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Review of Integrated structured light architectures

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Abstract: This research presents a novel laser architecture enabling adaptive, programmable light synthesis with coherent beam combinations for spatio-temporal control. The study showcases the generation of customizable light structures, offering new avenues in photonics.

INTRODUCTION

Manipulating light structure is crucial for advancing quantum computing, optical communications, and particle physics applications. Inspired by natural examples like the intricate coloration seen in peacock feathers and photonic structures in butterfly wings, structured photonics has led to significant developments in producing specialized beams with properties such as orbital angular momentum (OAM) and optical vortices. While impactful, current technologies like spatial light modulators are limited by operational constraints, particularly at high power, which restricts comprehensive control over light's spatio-temporal features. This research introduces an innovative laser architecture using coherent beam combination to achieve complete spatio-temporal modulation, overcoming existing technological limitations and paving the way for dynamic and programmable light synthesis with potential transformative applications.

METHODS

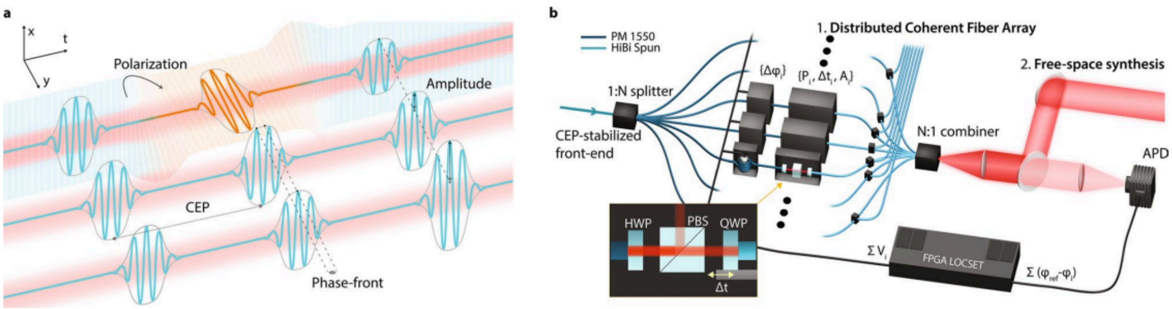

Fig. 1. (a) conceptual depiction of a transversely and longitudinally coherent optical comb and the corresponding primary elements that define how the electromagnetic field distribution will synthesize; and (b) the experimental configuration via coherent multi-channel coherent fiber array with a common CEP-stabilized front end, independent phase ($\Delta\varphi_i$), amplitude (A_i), polarization state ($\wp_i$), and timing (Δt_i) controls, and active locking via FPGA LOCSET using a single avalanche photodiode (APD) in the far-field. The output coherent output can be delivered in the form of a distributed coherent fiber array or the form of a free-space synthesized pulse. (Ref. [1], Fig. 1)

This work presents a new laser system with seven fiber-optic beamlines delivered by a carrier-envelope phase (CEP)-stabilized, mode-locked femtosecond laser. The laser emits at a telecommunication wavelength and maintains phase stability through a feed-forward phase-noise reduction technique. The stability of the CEP is quantified using the equation:

$$\Delta\phi_{CEP} = \sqrt{\phi_{CEP}(t) - (\phi_{CEP}(t))^2}$$

This ensures that fluctuations in the CEP are minimized, enabling precise control over the temporal coherence of the laser pulses. Each beamline is independently manipulated using phase modulators linked to a field-programmable gate array (FPGA), enabling accurate phase setting and synchronization with a reference beamline.

Each beamline was independently manipulated using phase modulators linked to a field-programmable gate array (FPGA) enabling accurate phase setting and synchronization with a reference beamline. The experimental apparatus controls each beamline's amplitude, phase, polarization, and timing. Circularly birefringent fibers were used to preserve the stated polarization state through the system, while modulators based on piezoelectric elements, positioned in delay stages, adjusted both the phase and intensity. The manipulation of the relative phase $\Delta\phi_i$ for each beamline follows:

$$\Delta\phi_i = \phi_i - \phi_{ref}$$

Here, ϕ_i represents the phase of an individual beamline, and ϕ_{ref} is the reference phase. Integration of these individually tuned beamlines was achieved by using a micro-lens array with a hexagonal layout, allowing the creation of an advanced, coherent output with flexible spatio-temporal arrangements, as shown in Figure 1.

