Applied Physics A (2022) 128:598
https://doi.org/10.1007/s00339-022-05744-1

Applied Physics A
Materials Science & Processing

A micro-iridescent focus generated from a microsphere on a reflective nanograting

Song Zhou[1] · Youzhou Shi[2,3] · Kaiwei Li[4] · Wenchao Zhou[3]

Received: 27 December 2021 / Accepted: 31 May 2022 / Published online: 21 June 2022

Abstract

Nanoscale high-intensity illuminations can be produced by dielectric microspheres, which are used for super-resolution imaging and optical nonlinear enhancement. Herein, a microscale chromatic dispersion assisted of a microsphere is experimentally presented. We find that a micro-iridescent focus can be generated from a microsphere put on a reflective nanograting under an oblique white-light illumination. The size of the micro-iridescent focus is smaller than the diameter of the microsphere, and the long wavelengths of light contributing to the micro-iridescent focus are distributed farther away from the microsphere. Furthermore, a curved-iridescent focus can also be obtained. Finally, it shows that the direction of the micro-iridescent focus is perpendicular to that of the reflective nanograting and the role of oblique illumination in experiments is discussed numerically. Our works present that a microsphere on a reflective nanograting can produce a microscale chromatic dispersion. This novel structure may have potential applications in the miniaturization of optical spectrometers.

Keywords Chromatic dispersion · Microsphere · Photonic jet

1 Introduction

The photonic nanojet (PNJ) is a new type of illuminating technique produced by a dielectric microsphere under a far-filed optical illumination. Later studies indicated that the PNJ generated from a microsphere was a nanoscale high-intensity focus [1–4]. Due to their ability to manipulate the light in a subwavelength high-intensity focus, dielectric microspheres have been successfully used in super-resolution imaging [5–8] and optical nonlinear enhancement [9–11].

The complex structure composed of a microsphere and the observed object may cause a slight chromatic dispersion of white light. In [12], a slight chromatic dispersion could be observed in an optical microscope image of a 100 µm $BaTiO_3$ microsphere aligned on top of adenovirus clusters. The slight chromatic dispersion could also be seen in optical images of the grating under the microsphere, respectively, taken at a slant angle of 20 and 40 degrees in [13]. On the other side, we presented an optical switch for light-route selection depending on the incident light wavelength using a micro-cylinder under an asymmetric illumination in [14]. These results indicate that dielectric microspheres placed at the appropriate background can produce a microscale chromatic dispersion of white light. The microscale chromatic dispersion can provide potentials for miniaturizing dispersive optics.

In this work, a microscale chromatic dispersion assisted of a microsphere is experimentally investigated. Considering that the gratings are usually adopted for dispersive optics, a microsphere is put on DVD stripes and they are illuminated under an oblique white-light illumination. Two kinds of microscopes are used to observe the chromatic

---

✉ Song Zhou
zs41080218@126.com

✉ Wenchao Zhou
zhouvc@ciomp.ac.cn

[1] Jiangsu Key Laboratory of Advanced Manufacturing Technology, Faculty of Mechanical and Material Engineering, Huaiyin Institute of Technology, Huai'an 223003, China

[2] University of Chinese Academy of Sciences, Beijing 100039, China

[3] State Key Laboratory of Applied Optics, Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, Changchun 130033, China

[4] Institute of Photonics Technology, Jinan University, Guangzhou 510632, China

dispersion. And the properties of the micro-iridescent focus are discussed. Finally, the relation between the direction of the micro-iridescent focus and the direction of DVD stripes is investigated, and the role of oblique illumination is discussed numerically.

2 Materials and methods

The method to obtain the microscale chromatic dispersion in this work can be briefly described as follows. Materials for the microscale chromatic dispersion are shown in Fig. 1. A Keyence VHX-1000 microscope is chosen as one kind of microscope to provide a white-light illumination and obtain the images of the chromatic dispersion. The Keyence VHX-1000 microscope has two arms, one for DVD strips and microspheres detections and the other for observing the chromatic dispersion. The image of the DVD stripes is given in Fig. 1a. Two kinds of sizes of $BaTiO_3$ microspheres with 180 ~ 212 µm and 45 ~ 53 µm are adopted in our experiments. The observed images taken by the Keyence VHX-1000 microscope are shown in Fig. 1b for a $BaTiO_3$ microsphere with a diameter ~ 210 µm and Fig. 1c for a $BaTiO_3$ microsphere with a diameter ~ 52 µm, respectively. The chromatic dispersion can be easily observed near a microsphere using the microscope. The other microscope consists of a 100X magnifier and a cellphone used to observe the micro-iridescent focus. The microscope with a 100X magnifier and a cellphone is also utilized to investigate the relation between the direction of the micro-iridescent focus and the direction of DVD stripes.

