Imaging Liquid Crystal Polarimeters

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Outline

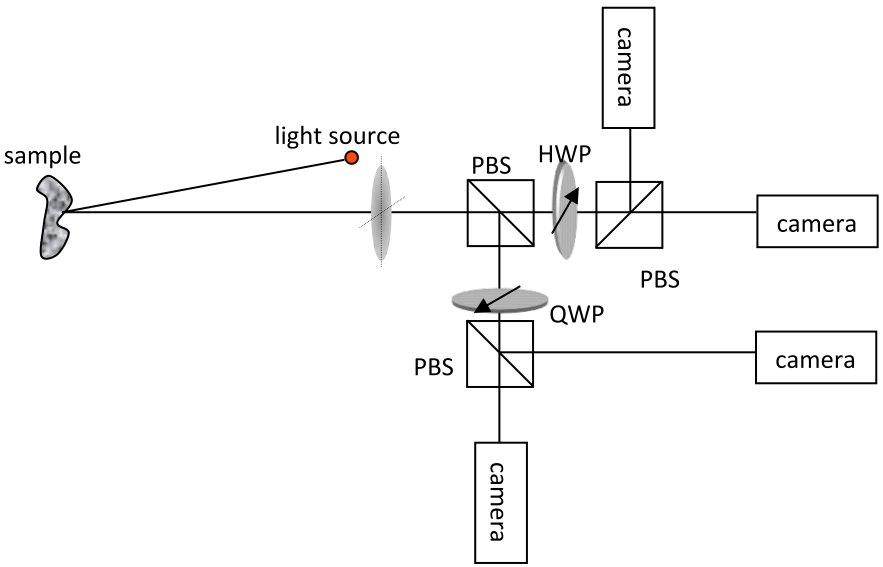
- Dynamic Imaging polarimeters:
  - State of the art
  - Liquid crystal polarimeters
- Our polarimeter:
  - Basic LC usage
  - Advanced LC usage
- Postprocessing ot time-multiplexed polarimetric images

Introduction

- Our aim:
  - Design a high-speed (faster than 200 fps) imaging Stokes polarimeter for the visible range
- State of the art
  - Most dynamic polarimeters are limited to a few tens of fps

Possible architectures

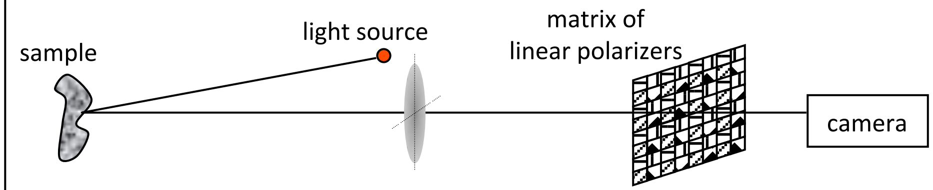
Division of amplitude



V.L. Gamiz, "Performance of a four channel polarimeter with low light level detection", SPIE **3121**, 35-46 (1997).

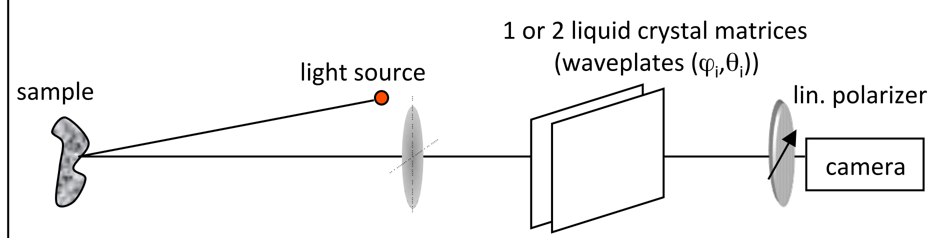
J. L. Pezzaniti *et al.*, "Four camera complete Stokes imaging polarimeter", SPIE **6972**, 69720J (2008).

Division of wavefront



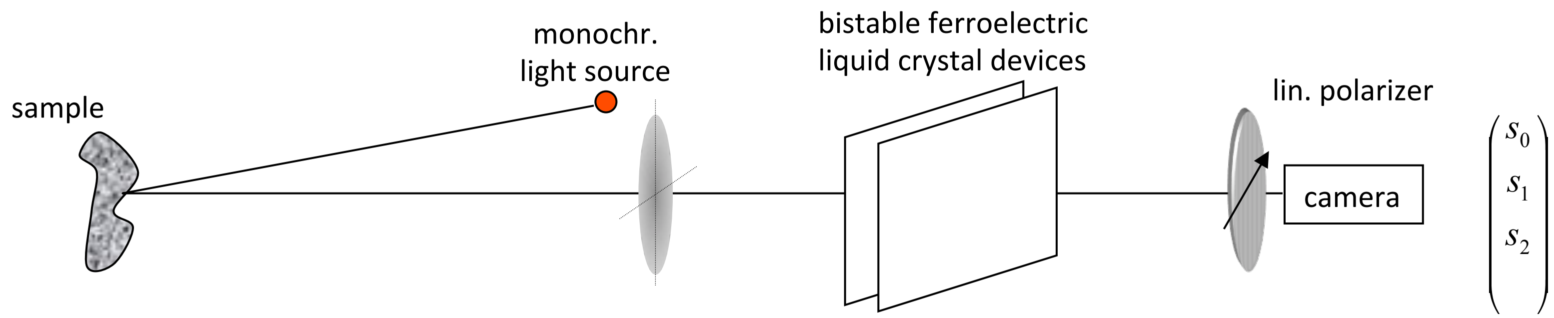
C.S.L. Chun *et al.,* "Polarization-sensitive infrared sensor ...", SPIE **3121**, 55-62 (1997).

