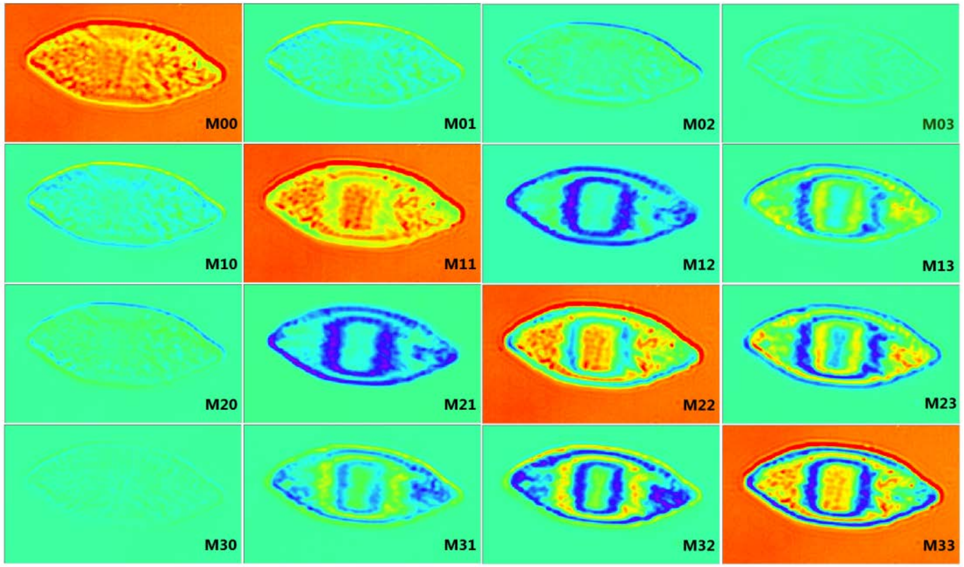
Beyond polarization microscopy: **Mueller matrix microscopy**



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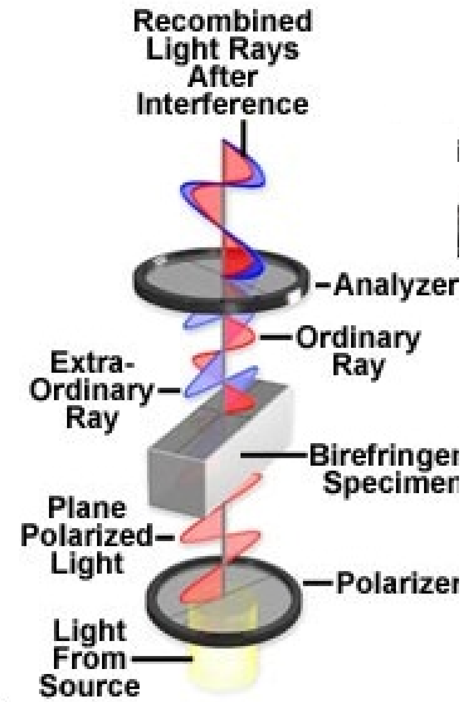
Outline

1. Polarization microscopy imaging
2. Basics of Mueller polarimetry
3. The Mueller matrix (MM) microscope
   - Instrument design
   - Data analysis. Generation of 16 images
4. Quantification of optical properties in trans-illumination and epi-illumination
5. Mueller matrix microscopy examples
6. Conclusions and perspectives

Polarization microscopy imaging

Optical microscopy with **polarized light.** Started more than **175 years ago**, but has seen few changes since then

Henry Fox Talbot (1834)
-a pair of plates of tourmaline
-a pair of nicols prims



http://www.microscopyu.com/

Studied in **birefringent** samples.

From a polarization microscope to a Mueller matrix microscpe

A **polarization microscope** converts a change in the azimuth of polarization into a change in color (due to interference) and/or intensity

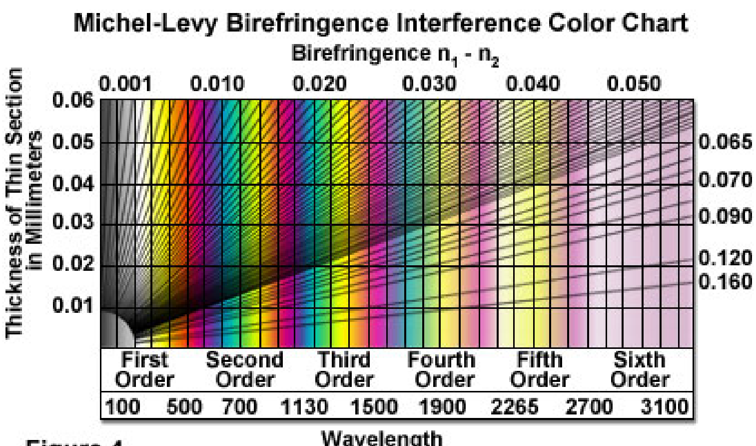
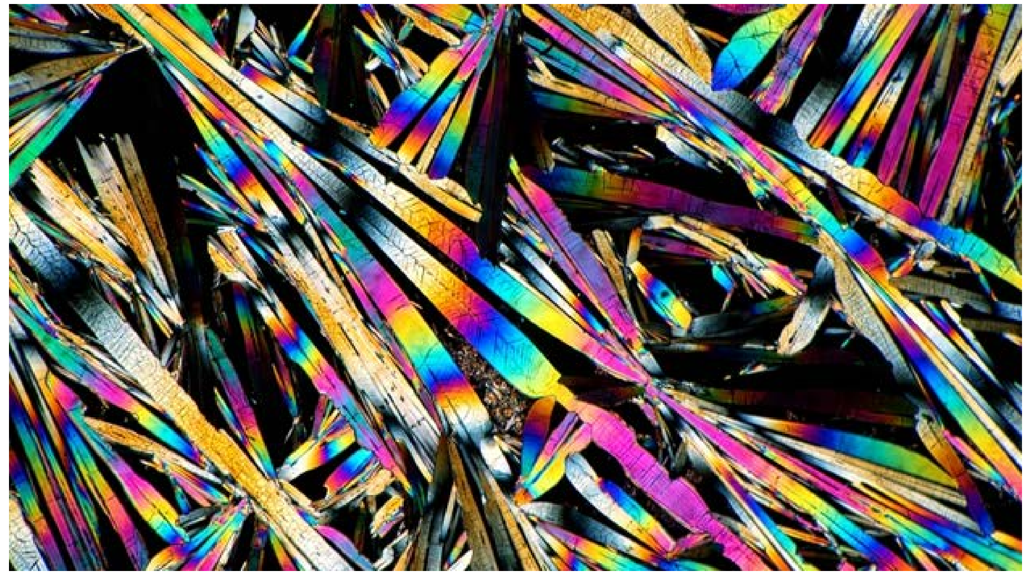


Figure 4



A **Mueller matrix microscope** fully determines the change of polarization at a certain wavelength through measurement of the space-resolved Mueller matrix.

$$S_{out} = M_{sample} S_{in} \qquad M_{sample} = \begin{bmatrix} m_{00} & m_{01} & m_{02} & m_{03} \\ m_{10} & m_{11} & m_{12} & m_{13} \\ m_{20} & m_{21} & m_{22} & m_{23} \\ m_{30} & m_{31} & m_{32} & m_{33} \end{bmatrix}$$

Basics of polarimetry applied to Mueller matrix microscopy

16 images $\begin{bmatrix} m_{00} & m_{01} & m_{02} & m_{03} \\ m_{10} & m_{11} & m_{12} & m_{13} \\ m_{20} & m_{21} & m_{22} & m_{23} \\ m_{30} & m_{31} & m_{32} & m_{33} \end{bmatrix}$

Trans-illumination

- <u>Circular dichroism</u>
- Circular birefringence
- <u>Magnitude and azimuth of linear dichroism</u>
- Magnitude and azimuth of linear birefringence

Epi-illumination

- Circular reflectivity
- <u>Circular phase shift</u>
- Magnitude and azimuth of linear reflectivity
- <u>Magnitude and azimuth of linear phase shift</u>

* **<u>Underlined</u>.** Optical effects due to absorption or extinction

& Depolarization!

