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Review of *Integrated Structured Light Architecture*: Channel Discretization Effects on OAM Beam Error and Finesse

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INTRODUCTION

An essential tool within the field of photonics is structured light, a phenomenon in which engineers intentionally manipulate a beam's amplitude, phase, polarization, and angular momentum to create complex spatial and spatiotemporal distributions. Structured light underlies transformative applications across a wide range of fields, such as molecular physics, nonlinear optics, quantum sciences, and particle physics [1]. However, current state of the art technologies for shaping structured light, such as spatial light modulators (SLMs), have several notable limitations. For instance, SLMs can control the phase and amplitude of structured light but not temporal features such as the pulse front and carrier-envelope phase (CEP). Additionally, SLMs have low damage thresholds that make them unsuitable for high-power or ultrafast applications [1].

To address these limitations, Lemons *et al.* propose a novel architecture in their paper *Integrated Structured Light Architecture* [1]. Their approach coherently combines multiple fiber-delivered beamlines whose amplitude, phase, CEP, timing, and polarization are independently programmable prior to synthesis. This architecture not only enables highly customizable, time-varying structured light, but also addresses power limitations through the use of coherent beam combination, a technique demonstrated to scale to kilowatt-level powers.

In order to exemplify the flexibility of their architecture, Lemons *et al.* model a first-order orbital angular momentum (OAM) beam using a varying number of discretized beamlines. OAM beams possess helical wavefronts and carry quantized orbital angular momentum, making them valuable in applications such as optical communications, microscopy, and imaging [2]. Lemons *et al.* mention that some applications may require higher finesse than demonstrated with the lowest discretization example of 7 channels. Finesse is traditionally defined as the ratio of a system's free spectral range to its linewidth, reflecting how precisely an optical system can resolve or reproduce phase and amplitude structure. Because an ideal first-order OAM beam contains all of its power in a single azimuthal Fourier component, discretizing its continuous helical phase introduces additional angular harmonics, analogous to linewidth, that reduce spectral purity [3]. Therefore, the distribution of power across these harmonics can provide a measure of effective finesse.

In this paper, we analytically examine the effects of discretization on OAM beam synthesis by comparing a continuous helical phase ramp to its N-channel discretized approximations. We compute each discretized model's mean square error (MSE) from the ideal model, comparing our results to trends presented in Lemons *et al.* We also derive an effective finesse based on angular spectral purity to determine whether beam fidelity improves with the number of channels. As the number of discretized channels in a structured light system increases, the MSE

from an ideal OAM beam is expected to decrease and the effective finesse is expected to increase. We also calculate the change in MSE and the change in relative finesse between successive discretization levels in order to identify a point at which improvements in MSE and finesse begin to plateau. This analysis provides an estimate of a practical upper bound on the number of discretized channels required.

METHODS

In order to calculate the MSE for our discretized OAM beam models, we first model a first-order ideal OAM beam with unit amplitude and a continuous helical phase ramp,

$$E_{ideal}(\phi)=e^{i\varphi}, \tag{1}$$

where $\varphi \in [0, 2\pi)$. We then model a discretized OAM beam with N channels of width $\Delta\varphi = 2\pi/N$. For each k-th channel, where $k \in [1, N]$, the phase is held constant at

$$\varphi_k=2\pi(k-1)/N. \tag{2}$$

The discretized OAM field is therefore defined piecewise as

$$E_N(\varphi)=e^{i\varphi_k} \tag{3}$$

where $\varphi \in [2\pi(k-1)/N, 2\pi k/N)$. We evaluate this model over the horizontal channel numbers N = 7, 19, 37, 61, 91, 127, 169, and 217, extending the set of discretization levels presented in Lemons *et al.* We then calculate the MSE between the ideal and discretized fields using

$$MSE(N)=\frac{1}{2\pi}\int_0^{2\pi}|E_{ideal}(\varphi)-E_N(\varphi)|^2 d\varphi \tag{4}$$

After computing MSE for each discretized model, we calculate the absolute change in MSE, $|\Delta MSE|$, between successive values of N (for example, between N = 7 and N = 19). We first compare both the direct MSE values and the MSE-vs.-N relationship with the results presented in Lemons *et al.* We then adopt the threshold $|\Delta MSE| < 0.001$ to indicate that additional channels yield no significant improvement.

