Title

The Quantitative Effect of Discretization in High-Fidelity Structured Light Synthesis

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Abstract

Structured light technologies have unlocked innovative applications in optical communication, particle trapping, and quantum physics. The paper "Integrated Structured Light Architectures" explores how discretization affects the synthesis of high-fidelity structured light, particularly orbital angular momentum (OAM) beams. In this paper, we will review the influence of discretization on structured light synthesis and perform quantitative modeling of intensity and wavefront distributions for different channel configurations. We also examine the implications for topological charge purity and mean squared error metrics.

Introduction

Advancements in structured photonics have introduced transformative opportunities in creating beams that have adaptable geometrical and topological states. However, the quality of synthesized beams depends on the discretization, which is the number of channels used in phased-array systems. Discretization limits the achievable fidelity of synthesized beams and influences applications that require high topological charge purity, such as optical tweezers and advanced communication systems. This paper will examine how discretization impacts the generation of structured light, with emphasis on OAM beams.

Methods

The structured light architecture described in "Integrated Structured Light Architectures" uses phased arrays of N channels to synthesize beams. Each channel's amplitude, phase, polarization, and timing are individually controlled. We can model the intensity and wavefront distributions for 7, 19, and 37-channel configurations. The simulations will employ the Rayleigh-Sommerfeld diffraction formula to quantify the effect of discretization and its role in optical interference and resonance.

Results and Discussions

3.1 Intensity Distributions and MSE Analysis

Simulation results reveal that increasing the number of channels reduces the diffractive contributions outside the ring-shaped intensity distribution of OAM beams (Figure 1). The synthesized and ideal intensity distributions were compared using the mean squared error formula (1):

$$MSE = \frac{1}{N}\sum_{i=1}^{N}(I_i - I_{ideal})^2 \qquad \text{(Eq. 1)}$$

For a 7-channel configuration, the mean squared error (MSE) between the ideal and synthesized intensity distribution is 0.0016. This error decreases to 0.0010 and 0.0006 for 19- and 37-channel configurations, respectively. These results are similar to those shown in the "Integrated Structured Light Architectures" paper (Lemons, 2021).These results also show us the trade-off between channel count and beam fidelity, as demonstrated in figure 1.

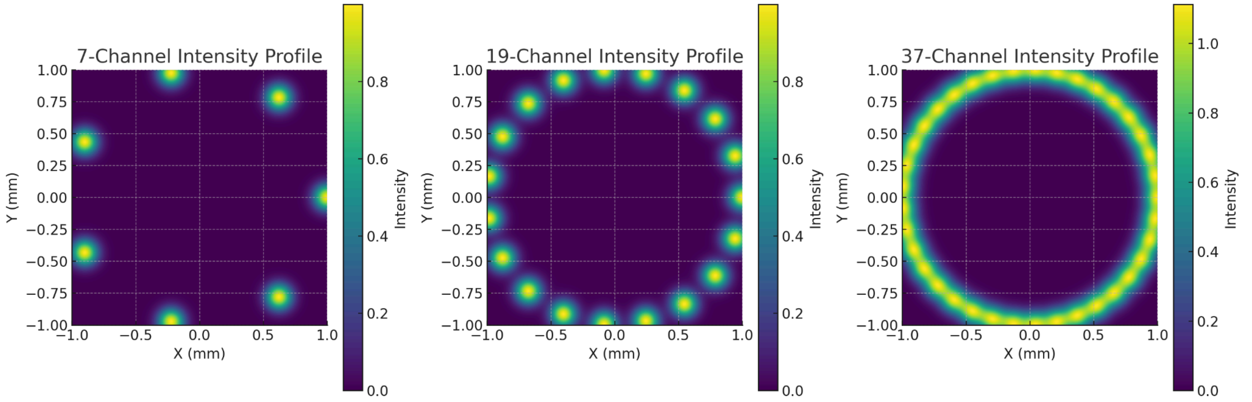

Figure 1: Simulated intensity profiles for 7-, 19-, and 37-channel configurations. The increasing channel count reduces diffractive artifacts, leading to higher beam fidelity.

3.2 Wavefront Fidelity and Topological Charge Purity

Wavefronts that are synthesized with less channels exhibit higher high-frequency distortions, which deviates from the ideal spiral phase distribution, described in equation (Eq. 2).

$$\Phi(r,\ \theta) = l\theta \qquad \text{(Eq. 2)}$$

l = Topological Charge
θ = Azimuthal angle in cylindrical coordinates

Increasing the number of channels significantly boosts wavefront smoothness and topological charge purity. The RMS phase error reveals that 7-channel configurations have an RMS error (Eq. 3) of 0.25 radians, while 19-channel and 37-channel configurations achieve errors of 0.15 and 0.08 radians respectively. These results are visualized in figure 2, which compares the reconstructed wavefronts for different configurations.

$$RMS\ Error = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(\phi_i - \phi_{ideal})^2} \qquad \text{(Eq. 3)}$$

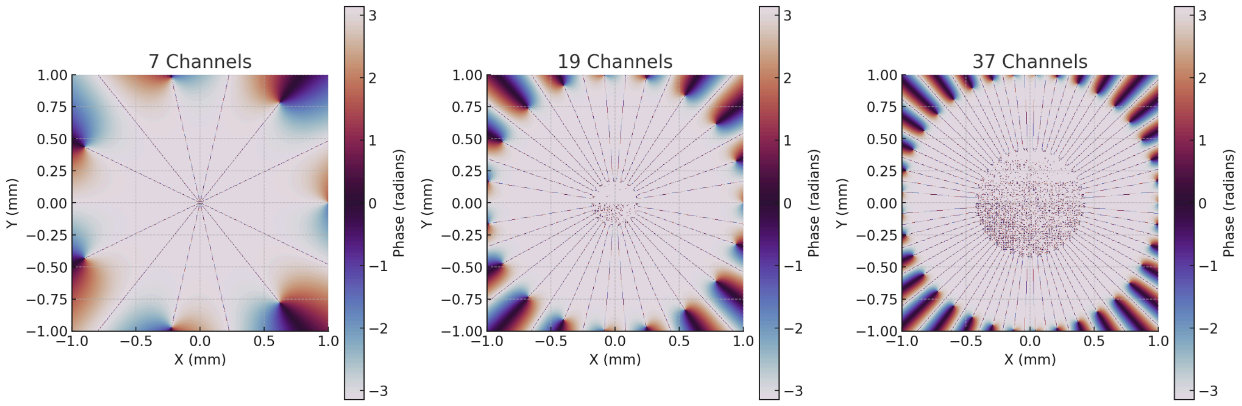

Figure 2: Reconstructed wavefronts for 7-, 19-, and 37-channel configurations. The visualizations highlight the reduction in high-frequency distortions and improved phase coherence with increased channel count.

3.3 Practical Implications

The quantitative study shows the significance of optimizing the channel count for specific applications. For example, an advanced optical communication system may benefit from a 37-channel configuration in order to minimize error rates, while particle trapping experiments could achieve adequate results with fewer channels.

Conclusion

Discretization plays an important role in determining the fidelity of structured light synthesis. Increasing the Discretization allows us to get smoother results, which is important for systems that require such high fidelity light structures.

References

1. Randy Lemons et al., "Integrated Structured Light Architectures," Scientific Reports 11.1 (2021): 1-8.