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Centre d'optique, photonique et laser

Ultra-compact polarimeters on a silicon chip

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Outline

- Introduction
  - Performance in presence of noise
- Full-Stokes polarimeters in silicon photonics
- Spectropolarimeter on a silicon chip

Parallel processing of polarization & intensity

Fiddler Crab

Samuel P. Smithers et al., SCIENCE ADVANCES, 2019.

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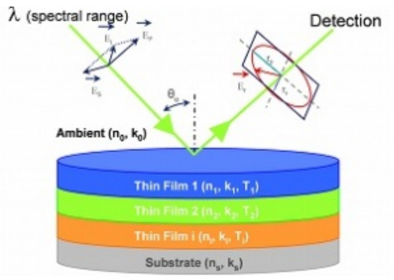
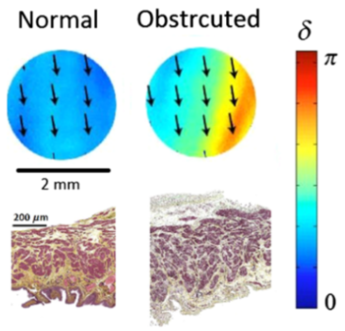
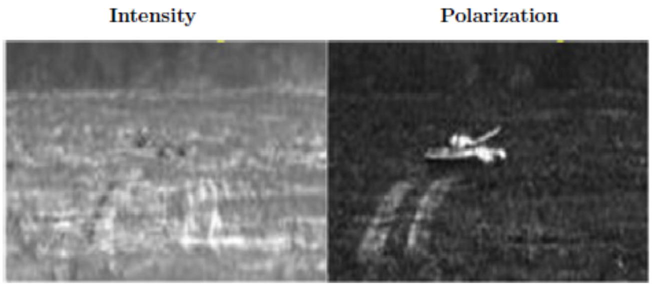
Polarization conveys some unique information

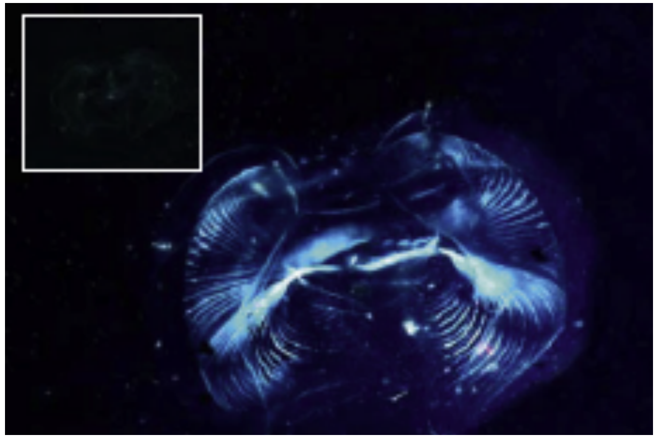
Material: optical constant



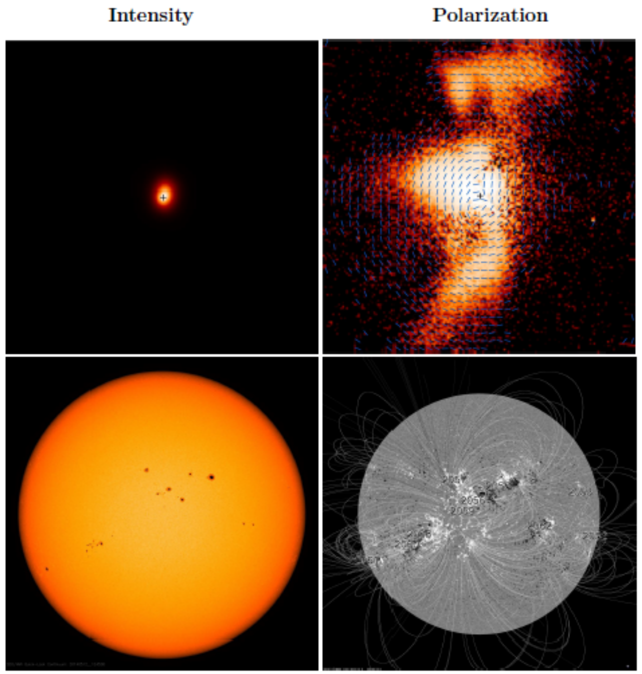


Target detection: identify the object from the background



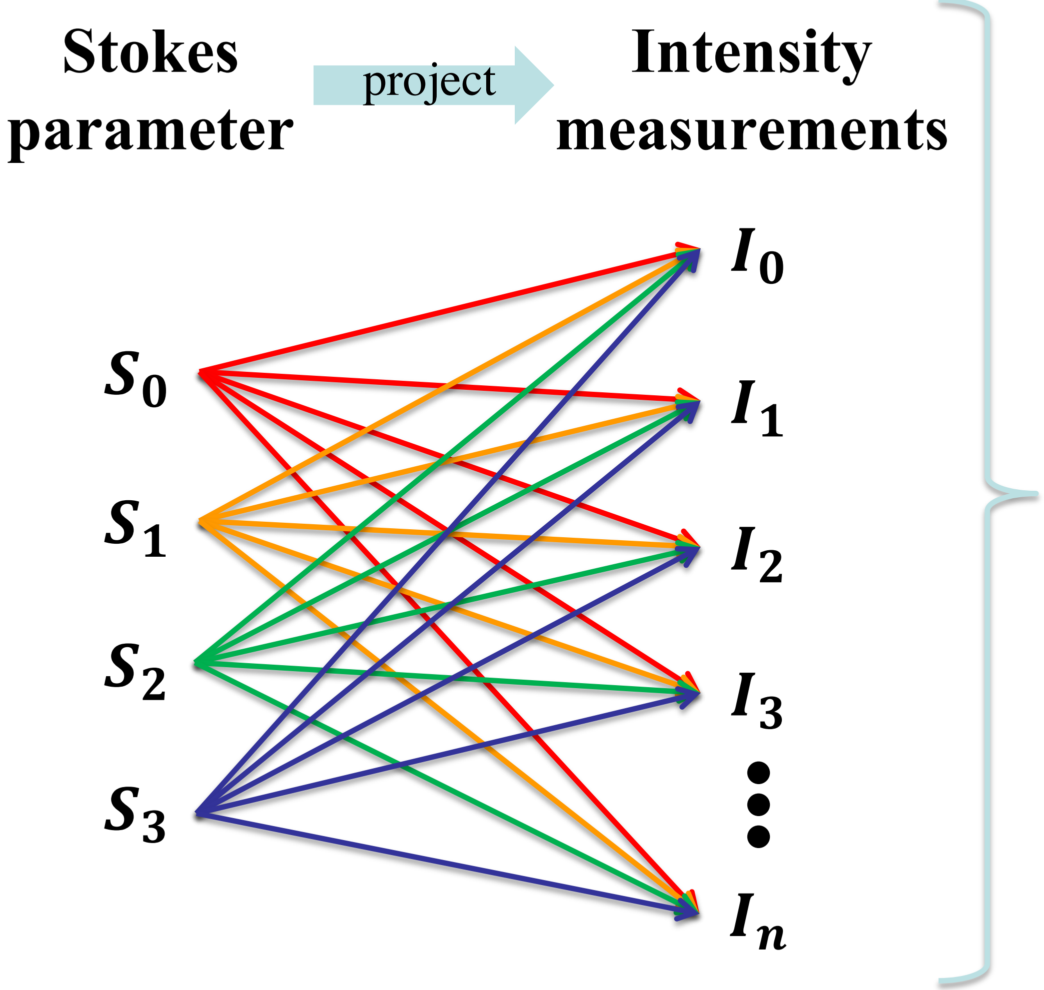


Astronomy: magnetic field distribution



[1] Wehner, R. *J Exp Biol 2001, 204, (Pt 14), 2589-96*.
[2] Wang, X.; Yan, X.; Lv, G.; Fan, T. Infrared Physics & Technology 2013, 58, 5-11.

Stokes polarimetry: measurement principle



$$\mathbf{I} = \mathbf{W} \cdot \mathbf{S}$$

$$\mathbf{S} = \mathbf{W}^{\dagger} \cdot \mathbf{I}$$

$\mathbf{W}^{\dagger}$ denotes the generalized inverse of $\mathbf{W}$

Stokes polarimetry: influence of noise

rank $(\mathbf{W}^{\dagger}) = 4$, full-Stokes vector can be reconstructed

$$\mathbf{S} = \mathbf{W}^{\dagger} \cdot \mathbf{I}$$

$$\mathbf{S}' = \mathbf{W}^{\dagger} \cdot (\mathbf{I} + \Delta\mathbf{I}) \quad \Rightarrow \quad \Delta\mathbf{S} = \mathbf{W}^{\dagger} \cdot \Delta\mathbf{I}$$

$\Delta\mathbf{I}$ is Gaussian noise:

$$\frac{\|\Delta\mathbf{S}\|}{\|\mathbf{S}\|} \leq \|\mathbf{W}^{\dagger}\| \cdot \|\mathbf{W}\| \frac{\|\Delta\mathbf{I}\|}{\|\mathbf{I}\|}$$

Condition number:
Minimum value $\sqrt{3}$

$\Delta\mathbf{I}$ is Poisson noise:
$(\Delta\mathbf{I})^2 \propto \mathbf{I}$

$$E(\Delta\mathbf{S}(\Delta\mathbf{S})^T) = \mathbf{W}^{\dagger} \cdot \begin{pmatrix} (\mathbf{W}\mathbf{S})_1 & 0 & 0 & & 0 \\ 0 & (\mathbf{W}\mathbf{S})_2 & 0 & \cdots & 0 \\ 0 & 0 & (\mathbf{W}\mathbf{S})_3 & & 0 \\ & \vdots & & \ddots & \vdots \\ 0 & 0 & 0 & \cdots & (\mathbf{W}\mathbf{S})_n \end{pmatrix} \cdot (\mathbf{W}^{\dagger})^T$$

