Title
New method for Integrated structured light architectures_Jiajun Xu

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Integrated structured light architectures

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Abstract: A novel programmable laser architecture enables adaptive structured light generation using coherent beam combination and carrier-envelope phase control, overcoming limitations in ultrashort pulse manipulation and improving near-field modeling via the Huygens-Fresnel Principle.

1 INTRODUCTION

Since previous light modulators failed to measure the temporal intensity distribution or control the carrier-envelop phase in ultrashort pulse manipulation, a programmable laser architecture for dynamic and adaptive structured light generation, introduced by the team of Randy Lemons, overcomes the difficulties above and successfully achieves continuous amplitude, active polarization and carrier-envelop phase(CEP) modulatoin together, enabling the design of light bullets with built-in programmable structure to be exploited adaptively.(1) It leverages coherent beam combination, precise phase control, and carrier-envelope phase (CEP) stabilized laser of which the output is split into multiple beamlines, each modulated for amplitude, phase, polarization, and timing. The system demonstrates the synthesis of complex spatiotemporal light structures, including vortex beams and polarization topographies. Real-time phase modulation is achieved through FPGA-based LOCSET, enabling dynamic phase-front evolution and polarization control. They showed some impacts of The laser such as discretization, where increasing the number of channels improves beam fidelity by reducing artifacts and enhancing topological charge purity. The architecture, validated through numerical and experimental results, offers scalability and potential for applications in quantum optics, nonlinear photonics, and high-power laser systems. Not only can the new architecture drive innovation in the manufacturing and communication industries, improve efficiency, and reduce costs, but also contribute to fundamental discoveries in physics, chemistry, and biology.The new archeteture might be used in High-Power Lasers for Material Processing, enabling precision micro-machining, cutting, and etching for advanced manufacturing, and facilitating the creation of delicate structures in electronics and biomedical devices. It also supports high-dimensional entanglement and quantum information processing, assisting in the development of secure quantum communication protocols.

However, the numerical method, the Discrete Fast Fourier Transform (DFT) and the angular spectrum evaluation method of the Rayleigh-Sommerfeld diffraction formula, Randy Lemons' team used have some problems in complex situtation , Although the Discrete Fast Fourier Transform (DFT) and the angular spectrum evaluation method of the Rayleigh-Sommerfeld diffraction formula are commonly used in optics, particularly in simulating and analyzing diffraction patterns of waves propagating through or from apertures, they still have problems such as inaccuracy in the near field of angular spectrum method. The angular spectrum method is primarily designed for far-field (Fraunhofer) diffraction. Its accuracy in near-field (Fresnel) diffraction is limited, especially for small distances where the angular spectrum may not be fully valid.(2) Also, since the DFT assumes periodic boundary conditions, the presence of sharp edges or discontinuities in the simulated field (like the boundaries of an aperture) can introduce spurious diffraction patterns or artifacts. Therefore, we need a new method to reconstruct the light intensity distribution in the near and far field, avoiding the problems that the team of Randy Lemons encountered.

The new method is the method of Huygens-Fresnel Principle. The near field is the region where the distance from the source is small relative to the wavelength of the light. In this region, the wavefronts are curved and not yet fully formed into plane waves as they would be in the far field. The curvature of the wavefronts is pronounced, and each point on the wavefront can be treated as a source of secondary spherical waves that propagate towards the observation point. This makes the Huygens-Fresnel principle an ideal tool in the near field as it is based on the principle of wavefront propagation and diffraction, which are especially pronounced in the near field.

The Huygens-Fresnel Principle plays a significant role in the manipulation of light and understanding of various optical phenomena. While its formulation is theoretical and rooted in wave optics, it has a profound impact on practical applications that influence our daily life, technology, and broader societal developments.It enables the design of high-resolution optical instruments by guiding the manipulation of light through apertures and ensuring accurate focusing of light rays. Techniques like microscopy, optical coherence tomography (OCT), and endoscopy rely on understanding how light interacts with tissue at microscopic scales. The Huygens-Fresnel principle helps design these systems by allowing scientists and engineers to model how light propagates through tissue and create clear, high-resolution images.The functioning of cameras, whether in smartphones or professional equipment, relies heavily on optics. The way light enters the camera through apertures (lenses), and the diffraction and interference that occur within the system, are analyzed using principles from Huygens-Fresnel. This understanding is essential for producing high-quality images.

