Dielectric particle-based strategy to design a new self-bending subwavelength structured light beams

I V Minin and O V Minin

School of Nondestructive Testing, Tomsk Polytechnical University, Tomsk, Russia

E-mail: prof.minin@gmail.com

Abstract. During last 2 years it was shown that an electromagnetic field can be made to curve after propagation through a simple dielectric material of special shape, which adds a new-found degree of simplicity. This effect was termed 'photonic hooks' – it is an unique electromagnetic beam configuration behind a mesoscale dielectric particle with a broken symmetry and differ from Airy-family beams. PH features the radius of curvature, which is about 2 times smaller than the electromagnetic wavelength – this is the smallest curvature radius of electromagnetic waves ever reported. The nature of a photonic hook is in dispersion of the phase velocity of the waves inside of particle, resulting in interference. Here, we report a new dielectric particle-based strategy to design self-bending subwavelength structured light beams.

1. Introduction

The word "optics" is derived from the ancient Greek philosophers term meaning "appearance, look" and was based on the idea that light propagates along straight lines expanding as they travel. For example, Euclid wrote his "Optica" in about 300 BC [1] in which he postulated that light travelled in straight lines. The development of Maxwell's electrodynamics further reinforced these notions by ensuring the conservation of electromagnetic momentum. The possibility that a wave packet can freely accelerate even in the absence of an external force was first discussed four decades ago [2]. As indicated in [2], this is only possible as long as the quantum wave function follows an Airy-function profile. The most unusual aspect of Airy beams is that their paths seem to bend: whereas the axis of a Gaussian beam always follows a perfectly straight line (in homogeneous propagation medium).

Due to the center of such beams seems to follow a nonlinear path, accelerating perpendicular to the initial beam direction, despite the absence of external forces acting on the moving photons, such beams are referred to as self-accelerating. In 2007, this Airy self-acceleration process was suggested and experimentally observed for the first time in optics [3, 4]. It is important to note that for finite power Airy beams, while the local intensity features do self-bend in a self-similar fashion, the Ehrenfest theorem still holds thus preserving the balance of the transverse electromagnetic momentum. Ever since, this class of accelerating or self-bending beams has attracted considerable attention and found applications in many and diverse fields, especially in the paraxial domain. In the past few years, other types of Airy-like accelerating curved beams have been intensely explored; among them: "half Bessel" [5], Weber (travel along parabolic) and Mathieu (travel along elliptic curves) beams [6, 7]. These beams are by nature non-paraxial and hence can bend at larger angles. In all cases, these Airy-like wavefronts propagate on a curved trajectory over many Rayleigh lengths while defying diffraction effects. Until recently, they provided the only example of "curved light transport" in nature with curvature more than several wavelength.

2. Photonic nanojet

In 2004, Chen et al. coined a new term "photonic nanojet" (PJ) for the sub-wavelength-scale near-field focusing at the shadow side of a mesoscale (with dimensions of several units of wavelength) dielectric particle [8]. By increasing the dimensions of a spherical particle the electromagnetic field structure evolves and tends to be more localized and directed forward. Despite the beneficial performance of PJs in several applications, up to date, all photonic nanojet beams are fundamentally similar – single-colored and straight [9].

3. Photonic nanojet based airy-like beams

From the geometrical optics point of view the rays of light in an Airy beam cross each other, staying on one side of an enveloping curve. Each of the rays is briefly tangent to the envelope at some point. Such an envelope of a rays system is called caustics, which are common features in everyday life. In some papers, curvilinear caustics were studied in the diffraction of an off-axis limited size wave (the size of the beamwaist is less than the particle diameter) on a dielectric cylinder. However, no one argued that the caustic curve in this case is an Airy-like beam (Figure 1a) formed near the shadow surface of dielectric cylinder or hemicylinder (Figure 1b, Figure 2a). As Bernhard Baruch told in New York Post (24 June 1965): "Millions saw the apple fall but Newton was the one who asked why".