Polarization dependence

Stokes polarimetry: optimal frame

Gaussian noise

κ : condition number

Poisson noise:

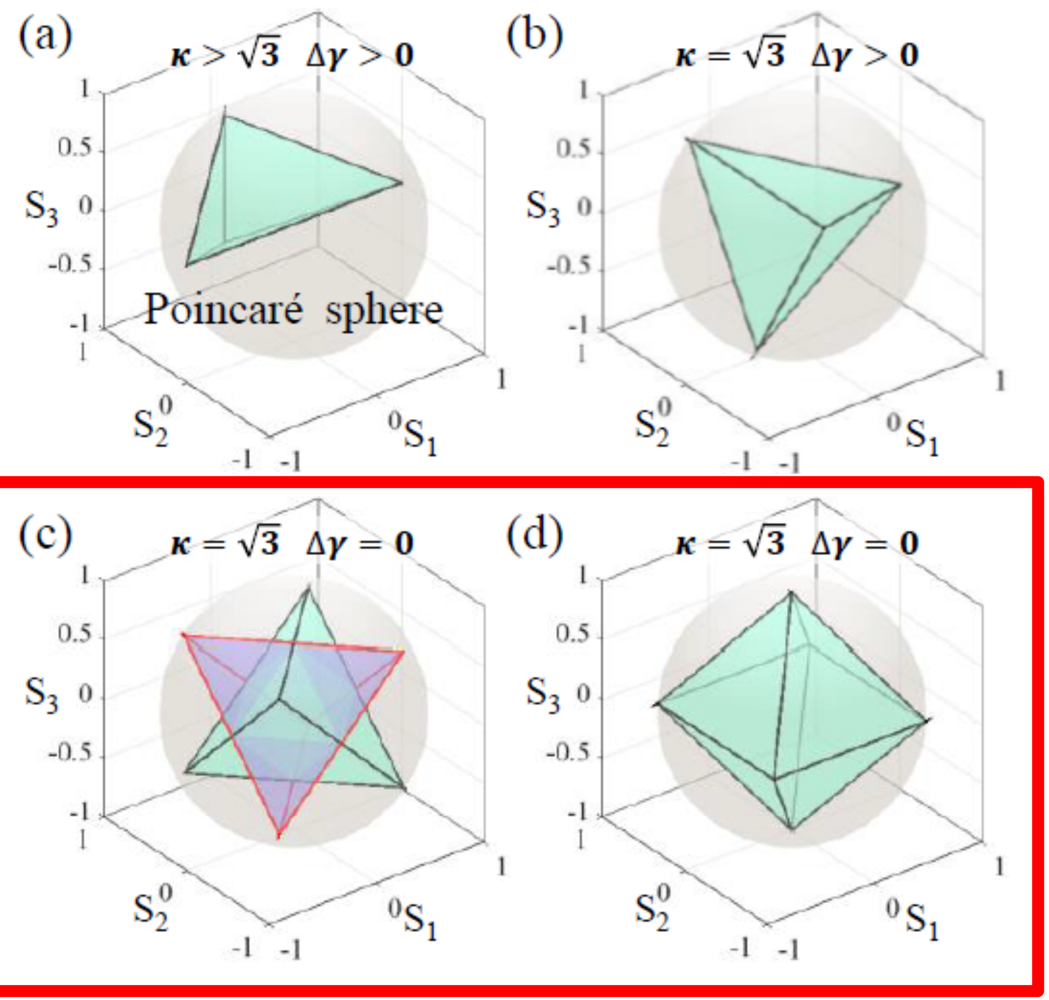
$$\Delta\gamma = E(\Delta S(\Delta S)^T)_{max} - E(\Delta S(\Delta S)^T)_{min}$$

$$W_{i1}^2 = W_{i2}^2 + W_{i3}^2 + W_{i4}^2 = 1$$

Measurement frame:

$$\mathbf{w}_i = (W_{i2}, W_{i3}, W_{i4})$$

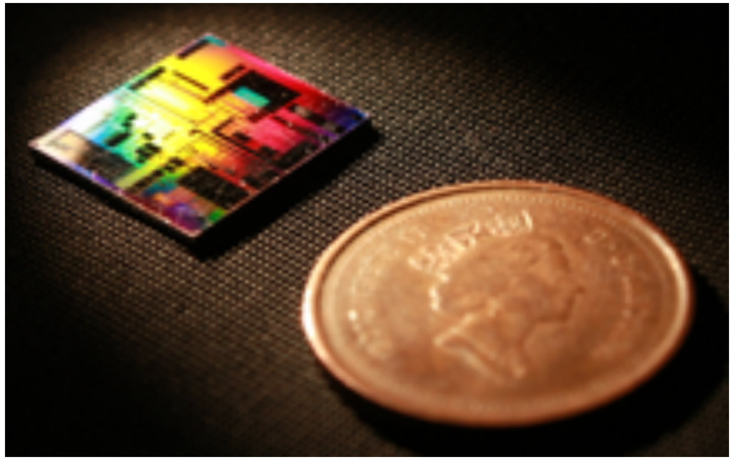
A polyhedron can be built



[1] M. R. Foreman, A. Favaro, and A. Aiello, Physical review letters 115, 263901 (2015).

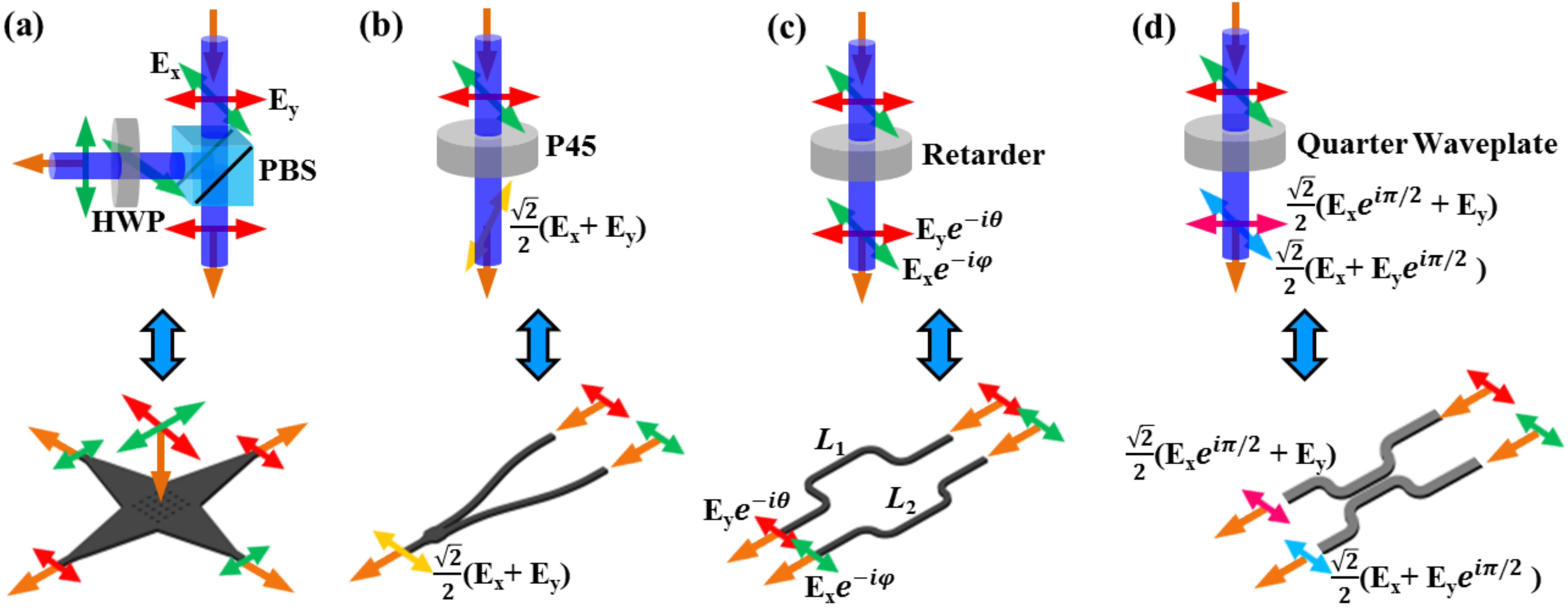
Polarimeters in silicon photonics: why?

