Subgroup Meeting Report

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Subgroup Meeting Report

1 Paper Reading: Matrix Fourier optics enables a compact full-Stokes polarization camera

Today's report

Current Progress

Matrix Fourier Optics → Polarization Gratings → Design Strategy and Optimization

Experiment → Full-Stokes Polarization Imaging

2 Course learning

Watch lecture videos about **Computational Imaging**

Watch lecture videos about **Machine Learning**

3 Deal with affairs

Campus safety training, Laboratory safety training, etc

Subgroup Meeting Report

Outline：

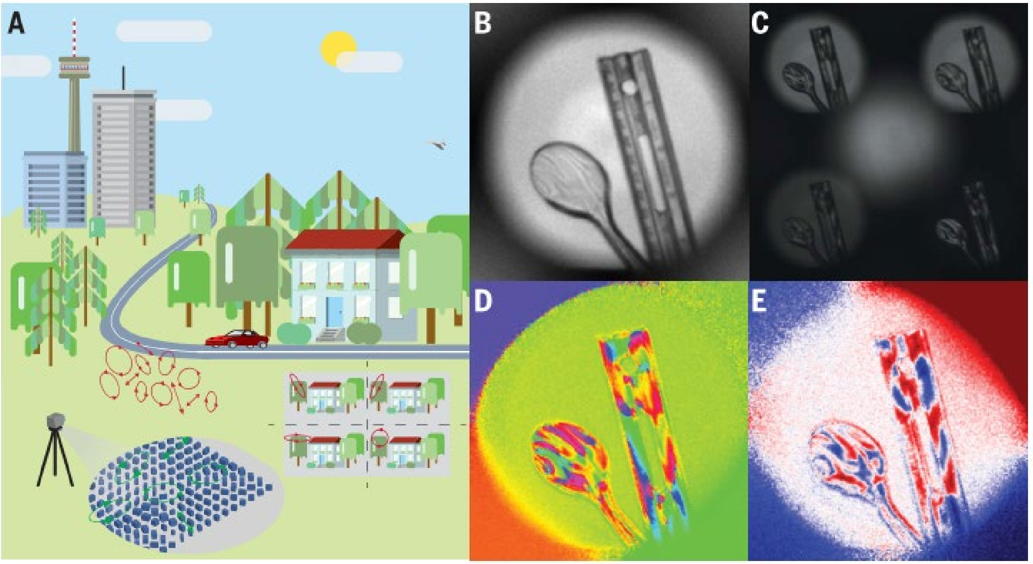
I - Background
II - Matrix Fourier optics
III - Parallel polarization analysis by unitary polarization gratings

IV - Design strategy and optimization
V - Experiment
    Tetrahedron grating design
    Mueller matrix polarimetry and results
VI - Full-Stokes polarization imaging
    Design of an imaging system
    Polarization imaging

METASURFACES

Matrix Fourier optics enables a compact full-Stokes polarization camera

Noah A. Rubin[1], Gabriele D'Aversa[1,2], Paul Chevalier[1], Zhujun Shi[3], Wei Ting Chen[1], Federico Capasso[1*]



I - Background

General Definition:

Polarization of light is determined by the path taken by $\vec{E}(\vec{r},t)$ in time.

For a plane wave:

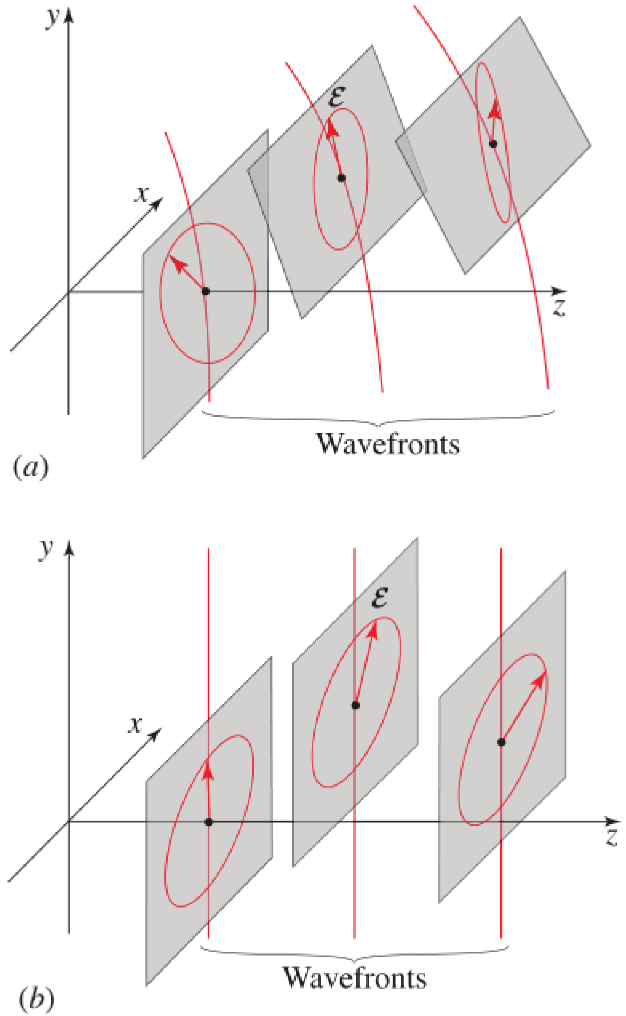
The polarization ellipses are the same everywhere.