3 Results and discussion

The images of microspheres on three kinds of substrates taken by the Keyence VHX-1000 microscope are shown in Fig. 2. The structures are illuminated under the arm with a ring of white LED lighting. The images of the bigger size (180 ~ 212 µm) of $BaTiO_3$ microspheres on a silicon wafer and a Blu-ray disk [12] are shown in Fig. 2a and Fig. 2b, respectively. The image of both two kinds of sizes of $BaTiO_3$ microspheres put on DVD stripes in Fig. 1a is given in Fig. 2c. It shows that a pair of iridescent wings are symmetrically distributed around a microsphere. And the long wavelengths of light contributing to the iridescent wings are distributed farther away from the microsphere. The results shown in Fig. 2c indicate that the direction of the

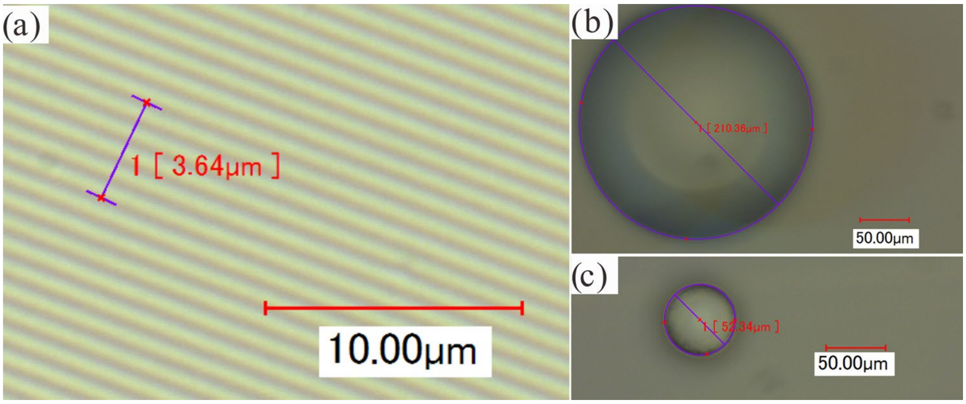

Fig. 1 Materials for the microscale chromatic dispersion. **a** DVD stripes observed using the Keyence VHX-1000 microscope, **b** a ~ 210 µm $BaTiO_3$ microsphere seen using the Keyence VHX-1000 microscope, and **c** a ~ 52 µm $BaTiO_3$ microsphere seen using the Keyence VHX-1000 microscope