- Large
- Expensive
- Non-portable

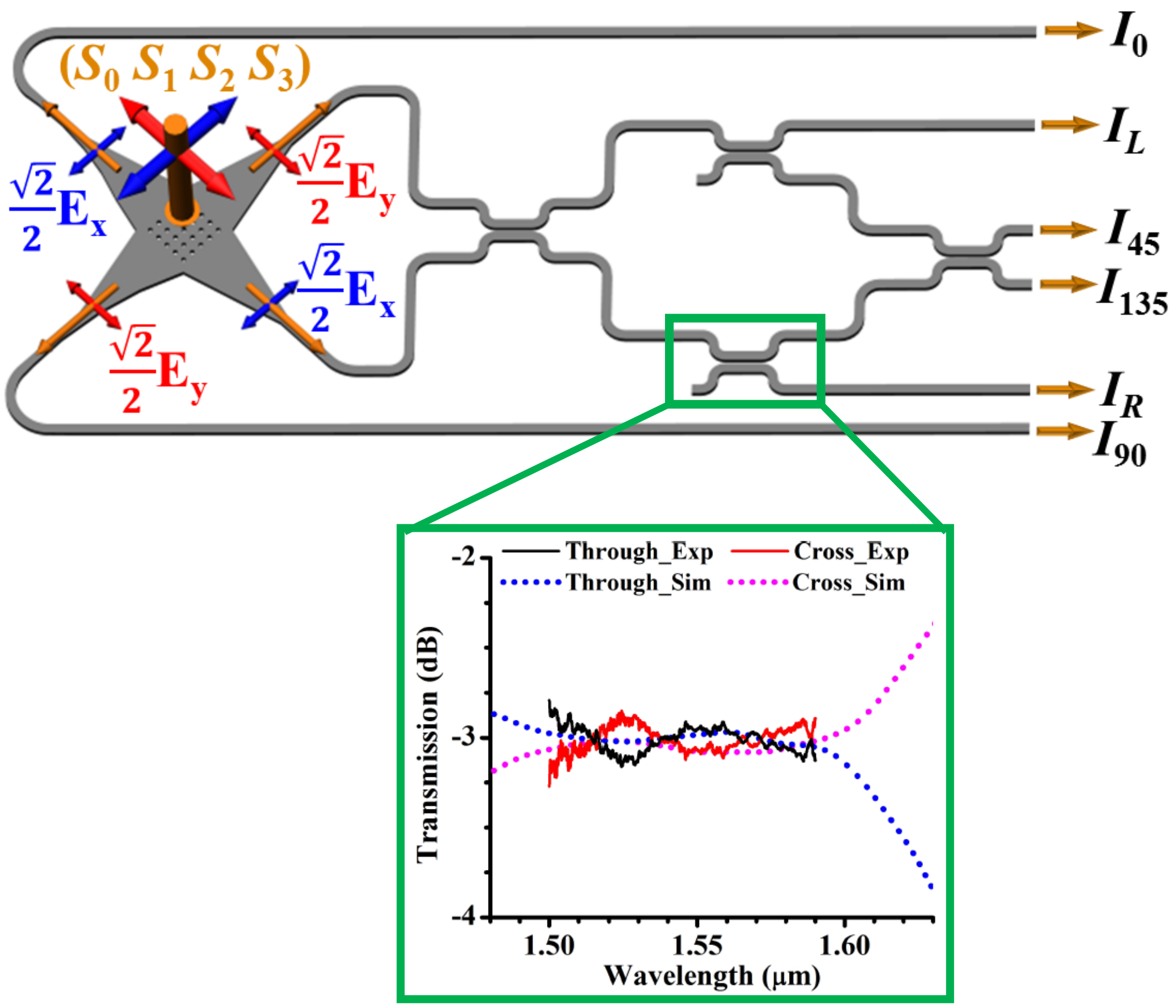


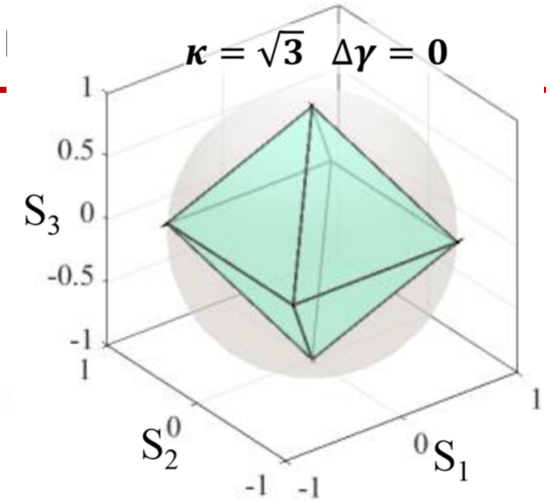
- Compact
- Low-cost
- Portable
- COMS-compatible
- Low power consumption

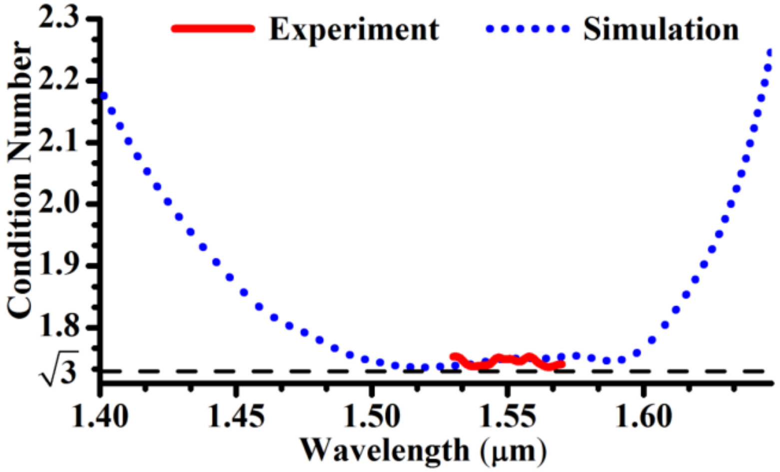
Polarimeters in silicon photonics: how?



Polarimeter with 6 photodetectors

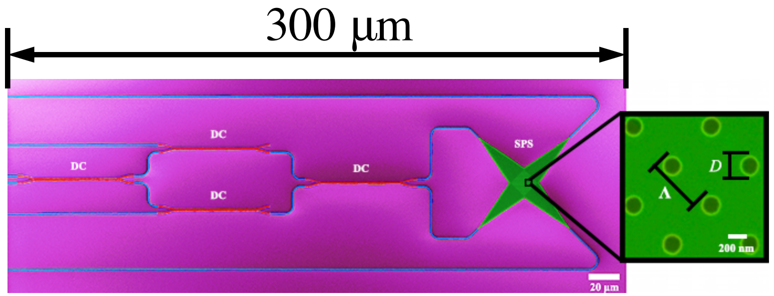


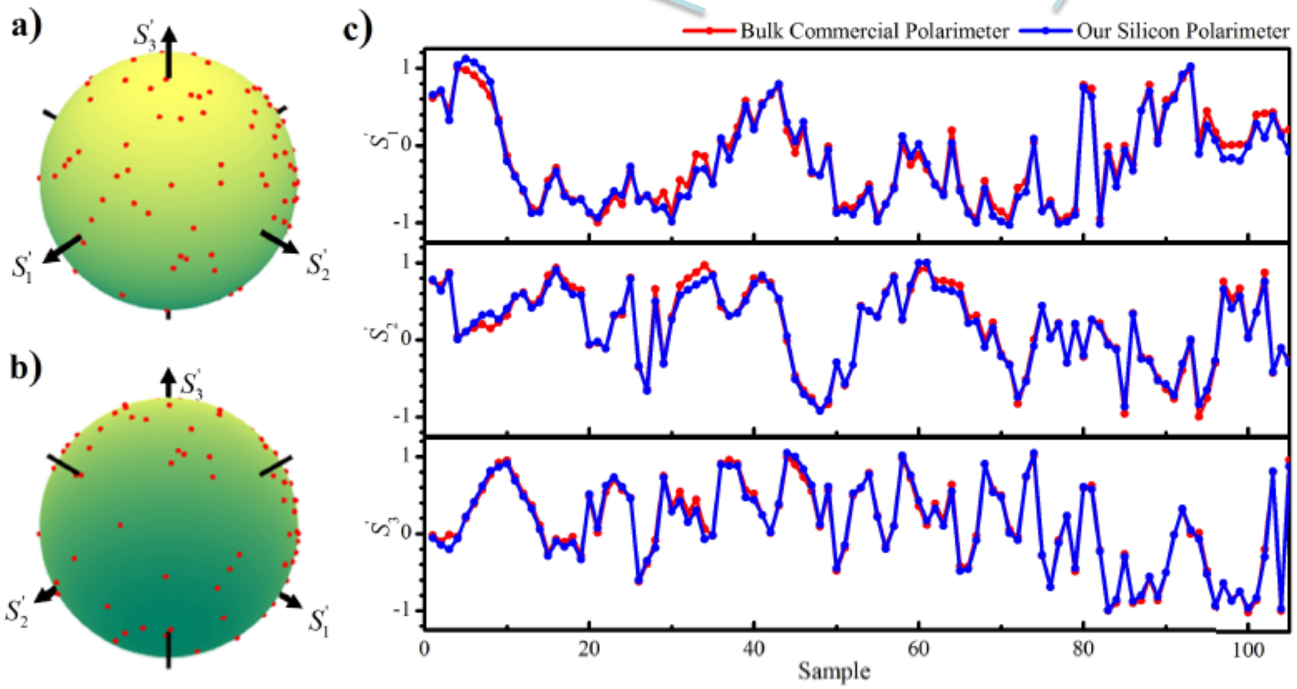




[1] Lin Z, et al. Optics express, 2019, 27(4): 4867-4877.

Polarimeter with 6 PDs: experiment





[1] Lin Z, et al. Optics express, 2019, 27(4): 4867-4877.

Polarimeters with 4 PDs

The advantage of 6 intensity measurements to 4 intensity measurements:

- Less photodetectors
- Equally Weighted Variance (EWV):

