Title

Quantitative Fidelity Analysis in Structured Photonics

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Abstract: This study examines the impact of discretization on fidelity in structured photonics, with a specific focus on coherence preservation and spatial alignment in a phased array architecture.

INTRODUCTION

Structured light in photonics enables precise spatial control of light, which is crucial for advanced applications in the fields of quantum optics, holography, and imaging. This control is achieved by modulating the fundamental properties of light, such as phase, amplitude, and polarization, to generate tailored spatial patterns that meet specific application needs. Despite its transformative potential, the field faces significant challenges in maintaining fidelity and coherence in structured light systems.

A key limitation in structured photonics stems from the reliance of spatial light modulators (SLMs), which excel at controlling light properties but struggle with high-power ultrashort pulses and adaptive programmability. In their 2021 study, Lemons et al. addressed these challenges with a coherent beam combination architecture. This phased array configuration integrates spatio-temporal control, phase locking, and polarization adaptability, enabling the generation of highly versatile light structures, including vortex beams and optical bullets.

While Lemons et al. demonstrated programmability and scalability of their architecture, achieving high fidelity remains a persistent issue as channel counts increase. The study highlights phased array limitations in phase coherence preservation and interference effect mitigation.

Based on this foundation, this critical review examines the impact of discretization on fidelity within structured light systems. The effects of varying channel counts on coherence and structural alignment are assessed quantitatively to provide insights into the trade-offs between finer spatial control and practical challenges in high-channel systems. This paper evaluates Lemons et al.'s findings and extends the discussion by addressing the practical barriers of high-fidelity structured light generation.

METHODS

Structured light in a phased array system can be represented by combining multiple Gaussian beams, each defined by specific amplitude A_n, phase, and position (x_n, y_n) within the array. When these beamlines recombine, they produce an interference pattern that approximates a continuous light field as the discretization (number of channels) increases.

The total field $E(x, y)$ for N beamlines is expressed as:

$$E(x, y) = \sum_{n=1}^{N} A_n \exp\left(-\frac{(x - x_n)^2 + (y - y_n)^2}{w^2}\right) \exp(i\phi_n) \tag{1}$$

where w is the beam width, and A_n denotes the amplitude of each beamline. As N increases, the synthesized light field becomes smoother and more closely resembles an ideal continuous profile.

Assessing the fidelity of the synthesized light field to the ideal profile is essential for understanding the practical trade-offs in discretized structured light systems. Fidelity metrics like Mean Squared Error (MSE), Structural Mean Squared Error (SMSE), and Perceptual-Fidelity Aware Mean Squared Error (PAMSE) are important for analyzing the quality of structured light profiles. While MSE is computationally simple and widely used, it is limited in its ability to capture human perception of fidelity due to its pixel-wise nature (Xue et al., 2013). SMSE addresses this by incorporating structural information, while PAMSE extends this approach by emphasizing perceptually relevant features, making these metrics highly suitable for structured photonics applications requiring both precision and perceptual coherence.

Mean Squared Error (MSE): Measures structural alignment between ideal and discrete profiles, focusing on luminance, contrast, and structural similarity:

$$\text{MSE} = \frac{1}{n} \sum_{i=1}^{n} (I_{\text{ideal}}(i) - I_{\text{discrete}}(i))^2 \tag{2}$$

where I_{ideal} and I_{discrete} represent the intensities of the ideal continuous profile and the discrete profile, respectively.

Structural Mean Squared Error (SMSE): SMSE extends MSE by incorporating structural components, focusing on local features such as gradients and edges. It accounts for both intensity variations and structural coherence:

$$\text{SMSE} = \frac{1}{n} \sum_{i=1}^{n} (\Delta I_{\text{ideal}}(i) - \Delta I_{\text{discrete}}(i))^2 \tag{3}$$

where ΔI indicates the gradient of the intensity.

Perceptual-Fidelity Aware Mean Squared Error (PAMSE): PAMSE builds on SMSE by applying a Gaussian smoothing filter, which prioritizes perceptually relevant features over minor local artifacts. This approach emphasizes coherence and spatial alignment in broader spatial distributions.

$$\text{PAMSE} = \frac{1}{n} \sum_{i=1}^{n} (G * \Delta I_{\text{ideal}}(i) - G * \Delta I_{\text{discrete}}(i))^2 \tag{4}$$

A Python-based simulation was conducted to model the ideal continuous profile and discrete channel profiles for channel configurations 7, 19, and 37 channels. The discrete profiles were generated by summing Gaussian beams at specific positions with assigned phases. The above metrics were utilized in the simulation to analyze the effect of channel count on fidelity and coherence on the structured light profile.

RESULTS AND INTERPRETATION

Quantitative Analysis

Table 1 below presents fidelity metrics across the channel configurations tested: 7, 19, and 37 channels. Contrary to expectations, error values increase with higher channel counts, indicating reduced fidelity at finer discretization.

Table 1. Fidelity Metrics for Different Channel Configurations

Profile	MSE	SMSE	PAMSE
Ideal Profile	0.000000	0.00000	0.000000
7 Channels	0.013446	0.016713	0.013359
19 Channels	0.074887	0.093385	0.074515
37 Channels	0.274785	0.349523	0.273462

The Mean Squared Error (MSE) increased with the number of channels, indicating that the cumulative intensity deviations from the ideal profile grew with finer discretization. This result, although counterintuitive, suggests that higher channel counts amplify phase misalignment and interference effects between channels, thus complicating coherence.

The Structural Mean Squared Error (MSE), which captures local structural fidelity by gradient and edge focus, followed a similar trend. SMSE results underscore the deterioration of local structural coherence with a greater number of channels. This observation is likely due to increased interference among overlapping beams.

Finally, the Perceptual-Fidelity Aware Mean Squared Error (PAMSE) showed a steadier increase, indicating that perceptual coherence remains relatively stable at higher channel counts. The observed effect suggests that although perceptual resemblance is somewhat preserved, the fidelity loss observed in structural metrics (MSE and SMSE) indicates practical limits on fidelity as discretization increases.

Interpretation of Results

These results reveal a constraint in structured photonics between increased spatial control and high-fidelity wavefront coherence maintenance. Even though higher channel counts should theoretically improve control, the practical challenges of phase alignment and interference result in a decrease in fidelity, as seen in the error metrics. This partly aligns with the conclusions of Lemons et. al (2021), who highlighted the limitations of phased arrays in achieving high-fidelity structured light due to phase coherence challenges.

Lemons et al.'s phased array architecture, which incorporates coherent beam combination and phase-locking techniques, demonstrates a promising approach to spatial and temporal field control. Nevertheless, achieving precise phase alignment becomes increasingly challenging as the number of channels increases. This critical review reinforces Lemons et al.'s suggestion for advanced locking methods and better interference management strategies.

CONCLUSIONS

In conclusion, increased discretization in structured photonics presents practical limitations in maintaining coherence for high-channel systems. This paper highlights the need for optimized phase-control techniques to maximize fidelity and aligns with Lemons et al.'s focus on adaptive phase locking and interference correction.

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