Division of time



L.B. Wolff, T.A. Mancini, P. Pouliquen and A.G. Andreou, "Liquid crystal polarization camera", IEEE Trans. Rob. Autom. **13** (2), 195-203 (1997).

Temporal multiplexing with 2 FLC devices



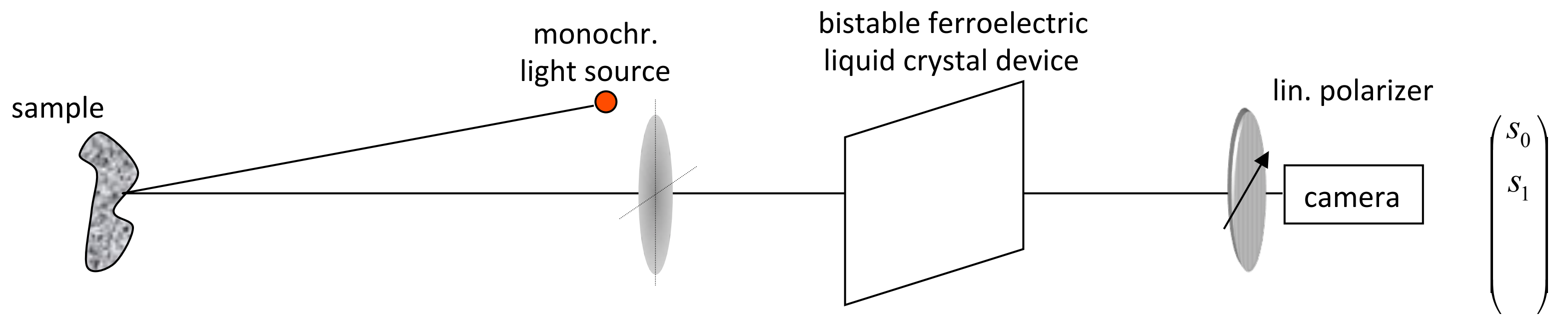
👍: high-speed (up to 1 kHz)

👎: cascade of two LC devices

A.M. Gandorfer, "Ferroelectric retarders as an alternative ...", Opt. Eng. **38** (8), 1402-1408 (1999).

Y. Hanaoka, "Ferroelectric Liquid Crystal Polarimeter ...", Solar Physics **222**, 265-278 (2004).

Temporal multiplexing with 1 FLC device



👍: high-speed (up to 1 kHz)

👎: without cascading two LC devices, only $\begin{pmatrix} s_0 \\ s_1 \\ \\ \end{pmatrix}$ available

A. Jaulin, L. Bigué et P. Ambs, "High-speed degree of polarization imaging with a ferroelectric liquid crystal modulator", Opt. Eng. **47** (3), 033201 (2008).

LC polarimeters: summary

Author	LC devices	Number of Stokes components configuration	speed
Wolff (1997)	2 TN LC	3 $\varphi=\pi$, $\theta=\{0,\pi/8,\pi/4,3\pi/8\}$	low
Chipman (1997)	2 NLC	4 $\varphi=\{2$ optimized retardances$\}$, θ=fixed	low
Blakeney (2002)	1 TN LC	4 φ: varying, θ : varying	low
Gandorfer (1999)	2 FLC	3 $\varphi=\pi$, $\theta=\{0,\pi/8,\pi/4,3\pi/8\}$	high
Bigué (2006 -)	1 FLC	?	high