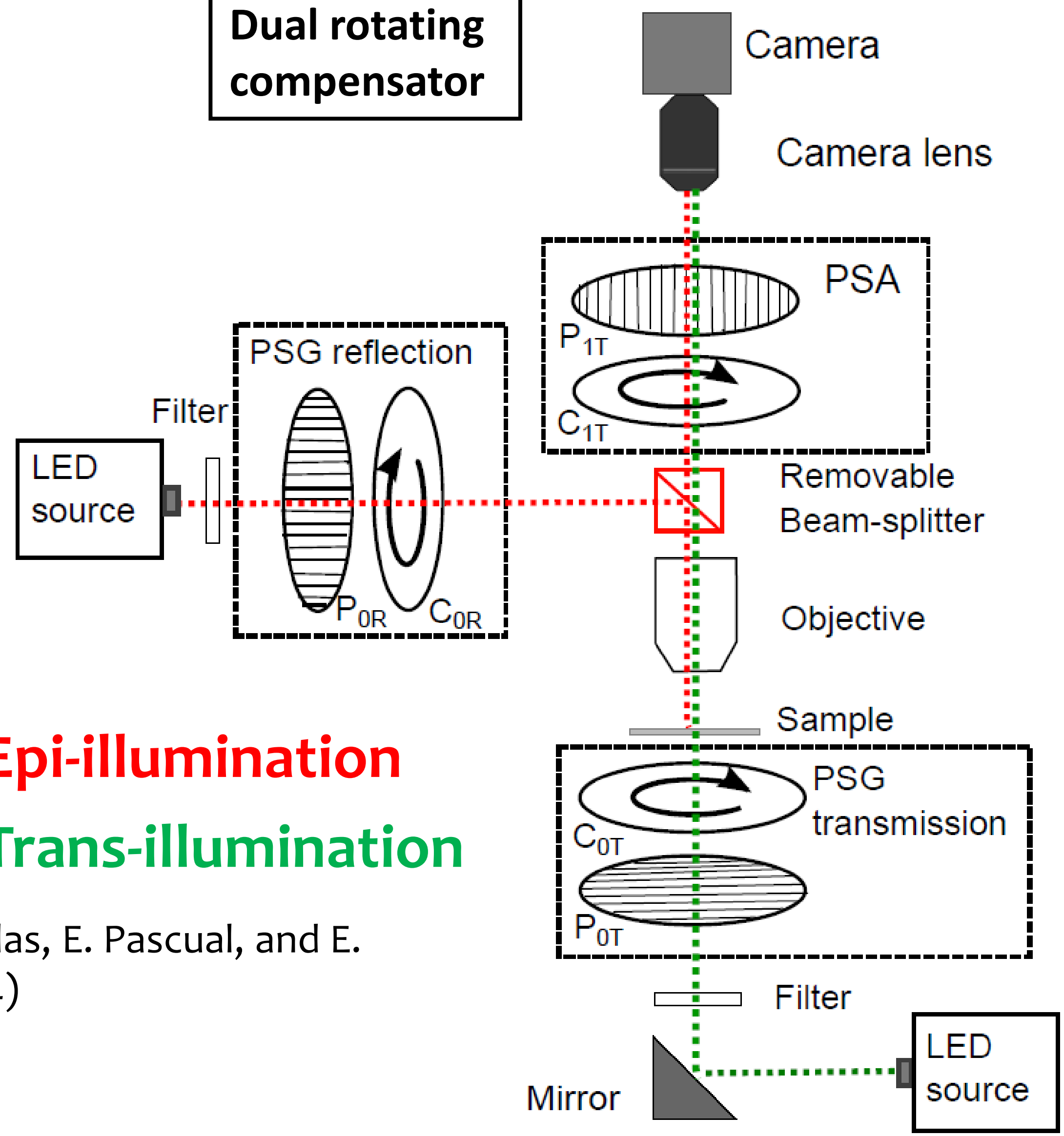
O. Arteaga and A.Canillas, Opt. Lett. **35**, 559-561 (2010)
R. Ossikovski, Opt. Lett. **36**, 2330-2332 (2011)
H. D. Noble and R. A. Chipman, Opt. Express **20**, 17-31 (2012)
O. Arteaga, E. G. Caurel and R. Ossikovski, submitted to Opt. Lett. (2014)

Instrument design

Instrumentation-wise a MM microscope is an automatized polarization microscope. Key elements:

- Two polaroid polarizers
- Two rotating compensators
- A camera
- A monochromatic light source

