High-resolution label-free cellphone microscopy using contact ball lenses

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***Abstract*— It is shown that an imaging system of a millimeter-scale ball lens made by LASFN35 glass with index n=2.05 at λ = 480nm contacting objects can be used to improve the resolution of cellphone-base microscopy. The resolution can be improved from ~35 μm to ~600nm over a ~20*20 μm² field of view by real imaging through the contact ball lens. With optimization of parameters of the contact ball lenses, finer resolution can be achieved, which can lead to a wide range of applications in mobile biomedical imaging.**

Keywords—lenses, imaging, superresolution

I. INTRODUCTION (*HEADING 1*)

Developing hand-held and lightweight imaging systems is of interest for microscopy diagnostics and for immediate identification of biomedical threats. A natural way to achieve such imaging is replacing bulky microscopes with cellphone cameras [1, 2]. However, their performance is subjected to a tradeoff between the resolution and field-of-view (FOV) inherent to optical systems. Previous studies were mainly concentrated on fluorescent (FL) imaging [3-6] with microlenses separated from FL objects which provided modest image magnifications. The best resolution values were limited at ~1.5 μm level [5].

In this work, we propose a different approach to cellphone microscopy based on real imaging by ball lenses placed in contact with the object. We demonstrate that our approach allows simple label-free imaging [7] of nanoplasmonic objects with resolution ~600 nm which is three times better than previously reported resolution of FL objects in Ref. [5]. Imaging by contact microspheres has been extensively studied using high quality microscope objectives without any use of cell phones [8-13]. It was demonstrated that a potential resolution of about λ/7 can be achieved by both imaging nanoplasmonic structures and imaging of fluorescent (FL) objects coupled to plasmonic metasurfaces with sufficiently small periods [14-18]. This resolution exceeds the resolution limit of both the microscope objective and solid immersion lens. This super-resolution ability of such lenses is related to the additional magnification of the virtual image obtained with the inclusion of the object's near-fields. The mechanisms of such imaging are still under debating in the literature [18-20].

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In this work, we propose to use ball lenses placed in contact with the object of studies without using expensive microscope objectives or heavy and bulky microscope stands. The imaging can be provided by ordinary cellphone cameras focused on hugely magnified images of these objects produced by the ball lenses with index of refraction sufficiently close to two. Some preliminary results of such studies were presented in [21]. The material of the contact ball lens is LASFN35, with refractive index n = 2.05 at λ = 480 nm. The real imaging through such ball lens with refractive index closer to 2 will provide large magnification, therefore significantly improve the resolution of the imaging system when it is limited by the pixelization. The real imaging cellphone microscopy through contact ball lens can provide a magnification larger than 30 times and achieve a resolution around 600nm.

II. EXPERIMENTAL RESULTS

It is important to recognize that the resolution of ordinary cellphone cameras is restricted due to finite size of the pixels. For this reason, additional magnification of the image is required for increasing the resolution of cellphone cameras. In our proposal this additional magnification comes from the contact ball lens, as schematically illustrated in Figure 1(a). The illumination is provided by the white light source from below through a diffuser. The magnified real image is captured by the cellphone camera that improve the total resolution of the system. In the limit of geometrical optics, the lateral image magnification (M) of ball lens is determined by the following equation [11, 13]:

$$(n', d, g) = \frac{n'}{2(n'-1)\left(\frac{2g}{d}+1\right)-n'}\ , \qquad (1)$$

Where d is the diameter of the ball lens, $n' = {}^{n_{sp}}/_{n_0}$ is the refractive index contrast between the ball lens and object space, and g is the gap between the object and ball lens. At λ = 480 nm, the LASFN35 glass has a refractive index n = 2.04916, and the magnification of a contact LASFN35 ball lens can be estimated to be M = 41.8 in the paraxial geometrical optics approximation. In the real physical experiment, the imaging is determined by the wave as opposed to geometrical optics. We define the focusing distance (d) as

the distance from object to image, and for a contact ball lens, the relationship between Magnification (M) and focusing distance (d) is determined by the following equation:

$$M = 2\frac{d}{D} - 1, \quad (2)$$

Where D is the diameter of ball lens. It shows that the magnification is only determined by the refractive index and different diameter of ball lens should have same magnification. For a fixed magnification, larger diameter ball lens should have longer focusing distance. Figure 1(b) shows the theoretical and experimental magnification and focusing distance for LASFN35 ball lens at λ = 480nm with diameter D = 0.5mm, 1.0mm, and 2.0mm. The experimental results show good agreement with the real imaging mechanism, but the absolute value of magnification is less than the predictions of geometrical optics based on paraxial approximation. Still, experimental M values were found to exceed 30 which allows to improve the resolution of the whole imaging system.