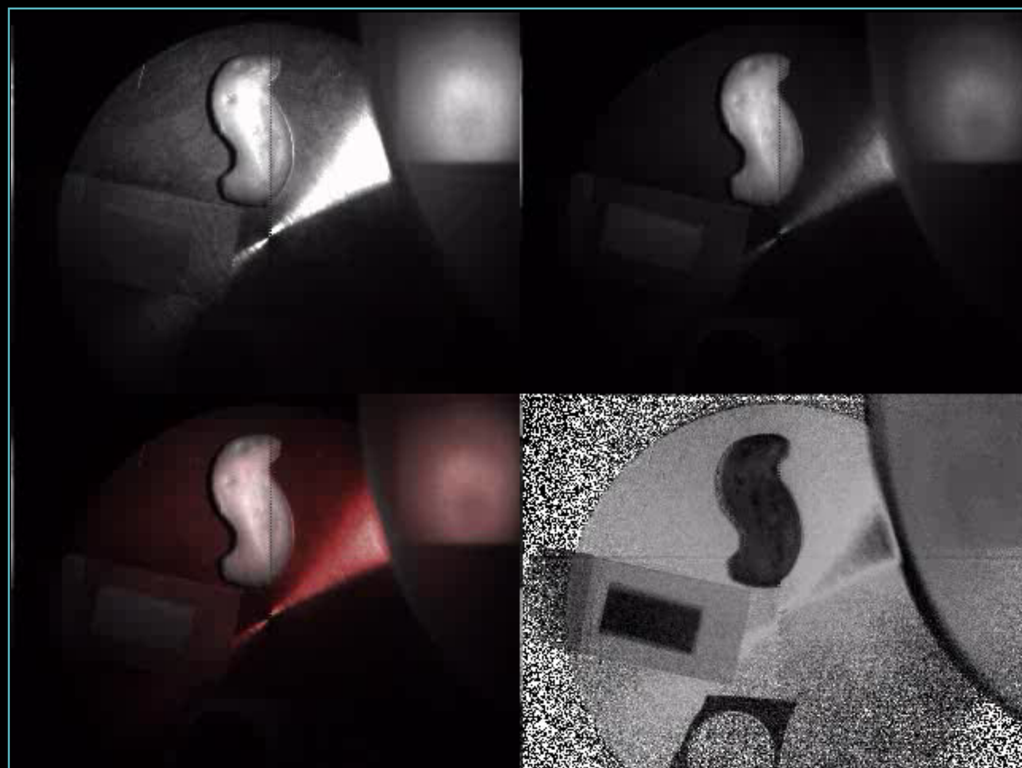
Our passive portable polarimeter

- polarizing element:
  - BNS, Inc. MS series rotator
- interferometric filter @ 633 nm
- camera:
  - AVT Pike F032B (DCAM CCD)
  - VGA@205 Hz (8 bits)
  - 320x240@360 Hz

A. Jaulin, L. Bigué et P. Ambs, "High-speed degree of polarization imaging with a ferroelectric liquid crystal modulator", Opt. Eng. **47** (3), 033201 (2008).

