Application of polarization-entangled photon pairs for studying the density of microorganisms

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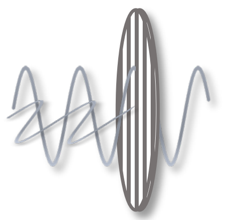
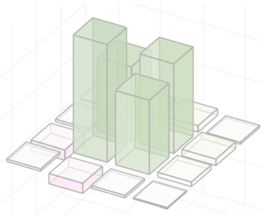
https://www.iap.uni-jena.de/nano-quantum-optics

Outline



Why quantum polarimetry?

Polarization based probing with Bell states



Showcase: detecting microorganisms in water

Polarization is a valuable information channel

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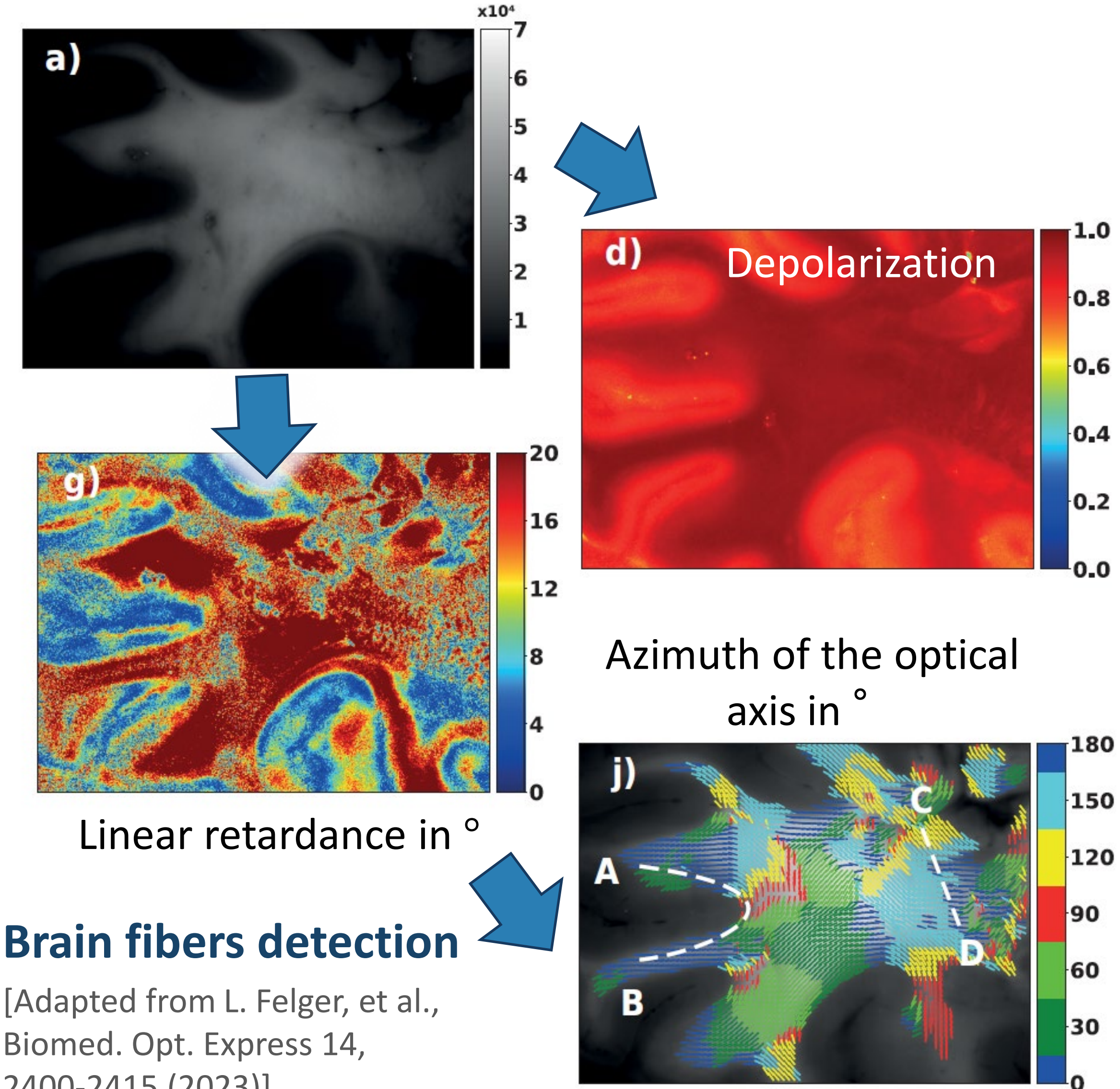

Brain fibers detection

[Adapted from L. Felger, et al., Biomed. Opt. Express 14, 2400-2415 (2023)]

Polarization response → specimen's properties:

- birefringence
- polarization selectivity in reflection/transmission
- chemical composition

Applications:

- optical biomedical diagnostics
- control of nonlinear phenomena
- technical characterization
- remote sensing
- quantum communication, computing, and metrology

→ acknowledged methods of **Stokes and Mueller polarimetry**

[J. Opt. Soc. Am. A 33, 1396-1408 (2016)
Light: Sci. Appl. 10, 194 (2021).]

