Title

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Author

Warner, Dylan Michael

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Dylan Warner[1]
[1]Department of Electrical and Computer Engineering, University of California, Los Angeles, CA 90095, USA

Abstract: We review the integrated structured light architecture of Lemons et al., re-deriving polarization states via Stokes parameters and quantifying discretization-induced phase errors to assess beam quality and broader photonic applications.

INTRODUCTION

Structured light, in which the amplitude, phase, and polarization of an optical field are engineered in space and time, enables applications ranging from high capacity optical communication to microscopy, optical trapping, and advanced material processing. The ability to program these degrees of freedom on demand is central to modern photonics, yet many platforms rely on bulky spatial light modulators or fixed diffractive optics that limit speed, robustness, and power handling. Lemons et al. propose an integrated structured light architecture based on coherent beam combination that offers spatio temporal programmability of the optical field: multiple discretized beamlines from a mode locked laser are individually controlled in amplitude, phase, polarization, and timing, and then coherently recombined to synthesize complex target fields such as vortex beams and polarization structured beams. This light by design approach connects directly to concepts developed in Principles of Photonics, where polarization states are mapped onto the Poincaré sphere and arbitrary fields are represented as superpositions of simpler modes. In this review I focus on how that theoretical framework can be used to analyze and interpret the Lemons et al. architecture. First, I examine polarization control using Jones calculus and Stokes parameters to show how the states generated by the system can be mapped onto the Poincaré sphere and how this mapping can be used to validate polarization claims. Second, I analyze the effect of discretization in coherent beam synthesis by modeling how a finite number of beamlines approximates a continuous phase profile and by quantifying the resulting phase error as a function of the number of channels. Together, these two perspectives provide a critical evaluation of how well the proposed architecture realizes high fidelity polarization and phase control and highlight its broader relevance for integrated photonics.

METHODS

Polarization Representation and Stokes Parameter Framework

A quasi monochromatic beam propagating along z can be represented in the Jones formalism by a complex two component vector

$$E = \left[E_x ,\ E_y\right] = \left[\left|E_x\right| e^{i\Phi_x} ,\left|E_y\right| e^{i\Phi_y}\right]$$

From this, the Stokes parameters are defined as

$$S_0 = \left|E_x\right|^2 + \left|E_y\right|^2, \qquad S_1 = \left|E_x\right|^2 - \left|E_y\right|^2$$
$$S_2 = 2\Gamma(E_x E_y^*),\ S_3 = 2Im(E_x E_y^*)$$

and the normalized Stokes vector (s_1, s_2, s_3) is given by

$$s_1 = \frac{S_1}{S_0}; \qquad s_1 = \frac{S_2}{S_0}, \qquad s_1 = \frac{S_3}{S_0}$$

The triplet (s_1, s_2, s_3) corresponds to a point on the Poincaré sphere, providing a compact geometric representation of the polarization state. This is the framework implicitly used when reconstructing polarization topographies and polarization singularities from synthesized fields in integrated structured light architectures.

To make this concrete, I consider three canonical states that form a basis for interpreting more complex polarization patterns:

Linear Horizontal (H): $E_H = [1\,,0]$

Linear at 45°: $E_{45} = \frac{1}{\sqrt{2}}[1\,,1]$

Right hand circular (RHC): $E_{RHC} = \frac{1}{\sqrt{2}}[1\,,-\,i]$

Evaluating the Stokes parameters and normalized coordinates for these states yields the entries summarized in Table 1. These simple examples serve as reference points for interpreting the spatially varying polarization states synthesized in the experiment.

State	Description	Jones Vector E	(S_0, S_1, S_2, S_3)	(s_1, s_2, s_3)
P1	Linear H	$[1\,,0]$	(1,1,0,0)	(1,0,0)
P2	Linear 45°	$\frac{1}{\sqrt{2}}[1\,,1]$	(1,0,1,0)	(0,1,0)
P3	Right hand circular	$\frac{1}{\sqrt{2}}[1\,,-\,i]$	(1,0,0,-1)	(0,0,-1)

Table 1. Example Stokes vectors and Poincaré coordinates for canonical polarization states.

In the Lemons et al. platform, each beamline can be assigned a distinct polarization state before coherent combination. By associating these local states with points on the Poincaré sphere, one can reconstruct the spatial polarization structure and verify whether synthesized radial, azimuthal, or more exotic fields occupy the expected trajectories on the sphere.

Discretization Model for Coherent Beam Synthesis

The integrated structured light architecture approximates a desired continuous transverse phase profile $\phi_{ideal}(\theta)$, for example a helical phase $\phi_{ideal}(\theta) = l\theta$ for an orbital angular momentum (OAM) mode of charge l, with a finite number N of discrete beamlines located at angular positions $\theta_k = 2\pi k/N$.

In the ideal case, the phase at each channel would be

$$\phi_{ideal}(\theta_k) = l\theta_k = l2\pi k/N$$

However, practical constraints in the electronic and optical control hardware mean that the phase at each channel is realized with finite resolution, and the overall phase profile is effectively piecewise constant between channels. This can be approximated as a uniform phase quantization step of size

$$\Delta\phi = \frac{2\pi k}{N}$$

so that the realized phase profile is

$$\phi_{disc}(\theta) \approx \phi_{ideal}(\theta_k) \qquad \text{for} \qquad \theta \in [\theta_k, \theta_{k+1})$$

Under a standard quantization model, the local phase error $\delta\phi(\theta) = \phi_{disc}(\theta) - \phi_{ideal}(\theta)$ is assumed uniformly distributed in the interval $[-\ \Delta\phi/2, -\ \Delta\phi/2,]$. The root mean square (RMS) phase error is then

$$\epsilon_{RMS} = \sqrt{\left(\delta\phi^2\right)} = \frac{\Delta\phi}{\sqrt{12}} = \frac{2\pi}{N\sqrt{12}}$$

This expression provides a simple way to quantify the benefit of increasing the number of channels. Doubling N halves $\Delta\phi$ and thus halves ϵ_{RMS}.