Under controlled illumination conditions

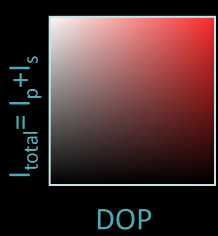
I_p



I_s

DOP

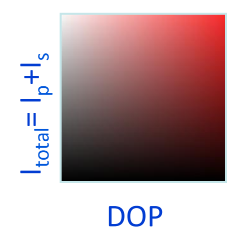
grabbed at 360 fps



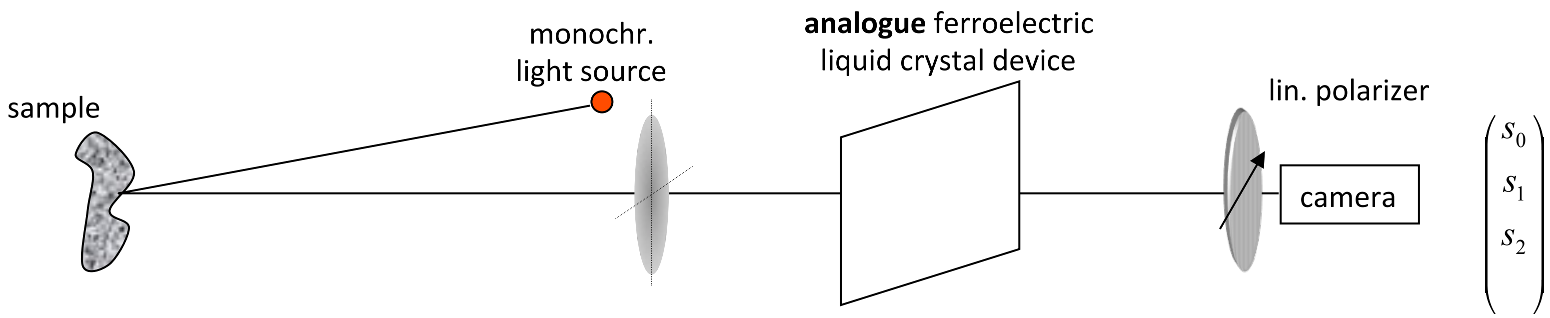
Outdoor tests

grabbed at 240 fps

DOP



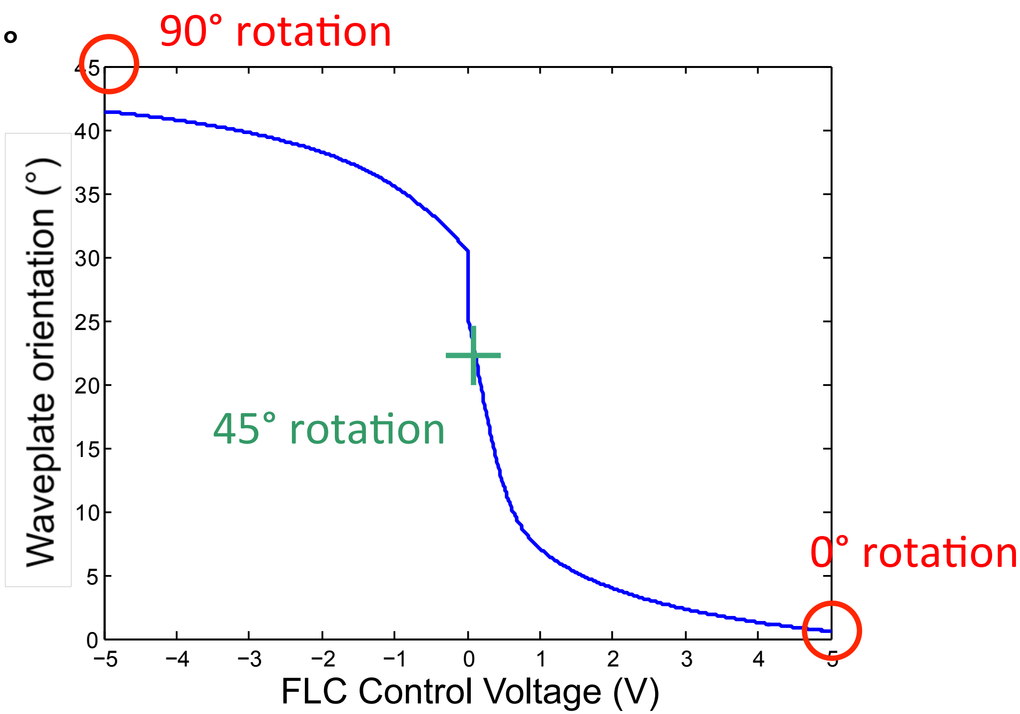
Temporal multiplexing with 1 FLC device



👍: high-speed (up to 1 kHz)

Analogue ferroelectric device : genuine tunable half-wave plate ?

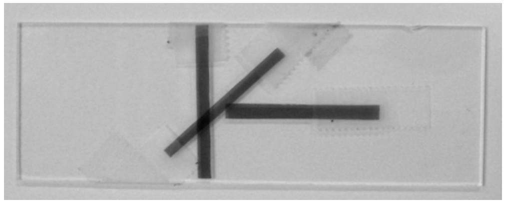
- What we need:
  - An intermediate drive level in order to rotate polarisation direction of 45°

