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A photonic hook based on deliberately breaking the spatial symmetries of a particle or irradiating radiation

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It has been shown that a photonic hook can be created in a relatively simple and cost-effective manner using patchy mesoscale particles with deliberately broken spatial symmetries or irradiating radiation. The equivalence of various photonic hook generation schemes has been demonstrated.

Keywords: photonic hook, field localization, particles with broken symmetry.

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Microscopy based on mesoscale particles has proven itself as a promising tool to overcome the fundamental diffraction limit. At the same time low image contrast in this case may be overcome, for example, with the help of a so called photonic hook (PH) discovered in 2015 [1,2]. A PH being a variety of a photonic jet [3], is a new type of an artificially created curved localized beam of the short-range field with the curvature radius usually smaller than the wavelength. The principle of action is based on the combination of effects of wave interference and phase speeds [4]. The PH is generated, when light passes through the mesoscale dielectric particle with the specifically disturbed geometry (Janus-particle [5]) in its shape or structure of the material [4]. The simplest version of the PH was implemented on the basis of a combination of a wedge-shaped prism and a cuboid [1,2,4]. In general the formation of the photonic hook with the particles having different nature of asymmetry (shape, refractive index and structured radiation) was studied quite in detail and was summarized in [4]. The PH phenomenon was experimentally confirmed in the terahertz and optical ranges, acoustics, and also in the case of focusing of surface plasmon waves [4].

At the same time it should be noted that the potential capabilities of Janus-particles based on a combination of a wedge-shaped prism and a cuboid are rather broad, but are not yet well-presented in the literature. Thus, the above papers used a particle upon incidence of a plane wave front from the side of its wedge-shaped part. And the PH was formed in the shadow part of the particle along the direction of radiation incidence [1,2,4], i.e. the phase modulation of the illuminating wave was carried out along the direction of the radiation spread. However, as the additional studies have shown, the PH is also formed upon incidence of radiation perpendicularly to the base of the limited symmetrical Janus-particle. But the review of this case is beyond the scope of this paper.

Structured radiation by partial blocking of incident radiation of the symmetrical particle that forms the PH was proposed in [6,7]. Later (in 2022) it was demonstrated [8] that the localized field in the form of a photonic hook may be obtained by partial application of a metal aluminum film [9,10] onto mesoscale dielectric sphere or cylinder. Such mesoscale dielectric particle is a type of patchy particles, which are particles with a surface anisotropic pattern (patches [10]) or limited symmetrical external shape [11–13]. The composite patch particles with heterogeneous structure may provide for additional degrees of control over the electromagnetic field localization. In such mesoscale particles the film applied into the surface of the particle or located near the illuminated surface of the particle [7] acts as the aperture diaphragm blocking a part of the incident beam to form the PH. However, the comparative analysis of the above configurations that lead to a similar result has not yet been conducted.

Further we will show that in our opinion the partial blocking of radiation using a screen located near the illuminated surface of the particle and microparticles with the patches are in fact the equivalent solutions, since the particle „is not aware of“ the nature of the incident structured radiation. From this position the particle with the external screen for PH formation may be treated as a patch particle. We will show that PHs with similar characteristics may be obtained using dielectric patch particles that partially block the incident wave front or are partially coated with metal/dielectric films or by means of intentional strain of the surface. With account of the limitations of the publication volume, we further focused mainly on the curvature of the photonic hook as its key parameter [2,4].

We consider a 2D model of the particle (microcylinder). Fig. 1 presents the schematic images of the 2D cross section of the studied models. The thickness of the plane aluminum screen (Fig. 1, a) was 200 nm ($\sim 0.5\lambda$), as well as the thickness of coating of the upper surface of the cylinder with Al or Si films (Fig. 1, b). To calculate the 2D-models shown in Fig. 1, we use the finite element method implemented in the known COMSOL suite. All the

