Review on "Integrated Structured Light Architectures" (Lemons 2021)

By Mark Diamond

Abstract: The proof-of-concept of a novel 7-beam composite laser array with individually controlled beams is described and its programmability of polarization states is examined in further detail with regards to the states of the Poincaré sphere.

INTRODUCTION

The researchers propose a new laser architecture that allows for generation and real-time manipulation of the light intensity profiles at a destination in any desired pattern varying in space and time. They aim to create a composite laser structure that is programable in several degrees of freedom, including amplitude, linear momentum, spin angular momentum (SAM), and orbital angular momentum (OAM). By being able to manipulate all these parameters of light in a laser beam, further areas of research may be opened up for study that weren't possible due to limitations in the controlling all the properties of the source laser.[1]

Currently existing methods of achieving structured light often lack several key properties for fully custom light shaping, cutting out a large range of possible light structures that can be made, thus hindering many other possible applications requiring structured light beams.[1]

Therefore, the researchers propose a general configurable laser architecture with all of these degrees of freedom able to be programed and adapted. The architecture is an array of laser beams, each with separate controls for amplitude, carrier envelope, relative phase, and polarization. When combined these individually-controlled beamlines can create a wide variety of light structures.

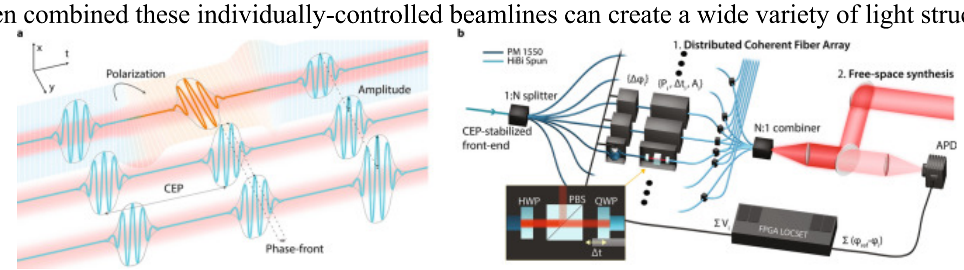


Fig. 1. The various degrees of freedom (a) and architecture of the laser configuration (b). (Ref [1], Fig. 1).

As shown in Fig. 1.b, an initial laser beam is split into N separate beamlines, which each undergo individual modulation states of phase ($\Delta\phi_i$), polarization state (P_i), timing (Δt_i), and amplitude (A).[1] The beams are then recombined and are sent through a feedback loop that keeps the initial beamlines in sync.

METHODS

One section of the paper talks about polarization topography, which is the idea of changing the polarization states of each individual laser beam to form a composite varying polarization across the full beam. Three experimental examples of this are shown below in Fig. 2.

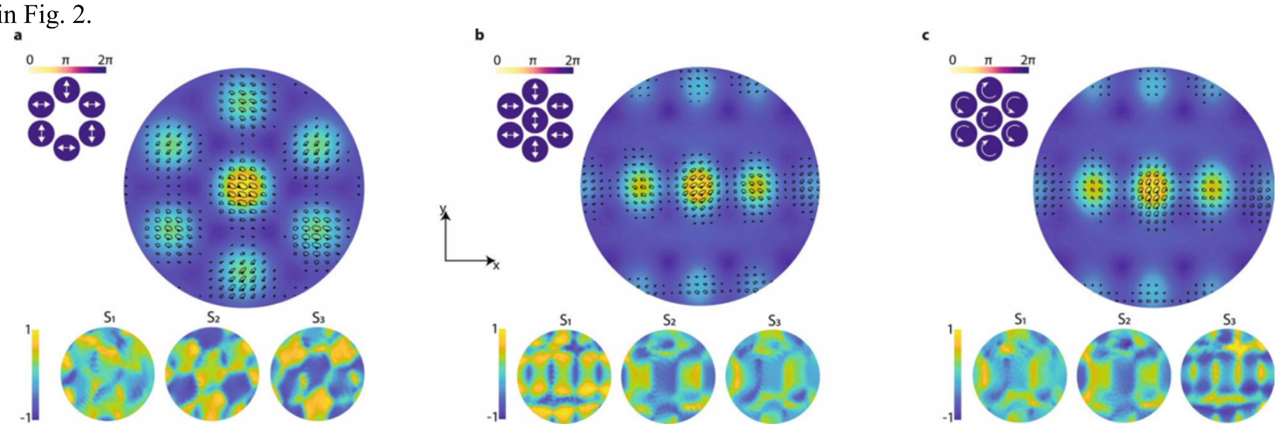


Fig. 2. Experimental polarization array states of 6-beam configuration, with Stokes projections (S1, S2, S3) below. (Ref [1], Fig. 4).

The elliptical arrows across each diagram represent the spin angular momentum distribution across the beam, While the color gradients are the far-field projected beam intensities of each configuration. The researchers chose to keep all of the beamlines at the same phase and amplitude, and only varied the polarizations of each.[1] As can be seen, the polarization states at the center of each intensity region have greater magnitudes than at points with less intensity, caused by constructive and destructive interference between the beamlines. Likewise, the polarization states also experience this interference, as can be seen by larger or smaller elliptical arrows.

