Digital polarization holography: challenges and opportunities

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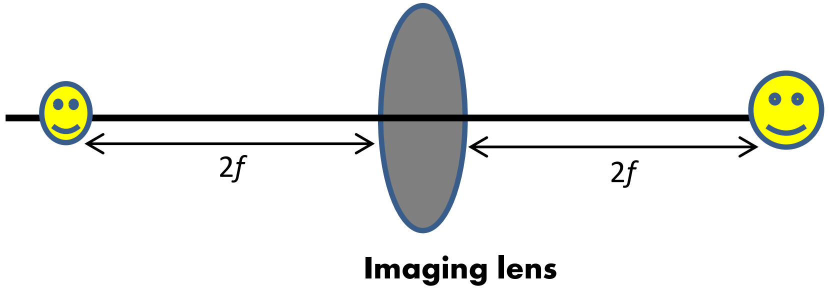
Outline

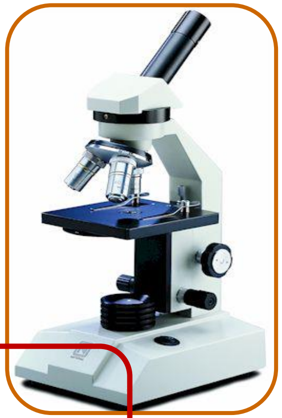
- Background
- Optical Imaging
- Digital Holography
  - ✓ Recording and reconstruction of wavefront
  - ✓ Polarization holography
  - ✓ Jones matrix imaging
- Randomness assisted imaging
  - ✓ Speckle illumination polarization holography
  - ✓ Stokes holography
  - ✓ Holography with higher order Stokes correlations
- Conclusion

Optical Imaging

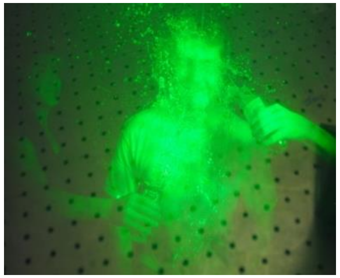
❖Replica at imaging plane



❖Microscopy: improvement in resolution possible by tailored illumination



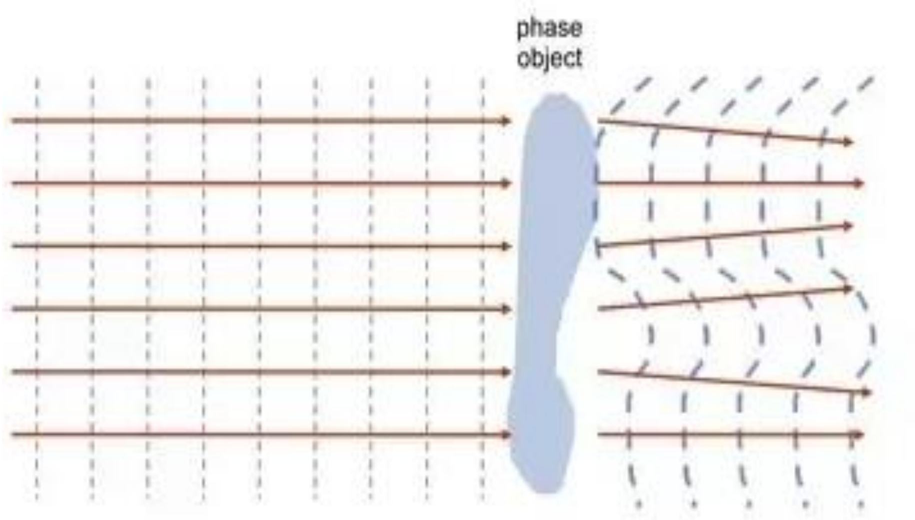
❖Holography: Provides 3D complex field reconstruction



❖Optical imaging through randomness

Phase objects

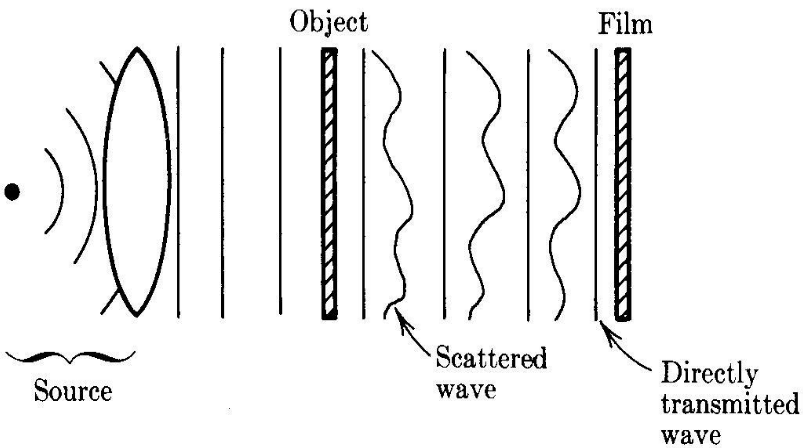
- Transparent specimen
- Do not absorb or scatter light
- Instead produces a phase change of light



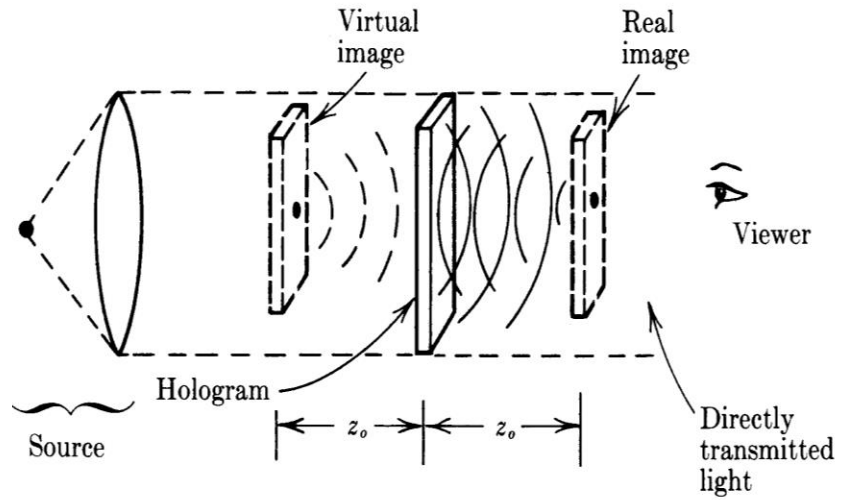
Quantitative Phase Imaging

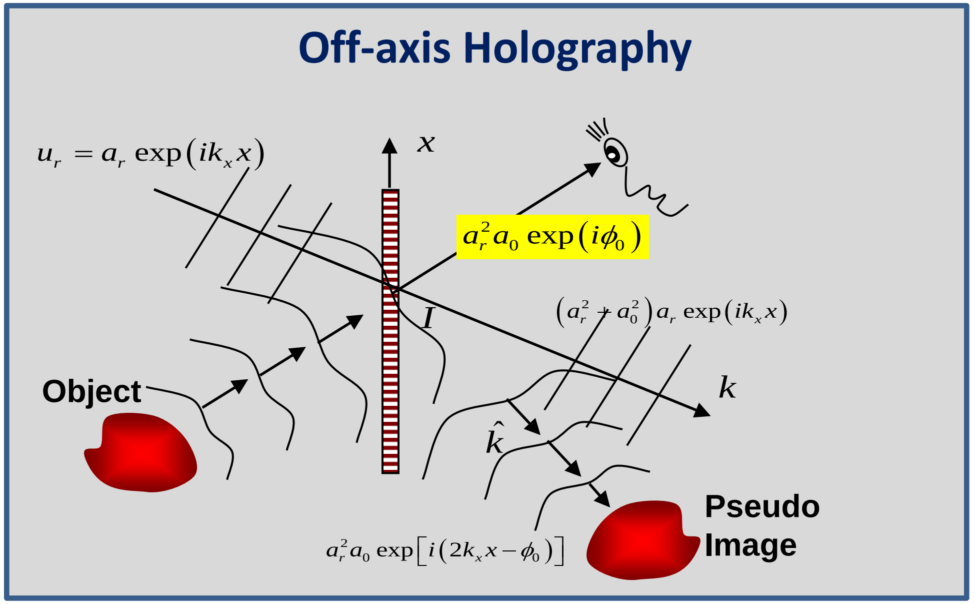
Holography

Gabor's Holography: In line Holography



$$I = |U|^2$$
$$= |O + R|^2$$
$$= |O|^2 + |R|^2 + O^*R + OR^*$$
$$= I_o + I_r + 2\sqrt{I_o I_r} cos\varphi$$

