SCIENCE CHINA
Physics, Mechanics & Astronomy

• News & Views •

April 2017 Vol. 60 No. 4: 044231
doi: 10.1007/s11433-017-9005-8

Breaking the diffraction limit in far field by planar metalens

Fei Qin[1,2], and MingHui Hong[2*]

[1] *Institute of Photonics Technology, Jinan University, Guangzhou 510632, China;*
[2] *Department of Electrical and Computer Engineering, National University of Singapore, Singapore 117583, Singapore*

Received January 17, 2017; accepted January 21, 2017; published online February 21, 2017

Citation: F. Qin, and M. H. Hong, Breaking the diffraction limit in far field by planar metalens, Sci. China-Phys. Mech. Astron. **60**, 044231 (2017), doi: 10.1007/s11433-017-9005-8

Optical lens is of fundamental importance in both scientific researches and industrial communities, especially for the aspects of optical focusing and imaging. In traditional optics, the light modulation property is limited by the Rayleigh Criterion ($0.61\lambda/NA$), and therefore the development of an ideal lens that produces sub-diffraction limit focusing and imaging has been a dream of lens makers all the time. Intensive effort has been made to break this barrier for centuries, however, all the reported techniques suffer from certain limitations for general applications, such as near-field operation, small field of view, or object dyeing which works only for a narrow-class of samples [1-3].

Recent advance in this field is the demonstration of super-oscillatory lens (SOL) [4,5]. Super-oscillation in optics is one kind of destructive interference of light with different spatial frequencies that the band-limited functions are able to oscillate faster than their highest Fourier components at some points [6,7]. By precisely tailoring the interference of a large number of beams diffracted from a nanostructured binary amplitude mask, a sub-diffractive focal spot can be created at a distance beyond the near-field of the mask. Then the non-invasive sub-wavelength imaging for the specimen can be obtained by scanning the sample point by point. The most distinguish advantage of this technology is that it could be used for universal specimen and does not depend on the luminescence of the object, and the sample can be placed away from the evanescent region. Besides the periodically or quasi-periodically zone plate, super-resolution focusing property also can be demonstrated by optical nanosieve with circular symmetry [8]. However, there are several intrinsic factors limit the real industrialization after SOL was invented, such as the inevitable strong side-lobes outside the central spot, complicated sample fabrication process due to the sub-wavelength feature sizes, short working distance and short depth of focus. To surmount these inherent barriers and bring the academic concept into practical applications is always a big challenge.

Ultrathin flat lens made by graphene oxide (GO) is able to effectively manipulate the phase and amplitude of an incident beam simultaneously [9]. The GO lens is made via the photo-reduction process to convert the GO into reduce GO (rGO). Through precisely control of the laser power, the local physical properties of the GO film can be continuously tuned, including the reduction of film thickness, the increase of refractive index and the decrease of transmission/increase of extinction coefficient, thus provide flexibility in designing the lens by controlling both the amplitude and phase. It demonstrates a far-field 3D sub-wavelength focusing ($\lambda^3/5$) with a very broadband working range from visible to near infrared, and the focusing efficiency is up to 32% over the entire band. Through carefully designing of the lens parameters, the shift of the focal length over the all visible range can be smaller than the depth of focus, then realize a sub-wavelength focusing with minimal chromatic aberration.

In order to alleviate the effect from the side-lobes, one probable method is to push the strong side-lobe away from the center super-oscillatory spot [10]. Through padding 29 zero intensity positions between the main spot and the side-lobe to suppress the high side-lobe near the center, Huang et al.

---

*Corresponding author (email: elehmh@nus.edu.sg)

[10] have shown a constructed super-oscillatory spot with a size of about 0.34λ and the high side-lobe about 15λ away from the center by using a binary phase zone plate. This design principle also can be used in the super-resolution telescope to restore some local Fourier component beyond the cut-off frequency of the telescope system [11]. Optimization is the commonly used method to design super-oscillatory lens by adjusting the central radius and width of each belt in a zone plate. An optimization-free design principle is presented in this work, and also proposed a super-oscillatory criterion (SOC) in optical focusing, expressed as r_s=0.38/$f_{\max}$ ($f_{\max}$ is the maximum spatial frequency), which determines whether the super-oscillatory focusing occurs or not [10].

