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Recent Advances on Tunable Vortex Beam Devices for Biomedical Applications

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
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Abstract

The optical vortex beams carrying orbital angular momentum (OAM) recently have unveiled great potential to be widely applied in advanced biomedicine, e.g. manipulating and assembling DNA, detecting biomolecule, organic illumination, single-cell nanosurgery, etc. However, it is an everlasting challenge to produce the proper vortices devices for corresponding applications. To this end, the tunable properties of OAM beams need to be produced. The spectrum-tunable property is related to the tuning of the response of target molecules. The OAM-tunable property can control the number and distribution of target particles. Moreover, the polarization-tunable property can be used to reduce photodamage. Hereinafter, we give a prompt review of the recent advances on tunable vortex beam devices for biomedical applications.

Abbreviations: OAM: Orbital Angular Momentum; AIFG: Acoustically-Induced Fiber Grating; MEMS: Micro-Electro-Mechanical-System; HLG: Hermite-Laguerre-Gaussian; HIG: Helical-Ince-Gaussian; AMC: Astigmatic Laser Mode Converter; PWE: Paraxial Wave Equation; LCD: Liquid-Crystal Display; SLM: Spatial Light Modulator

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Optical vortex beams are at the heart of a number of novel research directions, which are the light beams with a helical wavefront carrying orbital angular momentum (OAM), giving rise to a phase singularity at the center of light field [1-3]. In 2004, X Zhuang [4] unveiled that a DNA molecule can be manipulated by a vortex beam which plays a role of optical tweezer. Moreover, she discovered that the position, rotation, even condensation of the target DNA or other biomolecule can be flexibly controlled so as to do biomolecules assembling engineering via tuning the corresponding vortex beam [5-8]. With more researches on the interaction between matters and optical OAM hatched in recent years, vortex beams were gradually developing more and more powerful advanced applications in biomedicine [9]. Utilizing the coupling between the chirality of molecule and the chirality of OAM of vortex beams [10-12], one can detect, select and sort the target molecules with special chirality or enantiomorphism, offering an alternative to existing bio-sensing technologies [13,14]. With the development of the tunable vortex beams in nanometer-sized subcellular structures [15-17] and the optimization of

the polarization-tunable property [18-20], the optical tweezers developed the functionality of transporting subcellular organelles and exerting less photodamage on the trapped particle, which has been used in advanced single-cell nanosurgery [21].

In 2006, F Tamburini et al. [22] unveiled that the Rayleigh criterion limit (diffraction limit) can be overcome with optical vortices in imaging process, which extend the novel super-resolution imaging technology using vortex beams. Then, researchers reported that the resolution in this super-resolution imaging can be further improved by using optical vortex lattices i.e. the vortex beam with multiple singularities and singularity arrays [23]. Moreover, through tuning the polarization structure of the vortex beam, the resolutions of the superresolution imaging technology can be close to 100 nm, which is capable of clearly observing biological cells [24,25]. Therefore, the development of large-range tunable vortex beams can largely improve the super-resolution imaging for the application of biomedical photonics. In this year, a breakthrough in vortices generation is that the vortex beam can be generated in organic material [26], which has great potential to develop

novel organic illumination technologies and further be used in microimaging subcellular dynamics in multicellular organisms [27] in the future.

According to the above review, the development of tunable vortex beams largely promoted the related biomedical applications. In contrast to the conventional fundamental mode beam, the vortex beams have spatial structures with structured OAM and polarization properties. Thus, besides the conventional wavelength-tunable property, its tunable properties also include OAM-tunable and polarization-tunable properties. All these three kinds of tunable properties provided distinct directions for improving the related biomedical applications. Therefore, it is meaningful to investigate the vortex beams devices with more powerful tunable properties. For the wavelength- and OAM-tunable vortex beams devices, recent advances can be divided into two categories, single-singularity topological charge tuning and multiple singularities distribution tuning. The former one will be discussed first. Although the technologies for wavelength-tunable and OAM-tunable lasers are existed for a long time, yet the generation of wavelength and OAM simultaneously tuning lasers is a cutting-edge topic.

In 2016, W Zhang et al. [28] developed a method for the optical vortex generation with wavelength tunability via an acoustically-induced fiber grating (AIFG) driven by a radio frequency source. By tuning the frequency of RF driving signal, topological charge of the generated optical vortex can be converted to $0\sim\pm1\hbar$ within the wavelength range 1540 nm - 1560 nm. However, the OAM tuning range is limited to $0\sim\pm1\hbar$, leading to scant applications. In 2017, V Lyubopytov et. al. [29] expand the OAM tunable range to $0\sim3\hbar$ by using a new on-chip micro-component – tunable Micro-Electro-Mechanical-System (MEMS)-based Fabry-Perot filter integrated with a spiral phase plate. In the same year, Q Liu et al. [30] reported a design of a wavelength- and OAM-tunable vortex beam in Er:YAG laser where the tunable parameters are 8.4nm range of wavelength and $0\sim\pm2\hbar$ OAM. In early 2018, our group [31,32] presented a dual-off-axis pumping scheme in Yb:CaGdAlO4 (Yb:CALGO) lasers with external mode converter to generate wavelength- and OAM-tunable vortex beams, with wavelength-tunable range across 10 nm and a large OAM-tunable range of $0\sim\pm15\hbar$, which for the first time breaks ten-level OAM range in wavelength- and OAM-tunable vortex beams to the best of our knowledge. The whole system is free of extra tuning devices and the light source is simply structured and easy to implement on a relatively low cost.