a)   b)
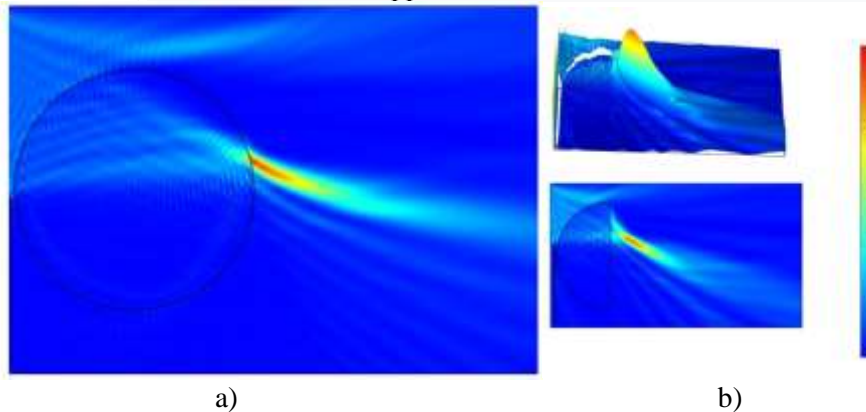
Figure 1. Formation of near field Airy-like beam by dielectric particles: cylinder (*a*, left) and by transversely oriented dielectric hemicylinder (*b*, right).


a)   b)
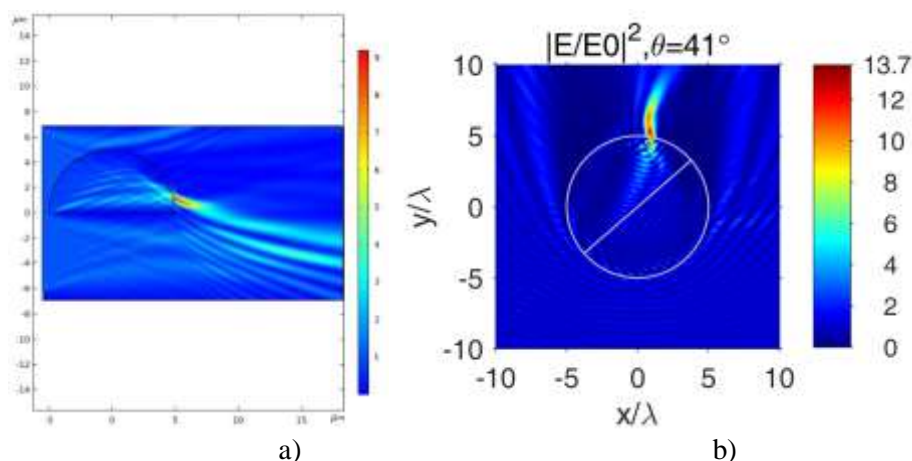
Figure 2. Formation of near field Airy-like beam by longitudinally oriented dielectric particles: hemicylinder (*a*, left) and photonic hook (see Paragraph 5 below) by two hemispherical particles with different refractive index (*b*, right).

Nevertheless, the acceleration of photonic jets on the basis of the approaches considered above is much less than on the basis of a cuboid with broken symmetry. Moreover, the subdiffraction value of the main beam lobe was not observed yet.

4. Double curved jet based on edge diffraction

It is well known that under diffraction on dielectric edge in the Fresnel approxiation the edge wave has the eikonal $S \sim Z+X^2/2Z$) [10] and a solution of the diffraction at the edge of the semi-infinite opaque screen [11] is a paraxial 2D light for which the argument of the complex amplitude function is depends on variables, like X^2/Z, where X is the transverse coordinate, and Z is the longitudinal coordinate.
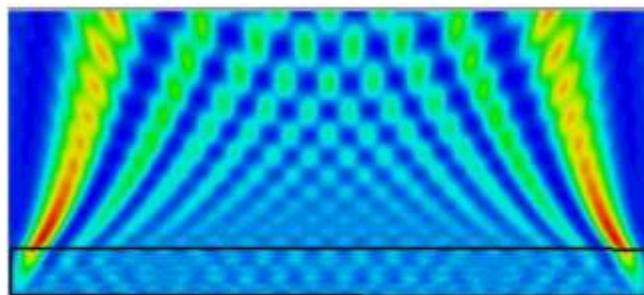
Figure 3. Double-edged curved light beams.

It means that instead of the Airy beams which have a parabolic ray path $y=x^2$, whereas the considered edge beams in question propagate along a root-parabolic path $y=sqrt(x)$ (Figure 3).

5. Photonic hook

Recently, a new family of near-field localized curved light beams, which differs from the family of Airy beams and is formed in the near-field zone: the so-called "photonic hook" (PH) has been discovered by I.V. Minin and O.V. Minin [9].