A new concept of supercritical lens (SCL) composed of a series of concentric transparent belts is proposed recently, which has a focusing spot slightly larger than SOC (0.38λ/NA) and a needle-like focal region with its DOF $\Delta z>2\lambda/NA^2$ that differs from traditional spherical lenses [12,13]. Based on the 405 nm supercritical lens, a SCL microscopy is built to demonstrate a sub-diffraction limit imaging capability of resolving 65 nm gap in air with an ultra-long working distance of 55 µm (135λ). It also shows the first demonstration of mapping the horizontal details of a 3D object by only one-time scanning process, which significantly extends the scope to the regimes that are unexploited in traditional microscopies. Distinguished from all other planar meta-lenses, the nanoscale imaging resolution is realized by a lens with microscale feature size. Such lens could be fabricated by a commercial laser pattern generator with high speed and low cost. This breakthrough can fill the gap between laboratory proof-of-concept demonstrations and practical applications for the super-resolution imaging.

In general, the planar metalens has a new and unbeatable advantage over the conventional optics, and provides a solution to break the diffraction limit in far field. The process is physical and can be operated at any wavelength. One could envision that the performance of the planar metalens could be further enhanced by refining the design and combining with other techniques [14]. It would open a new avenue for many applications, including non-invasive super-resolution imaging, highly integrated photonic chip, ultra-precision light harvesting and nanolithography.

This work was supported by the National Research Foundation, Prime Minister's Office, Singapore under its Competitive Research Program (Grant No. NRF-CRP10-2012-04).

1 N. Fang, H. Lee, C. Sun, and X. Zhang, Science **308**, 534 (2005).
2 X. Zhang, and Z. Liu, Nat. Mater. **7**, 435 (2008).
3 K. I. Willig, S. O. Rizzoli, V. Westphal, R. Jahn, and S. W. Hell, Nature **440**, 935 (2006).
4 E. T. F. Rogers, J. Lindberg, T. Roy, S. Savo, J. E. Chad, M. R. Dennis, and N. I. Zheludev, Nat. Mater. **11**, 432 (2012).
5 G. Yuan, E. T. F. Rogers, T. Roy, G. Adamo, Z. Shen, and N. I. Zheludev, Sci. Rep. **4**, 6333 (2014).
6 M. V. Berry, J. Phys. A-Math. Theor. **46**, 205203 (2013).
7 M. V. Berry, and S. Popescu, J. Phys. A-Math. Gen. **39**, 6965 (2006).
8 K. Huang, H. Liu, F. J. Garcia-Vidal, M. Hong, B. Luk'yanchuk, J. Teng, and C. W. Qiu, Nat. Commun. **6**, 7059 (2015).
9 X. Zheng, B. Jia, H. Lin, L. Qiu, D. Li, and M. Gu, Nat. Commun. **6**, 8433 (2015).
10 K. Huang, H. Ye, J. Teng, S. P. Yeo, B. Luk'yanchuk, and C. W. Qiu, Laser Photonics Rev. **8**, 152 (2014).
11 C. Wang, D. Tang, Y. Wang, Z. Zhao, J. Wang, M. Pu, Y. Zhang, W. Yan, P. Gao, and X. Luo, Sci. Rep. **5**, 18485 (2015).
12 F. Qin, K. Huang, J. Wu, J. Jiao, X. Luo, C. Qiu, and M. Hong, Sci. Rep. **5**, 9977 (2015).
13 F. Qin, K. Huang, J. Wu, J. Teng, C. W. Qiu, and M. Hong, Adv. Mater. in press (2016).
14 X. G. Luo, Sci. China-Phys. Mech. Astron. **58**, 594201 (2015).