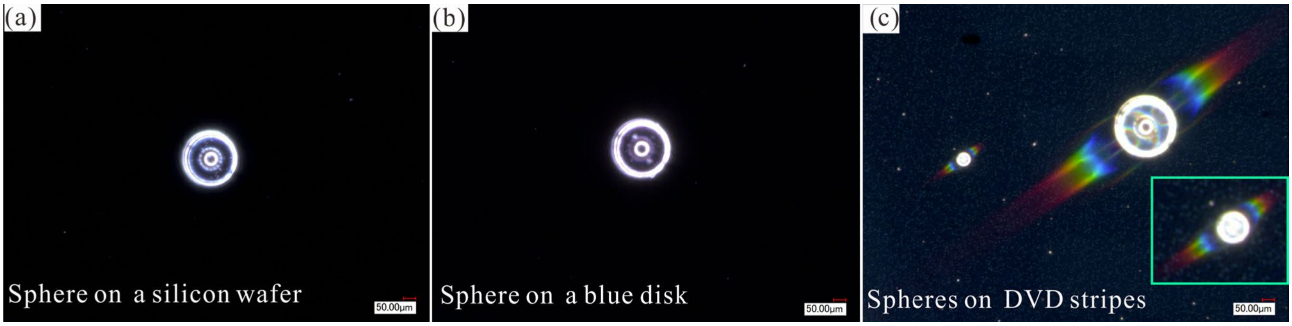

Fig. 2 The images of microspheres on three kinds of substrates. **a** A bigger size (180 ~ 212 µm) of $BaTiO_3$ microsphere on a silicon wafer, **b** the bigger size of $BaTiO_3$ microsphere on a Blu-ray disk, and **c** both two kinds of sizes of $BaTiO_3$ microspheres on DVD stripes. The enlarged image of the smaller size of $BaTiO_3$ microsphere on DVD stripes is shown in the inset (**c**)

iridescent wings is independent of the diameters of microspheres. However, there are no chromatic dispersions when the microspheres are put on a silicon wafer or a Blu-ray disk shown in Fig. 2a and Fig. 2b. Due to the ring of white LED lighting, it is complicated to analyze the results shown in Fig. 2. In the following parts, we chose a simple microscope with a single white LED lighting for investigating the chromatic dispersion of microspheres on DVD stripes.

In Fig. 3a, the bigger size of $BaTiO_3$ microspheres on DVD stripes, which have a strong chromatic dispersion under a white-light illumination, is placed under a 100X magnifier. Then, the enlarged images are taken by a cellphone. In Fig. 3b, the 100X magnifier is presented. It has a white LED lighting for providing an oblique white-light illumination. The images of the bigger size of $BaTiO_3$ microspheres put on a Blu-ray disk and the DVD stripes shown in Fig. 1a obtained by the microscope shown in Fig. 3a are provided in Fig. 3c and Fig. 3d, respectively. And the image of the bigger size of $BaTiO_3$ microspheres on the DVD stripes shown in Fig. 3a is given in Fig. 3e. By comparison, a micro-iridescent focus can be observed when $BaTiO_3$ microspheres are put on the two kinds of DVD stripes. While, there is no chromatic dispersion of a microsphere put on a Blu-ray disk. The micro-iridescent focus with a “Jet” shape is enlarged in the insert I of Fig. 3e. While in the insert II of Fig. 3e, a, “Hook” shape is enlarged. The pattern of the “Jet” shape is similar to that of a PNJ. And the pattern of the “Hook” shape is similar to that of a photonic hook [15–17], which is a curved jet. From Fig. 3e, it can be seen that there is a shadow near the microsphere and the micro-iridescent focus is distributed inside of the shadow. It is also indicated that the length of the micro-iridescent focus is shorter than the diameter of the microsphere. In contrast, the micro-iridescent focus has the same color position distribution as the pair of iridescent wings obtained in Fig. 2c, whose long wavelengths are distributed farther away from the microsphere. And the “Jet” shape and the “Hook” shape can be changed by moving the magnifier shown in the attached video.

To obtain the relation between the direction of the micro-iridescent focus and the direction of DVD stripes, the placed direction of the magnifier shown in Fig. 3a is changed. The diagram for the change direction of the magnifier is shown in Fig. 4a, and the observed results with the direction of the magnifier shown in Fig. 4a are shown in Fig. 4b, c. There are huge differences between the chromatic dispersion shown in Fig. 3e and Fig. 4b. In Fig. 4b, there is no shadow near the microsphere. The chromatic dispersion is distributed on both sides of the microsphere. By comparison, the projection of the incident light on the DVD surface is mainly along the radial direction of the DVD shown in Fig. 3a, while that is mainly along tangential direction of the DVD shown in Fig. 4a. However, the directions of the chromatic dispersion both in Fig. 3a and Fig. 4a are mainly along the radial direction. It indicates that the direction of the micro-iridescent focus shown in the insert I of Fig. 3e is perpendicular to the DVD stripes.

