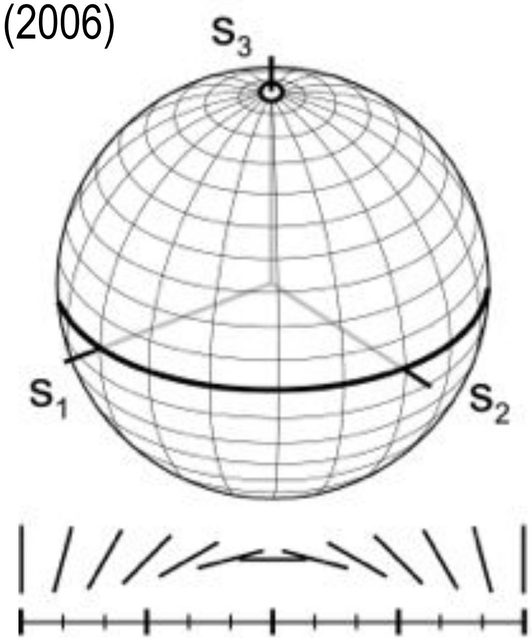
- 100% single-order diffraction
- Polarization-sensitive 1st orders
- ~ 1000 lines/mm and smaller
- Wide wavelength tuning (UV to MIR)

→ A novel diffractive element, with the best of "thick" and "thin" gratings.



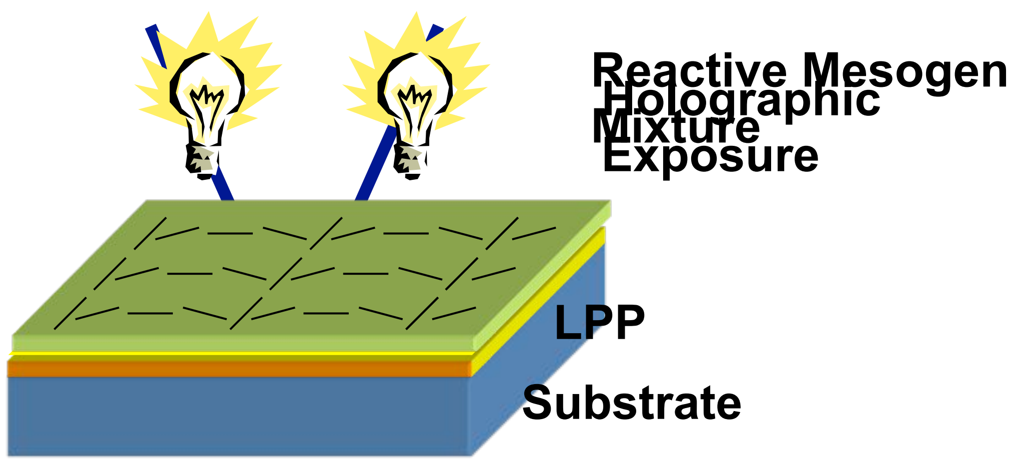
Holographic Polarization Gratings in LPP and LCs

Eakin et al., *Applied Physics Letters* **85** (2004)
Jones and Escuti, *SID Digest* **37**, 1443 (2006)



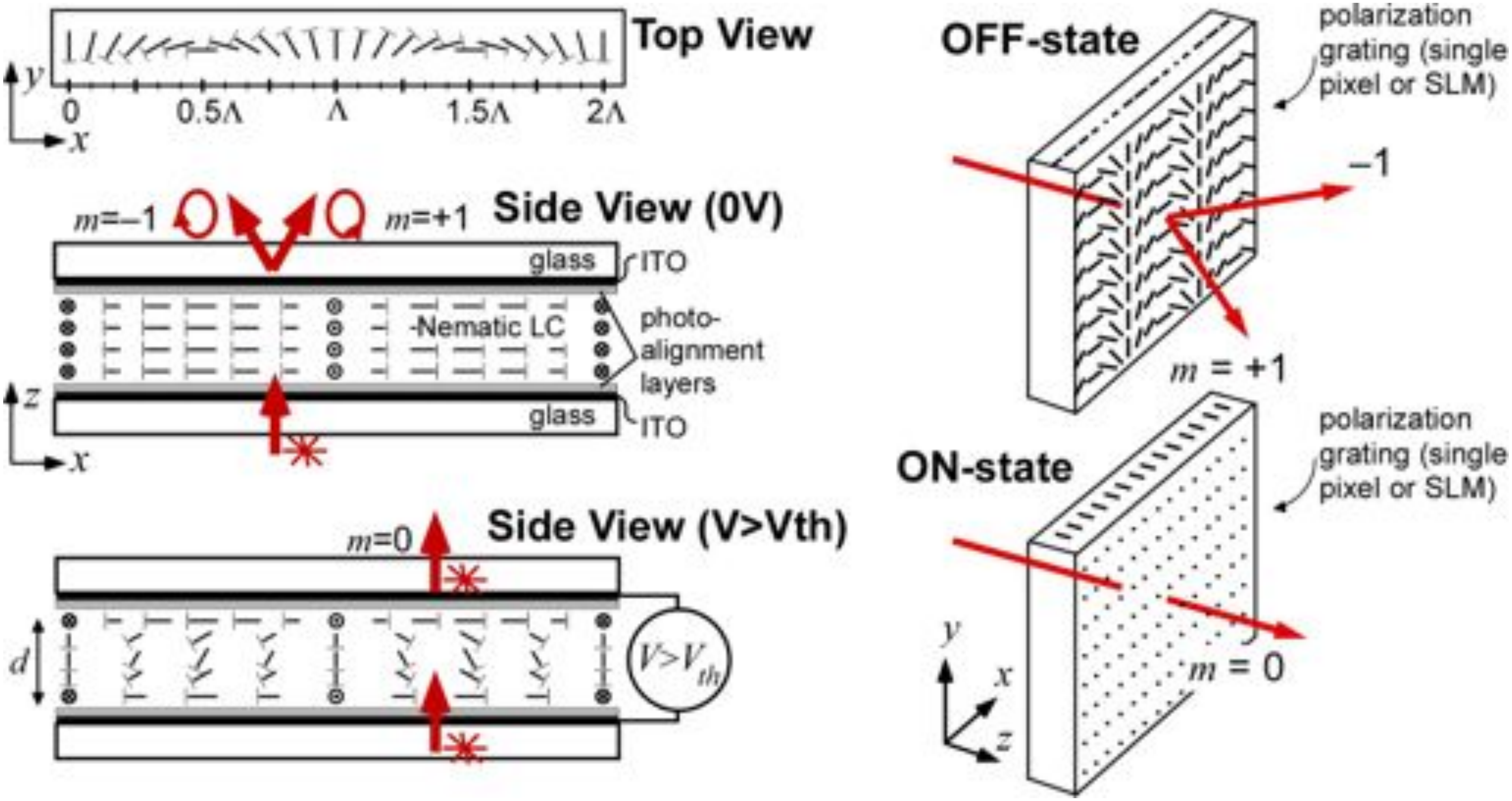
Basic Procedure

- Record Linear Polarization Grating onto Photo-Alignment Layer (e.g. Rolic LPP)
- Coat with liquid crystal monomer mixture (e.g. C3M + photoinits + surfactant + etc.)
- Polymerize



(also) Switchable LC PGs

$$\mathbf{n}(x) = [\sin(\pi x/\Lambda) \quad \cos(\pi x/\Lambda) \quad 0]$$



Properties of PG (narrowband)

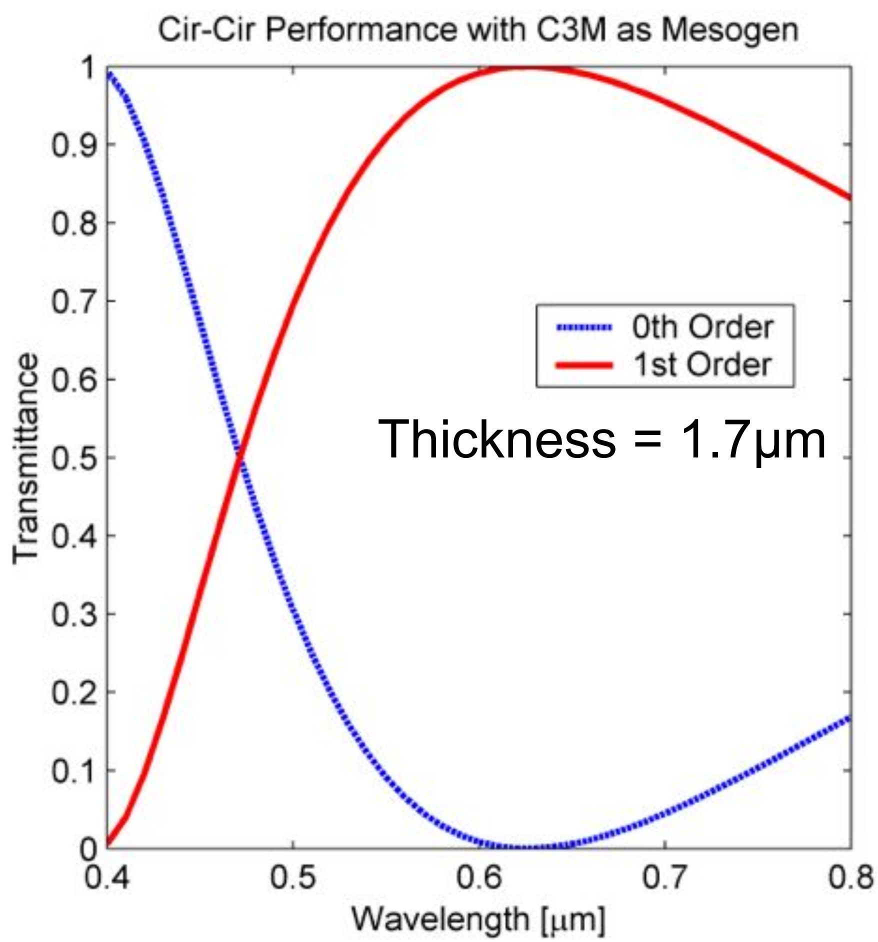
- For RCP/LCP:

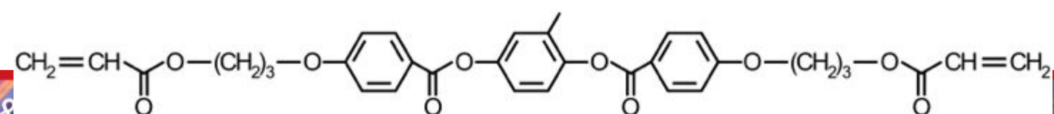
$$\eta_{\pm 1} = \sin^2\left(\frac{\pi \Delta n L}{\lambda}\right)$$

- Calculated using C3M as mesogen

$$\Delta n(\lambda) = 0.1528 + \left(0.111/\lambda\right)^2$$

=> First maximum occurs at relatively thin layers

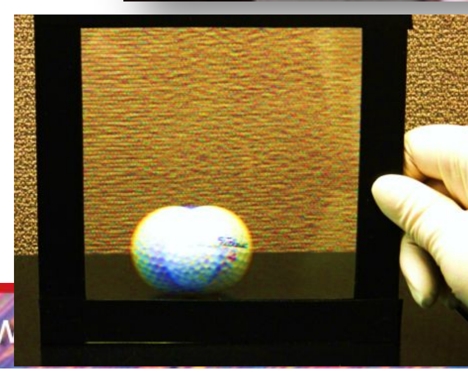


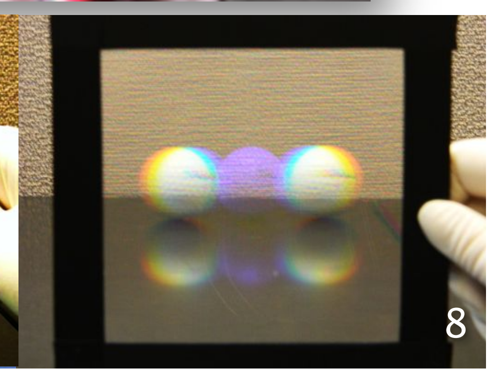


Large Area PGs

Miskiewicz, Escuti, et al., *Proc SPIE* **8395** (2012)

- Initial results, (ImagineOptix projects)
- 13 cm x 13 cm aperture
- ~6 µm period, ±0.01 µm
- Fabricated both VIS & NIR
- Wavefront typically better than lambda/30 (RMS, @ 633nm) across aperture
- Scales to 20 cm diameter