Dual rotating compensator

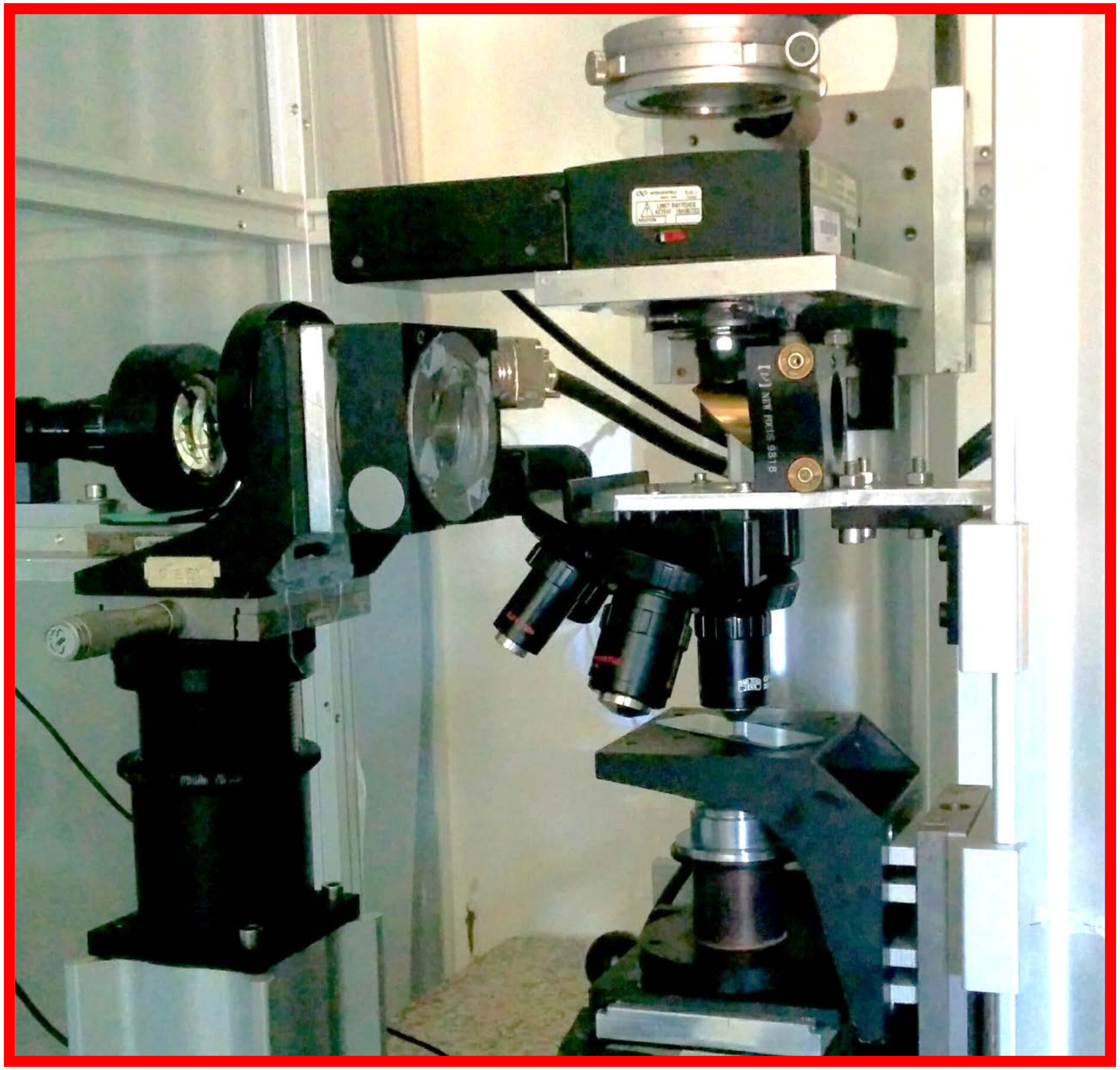


Epi-illumination

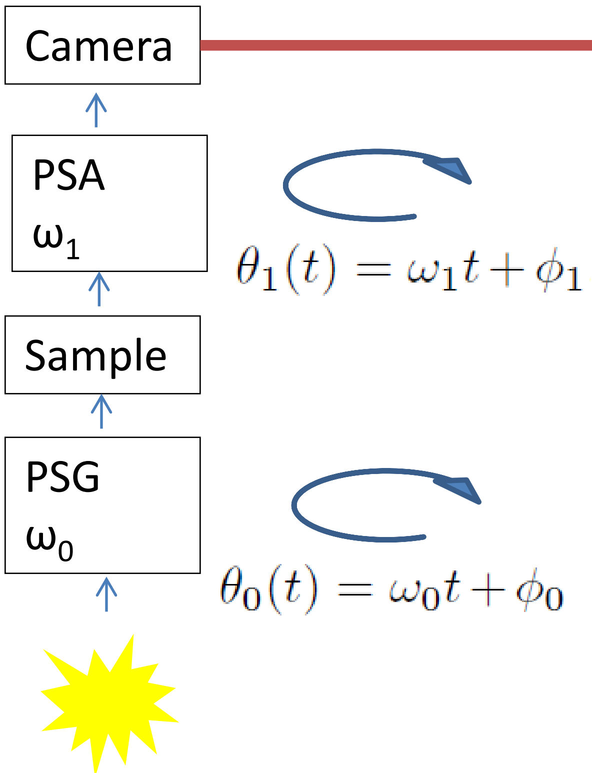
Trans-illumination

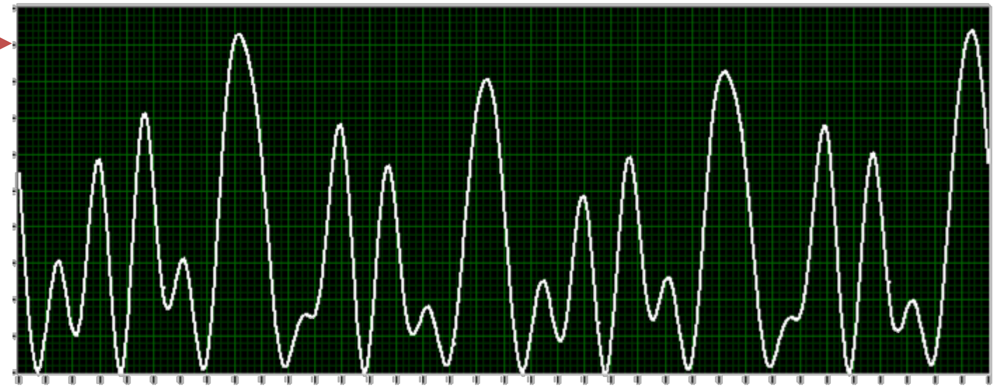
O. Arteaga, M. Baldrís, J. Antó, A. Canillas, E. Pascual, and E. Bertran, Appl. Opt. **53**, 2236-2245 (2014)

Instrument design



Data analysis (I). Overview





I (t)

The intensity waveform depends on:

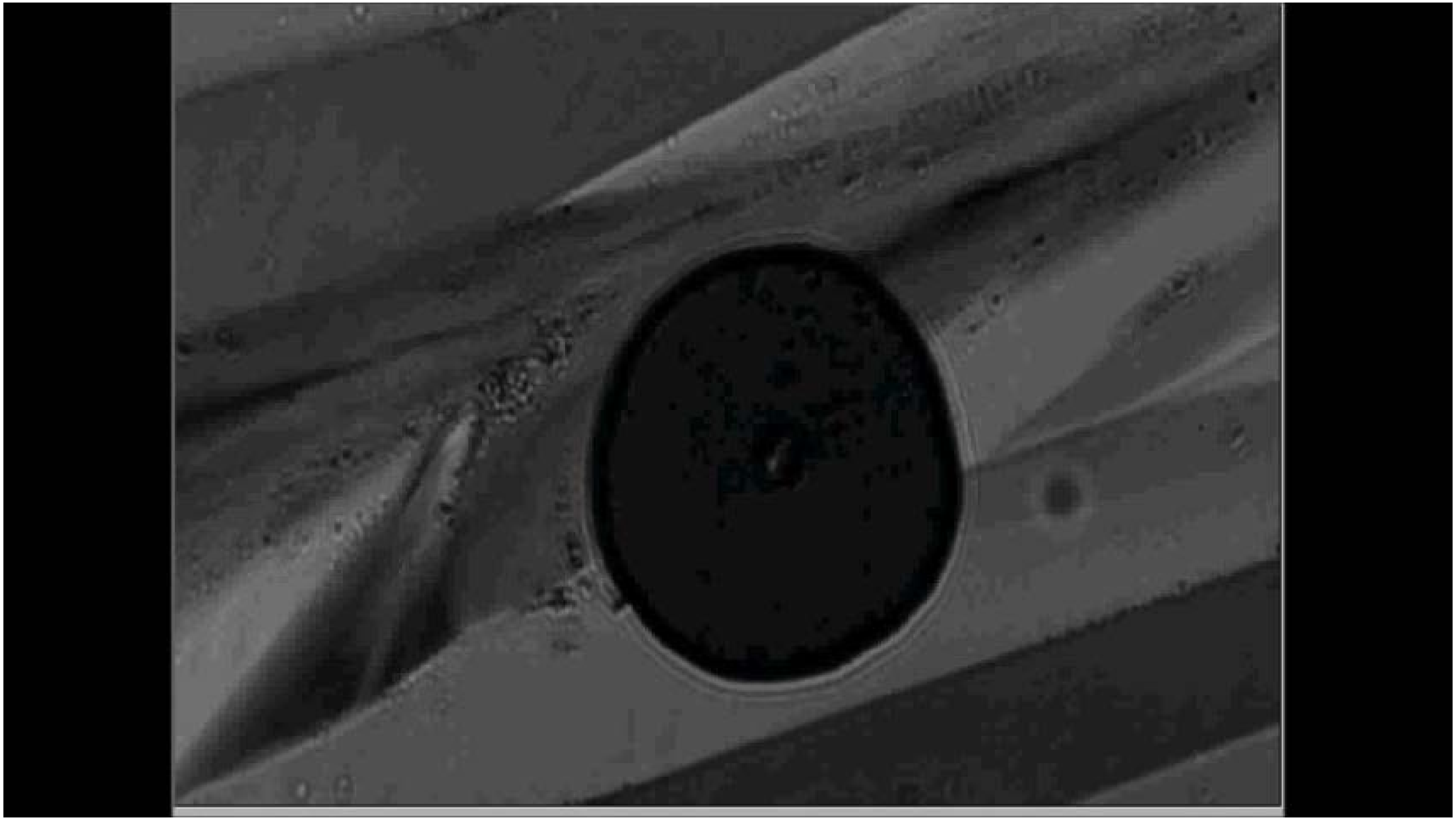
- The rotation speed of the compensators
- Their phase offset
- Their retardation values
- The Mueller matrix of the sample (pixel depending!)

Fourier Analysis!

