

## Special Issue on Photonic Jet: Science and Application

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# Special Issue on Photonic Jet: Science and Application

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Photonic jets (PJs) are important mesoscale optical phenomena arising from electromagnetic waves interacting with dielectric particles with sizes around several to several tens wavelengths ( $\sim 2\text{--}40 \lambda$ ). It generates a narrow, high-intensity beam at the shadow-side of the 'particle lenses' made from microspheres, cylinders (fibers), cubes, disks and others, even including biological cells and spider silks. A PJ has the capability to focus light beyond the classical diffraction limit, thus permitting many possibilities and applications: for example, super-resolution imaging, nanosensing, detection, patterning, trapping, manipulation, waveguiding, signal amplification (e.g., Raman, photoluminescence and second-harmonic generation) and high-efficiency signal collection, among others.

The earliest studies on PJ effects were reported in 2000 by Luk'yanchuk and co-workers [1,2]. They theoretically analyzed optical resonance and near-field effects [1], and verified experimentally [2]. By using 500 nm silica particles and a 248 nm-wavelength laser source, they obtained 100 nm hillocks ( $\sim \lambda/2.5$ ) on a silicon surface [2]. Related works were carried by several groups between 2000 and 2004 [3,4]. Not knowing these works, Chen et al. reported in 2004 a theoretical subwavelength focusing effect by microcylinders and coined the terminology 'photonic nanojet' (PNJ) [5], which has since been widely used. A simplified term, 'photonic jet' (PJ), was also used by researchers in the field since 2005 [6,7]. In 2014, Minin et al. showed that a photonic jet can be formed from a three-dimensional particle of an arbitrary shape if the mesoscale condition is met [8,9]. In the past two decades, the field of PJ has undergone rapid growth and developments, driven by new innovations and discoveries. Among them, the most notable developments include the following: white-light microsphere nanoscope (2011) [10], spider silk superlens and metamaterial solid immersion lens (2016) [11,12], the discovery of photonic hooks (2016) [7,13], THz super-resolution imaging (2017) [14], single-cell biomagnifier (2019) [15], Plano-Convex-Microsphere (PCM) superlens (2020) [16,17], lipid droplets microlenses (2021) [18], PJ-mediated optogenetics (2022) [19] and others. More information on the past, present and future of PJ technology can be found in refs. [7,9,20–22].

This Special Issue focuses on the most recent advances and trends in PJ research. A total of 10 papers were selected and published, including a review of the field (one paper) [23], photonic hooks (three papers) [24–26], the modulation of PJ beam (three papers) [27–29], super-resolution imaging (three papers) [25,30,31], and scanning nanopatterning (one paper) [32]. Photonic hooks, field modulation and super-resolution imaging are the main topics in this Special Issue, which reflect the current research focus and trends. We highlight the key contribution and merit of the selected papers below according to the topics.

- Review on PJ-based trapping, sensing, and imaging

Li et al. reviewed the current types of microsphere lenses for PJ applications and their principles and applications in optical nano trapping, signal enhancement and super-resolution imaging, with particular emphasis on biological cells and tissues [23]. They



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envisage that in vivo nanomanipulation and biodetection will be the future trends. This review is an important addition to the existing literature on PJ technology, with refined focuses on trapping, sensing and imaging.

- Photonic hooks (PHs)

A PH is a new type of self-bending PJ beam, with a curvature that is less than the wavelength and differs from Airy-family beams [33]. Such structured beams were theoretically predicted in 2016 [7] and experimentally demonstrated in 2019 [34] based on dielectric Janus particles with broken symmetries in its geometry. Other methods for generating PH include asymmetric beam excitation and two material-composition particles, among others [22,33,35]. In the current issue, Tang et al. proposed a new method of using patchy microcylinders (i.e., partially metal-coated) for the generation of PHs [24] having in mind [35]. By rotating the patchy microcylinders, PHs with different curvatures were successfully demonstrated, and a bending angle of 28.4 degree and curved-line width of  $0.36 \lambda$  were reported. Based on this work, the authors extended their work to patchy microspheres and experimentally demonstrated, for the first time, the effect of PHs on super-resolution imaging [25]. They showed that PHs generated by patchy microspheres provide an effective oblique illumination of imaging objects, which leads to the considerable improvement of near-field imaging contrast, thus providing a new mean to optimize microsphere-based super-resolution techniques. On the other hand, Yue et al. demonstrated a new concept of using PHs for photonic switching [26,36]. When two-wavelengths beams, 1310 nm and 1550 nm, pass through a right-trapezoid dielectric Janus particle, they were separated and guided to different routes because of different bending strengths [26], thus permitting effective photonic switching on microscale through a simple dielectric particle. Potential applications in photonic integrated circuit are envisaged.

