Title

Application of Poincaré Sphere in Structure Photonics

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Abstract: This review assesses an integrated structured light architecture based on phased array synthesis and calculates the data points on the Poincaré Sphere through the utilization of Stokes parameters and cross-correlation techniques.

INTRODUCTION

Structured photonics expands new possibilities for light control by facilitating precise adjustments over various properties of light. The intricate generation and manipulation of structured light can be explored through programmable spatio-temporal variant field vectors, amplitudes, and phase distributions. [1] As the tools to create and detect structured light have improved, numerous applications of structured photonics have arisen [2]. For example, Bessel light bullets — utilized in optical trapping, precision drilling, and laser acceleration — require tightly-focused and temporally short pulses [3]. Unfortunately, due to technological limitations, current applications of structured photonics, particularly spatial light modulators, are incapable of utilizing all degrees of freedom [1]. In addition, the low operational damage threshold of spatial light modulators hinders the application of structured light that requires MW- and W- power levels, such as ultrashort pulse manipulation.

An alternative approach to structured photonics, phased arrays, has exemplified the creation of complex light beams through the coherent combination of femtosecond pulses [1]. This research paper introduces a laser architecture that takes advantage of the synthesis of phased arrays and programmable field-amplitude, carrier-envelope, relative phase, and polarization [1]. Tiled phased arrays allow for the customizability of all 3-dimensional wave vector distribution parameters to produce structured light pulses, vortex, and orbital angular (OAM) momentum. The potential impact of phased-array based laser architecture is substantial, heralding new possibilities of light manipulation and promising advancements in nonlinear topological and nuclear photonics [1].

METHODS

The experimental configuration of the proposed light architecture surpasses the shortcomings of spatial light modulators by facilitating customizable light bullets. The system begins with a laser oscillator delivering 140 mW of power in 175 fs pulses [1]. The signal passes through a carrier-envelope phase (CEP) stabilizer and an ultralow phase-noise feed-forward technique is conducted to reduce pulse-to-pulse jitter. A 1:N beam splitter divides the signal into N beamlines and sets one beamline as the benchmark for observing and adjusting inter-beamline phase offset through field-programmable gate array (FPGA) [1]. Due to CEP stabilization, all the beamlines have consistent phases. With the exception of the reference beamline, the field parameters of all beamlines are actively monitored and altered. The phase modulator within each beamline can alter the beamline's phase relative to the reference beamline by employing FPGA. The half wave plate, quarter wave plate, and polarizing beam splitter can manipulate the intensity and polarization of light. When field vector customizations are final, circularly birefringent fibers maintain the final polarization state before the beamlines, arranged hexagonally to align at the same time and place at the photodiode, are combined [1].

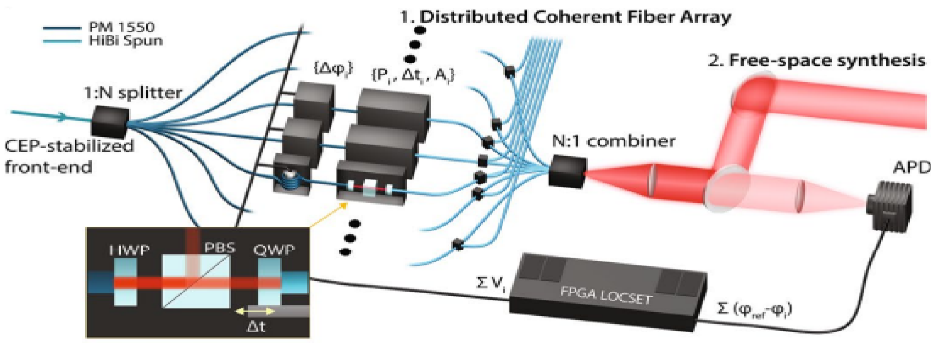

Figure 1: Experimental Configuration of Laser Architecture (Ref. [4], Fig 1b).

The local polarization ellipse across a certain area in an image can be illustrated on a polarization vector map if the Stokes parameters are calculated. To obtain Stokes parameters, seven images are taken: one for a full-field image and six for the projections on the Poincaré sphere [1]. The six projections pertain to horizontal and vertical (linear polarization), diagonal and anti-diagonal (linear polarizations at 45 degrees and -45 degrees), and right-handed and left-handed (circular polarizations) [5]. These polarization pairs represent the extreme points for each of the Stokes parameters. These images of size NxM can be captured by using a system that consists of a quarter-wave plate, a half-wave plate, a polarizing beam splitter, and an InGaAs camera [1]. A quarter-wave plate, composed of anisotropic material and possessing a quarter-period thickness, is used to convert a linearly polarized wave to an elliptically polarized wave [4]. A half-wave plate possesses a half-period thickness and is used to rotate the polarization direction of a linearly polarized wave by assessing the angle between the incident linear polarization and the principle axes. The optical field is elliptically polarized when the polarization unit vector is not constant [4]. Smaller images of nxm pixels are also taken to ensure consistency in the field region [1]. The normalized cross-correlation between the smaller images and the projection is calculated and the maximum cross-correlation indicates identical field regions. Furthermore, the projections are cropped to NxM when the maximum cross-correlation is found; these images can then be used to calculate the field' local Stokes parameters. The polarization ellipse can be described by the eccentricity, e, tilt relative to a fixed axis(θ), and the chirality which is determined by the sign of S_3.