RESULTS AND INTERPRETATION

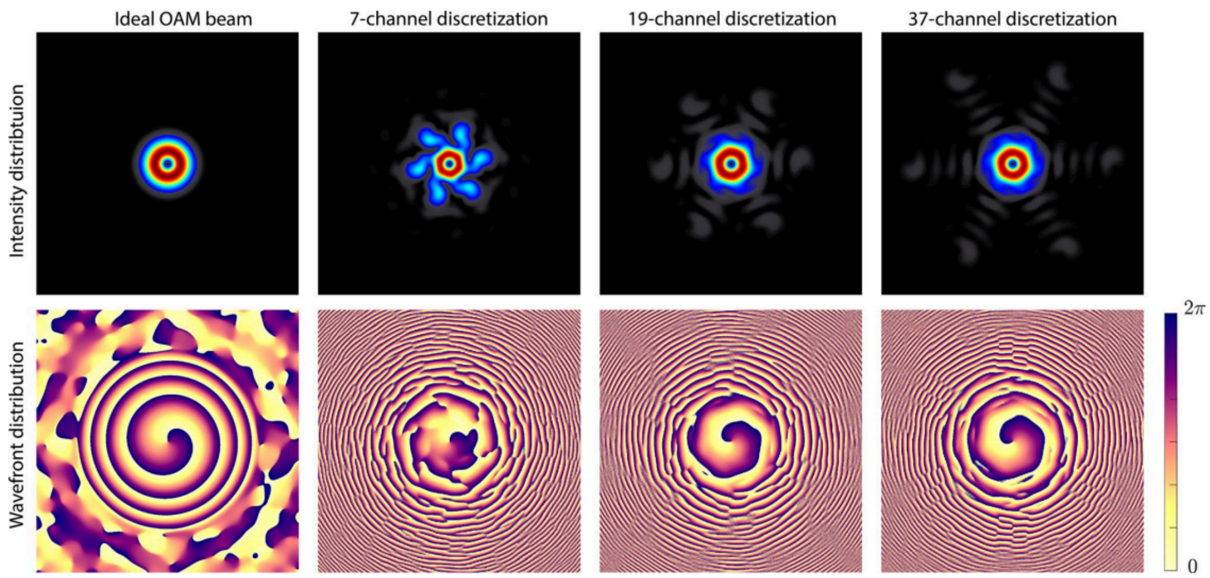

Fig. 2. Modeled first-order OAM beam intensity (first row) and wave front (second row) distributions for the ideal representation (first column) and 7-, 19-, and 35-channel hexagonal configurations (second through fourth columns, respectively). (Ref. [1], Fig. 5)

The experimental results confirm the system's ability to generate structured light beams with precise spatio-temporal control. As shown in Figure 2, with a 7-channel configuration, the system successfully created orbital angular momentum (OAM) beams featuring distinct topological charges and dynamic phase distributions. The generated beams demonstrated high alignment with ideal configurations, supported by low mean squared error (MSE) values between measured and theoretical intensity distributions.

Additionally, the system displayed remarkable versatility in creating polarization topographies. It effectively incorporated various polarization states, such as alternating spin angular momentum, into the beam structure. This capability highlights the robustness of the experimental setup in maintaining coherence across multiple beamlines and aligns well with theoretical expectations.

Another significant finding was the system's adaptability in dynamically controlling phase singularities and chirality, enabling the generation of complex interference patterns. This adaptability positions the system as a valuable tool for high-precision applications, such as optical communication and quantum information processing. Moreover, simulations and preliminary experiments with higher channel configurations, such as 19 and 35 channels, demonstrated enhanced beam quality and complexity, including reduced diffraction effects and improved topological purity. These results indicate the system's scalability and its potential to push the boundaries of structured light applications in advanced imaging and high-capacity data transmission.

CONCLUSIONS

This research establishes that coherent beam combinations can be used to create structured light with adaptive and programmable characteristics. The architecture, with its integrated field controls for phase, amplitude, polarization, and timing, advances the capabilities of current light-shaping technologies. Future directions include expanding to higher-channel configurations for even more intricate beam structures and exploring applications in quantum photonics and on-chip accelerators. This work lays the groundwork for innovations in optical communications, quantum information processing, and new light-matter interaction technologies.

REFERENCES

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