Poisson noise: $\mathrm{EWV}_{Poi} = 10 S_0$

Gaussian noise: $\mathrm{EWV}_{add} = 10 N \sigma_n^2$

Number of intensity measurements

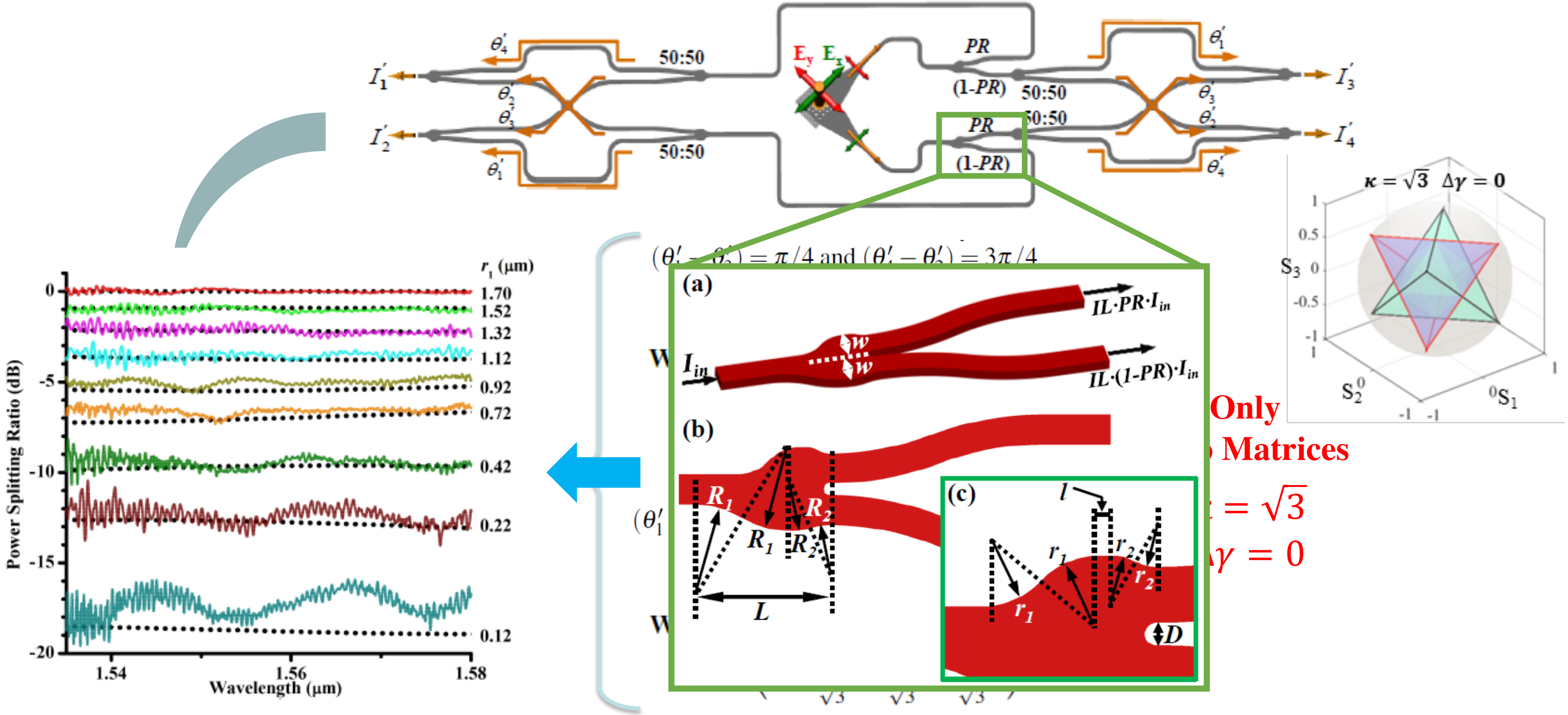
Division of amplitude

4 PDs

$\Delta\gamma = 0, \kappa = \sqrt{3}$

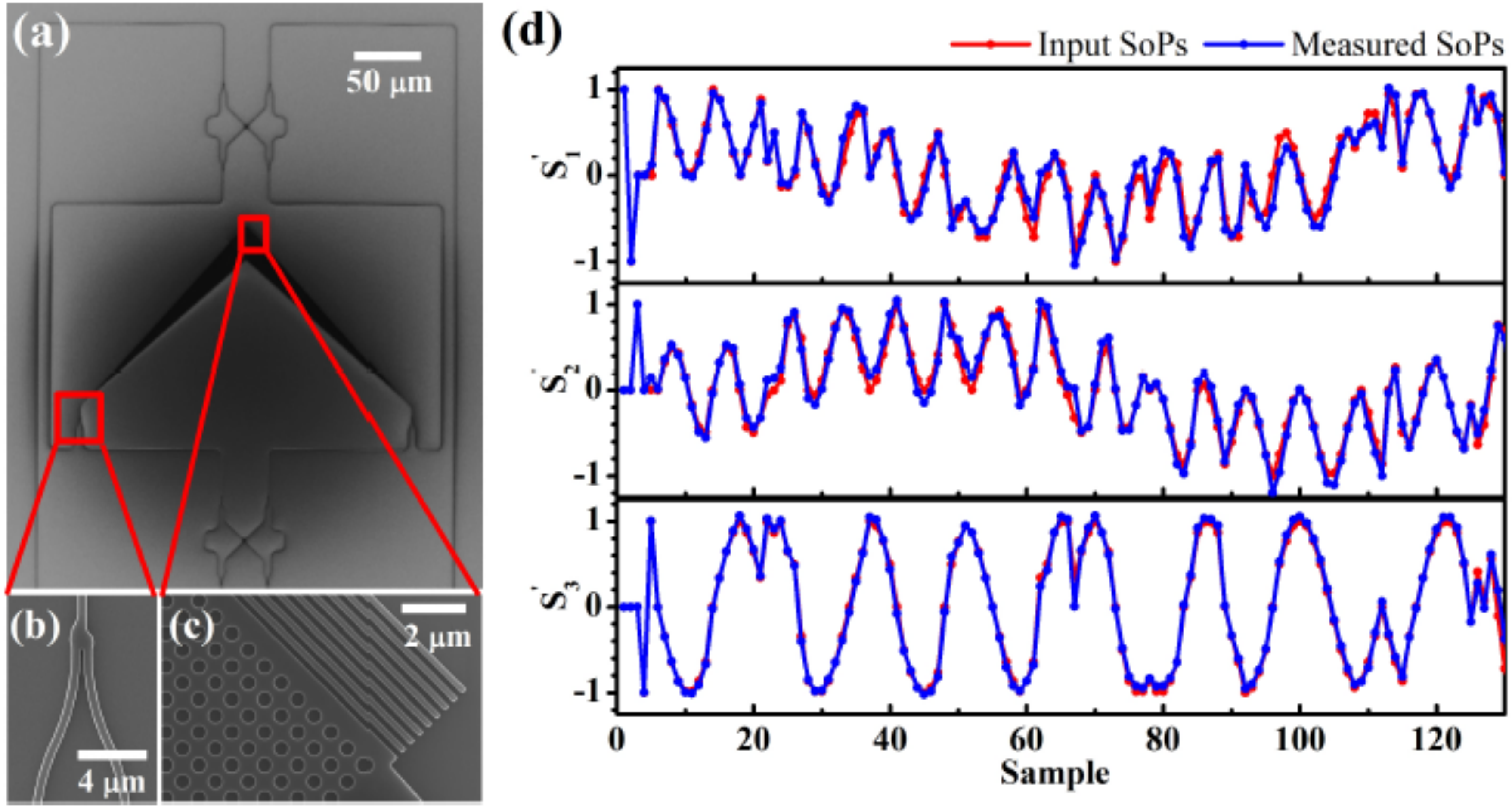
Optimal performance

Polarimeters with 4 PDs: design



[1] Wei Shi, et al. APL Photonics 4.10 (2019): 100806.
[2] *Z. Lin and W. Shi, "Broadband, low-loss silicon photonic Y-junction with an arbitrary power splitting ratio," Optics Express 27, 14338–14343 (2019).*

Polarimeters with 4 PDs: experiment

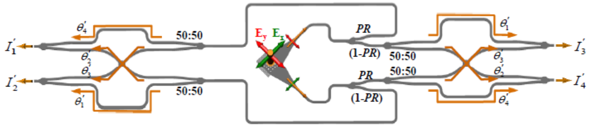


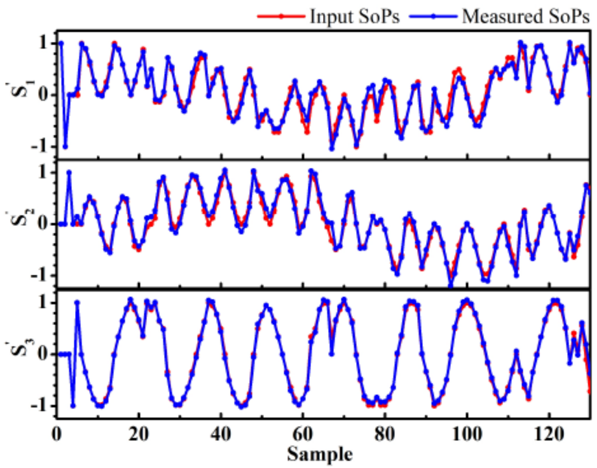
[1] Wei Shi, et al. APL Photonics 4.10 (2019): 100806.

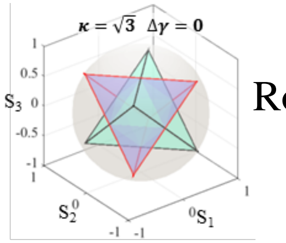
[2] *Z. Lin and W. Shi, "Broadband, low-loss silicon photonic Y-junction with an arbitrary power splitting ratio," Optics Express 27, 14338–14343 (2019).*