A kind of holography…

CREATING THE PATTERN

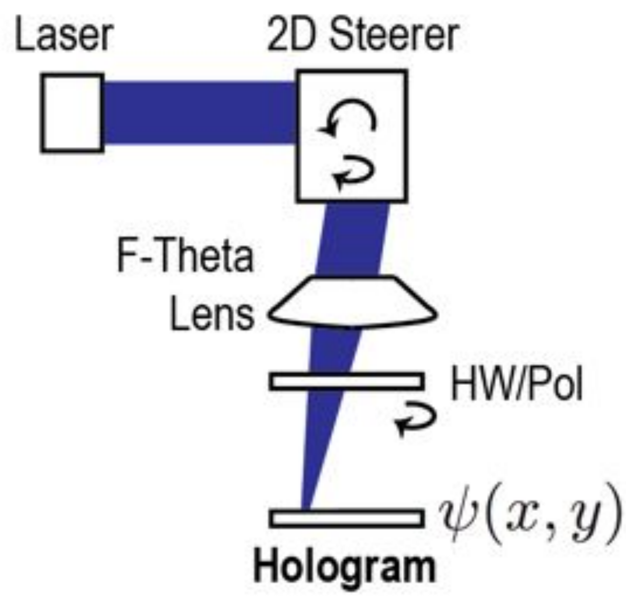
Fabrication Approach 1 (Interference)

- Many holographic methods are well known in prior art, some better than others

Fabrication Approach 2 (scanning)

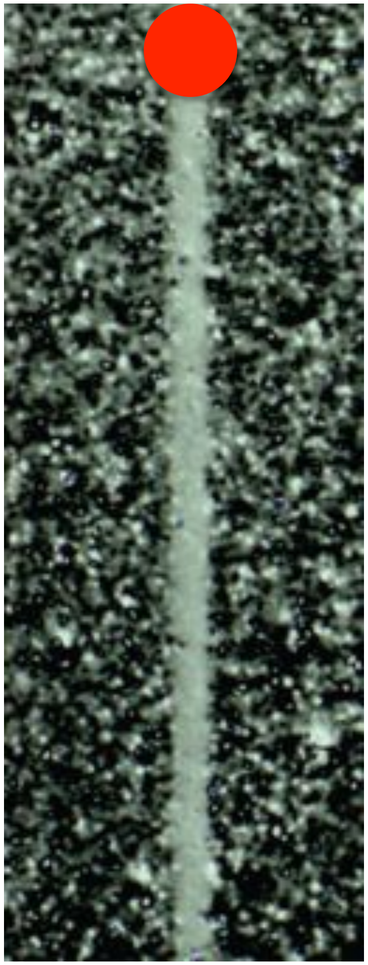
- System for CGH recording
- 325 nm UV laser
- Degrees of freedom
  - XY Translation
  - Polarization Angle
  - Power
  - Beam size

- LPP can be exposed multiple times
  - Different polarizations
  - Different fluences
- LC response is non-trivial
- Prior modeling is inadequate

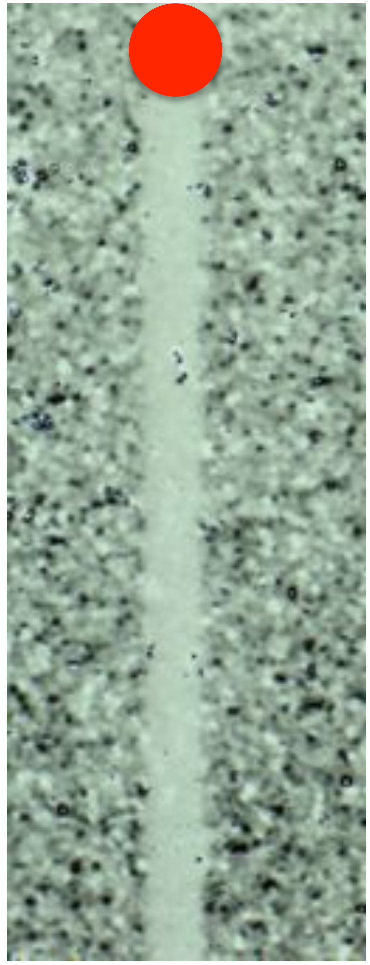


[1] M. N. Miskiewicz and M. J. Escuti. Direct-Writing of Complex Liquid Crystal Patterns. Opt. Express. 2014. (in press)

Scanning Position



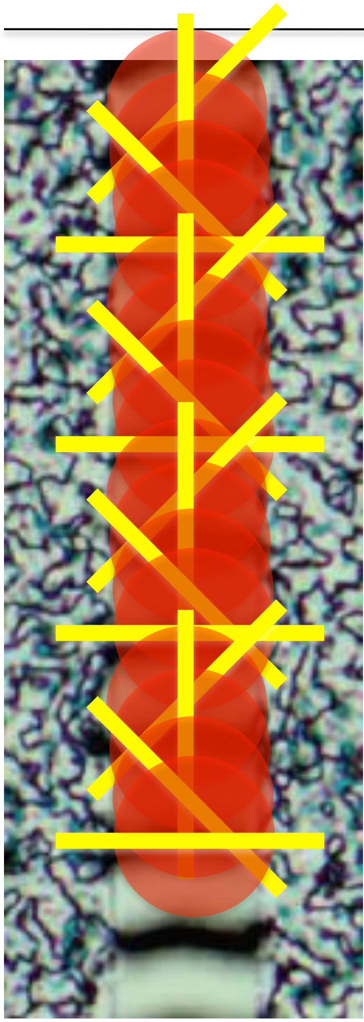
Faster =
Lower Fluence



Slower =
Higher Fluence

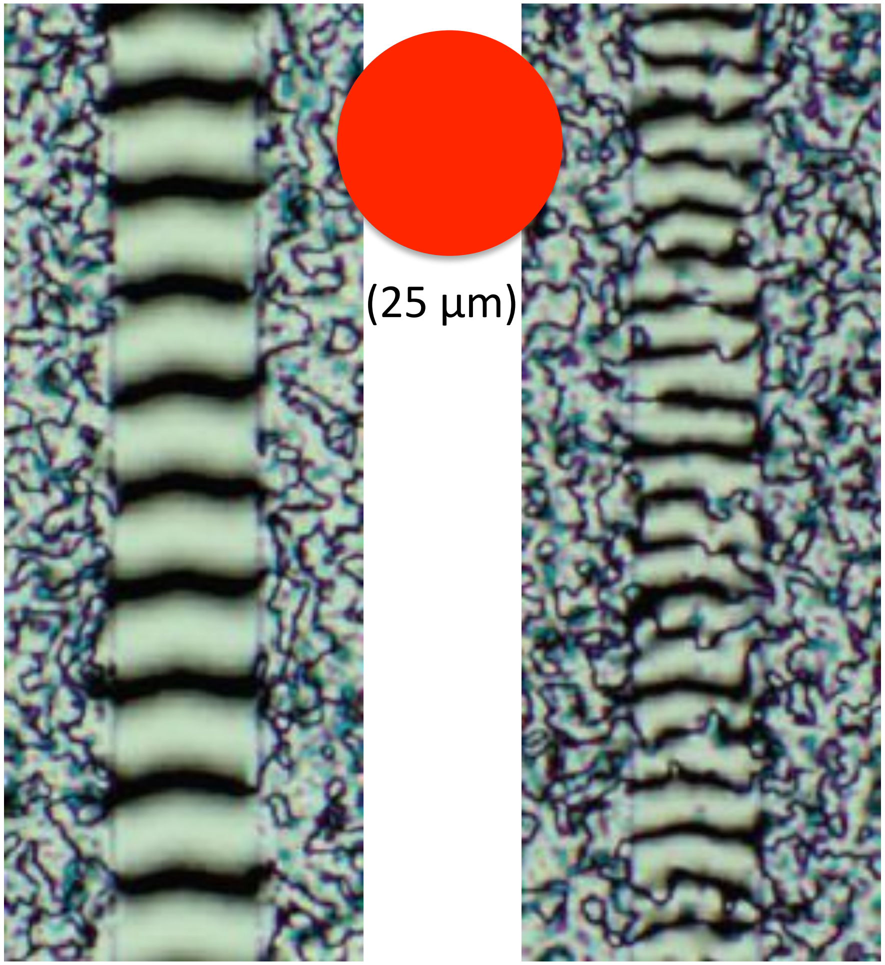
- Constant speed within scan
- Vary from line to line
- (here)
  Straight lines, vertical & horizontal

Scanning both Position & Polarization



- Steady velocity
- Steady rotation

Scanning both Position & Polarization

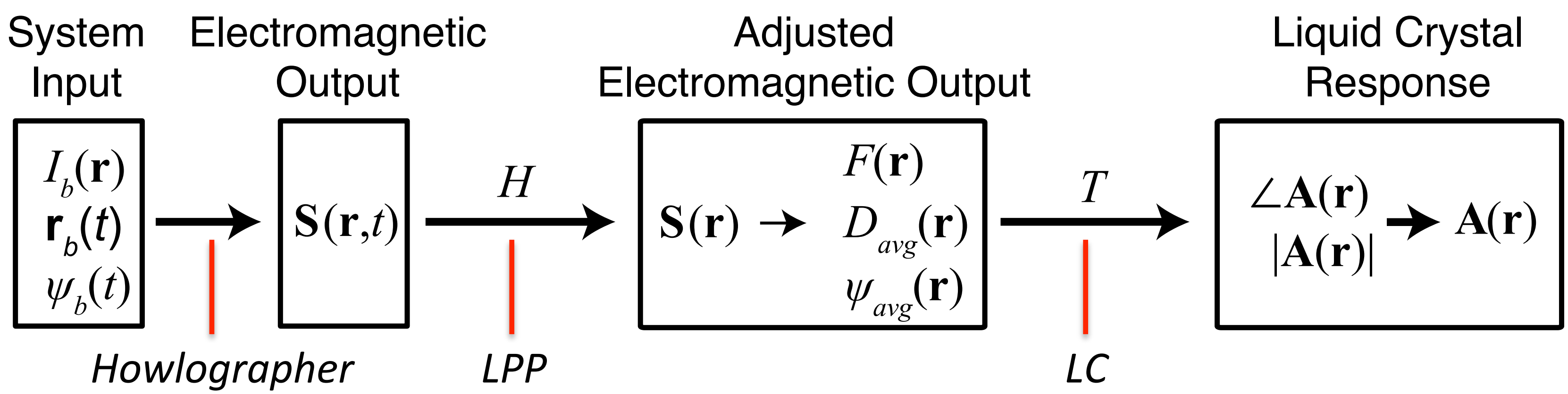


Slower Rotation
= **Larger** Period

Faster Rotation
= **Smaller** Period

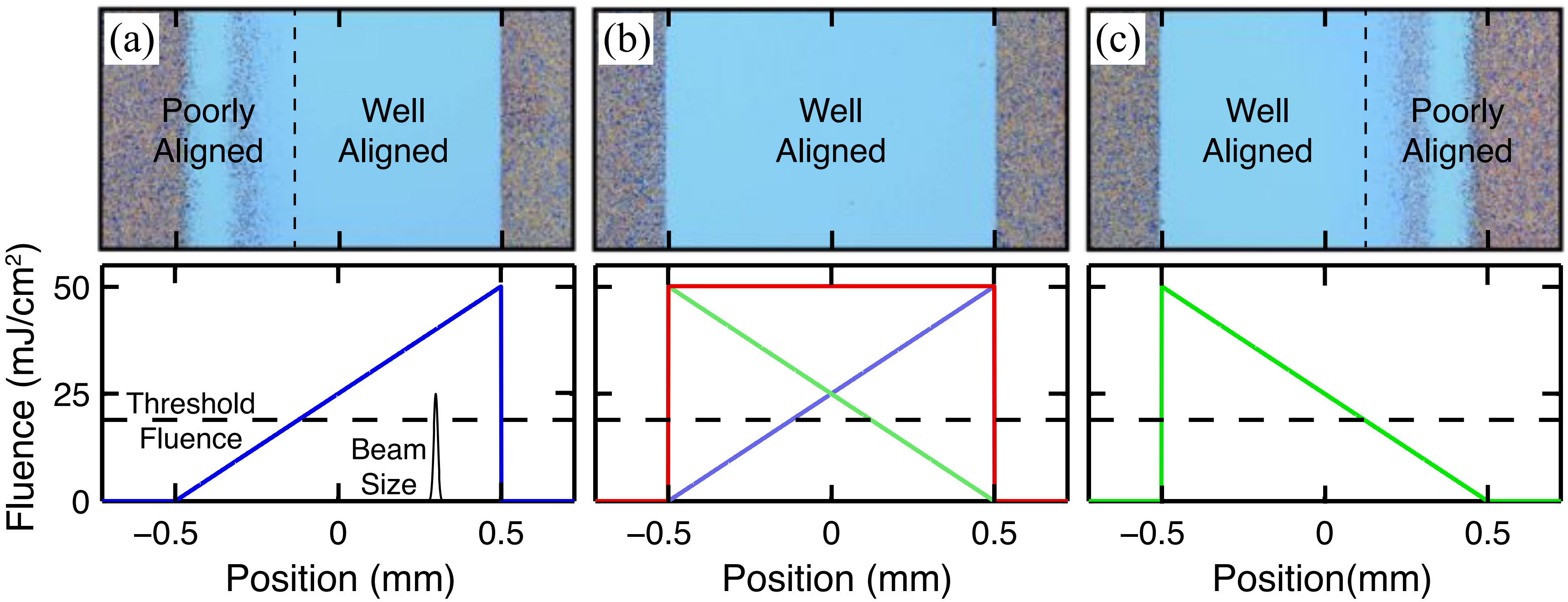
- Varied ratio of speed : rotation
- (here)
  Straight lines
- Minimum period before defects