The microscale chromatic dispersion is different from the iridescent structural color shown in [18]. The generation

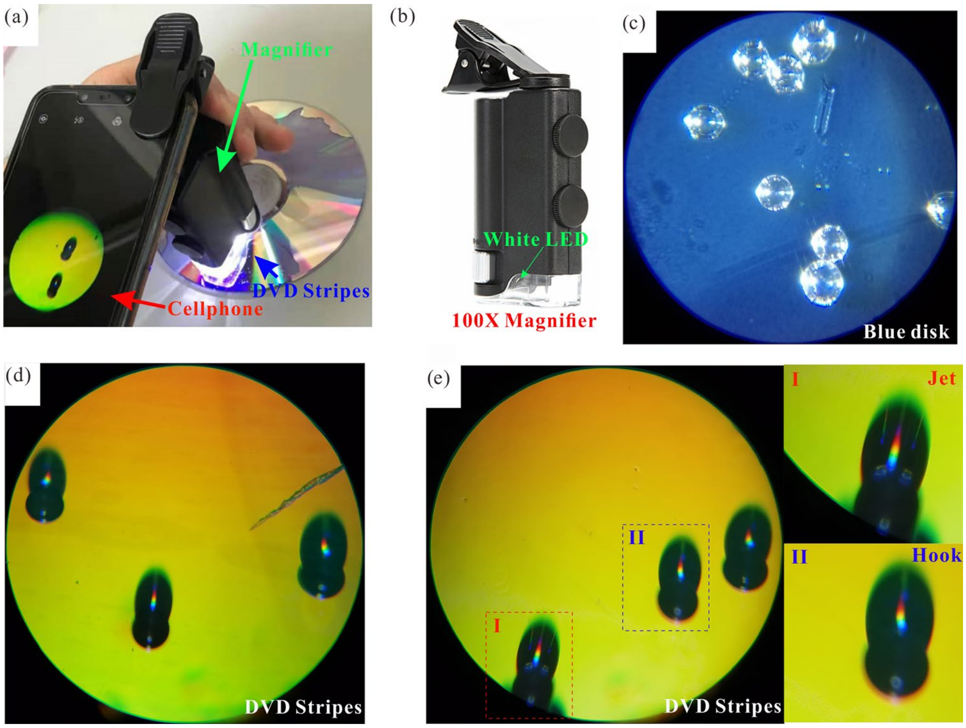

Fig. 3 A micro-iridescent focus generated from a microsphere on two kinds of stripes. **a** A microscope consists of a magnifier and a cellphone for observing the micro-iridescent focus, **b** the 100X magnifier shown in (**a**) with a white LED lighting providing an oblique white-light illumination, **c** the image of microspheres on Blu-ray disk, **d** the image of microspheres on the DVD stripes shown in Fig. 1a, and **e** the image of the micro-iridescent focus from microspheres on another kind of DVD stripes including a “Jet” shape enlarged in insert I and a “Hook” shape enlarged in insert II

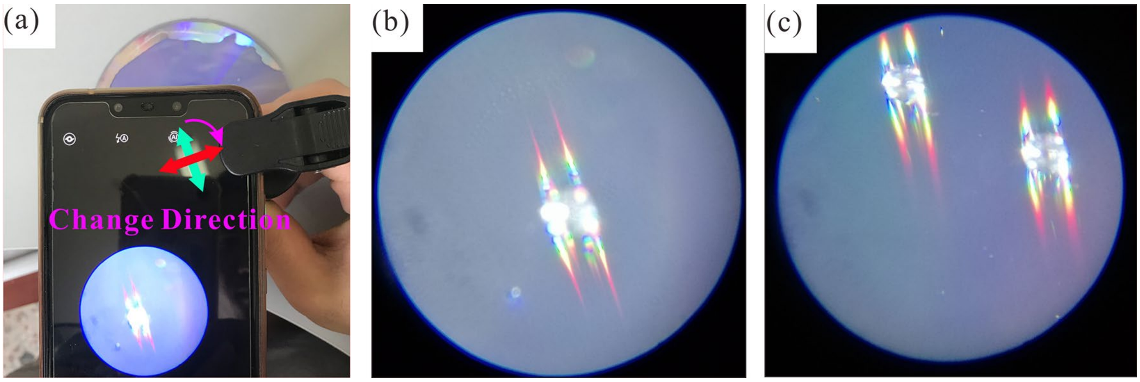

Fig. 4 The chromatic dispersion with another direction of the 100X magnifier. **a** A microscope consists of a magnifier and a cellphone, where the direction of the magnifier is different from Fig. 3a, **b** the chromatic dispersion of a bigger size of $BaTiO_3$ microsphere with the microscope shown in (**a**), and **c** the chromatic dispersion of two $BaTiO_3$ microspheres with the same size shown in (**b**) under the microscope shown in (**a**)

