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Verifying Intensity Profiles for a Beamlet Array Through Python Simulation

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Abstract: Within this work, I independently verify the intensity profile results presented by Lemons et al. in "Integrated structured light architectures." The Python simulations I programmed and ran verified their findings.

INTRODUCTION
Structured light architectures have revolutionary applications in advanced fields of physics, quantum computation, and many other fields. In the field of quantum information processing, structured light architectures promise higher data rates and lower amounts of information dedicated to parity. In nanobiology, structured light was utilized as 'tweezers' to trap DNA particles and single proteins. In atomtronics, structured light could also serve as the basis for analogues of electric circuits in superfluid systems. In all of these contexts, a major challenge is the inability to generate fully tailored light architectures that take advantage of every possible degree of freedom [2].

In response to this issue, the paper "Integrated structured light architectures" [1] explores the possibility of a structure that enables fully programmable light bullets, their generalized laser architecture. In particular, their architecture consists of a beamlet array in which one central source is split up and each segment is manipulated independently. The central concept behind this idea lies in full parameter programmability, ideally enabling an extremely generalizable system with the potential to create fully customizable architectures. Within this paper, the authors present intensity graphs meant to demonstrate the efficacy of their system, shown in Figure 1.

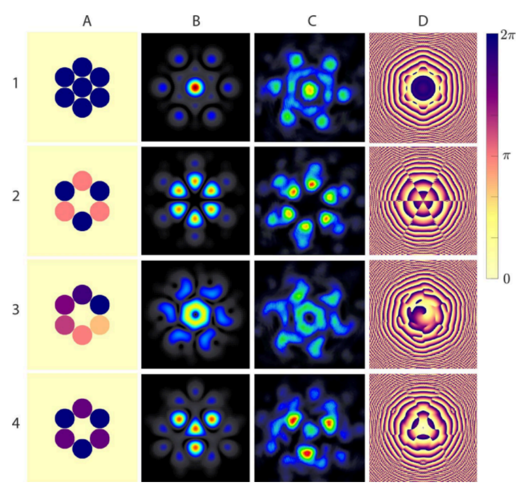

Fig. 1. Beam intensity and phase profiles translated into far-field intensity and phase characterizations (Ref. [1], Fig. 2).

Altering only the initial phases and intensities of 7 beamlets, their model achieves a huge variety of intensity and phase patterns. By simulating the far-field propagation of these beamlets using Fourier transforms and the same initial conditions, my experiment attempts to confirm the findings displayed in their demonstration.

METHODS

While the paper itself does cite a beamlet propagation model used as a basis for the figures provided, the link itself is outdated and leads to an empty page. As such, most of my model is based upon the generalized parameters provided in the paper's "Beam propagation model" passage [1].

The Python my reconstruction is based upon utilizes several equations within electromagnetic wave propagation. The first function I use performs a fast Fourier Transform on an input field and applies the free-space propagation transfer function shown in Equation 1. After applying said transfer function, an inverse FFT is applied to view the result in the spatial domain.

$$H(f_x, f_y) = exp[j * 2\pi z\sqrt{\frac{1}{\lambda^2} - {f_x}^2 - {f_y}^2}] \quad (1)$$

The propagation function itself also includes a mask to ensure evanescent waves with particular frequency-wavelength products aren't expressed in the final product, eliminating non-physical effects that might propagate otherwise. When input with specified beamlet parameters and the right z to serve as far-field distance, this function allows us to effectively model the far-field propagation of any desired array.

As for assumptions, the paper details the experiment occurs at "C-band telecom wavelength range", so $\lambda = 1.55\ \mu m$ is assumed for this propagation. In addition, within the figure my experiment is attempting to verify, the initial phases for each beamlet are indicated by color, not number. The color bar reference itself is only labelled at $\pi/3$ intervals, and as a result, the initial conditions I assumed for each trial are all multiples of $\pi/3$ or $\pi/2$. Fortunately, within the demonstration, amplitudes for each beamlet are restricted to $A \in \{0, 1\}$, so no assumptions are necessary. The beam waists and spacings within the hex array itself were harder to verify, as there aren't any axes or citations within the paper to rely on. Assuming that the entirety of this experiment relies upon coherence and interaction between the beamlets, I designated a relatively large beam waist size of $w = 0.2$ mm and array spacing of 0.66 mm. These parameters, while not necessarily ideal for the telecom wavelength, ensure coherences in the far-field were large enough to witness and match against a reference when plotted [1]. These assumed numbers weren't simply chosen at the beginning and never altered, but rather tuned after initial general assumptions were made to ensure maximum visibility in the final far-field plots.

For the beamlets themselves, I utilize an assumed Gaussian beam expression as shown in Equation 2. Each instantiation has separate amplitude parameters and can be multiplied by a corresponding phase delay prior to the propagation function to simulate different initial relative phases.

$$E(x, y) = A_0 exp(-\frac{(x-x_0)^2+(y-y_0)^2}{{\omega_0}^2}) \quad (2)$$

To simulate the initial positions of the hexagonal array, code is present to establish the central beam while 6 others are in a hex pattern around it. For implementation, I string all of these functions together with custom amplitudes and phase additions for each test case to compare against the paper's demonstrations. The near field distance was also something tuned, and was estimated using the approximate far-field distance formula shown in Approximation 1. This approximation yielded roughly ~32 meters, which proved sufficient for testing purposes.

$$z \gg \frac{2L^2}{\lambda} \tag{1}$$

Lastly, in order to ensure the actual beamlet array is verified and not the simulation, my experiment will be visually compared against measured results, not simulations. All functions are implemented within a Python Google Colab notebook with the aid of the numpy and matplotlib libraries.

