Batch Fabrication of Broadband Metallic Planar Microlenses and Their Arrays Combining Nanosphere Self-Assembly with Conventional Photolithography

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Abstract

A novel low-cost, batch-fabrication method combining the spin-coating nanosphere lithography (NSL) with the conventional photolithographic technique is demonstrated to efficiently produce the metallic planar microlenses and their arrays. The developed microlenses are composed of subwavelength nanoholes and can focus light effectively in the entire visible spectrum, with the foci sizes close to the Rayleigh diffraction limit. By changing the spacing and diameter of nanoholes, the focusing efficiency can be tuned. Although the random defects commonly exist during the self-assembly of nanospheres, the main focusing performance, e.g., focal length, depth of focus (DOF), and full-width at half-maximum (FWHM), keeps almost invariable. This research provides a cheap way to realize the integrated nanophotonic devices on the wafer level.

Keywords: Planar microlens, Batch fabrication, Nanosphere lithography, Self-assembly

Background

Microlenses as a class of most ubiquitous optical components, aiming to manipulate and focus light at the micro-/nanoscale, have important applications, such as display technology [1], laser beam collimation [2], molecular detection [3], and optical information storage [4]. Though refractive microlenses are extensively used in commercial devices with high optical throughput, they inevitably suffer from bulky size, chromatic, and spherical aberrations [5]. On the other hand, diffractive microlenses exhibit less aberration, but their physical size and complex three-dimensional (3D) surface profiles make them less useful in miniaturized and highly scaled devices. Furthermore, their fabrication requires precise alignment during multiple lithographic processes, which also limits their adoption in highly integrated micro-/nano-optical devices [6, 7].

Substantial efforts have been devoted to exploring plasmonics in recent years [8–10], due to the unique capability to route and manipulate light at the nanometer length scale. As an important category of plasmonic devices, plasmonic lenses based on thin nanostructured metallic films were proposed and developed [11–17]. Surface plasmons (SPs) on metallic films are excited by the interaction of incident light with the charge oscillations on the lens’ entrance surface and are squeezed into the nanoapertures. After passing through the whole metallic films in specific waveguide modes, SPs change to the propagating waves again. The sub-waves transmitting from all the nanoapertures will interfere with each other and form a light spot with the maximum intensity at a certain distance away from the lens’ exit surface, which are also named as the focusing spot and the focal plane. Consequently, metallic planar microlenses comprising of nanoaperture arrays are potential candidates for conventional dielectric-based refractive lenses, bringing out subwavelength, yet broadband focusing and allowing all-optical or opto-electronic single-chip integration. However, all the microlenses composed of nanostructures require the high-precision nanofabrication techniques,
such as electron-beam lithography (EBL) and focused ion beam (FIB) milling. Although they are powerful tools for prototyping microlenses, these processes are expensive, time consuming, and not suitable for the large-area parallel fabrication.

Recently, a kind of microlens based on nanoholes capable of focusing all wavelengths in the visible spectrum to a single spot was reported by employing a batch-fabrication method of soft interference lithography (SIL) followed by a nanopatterning procedure [18]. Unfortunately, this method is not ideal for microlenses because the nanoholes around the periphery show significantly smaller diameter than that of the central ones, and some are even blocked, causing a large deviation of the focal length from the design. Therefore, developing a versatile and large-area fabrication technique for microlenses is crucial for their practical applications; nonetheless, the effective method using the current top-down or bottom-up approaches still remains a big challenge. Moreover, it is worthwhile to investigate the random defects on the focusing performance and the coupling effect between adjacent microlenses.

The promising large-area fabrication methods, such as photolithography, laser interference lithography (LIL), and nanosphere lithography (NSL), enable the creation of various nanostructures. Photolithography is widely used in microelectronics to manufacture integrated circuits (ICs). The combination of short-wavelength light sources, including deep ultraviolet (DUV) and extreme ultraviolet (EUV), and innovations, such as immersion lithography and phase shift masks, have pushed the feature size well into the nanometer scale [19, 20]. Although the traditional mask-based optical lithography is well established and widely used in the IC industry, it is also very expensive both to set up and to operate. As a much simpler and cheaper scale methodology, LIL is based on the interference of several coherent laser beams and can produce one-dimensional (1D), two-dimensional (2D), and 3D periodic structures with feature dimensions approaching 20 nm [21]. But suffering from the restriction of technology, LIL is difficult to produce the patterns over centimeter scale [22]. NSL is a typical colloidal self-assembly technique, which meets the effective nanofabrication in a highly parallel, wafer-scale, inexpensive way and uses hexagonal close-packed nanospheres of mainly polystyrene (PS) or silica as masks or templates for photolithography, evaporation, deposition, etching, imprinting, etc. [23, 24]. Because of the hexagonal close-packed arrangement of nanospheres, this results in a similar array of nanostructures. Moreover, such structures can exhibit the grating effects, for instance, the extraordinary optical transmission (EOT) performance of nanohole arrays, generally as a result of the excitation of surface plasmon polaritons (SPPs) [25]. This is specifically important for many possible applications such as surface-enhanced Raman scattering (SERS), enhanced detection of infrared (IR) vibrations, solar cells, and enhanced fluorescence [26–29].