The spin angular momentum directions were calculated with the experimentally measured Stokes parameters, shown in the three circles labeled S_1, S_2, and S_3. Stokes parameters are physical intensity distributions that result from the light undergoing specific series' of polarizing events for each parameter.[2] As such, the researchers were directly captured and measured the Stokes parameter projections through a polarizing optical system.[1]

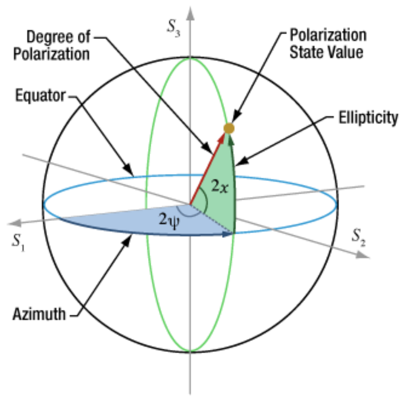
The Poincaré sphere is a graphical representation that helps to visualize polarization states by mapping properties of the polarization ellipses to the surface of a sphere in spherical coordinates.[3] The first property is the eccentricity, which is the measure of how "flat" the ellipse is. An eccentricity of 0 corresponds to a perfect circle, while an eccentricity of 1 corresponds to simply a flat line.[2] The second property is the angle, θ, that the major axis makes with the horizontal axis, referred to as "tilt" by the paper. Note that this half the value that Eq. (2) gives.

The eccentricity (e) and tilt (θ) of the ellipse is given by the paper as:[1]

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

The Stokes parameters, S_1, S_2, and S_3, are cartesian coordinates, and therefore represent transformations of the ellipse properties between the spherical and the cartesian space.[3] Finally, the paper mentions that the third Stokes parameter, S_3, determines the chirality of the polarization (left-handed or right-handed). It is at this point that the paper ends its explanation on its method of calculating the polarization states of the beamlines.

However, a much more visual and intuitive method of verifying the polarization states shown in the results would be to actually use the Poincaré sphere instead in order to derive the equations stated in the paper. Fig. 3 below shows the Poincaré sphere.



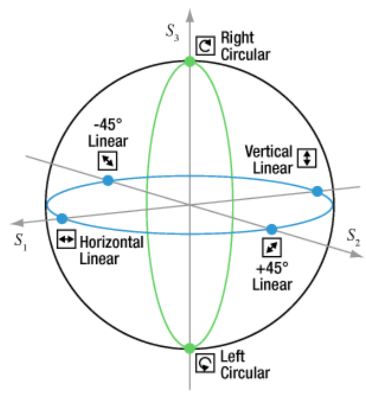


Fig. 3. Poincaré sphere, showing spherical coordinate angles (a) and mapped polarization states (b). (Ref [3], Fig. 1, 2).

The first thing to note is the relationship between the cartesian Stokes parameters, S_1, S_2, and S_3, and the spherical coordinates represented by the azimuth angle, 2ψ, and ellipticity angle, 2χ, shown in Fig. 3.a. The azimuth angle is measured from the S_1 axis in the direction shown, and the ellipticity angle is measured from the S_1 - S_2 plane. As the full-intensity polarization states are located on the surface of the sphere, this discussion will not consider the radius component, R, and will take the Poincaré sphere to be a normalized unit sphere (R=1). Points on the interior of the sphere indicate partial destructive interference and a corresponding decreased beam intensity and polarization state.[3]

The relationship between the Stokes parameters and 2ψ and 2χ are given by the following equations:[3]

$$S_1 = cos(2\chi)\, cos(2\psi) \quad (3) \qquad S_2 = cos(2\chi)\, sin(2\psi) \quad (4) \qquad S_3 = sin(2\chi) \quad (5)$$

In order to build the relationship between the Stokes parameters and the ellipse properties of eccentricity and tilt in Eq. (1) and Eq. (2), we square Eq. (3) and simplify using trigonometric identities, as shown below:

$$S_1{}^2 = \cos^2(2\chi)\cos^2(2\psi)$$
$$S_1{}^2 = \cos^2(2\chi)\,[1-\sin^2(2\psi)]$$
$$S_1{}^2 = cos^2(2\chi) - cos^2(2\chi)sin^2(2\psi) \quad (6)$$

Note that the second term in Eq. (6) is simply equal to Eq. (4) squared, or $S_2{}^2$.

$$S_1{}^2 = \cos^2(2\chi) - S_2{}^2$$
$$S_1{}^2 + S_2{}^2 = \cos^2(2\chi)$$
$$\sqrt{S_1{}^2 + S_2{}^2} = cos(2\chi) \quad (7)$$

Conveniently, Eq. (7) is equal to the $\sqrt{S_1{}^2 + S_2{}^2}$ term in the eccentricity equation, Eq. (1). Therefore, we can substitute, like so:

$$e = \sqrt{\frac{2\sqrt{S_1{}^2+S_2{}^2}}{1+\sqrt{S_1{}^2+S_2{}^2}}} = \sqrt{\frac{2\cos(2\chi)}{1+\cos(2\chi)}} \quad (8)$$

Therefore, it is found that the eccentricity is only a function of 2χ, the ellipticity angle, hence the name. Graphically, this means that any and all changes in the eccentricity of the polarization ellipse corresponds to a movement of polarization state along the lines of longitude of the Poincaré sphere, such as the green circle shown in Fig. 3.b.

