Towards real-time endoscopic depolarization sensing by orthogonally-polarized states mixing

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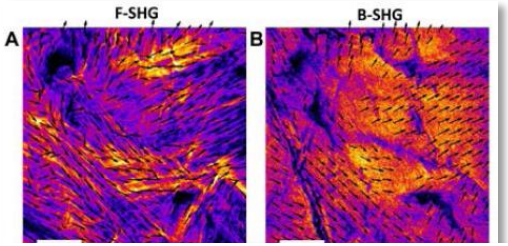
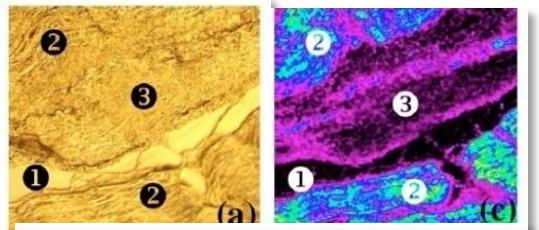
Introduction

Polarimetric imaging main fields of interest

- Active imaging:
  - Target polarimetric detection/identification
- Biomedical domain:
  - Disease-specific polarimetric properties
  - ➢ Skin cancer/burns, mucous membranes diseases, liver cirrhosis, cervix/colon cancer…



Latour et al., Biomed. Opt. Express 3, 1 (2012)



Desroches et al., Opt. Lett. 34, 3409 (2009)

Relevant parameters

- Birefringence, dichroism, depolarization

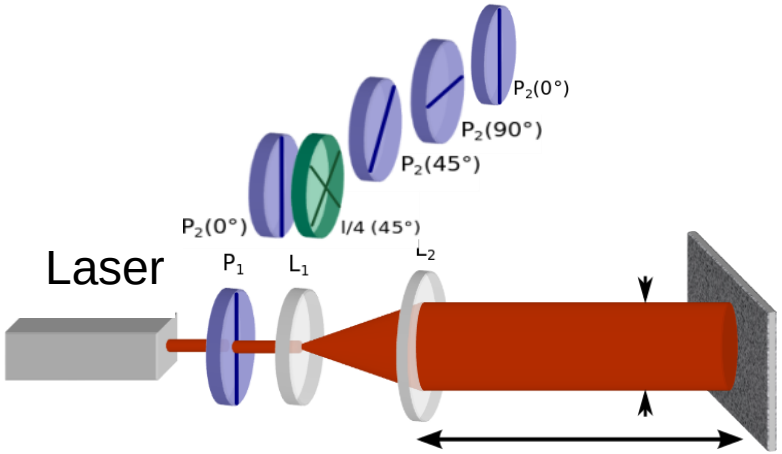
Motivation

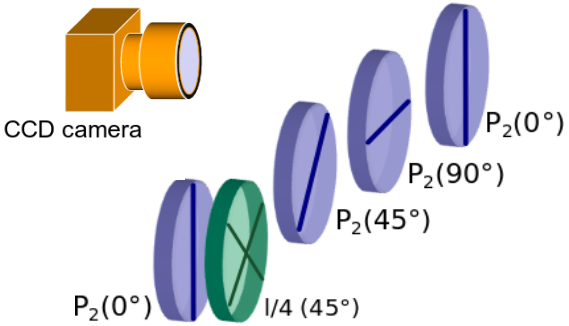
- Achieving ***in situ***, ***in vivo*** and **real-time endoscopic depolarization** imaging

Strong applicative potential for solving a persistent technical challenge

Mueller Imaging: depolarizing samples characterization

4 states of polarization for illumination





4 states of polarization for analysis

Stokes vector: $\vec{S} = \begin{pmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{pmatrix} = \begin{pmatrix} I_x + I_y \\ I_x - I_y \\ I_{+45°} - I_{-45°} \\ I_{RC} - L_{LC} \end{pmatrix}$

M : Mueller matrix

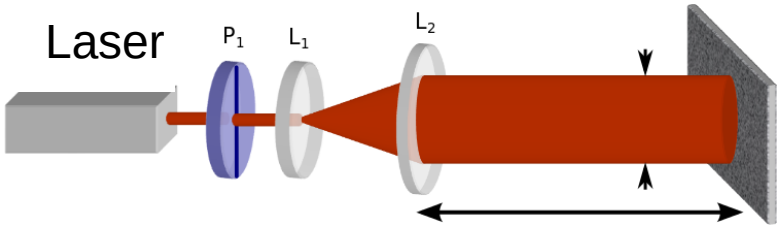
$$\begin{pmatrix} S_0^{out} \\ S_1^{out} \\ S_2^{out} \\ S_3^{out} \end{pmatrix} = \begin{pmatrix} m_{00} & m_{01} & m_{02} & m_{03} \\ m_{10} & m_{11} & m_{12} & m_{13} \\ m_{20} & m_{21} & m_{22} & m_{23} \\ m_{30} & m_{31} & m_{32} & m_{33} \end{pmatrix} \begin{pmatrix} S_0^{in} \\ S_1^{in} \\ S_2^{in} \\ S_3^{in} \end{pmatrix}$$

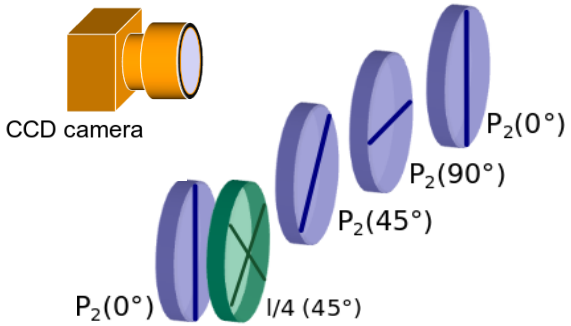
Features:

- Requires 16 image acquisitions
- Full characterization, comprehensive information: sometimes not all of it is essential!