of the micro-iridescent focus profits from the microscale illumination provided by the microspheres. The properties of the micro-iridescent focus are mainly related to the diameter and the refractive index of the microsphere, the sizes of the DVD stripes, and the relation between the direction of the incident light and the direction of the DVD stripes. Although there are not enough detailed experiments to show how these parameters affect the micro-iridescent focus, we provide a new kind of microscale chromatic dispersion. Our results provide a novel way to miniaturize dispersive optics [19].

In our experiments, the oblique illumination is similar to that shown in [20, 21]. In [20, 21], the oblique irradiation of a microsphere was used to make special nanostructures. It was indicated that the nanodent center positions kept away from the contact point of the sphere and the supporting surface in [20], when the incident angle increased. To study the role of the oblique irradiation in our experiments, we simulate a 2D model and the results are shown in Fig. 5. The simulated method can be found in [3] and the medium of the mirror is set to gold. In [22], it presented that the maximum intensity was not distributed at the touch point of the sphere and the supporting surface, when the incident light was illuminated vertically. It can be seen that the maximum intensity is not at the shadow of the cylinder when the incident angle is chosen as $\theta = 10°$ in Fig. 5b. When the incident angle is selected as $\theta = 20°$, the maximum intensity appears between the cylinder and the supporting mirror in Fig. 5c, while the maximum intensity in Fig. 5c is about more than two times of that in Fig. 5a. As the incident angle turns into $\theta = 30°$, the maximum intensity moves to inside of the cylinder in Fig. 5d. In [23], it presented that the oblique irradiation caused high diffracted mode reflected from samples propagating through the sphere to enhance the image contrast. In [24], it was demonstrated that one could use the characteristic parameters of the PNJ of the solid microspheres observed with monochromatic light with suitable λ to interpret the experimental results obtained with the PNJs generated by polychromatic light, such as the white LED illumination. Moreover, it indicates that the structure consisted of a $BaTiO_3$ microsphere on a reflective surface could not produce a dispersion in Fig. 2a. Based on the above, a microscale and high-intensity illumination can be provided by the structure composed of a $BaTiO_3$ microsphere on DVD stripes illuminated under an oblique white LED irradiation with an appropriate angle. Then, the microscale and high-intensity white illumination is dispersed by the nano-stripes of the DVD and the micro-iridescent focus is collected by the camera.

4 Conclusion

In conclusion, a microscale chromatic dispersion assisted by a microsphere is experimentally presented. We find that a micro-iridescent focus can be generated from a $BaTiO_3$ microsphere on DVD stripes under an oblique white-light illumination. The long wavelengths of light contributing to the micro-iridescent focus are focused farther away from the microsphere. The length of the micro-iridescent focus is shorter than the diameter of the microsphere. And a curved-iridescent focus can also be observed in the microscope. It is confirmed that the direction of the micro-iridescent focus is perpendicular to that of DVD stripes. In future work, the properties of the chromatic dispersion of a microsphere on a reflective nanograting will be studied in detail. This novel structure may have potential applications in the miniaturization of optical spectrometers.