Plugging in $2\chi = 0°$, it is found that $e = 1$, indicating that points along the equator of the Poincaré sphere (equivalently, the S_1 - S_2 plane, with $S_3 = 0$) have ellipses that are completely flat. In other words, they are linearly polarized. Conversely, when $2\chi = 90°$, $e = 0$, which indicates perfectly circular polarizations at the north and south poles of the sphere (where $S_1 = S_2 = 0$, and $S_3 = 1$). These conversions can be verified by looking back at Eq. (3) through Eq. (5).

Now, the azimuth angle, 2ψ, will be explored. The azimuth angle on the Poincaré sphere is related to the tilt of the polarization ellipse, θ, given by Eq. (2). Taking Eq. (2) and substituting Eq. (3) and Eq. (4), we have:

$$2\theta = \tan^{-1}\frac{S_2}{S_1} = \tan^{-1}\left(\frac{\cos(2\chi)\sin(2\psi)}{\cos(2\chi)\cos(2\psi)}\right) = \tan^{-1}\left(\frac{\sin(2\psi)}{\cos(2\psi)}\right) = \tan^{-1}(\tan(2\psi)) = 2\psi$$

$$\theta = \frac{2\psi}{2} \quad (9)$$

As it turns out, one half of the azimuth angle, $2\psi/2$, is actually the tilt angle itself, θ. Graphically, this means that as the polarization state moves across lines of latitude on the Poincaré sphere, such as along the blue circle in Fig. 3.b, the tilt of the polarization ellipse corresponds exactly to its azimuth angle divided by 2. For example, at $2\psi = 0°$, the tilt angle is 0°, meaning that the polarization state is either a horizontal line or an ellipse with a horizontally-aligned major axis. Likewise, if $2\psi = 45°$, the tilt is 22.5° and so the polarization state is a diagonal line or diagonally-aligned ellipse at 22.5° to the horizontal.

Finally, the S_3 Stokes parameter simply determines the chirality of the polarization ellipse. In other words, if S_3 is positive, then 2χ is positive, and the polarization is "right handed," moving in a clockwise direction looking into the beam propagating towards the viewer. This places the polarization state on the top hemisphere of the Poincaré sphere. If it is negative, the polarization is "left handed," or counterclockwise, and its state is on the bottom hemisphere of the Poincaré sphere.[3]

From this mathematical discussion, any point on the Poincaré sphere can be easily calculated, visually located, and interpreted given the Stokes parameters.

RESULTS AND INTERPRETATION

The researchers concluded that they were able to generate a programable light beam to have any custom polarization profile they wanted, giving their proof-of-concept for a 7-beam laser arranged in a 6-beam hexagonal pattern surrounding a center beam. Each beamline can be programed to vary intensity, phase, and polarization states. As Fig. 2 shows, the Stokes parameters were measured, calculated, and plotted over the far-field intensity distribution, showing a customizable and predictable relationship between the beamline parameters and the total resulting beam properties.

Using the Poincaré sphere method described in the previous section, we can verify these results quite easily and graphically by simply visually inspecting the Stokes parameter values at a chosen point, and plotting them as cartesian coordinates with the Poincaré sphere. Then, using Fig. 3, the shape of polarization ellipse is predicted.

CONCLUSIONS

The results of this study show that an extremely large number of configurations can be created with even just a few independently-programed beamlines in a composite laser array. By varying the polarization states, an arbitrary phase-front of a laser can be created at-will and dynamically manipulated. Possible further research on this subject may include work into deterministically finding the correct configuration of the beamlines given the desired total output beam properties, and developing a program to control such a system.

These findings have the potential to unlock many more fields of optical research that requires specific light structures not previously able to attain easily, or even at all. The researchers highlight certain fields, including optical quantum communications, image processing, and nonlinear topological photonics, in which it is hoped that this research can enable new and insightful breakthroughs.

REFERENCES

1. Lemons, Randy et al. “Integrated Structured Light Architectures.” *Scientific Reports* 11.1 (2021). Available: https://doi.org/10.1038/s41598-020-80502-y.

2. Libretexts. “4.1: Polarized light and the Stokes parameters.” *Physics LibreTexts*, 5 Mar. 2022. Available: https://phys.libretexts.org/Bookshelves/Optics/Physical_Optics_(Tatum)/04%3A_Stokes_Parameters_for_Describing_Polarized_Light/4.01%3A_Polarized_Light_and_the_Stokes_Parameters.

3. Thorlabs, Inc. “How is a Poincare Sphere useful for representing polarization states?” *Thorlabs*, 11 Sep. 2020. Online. Internet. 9 Dec. 2023. Available: https://www.thorlabs.com/newgrouppage9.cfm?objectgroup_id=14200.