To illustrate this scaling, I compute $\Delta\phi$and ϵ_{RMS} for representative channel counts N=8, 16, 32, 64 corresponding to increasingly fine discretizations of the desired phase profile. The results are summarized in Table 2 and can be visualized by plotting ϵ_{RMS} versus N.

N	$\Delta\phi = \frac{2\pi}{N}\,(rad)$	$\epsilon_{RMS} = \frac{2\pi}{N\sqrt{12}}\,(rad)$
8	0.79	0.23
16	0.39	0.11
32	0.20	0.057
64	0.10	0.028

Table 2. Phase step and RMS phase error as a function of the number of channels N.

RESULTS AND INTERPRETATION

Polarization States and the Poincaré Sphere

Lemons et al. demonstrate spatially structured polarization patterns, including fields with azimuthally varying linear polarization and polarization singularities where the state becomes indeterminate. Using the Stokes framework from the Methods section, each local polarization state can be mapped to a point on the Poincaré sphere. For an ideal azimuthally polarized beam, for example, the tip of the normalized Stokes vector would trace a great circle on the sphere corresponding to linear polarization with orientation angle equal to the azimuthal coordinate.

The simple examples in Table 1 match the textbook expectations. Horizontal, 45 degree, and right hand circular polarizations map to the positive S_1, positive S_2, and negative S_3 axes, respectively. In the context of the Lemons et al. architecture, these states serve as basis points for verifying experimental reconstructions. If the measured Stokes parameters at particular locations in the beam cross section correspond closely to these ideal coordinates, it confirms that the polarization control electronics and beamline optics are correctly generating the desired states.

Because the architecture allows independent control of each channel's polarization, the overall polarization field can be viewed as a superposition of these canonical states weighted by spatially varying coefficients. Deviations of measured Stokes points from their ideal locations on the Poincaré sphere provide a quantitative metric for polarization fidelity. For example, if a nominally right hand circular region yields a Stokes vector with $\left|s_3\right| < 1$ and nonzero s_1 or s_2, this directly reveals ellipticity or unintended linear components introduced by imperfect calibration. This type of analysis is consistent with the polarization reconstructions reported in integrated structured light experiments and offers a clear way to validate or refine their results using polarization theory.

Discretization Effects on Structured Beam Fidelity

The coherent beam synthesis scheme in Lemons et al. relies on a finite number of channels to approximate continuous transverse phase profiles such as those required for vortex beams. The quantization model developed in the Methods section allows us to connect the number of channels N to an RMS phase error that directly impacts beam quality.

Table 2 shows that for N=8 the phase step is approximately 0.79 rad and the RMS phase error is about 0.23 rad, which is more than 10 degrees of phase uncertainty. In Fourier optics, such large phase errors lead to noticeable distortions in the far field intensity profile. Side lobes become more pronounced, the central dark core of an OAM beam may partially fill in, and energy leaks into unwanted modes. For N=16, the RMS error drops to roughly 0.11 rad, and by N=32 to 64 it falls below 0.06 rad. At this level, the synthesized wavefront more closely approximates the ideal continuous phase, and high fidelity structured beams are expected.

If one plots ϵ_{RMS} as a function of N, the curve decreases approximately in proportion to 1/N. The relationship emphasizes the strong benefit of increasing the number of channels, but also suggests diminishing returns. Once ϵ_{RMS} is well below about 0.1 rad, further reductions may be limited by other factors such as amplitude errors, timing jitter, or alignment tolerances rather than phase quantization itself.

In experimental results of integrated structured light architectures, discretization manifests in the quality of reconstructed vortex and structured beams. Configurations with fewer effective channels show more pronounced intensity artifacts and less clearly defined topological features, whereas higher resolution configurations yield cleaner doughnut profiles and more accurate polarization structures. The simple quantization model employed here provides a quantitative explanation for these observations and highlights the tradeoff between hardware complexity, since more channels require more control electronics, and optical fidelity.

CONCLUSIONS

Using polarization theory and a simple discretization model, I have analyzed two core aspects of the integrated structured light architecture proposed by Lemons et al. which are polarization synthesis and phase discretization. Mapping the generated polarization states onto the Poincaré sphere through Stokes parameters provides a rigorous and visually intuitive framework for validating experimental polarization reconstructions and for diagnosing deviations from ideal behavior.

The discretization analysis shows that the finite number of beamlines inherently quantizes the phase profile, introducing an RMS phase error that scales as 1/N. For small N, this error is large enough to significantly degrade structured beam quality, while for $N \geq 32$ the error becomes sufficiently small that other imperfections may dominate. This tradeoff between complexity and fidelity is central to the design of future integrated structured light systems.

More broadly, the work of Lemons et al. illustrates how concepts from Principles of Photonics, including polarization on the Poincaré sphere and wavefront synthesis in Fourier optics, translate directly into real integrated photonic architectures. As coherent beam combination technologies and control electronics continue to advance, such architectures could play an important role in scalable LiDAR, high capacity optical communication, and ultrafast microscopy, where tailored light fields provide clear societal and technological benefits.

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