Multi-Dimensional Light Field Manipulation on Diverse Integrated Photonic Platforms

(Invited Paper)

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Abstract: We review advances in multi-dimensional (frequency, time, complex amplitude, polarization, spatial structure) light field manipulation on diverse integrated photonic platforms (silicon, silica, polymer, III-V, metal, fiber). Silicon photonic integrated circuits, femtosecond laser direct writing 3D photonic chips, InP active photonic integrated devices, and metasurfaces for shaping light are demonstrated. Potential applications and future perspectives are discussed.

1. Introduction

Photons have multiple physical dimensions (Fig. 1), including frequency, time, complex amplitude, polarization, spatial structure, etc. Almost all photon-related applications are about the manipulation of photon's physical dimensions. For example, tailoring the spatial structure of lightwaves can flexibly generate helically-phased or twisted light carrying orbital angular momentum (OAM) and more general structured light with spatially variant amplitude, phase and polarization distribution, which have attracted increasing interest in many applications ranging from optical manipulation to optical communications [1, 2]. Very recently, shaping light with integrated devices has become an important trend in light field manipulation for its small footprint, easy integration, high reliability, and superior performance. In addition, there have also been many types of photonic integration platforms, supporting various multi-dimensional chip-scale light field manipulation.

In this paper, we review recent progress in multi-dimensional light field manipulation on diverse integrated photonic platforms, such as silicon, silica, polymer, III-V, metal, and fiber (Fig. 1). In addition to traditional physical dimensions (frequency, time, complex amplitude, polarization), we focus more on chip-scale spatial structure manipulation using silicon-based photonic devices, femtosecond laser direct writing 3D photonic chips on silica and polymer, InP-based active integrated devices, metasurfaces on metal and fiber facet.

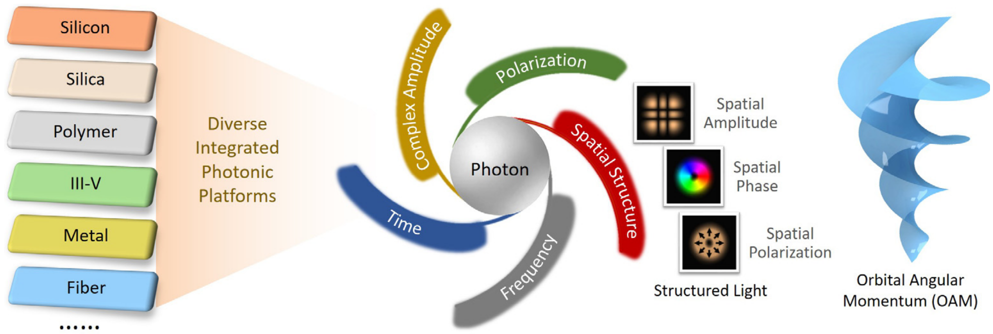

Fig. 1. Conceptual illustration of multi-dimensional (frequency, time, complex amplitude, polarization, spatial structure) light field manipulation on diverse integrated photonic platforms (silicon, silica, polymer, III-V, metal, fiber, etc.)

2. Silicon photonic integrated circuits for multi-dimensional optical signal processing [3,4]

Various silicon photonic devices can be employed to shape multiple physical dimensions of photons. For example, arrayed waveguide gratings (AWGs), spiral waveguides, Mach-Zehnder/microring modulators, asymmetric waveguides, and holographic gratings can manipulate the frequency/wavelength, time, complex amplitude, polarization and spatial structure physical dimensions of lightwaves, respectively. Monolithic integration of multiple unit devices on silicon platform, i.e. silicon photonic integrated circuits, can facilitate multi-dimensional optical signal processing. Shown in Fig. 2 are examples of chip-scale reconfigurable optical full-field manipulation for compact multi-functional photonic signal processor [3] and mesh-structure-enabled programmable multi-task photonic signal processor [4]. The former uses two modified AWGs and an array of Mach-Zehnder switches to implement diverse functions of optical filtering and reconfigurable optical add/drop multiplexing (ROADM), while the latter uses a scalable 2D mesh structure network of tunable Mach-Zehnder interferometers to implement various optical filtering functions, delay line, multi-port router, optical switch, accompanied by self-configurable operations.

