Title

Investigating Simulation Accuracy of an Integrated Structured Light Architecture: A Review

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Publication Date

2023-12-10

Investigating Simulation Accuracy of an Integrated Structured Light Architecture: A Review

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Abstract

In this review, the simulation model for the generalized laser architecture in Lemons et al is examined by comparing results for an ideal and discretized first-order orbital angular momentum beam (OAM). The model is based on the Rayleigh-Sommerfeld diffraction (RSD) formula; due to its discrete nature, we find that to mitigate large simulation errors, proper sampling and accurate representation of the object in the computational plane are critical for obtaining reliable and physically meaningful results.

Introduction

The ability to shape light fields according to specific application requirements is a powerful tool when creating devices with customizable functionalities. Structured photonics enables the development of adaptable light structures; however, accurate results are limited by technology that is unable to precisely control the optical fields in all their spatio-temporal degrees of freedom. The paper “Integrated structured light architecture” by Lemons et al., proposes a generalized laser architecture with controllable field-amplitude, carrier-envelopment, relative phase, and polarization. The architecture improves upon past demonstrations by incorporating not only programmable phase and amplitude modulation, but also carrier-envelope phase (CEP), pulse front, and polarization modulation control units for each beamline in the phased array. When the beamlines maintain a constant relative phase with respect to each other (i.e., maintain a coherent relationship) they can collapse into unique and applicable interference distributions [1].

The beamlines are collimated and synthesized in free space with a tiled-aperture micro-lens array, after being split from a femtosecond mode-locked laser at the C-band telecom wavelength of 1550 nm and phase-locked [1]. In the paper’s proof of concept, seven beamlines are controlled (with another being used as a reference) and arranged hexagonally to be detected at a photodiode.

This review investigates the effects of propagation distance and computational grid size on the beam propagation model of the proposed laser architecture, using the hexagonal configuration demonstrated in the proof of concept. The model is based on a discrete fast Fourier transform (FFT) angular spectrum evaluation method using the RSD formula, under the assumption of scalar propagation theory [2]. Due to the discrete nature of the FFT, proper sampling of the object and image planes is imperative to mitigate aliasing effects and ensure the precision of the obtained results. Using the simulation code provided in the paper [3], this review illustrates how varying parameters under the use of the discretized RSD can lead to very large calculation errors in the expected simulation results.

Methods

The impact of propagation distance and computational grid size on simulation results is examined for a first-order discretized OAM beam with seven beamlines, arranged in a hexagonal configuration. The center beamline is “off,” representing zero amplitude, while the six beamlines in the outer hexagonal ring are “on” with an amplitude of one. Each beamline is set to have a waist size of 1x1 mm and an aperture of 3x3 mm. For the ideal first-order OAM beam (with a waist of 3 mm and quantum numbers $p = 0, l = -1$), the phase increases continuously by 2π for one full counter-clockwise revolution around the propagation axis of the beam. This phase variation contributes to the helical wavefront and annular intensity profile associated with OAM beams. Both the near and far field is expected to represent a Laguerre-Gaussian (LG) mode of $LG_{0,-1}$. The intensity and wavefront distribution of the ideal and discretized OAM beam at the object plane and image plane (when propagated 10 meters) is shown in *Figure 1*. For the discretized beam, the phase varies uniformly by $2\pi/6$. It can be seen that as the ideal beam propagates, its intensity distribution remains the same, while the discrete beam loses its clear hexagonal formulation and begins to resemble the intensity and wavefront distribution of the ideal OAM beam at 10 meters.

