Title

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Review: “Integrated structure light architectures”

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Abstract: This study introduces a novel laser architecture for adaptive spatio-temporal control of light, leveraging coherent beam combination to generate structured light with versatile topological properties.

INTRODUCTION

The ability to control and manipulate light’s spatial and temporal characteristics has significant implications for both fundamental research and practical applications. The potential applications of this research are extensive and innovative, one notable example being the optical tweezer. An optical tweezer uses a highly focused laser beam to trap and manipulate microscopic particles, including cells and atoms, enabling precise control in biological and physical experiments.

This paper[1] by Lemons et al. is part of the recent decade’s evolution in the artificial structuring of light. It focuses on a novel approach to structuring light, enabling the manipulation of its geometrical and topological states; it seeks to make progress on certain bottleneck technologies by enabling full exploitation of all degrees of freedom in the quest to achieve fully adaptable structures of light. The approach involves creating phased arrays where each element, referred to as a beamline, can individually control various aspects: field amplitude, carrier-envelope, relative phase, and polarization.

The ability to precisely control these aspects of light allows for more detailed and nuanced studies of light-matter interactions. Researchers can observe how changes in the light’s structure affect its interaction with varied materials, leading to deeper insights into both fundamental and applied photonics.

METHODS

Lemons et al. developed a laser architecture based on the principle of coherent beam combination. This approach allows for the integrated control of various light properties, such as amplitude, linear and angular momenta. The primary innovation lies in the ability to engineer the spatio-temporal distribution of light in a highly adaptive manner. Below is a paraphrased list summarizing the experimental setup:

- The concept features $N = 7 + 1$ fiber-based beamlines, each originating from a femtosecond mode-locked laser operating in the C-band telecom wavelength range.

- The system uses a Carrier-Envelope Phase (CEP) stabilization technique with ultralow phase-noise, ensuring single-digit mrad pulse-to-pulse jitter for extended operation. CEP stabilization is crucial for maintaining absolute phase consistency across all beamlines.

- One beamline serves as a reference for monitoring and controlling the relative phase offset between beamlines using a self-synchronous, self-referenced custom Field-Programmable Gate Array (FPGA) phase-locking technique. The 7 beamlines are phase-locked to this absolute reference phase, allowing active manipulation and monitoring of measurable field parameters: phase (φi), amplitude (Ai), polarization state ($\wp i$), and timing (ti).

- Each beamline includes a phase modulator (piezoelectric transducer-based fiber stretcher) for user-defined phase relationships, interfaced with a computer-controlled FPGA.

- Intensity and polarization vector control for each beamline are achieved using a half waveplate, polarizing beam splitter, and quarter waveplate, mounted on a fiber pigtailed delay stage for timing adjustments. Post-manipulation, circularly birefringent fibers maintain each beamline's final polarization state before synthesis.

- The composite beam is collimated and synthesized in free space using a micro-lens array in a tiled-aperture configuration, with the seven beamlines arranged hexagonally for spatio-temporal overlapping at a photodiode. This photodiode is the sole optical detection component needed for the self-synchronous, self-referenced locking technique.

- The final product is a versatile laser architecture capable of delivering programmable laser pulses in various forms: as a free-space synthesized light bullet, an array of distributed coherent beamlines (fiber), or a hybrid of distributed fiber- and free-space beamlines.

Alongside experimental techniques, computational modeling played a significant role in predicting and analyzing the behavior of the structured light. Lemons et al. developed simulation tools[2] to design the phased arrays and to anticipate the outcomes of different configurations, aiding in the optimization of the experimental setup.

RESULTS AND INTERPRETATION

In the subset of the experiment described in figure 1, the researchers focused on manipulating just two parameters: the amplitude and relative phase of the beamlines. They specifically chose to control the amplitude (Ak) of each beamline to be either ‘on’ or ‘off’ and set the relative phase difference φk up to 2π. By limiting their adjustments to these two “knobs” and keeping other controllable parameters fixed, they aimed to demonstrate the effectiveness of amplitude and phase manipulation alone in generating complex intensity and phase distributions in the far field.

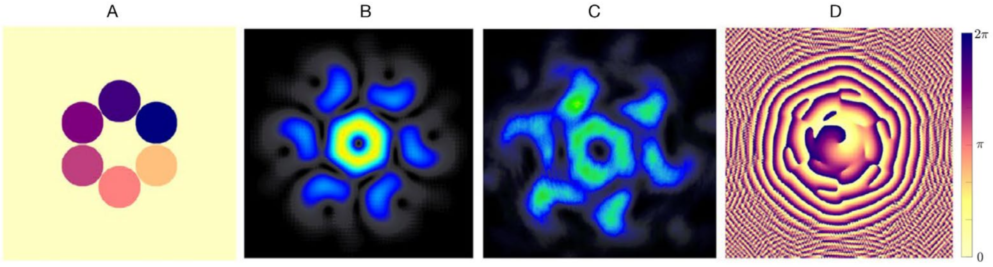

Fig. 1. (a) Amplitude and phase of hexagonal beamline arrangement, (b) simulated and (c) measured far-field intensity profile, (d) phase front, (Ref. [1], Fig. 2).