In addition to MSE calculations, we quantify how discretization affects the fidelity of OAM beams using a finesse-like angular spectral purity metric. We first compute the Fourier coefficients of the discretized OAM model using

$$c_m=\frac{1}{2\pi}\int_0^{2\pi}E_N(\varphi)e^{-im\varphi}d\varphi \tag{5}$$

where m is the OAM mode index. Each harmonic's modal power is given by $|c_m|^2$. For an ideal OAM beam, the total power is $|c_1|^2$. For a discretized beam, we define the effective finesse as

$$F(N)=\frac{|c_1|^2}{\sum_{m\neq 1}|c_m|^2}. \tag{6}$$

Here the numerator represents the power in the desired mode of the ideal OAM beam, and the denominator represents power that has leaked. We also calculate the normalized change in finesse between successive values of N using

$$\Delta F_{rel}=\frac{F(N_{i+1})-F(N_i)}{F(N_i)} \tag{7}$$

which expresses the improvement in angular spectral purity relative to that already achieved at the previous discretization level. We compare the F-vs.-N trend to validate whether finesse increases with discretization as expected. We then adopt a threshold $\Delta F_{rel} < 1.0$ to indicate that additional channels yield no significant improvement. We use Python within Jupyter Notebook to perform these calculations and then compare the results to the results, trends, and suggestions presented in Lemons *et al.*

RESULTS AND INTERPRETATION

Figure 1 shows the intensity and phase distributions of the ideal and discretized OAM beam models presented in Lemons *et al.* As the channel number increases from 7 to 37, both the intensity and wavefront profiles of the discretized beams more closely resemble those of the ideal beam. This provides visual evidence for the expectation that increasing channel count reduces discretization error, leading to lower MSE and higher effective finesse.

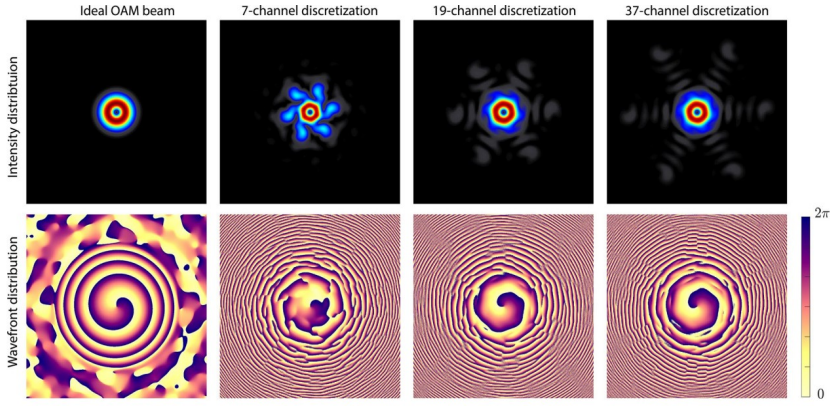


Fig. 1: Beam intensity and wave front distributions for the ideal first-order OAM beam model (first column) and the 7-, 19-, and 37-channel discretized OAM beam models (Ref. [1], Fig. 5).

The MSE, the successive |ΔMSE|, the effective finesse, and the relative successive finesse change (ΔF_{rel}) are displayed in Table 1. The relationships between MSE and N and between |ΔMSE| and N are plotted in Figure 2. The relationships between the effective finesse F and N and between ΔF_{rel} and N relationships are plotted in Figure 3.

Table 1. Mean Square Error and Effective Finesse of Discretized OAM Beam Models

Number of Channels	MSE	Effective Finesse	|ΔMSE|	ΔFrel
7	0.258	14.299	N/A	N/A
19	0.0362	109.132	0.222	6.632
37	0.00960	415.526	0.0267	2.808
61	0.00353	1130.448	0.00606	1.721
91	0.00159	2516.522	0.00195	1.226
127	0.000816	4902.028	0.000773	0.948
169	0.000461	8680.903	0.000355	0.771
217	0.000279	14312.740	0.000181	0.649

Lemons *et al.* report MSE values of 0.0016, 0.001, and 0.0006 for N = 7, 19, and 37, respectively. Our corresponding results (0.258, 0.0362, and 0.0096) are much larger, as expected considering we use a simplified angular model defined in Eq. 1 and Eq. 3. Nevertheless, our MSE results, shown in Table 1 and Figure 2, follow the expected trend of rapidly decreasing error with increasing discretization, indicating that finer discretization indeed produces beams that more closely approximate an ideal OAM. Using a threshold of $|\Delta MSE| < 0.001$ to indicate negligible improvement, we find that MSE first plateaus at N = 127, suggesting that additional channels beyond N = 127 provide minimal benefit.