Stokes Imaging: partially polarized beams characterization

1 state of polarization for illumination





4 states of polarization for analysis

Stokes vector:

$$\vec{S} = \begin{pmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{pmatrix} = \begin{pmatrix} I_x + I_y \\ I_x - I_y \\ I_{+45°} - I_{-45°} \\ I_{RC} - L_{LC} \end{pmatrix}$$

Degree of polarization:

$$DOP = \frac{\sqrt{S_1^2 + S_2^2 + S_3^2}}{S_0}$$

Features:

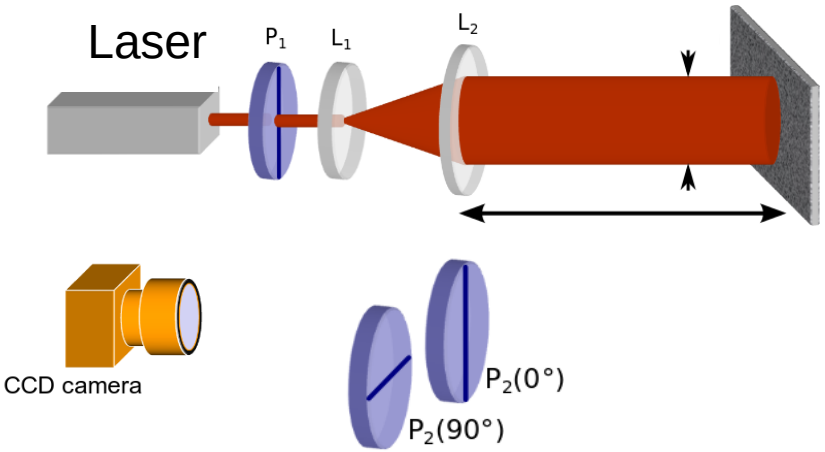
- Requires 4 image acquisitions
- Partial characterization of the sample polarimetric response

Orthogonal States Contrast Imaging

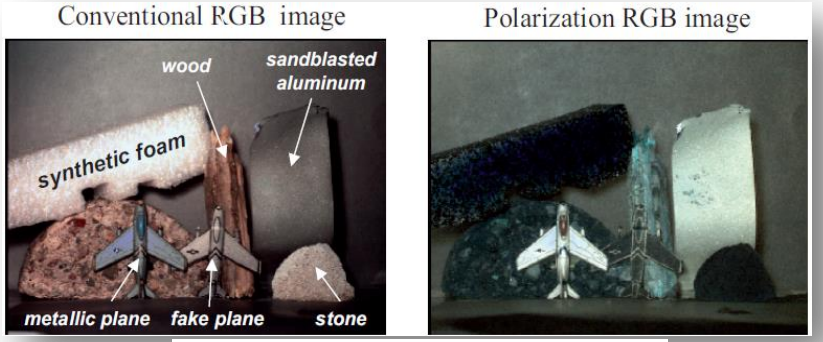
$$OSC = \frac{(I_{\parallel} - I_{\perp})}{(I_{\parallel} + I_{\perp})}$$

If the samples are purely depolarizing: $OSC = DOP$

1 state of polarization for illumination



2 states of polarization for analysis



Alouini et al., EPJAP **42**, 129 (2008)

Features:

- Requires 2 image acquisitions
- Partial characterization of the sample polarimetric response for purely depolarizing samples

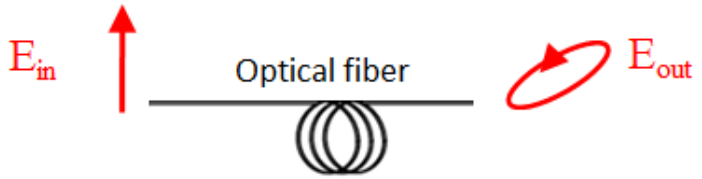
Endoscopic polarimetric imaging

Standard techniques requirement

- Precise control of the SOP of the illumination and analysis beams

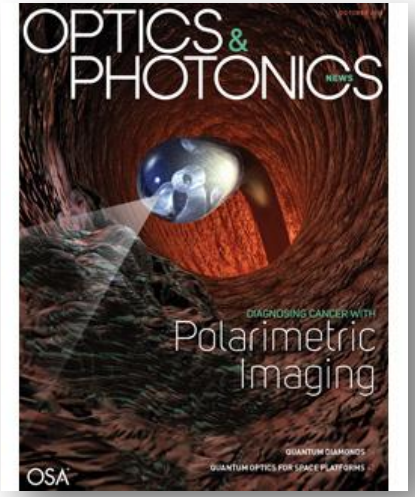
Endoscopic delivery of polarized beams

- Uncontrolled SOP modification (retardance undergone in the optical fiber)



Challenge for remote-sensing through optical fibers

Novikova et al., Opt. and Phot. News (Oct. 2012)



"In some medical fields, […] optical fiber is needed to deliver the light to inner cavities within the human body. **Thus, we must work to eliminate the polarimetric contribution of optical fiber to the acquired images**."

Shifting viewpoint

Focus on depolarization

- Biological tissues strongly depolarize light beams due to their heterogeneity and to scattering by cell nuclei, organelles and fibers
- Diseases and pathologies alter tissue composition, which modifies their depolarizing behavior

Endoscopic depolarization sensing

- Optical fibers do not bring depolarization but only a change of the state of polarization

Objective

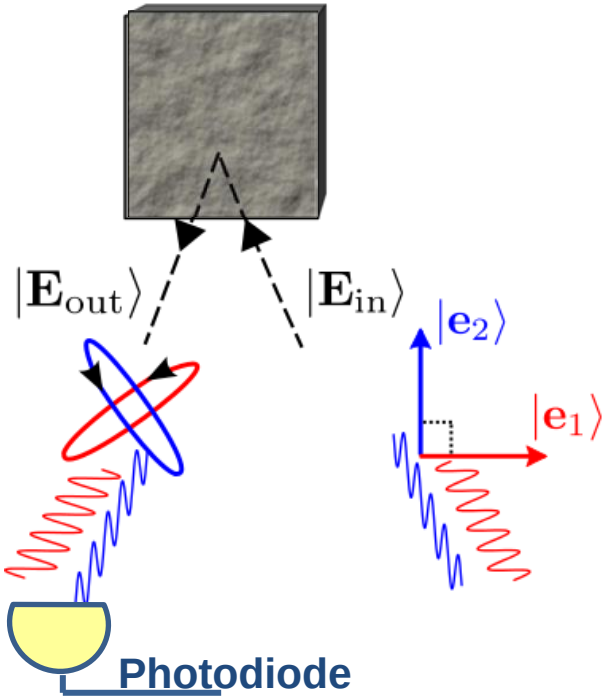
- Find out a way to directly measure depolarization strength