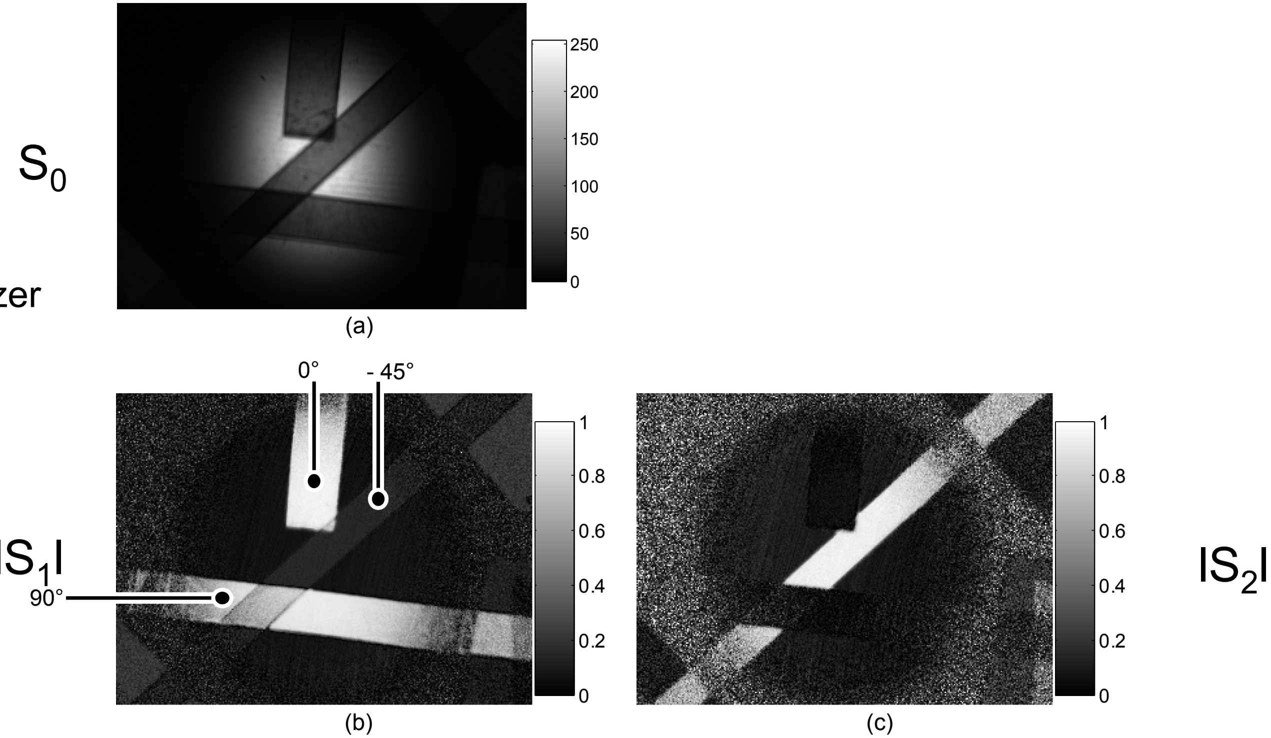


grey levels

Linear Polarization estimation @ 200 fps

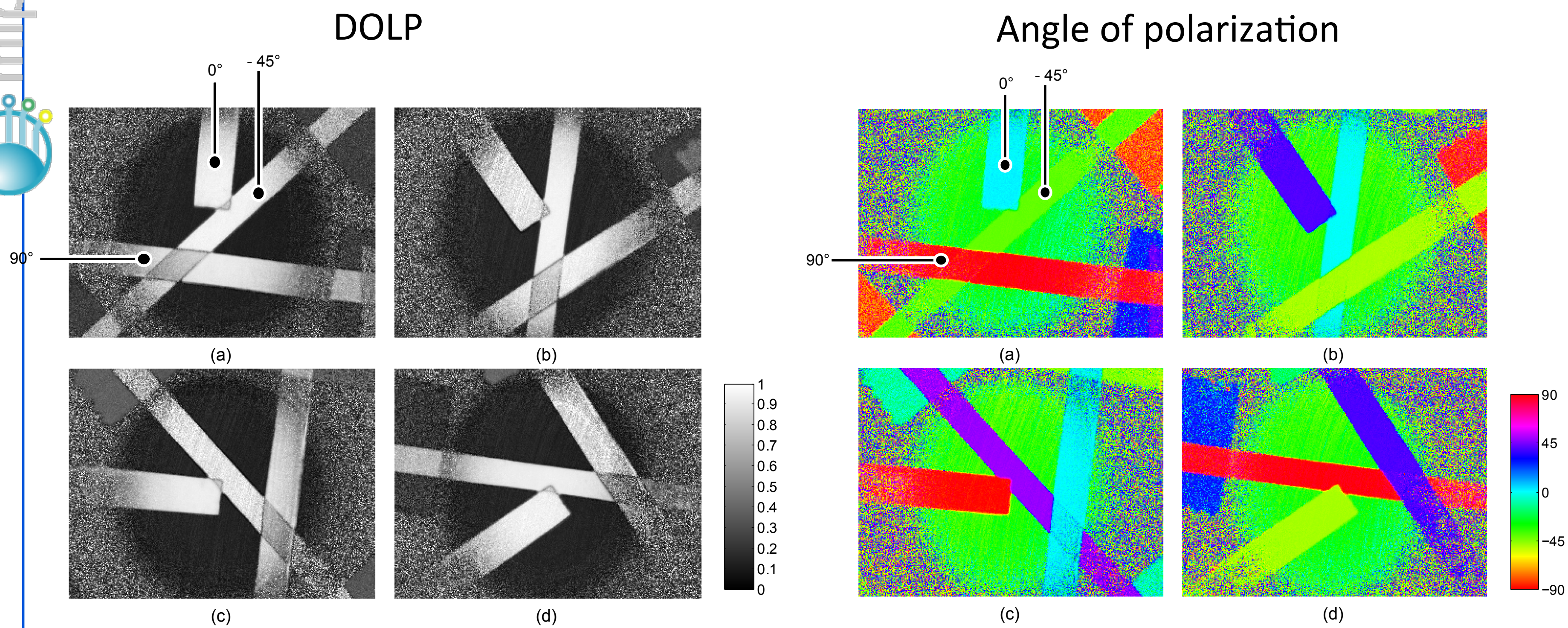
Original image: 3 strips of polarizer





L. Gendre, A. Foulonneau and L. Bigué, « Imaging linear polarimetry using a single ferroelectric liquid crystal modulator », Appl. Opt. 49 (25), 4687-4699 (2010).

Linear Polarization estimation @ 200 fps

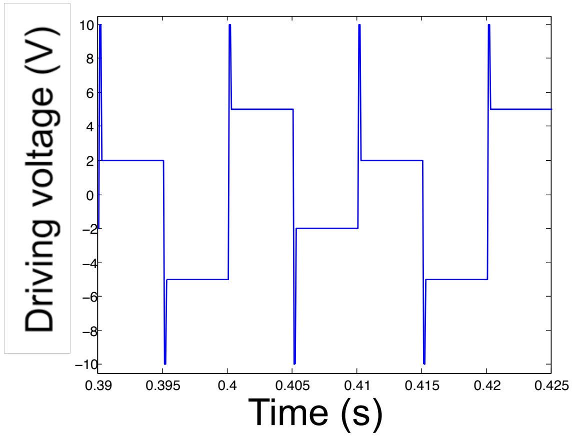


Estimating full linear polarization @200 fps is possible with an good accuracy (CN = 4.36)

L. Gendre, A. Foulonneau and L. Bigué, « Imaging linear polarimetry using a single ferroelectric liquid crystal modulator », Appl. Opt. 49 (25), 4687-4699 (2010).

What about estimating the whole polarization ?

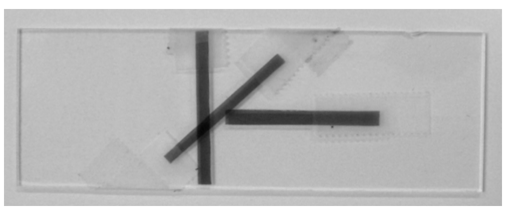
- An additional fourth configuration (voltage) is needed
- A shift in wavelength will make system matrix rank-4
- System control signal becomes complex, because LC modulator proves nonlinear, time-variant. An interactive optimization is led.