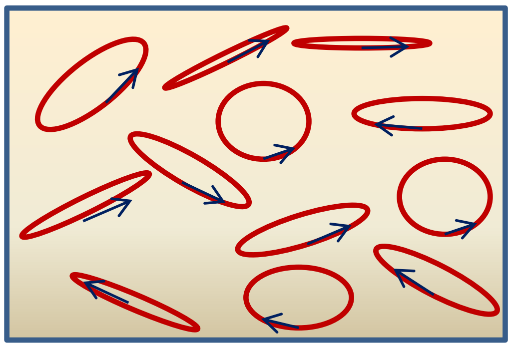




J. Goodman, Fourier Optics

Polarization

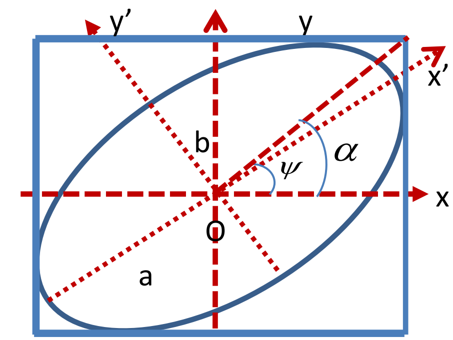
❖Polarization ellipse representation



$$\tan 2\psi = 2\frac{E_{0x}E_{0y}\cos\delta}{E_{0x}^2 - E_{0y}^2}$$

$$\tan\alpha = \frac{E_{0y}}{E_{0x}}$$

$$\sin 2\chi = (\sin 2\alpha)\sin\delta$$



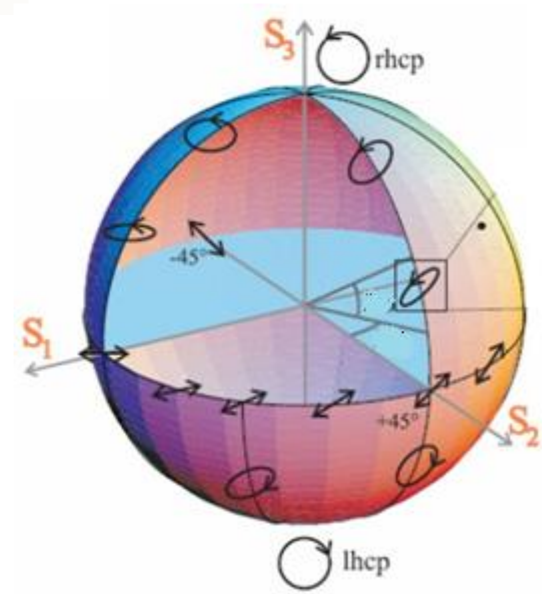
❖Poincare representation

$$S_0 = E_x^* E_x + E_y^* E_y$$

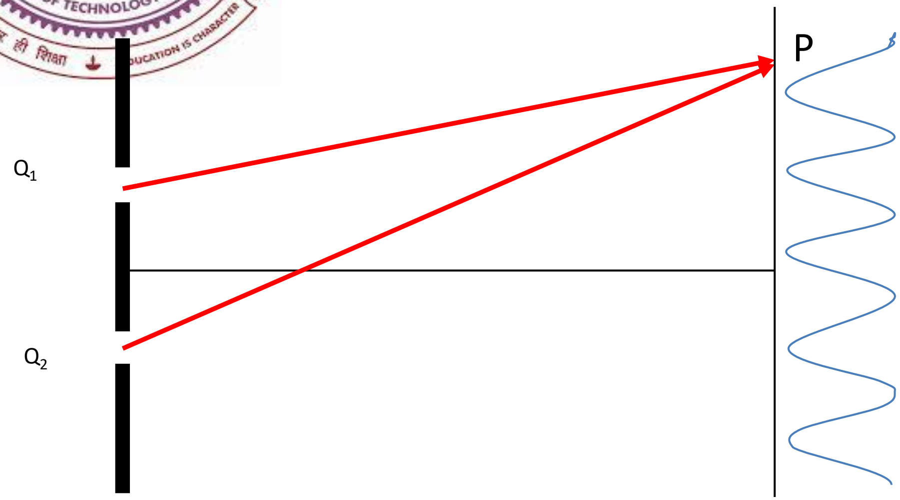
$$S_1 = E_x^* E_x - E_y^* E_y$$

$$S_2 = E_x^* E_y + E_y^* E_x$$

$$S_3 = i\left[E_y^* E_x - E_x^* E_y\right]$$



Significance of polarization



Interference effect:

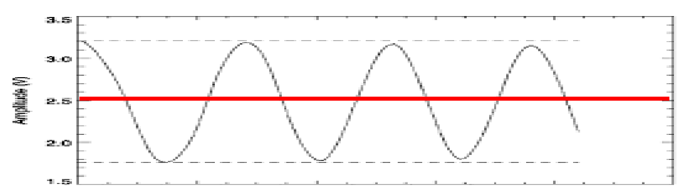
Fully coherent case: V=1

Fully incoherent case: V=0

$$V = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}}$$

$$I(r,\omega) = I^{(1)}(r,\omega) + I^{(2)}(r,\omega) + \sqrt{I^{(1)}(Q_1,\omega) I^{(2)}(Q_2,\omega)}\left[\mu(Q_1,Q_2;\omega)\exp\left\{ik\left(R_1 - R_2\right)\right\} + \mu(Q_2,Q_1;\omega)\exp\left\{-ik\left(R_1 - R_2\right)\right\}\right]$$

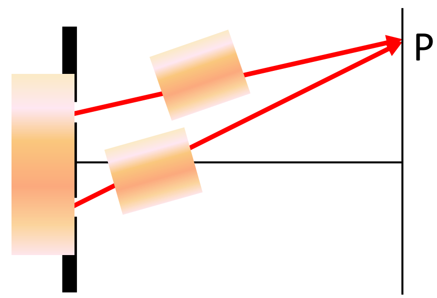
$$\mu(Q_1,Q_2;\omega) = \frac{\left\langle E^*(Q_1,\omega)E(Q_2,\omega)\right\rangle}{\sqrt{I^1(Q_1,\omega)\, I^2(Q_2,\omega)}}$$



✓ coherent light sources makes high visibility fringe

M. Born and E. Wolf, Principle of Optics

Generalized Interferometry



$$\begin{bmatrix} S_0(r) \\ S_1(r) \\ S_2(r) \\ S_3(r) \end{bmatrix}$$

✓Intensity modulation
✓Polarization modulation

$$S_n(r) = S_n^1(r) + S_n^2(r) + 2\sqrt{S_0^1(r)S_0^2(r)}\,\left|S_n(Q_1,Q_2)\right|\cos\left\{\arg\left[S_n(Q_1,Q_2) - k(R_1 - R_2)\right]\right\}$$

$$S_0(Q_1,Q_2) = \eta_{xx}(Q_1,Q_2) + \eta_{yy}(Q_1,Q_2)$$
$$S_1(Q_1,Q_2) = \eta_{xx}(Q_1,Q_2) - \eta_{yy}(Q_1,Q_2)$$
$$S_2(Q_1,Q_2) = \eta_{xy}(Q_1,Q_2) + \eta_{yx}(Q_1,Q_2)$$
$$S_3(Q_1,Q_2) = i\left[\eta_{yx}(Q_1,Q_2) - \eta_{xy}(Q_1,Q_2)\right]$$