Depolarization Sensing by Orthogonality Breaking (DSOB)

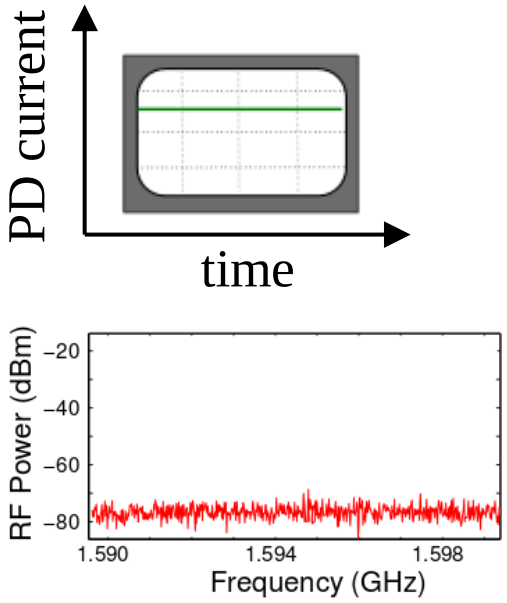
- Light probe beam: dual-frequency orthogonal polarizations field

$$|\mathbf{E}_{\text{in}}(\boldsymbol{r},t)\rangle = \frac{E_0}{\sqrt{2}} e^{-2j\pi\nu_1 t}\left[|\mathbf{e}_1\rangle + e^{-2j\pi\Delta\nu t}|\mathbf{e}_2\rangle\right] \quad \text{with} \quad \langle \mathbf{e}_1|\mathbf{e}_2\rangle = 0$$

Non depolarizing birefringent sample



Photodiode output



No interference beatnote signal

$$I_{out}^{\Delta\nu} = \text{tr}\left(\text{J}_\text{u}\Gamma^{\Delta\nu}\text{J}_\text{u}^{\dagger}\right) = 0$$

on a unitary Jones matrix $\mathbf{J_u}$

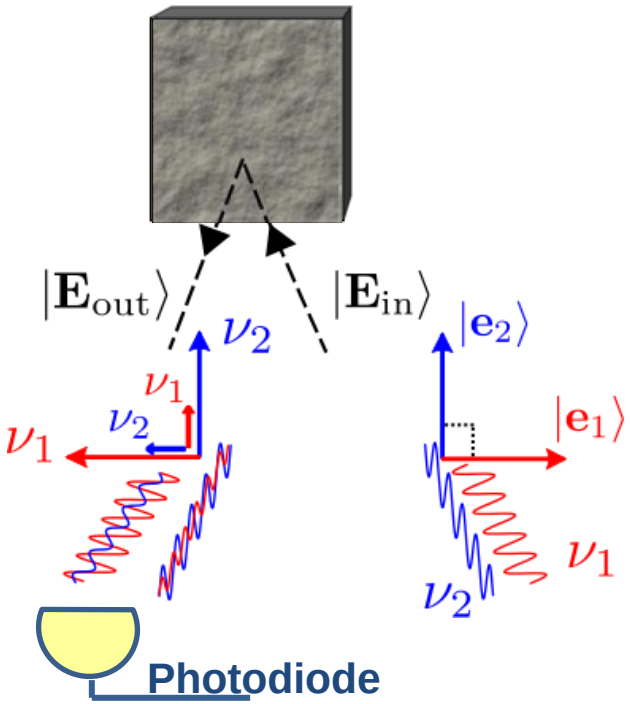
$$\left(\mathbf{J_u}\mathbf{J_u}^{\dagger} \propto \text{Id}\right)$$

Depolarization Sensing by Orthogonality Breaking (DSOB)

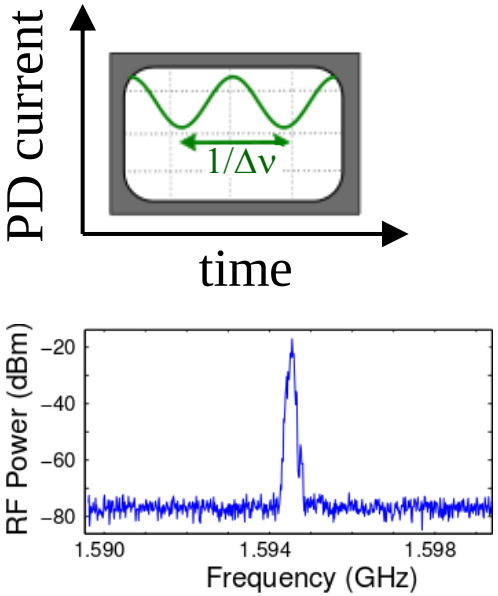
- Light probe beam: dual-frequency orthogonal polarizations field

$$|\mathbf{E}_{\text{in}}(\boldsymbol{r},t)\rangle = \frac{E_0}{\sqrt{2}} e^{-2j\pi\nu_1 t}\left[|\mathbf{e}_1\rangle + e^{-2j\pi\Delta\nu t}|\mathbf{e}_2\rangle\right] \quad \text{with} \quad \langle \mathbf{e}_1|\mathbf{e}_2\rangle = 0$$

