Title

Review of "Integrated structured light architectures"

Author
Zhang, Ivy

Publication Date
2023-12-11

Programming Light: A Review

Ivy Zhang

ABSTRACT

In this review of “Integrated Structured Light Architectures,” a high-level summary of the information, methods, and results presented in the paper is provided. Then the experimental intensity profiles of the generated laser patterns are interpreted and verified.

INTRODUCTION

Structured light refers to the manipulation of light in all its degrees of freedom. New developments in the methodology of its creation and manipulation have found numerous applications in various domains, including optical communications, optical sensing, and quantum information processing [1]. Current technologies, such as spatial light modulators for structured light engineering and phased arrays for coherent synthesis, still lack the ability for higher-order control and exploitation of numerous light characteristics [1].

To alleviate this technological gap, Randy Lemons and his team from SLAC National Accelerator Laboratory and Stanford University introduce a novel laser-based architecture to allow flexible, versatile, and programmable light control in the research paper "Integrated Structured Light Architectures” [1].

METHODS

The generalized laser architecture shown in Figure 1 allows the adaptive design of light bullets, including independent phase ($\Delta\varphi_i$), amplitude (A_i), polarization state ($\wp_i$), and timing controls (Δt_i) of each split field [1]. The experimental setup tracks the evolution of synthesized coherent phase arrays made up of seven beamlines, each with individual control of the light characteristics listed above.

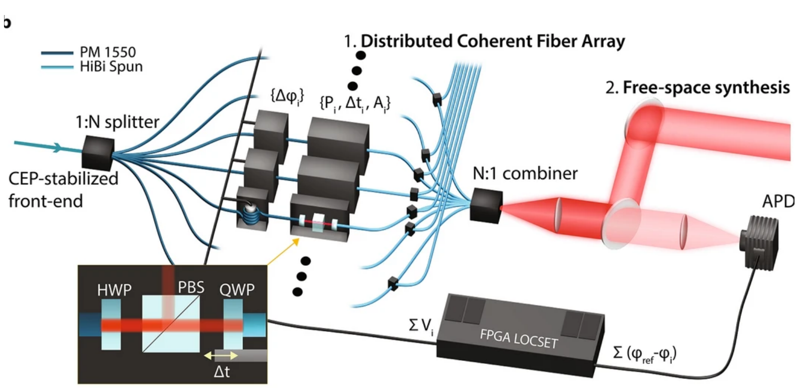

Figure 1: Overall Laser Architecture Structure

First, the front-end electromagnetic input is CEP stabilized, which ensures that all the resulting beamlines have some constant carrier-envelope offset frequency that is known [2]. Then, this laser is split into N beamlines, with one beamline designated as the reference. Using the FPGA LOCSET phase-locking technique, the total amplitude is maximized in order to verify that each of the beamlines are in phase. The phase difference between beamlines is set via user input and produced through a piezoelectric transducer based fiber stretcher, and the phases are set and locked with respect to each other and to the reference beamline through the FPGA with very little noise [1].

For the other characteristics, the intensity and polarization vector control units for each beamline consist of a half waveplate, polarizing beam splitter, and quarter waveplate placed on a fiber pigtailed delay stage for timing. Finally, the beamlines are “collimated and synthesized in free space with a micro-lens array” in a hexagonal configuration

[1]. The result is a laser architecture that can deliver highly coherent and structured light bullets that can produce specific intensity patterns and wave fronts that propagate through free space, as an array of fiber beamlines, or a hybrid of the two [1].

RESULTS AND INTERPRETATION

For demonstration purposes, seven beamlines with different phase relationships and amplitudes (either on or off) are configured to show the resulting intensity profile in far-field and phase distribution [1]. As can be seen in Figure 2, each configuration produces a different intensity profile and wave front phase distribution in far field as a direct result of phase and amplitude modulation [1].

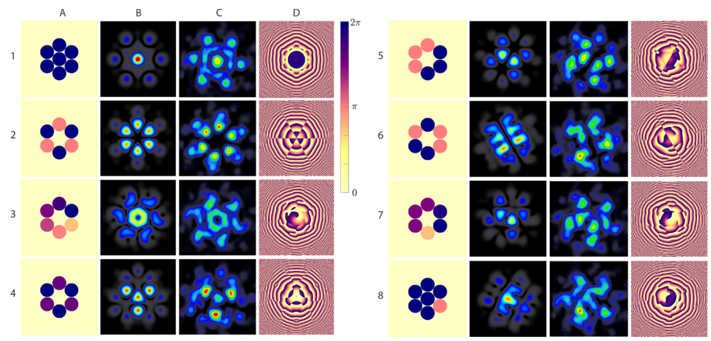

Figure 2: Near field beamline configuration, simulated and measured intensity profile, and phase distribution

The genetic algorithm (GA) that produces the distribution simulations are detailed in "Reconstruction and Optimization of Coherent Synthesis by Fourier Optics Based Genetic Algorithm" by Lemons and Sergio Carbajo [4]. The simulation algorithm is developed using the most general basic equation for optical wave propagation. The Helmholtz equation $\nabla^2 E + k^2 E = 0$ is derived from the more general set of wave equations that describe the spatio-temporal development of a monochromatic optical wave propagating in a homogeneous isotropic medium [3]. Since this holds true only for specific conditions, the paper assumes a free-space propagation. The seven beamlines are represented by plane-waves, and their intensities interfere according to Gaussian mode profiles [3]. The angular spectrum method structures the solutions of the Helmholtz equation as a convolution between the optical wave and the impulse response of the system, or the optical transfer function [4].

$$E(x,y,z) = \iint_{-\infty}^{\infty} \hat{E}(f_x, f_y, 0) e^{ikz\sqrt{1-\lambda^2\left(f_x^2+f_y^2\right)}} e^{i2\pi(f_x x + f_y y)} df_x df_y,$$

Details are left out about the specific constants used to represent the free-space system that the seven-beamlines propagate in, as well as differences between the free-space synthesis, fiber coupling, or the hybrid system that were options presented in Lemons' paper. Perhaps more work can be done to extend this theory in order to build upon the GA to accommodate simulations in different linear systems. The GA is then trained to optimize for a set amount of difference between simulated profiles and their experimental counterparts [4].