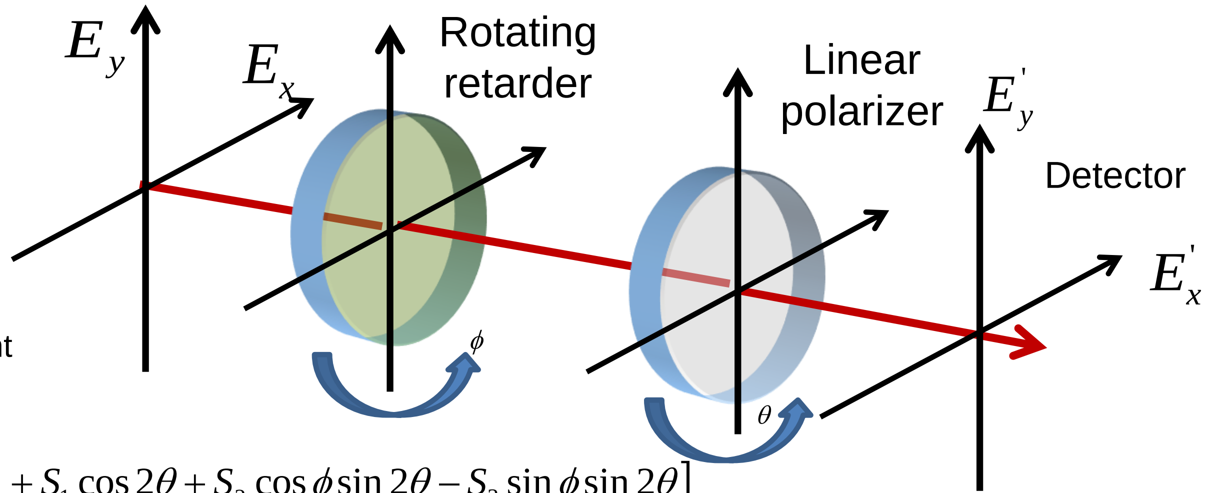
$$\eta_{ij}(Q_1,Q_2) = \frac{W_{ij}(Q_1,Q_2)}{\sqrt{trW(Q_1)trW(Q_2)}}$$

- ❖ **In general four kind of polarization modulation takes place**
- ❖ **Only one (first one) in conventional holography**

T. Setala, J. Tervo, and A. Friberg, Opt. Lett 31 (2006) 2208

Polarization Measurement

- Technique based on multiple images

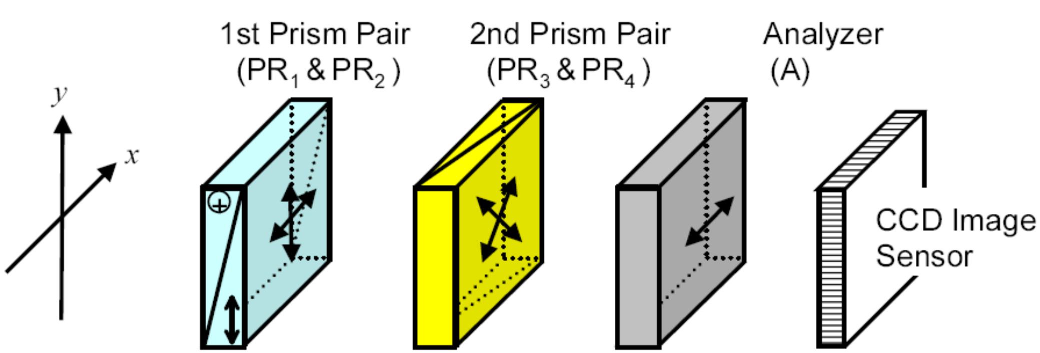


Ref. E. Collet, Chapter 6,Polarized Light

Stokes intensity formula

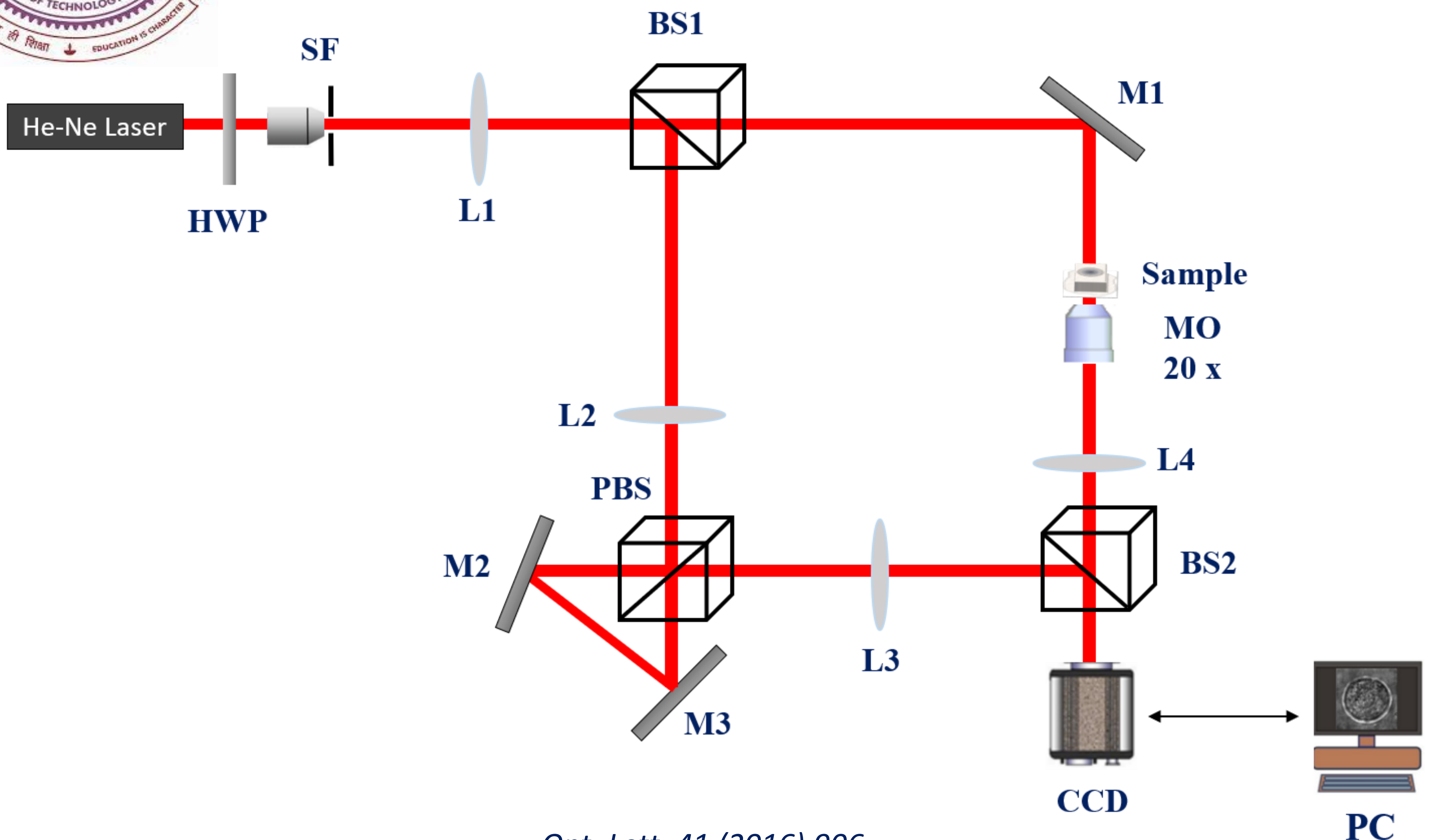
$$I(\theta,\phi)=\frac{1}{2}\left[S_0+S_1\cos 2\theta+S_2\cos\phi\sin 2\theta-S_3\sin\phi\sin 2\theta\right]$$

- Technique based on single shot



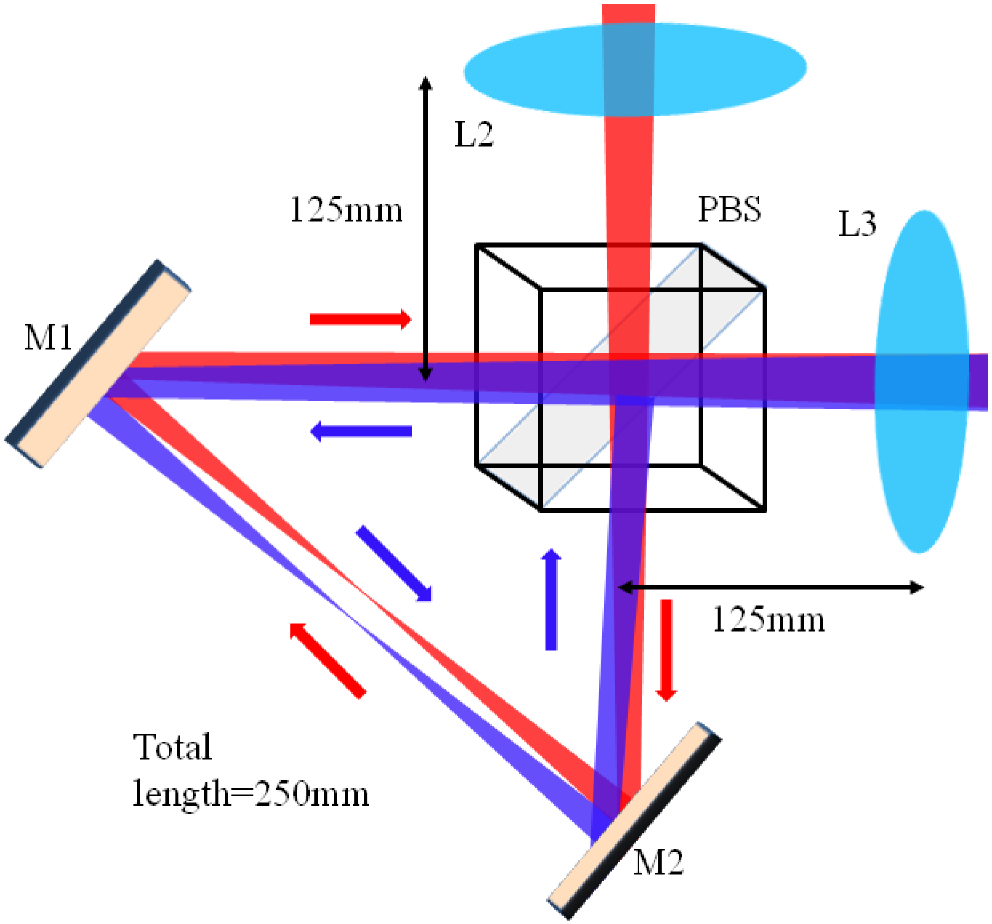
K. Oka and T. Kaneko, Opt. Express 11,1510 (2003)