→Can be described by a single ellipse.

→linearly/circularly/elliptically polarization

In paraxial optics:

Can be treated as plane wave approximately.



LP/CP/EP is only for describing plane wave/paraxial wave!

I - Background

Traditional perspective:

A intrinsic property of light.

Modern perspective:

With advances in micro-and-nanofabrication, the polarization state of light can be controlled point-to-point.

Related Works:

Diffractive optics, Polarization holography, and nanophotonics (metasurfaces), liquid crystal ……

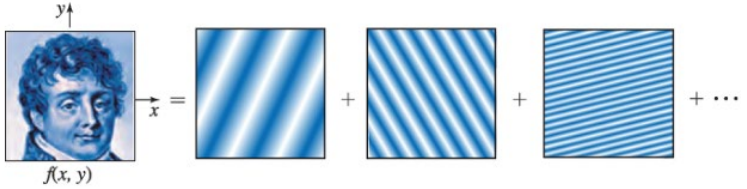
This Work:

Put forward a theory to summarize their functions.
Implement these functions in parallel.

II - Matrix Fourier Optics

A. Fourier Optics

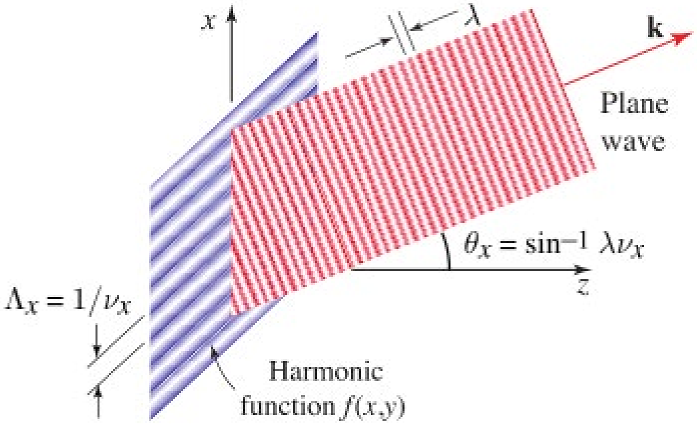
Use plane wave (harmonic function) expansion to decouple light's **interaction with systems** and **propagation in space**



The distribution of electromagnetic fields on a plane:

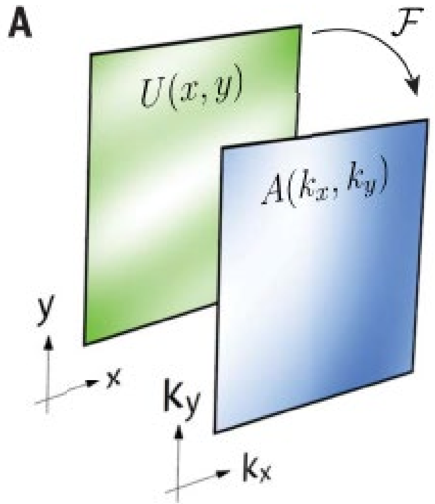
(e.g. The grating's transmittance function acts on the incident light)

$$\mathrm{U}(\mathrm{x},\mathrm{y}) = t(x,y)\mathrm{E}_0$$



Use plane wave (labeled by $\vec{k}$, i.e. direction) expansion:

$$\begin{cases} \mathrm{U}(\mathrm{x},\mathrm{y}) = \displaystyle\iint_{-\infty}^{+\infty} \mathrm{A}(\mathrm{k}_x,\mathrm{k}_y) e^{-i(\mathrm{k}_x x+\mathrm{k}_y y)} d\frac{\mathrm{k}_x}{2\pi} d\frac{\mathrm{k}_y}{2\pi} \\ \mathrm{A}(\mathrm{k}_x,\mathrm{k}_y) = \displaystyle\iint_{-\infty}^{+\infty} \mathrm{U}(\mathrm{x},\mathrm{y}) e^{i(\mathrm{k}_x x+\mathrm{k}_y y)} dxdy \end{cases}$$