System Description

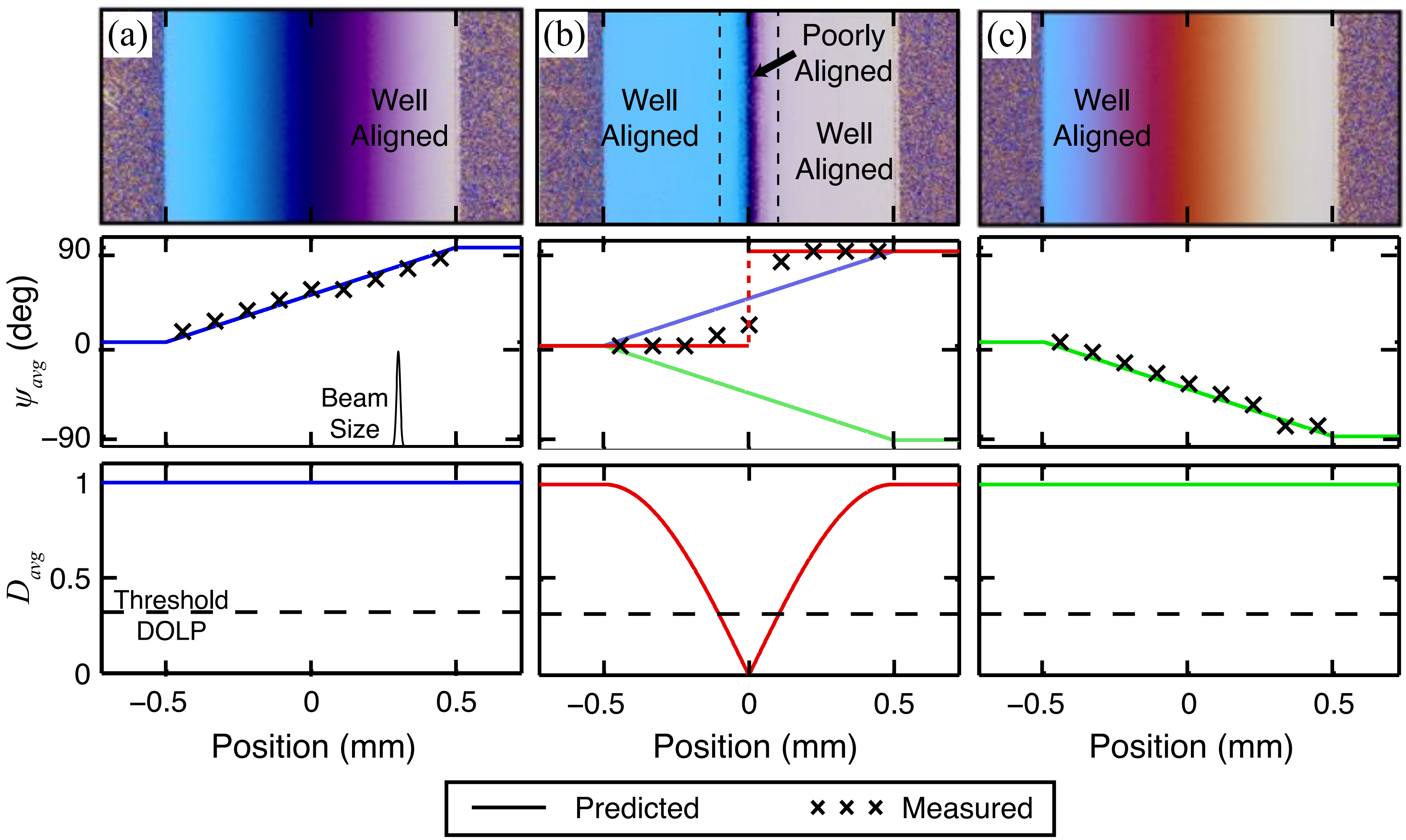


- LC aligns to fluence-weighted average polarization angle
- LC aligns well only if the fluence and DOLP are high enough

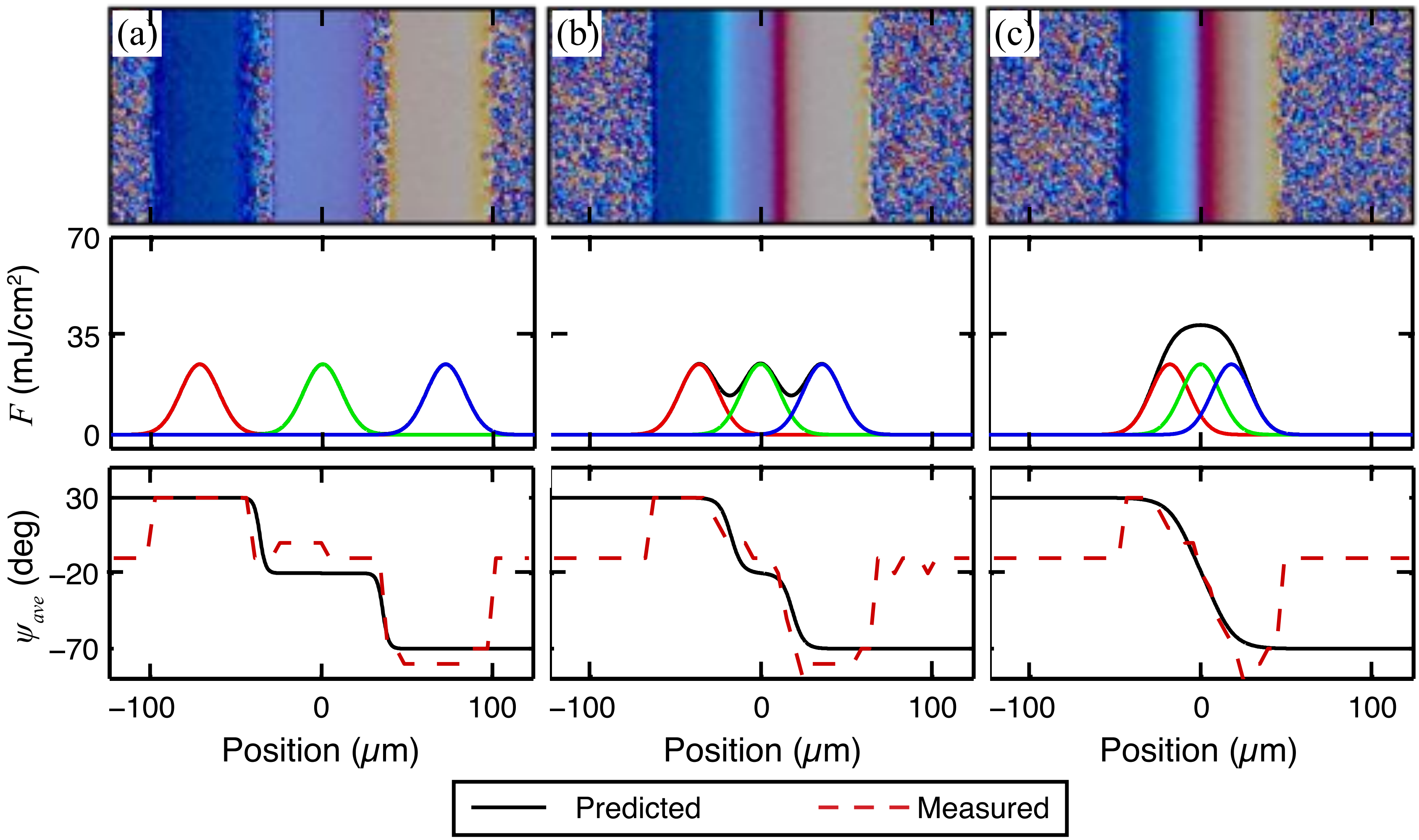
Fluence Dependence



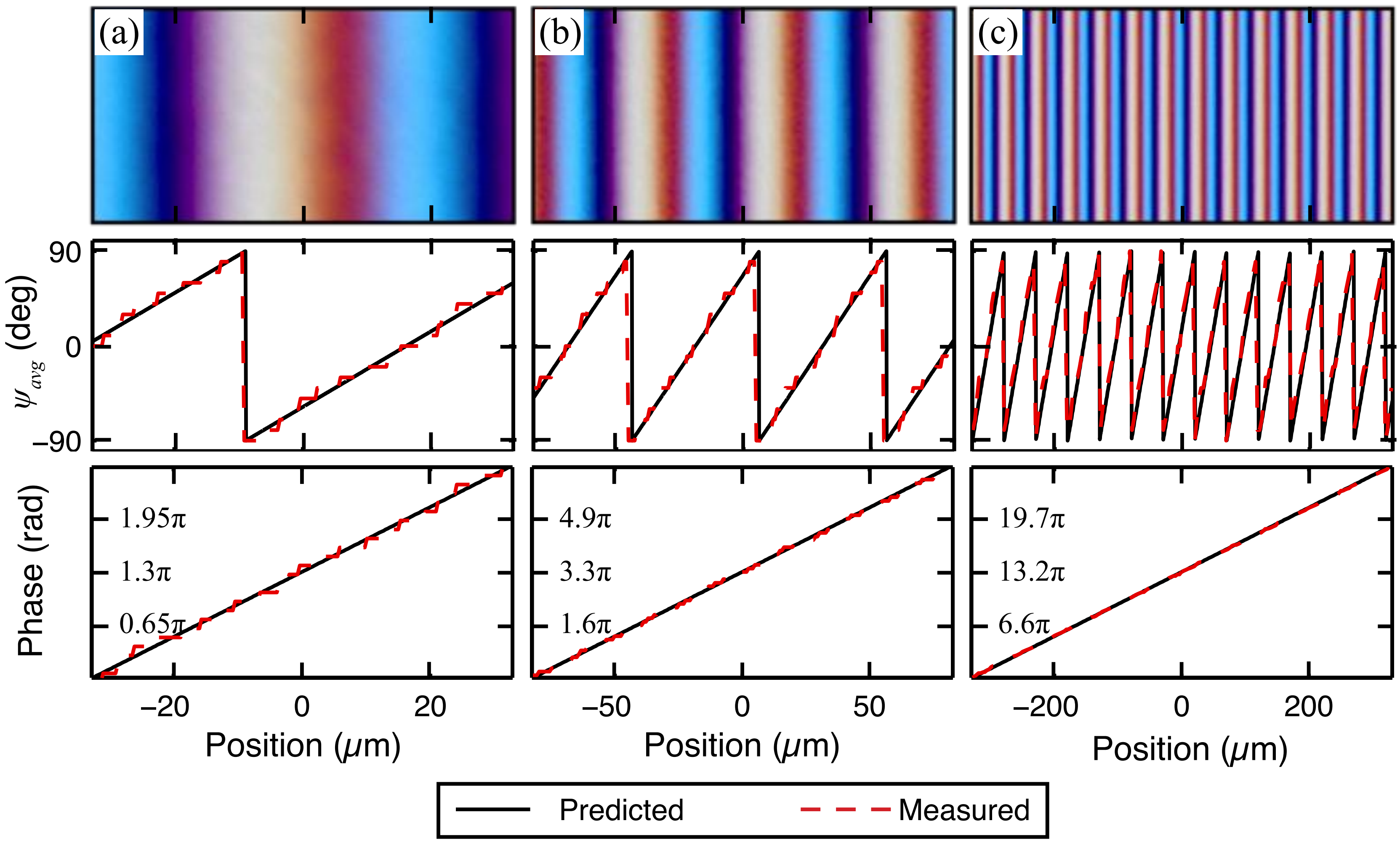
Orientation Averaging (i.e., DOLP)