Polarization Digital holographic microscope



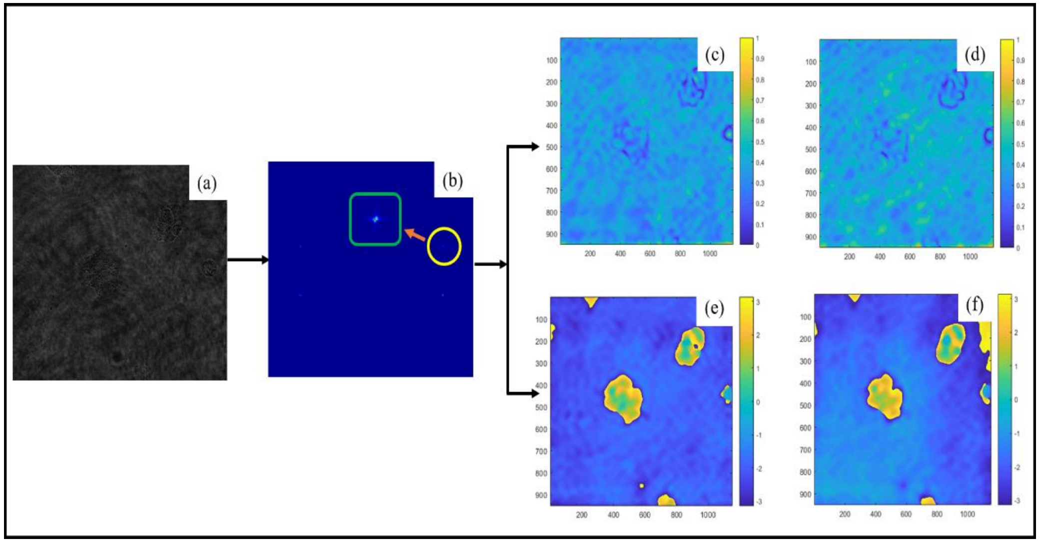
Opt. Lett. 41 (2016) 906

Angular & Polarization multiplexing

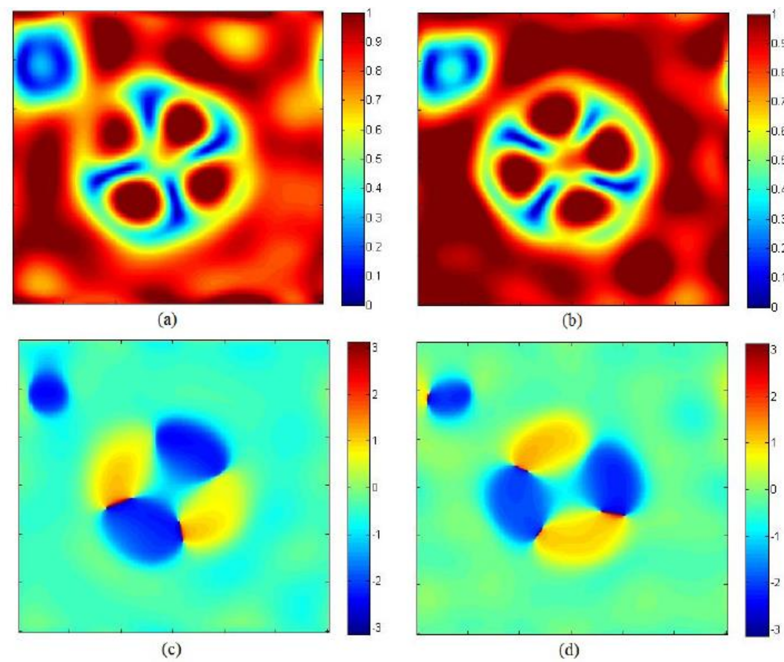


Opt. Lett. 41 (2016) 906

Imaged orthogonally polarized components

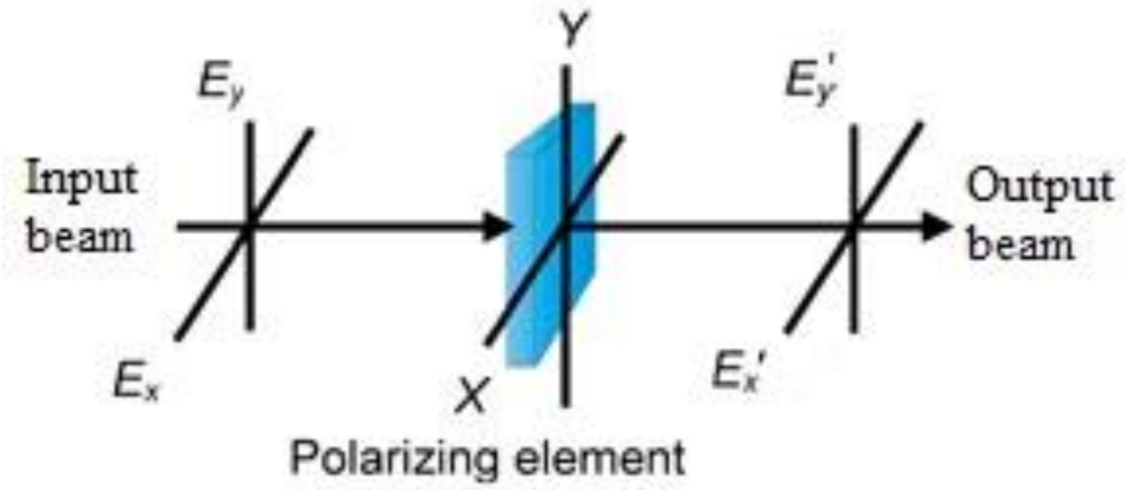


Biological cells