16 images

$$\begin{bmatrix} m_{00} & m_{01} & m_{02} & m_{03} \\ m_{10} & m_{11} & m_{12} & m_{13} \\ m_{20} & m_{21} & m_{22} & m_{23} \\ m_{30} & m_{31} & m_{32} & m_{33} \end{bmatrix}$$

Data analysis (II)



Data analysis (III)

$$I(t) = \begin{bmatrix} 1 \\ C_{2\theta_0}^2 + C_{\delta_0} S_{2\theta_0}^2 \\ C_{2\theta_0} S_{2\theta_0}(1 - C_{\delta_0}) \\ S_{\delta_0} S_{2\theta_0} \\ -(C_{2\theta_1}^2 + C_{\delta_1} S_{2\theta_1}^2) \\ -(C_{2\theta_0}^2 + C_{\delta_0} S_{2\theta_0}^2)(C_{2\theta_1}^2 + C_{\delta_1} S_{2\theta_1}^2) \\ -(C_{2\theta_0} S_{2\theta_0}(1 - C_{\delta_0}))(C_{2\theta_1}^2 + C_{\delta_1} S_{2\theta_1}^2) \\ -(S_{\delta_0} S_{2\theta_0})(C_{2\theta_1}^2 + C_{\delta_1} S_{2\theta_1}^2) \\ -C_{2\theta_1} S_{2\theta_1}(1 - C_{\delta 1}) \\ -(C_{2\theta_0}^2 + C_{\delta_0} S_{2\theta_0}^2)[C_{2\theta_1} S_{2\theta_1}(1 - C_{\delta 1})] \\ -[C_{2\theta_0} S_{2\theta_0}(1 - C_{\delta 0})][C_{2\theta_1} S_{2\theta_1}(1 - C_{\delta 1})] \\ -S_{\delta_0} S_{2\theta_0}[C_{2\theta_1} S_{2\theta_1}(1 - C_{\delta 1})] \\ S_{\delta_1} S_{2\theta_1} \\ S_{\delta_1} S_{2\theta_1}[C_{2\theta_0}^2 + C_{\delta_0} S_{2\theta_0}^2] \\ S_{\delta_1} S_{2\theta_1}[C_{2\theta_0} S_{2\theta_0}(1 - C_{\delta 0})] \\ S_{\delta_1} S_{2\theta_1} S_{\delta_0} S_{2\theta_0} \end{bmatrix}^T \begin{bmatrix} m_{00} \\ m_{01} \\ m_{02} \\ m_{03} \\ m_{10} \\ m_{11} \\ m_{12} \\ m_{13} \\ m_{20} \\ m_{21} \\ m_{22} \\ m_{23} \\ m_{30} \\ m_{31} \\ m_{32} \\ m_{33} \end{bmatrix}$$

$$I(t) = \mathbf{B}^T(t)\mathbf{A}$$

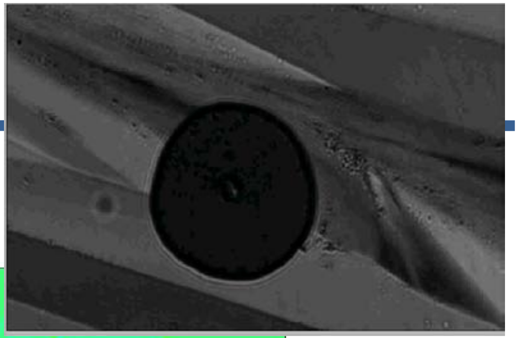
The intensity detected at every pixel of the camera needs to be demodulated.

B is the Nx16 demodulation matrix

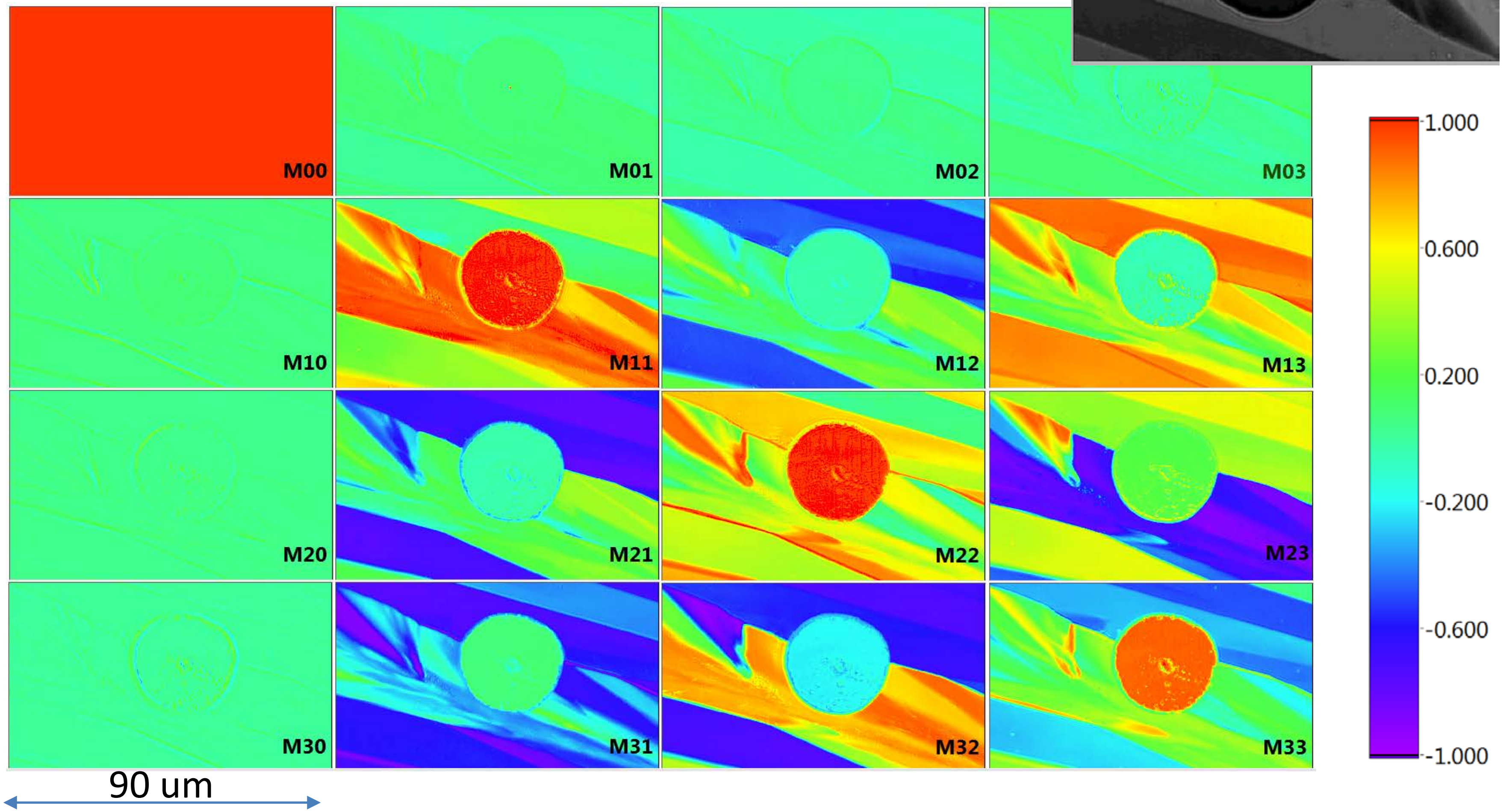
$$\mathbf{I} = \mathbf{B}^T\mathbf{A}$$
$$\mathbf{B}^T\mathbf{I} = \mathbf{B}^T\mathbf{B}\mathbf{A},$$
$$\mathbf{A} = (\mathbf{B}^T\mathbf{B})^{-1}\mathbf{B}^T\mathbf{I} = \mathbf{K}\mathbf{B}^T\mathbf{I}$$