$$e = \sqrt{\frac{2\sqrt{S_1^2 + S_2^2}}{1 + \sqrt{S_1^2 + S_2^2}}} \qquad\qquad 2\theta = \tan^{-1}\frac{S_2}{S_1}$$

RESULTS AND INTERPRETATION

The added complexities, such as CEP stabilization, independent control of field parameters, and FPGA-based LOCSET, as well as a higher tolerance of power levels of this integrated structured light architecture enables the design of light pulses [1]. The ability of phased arrays to coherently synthesize beams with varying degrees of freedom underscores their versatility and precision. Complex spatial arrangements of orbital angular momentum and polarization can be measured and depicted through the mapping of phase and Poynting vectors. The Poincaré sphere is a three-dimensional graphical representation in real space that provides a convenient means to describe polarized light and the polarization transformations that occur when the light propagates [6]. The points on the sphere are calculated using the orientation angle, α, and ellipticity angle, ϵ. The cartesian coordinates (x, y, z) of a point are the normalized Stokes parameters (S_1, S_2, S_3) while $S_0 = 1$ for normalized Stokes parameters. The orientation parameter α can be measured by taking the directional angle between the major axis of the ellipse and the x-axis [4]. Generally, the Stokes parameters can be calculated from the intensity distributions of a system [6].

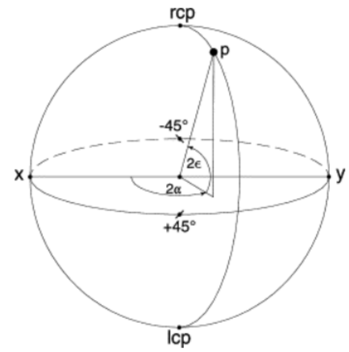

Figure 2: Poincaré Sphere (Ref. 6, Fig. 2b)

$S_0 = I_{0°} + I_{90°}$ $S_1 = I_{0°} - I_{90°} = \cos(2\epsilon)\cos(2\alpha)$

$S_2 = I_{45°} - I_{-45°} = \cos(2\epsilon)\sin(2\alpha)$ $S_3 = I_R - I_L = \sin(2\epsilon)$

When the projection image and the smaller images of nxm pixels share maximum cross-correlation, the local Stokes parameters can be calculated from the seven centered and subdivided images from the intensity distributions which in turn can describe the polarization ellipse.

If the horizontal and vertical intensity distributions = $I_{0°} = ⅔$, $I_{90°} = ⅓$ => $S_0 = I_{0°} + I_{90°} = 1$

$S_1 = I_{0°} - I_{90°} = ⅔ - ⅓ = ⅓$, If $I_{45°} = 1$, $I_{-45°} = ½$ => $S_2 = I_{45°} - I_{-45°} = 1 - ½ = ½$

eccentricity: $e = \sqrt{\frac{2\sqrt{S_1^2 + S_2^2}}{1 + \sqrt{S_1^2 + S_2^2}}} = \sqrt{\frac{2\sqrt{\left(\frac{1}{3}\right)^2 + \left(\frac{1}{2}\right)^2}}{1 + \sqrt{\left(\frac{1}{3}\right)^2 + \left(\frac{1}{2}\right)^2}}} = 0.8664$

tilt: $\theta = (½)\arctan(S_2/S_1) = (½)\arctan(½/ ⅓) = 4.7312°$

if $I_R = ¾$, $I_L = ½$ => $S_3 = I_R - I_L = ¾ - ½ = ¼$ => chirality is positive

Polarization ellipse elongated in one direction with right-handed circular polarization.

CONCLUSIONS

The comprehensive exploration of the Poincaré sphere in the context of structured light architectures reveals its indispensable role in representing and analyzing the polarization states of light. Through the use of Stokes parameters and optical equipment like wave plates and polarizing beam splitters, the study captures the nuanced transformations of polarization states as light propagates. The Poincaré sphere can represent all possible states of light polarizations which includes linear, circular, and elliptical polarizations. Since polarization states of light are inherently multidimensional, it can sometimes be difficult to visualize what is occurring; however, the Poincaré Sphere simplifies these concepts through a graphical representation.

REFERENCES

1. Lemons, Randy, et al. "Integrated structured light architectures." Scientific reports 11.1 (2021): 1-8
2. Liu, Jia-Ming. Principles of Photonics, Cambridge University Press, New York (2017)
3. “The Stokes Polarization Parameters.” *The Stokes Polarization Parameters*, spie.org/publications/fg05_p12-14_stokes_polarization_parameters?SSO=1. .
4. Liu, J.M. Principles of Photonics. Cambridge University Press, 2016
5. : Dennis MR, Alonso MA. 2017 Swings and roundabouts: optical Poincaré spheres for polarization and Gaussian beams. Phil. Trans. R. Soc. A 375: 20150441. http://dx.doi.org/10.1098/rsta.2015.0441
6. Sun, X., Geng, Y., Zhu, Q. *et al.* Unitary transformation for Poincaré beams on different parts of Poincaré sphere. *Sci Rep* 10, 14251 (2020). https://doi.org/10.1038/s41598-020-71189-2