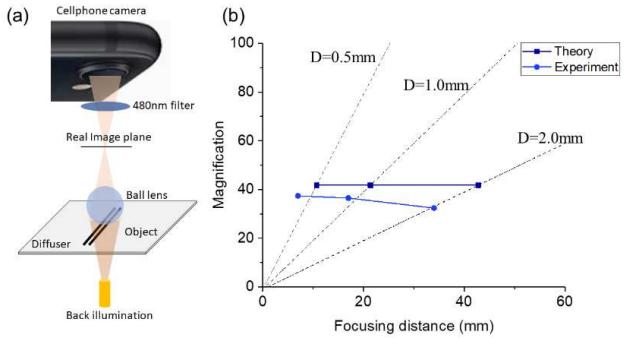

Figure 1 (a) Experimental setup of cellphone microscopy. (b) Plot representing magnification as a function of focusing distance.

Figure 2(a) shows the object we used for quantification of resolution. It is represented by a Au double-stripe array deposited on sapphire substrate. The width of the stripe is 1μm and the gap between two stripes is 0.7μm. The ball lens is directly placed on top of the object. A magnified image of such object is formed through the ball lens above the ball lens, as illustrated in Fig. 1(a). The cellphone camera is focused on this real imaging plane. Figure 2(b) show the image taken by cellphone camera through ball lens at λ = 480nm. Since the object is back-illuminated, the stripes are blocking light and appears black, the gap is transmitting light and appears bright.

Figure 2(c) showed the resolution quantification of the cellphone microscopy system. According to a Houston resolution criterion, to determine the resolution of imaging system, the intensity profile of a point-like object is fitted by a Gaussian point-spread function (PSF), and the resolution equals to the full width at half maximum (FWHM) divided by the magnification (M) of the system [11-13]. This procedure is based on measuring an intensity profile at certain cross sections of the stripes. It should be noted, however, that despite large M values provided by the contact microspheres, imaging of micron-scale features is still limited by the finite

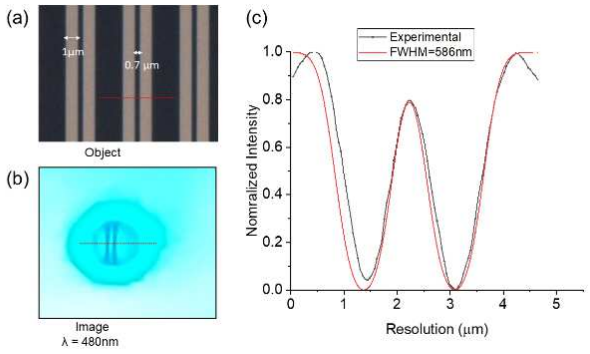

Figure 2 (a) double-stripe array as object (b) image by cellphone camera through ball lens (c) resolution quantification

size of the pixels of the cellphone camera. To determine the resolution, we convolute perfect object (drawn) with PSFs represented by Gaussian functions with different FWHMs. The FWHM of PSF providing the best fitting of the image profile and convolution result is selected as the resolution of the system. Our work shows that contact ball lenses allow to increase the resolution of cellphones by three times compared to other microlens solutions and by 50 times compared to direct imaging by the cellphones without using additional microlenses or objectives. The resolution in our experiment is calculated to be 600nm, which is close to one wavelength. It shows that use of contact ball lenses allows to achieve almost diffraction-limited resolution values.

III. Conclusion

The resolution of a cellphone camera objective is limited by the finite size of the pixels, and image magnification is required for improving the resolution. In previous work [1, 2], the magnification was provided by real-imaging system of ball lenses separated from objects by millimeter-scale distances. In this work, we developed an alternative approach to high-resolution cellphone microscope based on putting dielectric microsphere in a close contact position with the object. In this situation, the magnification of the system tends to increase under conditions that the index of ball lens is sufficiently close to two. We found that the imaging in such limit does not follow paraxial approximation in geometrical optics. As an example, the focusing distances are much shorter than predictions of geometrical optics. However, the main trends and dependencies are in a qualitative agreement with the geometrical optics. In particular, the refractive index of the LASFN35 ball lens reduces with the wavelength and in principle, it can be made even closer to two. This can allow even higher magnification values in the near infrared regime. It should be noted, however, that due to a fundamental tradeoff between the magnification and FOV, the latter tend to reduce at longer wavelengths. In our case, for illumination at 480 nm, FOV is limited around 20 μm for for a 2mm diameter ball lens. The most important advantages of the proposed technology is its ability to provide a label-free imaging (but it is capable to perform FL imaging) and its simplicity. It does not require complicated illumination systems or complicated

attachments to ordinary cell phone. However, it requires some capability to translate the ball lens to align it with the objects of interest.

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REFERENCES

[1] Z. J. Smith, K. Chu, A. R. Espenson, M. Rahimzadeh, A. Gryshuk, M. Molinaro, D. M. Dwyre, S. Lane, D. Matthews, and S. Wachsmann-Hogiu, "Cell-phone-based platform for biomedical device development and education applications," PLoS ONE 6, e17150 (2011).

[2] N. A. Switz., M. V. D'Ambrosio, and D. A. Fletcher, "Low-cost mobile phone microscopy with a reversed mobile phone camera lens," PLoS ONE 9, e95330 (2014).