O. Arteaga, M. Baldrís, J. Antó, A. Canillas, E. Pascual, and E. Bertran, Appl. Opt. **53**, 2236-2245 (2014)

Transmission measurement

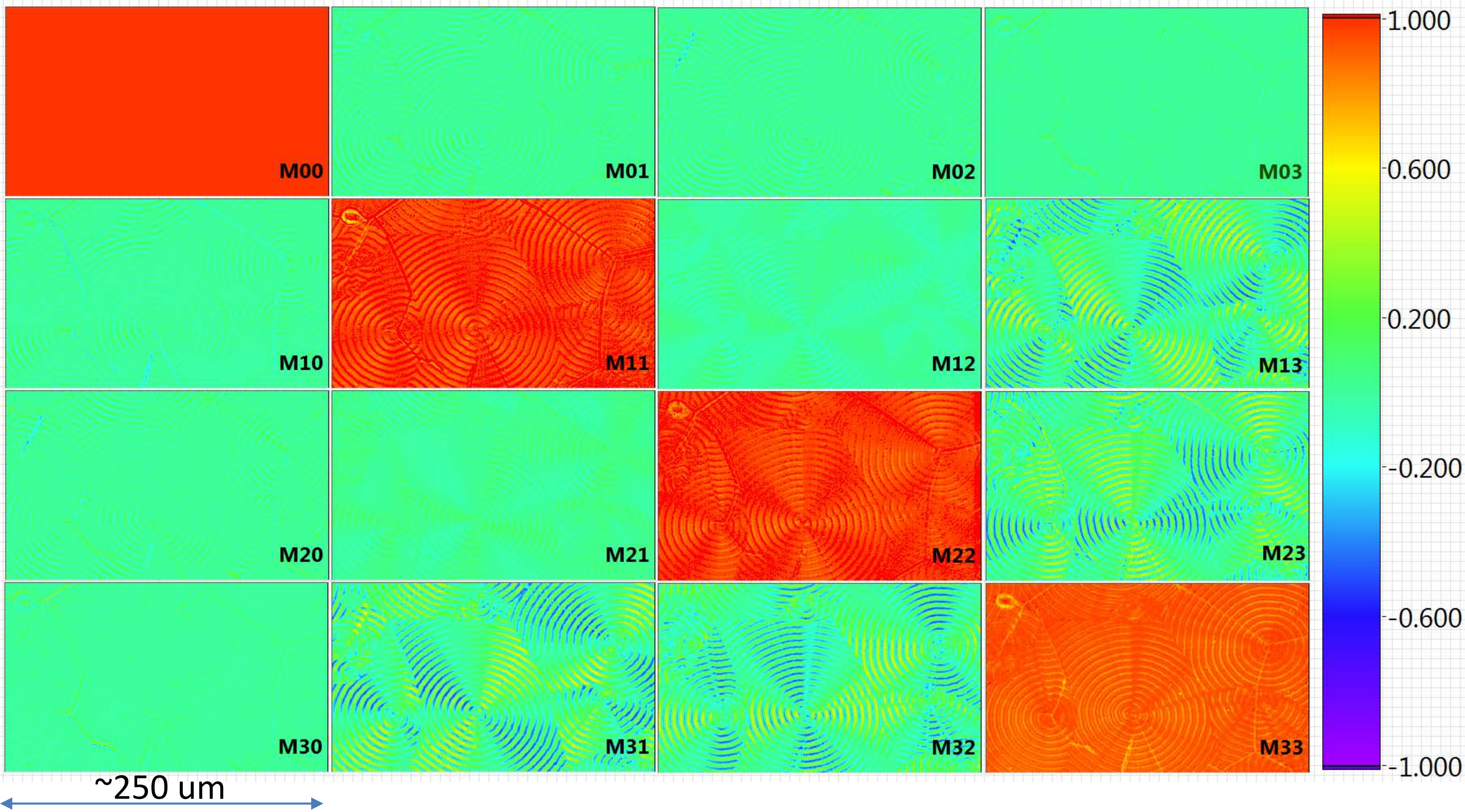


Policrystalline benzil sample (crystallyzed from the melt)



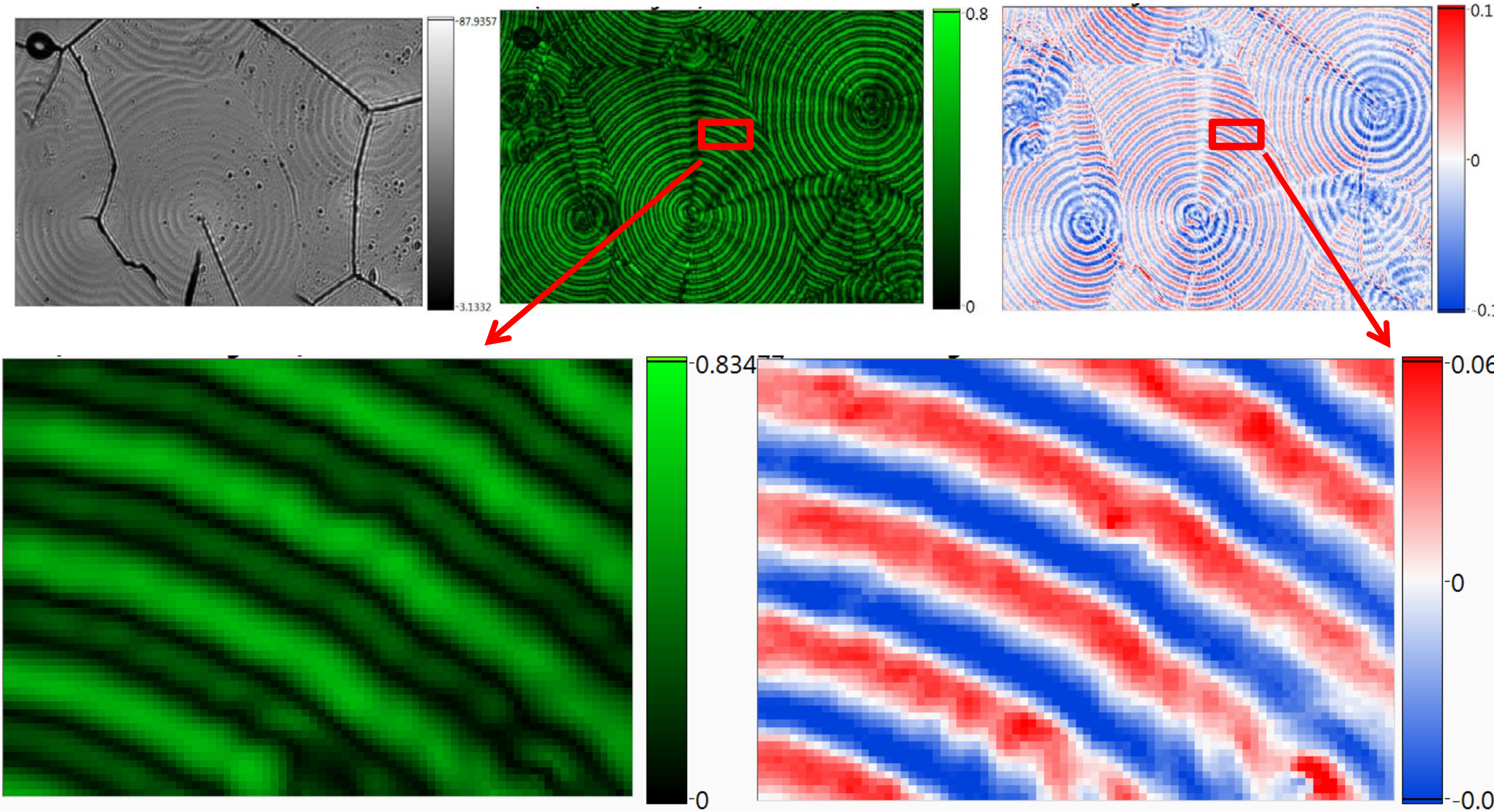
Transmission measurement (II)

Mannitol spherulites (535nm)