2 Method

2.1 Setup

The system Randy Lemons built is an advanced mode-locked laser system with carrier-envelope phase (CEP) stabilization for optical coherence and phase control. The oscillator delivers 140 mW of power, 175 fs pulses at 204 MHz repetition rate, and a 14.9 nm spectral bandwidth centered at 1.55 µm. A feed-forward (FF) system isolates and stabilizes the carrier-envelope offset frequency. Octave-spanning is achieved using nonlinear fiber and second harmonic generation in periodically poled lithium niobate. Phase locking is maintained using an acousto-optic frequency shifter (AOFS) and feedback systems.Optical phase alignment for seven channels is achieved via FPGA-based LOCSET, enabling high scalability and precise control. Phase errors are corrected in feedback loops with bandwidths up to hundreds of Hz. SPUN-HiBi fibers preserve circular polarization, and microlens arrays ensure precise collimation. A hexagonal aperture configuration facilitates free-space synthesis.

2.2 old method

In the article written by the team of Randy Lemons. Beam propagation is modeled with the Rayleigh-Sommerfeld diffraction formula using a discrete fast Fourier transform approach.(1).The Angular Spectrum Method (ASM) is the mathematical approach they chose. It is a powerful tool to model and propagate electromagnetic waves. It is based on decomposing a wavefield into its constituent plane waves, each traveling in a specific direction. These plane waves are then used to calculate the wavefield at any other plane along the direction of propagation. As ASM models how a wavefield $U(x, y, z)$ evolves as it propagates through free space, the wavefield $U(x, y, z)$ is represented terms of its spatial frequencies $(f_x,\ f_y)$ using a 2D Fourier transform:

$$\widehat{U}(f_x, f_y, z_0) = \iint U(x, y, z_0)e^{-i2\pi(f_x x + f_y y)}dxdy \tag{1}$$

, where $\widehat{U}(f_x, f_y, z_0)$ is the angular spectrum, representing the wavefield in the spatial frequency domain. To obtain the propagated wavefield $U(x, y, z)$, we calculate the inverse Fourier transform

$$U(x, y, z) = \iint \widehat{U}(f_x, f_y, z)e^{i2\pi(f_x x + f_y y)}df_x df_y \tag{2}$$

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2.3 New method

The method we propose is Huygens-Fresnel Principle, which modelsH the propagation of the wavefront based on the Huygens-Fresnel diffraction principle. It was invented by Christian Huygens who proposed that every point on a wavefront of light can be treated as a secondary source of spherical wavelets. As time progresses, these wavelets spread out from each point on the wavefront, and the new wavefront is formed by the envelope of these secondary wavelets.(3).Fresnel expanded on Huygens' principle by incorporating the concept of interference and diffraction.Fresnel's refinement accounts for the superposition of secondary wavelets from different points on the wavefront. It considers the distance between the observation point and the sources of the wavelets, the wavelength of light, and the geometry of the system. In his version, the total wave at any point is determined by summing (or integrating) the contributions from all points on the wavefront, weighted by the distance between the point and the sources. In its general form, the field at an observation point P (at a distance z from the aperture) due to a wavefront passing through an aperture A is given by:

$$U(P) = \frac{1}{i\lambda}\int \frac{e^{ikR}}{R}U(Q)dA \tag{3}$$

, where $U(P)$ is the field at the observation point P, $U(Q)$ is the field at a point Q on the aperture, R s the distance from the point on the aperture to the observation point P. If P is a point at (x, y, z), it can be expressed in the form below:

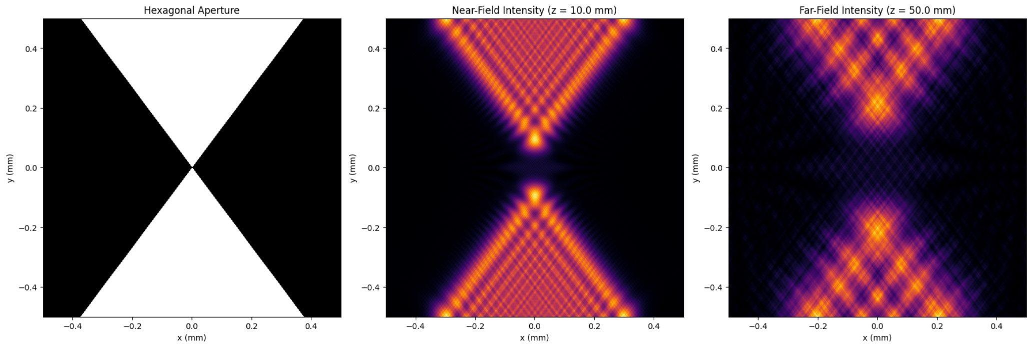
$$U(x, y, z) = \frac{e^{ikz}}{i\lambda z}\iint U(x_0, y_0, 0)e^{\frac{ik}{2z}((x-x_0)^2+(y-y_0)^2)}dx_0 dy_0 \tag{4}$$

, where z is the propagation distance, $k = 2\pi/\lambda$ wave number.

3 RESULTS AND INTERPRETATION

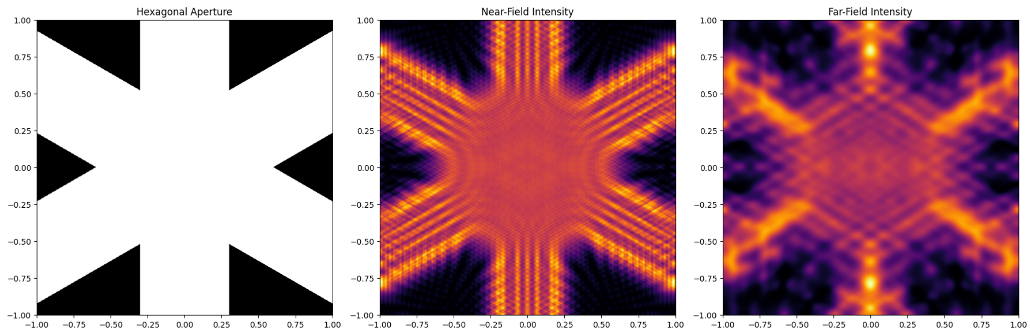
By implementing both methods to generate hexagonal phase-front graphs, a simulation of the hexagonal aperture will be set and will numerically propagate the wavefront to visualize near-field and far-field patterns. Below is the use of Angular Spectrum Method (ASM) method to create a hexagonal aperture and calculate near-field intensity and far-field intensity.

Fig 1. The graph of hexagonal aperture, near-field intensity and far-field intensity distribution using ASM



Below is the use of Huygens-Fresnel Principle to create a hexagonal aperture and calculate near-field intensity and far-field intensity.

Fig 2. The graph of hexagonal aperture, near-field intensity and far-field intensity distribution using HFP



The aperture shows a clear hexagonal geometry, which defines the spatial filtering of the wavefront. Both methods exhibit patterns dominated by aperture geometry. In the near-field, the light intensity is sharply concentrated and retains hexagonal symmetry due to minimal diffraction effects. The far-field pattern becomes less sharp and exhibits interference fringes. These are caused by the superposition of waves from different points in the aperture, leading to intricate constructive and destructive interference. The patterns become increasingly obscure when comes to far field because higher-order diffraction components blur the intensity distribution, and the hexagonal shape only influences the angular spectrum slightly. The shape of hexagon is more complete in the output produced using Huygens-Fresnel Principle method, meaning Huygens-Fresnel Principle method is better than ASM work in the near-field situation.

4 CONCLUSIONS

In contrast to the far field, where diffraction patterns are simpler and can be approximated by the Angular Spectrum Method (ASM) or Fraunhofer diffraction approximation, the near field requires the full treatment of the wavefront curvature and diffraction effects, which is precisely what the Huygens-Fresnel principle captures, and a the ASM might not provide accurate results for propagation over short distances, as it assumes a plane wave decomposition of the field that is less valid in close proximity to the source. Therefore, for detailed near-field simulations, Huygens-Fresnel might be preferable due to its physical basis. For efficient far-field calculations, ASM is more practical and computationally faster.The combination of both methods allows accurate modeling across different regimes.

5 REFERENCES

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