Polarimeters with 4 photodetectors

Optimal

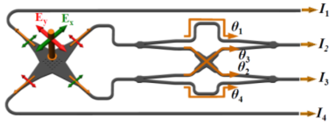


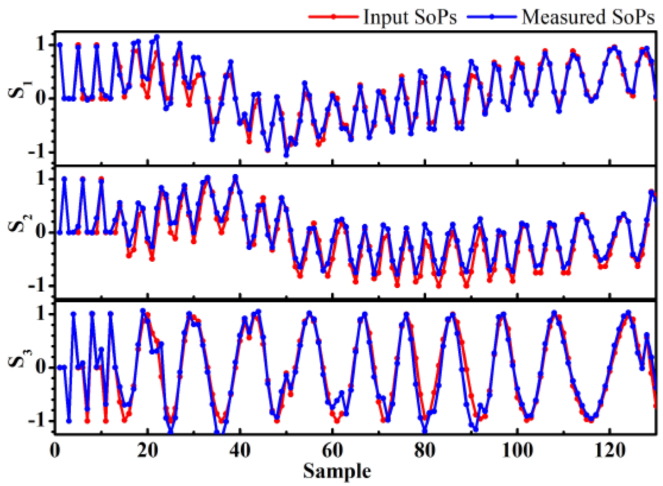


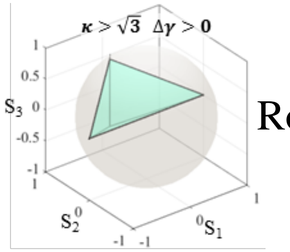


Root-mean-square=0.081

General







Root-mean-square=0.147

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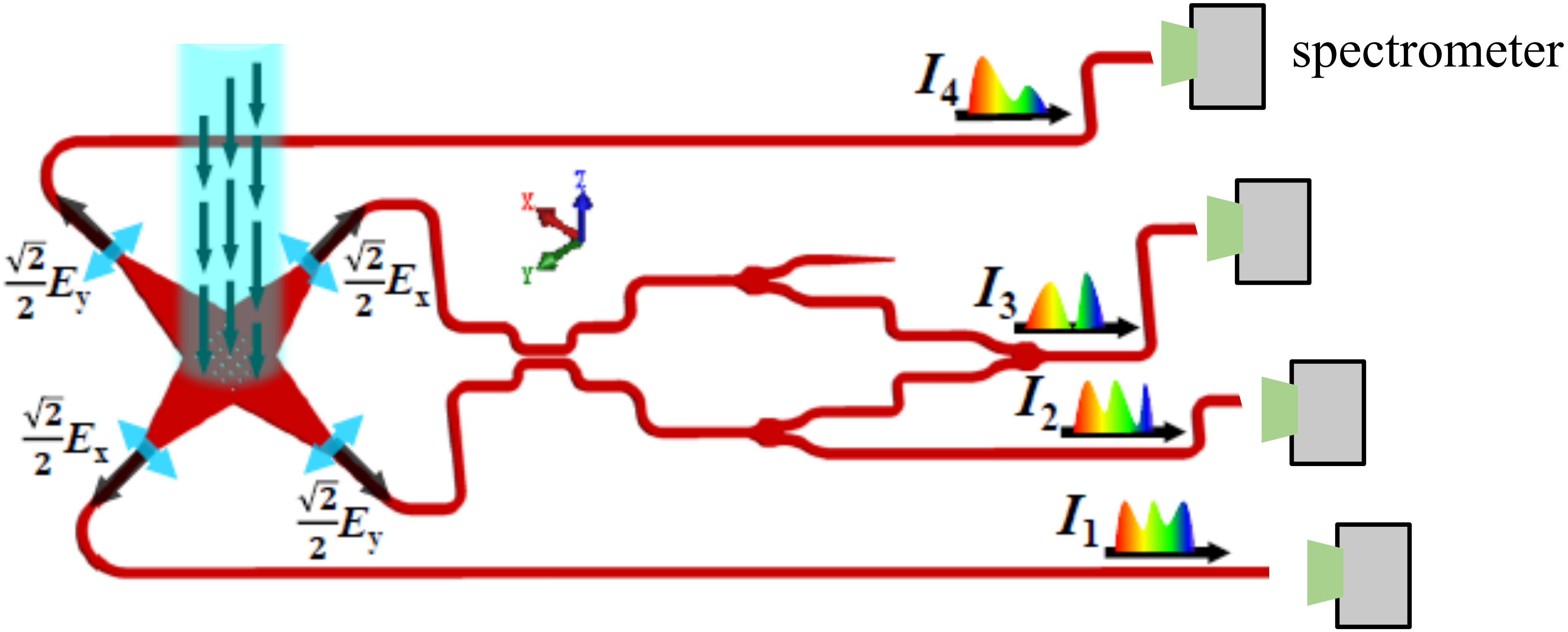
[1] Wei Shi, et al. APL Photonics 4.10 (2019): 100806.

Spectropolarimeter



[1] Wei Shi, et al. under review

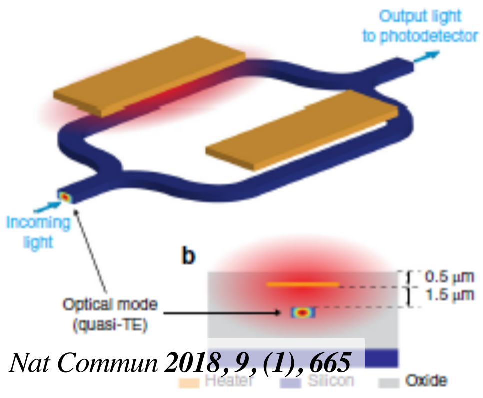
Integrated spectrometers

Fourier transform spectrometers

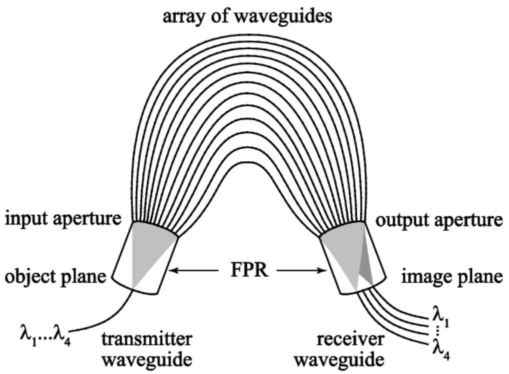
AWG spectrometers

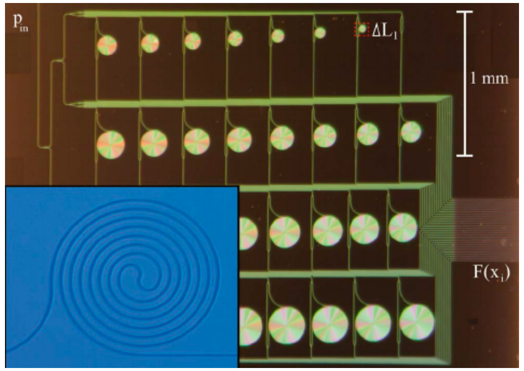
Spatial heterodyne FTS

Digital FTS

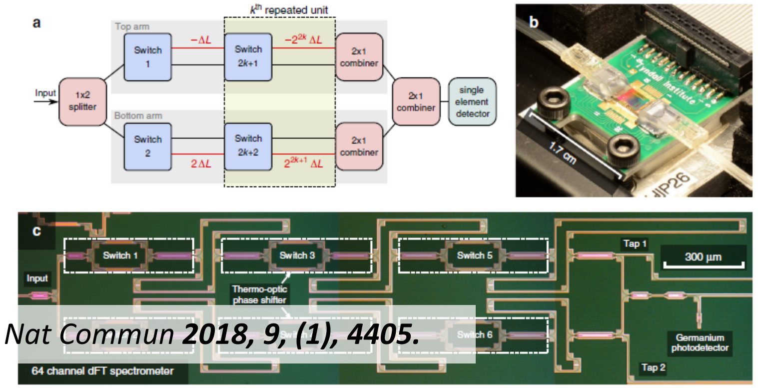


Nat Commun ***2018, 9, (1), 665***





Optics Letters 2019, 706 (5).



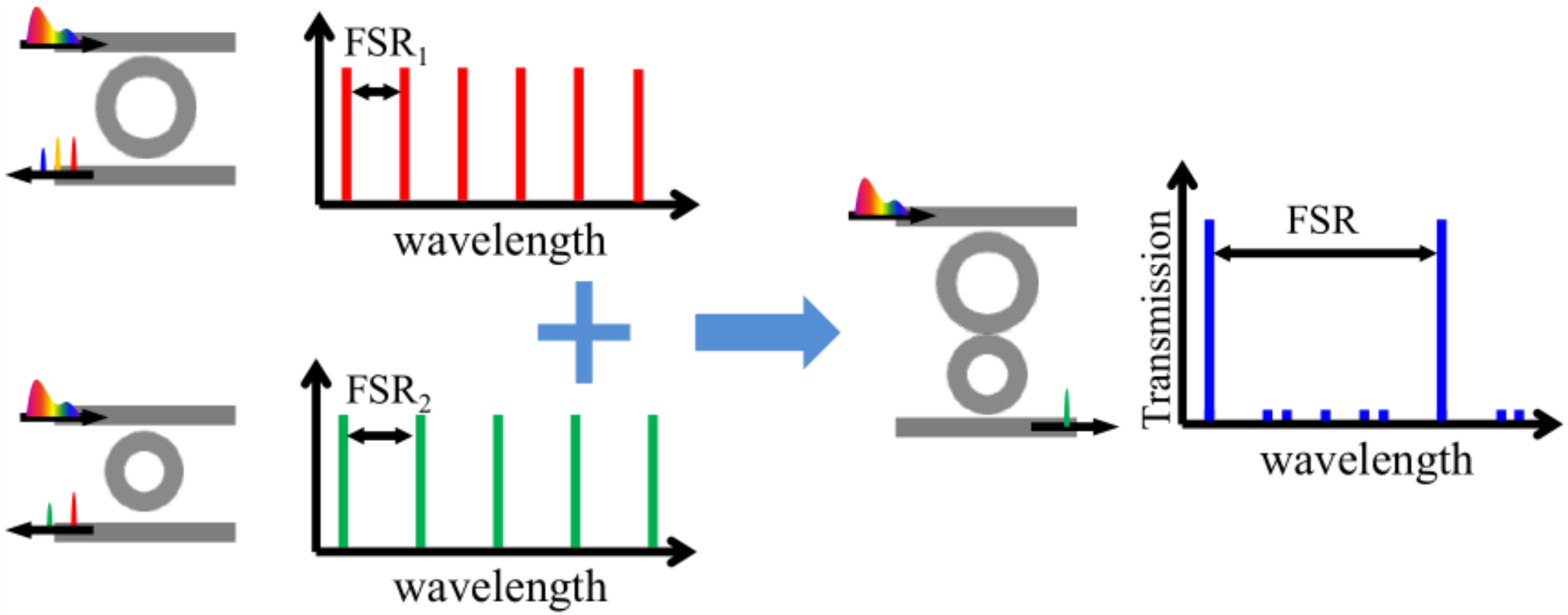
Nat Commun ***2018, 9, (1), 4405.***

2W tuning

Many PDs
Resolution-BW trade-off

Complex control

Spectropolarimeter : design of spectrometer



$$\mathrm{FSR} = \frac{\mathrm{FSR}_1 \cdot \mathrm{FSR}_2}{|\mathrm{FSR}_1 - \mathrm{FSR}_2|} = \frac{\lambda^2}{\pi |D_1 n_{g2} - D_2 n_{g1}|} \approx \frac{\lambda^2}{\pi n_{g1} |D_1 - D_2|}$$