Active research towards quantum-empowered polarimetry

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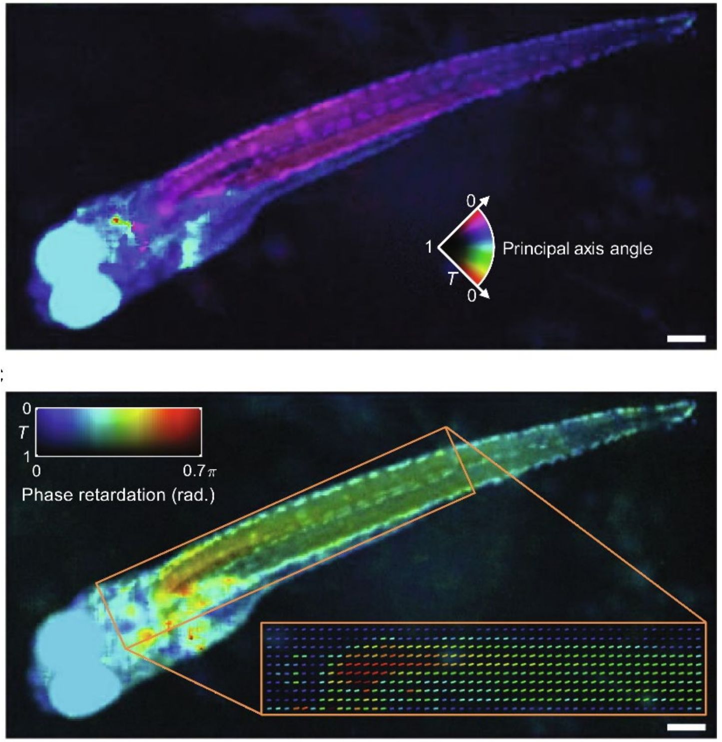
- Theoretical framework, incl. with entangled photons
- quantum holography via polarization-entanglement
- ghost polarimetry using classical light & with correlated photon pairs

A. Z. Goldberg, Phys. Rev. Research 2, 023038 (2020).
S. Magnitskiy, et al., Opt. Lett. 45, 3641-3644 (2020).
H. Defienne, et al., Nat. Phys. 17, 591-597 (2021).
V. Sukharenko, et al., Opt. Lett. 46, 2799-2802 (2021).
M. Kaur, et al., Sci. Rep. 11, 23636 (2021).
R. Camphausen, et al., Sci. Adv. 7, eabj2155 (2021).
S. Restuccia, et al., Phys. Rev. A 106, 062601 (2022).
S. Magnitskiy, et al., Opt. Lett. 47, 754-757 (2022).
A. Saxena, et al., Sci. Rep. 12, 21105 (2022).
A. Pedram, et al, arXiv:2304.08258 [quant-ph] (2023).
D. Agapov, D., Jetp Lett. (2024).
...



Birefringence of Zebra fish, sample scanning

[Adapted from Y. Zhang et al., Sci. Adv. 10, eadk1495 (2024)]

- Most recent: Birefringence imaging and realization of an ellipsometer

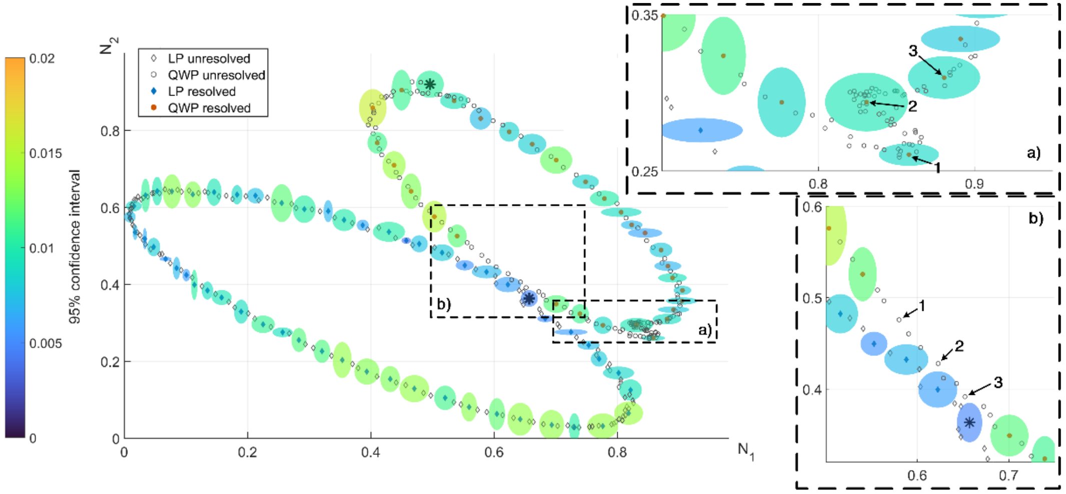
Y. Zhang et al., Sci. Adv.10,eadk1495(2024)

