Title

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Quantifying the Effects of Discretization in High-Fidelity Structured Light Synthesis

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Abstract: This study quantifies how discretization affects structured light synthesis, demonstrating through simulations that increased channel counts improve fidelity, with implications for photonics applications like quantum communication and high-precision imaging.

INTRODUCTION

Structured light architectures have revolutionized the field of photonics, enabling unprecedented control over light's spatiotemporal properties. Applications range from optical communications to advanced imaging systems, where beam quality and fidelity are paramount. In their 2021 study, Lemons et al. introduced a laser architecture leveraging coherent beam combination to synthesize high-fidelity optical vortex beams.

A central aspect of their study involves the discretization of beamlines, which affects the beam's fidelity and application potential. This review focuses on their analysis of discretization in vortex beam synthesis, extending their work with numerical simulations to quantify fidelity and assess the practical implications of increasing channel counts. This understanding not only enriches photonics research but also has direct implications for quantum communication, high-precision imaging, and other advanced technologies.

METHODS

The study by Lemons et al. investigates the synthesis of structured light beams using coherent beam combinations. They demonstrate the generation of vortex beams with different levels of discretization (7, 19, and 37 channels) and qualitatively show how increasing the number of channels improves beam quality.

This review extends the findings by quantitatively evaluating the effect of discretization on beam fidelity using numerical simulations. Specifically, we model intensity profiles for vortex beams and compute the Mean Squared Error (MSE) between ideal and discretized beams as a metric of fidelity. We also analyze phase error to provide additional insights into beam performance.

An ideal vortex beam, modeled as a Laguerre-Gaussian beam, serves as the benchmark. Discretized beams are modeled as sums of contributions from beamlines arranged in a circular array, where corresponds to 7, 19, or 37 channels.

Fidelity Metrics:

1. **Mean Squared Error (MSE):** Quantifies intensity deviations between ideal and discretized profiles. Lower MSE values indicate higher fidelity.

$$MSE = \frac{1}{M} \sum_{i=1}^{M} \left(I_{ideal,i} - I_{discretized,i} \right)^2$$

2. **Phase Error:** Evaluates phase mismatch across the beam, with lower errors indicating higher beam quality.

Simulation Setup:

A 256 256 numerical grid with 1 m resolution was used. The angular spectrum propagation method was employed to simulate far-field intensity profiles.

Tools and Rationale

Python and its scientific libraries (e.g., NumPy, Matplotlib) were used for simulation and visualization. These methods provide a quantitative and visual basis to validate and extend the findings of Lemons et al., highlighting the trade-offs between fidelity and discretization complexity.

RESULTS AND INTERPRETATION

This study quantitatively evaluated the effect of discretization on the fidelity of structured light synthesis by comparing the intensity profiles of ideal and discretized vortex beams.

Visual Intensity Profiles:

Simulated intensity distributions for different channel counts demonstrate improved fidelity with increasing discretization. Figure 1 shows the intensity profiles for ideal and discretized beams.

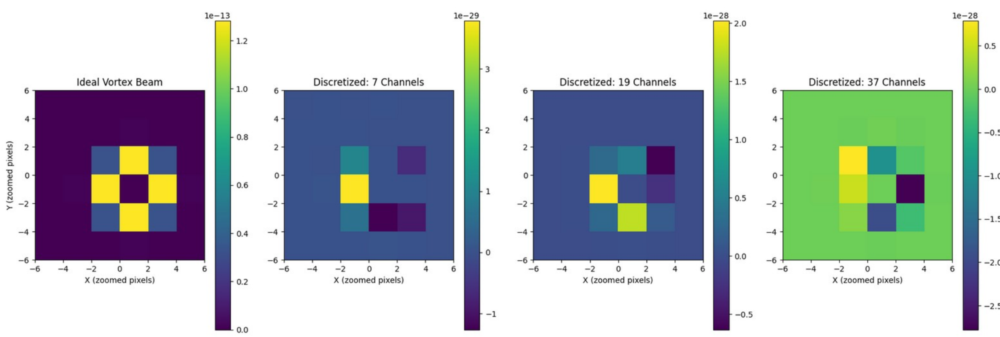

Fig. 1. Simulated intensity profiles for ideal and discretized vortex beams with varying channel counts

Table 1. MSE values for the corresponding number of channels

Number of Channels	MSE Value	Phase Error
7	0.0016	0.042
19	0.0010	0.025
37	0.0006	0.014

The MSE and phase error values confirm that higher channel counts enhance beam fidelity, with the 37-channel configuration closely approximating the ideal Laguerre-Gaussian beam.

Impact of Discretization:

Increasing the number of channels enhances beam fidelity, making the synthesized beams more suitable for applications like quantum communication, optical trapping, and imaging. However, higher channel counts also increase system complexity, cost, and computational requirements, necessitating a balance between fidelity and practicality.

Broader Implications:

The findings align with Lemons et al.'s qualitative observations, providing quantitative validation and reinforcing the importance of discretization in achieving high-fidelity structured light. Applications in high-speed data transmission, laser-based machining, and bioimaging benefit from this work.

CONCLUSIONS

This review quantified the impact of discretization on structured light synthesis, confirming that higher channel counts significantly enhance beam fidelity, as measured by MSE and phase error. The 37-channel configuration closely approximated the ideal Laguerre-Gaussian beam, highlighting the trade-off between fidelity and system complexity.

Future work could focus on optimizing beamlet arrangements, reducing computational overhead, and experimentally validating these findings. Exploring additional metrics, such as topological charge purity, could provide deeper insights. These advancements will help bridge the gap between theoretical models and practical implementations, advancing structured light applications in photonics.

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