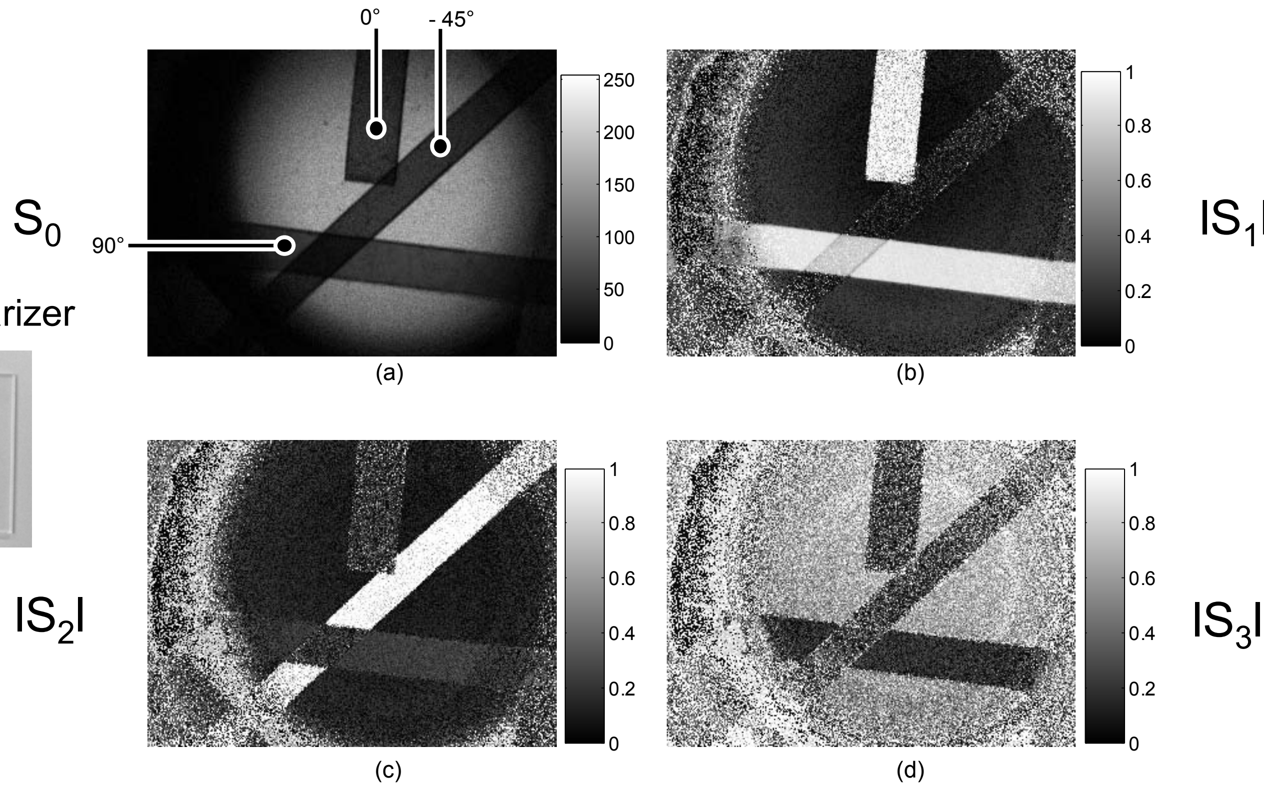


L. Gendre, A. Foulonneau and L. Bigué, « Full Stokes polarimetric imaging using a single ferroelectric liquid crystal device », Opt. Eng. **50** (8), 081209-1-9 (2011).

Full Polarization estimation @ 200 fps

Original image: 3 strips of polarizer



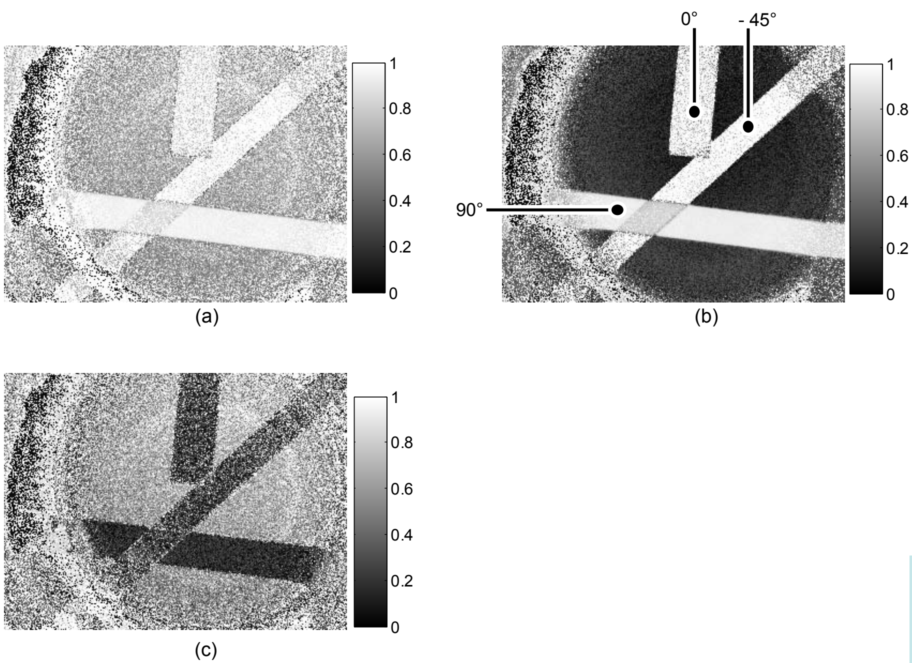


L. Gendre, A. Foulonneau and L. Bigué, « Full Stokes polarimetric imaging using a single ferroelectric liquid crystal device », Opt. Eng. **50** (8), 081209-1-9 (2011).