- Modulation of PJ beams

The ability to control and modulate PJ beams is essential for developing next-generation PJ devices and technologies. In principle, modulations can be achieved by various means, including tuning the particle's size, refractive index, surrounding medium, incident beam pupil and beam structure [37], the composition of particles (e.g., liquid crystals [38] and metamaterials [14,39]) and more. Here, Sergeeva et al. presented a new method for modulating PJs by using standing waves, which were achieved by positioning aluminum oxide hemispheres on top of a silicon substrate with a separation distance. The gap distance was chosen to match the phase conditions for constructive interference between incident and reflected beams [27] for effective modulation. The work offers a new pathway to design PJ-based integrated photonic devices. On the other hand, Lin et al. designed and manufactured a spider-silk-based metal-dielectric dome microlenses, which showed great performance in PJ modulations by using different metal casings [28]. When gold casing was used, the focusing intensity was maximized and increased by a factor of three due to the surface's plasmon resonance. This microlens could be used to scan a biological target for large-area imaging with a conventional microscope. In addition, Bouaziz et al. demonstrated another PJ modulation method based on fiber tip parameter tuning [29]. They showed that PJs were obtained when light is coupled in the guide's fundamental mode and when the base diameter of the microlens is close to the core's diameter and modulated by the sharpness of the tip. When the base diameter of the microlens is larger than the fiber core, the focus point tends to move away from the external surface of the fiber and has a larger width. The results of this study can be used as guidelines for the tailored fabrication of shaped optical-fiber tips according to the targeted application.

- Super-resolution imaging

Since the first demonstration of microsphere-assisted super-resolution imaging in 2011, the technology received wide attention and constant development by researchers across the world [21]. The field of development and roadmap has been systematically reviewed and summarized in refs. [20–22,40]. Note there are two types of particles super-

lenses used for super-resolution imaging in the literature: microsphere superlens [10] and metamaterial solid-immersion superlens [12], and both have different super-resolution imaging mechanisms. For microsphere superlens, the super-resolution mechanism is a combined contribution of several effects, including PJ focus, the excitation of super-resonance and whisper gallery modes, as well as substrate and partial and inclined illumination effects [21]. They lead to the conversion of high-frequency evanescent waves that contain near-field nanoscale information into propagating waves, which then reach the far-field and contribute to the formation of a magnified virtual image. Herein, by conducting rigorous electromagnetic simulations, Boudokha et al. provided new insight and evidence that microspheres are a natural collector and converter of evanescent waves to propagating waves using whisper gallery modes [30]. However, the evanescent-to-propagation-conversion (ETPC) efficiency can vary significantly ( $10^{-7}$  to  $10^{-1}$ ) depending on used microspheres. On the other hand, Dhama et al. designed and fabricated  $\text{TiO}_2$  metamaterial superlens in full-sphere shape for the first time and compared its imaging performance with commonly used  $\text{BaTiO}_3$  (BTG) microspheres under the same imaging settings [31]. Their results showed that the meta-superlens performs consistently better over the widely used BTG superlens in terms of imaging contrast, clarity, the field of view and resolution, which was further supported by theoretical simulation. In addition, as mentioned above, photonic hook (PH)-induced super contrast imaging was for the first time demonstrated by using a patchy microsphere [25] and asymmetric Janus particles [41]. These works will contribute to developments of more powerful, robust, and reliable super-resolution imaging systems, which have potential in revolutionizing the optical microscopy.

- Scanning nanopatterning

Alongside laser cleaning, surface nanopatterning are among the earliest applications of PJ effects. To fabricate arbitrary nanopatterns, various approaches such as angular beam scanning [42] and scanning Plano-convex-microsphere superlens [17] have been developed. Herein, Luo et. al. demonstrated a new laser-direct nanowriting system based on a combination of microsphere lens with an AFM cantilever and scanned over the sample's surface [31]. Using femtosecond laser sources, arbitrary silicon oxide nanopatterns with a feature size of 310 nm and height of 120 were directly fabricated in a single step. The proposed method shows the potential for the fabrication of multifunctional surfaces and silicon photonics and integrated chips.

We hope that this Special Issue will provide readers with a useful and timely update on the status and future trends of PJ research and mesotronics [7,20–22,33,43–47]. We thank all authors, reviewers and the *photonics* editorial team for their valuable contributions that brought this Special Issue to life.

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