In a photonic hook, individual light waves propagate along a straight line, but their relative phases and amplitudes are chosen so that the maximum energy in space forms a constant curved shape in time. Since the electromagnetic waves themselves propagate along linear paths, the energy density in the curved beam decreases with distance from the source.

Our recent research shows [12] that it is possible to produce a localized optical beam whose intensity peaks move along curved trajectories in the near-field. Unlike ordinary optical localized beams (like PJ), the photonic hook self-bends (i.e., transversely accelerates) throughout propagation in the near-field. PHs appear even in free space and do not require any waveguiding structures or external potentials. They are unique in the sense that their radius of curvature is substantially smaller than the wavelength, meaning that such structured light beams have the maximum acceleration among the known curvilinear beams. The curvature of electromagnetic waves with such a small radius was described for the first time in [12].

The realization of such curved near-field beams is possible based on the interaction of a plane wave with a mesoscale dielectric particle with broken symmetry. In [9, 12] we theoretically studied a PJ formed behind the symmetric particle with an equal rib and discussed some examples of PHs behind the mesoscale particles with broken symmetry. It is important to note that such a particle may be considered as a Janus particle since a PH is formed only when the particle is irradiated in one direction (and not in the opposite) [9]. The curve of the brightest region results from a complex near-field interference pattern inside the particle as the phase velocity disperses. Because of this shape, the time of the full oscillation phase of an optical wave varies in the particle unevenly. As a result, a curved light beam is produced at the exit from the particle (near its shadow surface). Besides, the curvature of

the beam can be adjusted by changing the wavelength, polarization of the incident light, as well as the geometric parameters of the dielectric particle.

One of an idiom supported by people since ancient times is ''Seeing is believing''. So the experimental verification of this accelerating near-field beams would be an additional proof of the PH concept, which can be used to control light at the new level. Recently, the existence of Minins' PH phenomenon has been verified experimentally for the first time using continuous-wave scanning-probe microscopy, operating at 0.25 THz due to the scalability of Maxwell's equations [13].

In Figure 4, we show the results of experimental PH visualization [13]. It can be seen that curvature of PH is about $\alpha =148^0$, the length of PH is less than two wavelengths with inflection point position near $Z=1.2\lambda$ from the shadow surface of the particle. In contrast to traditional Airy beams (generated using a complicated optical element with cubic phase or with a spatial light modulator behind the focus of a spherical lens [4–6]), a PH can be created using a compact mesoscale dielectric particle-lens. Moreover, the Airy beam consists of the main lobe and a family of side beamlets whose intensity decay exponentially [4–6]. Interestingly, in the case of PH, only the main lobe has a curved shape, and the family of curved sidelobes is absent. It was also shown that PH phenomenon is observed on a scale much smaller than Airy beams. In addition, it was shown for the first time that when switching two orthogonal states of linear polarization of the incident radiation, the photonic hook changes the direction of its curvature to the opposite. Note that the mesoscale dimensions and simplicity of the PH concept open a way for the practical integration of PH elements into lab-on-a-chip platforms and indicating their large scale potential applications.
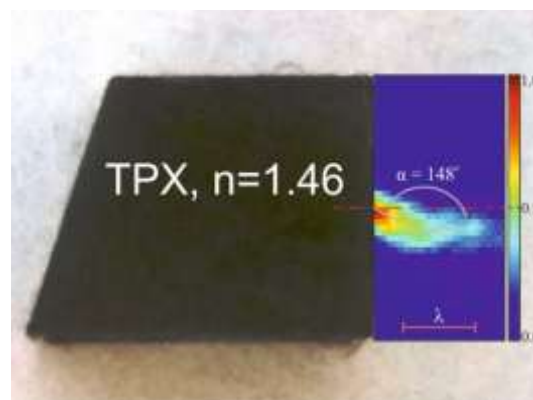
Figure 4. Experimental visualization of a photonic hook in terahertz

These particles are unique among micro objects because they provide asymmetry and can thus impart drastically different physical properties and directionality even with in a single particle. The broken symmetry offers efficient and distinctive means to realize the emergence of properties in unconceivable for homogeneous particles or symmetric particles. Moreover, since the formation of a photonic hook occurs on the basis of a particle with broken symmetry, such a particle may be considered as a Janus particle. The curved electromagnetic beam caustic is formed only when the asymmetric particle is irradiated in one direction - if the particle is pumped from the side of the prism (and not in the opposite) due to broken symmetry [9]. Also the shape of the dielectric particle considered above is not the only possible one.