Meng-Yu Xie, arXiv:2402.17401 [quant-ph] (2024)

News from our lab: the less measurements – the better

No imaging so far, but:

[**VB**, et al., APL Photonics 9 (4), 041301 (2024)]



- Nonlocal quantum differentiation of polarization objects

  A. Vega, et al., Phys. Rev. Applied 16, 064032 (2021).
  VB, et al., APL Photonics 9 (4), 041301 (2024).

- Nonlocality-enhanced precision in parameter estimation:
  QFI↑ $\geq 2\times$, becomes nonzero for birefringent samples

  A. Pedram, **VB**, et al., arXiv:2402.11932 [quant-ph] (2024).

- Polarization-based probing of subtle samples like monolayer cell cultures

  L. Zhang, **VB**, et al., arXiv:2401.10789 [physics.optics] (2024).

Today:

Detection of microorganisms in water at concentration as low as 1:1000 (250 μg/ml)

Outline

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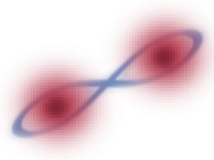
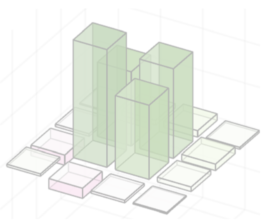


Polarization based probing with Bell states

Showcase: detecting microorganisms in water



Experimental arrangement

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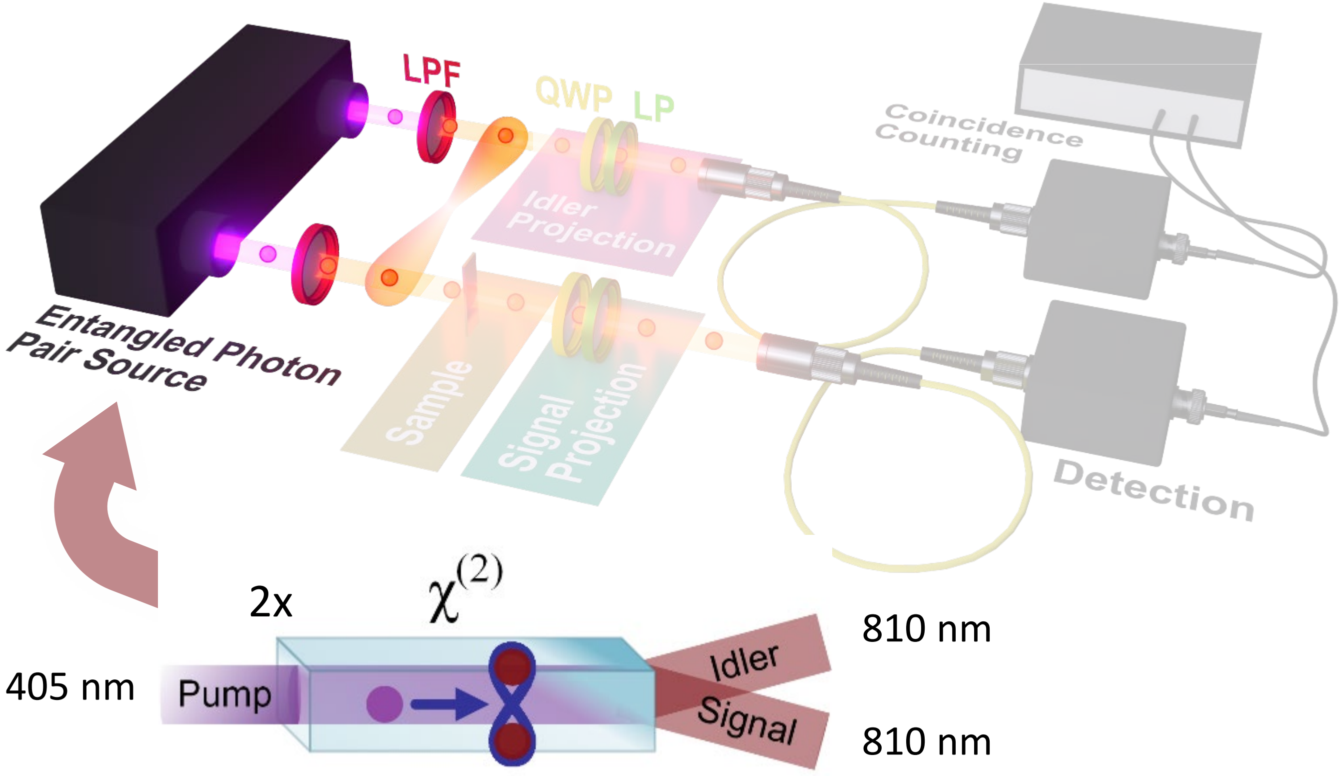
[**VB**, et al., APL Photonics 9 (4), 041301 (2024).]