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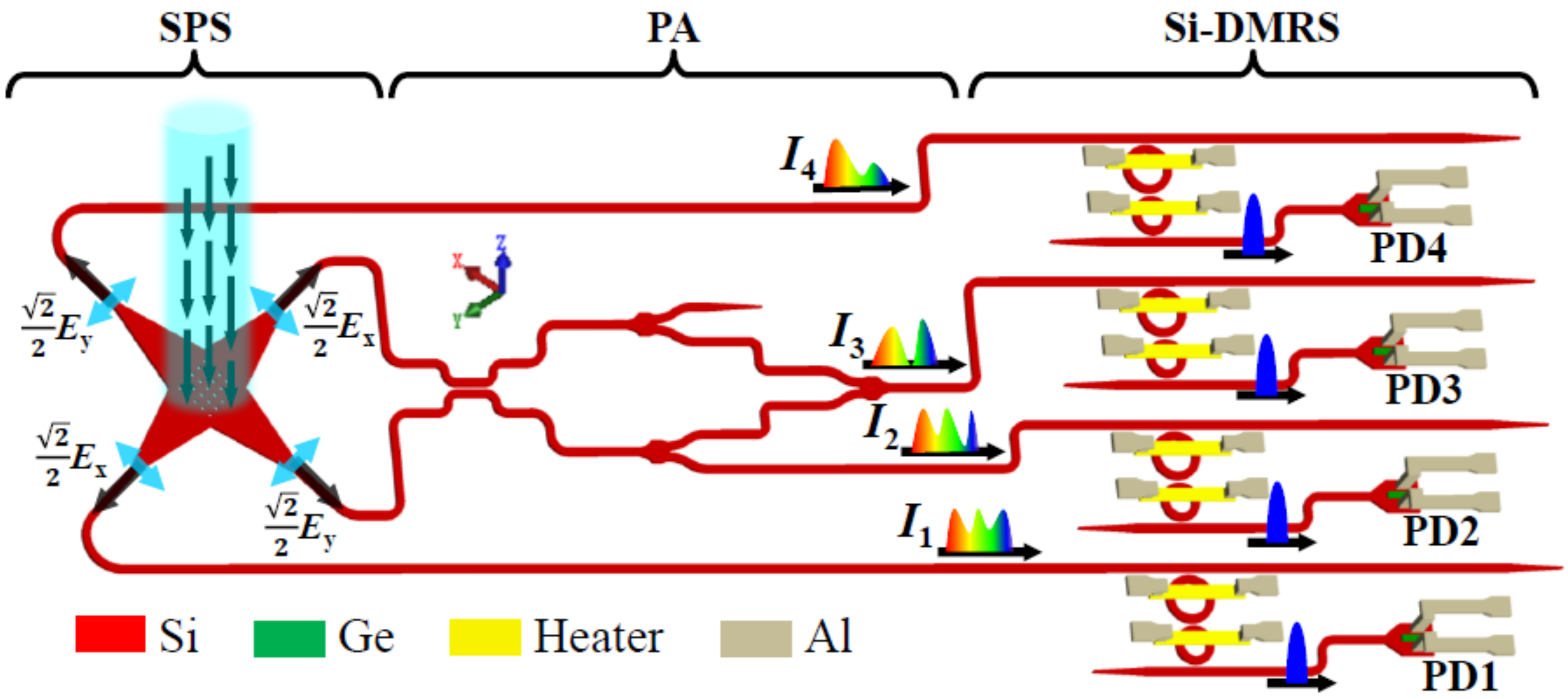
[1] Wei Shi, et al. under review

Spectropolarimeter : design of spectrometer



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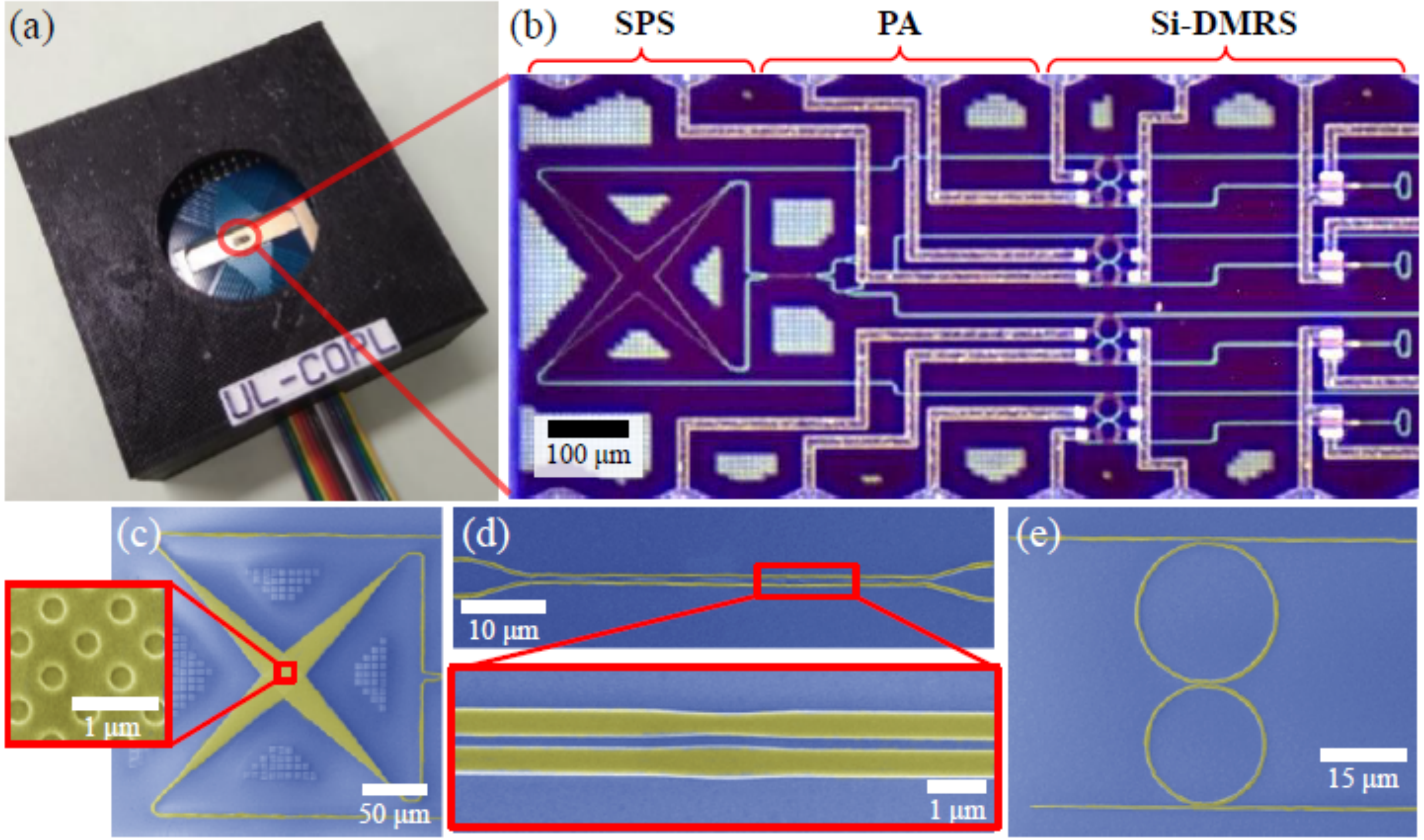
[1] Wei Shi, et al. under review