At the same time, the asymmetry of particles can be not external, but internal (Figure 5).
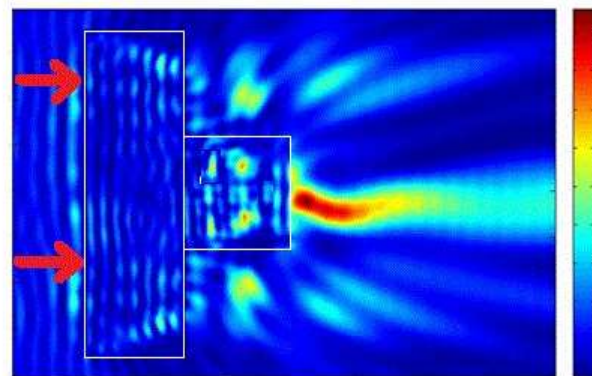
Figure 5. Formation of curved focusing beams by cubic particle with internal broken symmetry placed on dielectric substrate.

PH beam waist also has a cross-dimension smaller than the wavelength that makes high resolution possible. Thereby, the observed PH phenomenon can provide advantages over common photonic jets in imaging applications, similar to the beneficial character of the Airy beams over the Gaussian and Bessel beams reported in [14]. Moreover, it turned out that the photonic hook concept can be used to implement a manipulator to move particles along a curved path around transparent obstacles [15].

6. Photonic loop

Due to the phenomenon of focus bending is caused by the interference of waves inside the dielectric particleas the phase velocity disperses, the shape of the photon hook and the characteristics of curved near-field beams, depending on the specific application, can be quite exotic. For example, by choosing the shape of mesoscale particles we may control of phase delays across the wavefront and, thus, control a shape of localized near-field (Figure 6).
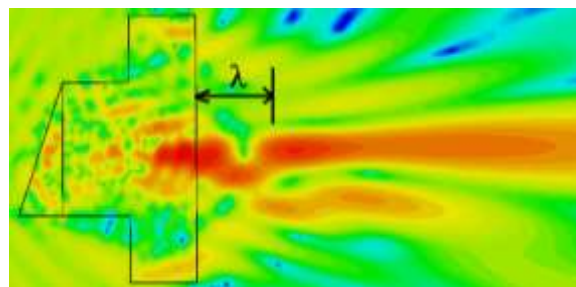
**Figure 6**. Example of a subwavelength photonic loop.

7. Plasmonic hook

The concept of photonic hook has gone beyond optics and penetrated other fields, including plasmonics. In 2010, the idea of Airy surface plasmon polaritons (SPPs) was introduced [16], and experimental observations soon followed [17]. However, in low-dimensional systems (in which at least in one of the three dimensions of the electronic state wave function is confined) until recently the families of Airy plasmon beams were the only beams that have a curved trajectory. But for Airy-type SPPs high beam acceleration is required to achieve significant curvature of the beam over the propagation length.

Our previous studies have shown that dielectric particle with broken symmetry can modulate the wave fronts of plane wave at will, achieving interesting physical effects such as photonic hook formation. The basic idea is to use a carefully designed particle to locally control the phases of the

impinging waves, thus, reshaping the wave fronts of refracted beams based on interferences. Inspired by this observation, we have propose to extend the idea of the dielectric particle with broken symmetry to control the wave fronts of surface wave. We can put a carefully designed particle on a plasmonic surface, which can also locally control the phase of an impinging surface wave. When a surface beam is launched on the plasmonic surface and strikes the particle, the incident surface wave gain different local phases from the refractions in the particle, thus, generating a refracted surface wave beam with the desired wave front.