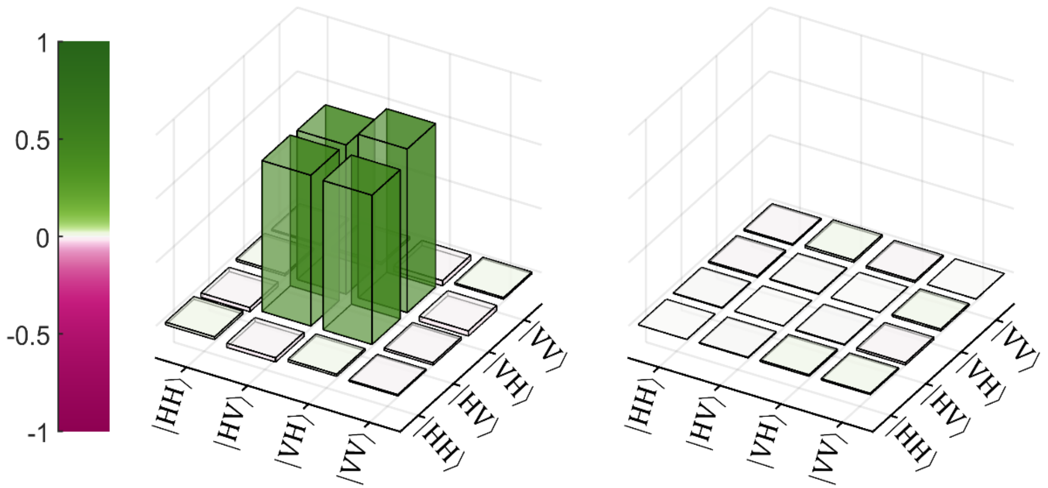


- Spontaneous parametric down-conversion (SPDC)
- 2 nonlinear crystals (ppKTP), type-II phase-matching
- Interferometer on beam displacers

- Quantum State Tomography, incl. maximum likelihood estimation algorithm
- Entanglement in polarization (S: signal, I: idler):

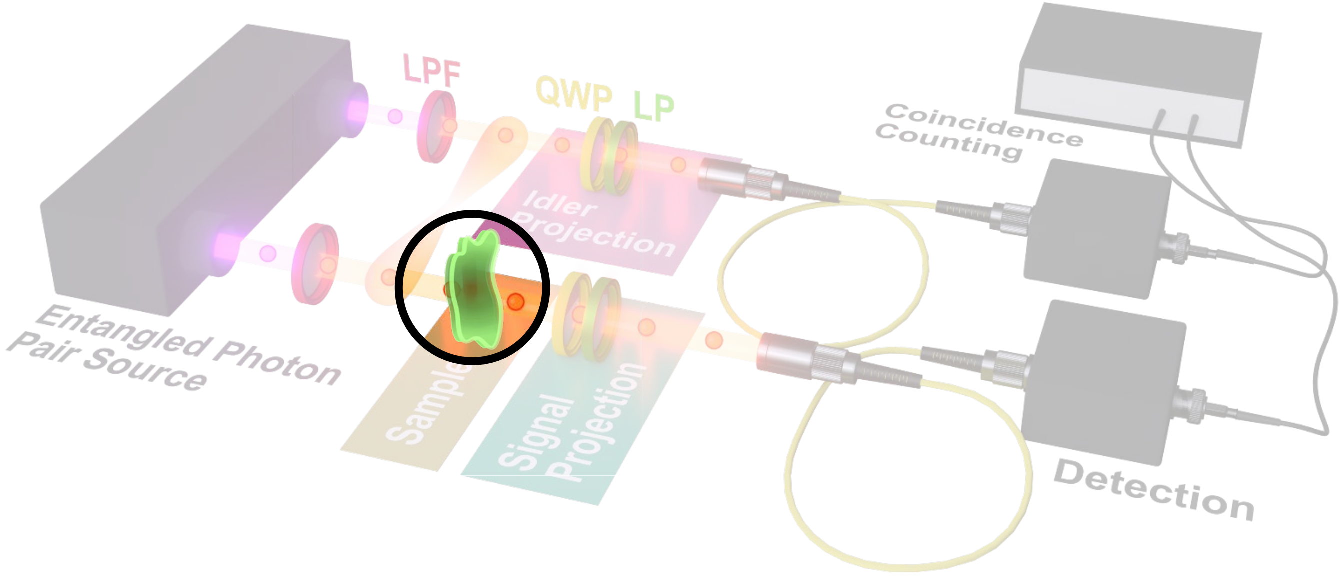
$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|H_S V_I\rangle + |V_S H_I\rangle\right)$$

