Full Polarization Vector and Phase Control of Femtosecond Structured Light

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Abstract: we present a laser architecture that synthesizes arbitrary 4D-structured femtosecond light with full polarization vector, transverse and longitudinal intensity, and wavefront control as a novel tool to probe and control matter.

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1. Introduction

Orbital angular momentum (OAM) carried by optical vortex beams has been extensively studied since its birth 25 years ago driven by its physical significance and potential for applications [1]. Laser beams with inhomogeneous polarization distribution, referred to as vector beams, are extensively used in a variety of applications including optical trapping and super-resolution microscopy. In addition, OAM beams with high intensity can exert forces and torque on particles, and have the ability to drive the motion of trapped particles. The success story of vortex beams tells us that high-precision 4D-control (time, phase, polarization and intensity) of ultrashort high-intensity laser pulses could open new research and technology avenues.

Currently, the most widely adopted method capable of creating laser pulses with programmable intensity, phase, and polarization is based on spatial-light modulator (SLM) technology. Despite their wide-ranged and popular use in photonics, SLMs that are suitable for ultrafast optical technology and beam physics exhibit severe limitations in usable average and peak powers due to thermal and photochemical damage – especially in the case of liquid crystal SLMs – and abrasion of dielectric or metallic surfaces [2]. On the other hand, coherent beam combination using fiber arrays (FA) has long sought to top its ever-increasing average power record, which now stands at the kW-level [3]. Fiber array performance and potential for ultrahigh brightness is yet to be overcome by any other optical technology. Here, we present a laser architecture that combines for the first time the key capabilities of both technologies – amplitude, phase, and polarization control from SLMs, and synthesis of high power lasers coherent combination of fiber arrays – to address the technological challenges of future programmable ultrabright laser sources with 4D control.

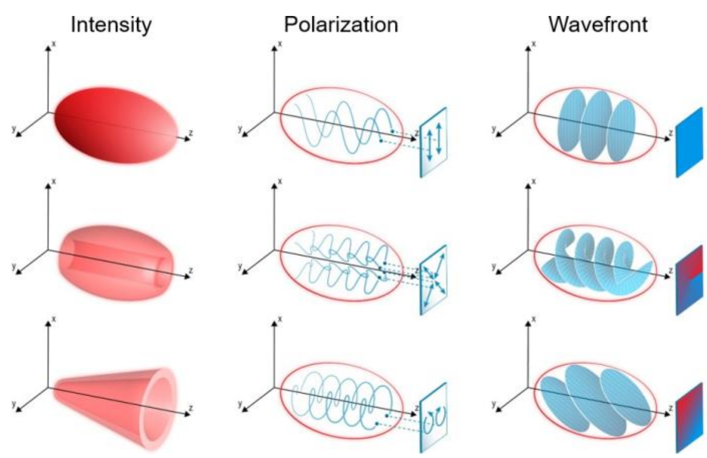

Fig. 1. Conceptual depictions of possible ULM beam characteristics. The examples given are broken down into intensity, polarization, and wavefront distributions.

2. System Architecture and Experimental Results

We refer to this technology as the Universal Light Modulator (ULM). The ULM prototype presented here consists of 7+1 beamlines. Each beamline is split from a femtosecond front-end laser (OneFive Origami-15). One beamline is used as a reference beam for phase locking, while the remaining 7 undergo active timing, phase, intensity and polarization control before coherently synthesizing a composite beam. Fig. 1 depicts some exemplary ULM beam characteristics, where any arbitrary field distribution may be generated by independently tailoring each beamline's degrees of freedom. We employ SPUN-HiBi fibers for individual beamline delivery. Unlike traditional PM fibers, SPUN-HiBi are designed to preserve linear and circular polarization. The composite beam is collimated with a microlens array in a tiled-aperture configuration arranged hexagonally. Relative time overlap/delay is achieved using a fiber pigtailed delay stage in each beamline. The intensity is modulated by a half waveplate and a polarization beam splitter integrated in the delay line. Phase control is achieved by means of 7 phase modulators (PZT-based fiber stretcher) capable of operating at bandwidths larger than 10 kHz. Using the LOCSET phase-locking scheme, we are able to synthesize the ULM beams with zero phase-shift for combining efficiency purposes as well as any other arbitrary composite non-zero phase-front regardless of each individual beamline's polarization state.

Fig. 2 showcases the ability to synthesize arbitrary femtosecond pulses. The first relevant step is to characterize the coherently combined far field distribution to benchmark the locking system and composite beam quality (Fig. 2.a-b). Our preliminary combining efficiency is ~40%, in proximity to previously published literature [4]. Fig. 2.c exemplifies a far-field distribution synthesized with non-zero phase distribution. Here, each beamline's relative phase difference with respect to the others, ϕ_k, is defined as $\phi_k = 2\pi(k-1)/N$, where N is the total number of beamlines in the combined output and $k \in \mathbb{Z}[1, N]$. That is, the beamlines are phase-offset such that they span over 2π, which is equivalent to generating a discretized first-order OAM beam. The central singularity appears as expected in a helical-like wavefront.

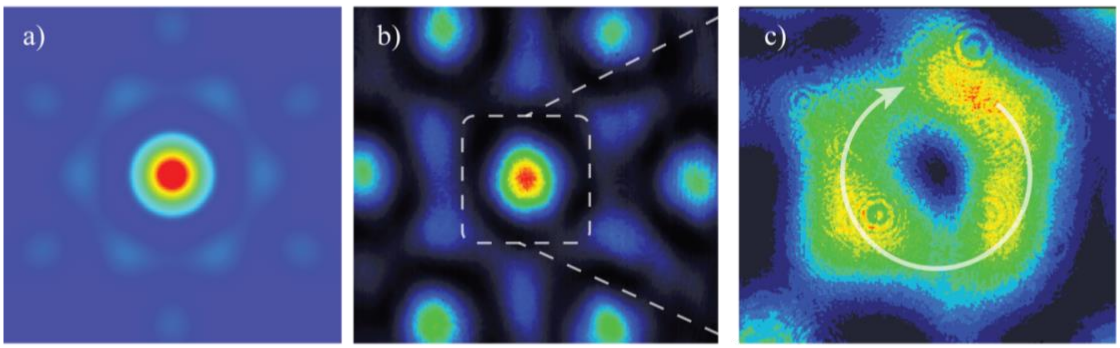

Fig. 2. Simulated (a) and measured (b) far-field intensity distribution of coherently combined (zero phase-shift) beamlet array, and (c) far-field intensity distribution with a discretely helical wavefront.

3. Conclusion

The ULM is based on an array of coherently combined fibers, each containing femtosecond pulses with controlled intensity, timing, phase, and polarization vector. The demonstration of the ULM represents the first integrative laser architecture capable of generating fully controlled topological polarization and phase structure of ultrashort pulses. This architectures is both scalable in peak and average power, and can support active carrier-envelope phase control and stabilization.

There is a vast range of potential ramifications for the ULM beyond ultrafast and nonlinear optics. As a prospective programmable turn-key source, the ULM does not depend on internal cavity optics to generate AOM beams and the controls are nearly decoupled from each other in order to enable the synthesis of beams with any desired polarization vector and topological phase structure. The underlying rationale for the ULM is not only power scalability of high-quality laser beams, but it extends further to exploit full control over individual fiber intensity, phase, timing, and polarization to synthesize arbitrarily complex and on-demand laser pulses capable of inspiring new beam shaping technologies and applications, such as relativistic [5] and tailored laser-particle interactions [6].

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