With the provided open source code [5], verification of the simulations can be done in MATLAB. With the default settings provided in the example code, which provide a hexagonal beam formation with a wavelength of 1.55 um (telecom), a configuration similar to the first row in Figure 2. As seen in Figure 4, the far field simulations of intensity and phase are similar with clear rings.

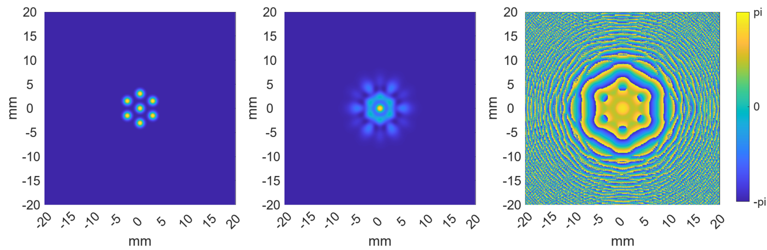

Figure 4: MATLAB Simulation of Row 1

Interestingly, varying the aperture, waist, and spacing of the beams in this hexagon pattern produces very different far field profiles. This effect was not detailed in the paper, so it must be assumed that there is some set value for each of these properties prior to the simulations to get the results shown in Figure 2. For example, as seen in Figure 5, we deviate from the default of {aperture = 3mm, waist = 1mm, beam distance = 3.05mm} to {aperture = 4mm, waist = 3mm, beam distance = 5mm}. The waist extends the area of max intensity to be closer to an even amplitude over the beams [3]. The intensity profile only shows one ring, with a phase singularity at the middle instead of a maximum. The phase profile also shows more overlap instead of clean rings, suggesting that these beams are closer.

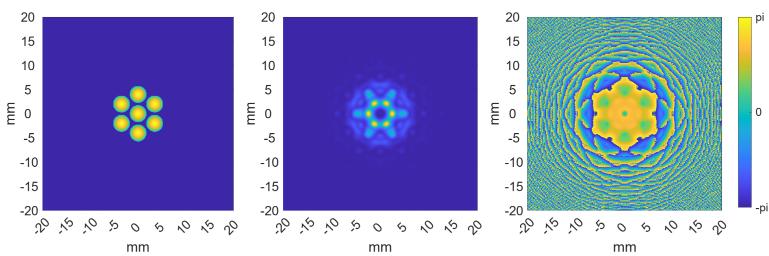

Figure 5: MATLAB Simulation Deviation

Finally, Figure 2 Row 3 is replicated to test the equidistant phase shifts between beams. As can be seen in Figure 6, these simulations are almost exactly the ones presented in the paper.

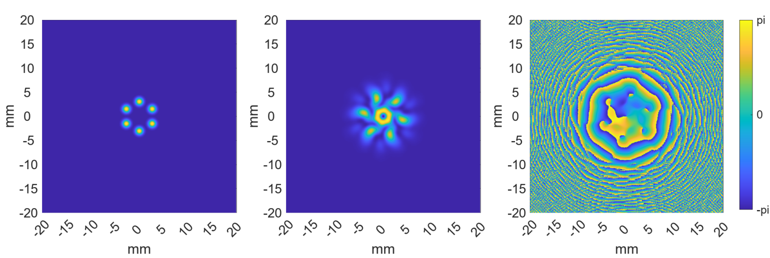

Figure 6: MATLAB Simulation of Row 3

CONCLUSION

In this scientific article, Lemons details a laser architecture that can produce optical fields with very specific intensity profiles and phase distributions by offering individualized characteristic modulation of coherent beamlines. With the assistance of the algorithm presented in a simple, user-friendly code notebook, verification of the simulations becomes simple and fun to experiment with. Further exploration can be done to recalculate the MSE for discretization as well as finding other interesting patterns. In the future, more research could be done to find specific applications of these light packets that necessitate this high-level of specificity and tuning. Analysis and discussion of tradeoff between this programmability, cost, and need would also be useful as this technology is developed and used more.

REFERENCES

[1] R. Lemons et al., “Integrated structured light architectures,” *Scientific Reports*, vol. 11, no. 1, Jan. 2021, doi: https://doi.org/10.1038/s41598-020-80502-y.

[2] D. R. Paschotta, “Carrier-envelope offset,” *The RP Photonics Encyclopedia*. https://www.rp-photonics.com/carrier_envelope_offset.html, (accessed Nov. 17, 2023).

[3] J. Liu, “Principles of Photonics,” Cambridge, UK: Cambridge University Press, 2016, pp. 90-91.

[4] Lemons, Randy, and Sergio Carbajo. "Reconstruction and Optimization of Coherent Synthesis by Fourier Optics Based Genetic Algorithm." arXiv preprint arXiv:2005.13671 (2020).

[5] Randy Lemons (2023). Coherent Optics Propagation and Modeling (https://github.com/slaclab/CCPM/releases/tag/1.0.0), GitHub. Retrieved November 17, 2023.