→ **xy coordinate space & k wave vector space**

II - Matrix Fourier Optics

B. Matrix Fourier Optics

The grating's transmittance function: 2x2 Matrix function: (i.e. Jones Matrix)

$$\tilde{J}(\mathrm{x},\mathrm{y})$$

Incident polarization light:

$$|E_0(x,y)\rangle$$

Plane wave expansion

$$\begin{cases} \tilde{J}(\mathrm{x},\mathrm{y})|E_0(x,y)\rangle = \iint\limits_{-\infty}^{+\infty} |A(\mathrm{k}_x,\mathrm{k}_y)\rangle\, e^{-i(\mathrm{k}_x x+\mathrm{k}_y y)} d\frac{\mathrm{k}_x}{2\pi} d\frac{\mathrm{k}_y}{2\pi} \\ |A(\mathrm{k}_x,\mathrm{k}_y)\rangle = \iint\limits_{-\infty}^{+\infty} \tilde{J}(\mathrm{x},\mathrm{y})|E_0(x,y)\rangle e^{i(\mathrm{k}_x x+\mathrm{k}_y y)} dxdy \end{cases}$$

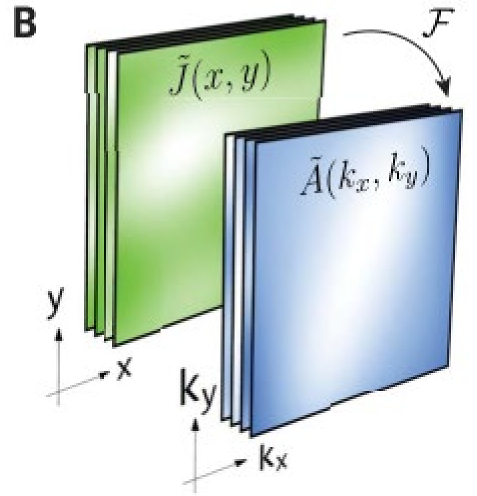
II - Matrix Fourier Optics

C. Special Case

1. Normal, uniform incident:

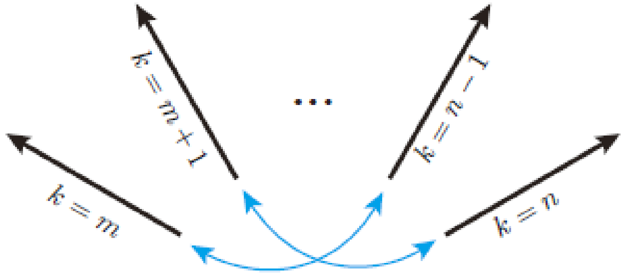
$$\tilde{J}(\mathrm{x},\mathrm{y})|E_0(x,y)\rangle \rightarrow \tilde{J}(\mathrm{x},\mathrm{y})|E_0\rangle$$

$$\Rightarrow \begin{cases} \tilde{J}(\mathrm{x},\mathrm{y}) = \displaystyle\iint_{-\infty}^{+\infty} \tilde{A}(\mathrm{k}_x,\mathrm{k}_y)e^{-i(\mathrm{k}_x x+\mathrm{k}_y y)} d\frac{\mathrm{k}_x}{2\pi} d\frac{\mathrm{k}_y}{2\pi} \\ \tilde{A}(\mathrm{k}_x,\mathrm{k}_y) = \displaystyle\iint_{-\infty}^{+\infty} \tilde{J}(\mathrm{x},\mathrm{y})e^{i(\mathrm{k}_x x+\mathrm{k}_y y)} dxdy \end{cases}$$



2. Normal, uniform incident & Periodic grating:

$$\Rightarrow \begin{cases} \tilde{J}(\mathrm{x},\mathrm{y}) = \displaystyle\sum_{\vec{k}} \tilde{J}_{\vec{k}}\, e^{-i(\mathrm{k}_x x+\mathrm{k}_y y)} \\ \tilde{J}_{\vec{k}} = \displaystyle\iint_{-\infty}^{+\infty} \tilde{J}(\mathrm{x},\mathrm{y})e^{i(\mathrm{k}_x x+\mathrm{k}_y y)} dxdy \end{cases}$$



Jones matrix of different traditional components

$$\tilde{J}(\mathrm{x},\mathrm{y}) = \sum_{\vec{k}\in\{l\}} \tilde{J}_{\vec{k}}\, e^{-i(\mathrm{k}_x x+\mathrm{k}_y y)}$$

Functions in parallel? Design in wave vector (k) space!