Fidelity 0.96; Concurrence 0.94



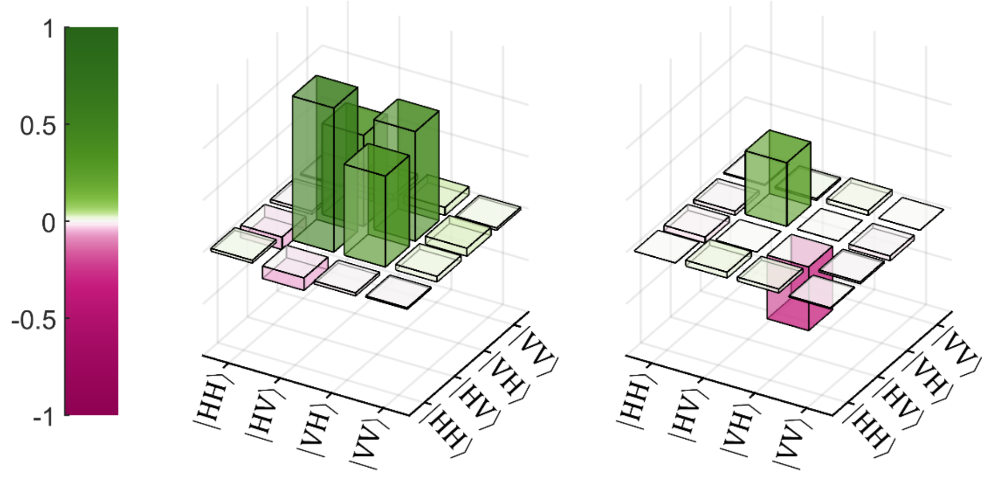
Experimental arrangement

[VB, et al., APL Photonics 9 (4), 041301 (2024).]



- Why not using this for sensing?
- Not necessarily full Mueller matrix is of interest
- Detection/discrimination as a target

- Apparent and not new: state changes due to complex/scattering obstacle for one of the partner photons
- So far: goal to revive or overcome entanglement loss → quantum communication



[E.g., Nat. Phys. 16, 1112–1116 (2020) and Nat. Phys. 19, 562–568 (2023).]

Probing of scattering samples

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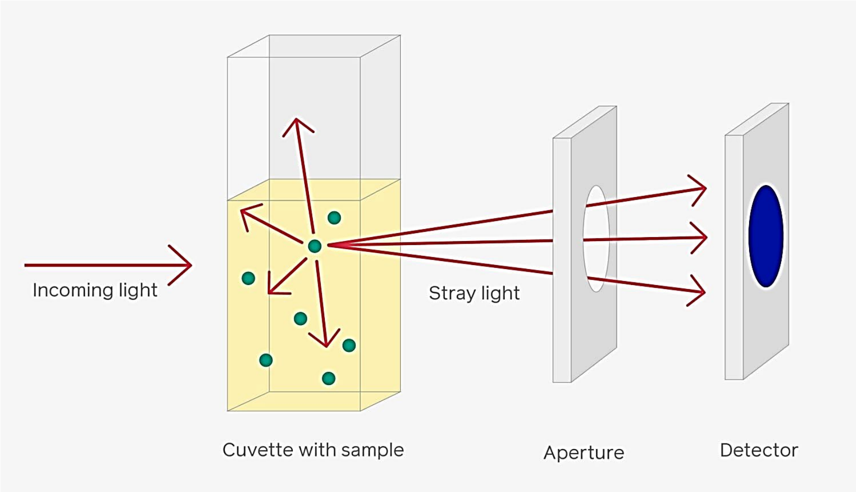
Monitoring of bacteria and other microorganisms for:

- microbiological pollution of water and food products
- development of new antibiotics and drugs
- studies of microorganisms' behavior, etc.

[IEEE Journal of Selected Topics in Quantum Electronics 9(2), 277–287 (2003).
Review of Scientific Instruments 83, 074301 (2012).
Communications Biology 3, 512 (2020).
PLOS ONE 17, 1–8 (2022)].

Transmission/scattering for bacterial culture density monitoring (example of OD600 measurement)