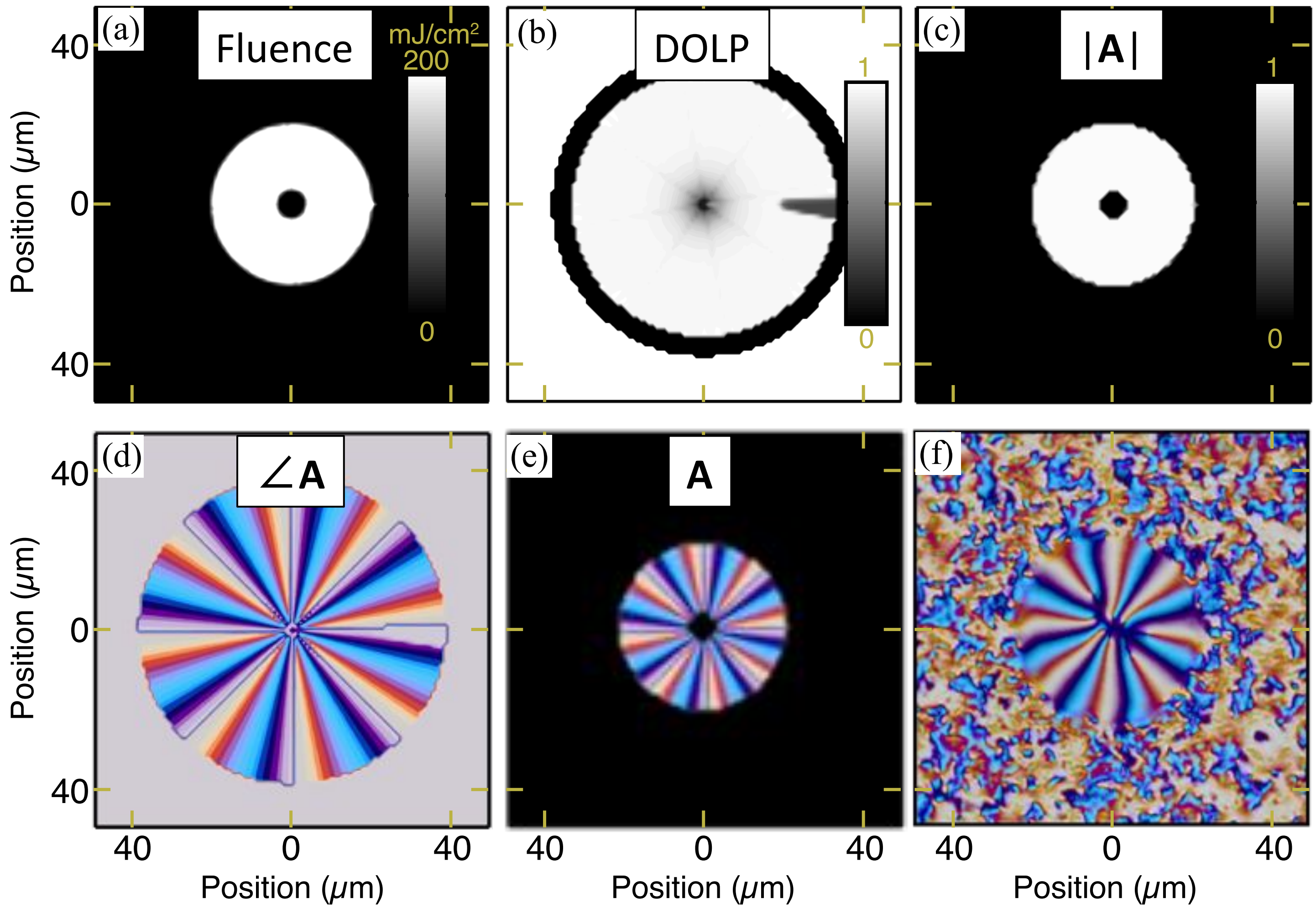
Smooth Profiles, Sub-Beam Features!



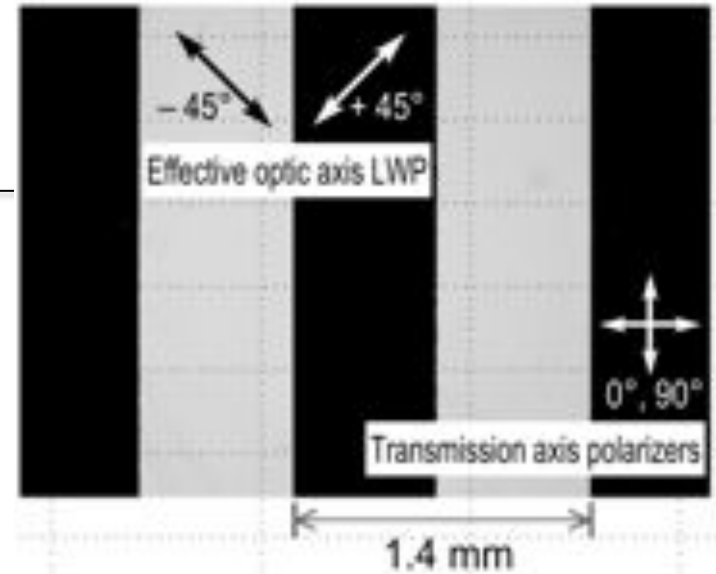
Ideal Polarization Grating Profile



Optimization for *q*-plate (q=4)



Capabilities



- Spatial resolution:
  - Accuracy: 10 nm (?) across 200 mm
- Phase slope:
  - ~0.5 wave/µm
- Discrete boundaries:
  - Down to 1 µm

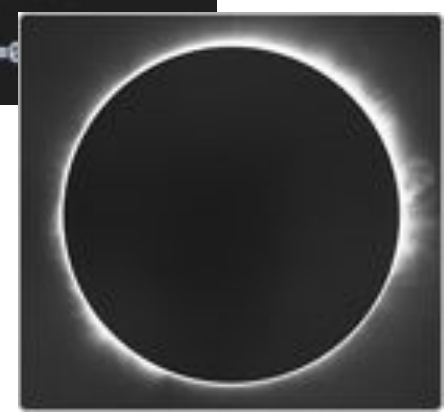
X pol

|| pol

[1] M. N. Miskiewicz and M. J. Escuti. Direct-Writing of Complex Liquid Crystal Patterns. Opt. Express. 2014. (in press)

Coronagraph Telescopes

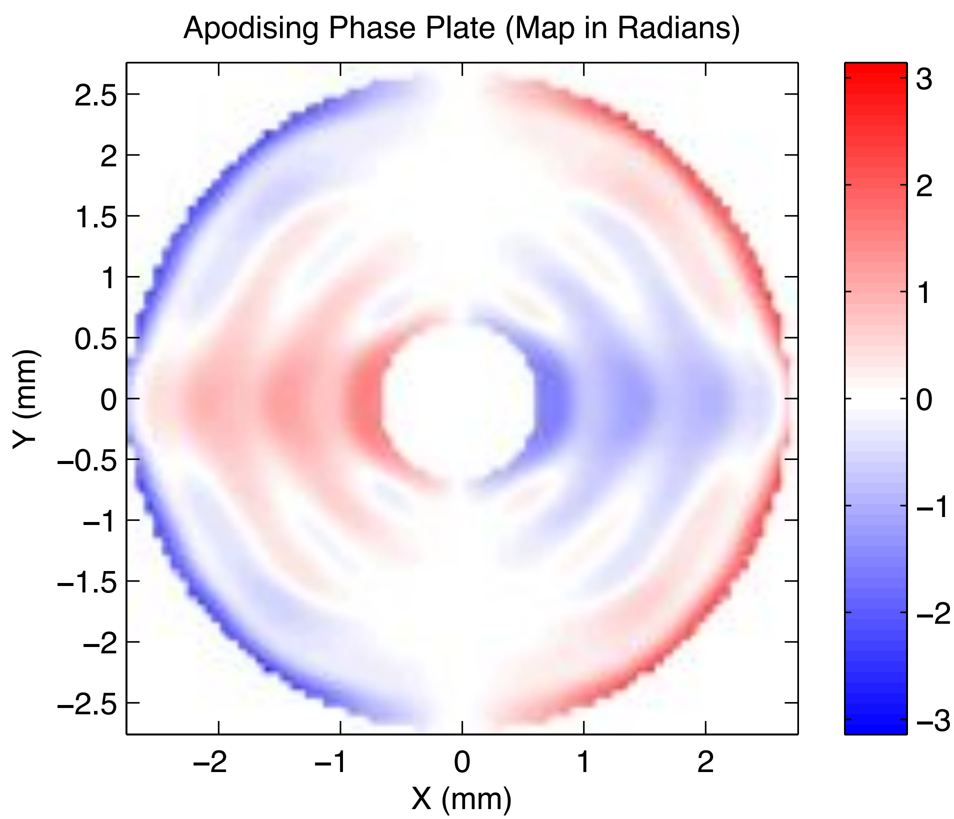
- Instrument to block light from bright star while resolving objects nearby
- Key for studying:
  - our Sun's corona
  - comets
  - **exo-planets**



Images from wikipedia.com and nikon.com

More generally: Apodizing Phase Plate

Snik, Escuti et al., *SPIE Proc* **8450** (2012)



For Finding Exo-Planets (U Leiden)

Snik, et al., *SPIE Proc* **8450** (2012)

