Title

Integrated Structured Light Architectures: Effects of Channel Discretization

Permalink

Author

Reyes, Jaz

Publication Date

2024-12-12

Critical Review of *Integrated Structured Light Architectures*: Effects of Channel Discretization

Jaz Reyes[1]

[1]*Electrical and Computer Engineering Department, University of California Los Angeles, 405 Hilgard Ave, Los Angeles, CA 90024, USA*
jazreyes@g.ucla.edu

Abstract: This paper reviews the role of channel discretization in structured light generation, emphasizing coherence metrics, mean squared error, and beam fidelity. Recommendations focus on hybrid free-space and guided designs to optimize performance and scalability.

INTRODUCTION

Structured light, characterized by tailored spatial and temporal properties, has revolutionized photonics, enabling advancements in communication, imaging, and quantum information processing. Lemons et al. [1] presented a novel laser architecture employing phased arrays to generate structured light with programmable characteristics. Their work underscored the importance of channel discretization in determining beam fidelity, particularly for orbital angular momentum (OAM) configurations, which are pivotal for encoding information in high-dimensional systems.

Coherence, a fundamental property of light, plays a critical role in maintaining the stability and quality of these beams. Spatial coherence ensures uniform phase relationships across the wavefront, while temporal coherence governs the stability of pulsed light. Discretization impacts both forms of coherence, introducing phase discontinuities and intensity artifacts that degrade beam quality. While Lemons et al. focus on MSE as a metric for beam fidelity, this review extends their findings by incorporating coherence-related analyses to evaluate the broader implications of discretization. By critically evaluating how discretization impacts coherence and beam quality, this review aims to propose strategies for overcoming the challenges of discrete beamline synthesis in structured light applications.

METHODS

Lemons et al. [1] quantified the effects of channel discretization on beam quality by calculating the mean squared error (MSE) between ideal and synthesized intensity profiles for 7-, 19-, and 37-channel configurations.

The MSE is calculated as:

$$MSE = \frac{1}{N}\sum_{i=1}^{N}\left(I_i^{ideal} - I_i^{measured}\right)^2$$

where I_i^{ideal} and $I_i^{measured}$ are the intensities of the ideal and measured beams, respectively, and N is the number of sampling points in the distribution. For the 7-channel configuration, the MSE is 0.0016, decreasing to 0.001 for 19 channels and 0.0006 for 37 channels, demonstrating a clear improvement in beam fidelity with increased discretization. To further analyze the role of coherence, additional metrics will be provided as a means for suggestive future study. The mutual coherence function quantifies spatial coherence across the beam wavefront, defined as:

$$\Gamma(x_1, x_2) = < E^*(x_1)E(x_2) > \ [3]$$

where $E(x)$ is the electric field at position x. Spatial coherence degrades with phase noise and discontinuities introduced by low-channel configurations. Coherence length, L_c, represents the spatial extent over which the beam remains coherent and is calculated as:

$$L_c = \frac{\lambda^2}{\Delta\lambda} \ [2]$$

where λ is the central wavelength and $\Delta\lambda$ is the spectral bandwidth. Lower-channel configurations are expected to exhibit broader spectral bandwidths due to increased phase distortions, reducing L_c.

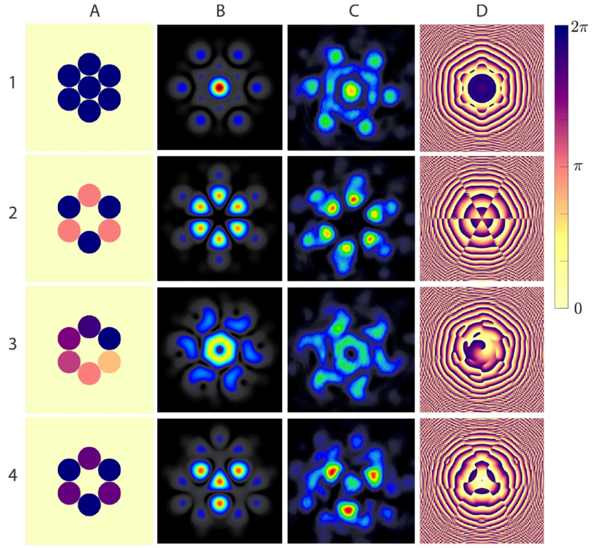

Fig 1. Far-field intensity and phase distributions (Ref. [1], Fig.2)