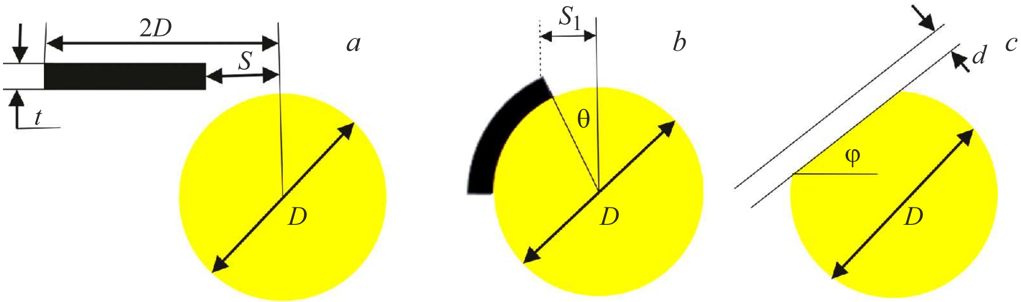

Figure 1. 2D cross section of the studied limited symmetrical mesoscale dielectric cylinders: partial blocking of incident plane wave front (*a*), partial coating with thin metal/dielectric films (*b*) and surface strain (*c*). The figures are not to scale. The particle is illuminated from top to bottom.

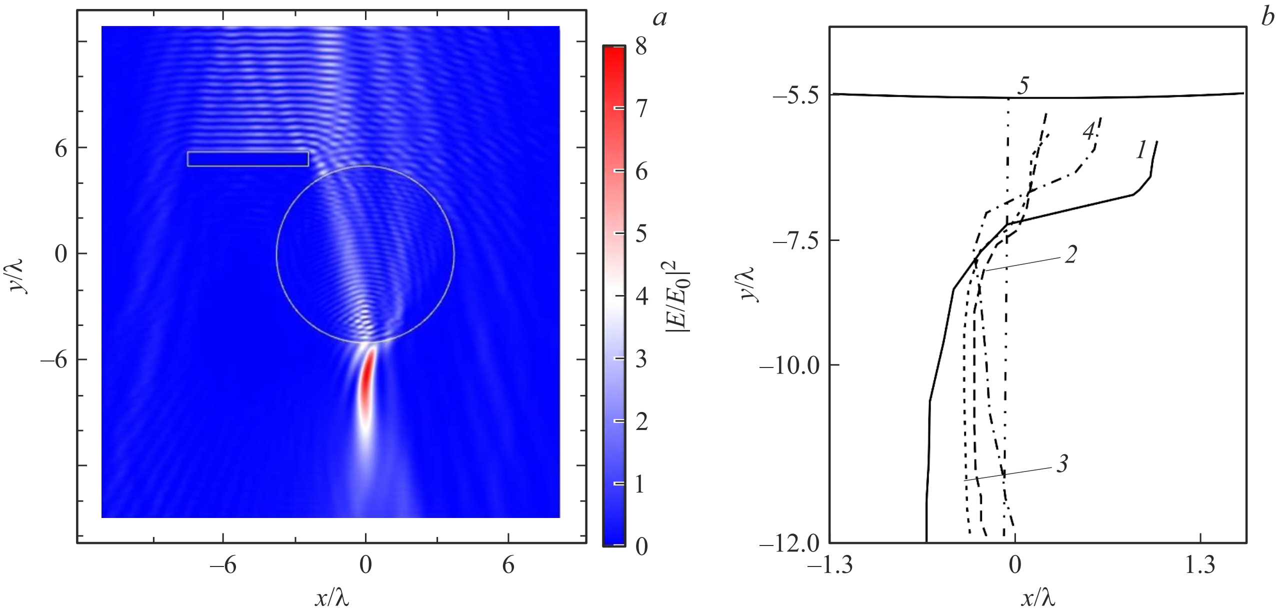

Figure 2. Formation of a photonic hook on the basis of the intentionally disturbed spatial symmetries of the particle. *a* — distribution of the field for the configuration given in Fig. 1,*a*; *b* — distribution of the field intensity maximum along FH: *1* — $S = 2700\lambda$ (Fig. 1,*a*), *2* — $\theta = 30^\circ$ (Al, Fig. 1,*b*), *3* — $\theta = 30^\circ$ (Si, Fig. 1,*b*), *4* — $S = 3500\lambda$ (Fig. 1,*a*), *5* — shadow boundary of the cylindrical particle.

countable space was limited to a system of layers ideally matched by absorption. The example chosen was a cylinder with a diameter of $D = 5\,\mu$m (or $\sim 12\lambda$, parameter of Mie size $q \sim 40$) made of PDMS (polydimethylsiloxane) with the refractive index of $n = 1.41$. Environment — air. The films we used were Al ($n = 0.50047 + 4.89788i$) or Si ($n = 5.4376 + 0.34209i$) [14] (Fig. 1,*b*) at wavelength $\lambda = 405$ nm. Origin — in the center of the cylinder.