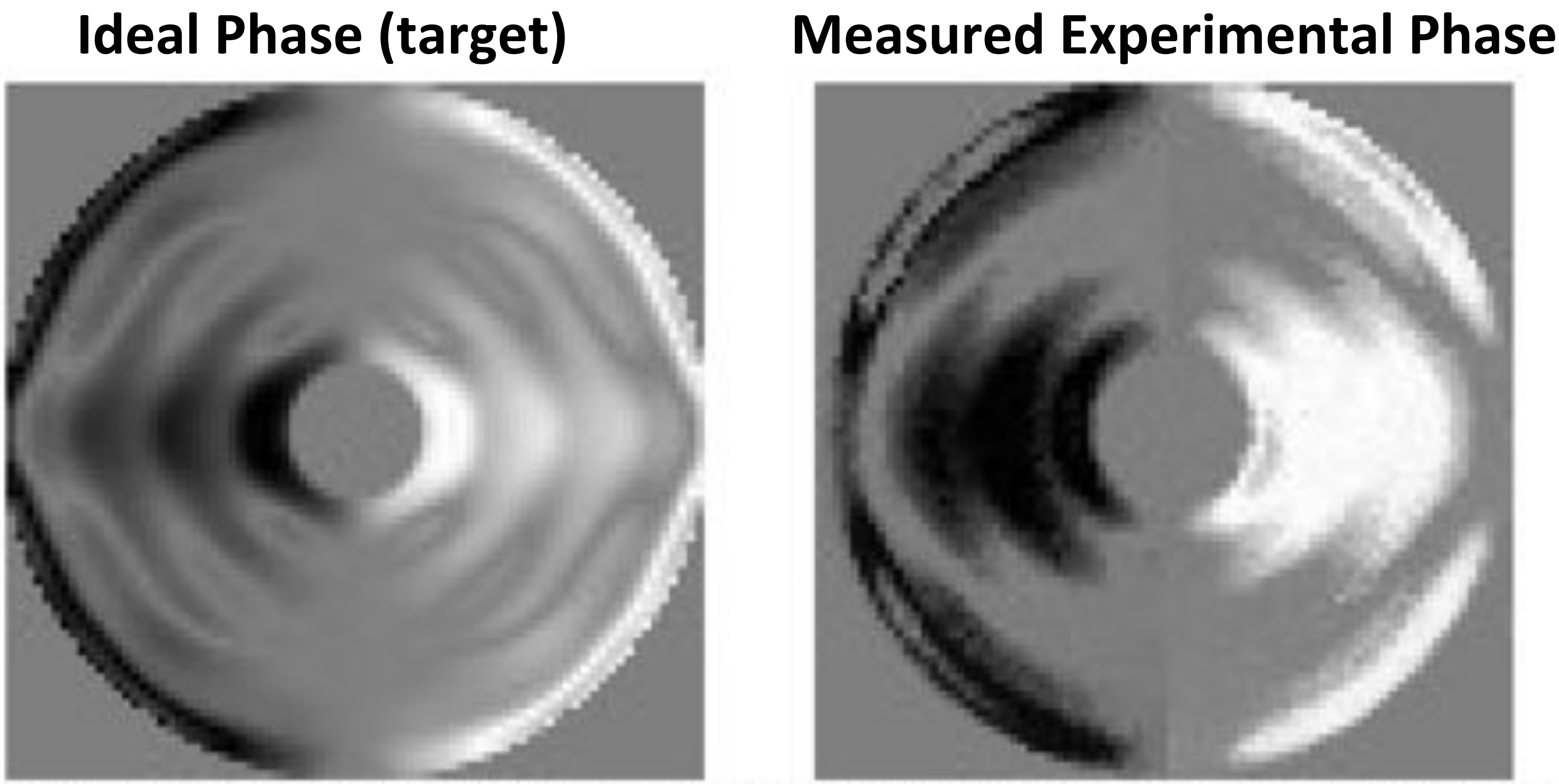
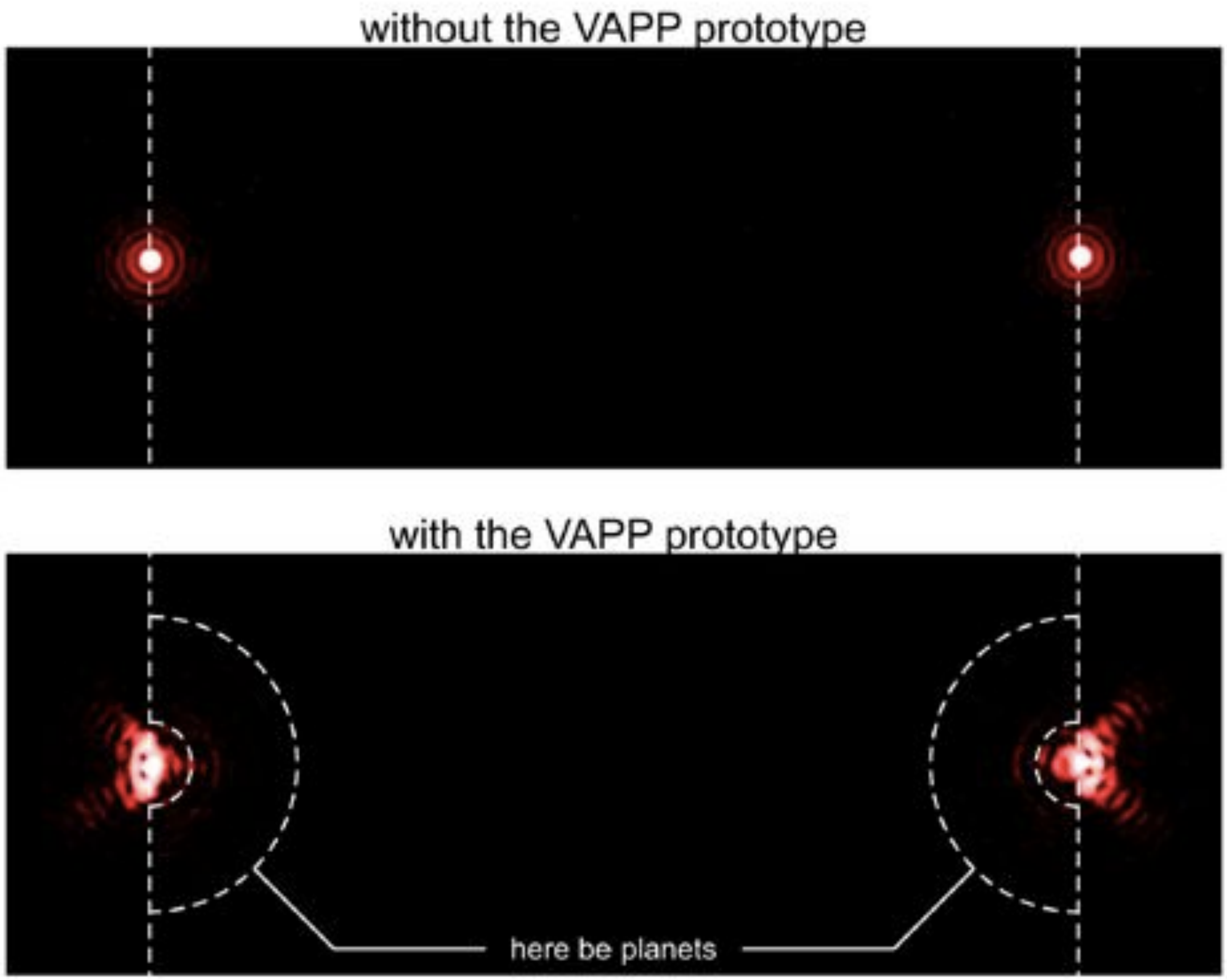


Figure 4. a) Ideal APP phase pattern (including phase wrapping as in measurement). b) Measurement of the vector-APP prototype phase pattern.

Grayscale = Black (–π rad) to White (+π rad)

For Finding Exo-Planets (U Leiden)

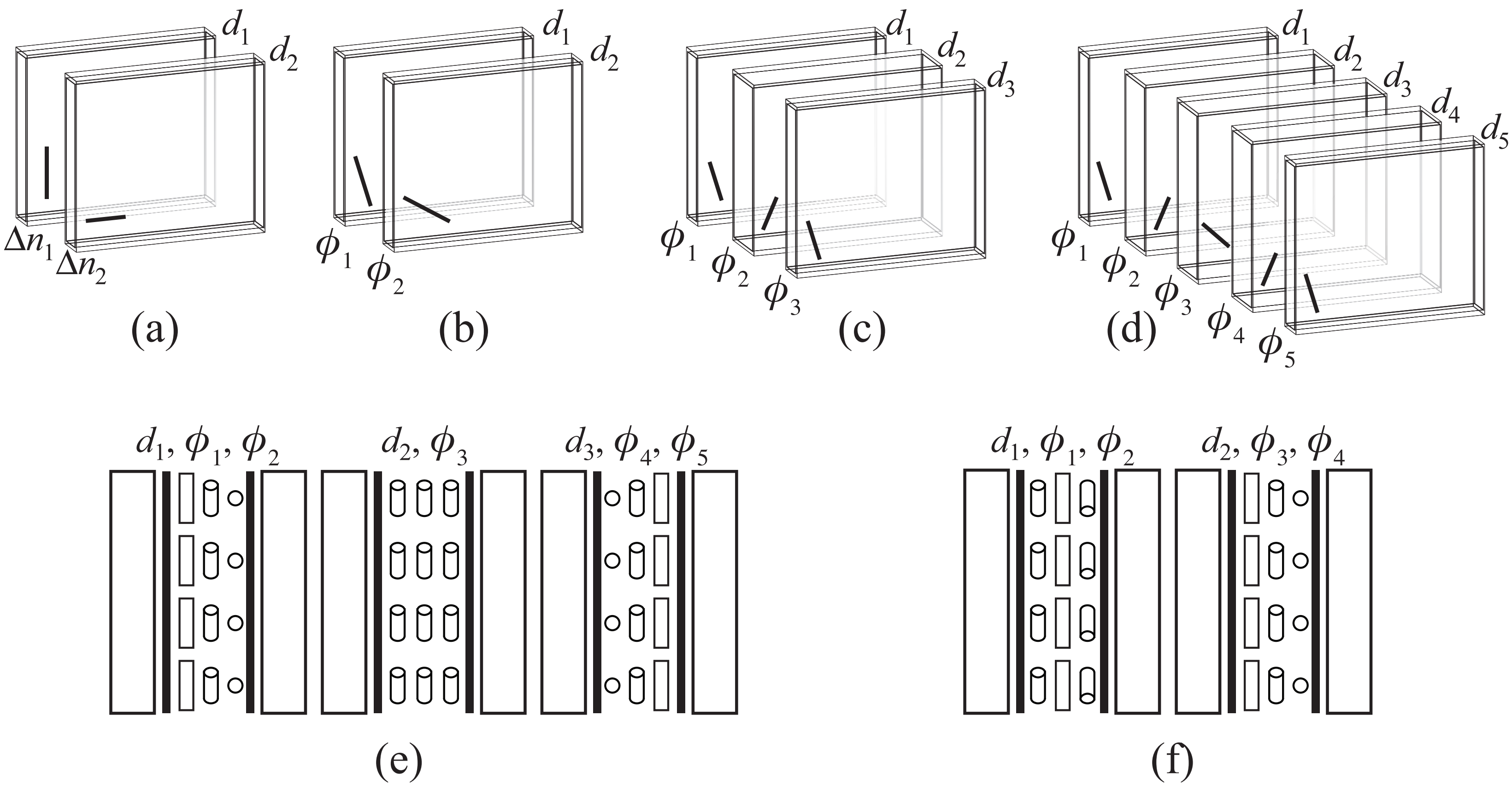
Snik, et al., *SPIE Proc* **8450** (2012)



Better retardation control

MULTI-TWIST RETARDERS
i.e., BETTER "WAVEPLATES"

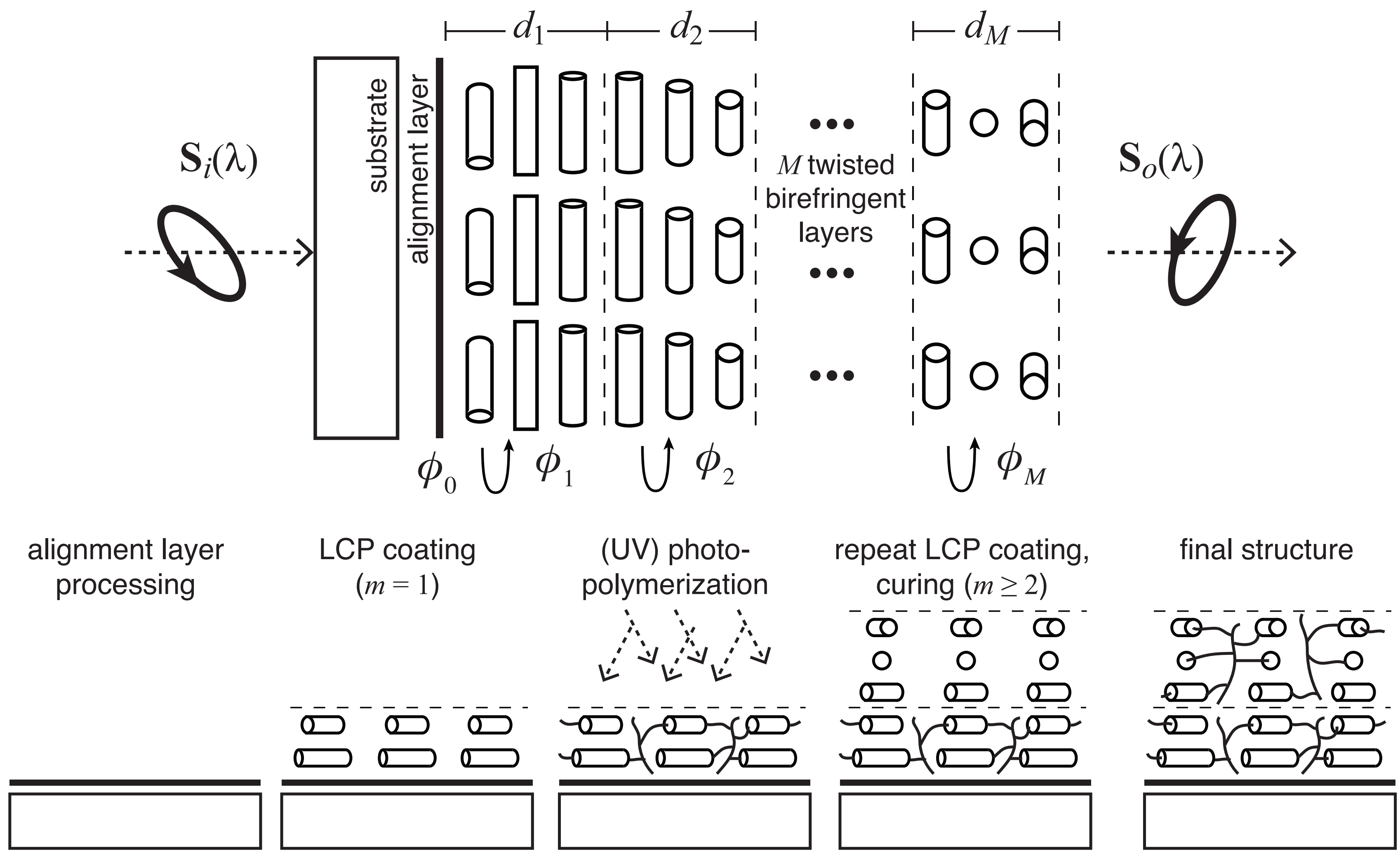
Prior Achromatic Retarders



- (a)-(d) multiple homogenous plates
- (e)-(f) multiple twisted LC plates, but each discrete