III - Parallel Polarization Analysis by Unitary Polarization Gratings

A. Polarization Analyzers
[Perspective of k-wave-vector space]

Each diffraction order: (bra, ket, dyadic tensor)

$$\tilde{J}_{\vec{k}} = a_k |p_k\rangle\langle q_k|$$

a_k: weight factor, $|p_k\rangle$: out put vector, $\langle q_k|$: detection vector

Function: Check specific polarization, output specific polarization

Example:

1. Input $|q_k\rangle$, maxium transmittance
2. Input Orthogonal polarization state $|q_k^{\perp}\rangle$, 0 output
3. Traditional grating, $|p_k\rangle = |q_k\rangle$

III - Parallel Polarization Analysis by Unitary Polarization Gratings

B. Recommended implementation method: Metasurface [Perspective of xy-coordinate space]

Local Jone Matrix: (pp phase)

$$\tilde{J}(x,y) = R(\theta(x,y)) \begin{bmatrix} e^{i\varphi_x(x,y)} & 0 \\ 0 & e^{i\varphi_y(x,y)} \end{bmatrix} R(-\theta(x,y))$$

Property:

1. unitary everywhere

$$\tilde{J}^{\dagger}(x,y)\tilde{J}(x,y) = I$$

2. Sampling grating

Satisfy both the requirement of xy-space and the k-space? NO!

III - Parallel Polarization Analysis by Unitary Polarization Gratings

C. Trouble: Conflict between xy-space and k-space

Previous researches on phase-only gratings have answered this question.

MUST SATISFY:

$$\tilde{J}_{\vec{k}} = a_k |p_k\rangle\langle q_k| \quad \rightarrow \quad \tilde{J}_{\vec{k}} = a_k |q_k^*\rangle\langle q_k|$$

This constraint **guarantees linear birefringence everywhere**, but it **DOES NOT guarantee unitary everywhere**

Physical significance:

1. Perspective of **Jones vector**: q_k and p_k are complex conjugate to each other
2. Perspective of **Poincaré sphere**: mirror about the equatorial plane
3. Perspective of **Stokes parameters**: change in sign of the third (chiral) Stokes component
4. Perspective of **Polarization Ellipse**: reverse the handedness of its rotation

Reference:

[1] L. A. Romero, F. M. Dickey, Theory of optimal beam splitting by phase gratings. I. One-dimensional gratings. J. Opt. Soc. Am. A Opt. Image Sci. Vis. 24, 2280–2295 (2007).

[2] L. A. Romero, F. M. Dickey, The Mathematical Theory of Laser Beam-Splitting Gratings. Prog. Opt. 54, 319–386 (2010).

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Everywhere unitary can be satisfied only when **it is a 2-order polarization analyzer** & **orthogonal polarization**

How to design high order polarization analyzer?

——Allow light to leak into the higher orders

To be continued

→ **IV - Design strategy and optimization**
- Analytic theory
- Numerical methods (ML)

Subgroup Meeting Report

ARTICLE

https://doi.org/10.1038/s41467-022-30439-9 OPEN

Ultra-compact snapshot spectral light-field imaging

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Ideal imaging, which is constantly pursued, requires the collection of all kinds of optical information of the objects in view, such as three-dimensional spatial information (3D) including the planar distribution and depth, and the colors, i.e., spectral information (1D). Although three-dimensional spatial imaging and spectral imaging have individually evolved rapidly, their straightforward combination is a cumbersome system, severely hindering the practical applications of four-dimensional (4D) imaging. Here, we demonstrate the ultra-compact spectral light-field imaging (SLIM) by using a transversely dispersive metalens array and a monochrome imaging sensor. With only one snapshot, the SLIM presents advanced imaging with a 4 nm spectral resolution and near-diffraction-limit spatial resolution. Consequently, visually indistinguishable objects and materials can be discriminated through SLIM, which promotes significant progress towards ideal plenoptic imaging.