Full Polarization estimation @ 200 fps

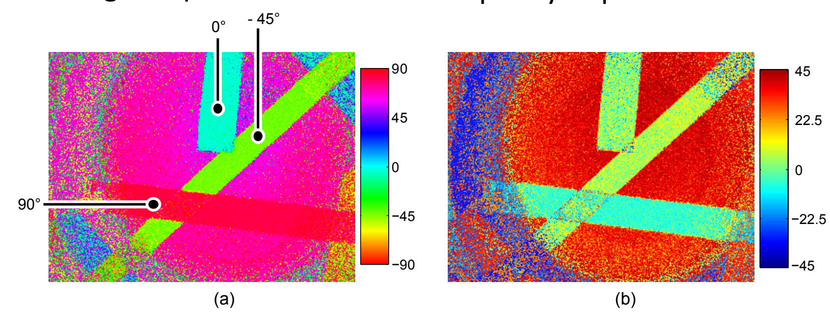
Degrees of Polarization

DOP DOLP



DOCP

Angle of polarization Ellipticity of polarization



L. Gendre, A. Foulonneau and L. Bigué, « Full Stokes polarimetric imaging using a single ferroelectric liquid crystal device », Opt. Eng. **50** (8), 081209-1-9 (2011).

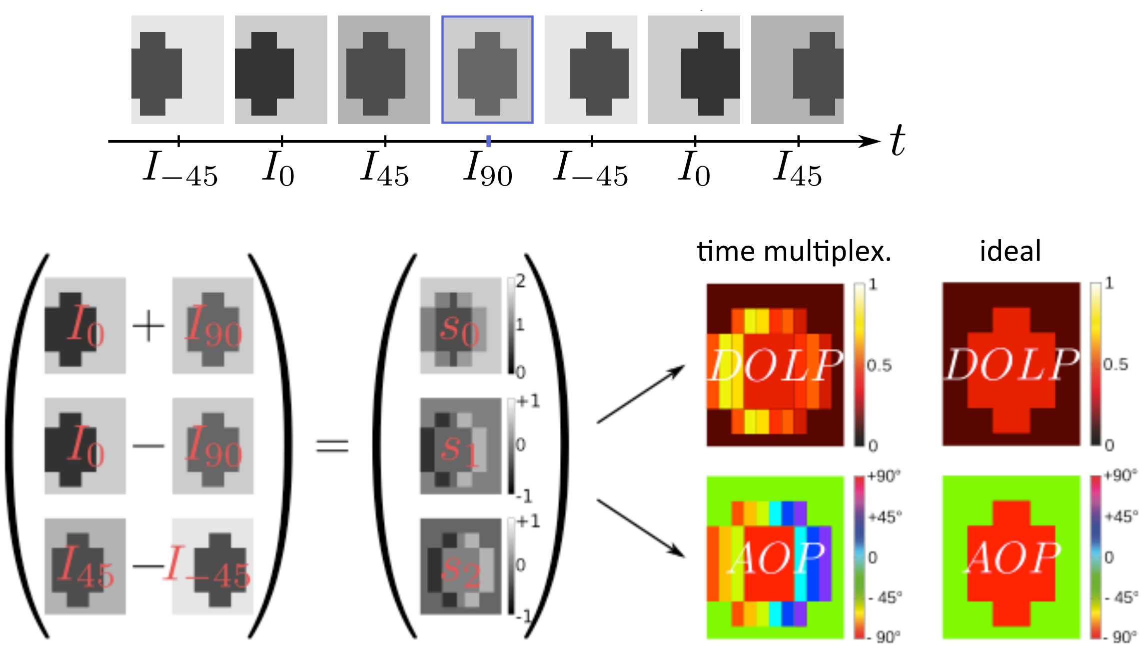
Back to outdoor tests


example with a static camera


example with a rotating camera

Artifacts appear when motion occurs : post-processing is necessary

Compensation for motion artifacts



- Direct artifact cancellation
  - Temporal median filtering
- Through motion estimation and registration
  - Rigid motion model
  - Block matching
  - Optical flow

Optical flow technique

$$E(\mathbf{w}(\mathbf{X})) = \iint \underbrace{\beta.B(X,\mathbf{w}(\mathbf{X})) + \gamma.G(X,\mathbf{w}(\mathbf{X}))}_{\text{data}} + \underbrace{\alpha.S(\nabla\mathbf{w}(\mathbf{X}))}_{\text{regularization}}\,\mathrm{d}x\,\mathrm{d}y$$

$$B(\mathbf{X},\mathbf{w}(\mathbf{X})) = \left|\mathbf{I}(\mathbf{X}+\mathbf{w}(\mathbf{X})) - \mathbf{I}(\mathbf{X})\right|$$ Gray level constancy

$$G(\mathbf{X},\mathbf{w}(\mathbf{X})) = \left\|\nabla\mathbf{I}(\mathbf{X}+\mathbf{w}(\mathbf{X})) - \nabla\mathbf{I}(\mathbf{X})\right\|$$ Gradient constancy

$$S(\nabla\mathbf{w}(\mathbf{X})) = \left\|\nabla\mathbf{w}(\mathbf{X})\right\|$$ Smoothness constraint

T. Brox, A. Bruhn, N. Papenberg and J. Weickert, "High Accuracy Optical Flow Estimation Based on a Theory for Warping", In Proc. ECCV 2004 4, 25–36 (2004).