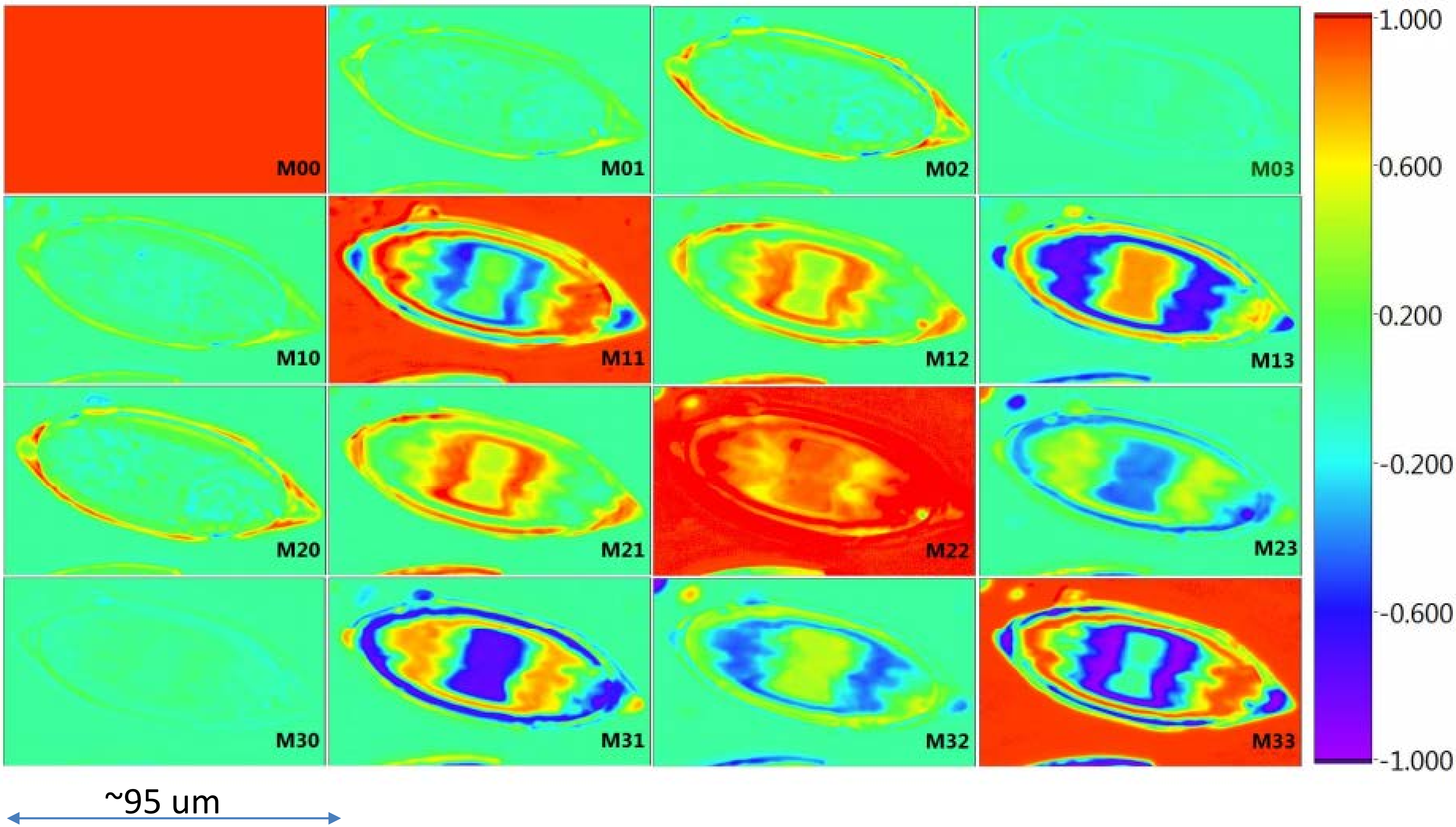
Transmission measurement (II)

Raw Unpolarized intensity | Magnitude of linear biref. (rad) | Circular birefringence (rad)



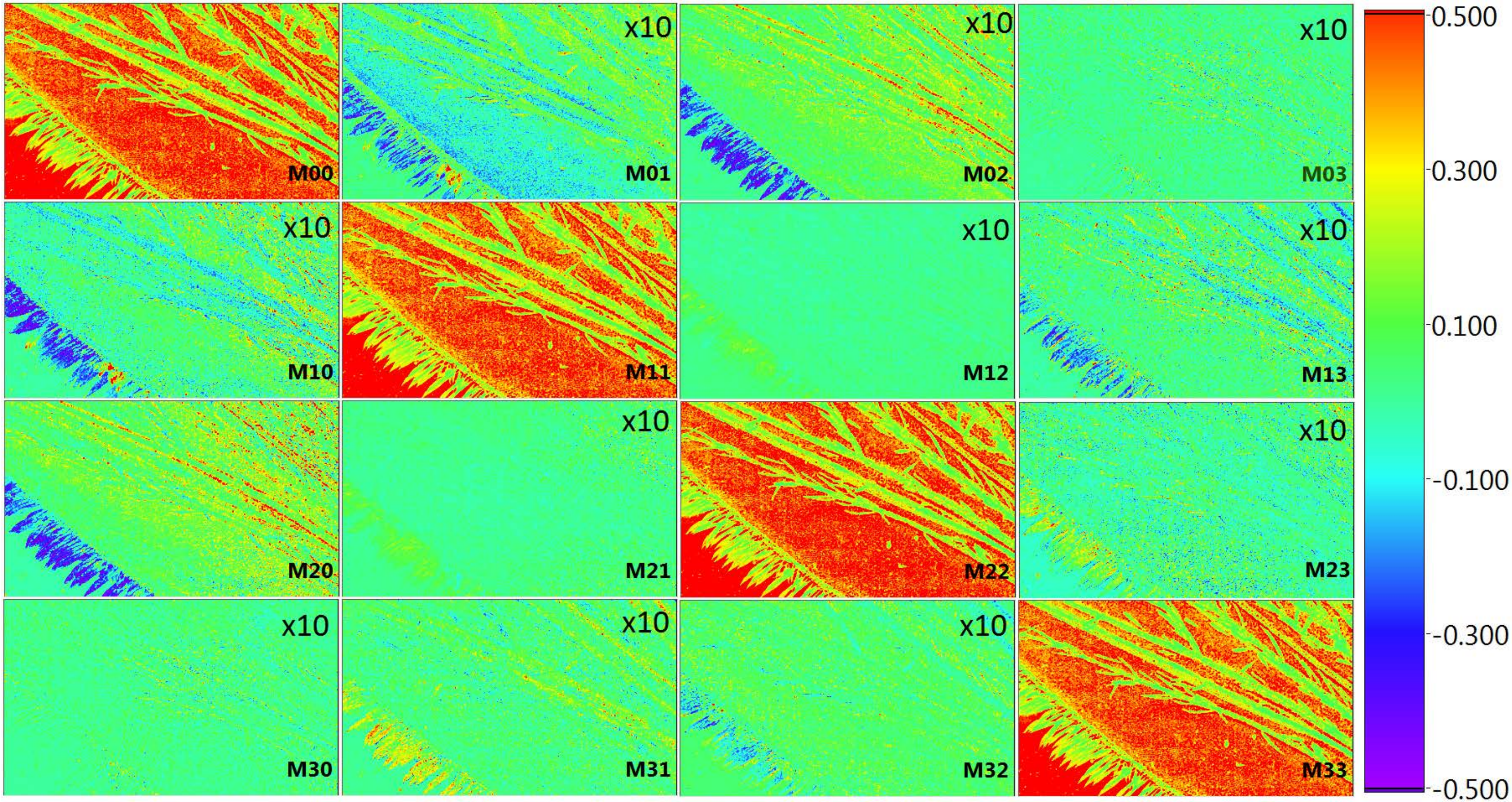
Transmission measurement (II)

Zeolite SiO2 microcrystal



Transmission measurement (III)

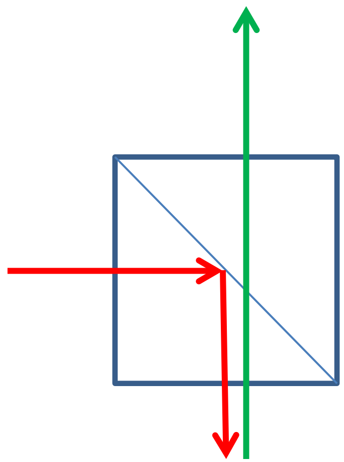
Mosquito wing



~1 mm

Reflection measurements (epi-illumination)