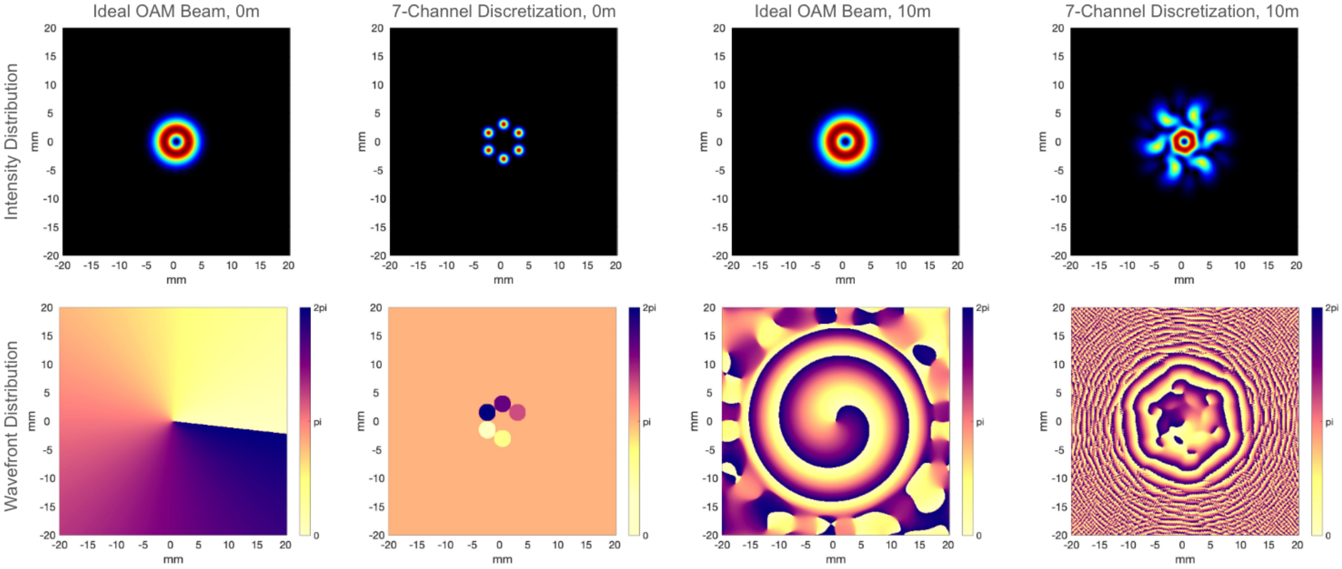

Figure 1. The intensity and wavefront distribution of the ideal and discretized OAM beam at the object plane (columns one and two), as well at the image plane after the beams have propagated for 10 meters (columns three and four).

Results

To conduct a comprehensive analysis of the influence of beam propagation distance on the fidelity of simulated intensity and wavefront distributions for the discretized beam, the propagation distance was systematically varied. The investigation was carried out using a consistent grid size of 40x40 mm and with the same beam parameters as in *Methods*. The obtained outcomes were then compared against the benchmark of an ideal OAM beam. A graphical representation of the results is provided in *Figure 2.* From *Figure 2,* it can be seen that as propagation distance increases for the ideal OAM beam, the intensity distribution retains the same shape, but appears larger. These simulation results are as expected, because LG beams exhibit diffraction-limited performance, meaning they retain the same shape over long distances. The appearance of a larger beam is due to the effective beam radius evolving with distance as given by *Equation 1.* Thus, if the image plane fully captures the ideal OAM beam at a given propagation (i.e., the object does not touch surpass the borders of the grid), then the simulation results are accurate [1].

$$w(z) = w_o\sqrt{1+\left(\frac{z}{z_R}\right)^2}$$

Equation 1. Evolving beam width of a Gaussian beam where z_R is the Rayleigh range, z is the axial distance from the beam's focus, and w_o is the waist radius of the beam [4].

