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An Analytical Review of Structured Light Architectures with Emphasis on Intensity and Phase Patterns

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Abstract: Light has the capacity to generate an outstanding array of optical phenomena through amplitude and angular momentum variations that can be demonstrated through a coherent beam laser architecture, which will be reviewed in this paper.

INTRODUCTION

With the ongoing advancements in solid state physics as well as photonics, the need for precise control over light's fundamental properties, such as amplitude, phase, polarization, and coherence has emerged. Structured light tailors these outlined properties of a light beam to create custom light fields, which have potential applications in fields including quantum information, optical communication, and biomedical imaging. These applications are possible due to the capability of structured light to leverage phenomena including orbital angular momentum variations and complex phase distributions to enhance data capacity, improve precision, and enable new light quantum states. A recent paper, *Integrated Structured Light Architectures*, explores an innovative technique for structured light generation, accomplished through coherent beam combination. With this technique, researchers were able to achieve spatio-temporal control over multiple parameters of light including phase, polarization, and momentum variables. Through utilizing a programmable, fiber-based laser array, researchers were able to surpass existing limitations of traditional spatial light modulators. Not only are existing spatial light modulators limited by operational damage thresholds, but they also cannot fully control the temporal aspects of a laser.

This review paper will analyze and expand on the groundbreaking research carried out by Stanford National Accelerator Laboratory Researchers through utilizing theory from *Principles of Photonics* by Jia Ming Liu. Through leveraging polarization theory, light modulation, as well as structure synthesis equations, this paper will expand upon aspects of structured light design and the properties of the engineered light. Through leveraging theoretical tools and analytical calculations, this review paper will computationally examine and validate the findings in the paper outlined and graphically present the findings.

METHODS

In *Integrated Structured Light Architectures*, the authors present an experiential framework to build a programmable laser array architecture to generate complex structured light fields. The primary method for beamline combination to synthesize structured light fields is coherent beam combination. A carrier-envelope phase stabilizer front-end enables splitting of the laser into multiple fiber-based beamlines. Next, active phase locking through FPGA control is achieved through a custom phase locking system to maintain coherent synthesis across the light beam [1]. This laser architecture can be observed in Figure 1 as outlined below.

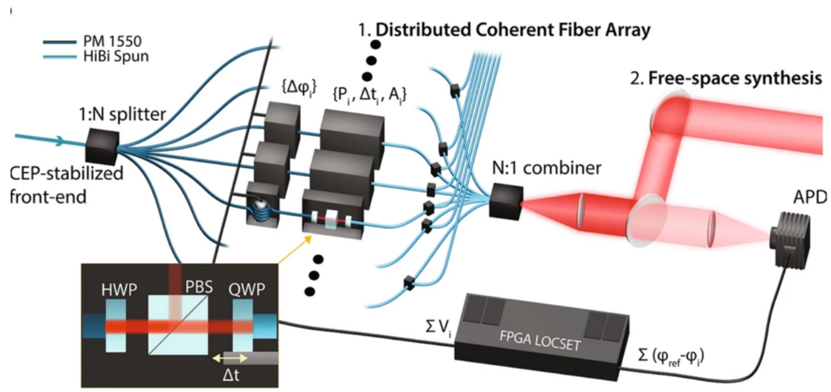

Fig. 1. Structured Light Architecture Coherent Fiber Array (Ref. [1], Fig. 1, b).

To verify the phase and intensity patterns of light depicted in the paper, with a focus on theoretical frameworks presented in *Principles of Photonics*, MATLAB iterations were employed to validate the results. To analyze and validate the phase and intensity patterns, near-field phase and amplitude combinations for varying beam patterns were used to retrieve corresponding intensity profiles. Next, far-field intensity distributions and phase maps were calculated utilizing equations and concepts from Liu's book [3]. The propagation of a Gaussian beam in free space is governed by equation (1).

$$E(x,y,z) = E_0 \frac{w_0}{w(z)} \exp\left(-\frac{x^2+y^2}{w(z)^2}\right) \exp\left(-i\left(kz + \frac{k(x^2+y^2)}{2R(z)} - \zeta(z)\right)\right) \tag{1}$$

This equation yields paraxial distribution and allows the modeling of Gaussian amplitude for each beam within the pattern. Through assigning Gaussian beam to individual beam spots, we can model the predicted behavior of the light arrangement. For near-field pattern generation, peripheral Gaussian beams are arranged in varying patterns using equation 2.

$$E(r) = \exp\left(-\frac{r^2}{w_0^2}\right) \tag{2}$$

Where $r = \sqrt{(x-x_i)^2 + (y-y_i)^2}$. Phase modulation is achieved through applying radial and angular phase shifts to each beam, as adapted from Liu's work on structured light. The far-field pattern and Fourier optics are calculated through taking the Fourier transform of the complex near-field electric distribution pattern, as described by the equation 3.

$$I_{\text{far}}(u,v) = |\mathcal{F}\{E(x,y,0)\}|^2 \tag{3}$$

Finally, to visualize the phase distribution to reveal phase singularities and interference patterns, we use the argument of the complex field $E = (x,y)$ to determine the phase distribution of the beam sample. Through employing these theoretical foundations in MATLAB simulations [4], we reproduce complex near-field and phase distribution graphs outlined.

