

Preface to the special issue on “Multi-Dimensional Light Field Manipulation: Methods and Applications”

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Compared with electrons, there is one distinct feature of photons, known as multiple physical dimensions. Frequency/wavelength, time, complex amplitude and polarization are typical physical dimensions of photons. Very recently, the spatial structure of photons, the only known physical dimension left, has attracted increasing interest in full access of photons worthy of exploration. Manipulating these physical dimensions of photons enables a diversity of light related applications such as trapping, sensing, metrology, microscopy, imaging, quantum information processing and optical communications. For instance, various multiplexing techniques such as wavelength-division multiplexing (WDM), time-division multiplexing (TDM) and polarization-division multiplexing (PDM) are widely used to increase the transmission capacity of optical communications. Moreover, advanced modulation formats such as m-ary phase-shift keying (m-PSK) and m-ary quadrature amplitude modulation (m-QAM) encoding multiple bits information into one symbol take full use of the complex amplitude physical dimension of lightwaves to increase the transmission capacity and spectral efficiency in coherent optical communications. Additionally, tailoring the spatial structure of lightwaves benefits the generation of various special light beams having inhomogeneous amplitude, phase and polarization distribution across the light beams. Generally, these special light beams can be called structured light, also known as tailored light, shaped light, sculpted light or custom light. There are several typical examples of structured light, such as Hermite-Gaussian (HG) light beams having spatially variant amplitude distribution, twisted light beams having spiral phase front and carrying orbital angular momentum (OAM), and vector light beams having spatially variant polarization distribution. Some other beams have both spatially variant amplitude and phase distribution, such as Laguerre-Gaussian (LG) and Bessel light beams. More complicated structured light may simultaneously have spatially variant amplitude, phase and polarization distribution. Even the space array light can be also considered as a general type of structured light accessing parallel spatial regions. Multi-core fiber (MCF), few-mode fiber (FMF) and multi-mode fiber (MMF) are typical fibers supporting structured light beams, i.e., different spatial mode sets of linearly polarized modes, OAM modes, eigenmodes. The space-division multiplexing (SDM) employing different spatial mode sets is considered to be the next frontier technique enabling continuous capacity scaling. Not only in optical communications, but also in other fields (such as optical trapping and manipulation), structured light has also played an increasingly important role. Recent years have witnessed the rapid development of light field manipulation exploiting physical dimensions of photons. The trends and challenges are in-depth exploitation of each physical dimension and multi-dimensional light field manipulation.

This special issue focuses on “Multi-Dimensional Light Field Manipulation: Methods and Applications”. The special issue includes 9 review articles, discussing in-depth exploitation of each physical dimension and multi-dimensional light field manipulation. The generation and detection methods, different scenarios and platforms (e.g., free space, fiber, integrated devices, micro and nano optical structures), and more diverse applications (e.g., long-haul optical transmission, short-reach optical interconnects, optical signal processing, optical trapping and manipulation) are important issues addressed in this special issue.

X. W. Du et al. [1] reviews joint timing and frequency synchronization algorithms in coherent optical orthogonal

frequency division multiplexing (CO-OFDM) systems. A timing estimation method by designing the pattern of the training symbol is presented. Both data-aided (DA) and blind (BL) approaches to estimate the carrier frequency offset (CFO) are provided. The joint timing and frequency synchronization approaches require only one OFDM symbol, ensuring not only the data transmission efficiency, but also the timing offset (TO) and CFO estimation performance. A modified BL zero-subcarrier power (ZSP) algorithm is proposed to further improve the CFO estimation performance by taking the power average over a series of OFDM symbols.

J. J. Yu [2] summarizes the recent research progress in spectrally efficient single carrier 400G optical signal transmission. By exploiting the complex amplitude physical dimension and using quadrature phase-shift keying (QPSK), 16-QAM and 64-QAM signals, ultra-long transmission distances over 10000, 6000 and 3000 km are demonstrated, respectively, assisted by large area fiber and all-Raman amplification. In order to improve the system performance and generate high-order QAM signals, advanced digital signal processing (DSP) algorithms such as probabilistic shaping and look-up table pre-distortion are employed to effectively optimize the transmission performance.

H. X. Wang et al. [3] present multi-channel phase regeneration of QPSK signals based on phase sensitive amplification. The phase regeneration configuration consists of two parts. One uses four-wave mixing (FWM) in highly nonlinear fiber (HNLF) to generate corresponding three harmonic conjugates precisely at the frequency of the original signals. The other one uses an optical combiner for coherent addition aiming at completely removing the interaction in phase regeneration stage. The results suggest that the scheme can optimize signal constellation to a large extent especially in high noise environment. The optical signal to noise ratio (OSNR) is improved by > 3 dB.