[3] H. Zhu, O. Yaglidere, T. Su, D. Tseng, and A. Ozcan, "Cost-effective and compact wide-field fluorescent imaging on a cell-phone," The Royal Society of Chemistry 11, 315-322 (2011).

[4] E. McLeod, Q. Wei, and A. Ozcan, "Democratization of nanoscale imaging and sensing tools using photonics," Anal. Chem. 87, 6434-6445 (2015).

[5] Q. Wei, H. Qi, W. Luo, D. Tseng, S. J. Ki, Z. Wan, Z. Göröcs, L. A. Bentolila, T. Wu, R. Sun, and A. Ozcan, "Fluorescent imaging of single nanoparticles and viruses on a smart phone," ACS Nano 7, 9147-9155 (2013).

[6] C. Vietz, M. L. Schütte, Q. Wei, L. Richter, B. Lalkens, A. Ozcan, P. Tinnefeld, and G. P. Acuna, "Benchmarking smartphone fluoresence-based microscopy with DNA origami nanobeads: Reducing the gap toward single-molecule sensitivity," ACS Omega 4, 637-642 (2019).

[7] Label-free super-resolution microscopy, Ed. V. Astratov (Springer, Cham, 2019).

[8] V. N. Astratov and A. Darafsheh, "Methods and systems for superresolution optical imaging using high-index of refraction microspheres and microcylinders," U.S. patent 9726874B2, priority date 2012-06-07, https://www.google.com/patents/US20140355108.

[9] A. Darafsheh, G. F. Walsh, L. Dal Negro, and V. N. Astratov, "Optical super-resolution by high-index liquid-immersed microspheres," Appl. Phys. Lett. **101**, 141128 (2012).

[10] A. Darafsheh, N. I. Limeropoulos, J. S. Derov, D. E. Walker Jr., V. N. Astratov, "Advantages of microsphere-assited super-resolution imaging technique over solid immersion lens and confocal microscopies," Applied Phys. Letters 104, 061117 (2014).

[11] K. W. Allen, N. Farahi, Y. Li, N. I. Limberopoulos, D. E. Walker, Jr., A. M. Urbas, V. Liberman, and V. N. Astratov, "Super-resolution microscopy by movable thin-films with embedded microspheres: Resolution analysis," Ann. Phys. (Berlin) 527, 513–522 (2015).

[12] K. W. Allen, N. Farahi, Y. Li, N. I. Limberopoulos, D. E. Walker, Jr., A. M. Urbas, and V. N. Astratov, "Overcoming the diffraction limit of imaging nanoplasmonic arrays by microspheres and microfibers," Opt. Express 23(19), 24484–24496 (2015).

[13] K. W. Allen, Y. Li, and V. N. Astratov, "Reply to "Comment on 'Super-resolution microscopy by movable thin-films with embedded microspheres: Resolution analysis," Ann. Phys. (Berlin) 528, 901-904 (2016).

[14] V. N. Astratov, N.I. Limberopoulos, and A. Urbas, "Super-resolution microscopy methods and systems enhanced by dielectric microspheres or microcylinders used in combination with metallic nanostructures," U.S. patent 9835870B2, priority date 2015-06-05.

[15] V. N. Astratov, A. V. Maslov, A. Brettin, K. F. Blanchette, Y. E. Nesmelov, N. I.Limberopoulos, D. E. Walker, and A. M. Urbas, "Contact microspherical nanoscopy: from fundamentals to biomedical applications Proc. SPIE10077, 100770S (2017).

[16] A. Bezryadina, J. Li, J. Zhao, A. Kothambawala, J. Ponsetto, E. Huang, J. Wang, and Z. Liu, "Localized plasmonic structured illumination microscopy with an optically trapped microlens," Nanoscale 9, 14907-14912 (2017).

[17] A. Brettin, F. Abolmaali, K. F. Blanchette, C. L. McGinnis, Y. E. Nesmelov, N. I. Limberopoulos, D. E. Walker, Jr., I. Anisimov, A. M. Urbas, L. Poffo, A. V. Maslov, and V. N. Astratov, "Enhancement of resolution in microspherical nanoscopy by coupling of fluorescent objects to plasmonic metasurfaces," Appl. Phys. Lett. 114, 131101 (2019).

[18] A. V. Maslov and V. N. Astratov, "Imaging of sub-wavelength structures radiating coherently near microspheres," Appl. Phys. Lett. 108, 051104 (2016).

[19] A. V. Maslov and V. N. Astratov, "Optical Nanoscopy with Contact Mie-Particles: Resolution Analysis," Appl. Phys. Lett. 110, 261107 (2017).

[20] A. V. Maslov and V. N. Astratov, "Resolution and reciprocity in microspherical nanoscopy: point spread function versus photonic nanojets," Phys. Rev. Appl. 11, to be published (2019).

[21] G. W. Bidney, A. Brettin, B. Jin, N. I. Limberopoulos, I. Anisimov, H. Li, A. V. Maslov, and V. N. Astratov, "Improving Cellphone Microscopy Imaging with Contact Ball Lenses," 2019 IEEE National Aerospace and Electronics Conference (NAECON), pp. 672-674 (2019)