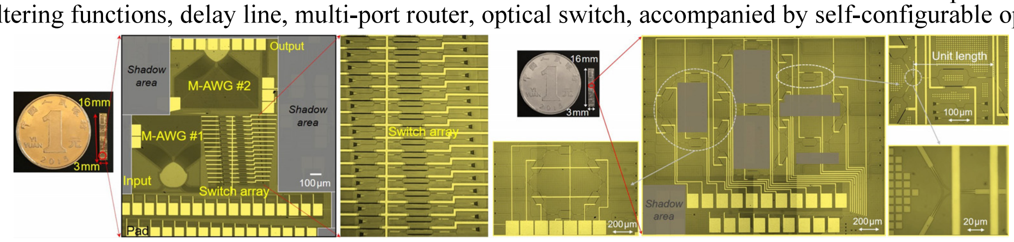

Fig. 2. Chip-scale reconfigurable optical full-field manipulation for multi-functional photonic signal processor and mesh-structure-enabled programmable multi-task photonic signal processor on silicon platform [3, 4].

3. Silicon photonic devices for twisting light [5-9]

The silicon platform can be also used to tailor the spatial structure of lightwaves [5-9]. Shown in Fig. 3 is one example of ultra-compact broadband polarization diversity twisted light generator with 3.6x3.6 μm^2 footprint [6, 7]. The silicon-based OAM-carrying twisted light emitter is formed by transferring a superposed holographic fork grating structure on top of a silicon waveguide, which can couple the in-plane waveguide mode to the out-of-plane free-space OAM mode. Broadband generation of polarization diversity OAM modes from 1500 to 1630 nm with high purity and efficiency are demonstrated [6]. By adding a backside metal mirror below the grating structure layer, the efficiency is improved by ~5 dB [7]. A digitized subwavelength surface structure is further employed to improve the performance of wavelength-/polarization-/charge-diverse twisted light generation [8]. In addition, twisted light lattice can be generated by using three parallel silicon waveguides with etched tilt gratings [9].

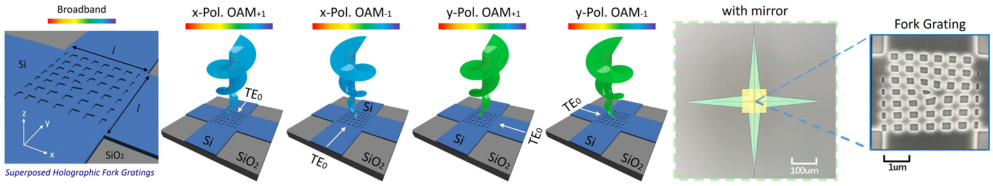

Fig. 3. Broadband polarization diversity twisted light generator (superposed holographic fork grating structure on top of a silicon waveguide) [6, 7].

4. Femtosecond laser direct writing 3D photonic chips on silica/polymer for structuring light [10-13]

As an important supplement to silicon platform, femtosecond laser direct writing technique is of great interest in fabricating 3D photonic chips. Shown in Fig. 4 are two typical examples of 3D photonic chips on silica and polymer platforms. For silica, the femtosecond laser writing induces a localized change of the refractive index near the laser foci in the silica substrate [10, 11]. For polymer, it relies on the two-photon polymerization (TPP) at the laser foci in the photoresist [12, 13]. The flexible design of the 3D trajectory of the foci creates various 3D photonic devices. One example in Fig. 4 is the 3D photonic chip based on trench waveguide structures, realizing the generation, multiplexing, demultiplexing, and exchange of OAM-carrying twisted light beams [10]. The similar technique can be used to fabricate low-insertion-loss 3D (de)multiplexing devices for few-mode fiber and multi-core fiber, supporting space-division multiplexing (SDM) applications [11]. Another example in Fig. 4 is the TPP-based 3D phase plates for generating special light beams, such as Bessel beams and Mathieu-Gauss beams [12, 13].

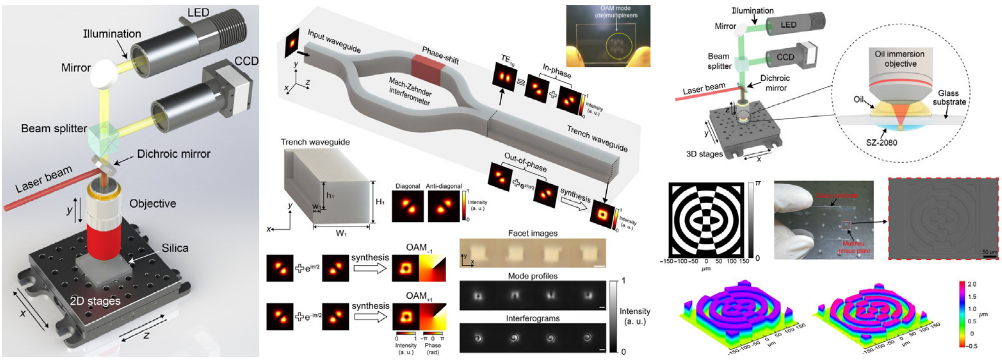

Fig. 4. Femtosecond laser direct writing 3D photonic chips for generating twisted light (trench waveguide structures on silica platform) and Bessel/Mathieu-Gauss beams (3D phase plates on polymer platform) [10, 12, 13].