J. H. Li et al. [4] exploit the spatial structure physical dimension of lightwaves, especially the spatial modes in conventional MMF. The key technologies to realize weakly-coupled mode-division multiplexing (MDM) transmission over conventional MMF are elaborated. Detailed mode characteristics in MMF and weakly-coupled mode multiplexer/demultiplexer (MUX/DEMUX) are discussed. After that, the up-to-date experiments for weakly-coupled MDM transmission over conventional OM3 MMF with intensity modulation and direct detection (IM-DD) are presented. The obtained results show that weakly-coupled MDM scheme is promising for high-speed optical interconnects and bandwidth upgrade of already-deployed MMF links.

J. P. Li et al. [5] exploit both the complex amplitude and spatial structure physical dimensions of lightwaves for short-reach optical interconnects. They review demonstrations of free-space and fiber high-speed data transmission based on the vector mode MDM (VMDM) techniques. The special vector modes are generated by the q-plate. The vector mode multiplexing is combined with direct-detection orthogonal frequency division multiplexing (DD-OFDM) to offer an available trade-off in system performance and complexity. The demonstrations of high data rate with direct detection show the potential of VMDM-DD-OFDM technique in large-capacity short-reach optical transmission links.

L. Zhu et al. [6] exploit multiple physical dimensions of lightwaves including the spatial structure for the generation of multiple optical vortices. Optical vortices carrying OAM have seen a variety of applications, in which simultaneous generation of multiple optical vortices are of great importance. They review the methods for the generation of multiple optical vortices in three different scenarios, i.e., 1-to- N collinear OAM modes, 1-to- N OAM mode array, and N -to- N collinear OAM modes. Diverse applications of multiple optical vortices in optical communications (OAM multicasting) and non-communication (OAM metrology) areas are also presented. Future trends, perspectives and opportunities are also discussed.

P. Li et al. [7] focus on the spatial structure physical dimension and give an overview of the modulations of OAMs on the propagation dynamics of scalar and vector light fields in free space. Firstly, the evolutions of canonical and noncanonical optical vortices are introduced and the modulations by means of local spatial frequency are analyzed. Secondly, the Pancharatnam-Berry phases arising from the spin-orbital interaction are reviewed, revealing the controlling of beam evolution referring to novel behaviors such as spin-dependent splitting and polarization singularity conversion. Finally, the propagation and focusing properties of azimuthally broken vector vortex beams are discussed.

C. H. Wan et al. [8] also focus on the spatial structure physical dimension of lightwaves and review the latest research progress on OAM detection with micro- and nano-optical structures. In a variety of OAM-involved applications, it is crucial to detect and discern different OAM states with high fidelity. The discussed OAM detections with micro- and nano-optical structures are based on plasmonics, photonic integrated circuits (PIC) and liquid crystal devices. These innovative OAM sorters are promising to ultimately achieve the miniaturization and integration of high-fidelity OAM detectors and spur numerous applications that harness the intriguing properties of the OAM-carrying twisted light.

H. B. Xin et al. [9] review the recent progress in fiber-based optical trapping and manipulation, including both photothermal and optical force based trapping and manipulation. They focus on five aspects: massive photothermal trapping and manipulation, evanescent field-based trapping and manipulation, dual fiber tweezers for single

nanoparticle trapping and manipulation, single fiber tweezers for single particle trapping and manipulation, and single fiber tweezers for multiple particle/cell trapping and assembly. Fiber-based optical trapping and manipulation show advantages of ease fabrication, compact configurations, flexible manipulation capabilities, ease of integration, and wide applicability

The 9 review articles selected in this special issue only show part of the recent advances in this rapid growing and flourishing field. One can expect to see more developments in multi-dimensional light field manipulation and many emerging applications.

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Jian Wang has devoted his research efforts to innovations in photonic integrated devices and frontiers of high-speed optical communications and optical signal processing. He has more than 300 publications in total, including 7 book chapters, 5 special issues, 7 review articles, 10 invited papers, 80 tutorial/keynote/invited talks (invited talk at OFC2014, tutorial talk at OFC2016), 12 postdeadline papers, and more than 100 journal papers published on *Science*, *Nature Photonics*, *Science Advances*, *Light: Science & Applications*, *Laser & Photonics Reviews*, *Optica*, *Scientific Reports*, *Optics Express*, *Optics Letters*, *Photonics Research*, etc. Jian Wang serves as the Topical Editor of *Optics Letters*, Topic Editor of *Chinese Optics Letters*, and Area Editor of *Microwave and Optical Technology Letters*. Jian Wang is also the frequent reviewer for more than 30 journals such as *Nature Photonics*, *Nature Communications*, *Advanced Materials*, *Light: Science & Applications*, *Physical Review Letters*, *Laser & Photonics Reviews*, *Optica*, *ACS Photonics*, *Advanced Optical Materials*, *Optics Express*, *Optics Letters*, *Scientific Reports*, etc.