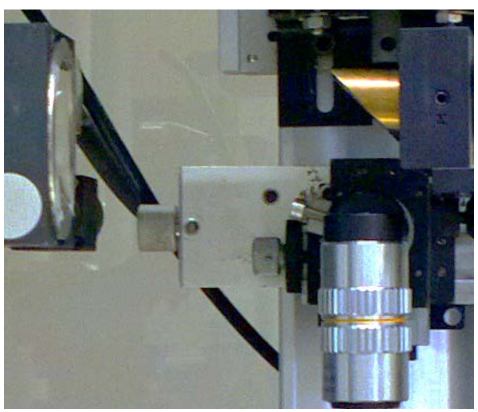
Even «non polarizing» beam splitters have rather large effects on the polarization



$$\mathrm{M}_E = \mathrm{M}_{W1}\mathrm{M}_S\mathrm{M}_{W0}$$

measured in transmission

measured with a reference mirror



$$\mathrm{M}_R = \mathrm{M}_{W1}\mathrm{M}_M\mathrm{M}_{W0}, \qquad \mathrm{M}_M = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$

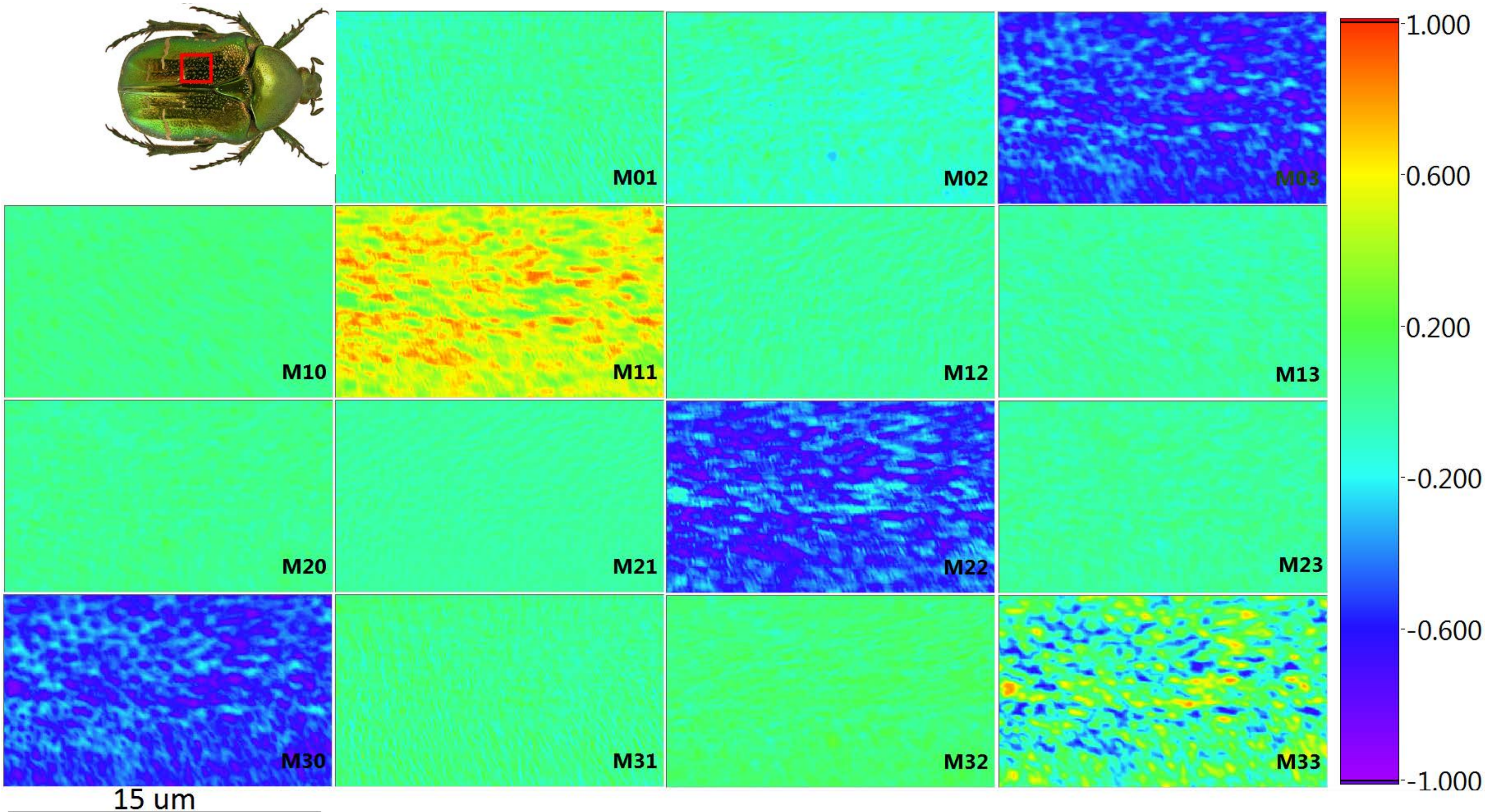
$$\mathrm{M}_{W0} = \mathrm{M}_M^{-1}\mathrm{M}_{W1}^{-1}\mathrm{M}_R.$$

$$\mathrm{M}_S = \mathrm{M}_{W1}^{-1}\mathrm{M}_E\mathrm{M}_R^{-1}\mathrm{M}_{W1}\mathrm{M}_M.$$

O. Arteaga, E. Kuntman. Proceedings of SPIE, art. nº 90990R, 2014.

Reflection measurements

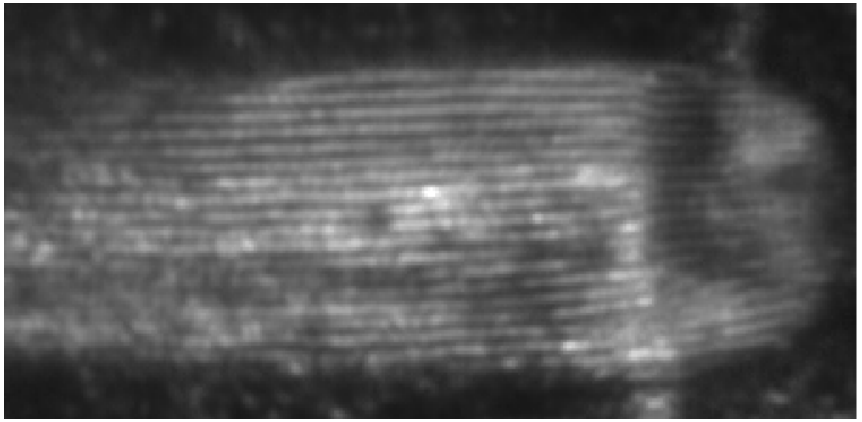
Cetonia Aurata beetle, structural chirality