Spectropolarimeter : prototype



[1] Wei Shi, et al. under review

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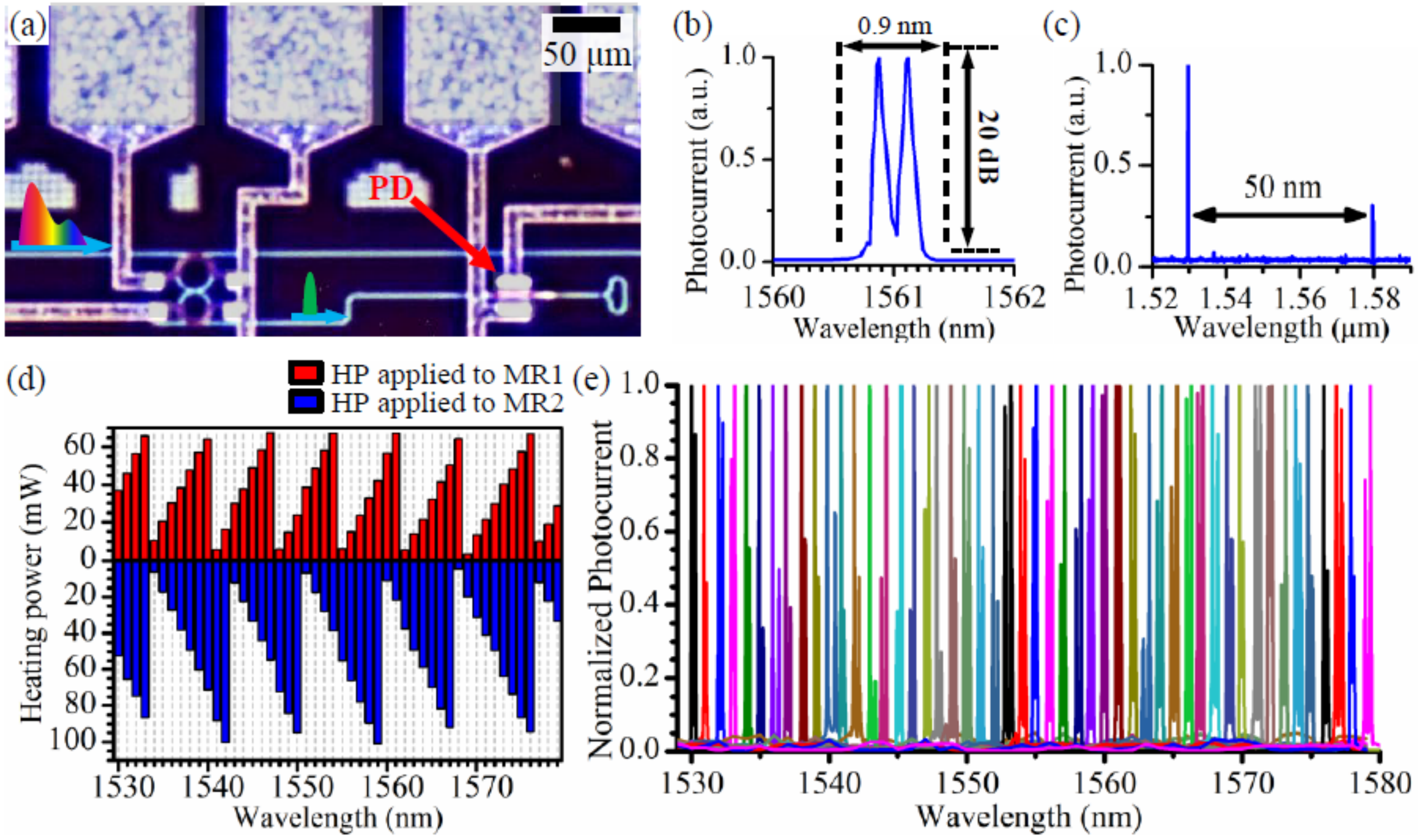
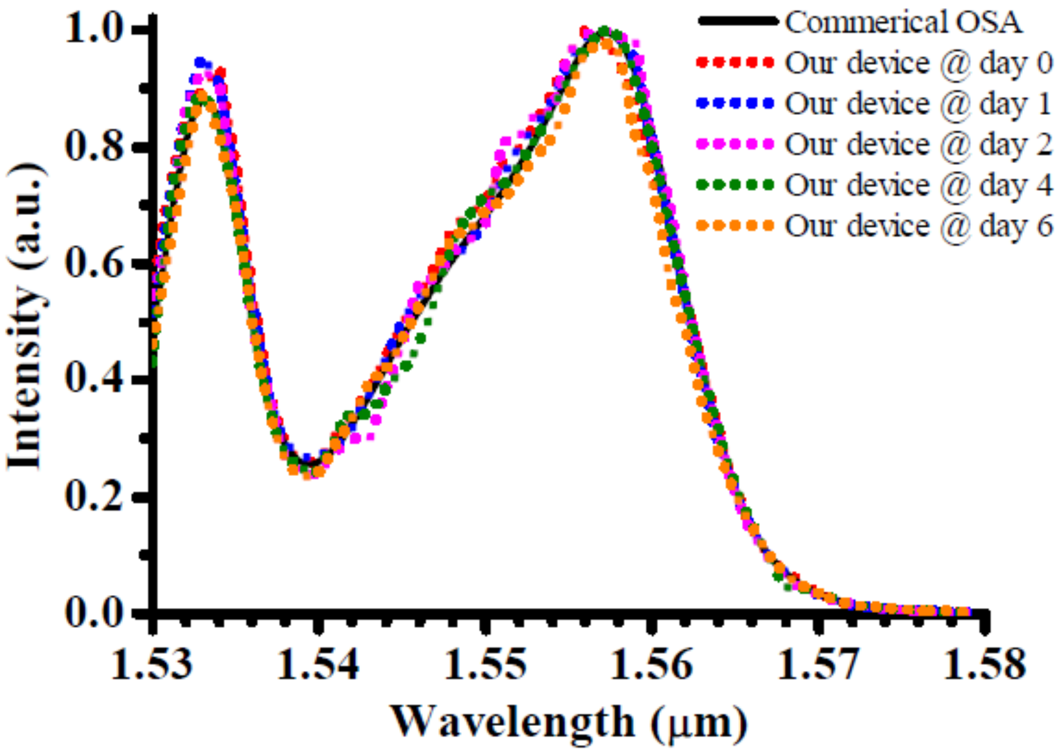
Calibration of the spectrometer



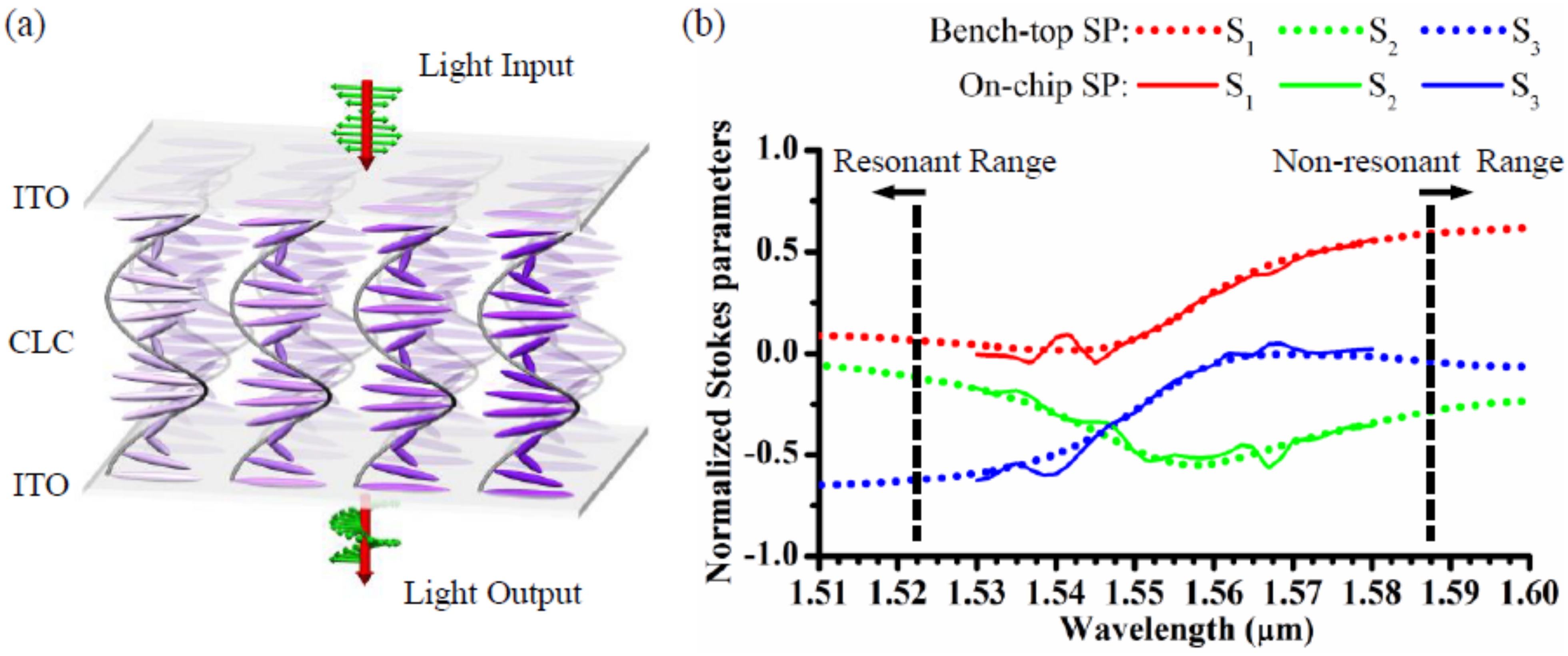
[1] Wei Shi, et al. under review

Performance of the spectrometer



[1] Wei Shi, et al. under review

Characterization of a chiral material



[1] Wei Shi, et al. under review

Summary

- Ultra-compact full-Stokes polarimeter using a CMOS-compatible fabrication process.
  - The optimal frame (in presence of both Gaussian and Poisson noises) is achieved, for the first time, in a silicon photonic circuit.
- Spectropolarimeter: on-chip probing information carried by both wavelength and polarization
- Promising for a broad application thanks to their compact footprint, low power consumption, low cost, and robustness

Thanks!

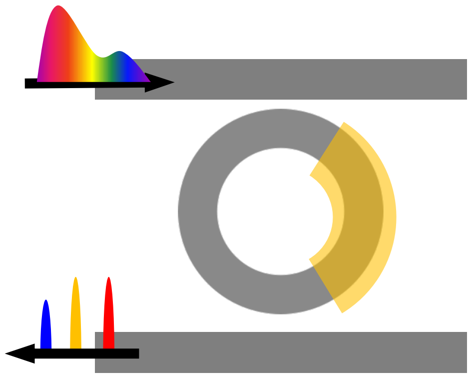
Our group's website:

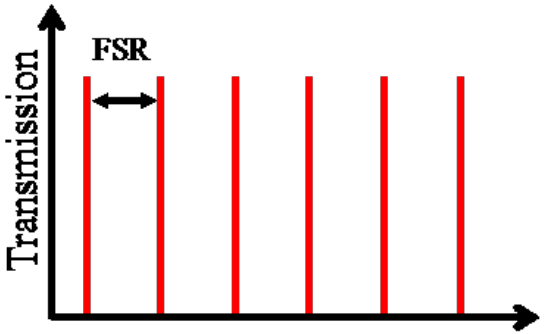
Acknowledgment:

Sentinelle Nord

NSERC CRSNG

Spectropolarimeter : design of spectrometer





Advantage:

Small footprint, low power consumption

Problem:

(1) the inverse relationship between the size and free spectral range (FSR)

FSR=50 nm → Diameter = 2 µm

(2)