RESULTS AND INTERPRETATION

Shown in Figure 2 is the result of my simulated experiment for each trial, with Figure 3 depicting the matching targeted distribution with real, measured intensities. In terms of evaluation, I decided on a general visual comparison, as the goal of this experiment is to validate that their measured distributions are possible at all with their given architecture. A method like image subtraction could be used to compare the simulation with the real measurements, but considering the amounts of assumptions made in the simulation as well as the many unknowns in how exactly the measured results were gathered, I decided a metric like image subtraction would be no more revealing than a general visual comparison.

As for the comparison between Figure 2 and Figure 3, a few trends persist across all trials. Before comparison, it is important to note that the simulation setup is essentially a 60 degree rotation of the measured setup as a result of the way the hex array was initialized. Comparing each of the array results to one another, the top row of each seems to match quite closely, the main difference being the amount of intensity detected in the measured graphs seeming much higher. Possible causes could be the simulation not assigning enough brightness to lower valued intensities, the simulation being too simplistic to entirely model the array at far-field, or any of the many assumptions made being incorrect.

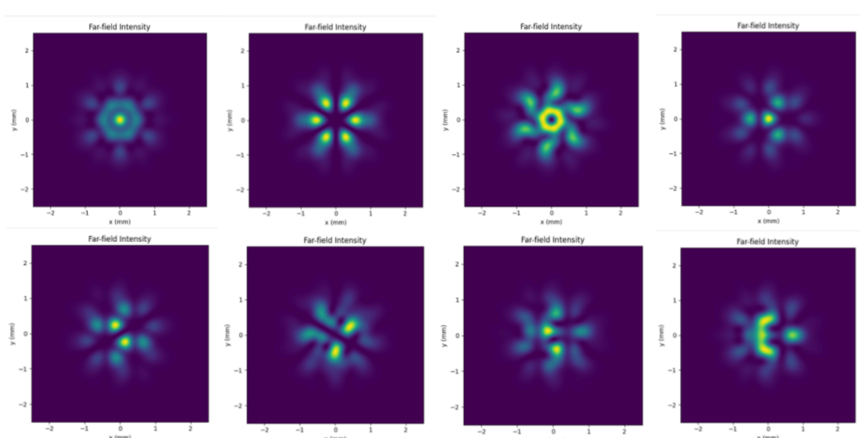

Fig. 2 Experimentally simulated beamlet array far-field intensity distribution

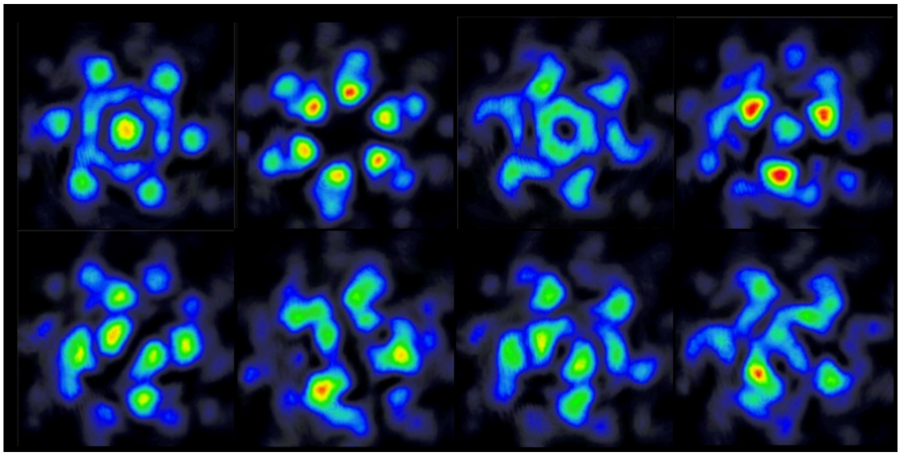

Fig. 3 Measured beamlet array intensity distributions (Ref. [1], Fig. 2)

In the bottom 4 trials of Figure 2 and Figure 3, the previously mentioned problems are even more exaggerated, with the higher intensities in Figure 3 resulting in patterns that look further separated from those in Figure 2. Regardless, the brightest parts of each figure remain consistent between them, with the main differences lying in the secondary components of each pattern.

Overall, the similarities between the measured and simulated intensities far outweigh the differences. The small differences present could very well be explained by the many potential reasons listed earlier, and it's very feasible that the beamlet array presented in the paper could generate the demonstration displayed in the original paper.

CONCLUSIONS

After simulating the hexagonal beamlet array within Python and comparing it to the original, I've concluded that the results of my experiment align with the results of the demonstration presented in "Integrated structured light architectures" [1] and validate their beamlet array for the given tests displayed. To further evaluate the efficacy of their design in the future, it's possible more trials could be conducted with amplitudes other than 0 or 1. Another possibility could be the testing of phase with the original trials to see if the results remain consistent. To further their original purpose of creating highly specific architectures with an extremely generalizable system, perhaps a desired structure could be algorithmically matched to a collection of starting conditions, at which point multiple systems could be further validated. In any case, this experiment validates the demonstration it set out to confirm.

REFERENCES

1. Lemons, R., Liu, W., Frisch, J.C. *et al.* Integrated structured light architectures. *Sci Rep* 11, 796 (2021). https://doi.org/10.1038/s41598-020-80502-y
2. Rubinsztein-Dunlop, H., Forbes, A., Berry, M.V. *et al.* Roadmap on structured light. *J. Opt.* 19, 013001 (2017). https://doi.org/10.1088/2040-8978/19/1/013001