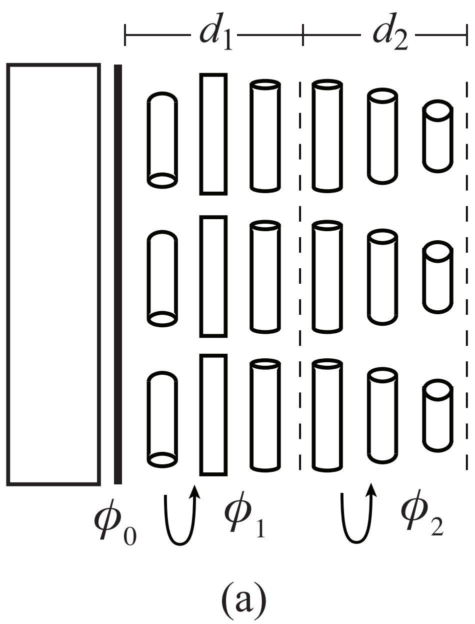
Multi-Twist Retarder (MTR) Concept

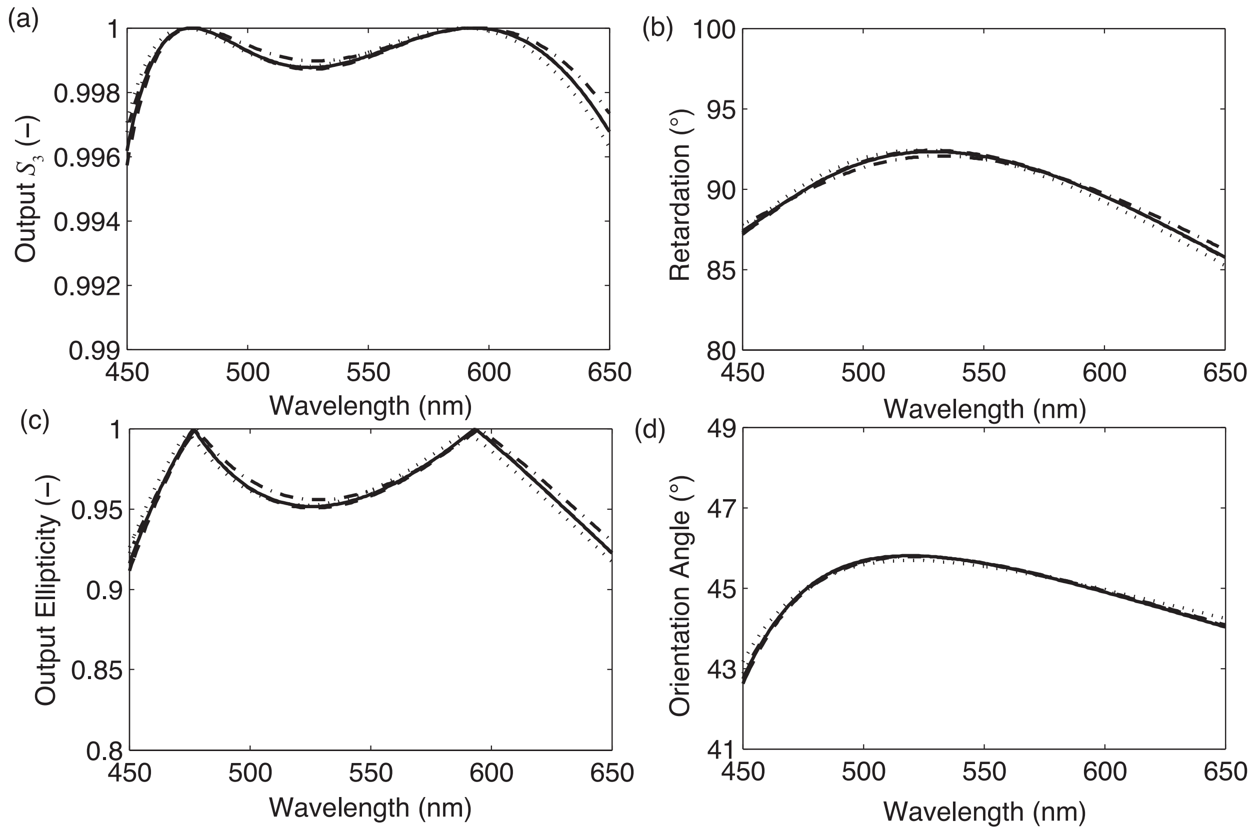
Komanduri, Escuti, et al., *Opt. Exp.* **21**, 404 (2013).



2TR Quarter-Wave

Komanduri, Escuti, et al., *Opt. Exp.* **21**, 404 (2013).

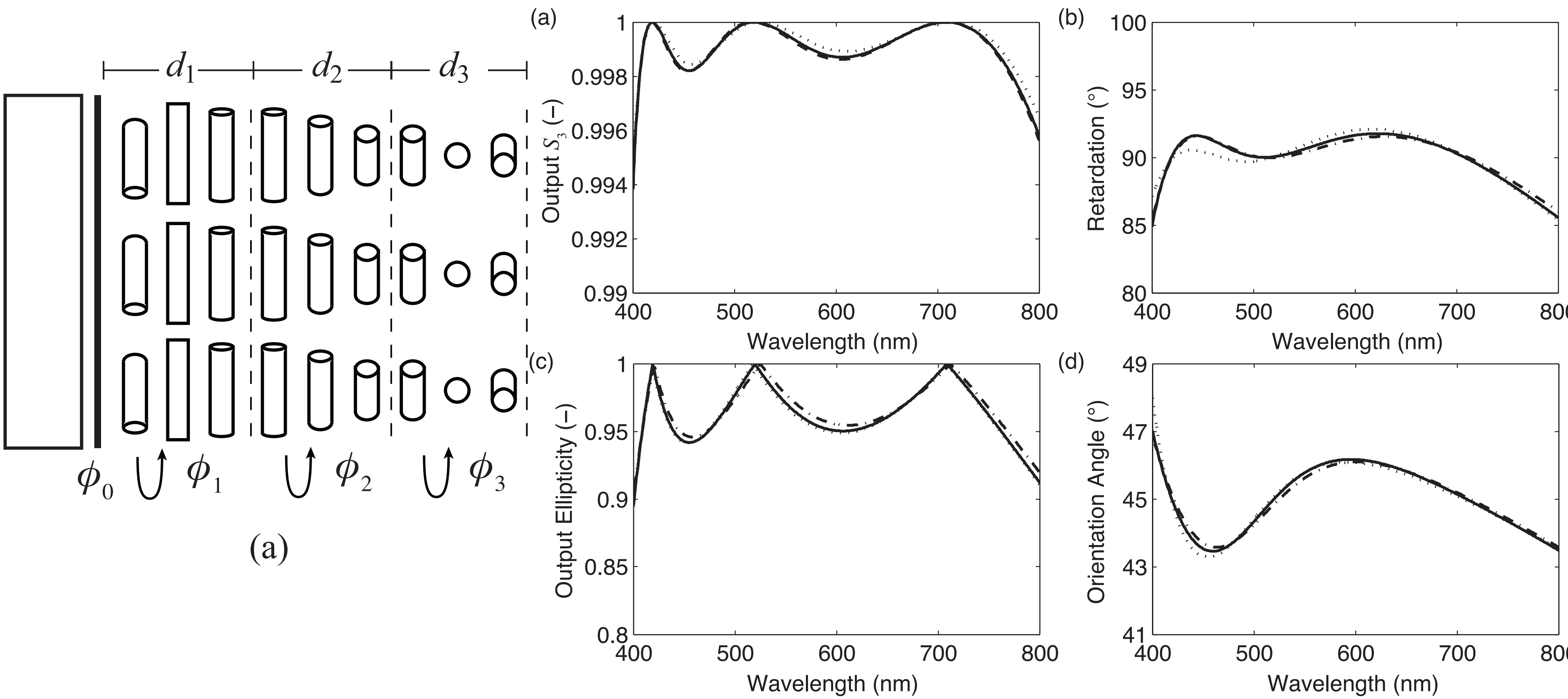




- E.g., covers RGB wavelengths
- Bandwidth of ~37% ($=\Delta\lambda/\lambda_0$)

3TR Quarter-Wave

Komanduri, Escuti, et al., *Opt. Exp.* **21**, 404 (2013).

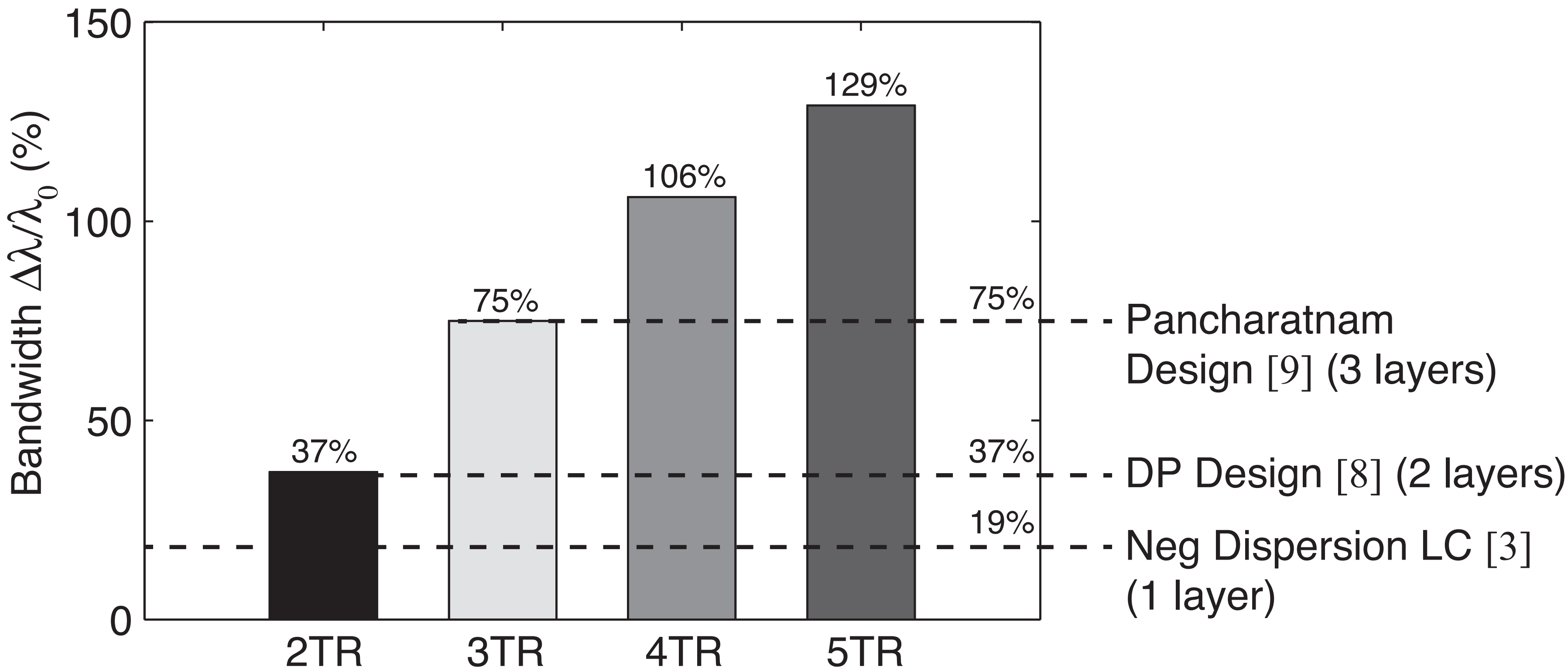


- E.g., covers full VIS wavelengths
- Bandwidth of ~75% (=$\Delta\lambda/\lambda_0$)

Achromatic Comparison

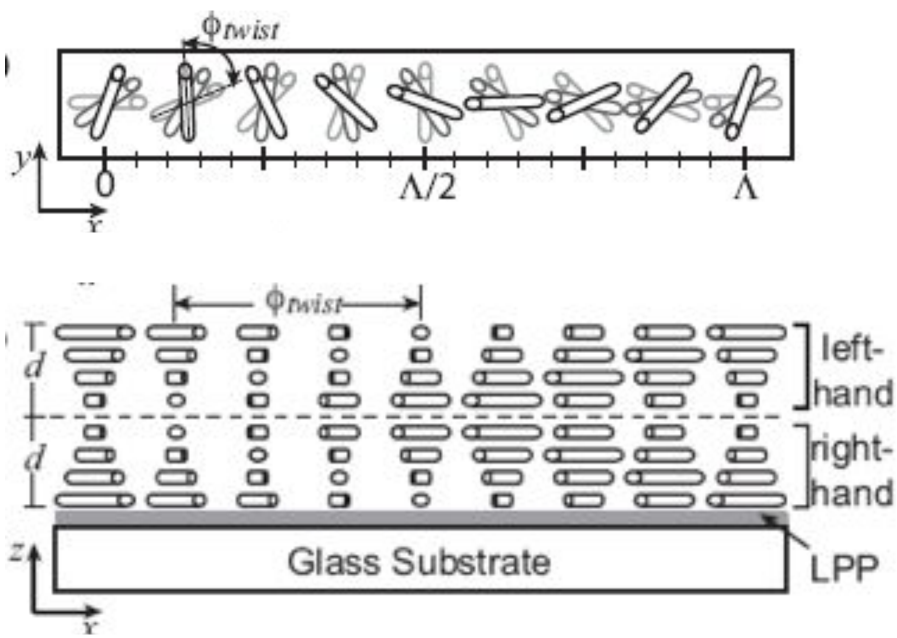
Komanduri, Escuti, et al., *Opt. Exp.* **21**, 404 (2013).