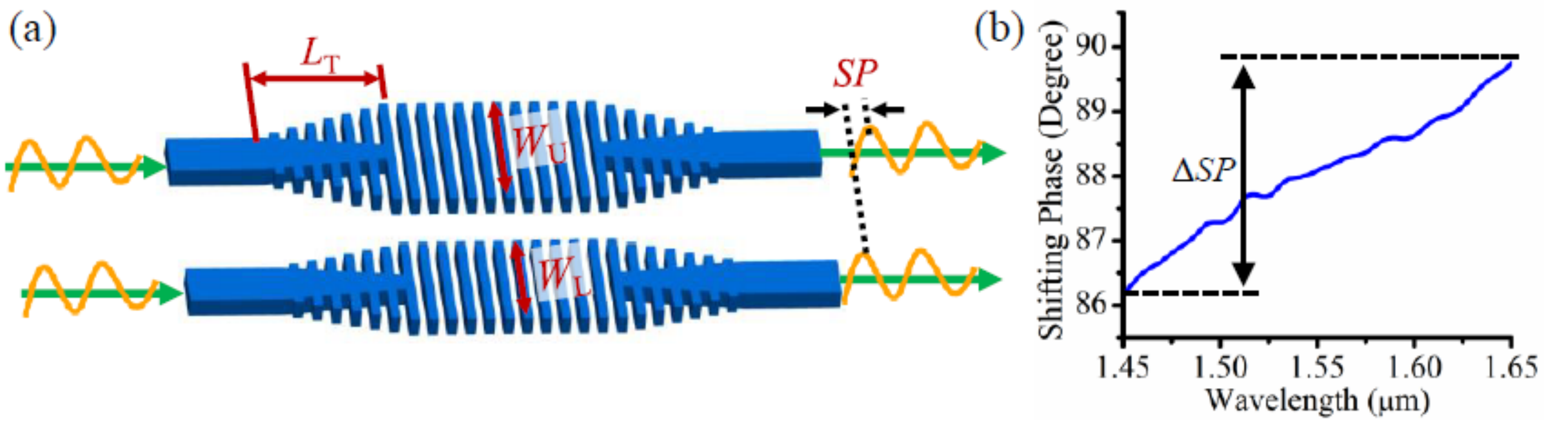
$$\Delta\lambda = \frac{\lambda}{n_{eff}} \times \frac{dn_{eff}}{dT} \Delta T$$

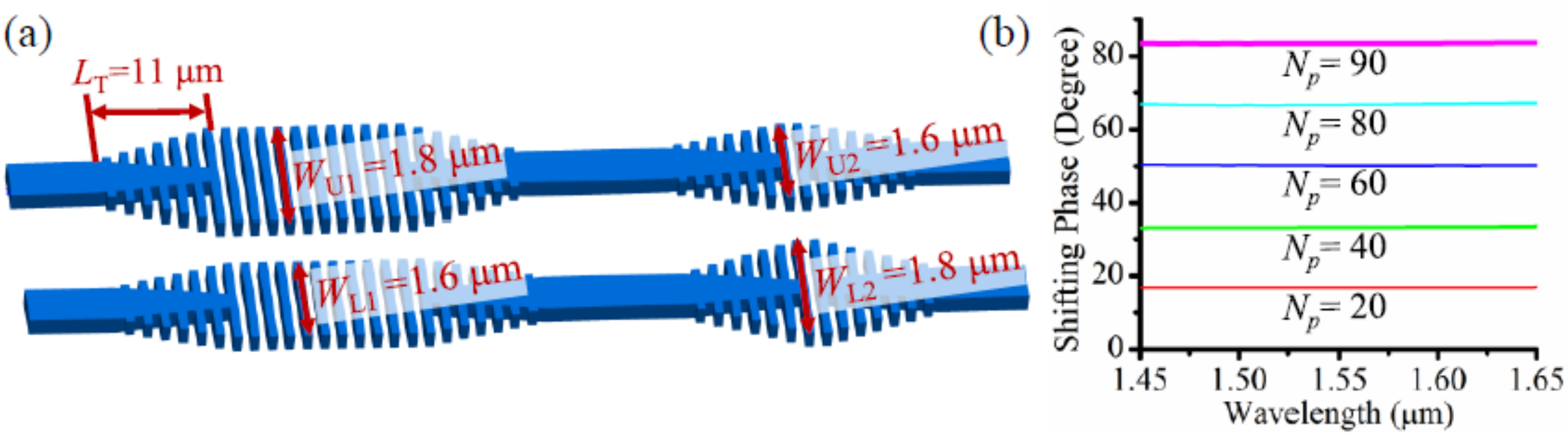
1 nm → 10 ºC

50 nm → 500 ºC

[1] Wei Shi, et al. under review

Broadband and optimal polarimeter





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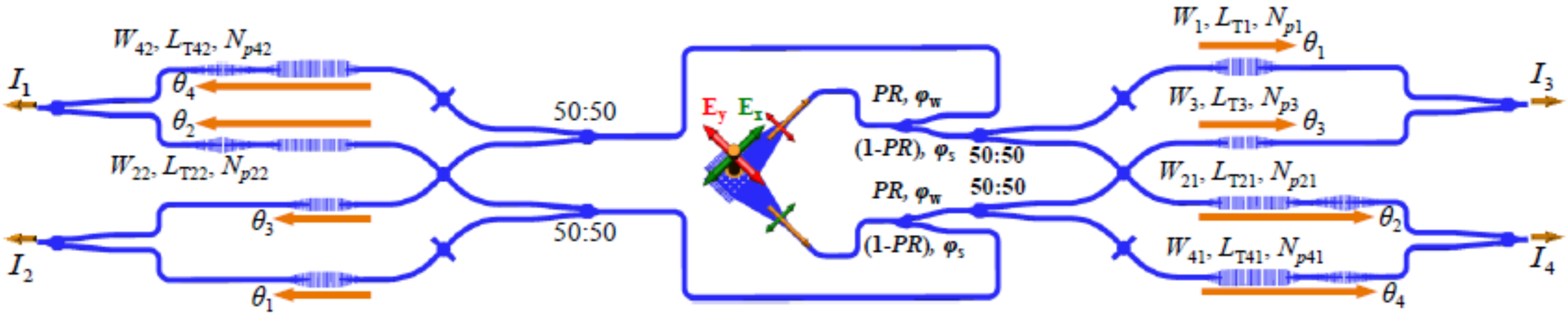
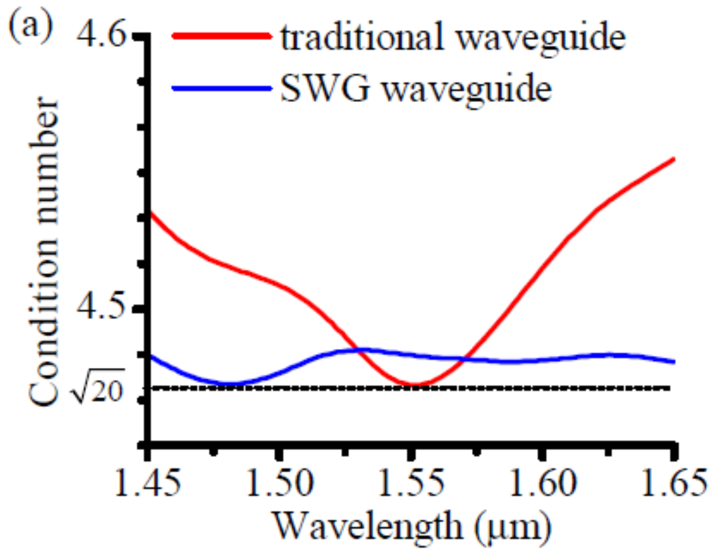
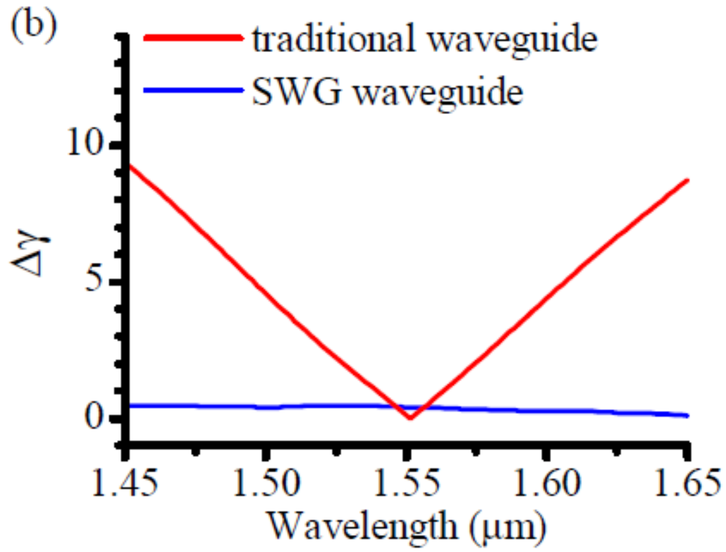
Broadband and optimal polarimeter



Gaussian noise

Poisson noise





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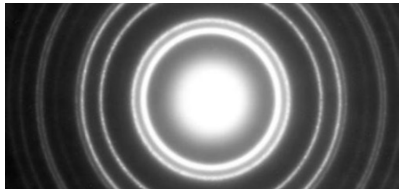
Introduction

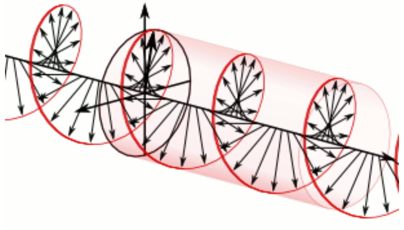
Intensity



Color (Frequency)

Had been studied for a long history

Polarization state



Stokes vector is used to describe the polarization since 1850s

[1] Wehner, R. *J Exp Biol 2001, 204, (Pt 14), 2589-96*.
[2] Wang, X.; Yan, X.; Lv, G.; Fan, T. Infrared Physics & Technology 2013, 58, 5-11.