5. InP active integrated devices for shaping vector beam laser [14, 15]

In addition to passive integrated devices, light field manipulation by active integrated devices provides a promising approach for structuring light free of external optical sources. We demonstrate a high-speed directly modulated cylindrical vector beam laser under electrical pumping based on a fully integrated III-V semiconductor platform [14]. InP-based microring cavities incorporating two sets of optimized second-order grating structures are employed to implement single-mode lasing and efficient emission assisted by ion implantation. High-speed modulation is achievable due to high-differential-gain multiple-quantum-well structure and small active region. Scalable 2D array integration is available because of the surface emission. Cylindrical vector beam lasers with ~50 dB side-mode suppression ratio (SMSR) and at 8-20 Gbit/s are demonstrated in the experiment [14]. Meanwhile, two grating-assisted concentric microcavities based on an InP platform are also proposed to emit both radially and azimuthally polarized beams [15].

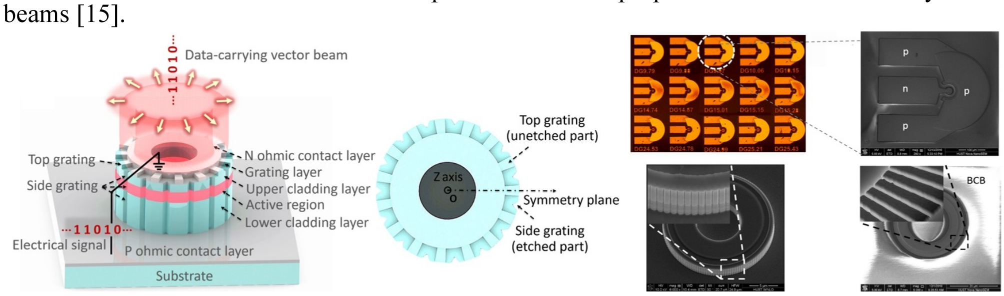

Fig. 5. High-speed directly modulated cylindrical vector beam laser under electrical pumping on a fully integrated III-V semiconductor platform [14].

6. Metasurfaces on metal and fiber facet for structuring light [16-19]

Remarkably, metamaterials and metasurfaces have also attracted great attention in light field manipulation. Both plasmonic and dielectric metasurfaces have been reported to tailor spatial structure of lightwaves [16]. Show in Fig. 6 are two example of metasurfaces on metal platform for structuring light. One is used for generating OAM-carrying vector beams based on two concentric rings in a gold film, with each ring composed of subwavelength rectangular apertures (localized spatial polarizers) with gradually varied orientation [17]. The other is used for generating structured light with phase helix and intensity helix based on reflection-enhanced plasmonic metasurfaces at 2 μm [18]. Moreover, metasurface structures can be also transferred onto the fiber platform, e.g. fiber facet. Shown in Fig. 7 is one typical example of meta-facet fiber for twisting ultra-broadband light with high phase purity [19]. The excitation of both linearly polarized and circularly polarized twisted light from either meta-facet side or planar-facet side is demonstrated in the experiment with favorable performance.

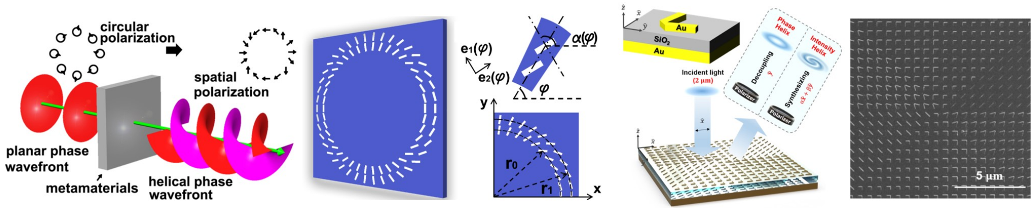

Fig. 6. Metasurfaces on metal platform for generating OAM-carrying vector beams [17] and structured light with phase helix and intensity helix [18].