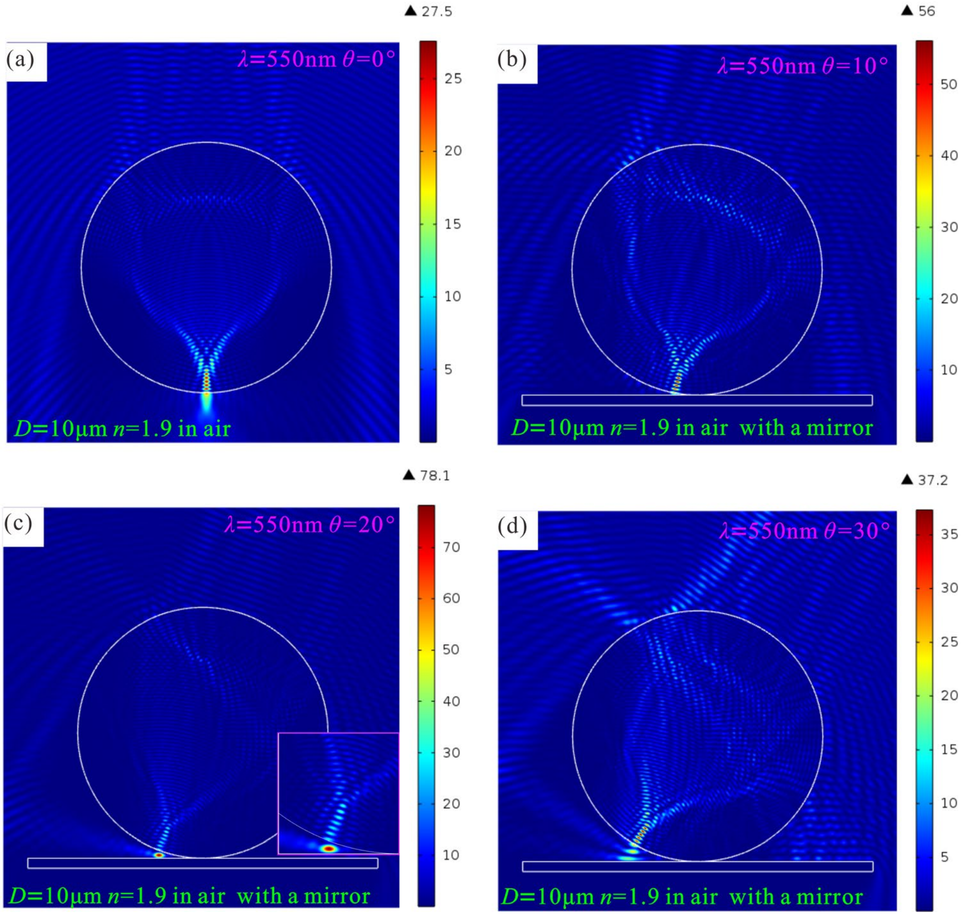

Fig. 5 Intensity distribution of a high-index micro-cylinder put in air under a plane wave in (**a**), intensity distribution of a high-index micro-cylinder put on a mirror under an oblique plane wave with incident angle $\theta = 10°$ in (**b**), $\theta = 20°$ in (**c**), and $\theta = 30°$ in (**d**). Simulated parameters chosen as the cylindrical diameter $D = 10$ μm, the index of the cylinder $n = 1.9$, and the incident wavelength $\lambda = 550$ nm

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s00339-022-05744-1.

Acknowledgements This work was supported by the Natural Science Research Program of Huai'an (No. HAB202153), National Natural Science Foundation of China (61974143) and Youth Innovation Promotion Association of the Chinese Academy of Sciences (2020223).

Declarations

Conflict of interest The authors declare no conflicts of interest.