As noted by Lemons et al., the received far-field phase distribution for various pulses in column D display singularities that arise from channel discretization. These singularities contribute to the degradation of both temporal and spatial coherence.

RESULTS AND INTERPRETATION

The results from Lemons et al. [1] demonstrate that channel discretization significantly impacts structured light generation, particularly regarding spatial and temporal coherence. For the 7-channel configuration, the far-field intensity distributions reveal noticeable diffractive artifacts and irregularities in the phase profiles. These artifacts, as seen in Figure 2 of Lemons et al., arise from incomplete phase matching and limited control over the wavefront due to the low number of beamlines. Such irregularities disrupt the spatial coherence of the synthesized beams, reducing the uniformity and stability of the phase relationships across the wavefront. As the number of channels increases to 19 and 37, the intensity distributions become smoother, and the phase profiles align more closely with those of ideal OAM beams. This improvement corresponds to enhanced spatial coherence, as the phase discontinuities are mitigated with the addition of more finely spaced beamlines. Higher channel counts reduce the high-frequency noise in the wavefront, leading to a more uniform mutual coherence function. Spatial coherence across the wavefront is essential for applications like free-space communication, where uniform beam profiles ensure efficient propagation and data integrity. Temporal coherence, another critical aspect, is influenced by the spectral characteristics of the synthesized beam. Higher discretization reduces the phase noise introduced by channel misalignment and increases the stability of the carrier-envelope phase. This reduction in spectral bandwidth correlates with improved coherence length, allowing for longer distances of coherent beam propagation. Although specific spectral bandwidth values are not provided in the article, it can be inferred that the spectral bandwidth decreases with increased channel discretization due to the suppression of noise artifacts. The enhanced temporal coherence makes these beams suitable for applications in high-precision quantum communication and ultrafast spectroscopy. However, the relationship between discretization and beam fidelity is nonlinear. Beyond 19 channels, the improvement in beam quality diminishes as the challenges of alignment and computational complexity become more pronounced. The increased number of beamlines demands greater precision in phase-locking and alignment, as small errors can accumulate and offset the benefits of additional channels. This finding suggests that while higher discretization improves coherence, practical constraints such as alignment precision and system stability ultimately limit scalability.

CONCLUSIONS

This review highlights the profound impact of channel discretization on the spatial and temporal coherence of structured light beams, as demonstrated by Lemons et al. [1]. Higher discretization levels improve beam fidelity by mitigating phase discontinuities and reducing spectral noise, resulting in enhanced spatial coherence and extended coherence lengths. These improvements are critical for applications such as free-space optical communication, high-dimensional quantum information systems, and ultrafast spectroscopy, where beam quality and stability are paramount. However, the relationship between discretization and beam quality is nonlinear. While increasing the number of channels to 19 or 37 significantly enhances coherence and fidelity, the diminishing returns beyond 19 channels underscore the practical challenges of alignment precision and computational complexity. These challenges suggest that scaling up discretization indefinitely is neither feasible nor efficient. Future research could possibly focus on hybrid approaches that integrate phased arrays with compact photonic devices to balance performance and scalability for the next generation of photonic devices.

REFERENCES

1. R. Lemons et al., "Integrated Structured Light Architectures," *Scientific Reports*, vol. 11, pp. 1–8 (2021).
2. J.-M. Liu, *Principles of Photonics*, Cambridge University Press (2016).
3. M. Born and E. Wolf, *Principles of Optics*, Cambridge University Press (1999).