Liquid crystal droplets

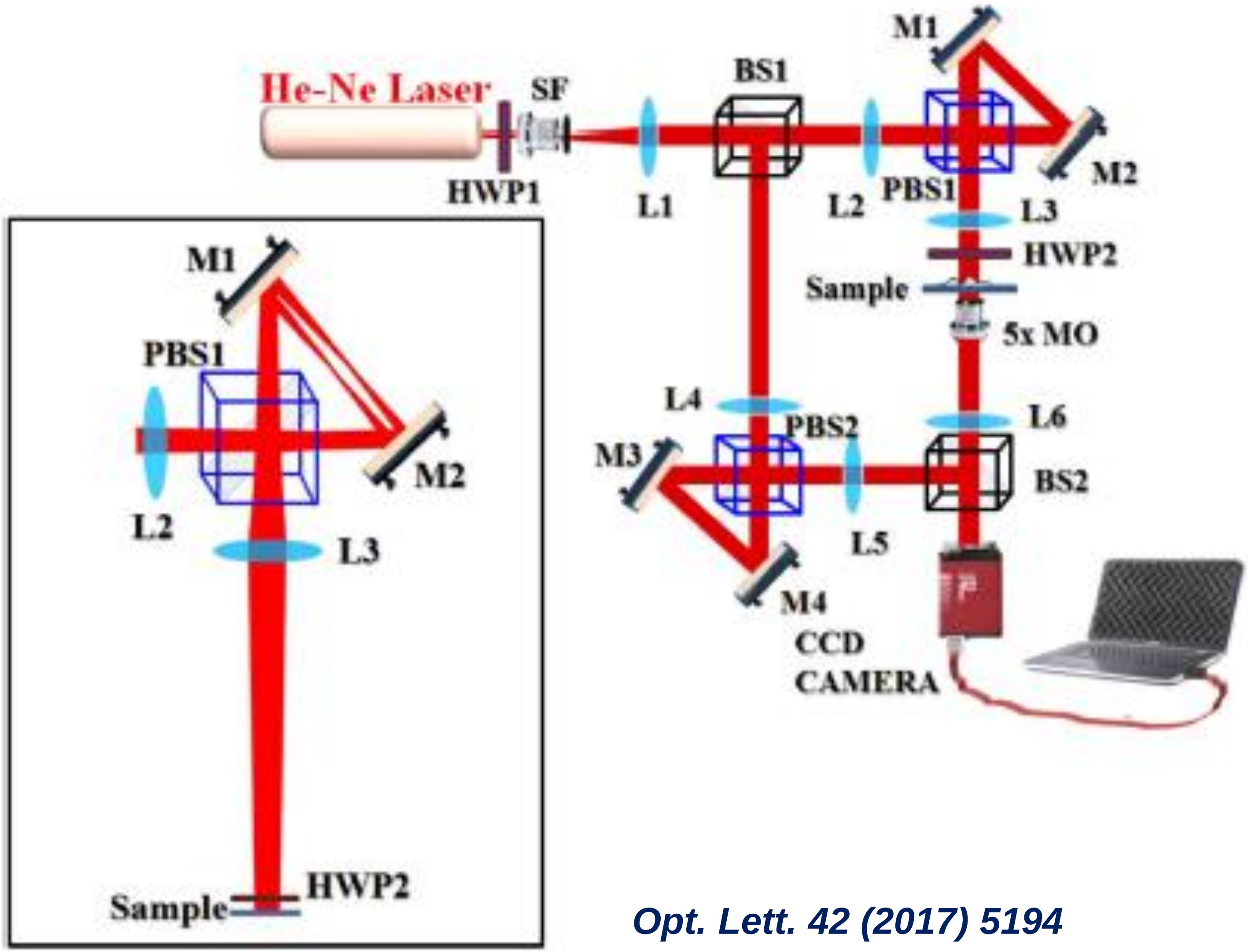
Light matter interaction: Jones matrix



- Jones matrix formalism

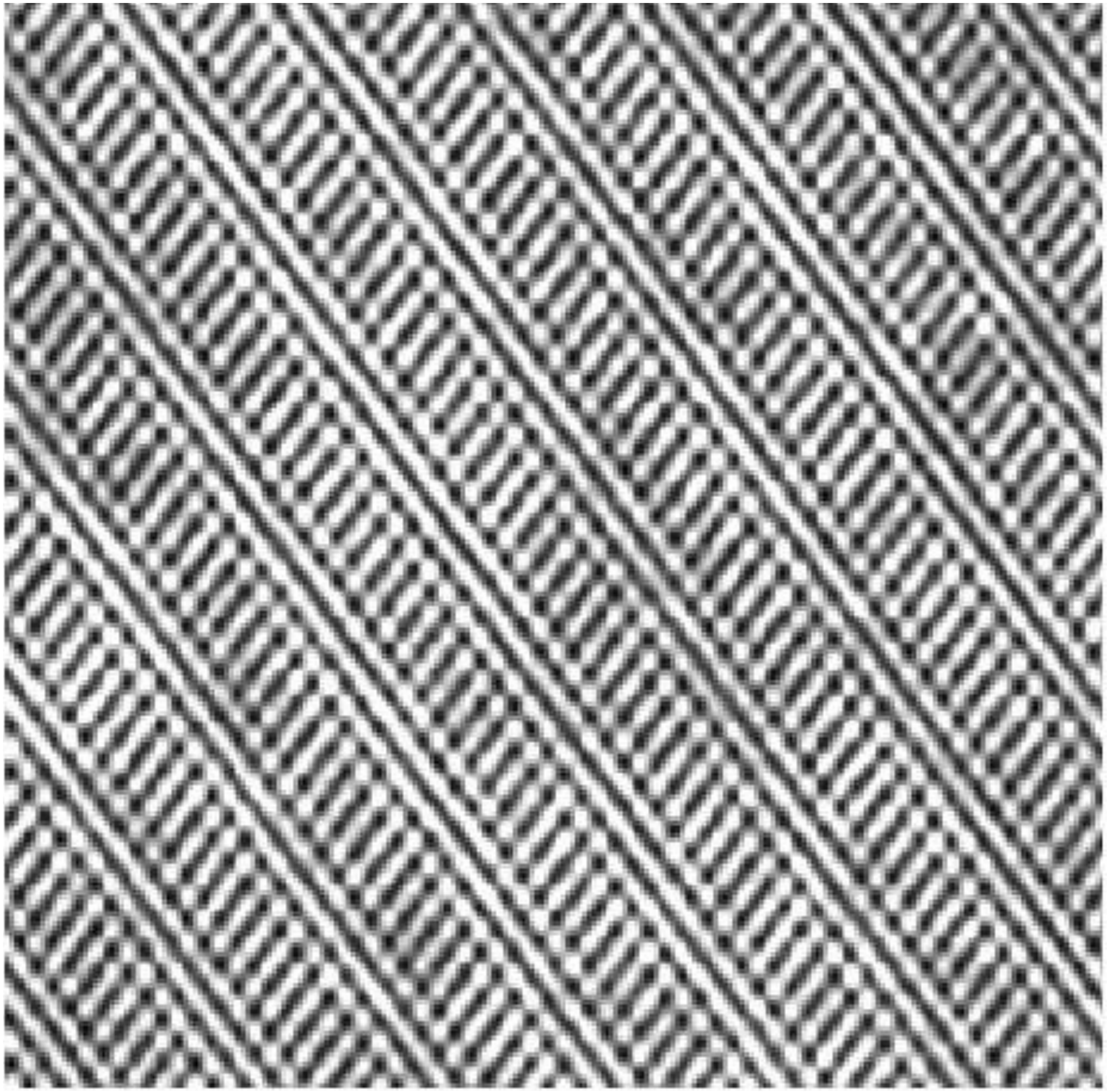
$$\begin{pmatrix} E'_x \\ E'_y \end{pmatrix} = \begin{pmatrix} j_{xx} & j_{xy} \\ j_{yx} & j_{yy} \end{pmatrix} \begin{pmatrix} E_x \\ E_y \end{pmatrix}$$