Modeling of the impact of partial screening of incident radiation (Fig. 1,*a*) demonstrated that it is possible to control the curvature of the localized field, adjusting the relative position and dimensions of the off-axis illuminating beam and the dielectric particle. Increase in the value of parameter S (distance along the axis of symmetry of the particle to the edge of the screen) causes increase in the photon PH curvature. However, it is associated with the decrease in its length [4,7].

A similar trend is observed for the particle, the upper surface of which is coated with Al or Si film (Fig. 1,*b*). In general the partial coating of the cylinder with dielectric having high refractive index is similar to metal coating. The effect of the parameter S_1 (distance from the axis of symmetry of the particle to the edge of the screen along the external surface of the particle) at PH is similar to the effect of the flat screen with the parameter S (Fig. 1,*a*). However, there are still minor differences observed (see Fig. 2,*b*, where the PH profile is shown along the radiation incidence direction). Fig. 2 clearly shows the point of the localized beam bending specific for the PH and not observed, for example, in the beans of the Airy family [4], and the subwavelength curvature of the localized field being one of the key distinctive features of PH [2,4].

Table 1 presents the main comparative characteristics of the generated PHs. The geometrical parameter that charac-

Table 1. Main parameters of PH

Parameter	Screen (Fig. 1, *a*)	Al-layer (Fig. 1, *b*)	Si-layer (Fig. 1, *b*)	Taper 1 (Fig. 1, *c*)	Taper 2 (Fig. 1, *c*)
PH length, λ [7]	6.4	6.34	6.42	6.59	5.38
Angle of deviation, deg [7]	9.8	6.6	5.6	13.5	12.5
Full width at half maximum, λ	0.8	0.72	0.71	0.63	0.63
$I_{\max}$	5.6	4.6	4.0	6.0	5.8

Note. Full width at half maximum was determined in the point of the maximum intensity of the field along the PH, $I_{\max}$ — value of maximum intensity of the field along the PH, normalized by the intensity of the field incident upon the particle, taper 1 — $d = 0.25\lambda$, $\varphi = 10^\circ$, taper 2 — $d = 0.25\lambda$, $\varphi = 20^\circ$.

terizes the screening of the radiation illuminating the particle surface (Fig. 1) is shown in Table 2. Based on the data of Fig. 2 and the results of modeling, the following conclusion may be made. The PH parameters for the flat external screen (Fig. 1, *a*) and the metal film partially applied on the cylinder (Fig. 1, *b*) are fully identical at the same value of incident radiation screening. For the silicon coating, the angle of particle coverage must be slightly larger than $\theta = 50^\circ$ due to the differences in the refractive indices of metal and silicon. In the last case the extent of apodization of the illuminating beam increases slightly, which, however, slightly decreases the energy efficiency of PH generation. On the other hand, the integral characteristics of PH may be identical for different types of screens located in front of the particle or applied on its surface.

Finally, let us briefly consider a homogeneous particle with a single-sided cut (Fig. 1, *c*), i. e. the cylinder with the cut part of the illuminated surface. In our simulations we varied both the thickness of the cut part of the particle d and the inclination angle of the cut φ.

According to the modeling results, shallow cuts (for example, $d \sim 0.25\lambda$) demonstrate the values of beam curvature being closer to the values for the PH based on a particle with an external screen (Table 1, Fig. 1, *a*). The hook curvature usually is maintained at smaller angles, whereas deeper cuts usually displace the PH (Fig. 2). The FH curvature increases as the particle asymmetry increases. The increase in the depth of the cut causes deviations in the values of the hook curvature with the case of the „reference“ version of the particle with the external screen (Fig. 1).

It is obvious that the achievement of the complete identity in the characteristics of the photonic hook formed by a particle with a screen and a particle with a removed segment is a complicated task. However, a comprehensive approach may solve this problem. For example, Fig. 3 shows the characteristics of the photonic hook for a particle with a removed segment and refractive index of the material reduced down to $n = 1.3$, which demonstrates this trend. Note that the above comparative characteristics of FH are the result of the prior optimization of each configuration providing for the best match with the „reference“ variant (Fig. 1, *a*).