Purely depolarizing sample



Photodiode output



Depolarization

⇓

Field orthogonality breaking

⇓

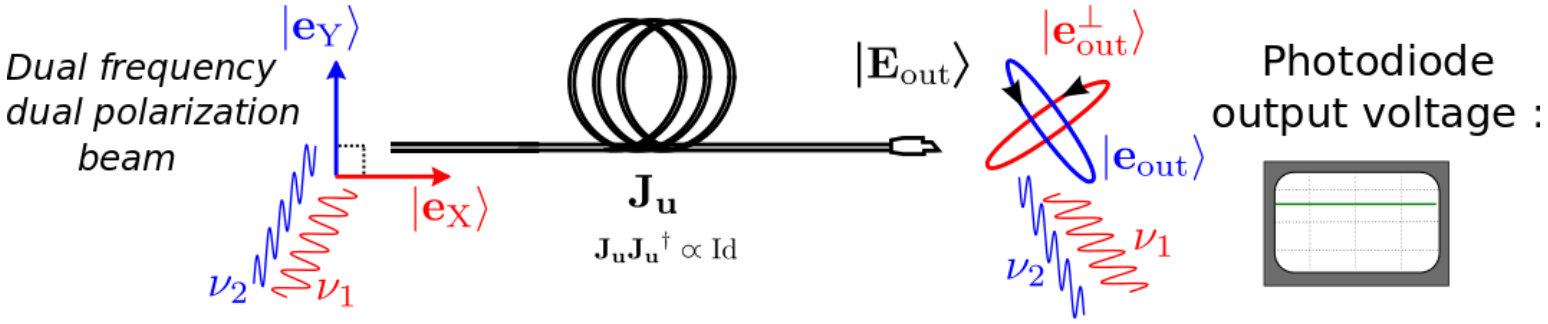
RF beatnote at Δν such that

$$C_{\text{out}}^{\Delta\nu,\,0} \triangleq \frac{P_{\text{out}}^{\Delta\nu}}{P_{\text{out}}^{0}} = 1 - \text{DOP}^2$$

Alouini, Fade, Patent FR11.5552 (2011)

Depolarization Sensing by Orthogonality Breaking (DSOB)

- Endoscopic delivery of light probe beam



- Fiber endoscope is essentially a linear retarder: unitary Jones matrix

Field orthogonality is preserved through unitary Jones matrices

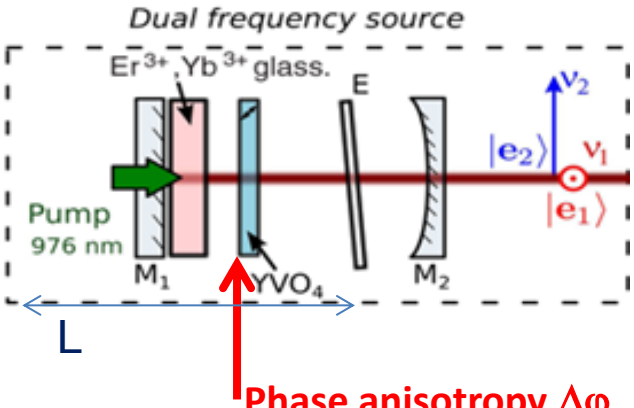
DSOB technique can be succesfully performed regardless of SOP modifications by the endoscope

➡ **Adapted to endoscopic applications**

Alouini, Fade, Patent FR11.5552 (2011)

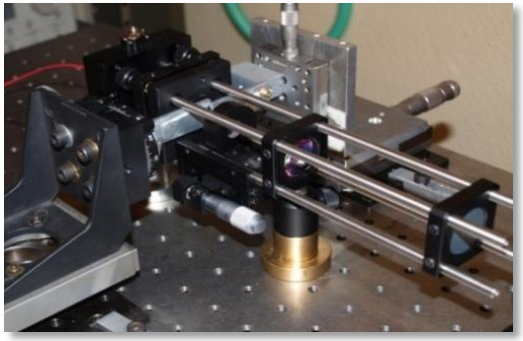
Proposed approach: realization

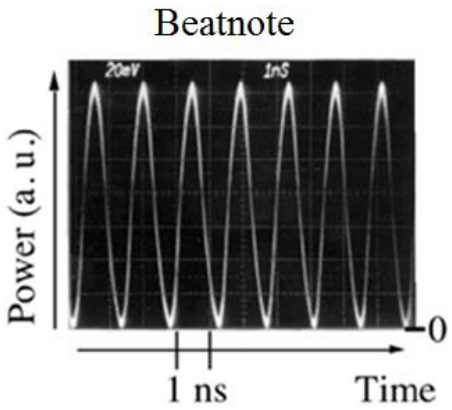
DSOB dedicated optical source: dual-frequency laser



$$\Delta\nu = \nu_2 - \nu_1 = FSR\,\frac{\Delta\varphi}{\pi}$$

where $FSR = \dfrac{c}{2L}$





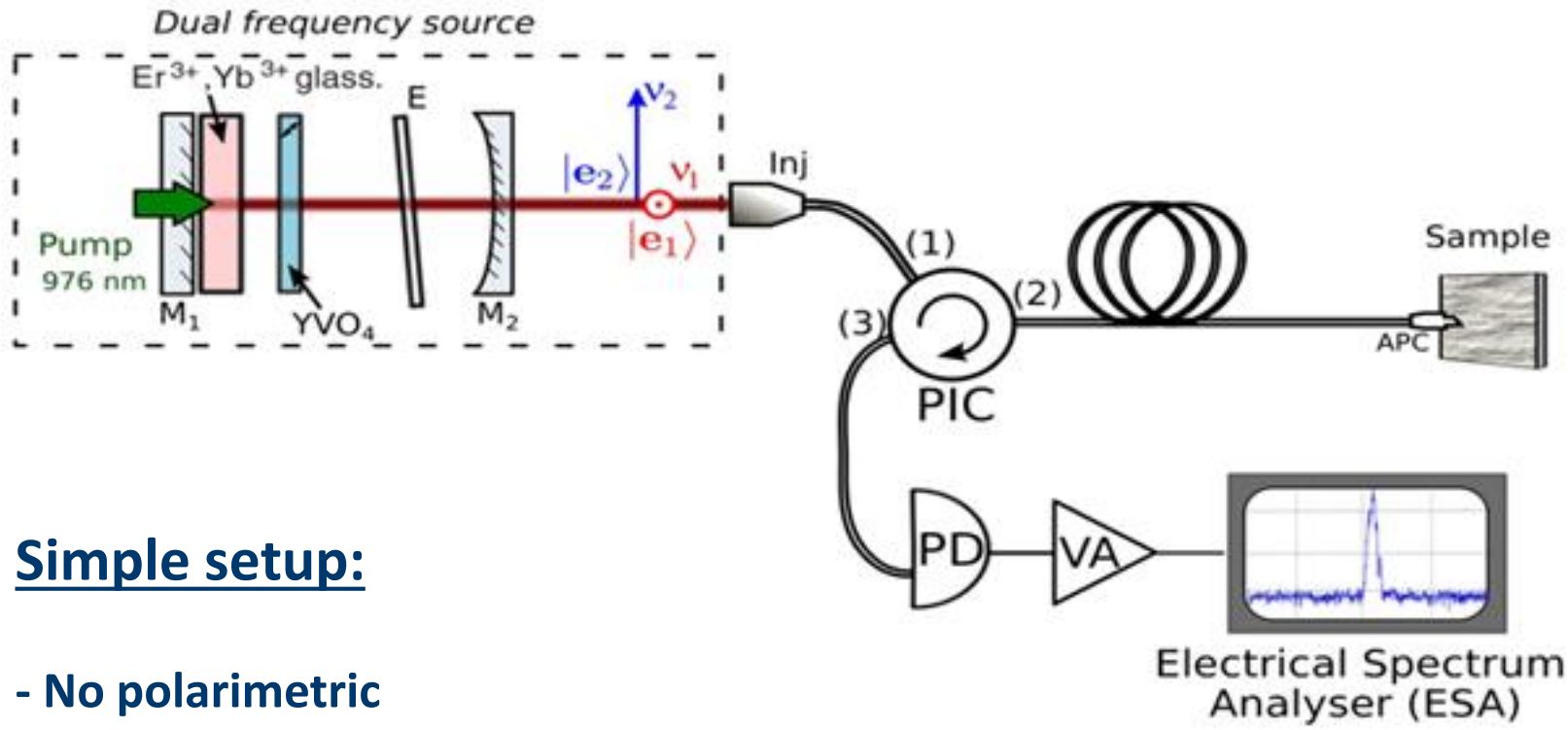
Frequency difference tunable from a few MHZ up to 40 GHz