In the context of light matter interactions and in applications such as optical tweezers, of particular interest is the “donut” shaped Laguerre-Gaussian LG01 mode which have well defined orbital angular momentum (OAM) and may be used to trap and rotate particles that are optically reflective and absorptive. The beam pattern in figure 1 approximates a LG01 mode, is achieved by hexagonal beamline arrangement with central beamline off, a helical phase offset that spans 2π and uniformly increases clockwise monotonically, described by $\varphi k = 2\pi(k-1)/N$; this creates a beam that is equivalent to a discretized first-order orbital angular momentum (OAM) beam. The presence of “additional structure” is a result of the discretization. The hexagonal arrangement and the helical phase of the beamlines leads to a superposition of electric fields[3] with a phase singularity at the center of these beams leading to a dark spot in the middle of a ring of bright intensity:

$$E_T(x,y) = \sum_{k=1}^{N} E_k(x,y) = \sum_{k=1}^{N} I_0 \exp\{\frac{-2((x-x_k)^2(x-x_k)^2)}{{w_0}^2}\} \exp\{i\emptyset_o(k)\}$$

Numerical simulations using Lemons et al. simulation tool[2] run by this author show the above E-field arrangement reproduces (Figure 2a) the approximately LG01 mode of figure 1b for the following parameters: beamline spacing 3.05mm, beam waists 1mm, propagation distance 8m. These parameters were varied in an attempt to improve the quality of the discretized LG01 mode.

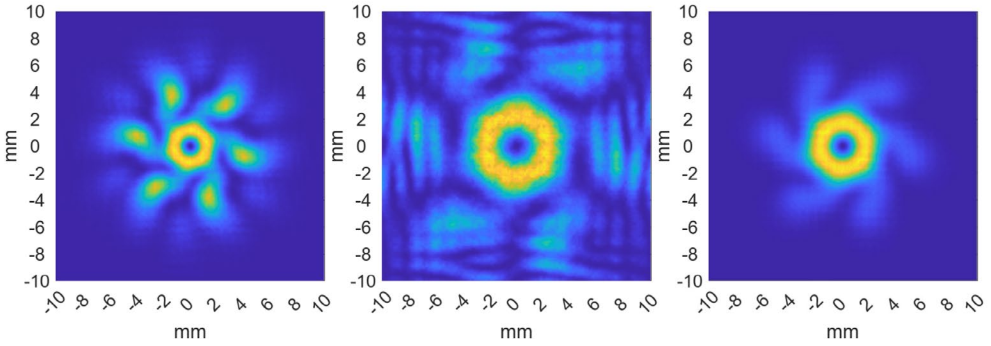

Fig. 2. Simulation by the author: (a) reproduction of figure 1b, (b) 16m propagation (c) distance between beamlines 2mm, (Ref. [2]).

In doubling the propagation distance (Figure 2b) the beam waist approximately doubles, consistent with the divergence of a gaussian beam. Interestingly the “additional structures” have a non-constant phase relationship, a feature that could be utilized when determining where in the beam path to place a target. For decreasing the distance between beamlines the “additional structures” are diminished and there appears to be an overall improvement in the approximation of the LG01 mode. This is the most promising result of our simulations, however, there may be practical reasons why Lemons et al. did not attempt to make the beamline spacing closer, such as limitations on the N:1 combiner.

CONCLUSIONS

The research by Lemons et al. marks a significant advancement in the field of structured photonics. It opens new avenues for the adaptive and integrated manipulation of light’s properties. The findings have potential applications across a broad spectrum of disciplines, from molecular physics to quantum and nonlinear optics. Future work in this area could further explore the practical applications of this technology and its integration into existing photonic systems.

REFERENCES

1. Lemons, R., Liu, W., Frisch, J. C., Fry, A., Robinson, J., Smith, S. R., & Carbajo, S. (2021). Integrated structured light architectures. Scientific reports, 11(1), 796.
2. Lemons, R. (2020). Coherent Optics Propagation and Modeling: Fourier optics based propagation and modeling of complex and arbitrary optical fields [Computer software]. MATLAB Central File Exchange. Retrieved from https://www.mathworks.com/matlabcentral/fileexchange/78550-coherent-optics-propagation-and-modeling.
3. Liu, J.-M. (2016). Principles of Photonics. Cambridge University Press.