References

1. B.S. Lukyanchuk, R. Paniagua-Domínguez, I.V. Minin, O.V. Minin, Z. Wang, Refractive index less than two: photonic nanojets yesterday today and tomorrow. Opt. Mater. Express **7**, 1820 (2017)
2. J. Zhu, L.L. Goddard, All-dielectric concentration of electromagnetic fields at the nanoscale: the role of photonic nanojets. Nano Adv. **1**, 4615 (2019)
3. O.V. Minin, I.V. Minin, Optical phenomena in mesoscale dielectric particles. Photonics **8**(12), 591 (2021)
4. A. Darafsheh, Photonic nanojets and their applications. J. Phys. Photonics **3**(2), 22001 (2021)
5. A. Darafsheh, Microsphere-assisted microscopy. J. Appl. Phys. **131**(3), 031102 (2022)
6. S. Kwon, J. Park, K. Kim, Y. Cho, M. Lee, Microsphere-assisted, nanospot, non-destructive metrology for semiconductor devices. Light-Sci. Appl. **11**(1), 1–14 (2022)
7. L. Chen, Y. Zhou, Y. Li, M. Hong, Microsphere enhanced optical imaging and patterning: from physics to applications. Appl. Phys. Rev. **6**(2), 21304 (2019)
8. L. Chen, Y. Zhou, R. Zhou, M. Hong, Microsphere – the future of optical microscopes: beating the diffraction limit with microsphere-assisted technology. PhotonicsViews **18**(3), 79–81 (2021)
9. H.S. Patel, P.K. Kushwaha, M.K. Swami, Photonic nanojet assisted enhancement of Raman signal: effect of refractive index contrast. J. Appl. Phys. **123**(2), 23102 (2018)
10. V. Gašparić, D. Ristić, H. Gebavi, M. Ivanda, Resolution and signal enhancement of Raman mapping by photonic nanojet of a microsphere. Appl. Surf. Sci. **545**, 149036 (2021)
11. P.B. Johnson, A. Karvounis, H.J. Singh, C.J. Brereton, K.N. Bourdakos, K. Lunn, J.J.W. Roberts, D.E. Davies, O.L. Muskens, M.G. Jones, S. Mahajan, Super-resolved polarisation-enhanced second harmonic generation for direct imaging of nanoscale changes in collagen architecture. Optica **8**(5), 674–685 (2021)
12. L. Li, W. Guo, Y. Yan, S. Lee, T. Wang, Label-free super-resolution imaging of adenoviruses by submerged microsphere optical nanoscopy. Light-Sci. Appl. **2**(9), e104 (2013)
13. P.-Y. Li, Y. Tsao, Y.-J. Liu, Z.-X. Lou, W.-L. Lee, S.-W. Chu, C.-W. Chang, Unusual imaging properties of superresolution microspheres. Opt. Express **24**(15), 16479–16486 (2016)

14. S. Zhou, K. Li, Y. Wang, Tunable photonic nanojets from a microcylinder with a dielectric nano-layer. Optik **225**, 165878 (2021)
15. L. Yue, O.V. Minin, Z. Wang, J.N. Monks, A.S. Shalin, I.V. Minin, Photonic hook: a new curved light beam. Opt. Lett. **43**(4), 771–774 (2018)
16. I.V. Minin, O.V. Minin, G.M. Katyba, N.V. Chernomyrdin, V.N. Kurlov, K.I. Zaytsev, L. Yue, Z. Wang, D.N. Christodoulides, Experimental observation of a photonic hook. Appl. Phys. Lett. **114**(3), 31105 (2019)
17. G. Gu, P. Zhang, S. Chen, Y. Zhang, H. Yang, Inflection point: a perspective on photonic nanojets. Photonics Res. **9**(7), 1157–1171 (2021)
18. A.E. Goodling, S. Nagelberg, B. Kaehr, C.H. Meredith, S.I. Cheon, A.P. Saunders, M. Kolle, L.D. Zarzar, Colouration by total internal reflection and interference at microscale concave interfaces. Nature **566**(7745), 523–527 (2019)
19. Z. Yang, T. Albrow-Owen, W. Cai, T. Hasan, Miniaturization of optical spectrometers. Science (2021). https://doi.org/10.1126/science.abe0722
20. Z. Wang, M. Hong, B.S. Luk'yanchuk, Y. Lin, Q. Wang, T. Chong, Angle effect in laser nanopatterning with particle-mask. J. Appl. Phys. **96**(11), 6845–6850 (2004)
21. J. Boneberg, P. Leiderer, Optical near-field imaging and nanostructuring by means of laser ablation. Opto-Electron. Sci. **1**(1), 210003 (2021)
22. L. Yue, B. Yan, J.N. Monks, R. Dhama, Z. Wang, O.V. Minin, I.V. Minin, Photonic jet by a near-unity-refractive-index sphere on a dielectric substrate with high index contrast. Ann. Phys-Berlin **530**(6), 1800032 (2018)
23. O.V. Minin, I.V. Minin, Terahertz microscope with oblique subwavelength illumination: design principle. Quantum Electron. **52**(1), 13 (2022)
24. A. Mandal, P. Tiwari, P.K. Upputuri, V.R. Dantham, Characteristic parameters of photonic nanojets of single dielectric microspheres illuminated by focused broadband radiation. Sci. Rep-UK **12**(1), 1–16 (2022)