Jones matrix microscopy from a single shot measurment



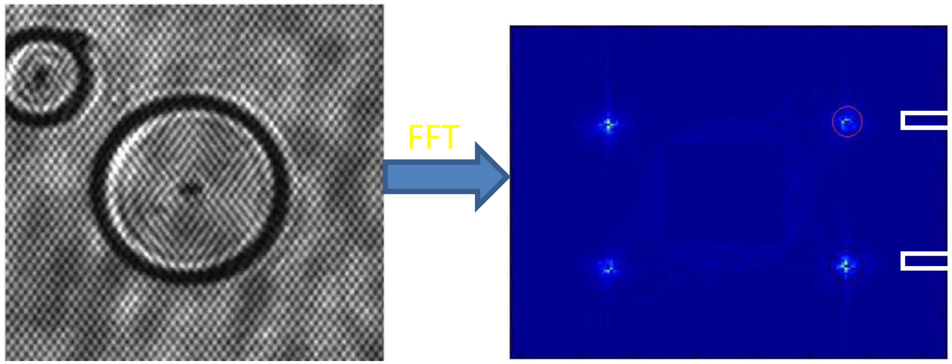
Opt. Lett. 42 (2017) 5194

Jones matrix microscopy: multiplexed hologram

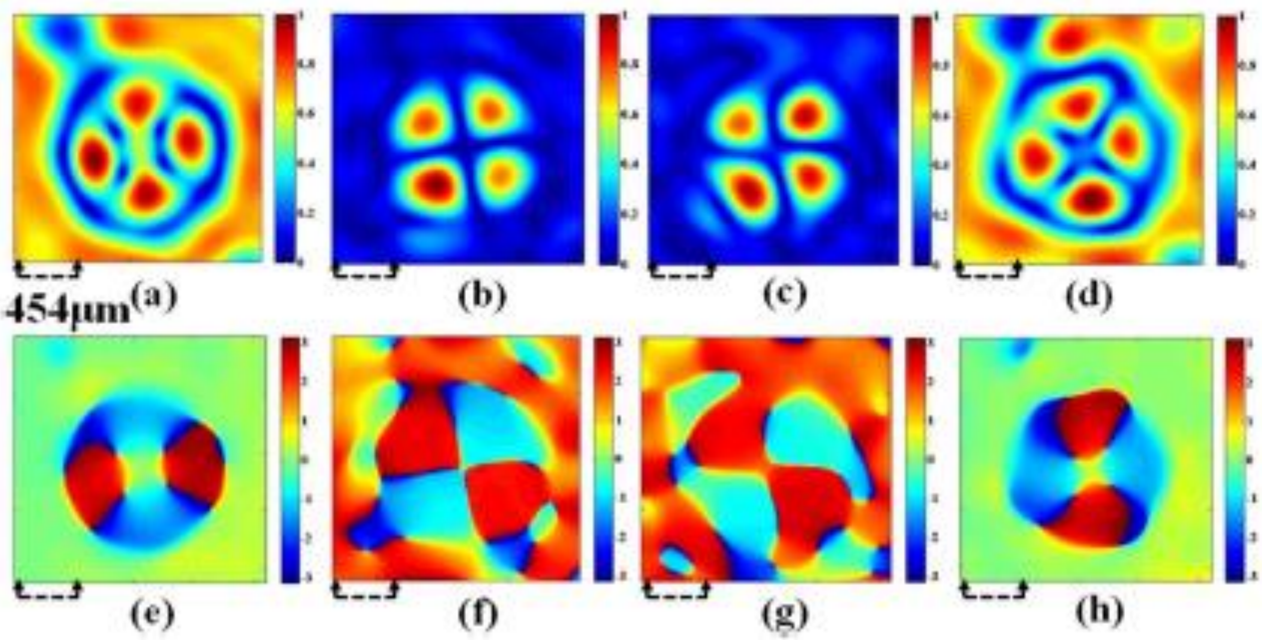


Opt. Lett. 42 (2017) 5194

Recovered Jones matrix elements

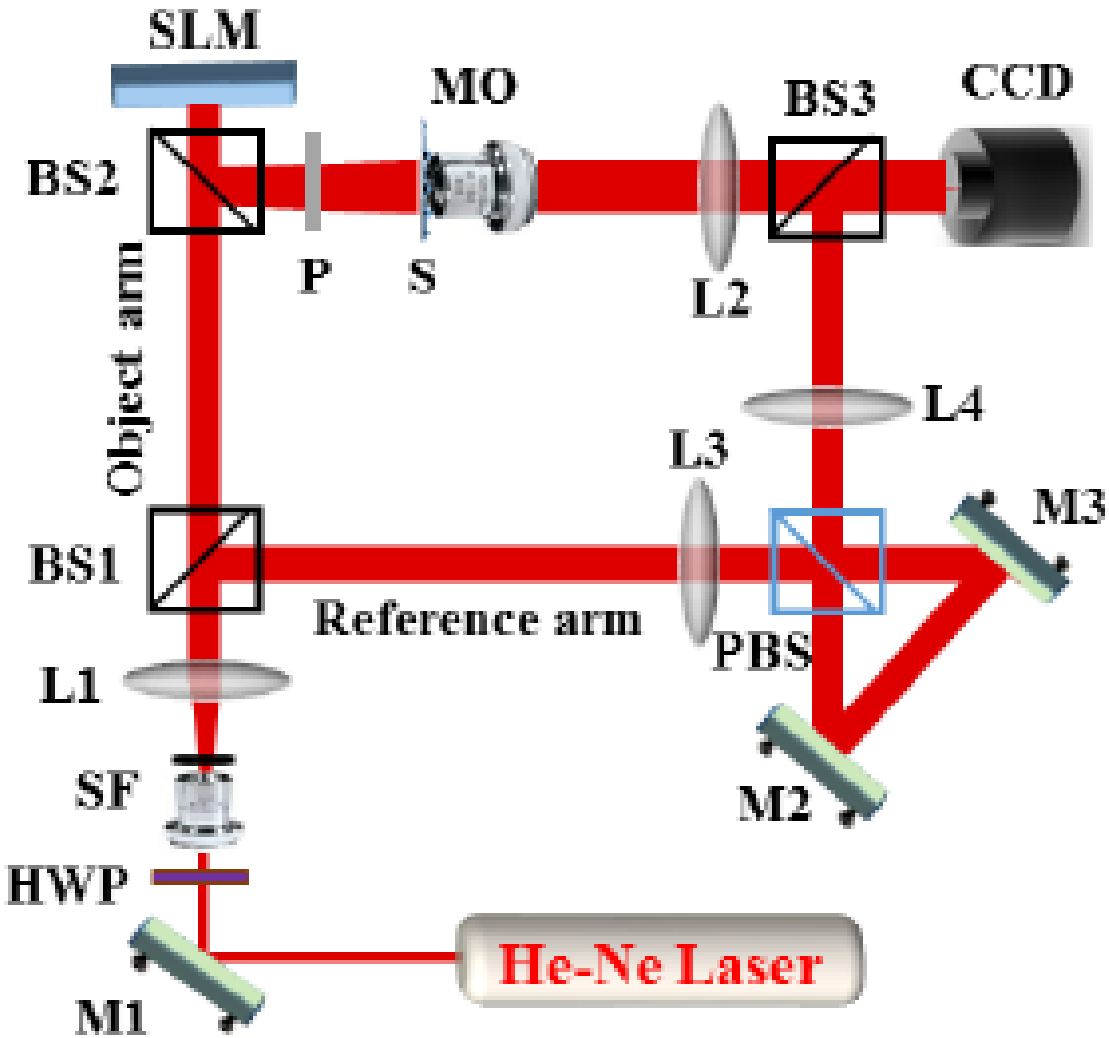


Jxx Jxy Jyx Jyy



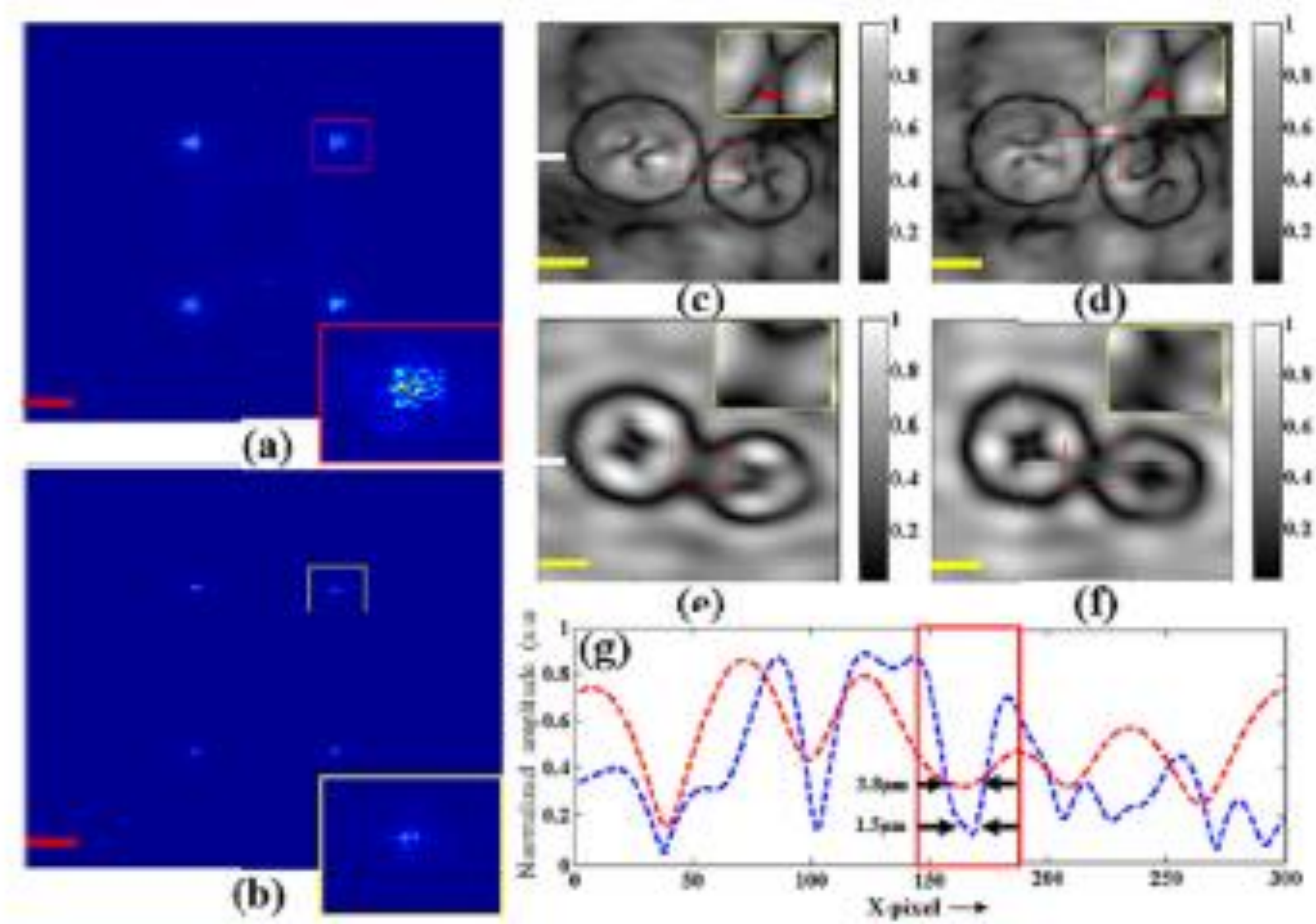
Opt. Lett. 42 (2017) 5194

Speckle field digital polarization holography



Optics Letter 44 (2019) 5711

Enhanced resolution

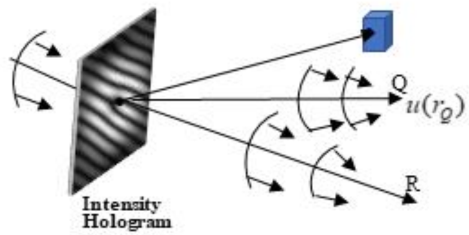


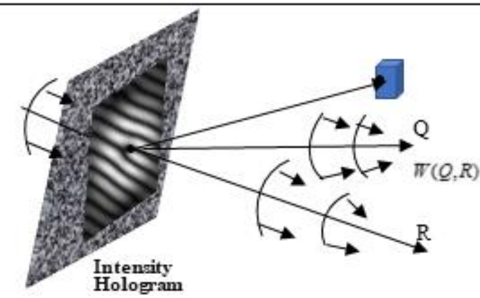
4-pentyl-4biphenyl carbonitrite (5CB-Sigma-Aldrich)

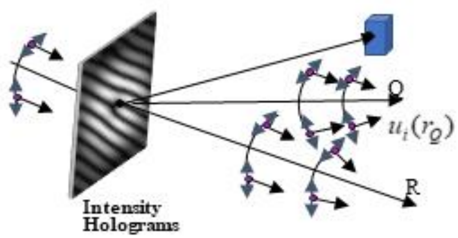
MO=5X & 0.1NA

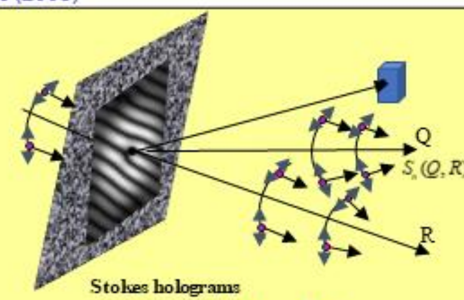
Optics Letter 44 (2019) 5711

Reconstruction of polarization holograms

<table>
<tr><th></th><th>Coherent reconstruction</th><th>Incoherent reconstruction</th></tr>
<tr><td>Scalar regime</td><td>