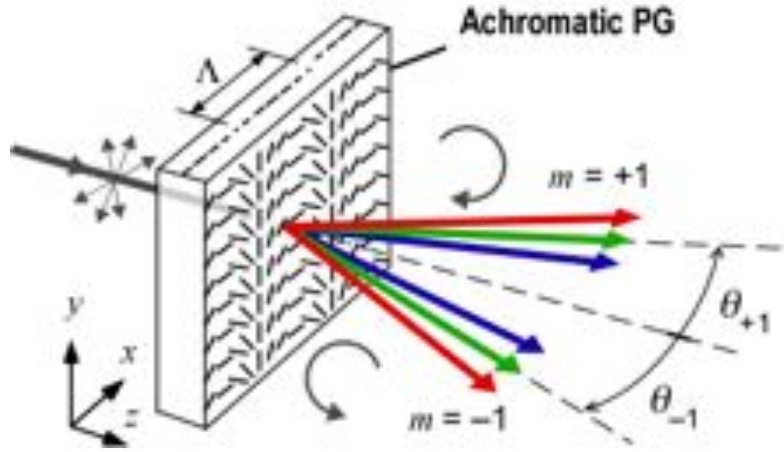
- VIS & IR achromatic QW and HW retarders, broader and/or precise than prior

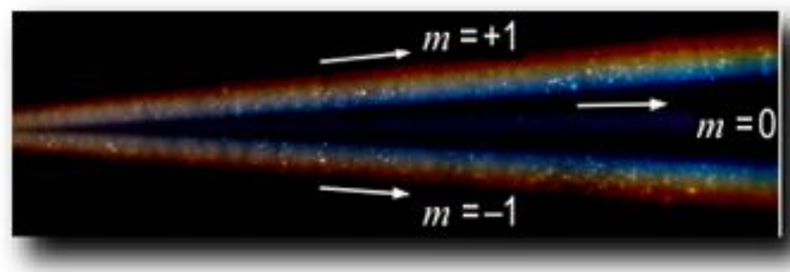


Polarization Gratings (broadband)

Oh and Escuti, *Opt Lett* **33**, 2287-2289 (2008).



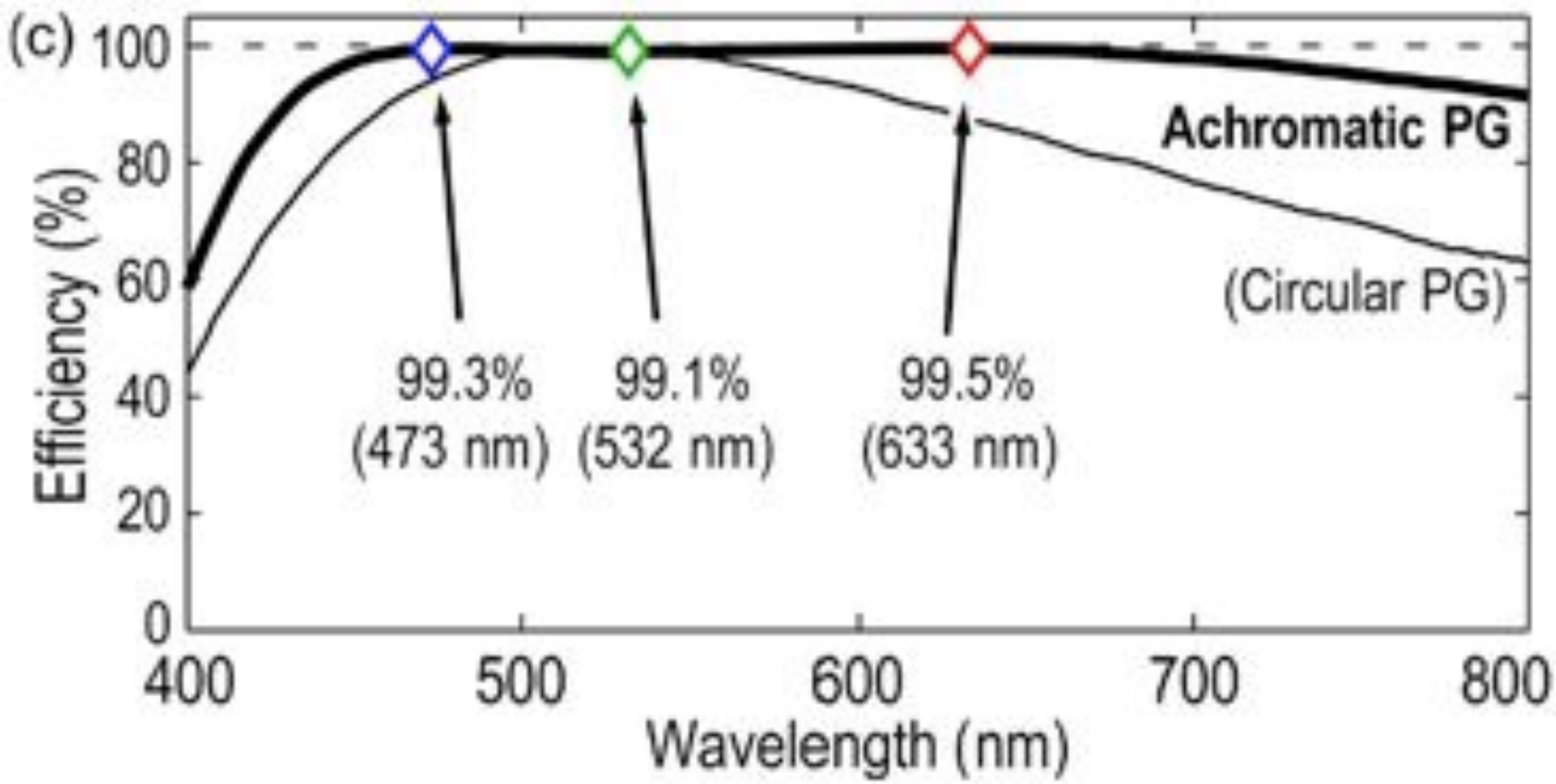




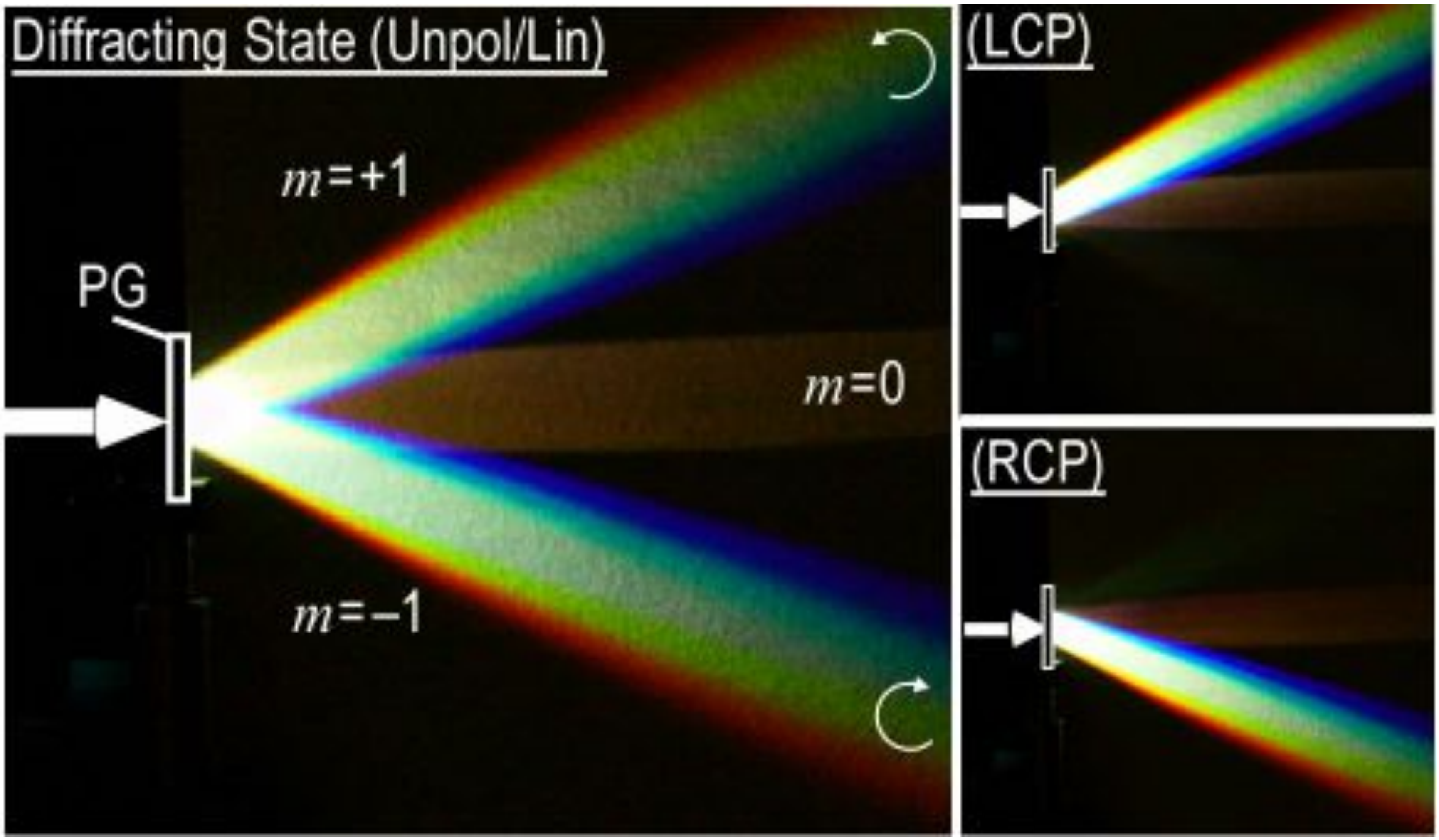
- Formed w/ reactive mesogens (RMs), forming liquid crystal polymer (LCP) film
- Completely distinct alignment mode (not Bragg or Raman-Nath grating)
- Functions as an extremely efficient, achromatic beam splitter
- 56% bandwidth (vs 13%)

PG (Broadband)

Oh and Escuti, *Opt Lett* **33**, 2287-2289 (2008).