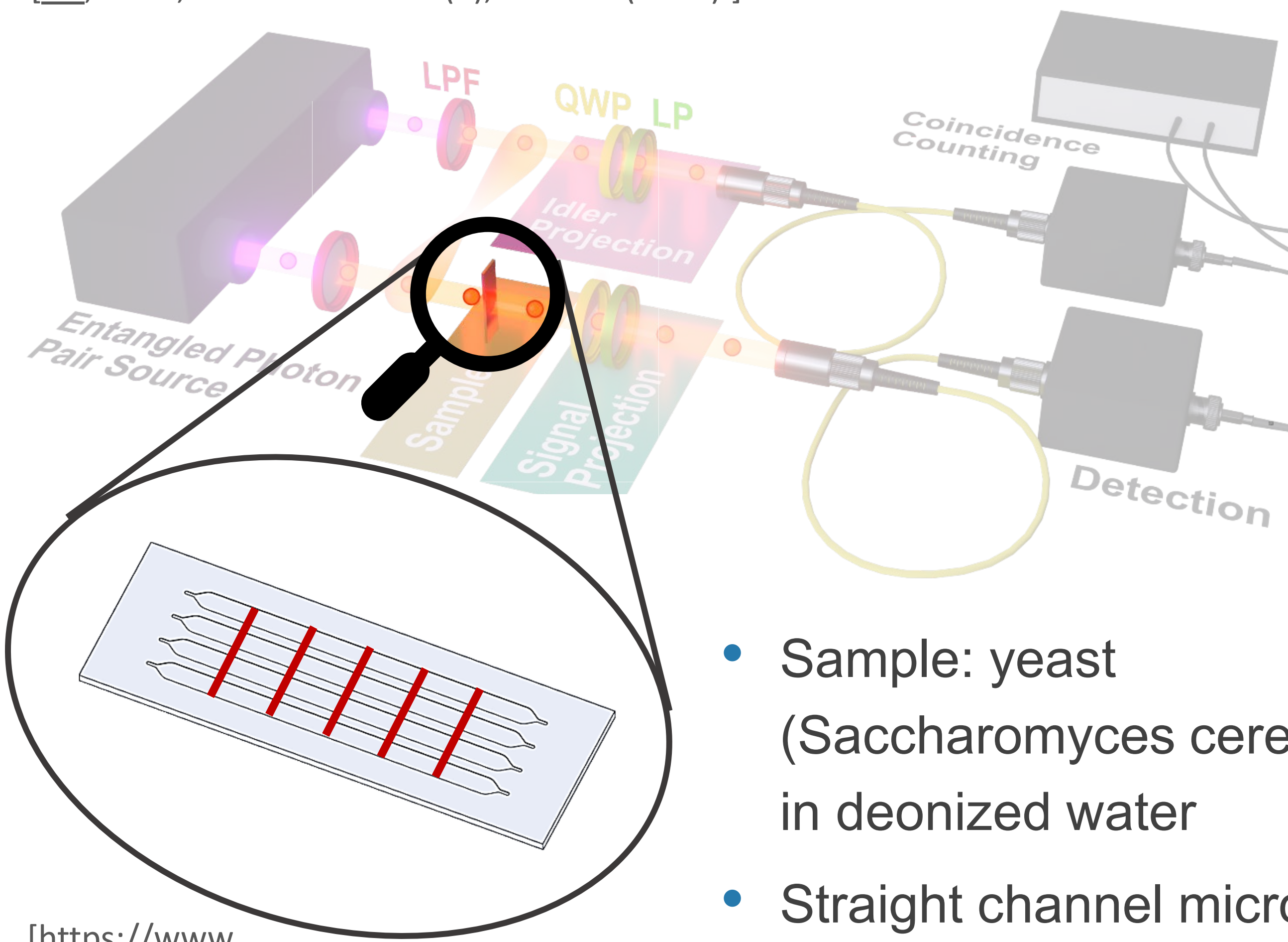


[https://byonoy.com/]

- Successful tests of method sensitivity to polarization-based sample response (down to retardance < $\lambda/10$*)
- Probing entangled state change due to scattering of one of the partner photons

[*VB, et al., in preparation.
L. Zhang, VB, et al., arXiv:2401.10789 [physics.optics] (2024).]

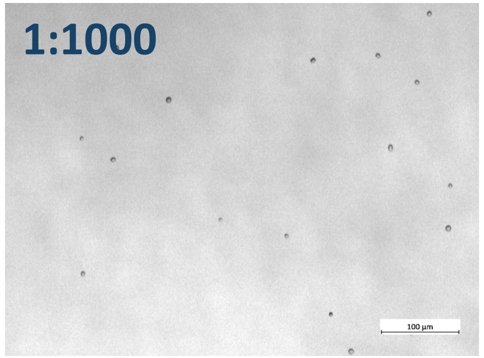
[**VB**, et al., APL Photonics 9 (4), 041301 (2024).]



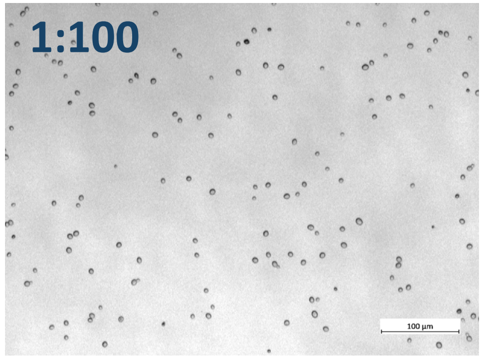
[https://www.
microfluidic-chipshop.com]

- Sample: yeast (Saccharomyces cerevisiae) in deonized water
- Straight channel microfluidic glass chip:
  lid of 250 µm thickness

- 4 channels, each:
  3.1 mm wide, 30 µm deep, 58.5 mm long
- Initial solution of 250 mg S. cerevisiae in 1 ml H_2O diluted 1:10, 1:100 and 1:1000
- Resultant tested concentrations:
  25 mg/ml, 2.5 mg/ml, and 250 µg/ml