Later in 2018, S Wang et al. [33] also adopted the similar method to generate wavelength- and OAM-tunable vortex beams. Moreover they employed a z-type cavity design to realize very low threshold and a thin film polarizer to precisely control the center wavelength. The final tunable range reached $0\sim\pm14\hbar$ for OAM and 14.5 nm for wavelength-tunable width. Around the same time, N Zhou et al. [34] designed and implemented a fiber-free space hybrid coupling laser device with wavelength and OAM tunable properties which solved the problem that large OAM is difficult to be tuned in fiber lasers. The OAM tunable range is $0\sim\pm10\hbar$ while the wavelength can be tuned to cover the entire C-band range of 1530–1565 nm. This is the first demonstration of ten-level OAM tunable lasers using fiber systems.

Compared with single-singularity topological charge tuning, multiple singularities topological charge tuning is much more sophisticated as it not only involves topological charge tuning but also involves singularities distribution manipulation, which plays a crucial role in optical tweezers and multi-particle manipulation. Although singularity splitting was found in mode converter several years after OAM was proposed, how to generate vortex beams with multiple singularities remains a hot research topic. To the best of our knowledge, absolute arbitrary control is not yet actualized, but various types of such vortex beams, their theory and generation methods have been reported including Hermite-Laguerre-Gaussian (HLG) beams [35-37], Helical-Ince-Gaussian (HIG) beams [38,39], fractional vortex beams [40-42], SU(2) wave-packet [43-45], and polygonal vortex beams [46,47]. Using an astigmatic laser mode converter(AMC) [48] was the earliest way to produce vortex beams. When the phase matching condition in the AMC is not strictly satisfied, singularly splitting phenomenon will appear in the output light field, forming HLG modes [35-37].

HG and LG beams are the solutions of paraxial wave equation (PWE) separable in Cartesian and circular cylindrical coordinates, respectively, while IG beams, proposed in 2004 [38], are the solutions of elliptical or hyperbolic coordinates, constituting the continuous transition modes between HG and LG beams. Soon later HIG modes were theoretically constructed exhibiting helical phase features as with LG beams [39] and then practically generated by using complex amplitude and phase masks encoded onto a liquid-crystal display (LCD) [49]. As a kind of multi-singularity beams, HIG beams were further successfully applied in optical trapping [50]. In 2004, vortex beams with fractional OAM were proposed [40,41], which has been a controversial topic. To physically demonstrate fractional OAM, topological charge is not comprehensive and various methods including OAM spectrum measurement [51,52], intrinsic and external OAM[53]. Similar to the famous mathematical paradox, the propagation of light through fractional vortex plates are descripted as fractional vortex Hilbert's Hotel[54].

However, G. Tkachenko et al. questioned the existence of perfect fractional vortex beams [55] and claimed that one cannot create perfect fractional vortex beams because of its phase and intensity disturbance introduced by fractional indexes which cannot be smoothed out. Anyhow, fractional OAM gave a peculiar family of multi-singularities vortex beams. As another special kind of multi-singularities vortex beams, SU(2) geometry modes are introduced by Y.F. Chen and attract much attention with its special features such as localized multi-path periodic ray trajectories, unusual power peaks, and as mentioned above, large fractional OAMs [43-45]. Recently, our group also exploited a new kind of multi-singularity beams: polygonal vortex beams [46,47], which is generated by a quasi-frequency-degenerate laser resonator with astigmatic transformation. These various kinds of multi-singularity beams represents the development of complex OAM distribution tuning technologies. For the polarization-tunable vortex beams devices,

the main tuning technologies focus on the control of polarization distribution.

The vortex beams can be classified into vector and scalar vortex beams [56,57]. The distribution of polarization is homogenous and inhomogeneous for a scalar vortex beams and a vector vortex beams, respectively. Vector vortex beams are paraxial solutions of the vector Helmholtz equation [58]. Special families of scalar vortex beams and vector vortex beams are illustrated by a point of high-order poincaré sphere [59]. In the past several years, Light beams with an inhomogeneous state of polarization have attracted much attention. Investigations and interest focused on the vector beams with radial and azimuthal polarizations. Such beams can be generated by an intracavity [60,61] or an external approach [62-67]. An example of intracavity method is a work of VG. Niziev's group [60]. They obtained the controlled vector vortex beams by using an intracavity Sagnac interferometer with a thin wire line across the center of the cavity was used to control the laser mode.

In the last decade, there are many ways to generate a vector vortex beam with more kinds of polarization structures outside the cavity. In 2016, D Naidoo et. al [68] designed a versatile method to generate arbitrary beams of high-order Poincaré sphere through intracavity q-plate controlling. For the external methods, vector vortex beams have been experimentally obtained by Q-plate or the combination of q-plate and spiral phase plate [62], radial/azimuth analyzer and radial/azimuth polarization [63,64], and the optically active plate [64]. However, these plates lack of tunable flexibility. With the development of programmable devices, spatial light modulator (SLM) is increasingly being utilized to generate vector vortex beams [65-67]. In 2017, a novel interferometric approach to generate arbitrary vector vortex beams on the high-order Poincaré sphere has been proposed by Shizhen Chen et al. [67]. In this year, more and more kinds of special structured polarized beams were successively reported with the control of the modulation of SLM [69-72].

To date, the vortex source devices with various tunable properties are successively reported, however, it is still a challenge to tailor a versatile method for all the wavelength-, OAM-, and polarization-tunable properties. Therefore, in the future, the appearance of novel tunable vortex source devices with more superior property and flexibility will have great potential to largely promote and develop more advanced biomedical technologies and applications.

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