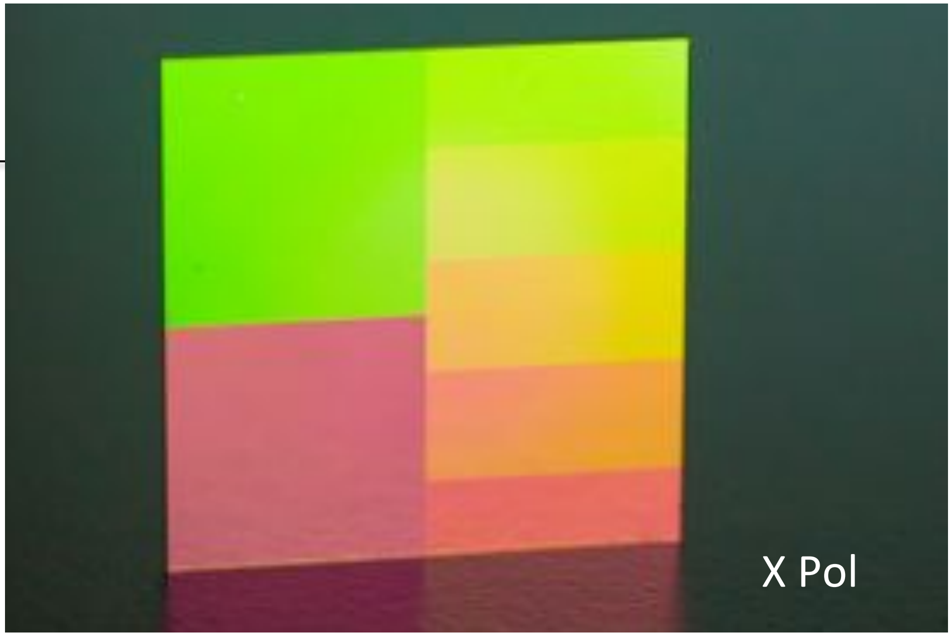


PG (broadband)



Chromatic MTRs

- Opposite of achromatic → Highly chromatic retardation
- Single substrate & alignment step
- Multiple layers of liquid crystals, self aligning

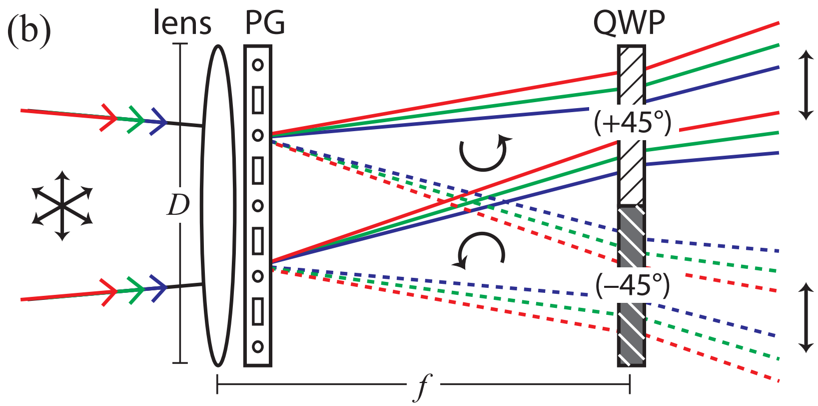


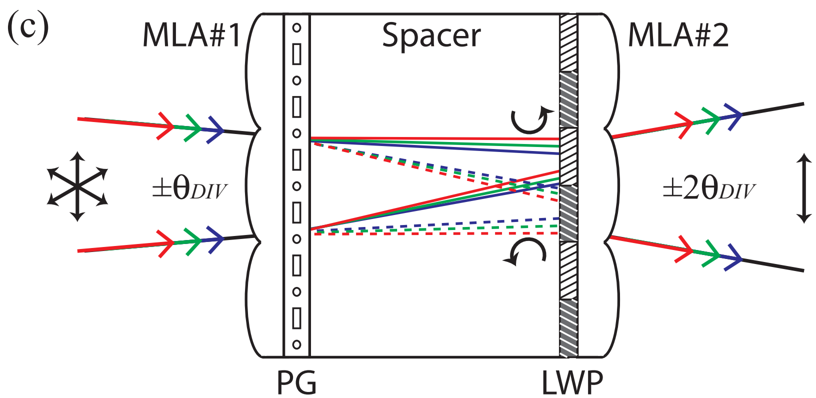
Convert unpolarized light to polarized w/ ~90% throughput (single pass)

3RD "GOOD IDEA"
POLARIZATION CONVERSION SYSTEM

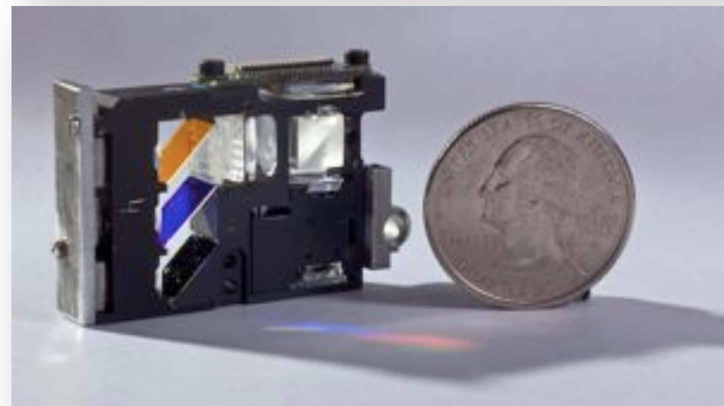
PG-PCS (90% eff)

Kim, Escuti, et al., *Appl. Opt.* **51** (2012)

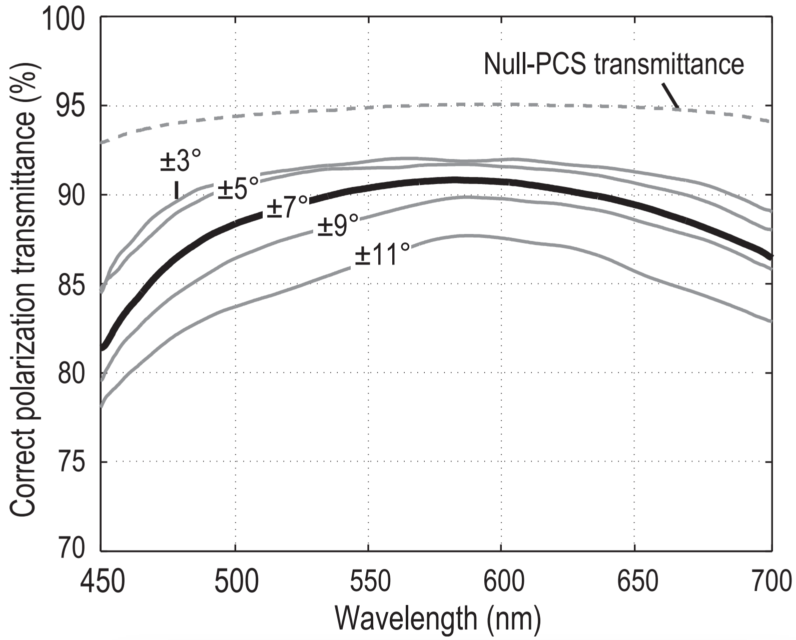


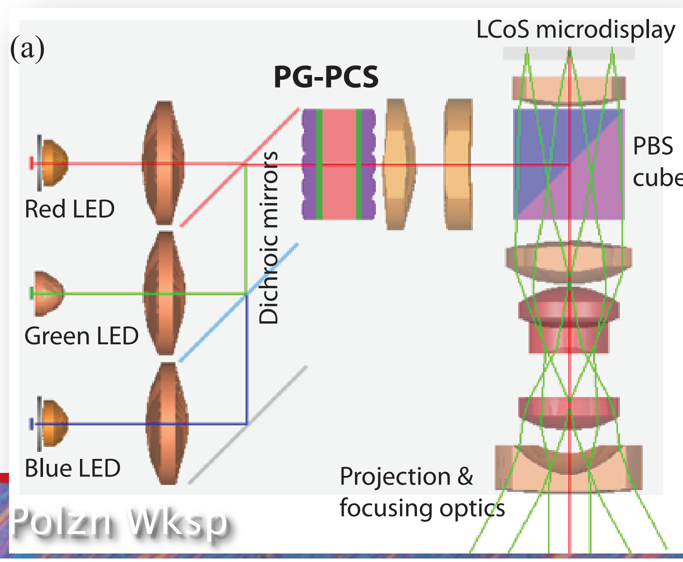


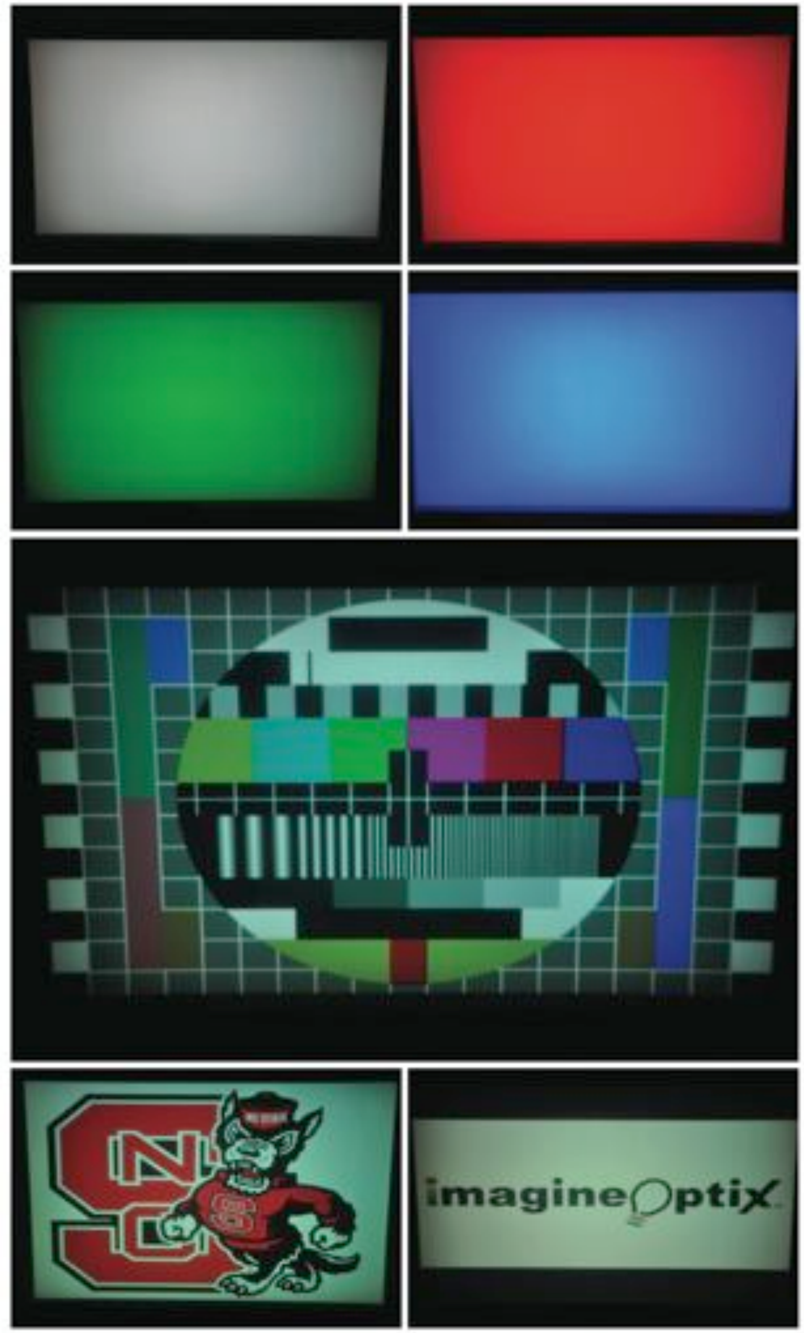
- ~ 90% (real) conversion from unpolarized to polarized @ f/1.8



Gen3 Pico-Projector (12 lm/W)







Summary

- <u>Arbitrary</u> LPP, LC alignment capability (down to few μm)!

- Follow-up and access to parts:
  - North Carolina State University (me)
  - And imagineOptix™

- Key Technology Features:
  - Arbitrary wavefront control (phase)
  - “Full” spectral control
  - ~100% efficiency for most wavefronts of interest
  - Large area optics
  - Proximity lithography (copies from master)

Oct 2011 Presidential Early Career Award for Scientists & Engineers (PECASE)

— the highest honor from the US Gov't for young academic researchers

Citation: **Michael J. Escuti**, NC State University
For *pioneering research in innovative liquid-crystal polarization gratings* and strong dedication to the education of students through collaborations with international academic teams and industries, and for active outreach in underserved communities.

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Dr Michael Escuti (mjescuti@ncsu.edu)

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2011 PECASE award, and prior

imagineOptix
Making Impossible Optics Possible.

Optoelectronics & Lightwave Engineering Group (OLEG @ NCSU)