250 µg/ml



2.5 mg/ml

Representative microscopic images, 10x

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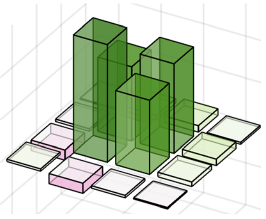

Showcase: detecting microorganisms in water

Results

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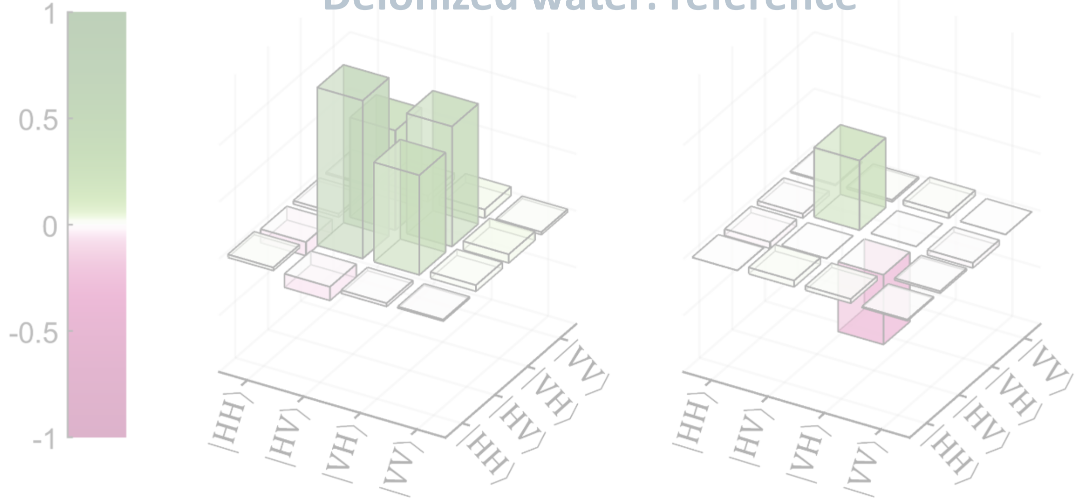
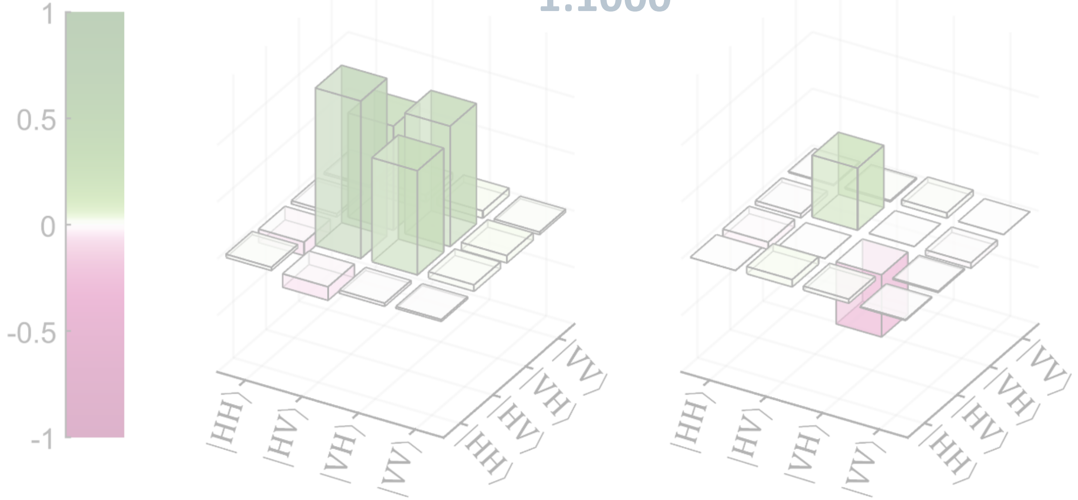
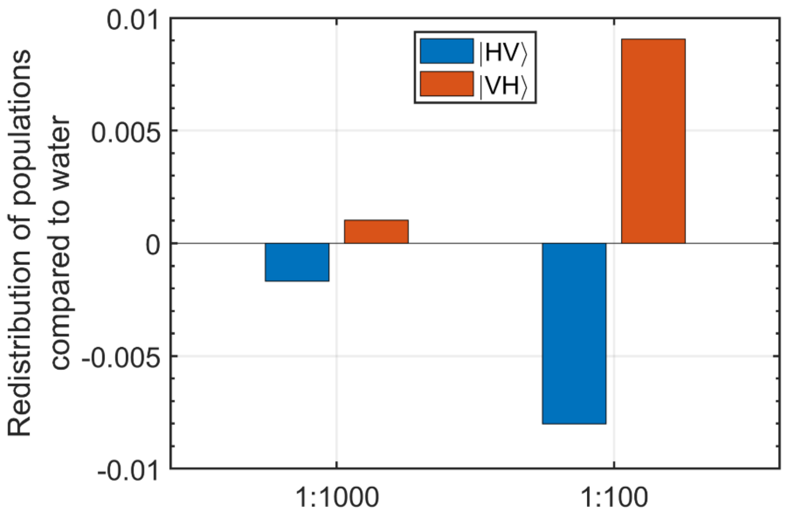
Deionized water: reference