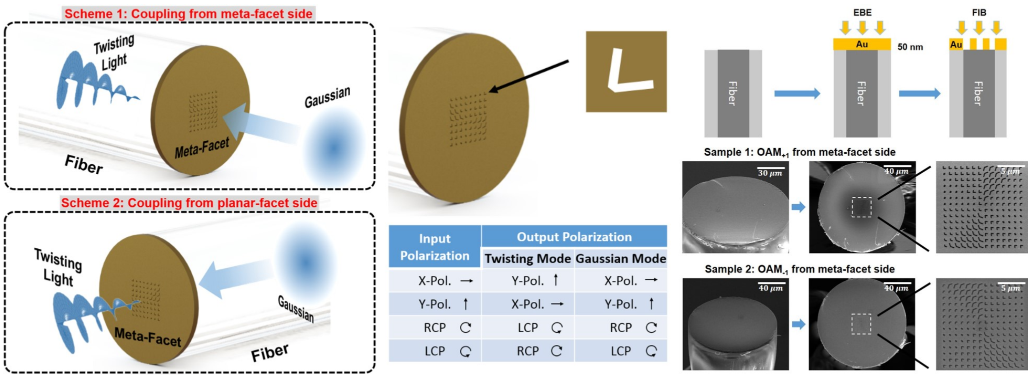

Fig. 7. Metasurfaces on fiber facet platform (meta-facet) for twisting linearly and circularly polarized ultra-broadband light with high phase purity [19].

7. Discussions

Multi-dimensional light field manipulation on diverse integrated photonic platforms may find wide applications in optical manipulation, optical trapping, optical tweezers, imaging, microscopy, optical sensors, optical metrology, quantum information processing, optical communications, optical signal processing [1-4, 10, 14, 20-29], etc. For example, silicon photonic integrated circuits and femtosecond laser inscribed 3D photonic chips can be combined to facilitate multi-dimensional optical signal transmission and processing [30]. The future development trend would be more diverse special light beams, material platforms, integration methods, manipulation functions, and emerging applications. For example, spatiotemporal light beams, silicon nitride/thin-film lithium niobate/2D materials, hybrid/heterogeneous integration, intelligent functions and applications would be of great interest.

8. Acknowledgement

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9. References

[1] A. M. Yao, et al., Adv. Opt. Photon. 3, 161-204 (2011).
[2] J. Wang, et al., Nature Photon. 6, 488-496 (2012).
[3] S. Zheng, et al., ACS Photon. 7, 1235-1245 (2020).
[4] X. Cao, et al., ACS Photon. 7, 2658-2675 (2020).
[5] N. Zhou, et al., Opt. Lett. 43, 3140 (2018).
[6] N. Zhou, et al., Sci. Adv. 6, eaay0837 (2020).
[7] Y. Zhu, et al., Opt. Lett. 45, 1607 (2020).
[8] X. Cao, et al., Nanophotonics, 11, 4551 (2022).
[9] J. Du, et al., Opt. Lett. 42, 5054 (2017).
[10] J. Wang, et al., Adv. Photon. 5, 036004 (2023).
[11] Y. Liang, et al., Adv. Photon. Nexus, 2, 036002 (2023).
[12] J. Wang, et al., Opt. Lett. 47, 5766 (2022).
[13] J. Wang, et al., Adv. Photon. Nexus, 2, 016011 (2023).
[14] X. Ma, et al., ACS Photon. 6, 3261-3270 (2019).
[15] S. Zheng, et al., Opt. Lett. 45, 2211-2214 (2020).
[16] J. Wang, Chin. Opt. Lett. 16, 050006 (2018).
[17] Z. Zhao, et al., Opt. Lett. 38, 932-934 (2013).
[18] Y. Zhao, et al., Appl. Phys. Lett. 112, 171103 (2018).
[19] Y. Zhao, et al., Appl. Phys. Lett. 113, 061103 (2018).
[20] L. Fang, et al., Optica 6, 61-66 (2019).
[21] L. Fang, et al., Phys. Rev. Lett. 127, 233902 (2021).
[22] Z. Ruan, et al., Nanoscale 12, 15620-15630 (2020).
[23] J. Zeng, et al., J. Lightwave Technol. 41, 2025-2040 (2023).
[24] L. Fang, et al., Nature Commun. 12, 4186 (2021).
[25] J. Liu, et al., Sci. Adv. 6, eaay0837 (2020).
[26] J. Liu, et al., Light Sci. Appl. 7, 17148 (2018).
[27] J. Liu, et al., Appl. Phys. Lett. 120, 131103 (2022).
[28] A. Willner, et al., Science 337, 655-656 (2012).
[29] J. Wang, Photon. Res. 4, B14-B28 (2016).
[30] K. Li, et al., PhotoniX 4, 14 (2023).