On the other hand, *Figure 2* illuminates that the discretized OAM beam requires more careful examination to avoid simulation error, as aliasing begins to occur rapidly with increasing propagation distance. This may be due to the additional structure in these distributions – which arise naturally from discretization – giving the beam a larger span over the grid [1]. The aliasing can be seen in the Moiré patterns and staircasing effects in the 7-channel beam's intensity profile when propagated 20m, 35m, 40m, and 60m, as high-frequency patterns in the image are being inadequately sampled. To prevent aliasing when using RSD, the Nyquist-Shannon sampling theorem states the sampling frequency should be at least twice the maximum spatial frequency present. As the propagation distance increases, the need for a larger computational image plane becomes more critical to accurately represent the evolving spatial frequencies in the diffracted discretized field. Otherwise, the improper sampling interval will cause a large aliasing error.

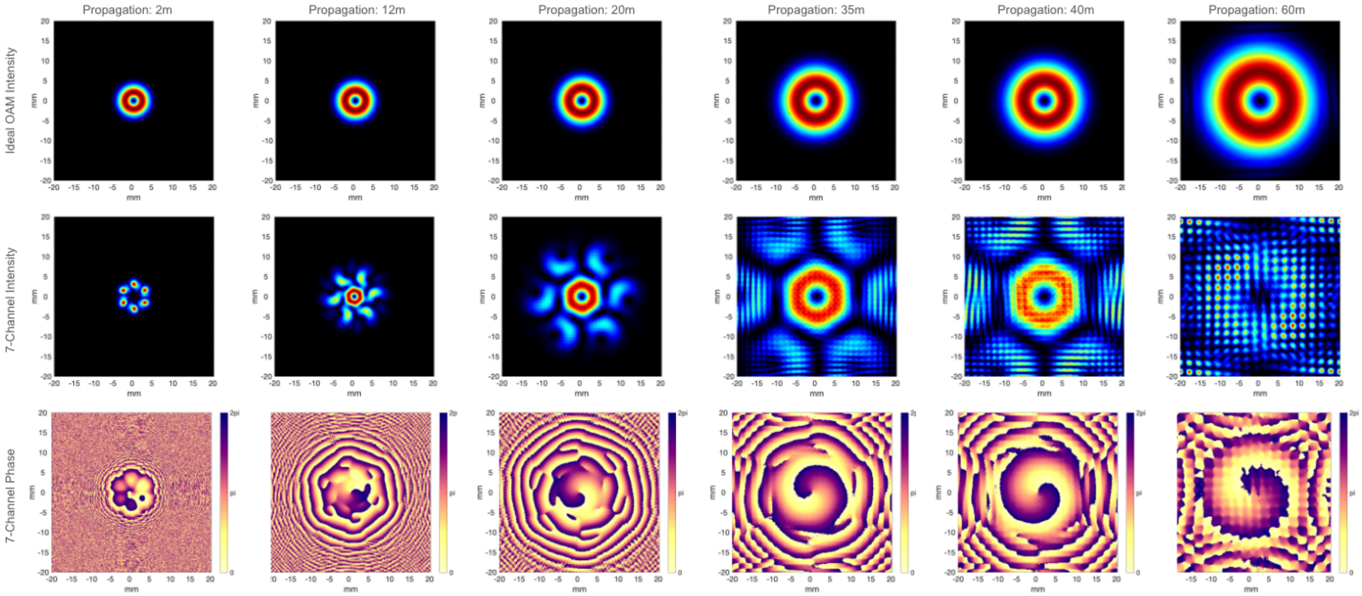

Figure 2. illustrates the impact of varying propagation distance on the ideal and discretized OAM beams intensity distributions. The wavefront distribution of the discretized beam is also shown in row three.

Conclusion

The results of the investigation demonstrate that the use of the discretized RSD can cause enormous calculation errors in simulations if the computational image plane does not fully capture the propagating beam. It was found that due to the diffraction of light in the discretized OAM beam, the size of the computation window must be selected to be larger than the object size to avoid aliasing with increasing propagation distance. These sampling considerations are vital for obtaining reliable simulations, whose robustness is crucial in predicting the nuanced behavior of the generalized laser architecture detailed in Lemons et al, in order for users to confidently compare and predict the advanced light structures in the physical model against precise simulations.

References

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