Ref. Leith & Upatnieks, "Reconstructed wavefronts and communication theory" J. Opt. Soc. Am. 52, 1123 (1962)</td><td>

Ref. M. Takeda et al., "Coherence Holography" Opt. Express 13, 9629 (2005)</td></tr>
<tr><td>Vectorial regime</td><td>

Ref. A. W. Lohman, "Reconstruction of vectorial wavefronts" Appl. Opt. 4 (1965) 1667</td><td>

Our recent contributions:</td></tr>
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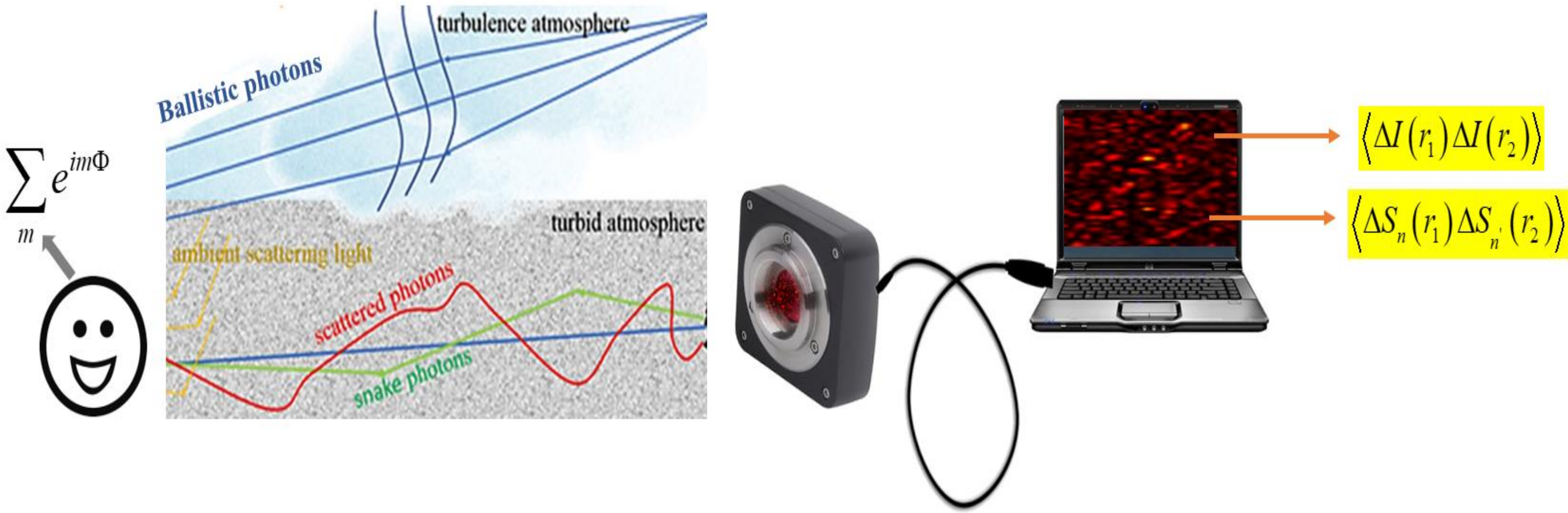
$$S_n(r) = S_n^1(r) + S_n^2(r) + 2\sqrt{S_0^1(r)S_0^2(r)}\,\left|S_n(Q_1,Q_2)\right|\cos\left\{\arg\left[S_n(Q_1,Q_2) - k(R_1 - R_2)\right]\right\}$$

Polarization imaging with correlations

1. Stokes Holography, Opt. Lett. 39 (2012) 966
2. Phase shifting holography with HBT method- Opt. Letter 45 (2020) 212; Opt. Express 28 (2020) 8145
3. HBT with polarized light: Opt. Express 26 (2018) 10801
4. Holography with higher order Stokes correlations, Phys. Rev. A 106 (2022) 013508