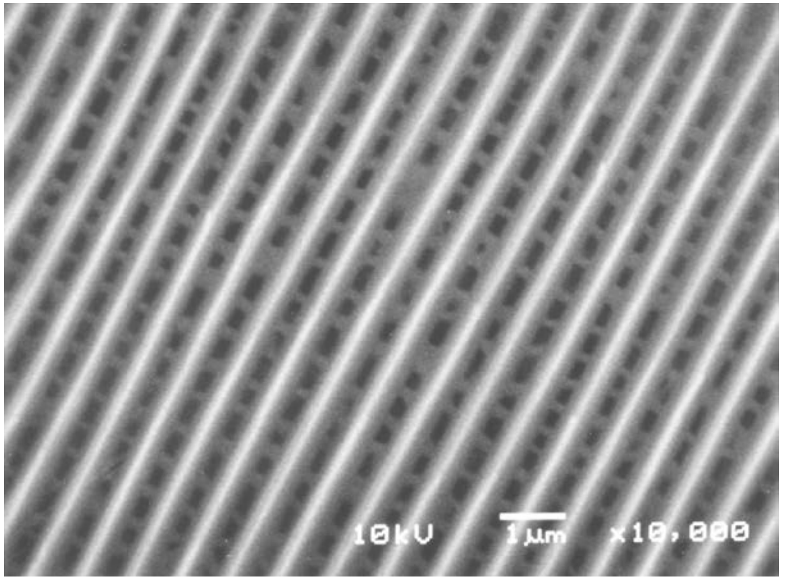


Reflection measurements

Cetonia Aurata beetles under circularly polarized light illumination

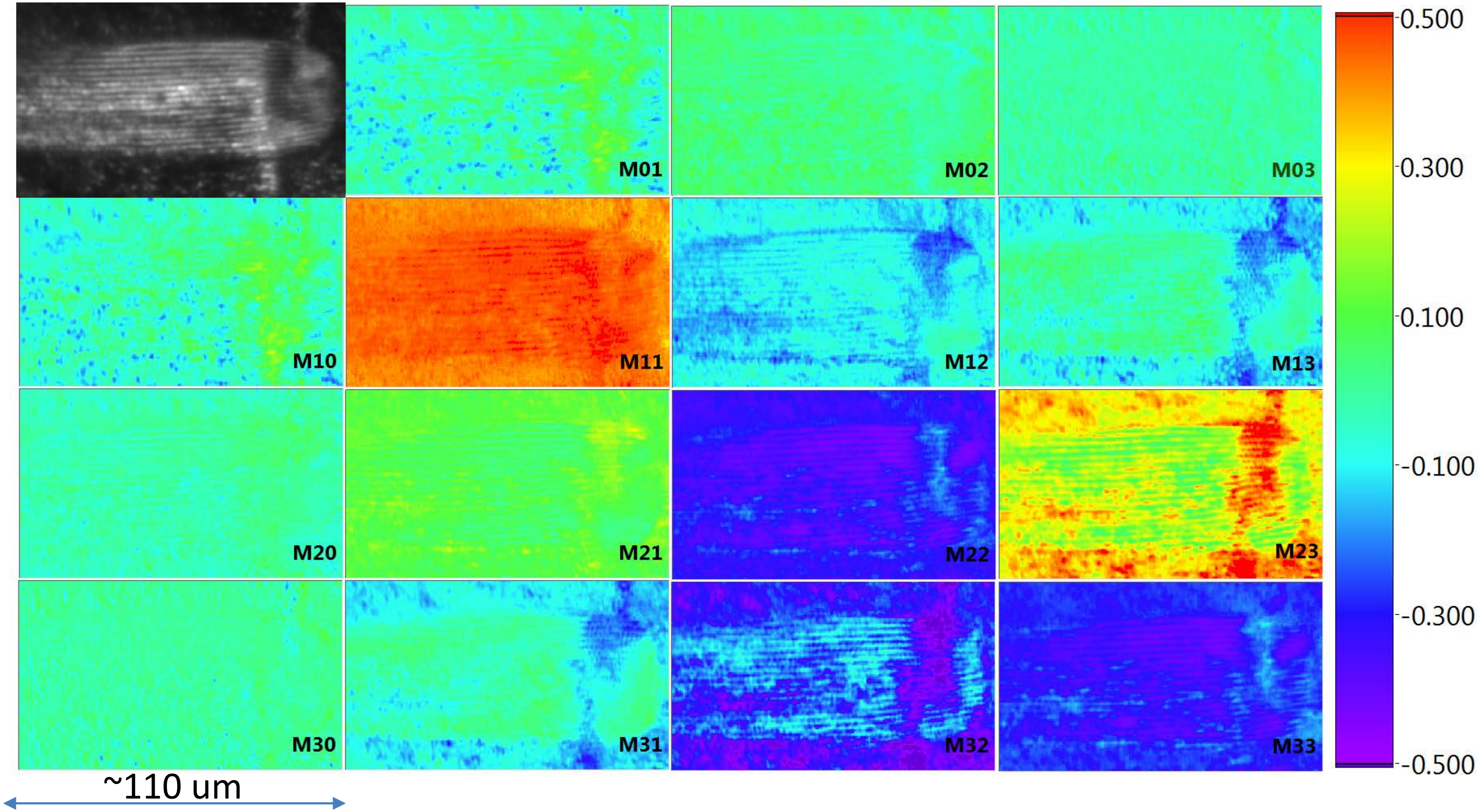
Reflection measurements (II)





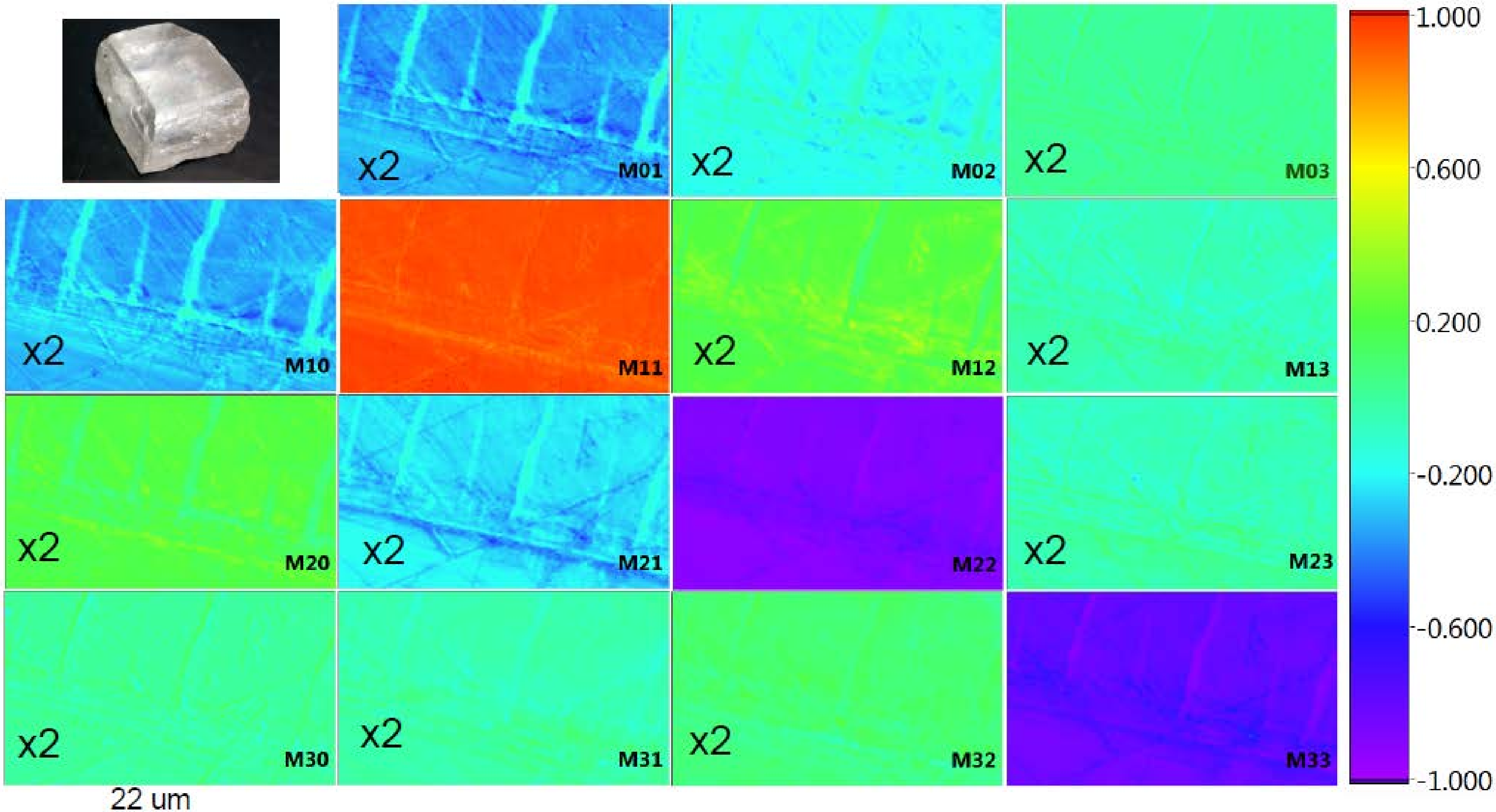
Reflection measurements (II)

Morpho butterfly, structural anisotropy



Reflection measurements (III)

Calcite, intrinsic anisotropy (highly birefringent crystal)



Summary: polarization microscopy vs MM microscopy

	Polarization microscope	Mueller matrix microscope
Operation	Manual	Automatic
Results	Mostly qualitative	Quantitative
Light Source	White light	Monochromatic light
Optical properties	Mainly linear birefringence	Many (eventually all)

Thank you!

funding:

MARIE CURIE ACTIONS

Polarimetry group

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