Table 2. Geometric screening of incident radiation

Parameter	Value $2S/D$ (Fig. 1, *a*) or $2S_1/D$ (Fig. 1, *b*)	Figure number
$S = 2700\lambda$	0.48	1, *a*
$S = 3500\lambda$	0.64	1, *a*
$S = 5000\lambda$	0.8	1, *a*
$\theta = 30^\circ$	0.5	1, *b*
$\theta = 40^\circ$	0.64	1, *b*
$\theta = 50^\circ$	0.77	1, *b*

Achievements in mesotronics open new prospects in the implementation of FHs based on heterogeneous particles. You may note that the PH concept has already found successful experimental confirmation and application for optical trapping and selective manipulation of biological objects [4], and in nano- and microstructuring of surfaces by development of curved craters. Note that the experimental confirmation of the mechanism of PH formation on the basis of a particle with an external screen (Fig. 1, *a*) is described in detail in [4,7], a particle with a metal film applied on its surface (Fig. 1, *b*) — in [8]. PH formation on the basis of a microcylinder with a removed segment (Fig. 1, *c*), as far as we know, has been considered for the first time, and such particle may be implemented practically by one of the available methods (for example, [15]).

In this paper it was shown that the different types of limited symmetrical Janus-particles, including the particles with the screen located in front or on their surface, act as a diaphragm blocking a part of the incident beam. The particles with the removed segments on the illuminated surface may generate PH due to their structural asymmetry. Particles coated partially with the material having low refractive index and high absorption (Al) or the material with high refractive index and low absorption (Si), demonstrate approximately the same PH parameters. The main characteristics of the PH, such as the bending angle and the length, may be modulated with the change in the illumination or parameters of the generating structure.

At the same time only the scheme of FH generation on the basis of the particle and the screen located near its illuminated side does not require modification of the particle itself, for example, application of an area coated with a metal or a dielectric film or cutting a part of the particle surface. In our opinion, this is a clear practical advantage of such PH generation scheme.