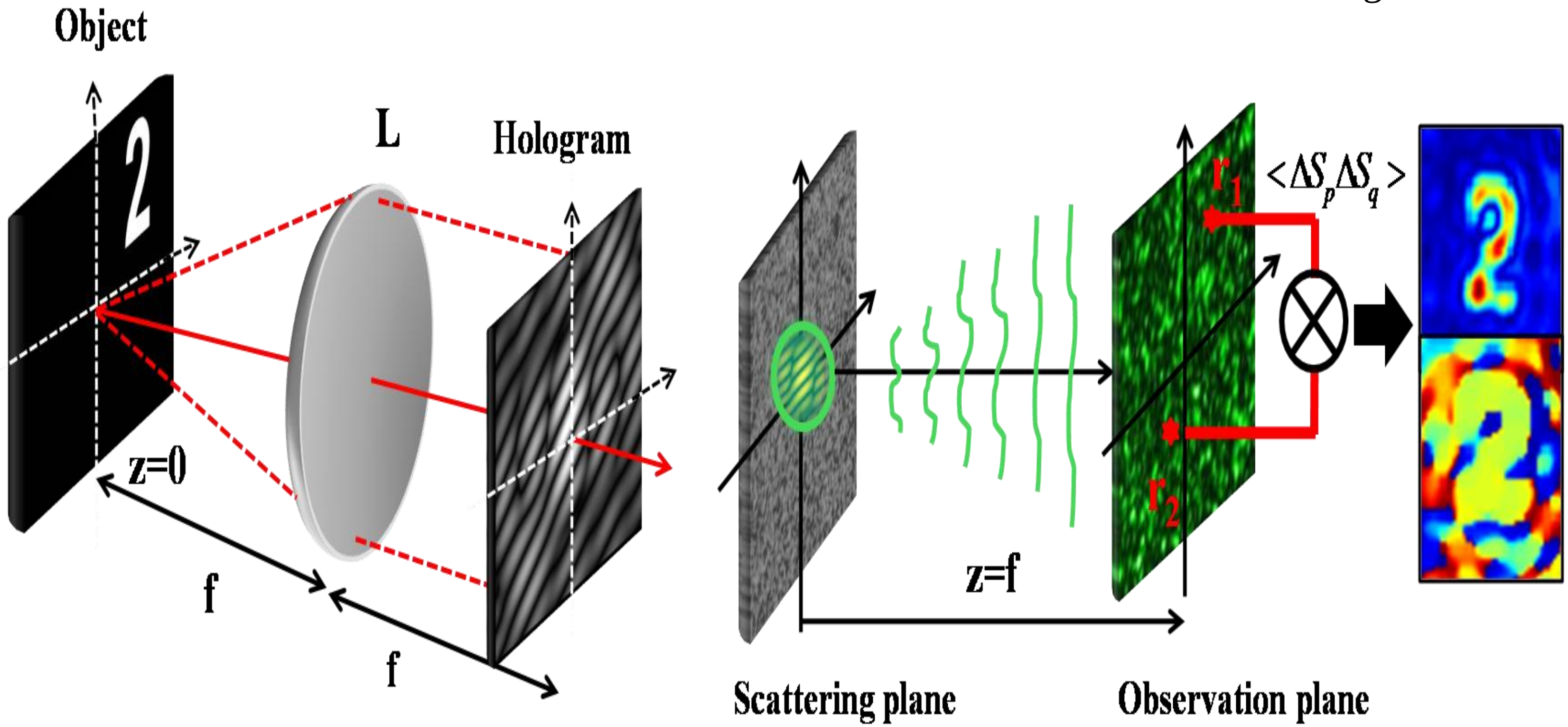
Holography with Stokes correlations



Holography with higher order Stokes correlations

Recording of Hologram

Reconstruction of Hologram



Phys. Rev. A 106 (2022) 013508

Holography with Stokes correlation

The correlation between SPs fluctuations is

$$C_{nm}(\Delta r) = \langle \Delta S_n \Delta S_m \rangle,$$

$$\begin{pmatrix} C_{00}(\Delta r) & C_{01}(\Delta r) & C_{02}(\Delta r) & C_{03}(\Delta r) \\ C_{10}(\Delta r) & C_{11}(\Delta r) & C_{12}(\Delta r) & C_{13}(\Delta r) \\ C_{20}(\Delta r) & C_{21}(\Delta r) & C_{22}(\Delta r) & C_{23}(\Delta r) \\ C_{30}(\Delta r) & C_{31}(\Delta r) & C_{32}(\Delta r) & C_{33}(\Delta r) \end{pmatrix}$$

Using un-polarized source: $W_{xy}(\Delta r)\, W_{yx}^*(\Delta r)=0$

$$C_{22}(\Delta r) = \mathrm{Re}[\, W_{xx}(\Delta r) W_{yy}^*(\Delta r]$$

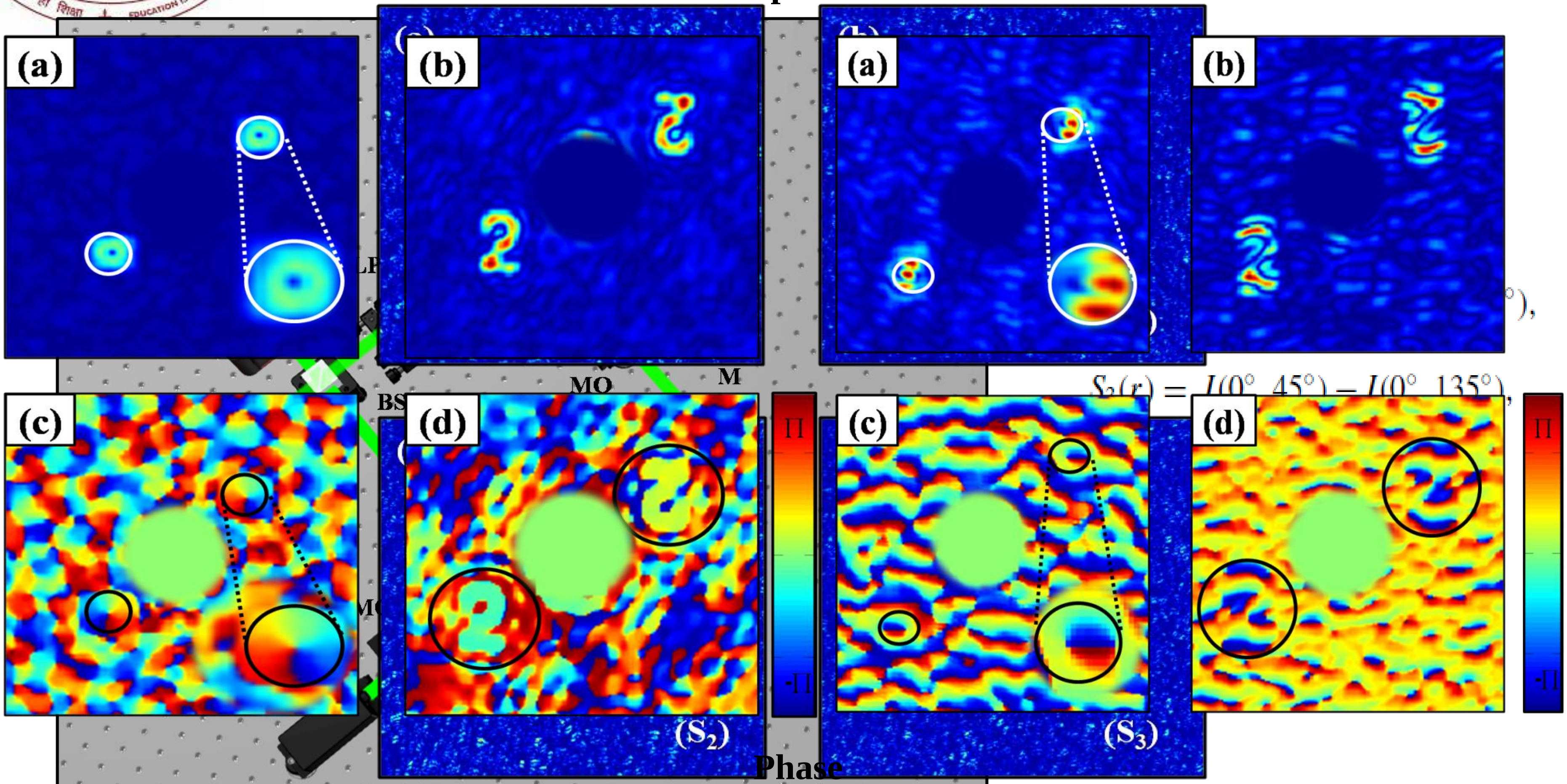
$$C_{32}(\Delta r) = i\, \mathrm{Im}[\, W_{xx}(\Delta r) W_{yy}^*(\Delta r)]$$

$$\boldsymbol{C(\Delta r) = C_{22}(\Delta r) + iC_{32}(\Delta r)}$$

Phys. Rev. A 106 (2022) 013508

Holography with Stokes correlation

Amplitude



Phase

Experimental measured Stokes parameters :(a)-(b) for l=1, (c)-(d) for number 2

Simulation Results

Experimental Results

Phys. Rev. A 106 (2022) 013508

Conclusion:

❖Polarization digital holography (PDH) is discussed and described in the context of recovery and reconstruction of the complete wavefront

❖Few experimental designs of the PDH are discussed

❖A possible extension of the digital holography with random light is also discussed

Acknowledgement

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Thank you