RESULTS AND INTERPRETATION

Through analyzing MATLAB simulations of near-field and far-field intensity and phase patterns for 2 varying beam formations, as discussed in the research paper, we can validate the researchers' findings on structured light, as affirmed by *Principles of Photonics*. The simulation seen in Figure 2 represents the near field arrangement and phase distribution of a seven-beam formation with a central Gaussian beam and six peripheral beams in a hexagonal arrangement:

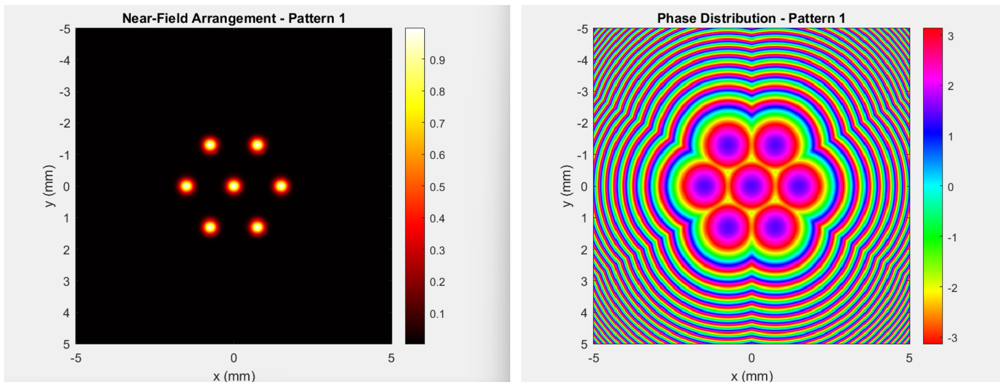

Fig. 2. a) Near Field Arrangement of Pattern 1 b) Phase Distribution of Pattern 1.

The simulation highlights the effect of the outlined near-field beam arrangement on near-field and far-field intensities, as well as the resulting phase distribution. The central beam enhances the near-field intensity and creates a concentrated far-field interference pattern [2]. Similarly, Figure 3 represents the near field arrangement and phase distribution of 6 hexagonal beams, resulting in a more uniform near-field intensity and a broader far-field intensity distribution. The outlined results mirror those of *Integrated Structured Light Architectures* very closely [5].

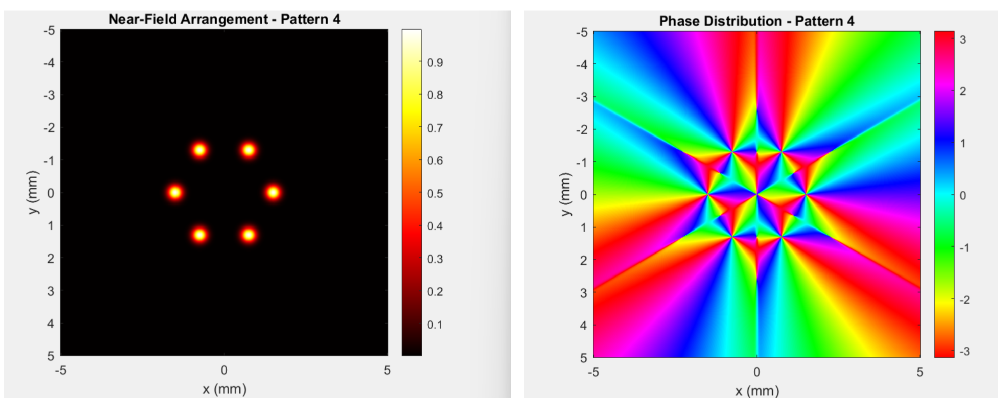

Fig. 3. a) Near Field Arrangement of Pattern 4 b) Phase Distribution of Pattern 4.

CONCLUSIONS

In the outlined research paper, *Integrated Structured Light Architectures*, researchers were able to construct a laser array architecture that was able to implement structured light formation through distributed coherent fiber array architecture. Based on the MATLAB analysis carried out, the theoretical findings reaffirm the practical finding in the published research paper. Through arranging Gaussian beams in specific formations and performing Fourier transforms, we were able to achieve near-field distribution as well as phase distribution patterns. The significance of these findings lies in their ability to accurately reproduce the conclusions from the original research paper. This review emphasizes the relevance of photonics theory in accurately predicting light behavior in engineered beam configurations. These outlined findings not only corroborate findings in *Integrated Structured Light Architectures,* but also builds the framework for manipulating phase and intensity in custom photonics applications.

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