Brunel et al. Opt. Rev. **4**, 550 (1997)

Alouini et al. Photon. Technol. Lett. **13**, 367 (2001)

Proposed approach: realization

Fibred test setup @ 1.5 µm:



Simple setup:

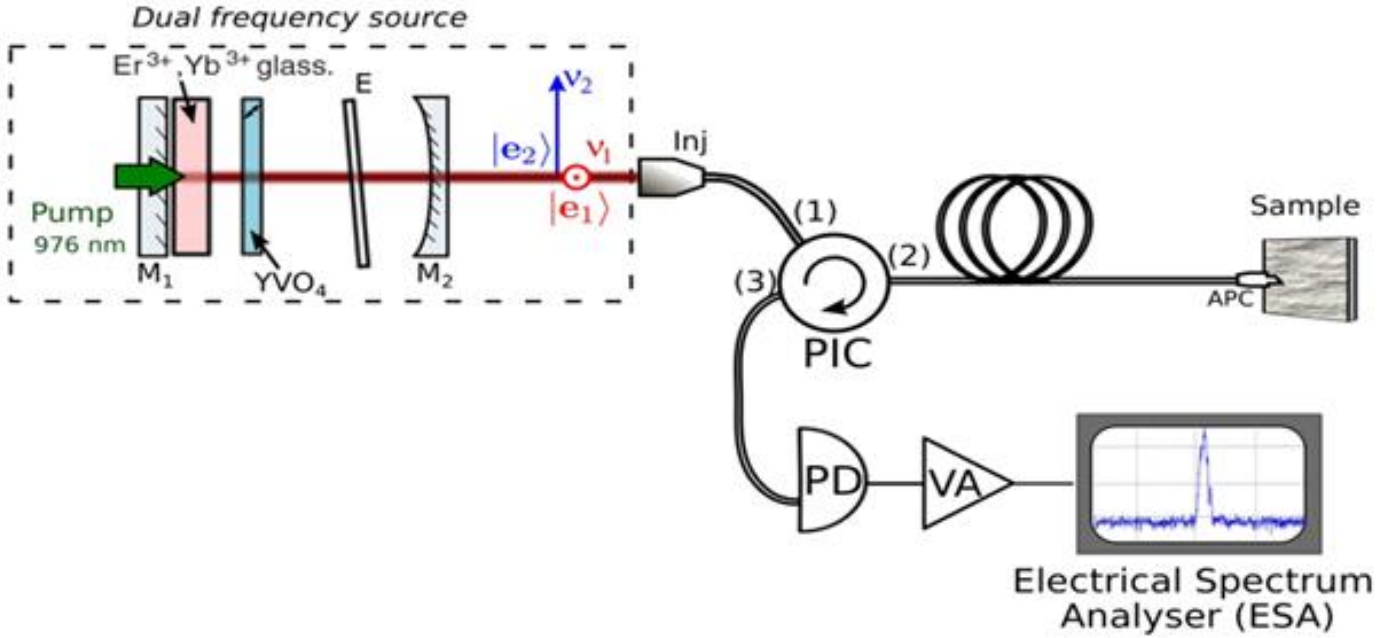
- No polarimetric components required

- Easily adaptable to commercial endoscopes

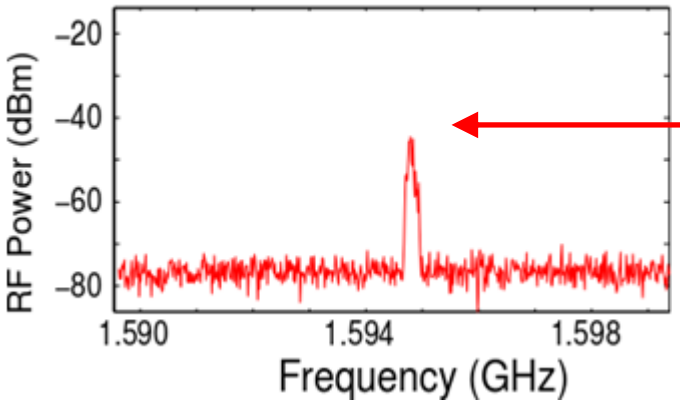
Fade and Alouini, Phys. Rev. Lett. **109**, 043901 (2012)

Proposed approach: realization

Fibred test setup @ 1.5 µm:



Mirror

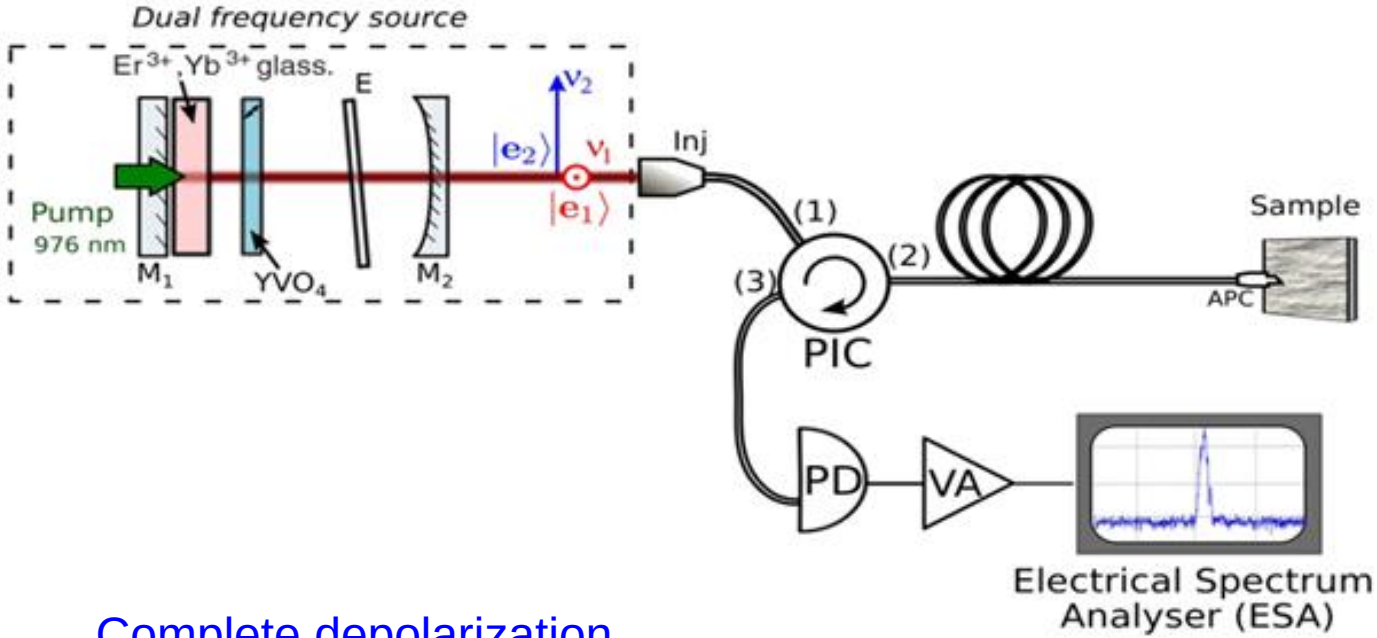


Residual signal at $\Delta\nu$ due to polarimetric imperfections in the optical circulator

Fade and Alouini, Phys. Rev. Lett. **109**, 043901 (2012)

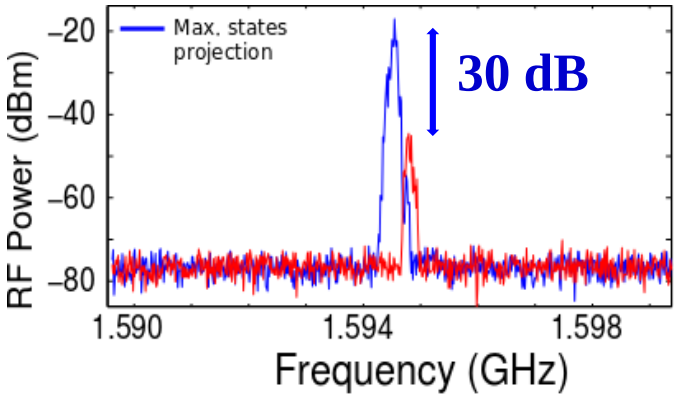
Proposed approach: realization

Fibred test setup @ 1.5 µm:



Perfect depolarizer

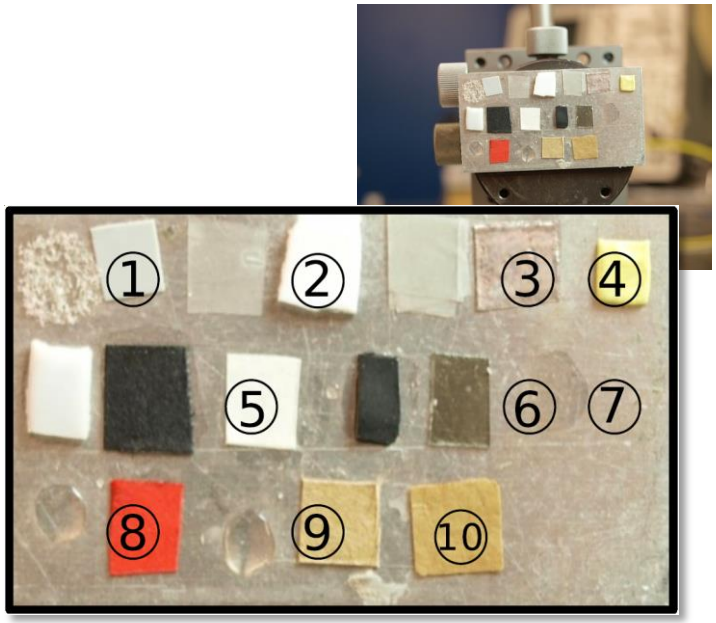
Complete depolarization



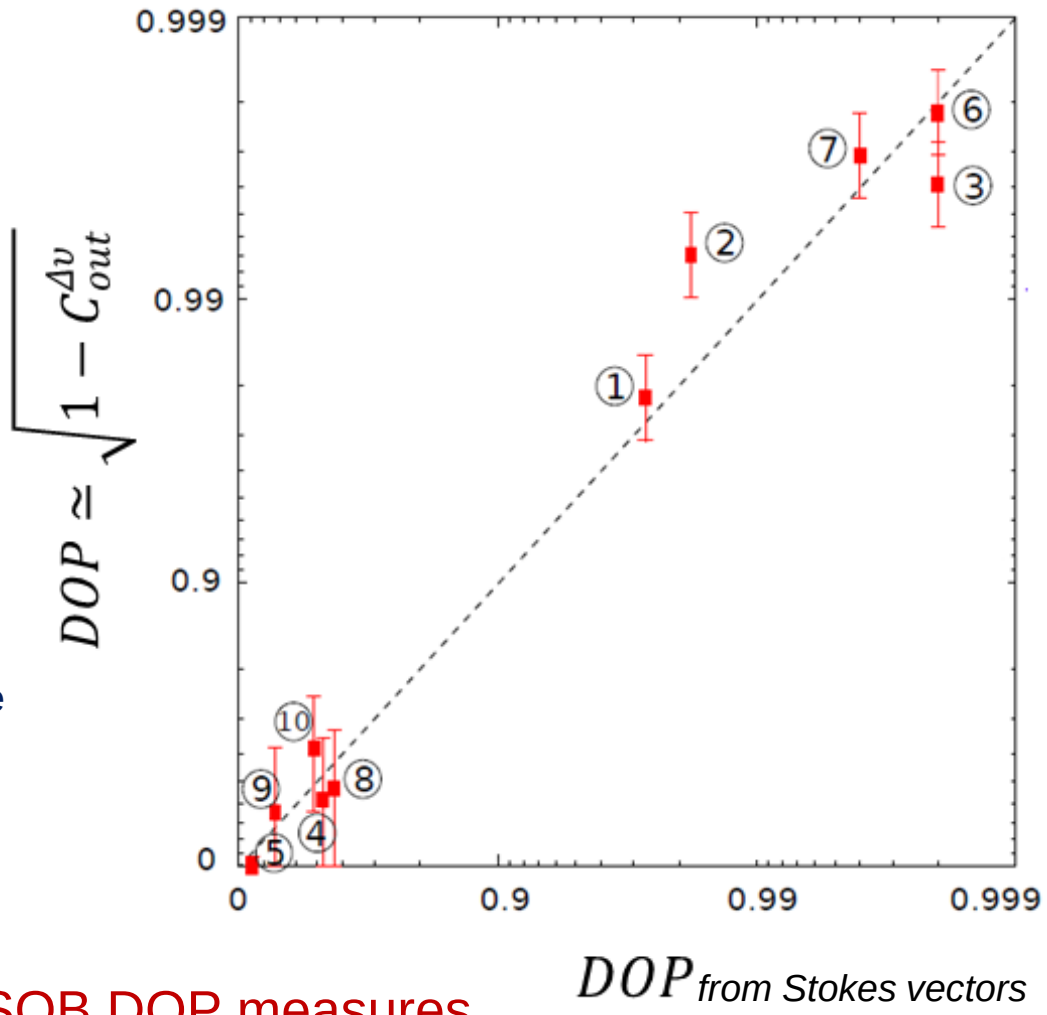
- Heterodyne detection ⇒ high SNR
- 30 dB dynamic range: 3 orders of magnitude
- The setup is still operating with 20 km fiber!

Fade and Alouini, Phys. Rev. Lett. **109**, 043901 (2012)

Experimental results



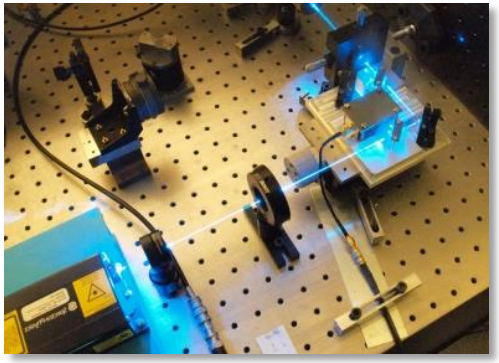
1: Grey tape
2: White plastic (PVC)
3: Metal adhesive
4: Adhesive paste
5: White paper
6: Dry cyanoacrylate glue
7: Aluminum
8: Red paper
9: Brown cardboard
10: Dry vegetal tissue

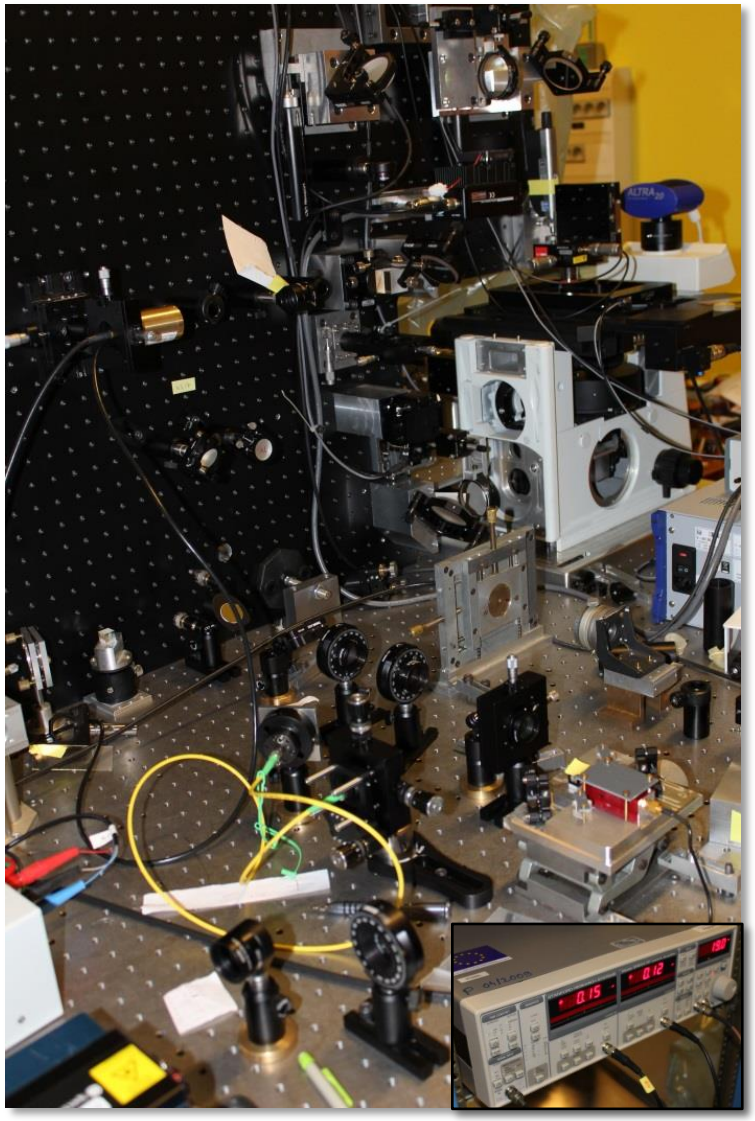


Very good agreement between DSOB DOP measures and commercial Stokes polarimeter

Fade and Alouini, Phys. Rev. Lett. **109**, 043901 (2012)