Effective finesse increases rapidly with N, as shown in Table 1 and Figure 3, confirming that increasing discretization concentrates more power into the desired OAM mode. Using a threshold of $\Delta F_{rel} < 1.0$ to indicate that relative improvements become negligible compared to earlier steps, we again find that discretization beyond N = 127 provides limited additional benefit within this model.

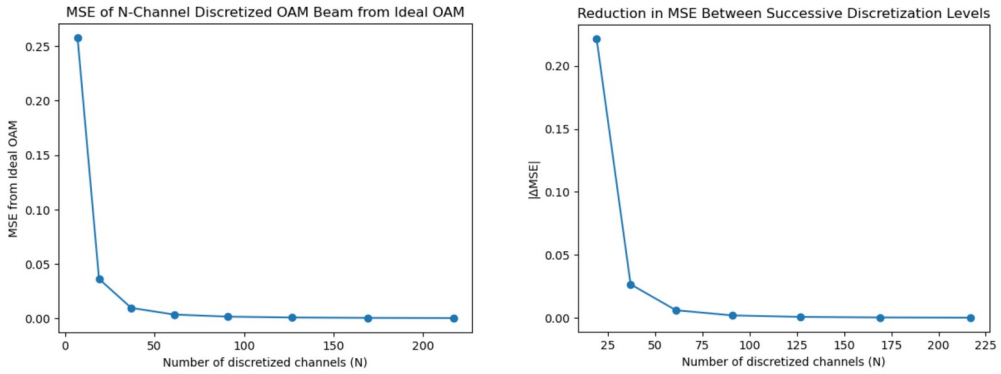


Fig. 2: Left: MSE between discretized OAM beam model and ideal OAM beam model as a function of the number of channels N. Right: Reduction in MSE between successive discretization levels, plotted versus the second N value in each pair.

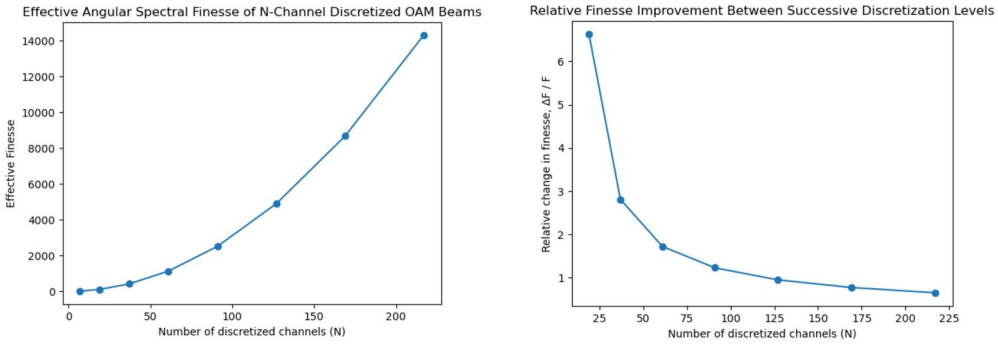


Fig. 3: Left: Effective angular spectral finesse of discretized OAM beam models as a function of the number of channels N. Right: Relative improvement in finesse between successive discretization levels, plotted versus the second N value in each pair.

CONCLUSIONS

This work examines the effects of discretization on the fidelity of modeled OAM beams. We evaluated the MSE and a finesse metric based on angular spectral purity in order to show that increasing the number of discretized channels improves beam fidelity, decreasing MSE and increasing effective finesse. However, this improvement displays diminishing returns as the number of discretization channels continues to increase. By applying threshold criteria to changes in MSE and finesse between successive discretization levels, we additionally found that improvements become negligible after N = 127 channels. This suggests that OAM beam synthesis does not require large discretization levels beyond this point and that moderate channel counts can achieve near-ideal fidelity performance in both MSE and finesse.

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