4D Pulse Shaping of Discretized Beam Arrays

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Abstract: We report on a novel ultrafast laser architecture capable of generating 4D arbitrarily distributed beams based on an array of coherently combined fibers, each containing femtosecond pulses with controlled intensity, wavefront, and polarization vector distribution.
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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, mostly driven by the physical significance and potential for applications [1]. Laser beams with inhomogeneous polarization distribution, referred to as vector beams, are intensively applied in a variety of applications including optical trapping, focusing, and microscopy, among many others. 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 a laser pulse could open new research and technology avenues. For example, laser accelerator, microbunching and electron vortices generation.

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.

In this paper, we present an 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. We refer to this technology as Universal Light Modulator (ULM). Figure 1 depicts the possible ULM beam characteristics. By adjusting almost every freedom of the individual laser pulses, it is possible to generate not only the conventional laser fields, but also some unconventional fields, such as radially polarized field, arbitrary tilted wavefronts.

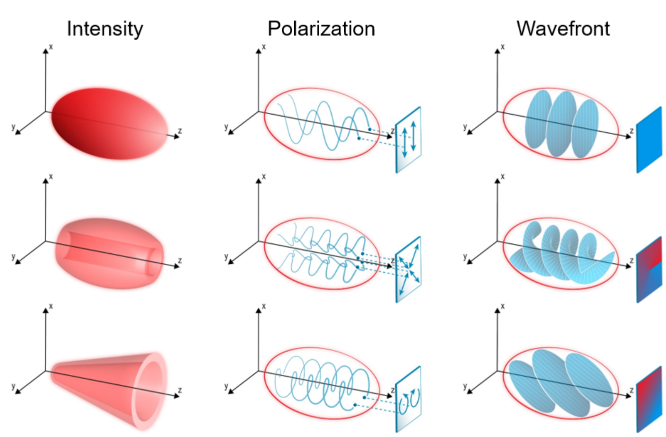

Fig. 1. Conceptual depictions of possible ULM beam characteristics. The examples given are broken down into intensity, polarization, and wavefront distributions.

2. Conceptual design

The proposed experimental setup for the ULM of 7 discretized fibers array is shown in Fig. 2. Out of the 8 beamline replicas from a femtosecond front-end PM 1 x 8 splitter, one will be used as a reference beam for phase locking, while the remaining 7 undergo the time, phase, intensity and polarization controls for coherent beam combining. The discretized 7-array beam will be collimated with a microlens array (μLA) in a tiled-aperture configuration. A high precision customized 7-array will be arranged into the hexagonal shape and inserted into a thin AR-coated fused silica substrate with at a pitch around 250-300 μm. Here we implement SPUN-HiBi fiber for the delivery of each individual channel. Traditional PM fibers maintain the polarization state only when the polarization direction is aligned along the slow axis of the fiber, thereby limiting the freedom of polarization vector distribution, as required by the ULM design. Unlike traditional PM fibers, SPUN-HiBi are designed to preserve linear and circular polarization so that the system could preserve the freedom of polarization control.

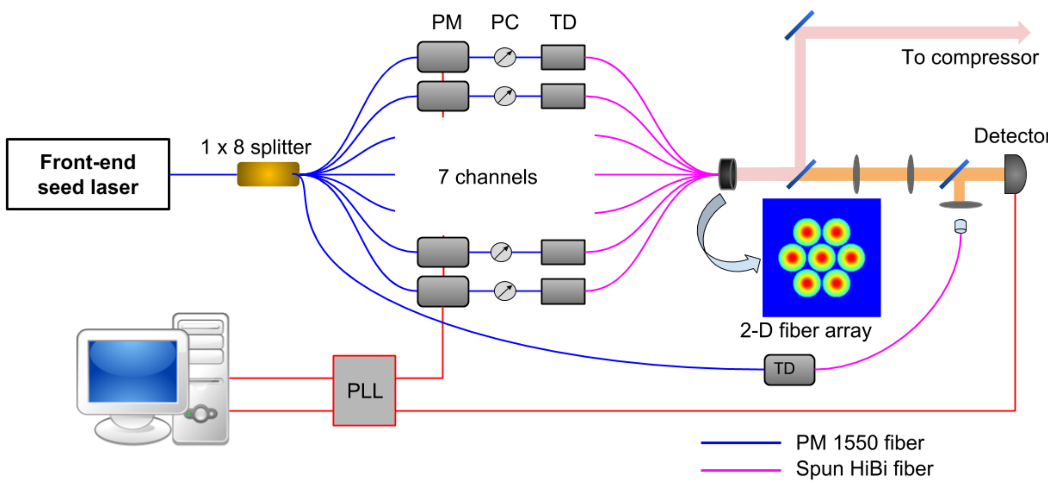

Fig. 2. Schematic of pulse shaping of discretized 7-channel beam arrays. PM: phase modulator; PC: polarization control; TD: time delay; PLL: phase-locked loop.

The time overlap/delay of the 7 ultrafast pulses is achieved by tuning the fiber pigtailed time delay stages from each channel. The intensity is modulated by a half waveplate and polarization beam splitter, which is to be built inside the delay stages to shrink the size of the system. By adding amplification stage(s) into each channel, the system could be easily upgrade to a intensity boosting one. The phase corrections are then compensated by means of 7 phase modulators (PZT-based fiber stretcher). The phase modulators are capable of compensating phase shift at bandwidths larger than 10 kHz, which is fast enough to eliminate any vibration or thermal induced noise. From the LOCSET locking scheme, we predict a high combining efficiency of the 7 beamlines. Finally, we will compress the 4D shaped ultrafast pulses to compensate for the dispersion of the fibers and ULM components.

3. Conclusion

The ULM is based on an array of coherently combined fibers, each containing ultrafast pulses with controlled intensity, timing, phase, and polarization vector. 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 discretized laser pulses capable of inspiring new beam shaping technologies and applications, such as relativistic and tailored laser-particle interactions.

References

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