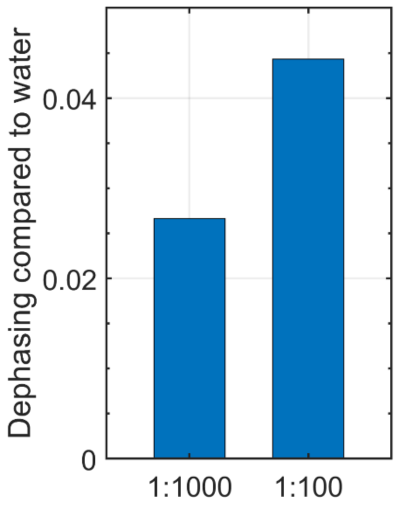
1:1000



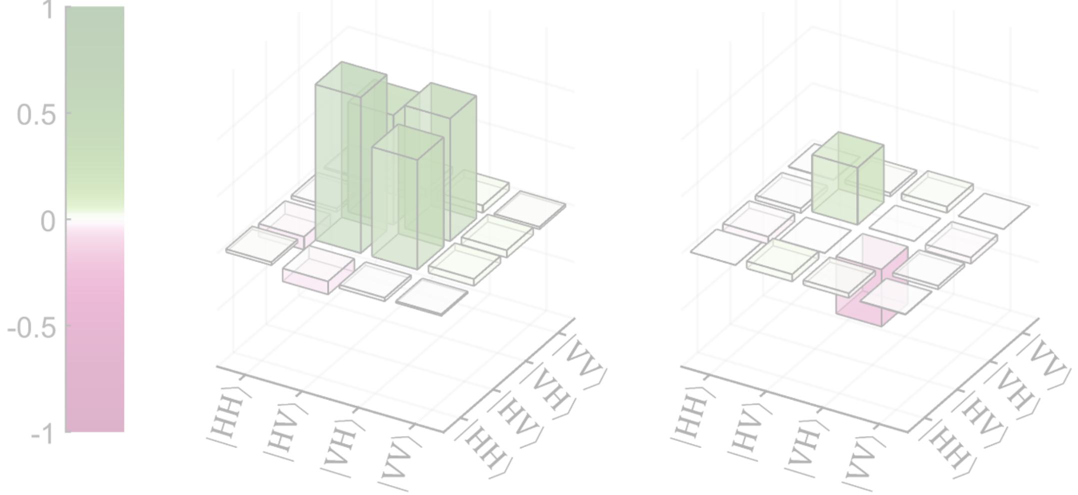
Change in real part



Absolute change in imag. part



1:100



Conclusions & outlook

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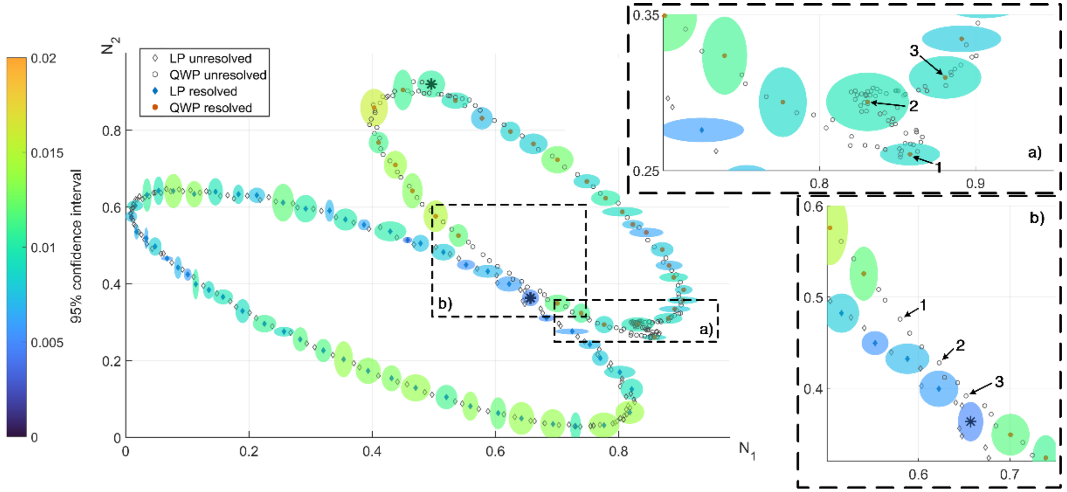
- Successful demonstration of applicability of polarization-entangled photons for detecting the microorganisms in water already at 250 µg/ml (1:1000) concentration
- Potential for discrimination of concentration levels
- Potential for monitoring of concentration with just two projections and corresponding coincidence measurement

[**VB**, et al., APL Photonics 9 (4), 041301 (2024)]



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ProChance career

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