Recently, the phenomenon of the photonic hook plasmon (PHP) was also introduced for SPPs propagating along metal-dielectric interfaces [18]. This concept is fundamentally simpler than the generation of the SPP Airy-family beams. It also demonstrated for the first time a simple and reliable real-time technique to dynamically control the curved trajectories of light beams over metallic surfaces by simply changing the illumination wavelength (without the need of any permanent guiding structures). The PHP propagates along wavelength scaled curved trajectory with a radius less than the SPP wavelength, which represents the smallest radius of curvature ever recorded for SPP beams, and can exist despite the strong energy dissipation at the metal surface (Figure 7). It is worth to note that the plasmonic PH is formed in the spatial region where the effects of evanescent fields play a significant role. The use of overlapping evanescent fields from several active radiators causes the specific interference interaction between the radiators which allow breaking the fundamental Rayleigh criterion.
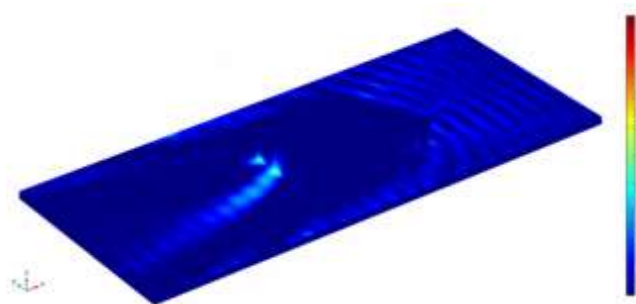
**Figure 7**. Example of plasmonic photonic hook.

From an applications perspective, photonic hook plasmons are important for the following main reasons. First, it demonstrates that the Airy plasmons now are not the only self-bending beams in two dimensions. Second, the photonic hook plasmons are self-bending localized field, giving us the means to control the flow of light on the surface in the near-field. Moreover, electromagnetic waves at the surface of a metal can be channeled into circuit components smaller than the diffraction limit. Importantly, these new possibilities prove that the concept of wave acceleration appears in general electromagnetism and can be observed in non-paraxial approximation in the near-field. Another important outcome is that the localized near-field beams no longer have to propagate only in a straight line - they can be self-bending.

8. Acoustical hook
The observation of a new type of near-field curved acoustic beam (acoustic hook) different from the Airy-family beams both through simulations and experiment recently was reported [19]. This new self-bending acoustical beam also was formed from a rectangular trapezoid of a dielectric material immersed in water. The origin of this curved beam is in the vortices of intensity flow that appear inside the solid due to the conversion of the incident longitudinal wave mode to a shear wave in a solid. These vortices redirect the intensity flow resulting in a bending of the beam.

9. Passive amplifier of airy beams

Detailed studies of the localization of the electromagnetic field by dielectric particles of arbitrary shape [9], and in particular, by cuboids, allow us to propose a method of amplifying of Airy-family beams. In fact, such dielectric structures play the role of a passive repeater (Figure 8).
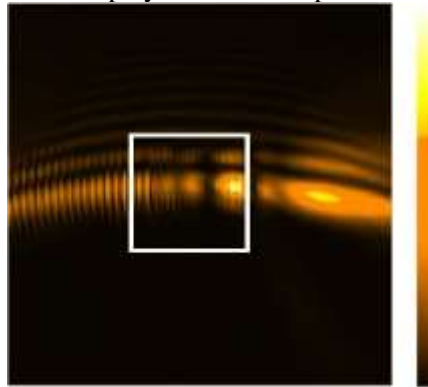
Figure 8. Example of Airy beam passing through dielectric cube.

10. Dynamic formation of Janus particles

The dynamic formation of Janus particles allows both control of the shape of the radiation localization region and opens the new way for obtaining new functional properties of structured fields. This same property can be used for optical switches, commutators, and various sensors. Similar effects can be observed in atmospheric physics, dew in nature, etc. For example, when a water drop freezes, its phase state changes from liquid to solid (ice). These materials have different properties and, in particular, different refractive index. As an example, Figure 9 shows the formation of a structured field behind a drop, consisting of water and ice. Similar effects can be observed upon evaporation of liquid droplets.
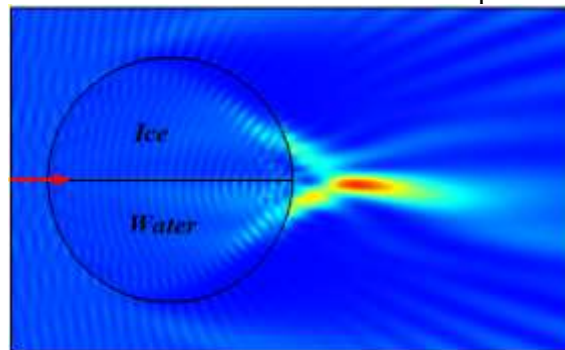
Figure 9. Structured light formation by water-ice droplet.