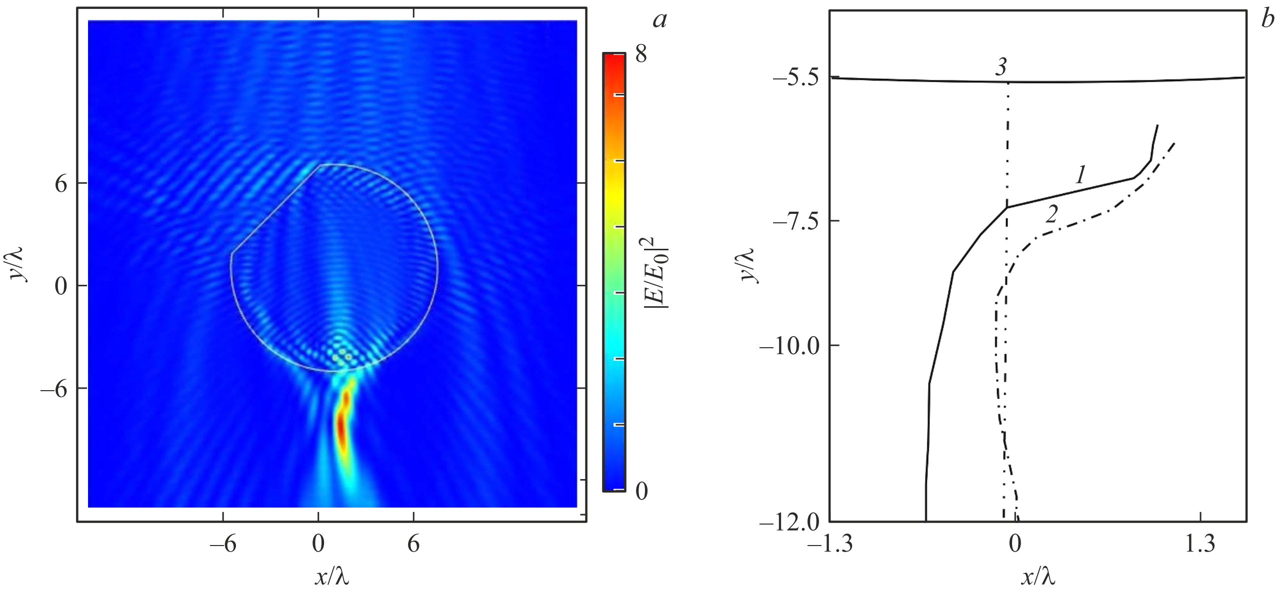

Figure 3. Formation of a photonic hook with a cylinder with the purposefully disturbed symmetry. *a* — distribution of the field intensity for the particle of configuration presented in Fig. 1, *c*, $n = 1.3$, $d \sim 1.2\lambda$; *b* — distribution of the field intensity maximum along the PH: *1* — $S = 3500\lambda$, $n = 1.41$ (Fig. 1, *a*), *2* — $n = 1.3$, $d \sim 1.2\lambda$ (Fig. 1, *c*), *3* — shadow boundary of the particle.

The energy advantage of the particle with the removed part of the illuminated surface consists in the absence of incident radiation screening. We believe that the PH generation mechanism may play a key role in the design of more improved and reliable systems of super-resolution visualization with higher contrast [16] on the basis of mesoscale particles. In general the results will help further development of the microscopy methods on the basis of mesoscale particles and will facilitate their use in mesotronics, biological sciences, nanotechnology etc.

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Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] I.V. Minin, O.V. Minin, *Ustroystvo dlya formirovaniya opticheskoy lovushki v forme fotonnogo kryuka*, patent RF 161207 (zayavl. 27.10.2015, opubl. 10.04.2016), byul. No 10 (in Russian). https://rusneb.ru/catalog/000224_000128_0000161207_20160410_U1_RU/?ysclid=mjmbtuv7vq891616389
[2] K. Dholakis, G.D. Bruce, Nat. Photon., **13**, 229 (2019). DOI: 10.1038/s41566-019-0403-9
[3] B. Luk'yanchuk, R. Paniagua-Domínguez, I.V. Minin, O.V. Minin, Z. Wang, Opt. Mater. Express, **7**, 1820 (2017). DOI: 10.1364/OME.7.001820
[4] I.V. Minin, O.V. Minin, *Photonic hook: from optics to acoustics and plasmonics* (Springer, Berlin, 2021).
[5] M. Lattuada, T.A. Hatton, Nano Today, **6** (3), 286 (2011). DOI: 10.1016/j.nantod.2011.04.008
[6] I.V. Minin, O.V. Minin, *Ustroystvo formirovaniya puchka Eyri v teragertsovom diapazone dlin voln*, patent RF 196430 (zayavl. 29.11.2019, opubl. 28.02.2020), byul. No 7 (in Russian). https://patentimages.storage.googleapis.com/9e/29/16/3a2868e27ee381/RU196430U1.pdf
[7] I.V. Minin, O.V. Minin, C.Y. Liu, H.D. Wei, Y. Geints, A. Korachesky, Opt. Lett., **45**, 4899 (2020). DOI: 10.1364/OL.402248
[8] C. Xu, T. Yang, P. Zou, R. Ye, Proc. SPIE, **12316**, 1231602 (2022). DOI: 10.1117/12.2642931
[9] A.B. Pawar, I. Kretzschmar, Langmuir, **25**, 9057 (2009). DOI: 10.1021/la900809b
[10] Z. Rozynek, A. Mikkelsen, P. Dommersnes, J.O. Fossum, Nat. Commun., **5**, 3945 (2014). DOI: 10.1038/ncomms4945
[11] G. van Anders, N.K. Ahmed, R. Smith, M. Engel, S. Glotzer, ACS Nano, **8** (1), 931 (2014). DOI: 10.1021/nn4057353
[12] L. Rovigatti, J. Russo, F. Romano, Eur. Phys. J. E, **41**, 59 (2018). DOI: 10.1140/epje/i2018-11667-x
[13] J.L. Lawson, N.J. Jenness, R.L. Clark, Opt. Express, **23**, 33956 (2015). DOI: 10.1364/OE.23.033956
[14] Refractive index Info. https://refractiveindex.info /?shelf =main&book=Al&page=Rakic
[15] N. Janoszka, S. Azhdari, C. Hils, D. Coban, H. Schmalz, A. Gröschel, Polymers, **13**, 4358 (2021). DOI: 10.3390/polym13244358
[16] B. Kachar, Science, **227**, 766 (1985). DOI: 10.1126/science.3969565

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