$\mathbf{X} = (x,y,t)$	Space-time coordinates
$\mathbf{I}(\mathbf{X})$	Image at time t from image sequence $\mathbf{I}$
$\mathbf{I}(\mathbf{X}+(0,0,1))$	Image at time $t+1$ from image sequence $\mathbf{I}$
$\mathbf{w}(\mathbf{X}) = (u(\mathbf{X}),v(\mathbf{X}),1)$	motion field at time t
$\mathbf{I}(\mathbf{X}+\mathbf{w})$	Image $\mathbf{I}(\mathbf{X}+(0,0,1))$ warped according to $\mathbf{w}$

Optical flow technique: our work

- Functional minimization using Euler-Lagrange equations

- 2 major changes compared to Brox:
  - Change in the derivation procedure
  - Change in gray level constancy term $\left\|\nabla \mathbf{I}\left(\mathbf{X}+\mathbf{w}(\mathbf{X})\right)-\nabla \mathbf{I}\left(\mathbf{X}\right)\right\|$

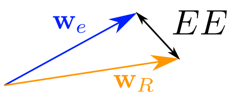
P. Marconnet, L. Gendre, A. Foulonneau and L. Bigué, Cancellation of motion artifacts caused by a division-of-time polarimeter, SPIE 8160, pp. 81600M (2011).

Results with non polarimetric images

- Test with Middlebury image set (http://vision.middlebury.edu/)
- Criteria:
  - Average Interpolation Error
  - Average Endpoint Error

$$AIE(I) = \sqrt{\frac{1}{N} \cdot \sum_{n=1}^{N} \left(I(n) - I_R(n)\right)^2}$$

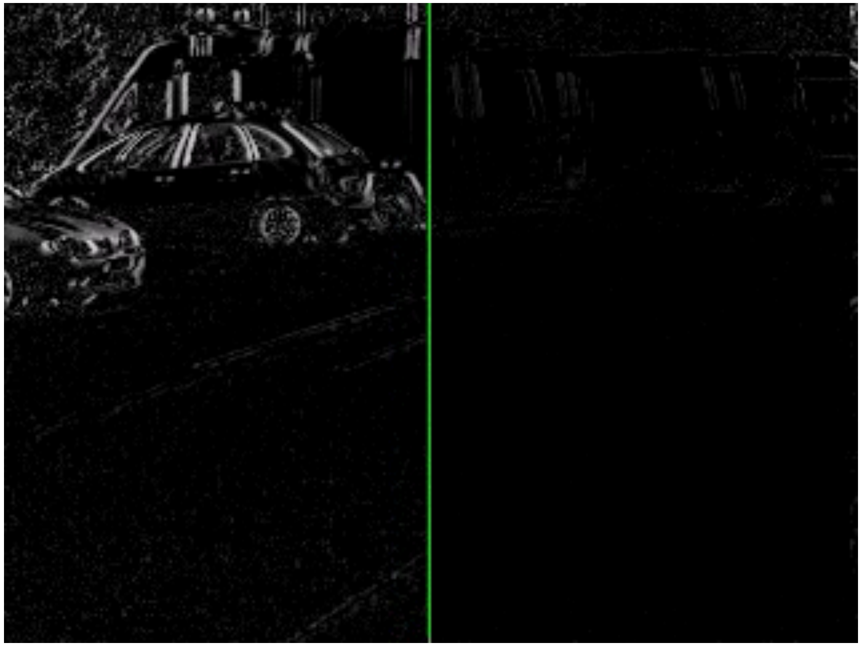
$$AEE(\mathbf{w}) = \frac{1}{N} \cdot \sum_{n=1}^{N} EE(n)$$



seq. #	1	2	3	4	5	6	7	8	9	10	11	12
AIE Brox	2.60	4.71	2.46	6.89	11.62	4.73	6.41	5.55	11.90	6.93	5.18	3.21
AIE Marc.	1.97	4.61	2.41	6.55	11.20	4.23	4.94	5.15	9.82	5.69	5.14	3.09
change (%)	**-24.4%**	**-2.1%**	**-2.3%**	**-5.0%**	**-3.6%**	**-10.7%**	**-22.9%**	**-7.2%**	**-17.5%**	**-17.9%**	**-0.8%**	**-3.8%**
AEE Brox	0.390	0.272	0.382	0.329	0.905	1.538	1.196	0.906	-	-	-	-
AEE Marc.	0.231	0.260	0.292	0.285	0.853	0.840	1.005	0.649	-	-	-	-
change(%)	**-40.7%**	**-4.7%**	**-23.5%**	**-13.4%**	**-5.7%**	**-45.4%**	**-16.0%**	**-28.3%**	**-**	**-**	**-**	**-**

P. Marconnet, L. Gendre, A. Foulonneau and L. Bigué, Cancellation of motion artifacts caused by a division-of-time polarimeter, SPIE 8160, pp. 81600M (2011).

Post-processing of a polarimetric sequence



original image processed image

Conclusion

- Our system:
  - Evaluation of 2, 3 (or 4) Stokes components
  - Use of a single FLC device
  - Images were obtained at 200-360 fps
- Future work:
  - Post-processing algorithm optimization

Is polarization really worth ?

Gili Air, Indonesia

Is polarization really worth ?

Gili Air, Indonesia