11. Conclusions

Finally, there are a few reasons that the concept of photonic hook [9,13,21,22] has penetrate other fields of modern physics (i.g., acoustics, plasmonics and THz) both in CW and pulsed [23] radiation as in transmitted as in reflection modes and has gone above and beyond optics. First, the PH phenomenon occurs under non-paraxial conditions and so the concept is common, thus opening interesting opportunities in other physical systems, i.g., acoustics, and ultrasonics. Second, the early experiments have revealed that PH beams are exceptionally easy to realize and manipulate.

We believe that the curved trajectory of PH is beneficial to photonics and the related disciplines. It could be used for advanced manipulation of nanoparticles, biological systems, material processing, and surgical systems, where curved sub-wavelength-scale optical beams are of great interest. The method could accommodate other applications, including particle acceleration and separation, short-

range micromanipulation, terahertz generation, near-field spectroscopy, laser machining of various guiding structures to include wavelength scaled division multiplexers, and interferometer beam-splitting and beam-coupling, to redirect an optical signal in meso- and nano-scale or even as a scalpel tips for potential use in ultraprecise laser surgery.

On a more fundamental level, the introduction of the photonic hook concept into the field of optics will help the scientific community to better understand the physical phenomena of accelerating near-field waves and to manipulate light in unusual ways. As it was mentioned in [22] "such elegant examples of structured light beams deepen our understanding of light propagation, and will fuel anticipation and excitement for the next generation of imaging and manipulation". Moreover, it has opened up new paths for new applications.

References
[1]   Burton H E 1945 *Journal of the OSA* **35**(5) 357
[2]   Berry M and Balázs N 1979 *American Journal of Physics* **47** 264
[3]   Siviloglou G, Broky J, Dogariu A and Christodoulides D 2007 *Physical Review Letters* **99** 213901
[4]   Siviloglou G and Christodoulides D 2007 *Optics Letters* **32** 979
[5]   Kaminer I, Bekenstein R, Nemirovsky J and Segev M 2012 *Physical Review Letters* **108** 163901
[6]   Aleahmad P, Miri M, Mills M, Kaminer I, Segev M and Christodoulides D 2012 *Physical Review Letters* **109** 203902
[7]   Zhang P, Hu Y, Li T, Cannan D, Yin X, Morandotti R, Chen Z and Zhang X 2012 *Physical Review Letters* **109** 193901
[8]   Chen Z, Taflove A and Backman V 2004 *Optics Express* **12** 1214
[9]   Minin I V and Minin O V 2016 *Diffractive Optics and Nanophotonics: Resolution below the Diffraction Limit* (Cham: Springer)
[10]   Kopylov Y and Popov A 1996 *Radio Science* **31** 1815
[11]   Born M and Wolf E 1986 *Principles of Optics* (Pergamon Press Ltd.: Maxwell House, N.Y.)
[12]   Yue L, Minin O V, Wang Z, Monks J, Snalin A and Minin I V 2018 *Optics Letters* **43** 771
[13]   Minin I V, Minin O V, Katyba G, Chernomyrdin N, Kurlov V, Zaytsev K, Yue L, Wang Z and N. Christodoulides D 2019 *Appl. Phys. Lett*. **114** 031105
[14]   Vettenburg T, Dalgarno H, Nylk J, Coll-Llado L, Ferrier D, Cizmar T, Gunn-Moore F and Dholakia K 2014 *Nature Methods* **11** 541
[15]   Ang A, Karabchevsky A, Minin I V, Minin O V, Sukhov S and Shalin S 2018 *Sci. Rep.* **8** 2029
[16]   Salandrino A and Christodoulides D 2010 *Opt. Letters* **35** 2082
[17]   Li L, Li T, Wang S, Zhang C and Zhu S 2011 *Phys. Rev. Lett*. **107** 126804
[18]   Minin I V, Minin O V, Ponomarev D and Glinskiy I 2018 *Ann. Phys*. **530** 1800359
[19]   Rubio C, Tarrazó-Serrano D, Minin O V, Uris A and Minin I V 2020 *Results in Physics* **16** 102921
[20]   Minin I V, Minin O V, Yue L, Wang Z, Volcov V and Christodoulides D 2019 *ArXiv:* 1910.09543
[21]   Minin I V and Minin O V 2019 *Proceeding of Fourth Russian-Belarusian Workshop "Carbon nanostructures and their electromagnetic properties"* 52–57
[22]   Dholakia K and Bruce G 2019 *Nature Photonics* **13** 229
[23]   Spector M, Ang S, Minin O V, Minin I V and Karabchevsky A. 2020 *Nanoscale Advances* **2(6)** 2595