From sensing to imaging





Illumination source

- Dual-frequency orthogonally polarized modes laser @ 488 nm

Free space imaging

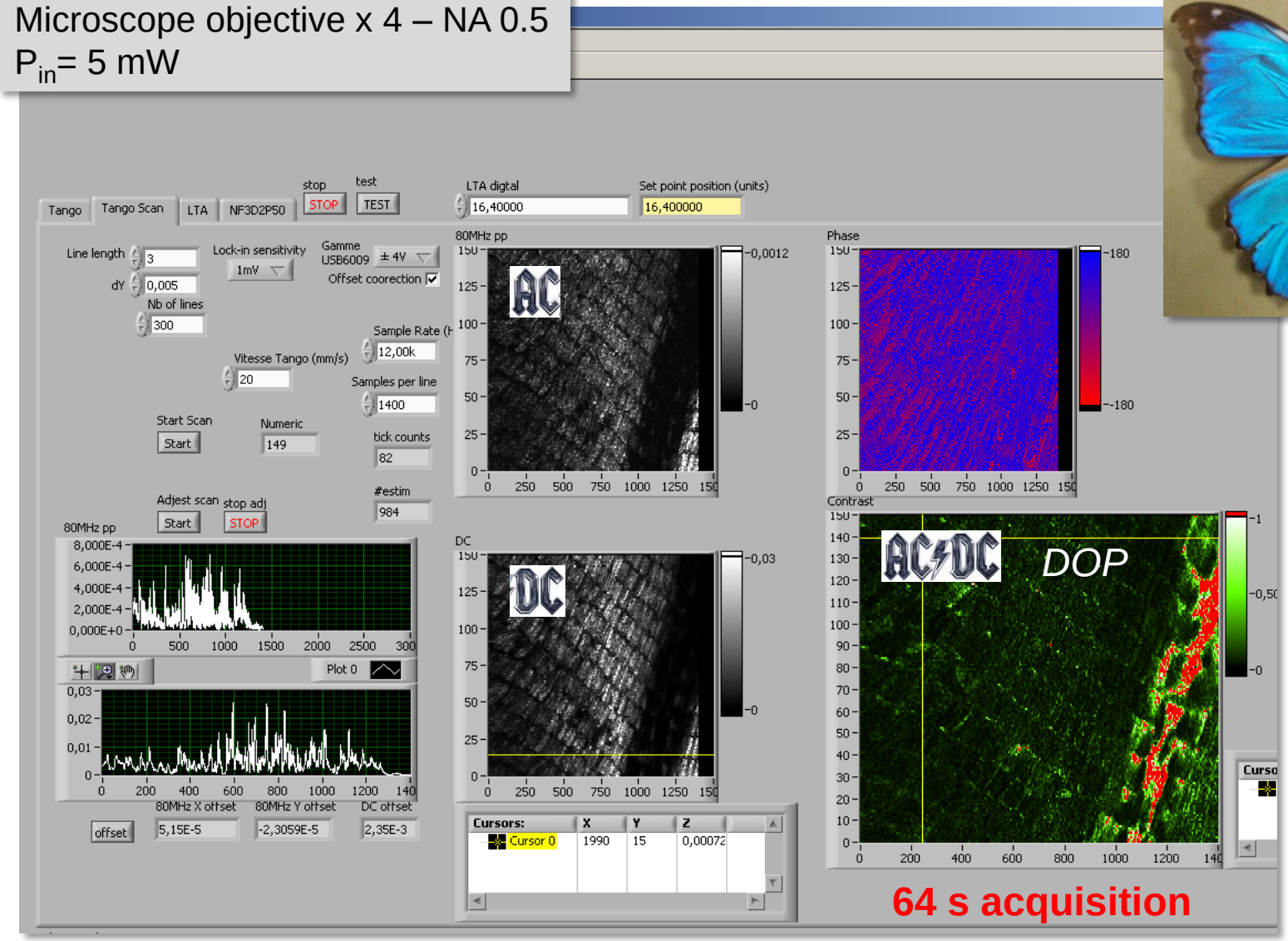
- Confocal microscope setup
- x,y motorized scanning stages

Detection

- High speed PD
- Onboard demodulation electronics (80 MHz)

From sensing to imaging

Microscope objective x 4 – NA 0.5
P_{in}= 5 mW



morpho butterfly

Acquisition time 1 min limited by the motorized stages

Conclusions and perspectives

Conclusions

DSOB: original technique using a microwave photonics approach

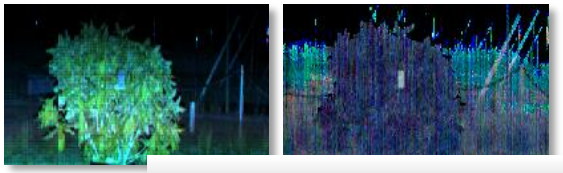
- Suitable for remote depolarization sensing through fibers
- No polarimetric components needed
- High dynamic range (heterodyne detection) & fast (< µs if $\Delta\nu$ > 100 MHz)

Highly adapted to endoscopic depolarization imaging

Perspectives

- Numerous setup architectures and materials under investigation
- Application to biomedical depolarization imaging:
  - Endoscopy and microscopy
  - Validation on samples of biological interest
- Real-time active IR polarimetric imaging

Mauna Kea Tech.



Alouini et al., Appl. Opt. **45**, 5223 (2006)

Acknowledgments

Thank you for your attention