In this work, our approach combines the advantages of the modified NSL, e.g., large-area and low-cost fabrication, with the conventional photolithographic technique to produce the desired metallic planar microlenses that are similar to the Odom’s “patches”. The realized microlenses as demonstrated can focus single wavelengths of light across the entire visible spectrum as well as the broadband white light with minimal divergence. Besides, via the simulation and experimental verification, the random defects commonly existing during the self-assembly procedure of nanospheres in nanohole arrays reveal no dramatic influences on the focusing performance of microlenses, which means the focal spots from different microlenses on the same wafer have the identical lateral dimensions, closing to the Rayleigh diffraction limit. The metallic nanohole-based microlenses and the so-developed NSL method presented here may open a door to design and fabricate a new type of microlenses for miniaturized transmissive planar micro-/nano-optical devices.

Methods

Bottom-up self-assembly of dielectric PS nanospheres as a simple and low-cost route to form subwavelength nanoholes often suffers from severe defects, e.g., dislocations, multilayer, and point or area vacancies. To address these issues, we undertake experimental studies of the spin-coating parameters, including the spinning velocity, acceleration, suspension proportioning, and the hydrophilic modification of substrate surfaces, on the quality of the formed self-assembled arrays over the whole 4-in. glass wafer. Although the optimized parameters are adopted to reduce the major defects (vacancies and multilayer) and create the corresponding nanohole arrays through pattern transferring, some dislocations and vacancies are still inevitable and shifted to the final nanohole structures.

Figure 1 illustrates the combination of a bottom-up (spin-coating self-assembly of PS nanospheres) and a top-down technique (photolithography) for low-cost, parallel fabrication of microlenses and their arrays. Firstly, the PS nanospheres (from microParticles GmbH) are spin coated onto glass substrates, forming a monolayer mask of nanospheres with the hexagonal lattice (Fig. 1a). After deposition of nanospheres, their size is modified via the oxygen plasma in a parallel plate reactor (Plasma Reactor, 0.75 Pa, O₂ 100 sccm, 80 W), as shown in Fig. 1b. In the next step, a 100-nm-thick gold layer is sputtered onto the monolayer PS nanospheres (Fig. 1c). After that, lift-off process is performed...
by the ultrasonic cleaning in tetrahydrofuran (THF), and a large-scale nanohole array is thus achieved (Fig. 1d). Then, the chromium (Cr) film is sputtered onto the first holey gold film (Fig. 1e) and patterned with the desired microlenses and their arrays by photolithography (Fig. 1f), which dominates the focusing performance of the ultimately achieved microlenses. Next, the Cr layer exposed by the opening areas is removed, leaving the holey gold nanoholes to transmit the incident light (Fig. 1g). After cleaning the residual photore sist, the designed microlenses and their arrays are realized (Fig. 1h).

Figure 2 shows the representative scanning electron microscope (SEM) images displaying various self-assembled morphologies of PS nanospheres with the lattice spacing \( P = 900 \text{ nm} \), i.e., the diameter of PS nanospheres employed. The self-assembled monolayers of PS nanospheres are orderly packed in a hexagonal lattice on the glass substrates in Fig. 2a, d. However, dislocations that are shown as "cracks" are still present, due to electrostatic repulsion between the particles [30], as well as the point vacancies. Figure 2b, c illustrates area vacancies, multilayer, and randomly packed defects, which are distributed in certain regions with a poor controllability when the spin-coating parameters are not optimized or disturbed.

Figure 3 shows the result of the visible-light diffraction on the nanospheres mask and digital camera pictures of the 4-in. wafer and a 10 mm \( \times \) 10 mm chip with various cells of microlenses. The individual microlens and its array are illustrated in Fig. 3d, in which the underlying nanoholes and the detached microlenses are clearly observed. It also reveals the existing random defects in the single microlenses.

In order to explore the focusing performance of the achieved microlenses, we compare the 3D finite-difference time-domain (FDTD) simulation results with the experimental testings. Our experimental setup, as described in Fig. 4, employing the Nikon inverted optical microscope as the main operating platform, is used to map the optical fields generated from the plane wave incident on the microlens. After transmitting through the microlens, a high-quality oil-immersion microscope objective (100\( \times \), NA = 1.49) images speckle patterns onto a CCD camera and is driven by the E-816 piezo controller (Physik Instrumente (PI)) with a stepping length of 100 nm. After collecting hundreds of 2D light slices, the 3D optical field along the propagating axis of microlens can be thus constructed.
Results and Discussion

I. Focusing performance of microlenses

The 3D model of microlens with the diameter of \( d \) having circular nanoholes arranged in a hexagonal lattice is established by using the FDTD method. The collimated, \( x \)-polarized light with an operating wavelength of 532 nm is illuminated, a well-defined focal spot (location of maximum intensity) is observed in the \( x-z \) plane (the same as \( y-z \) plane since the electromagnetic field is distributed symmetrically) through the center of the 4-\( \mu \)m microlenses, and the full-width at half-maximum (FWHM) of the spot at the focal plane is 1.25 \( \mu \)m (Fig. 5a), which is close to the Rayleigh diffraction limit of 0.912 \( \mu \)m calculated by 0.611/NA [31]. Furthermore, the far-field optical patterns are simulated with the lattice spacings of 522 and 900 nm, and the operating wavelengths of 532 and 633 nm are selected. The simulated focal lengths are 12 and 10.4 \( \mu \)m for the 4-\( \mu \)m microlens at \( \lambda = 532 \) and 633 nm, respectively, and the value increases to 46 \( \mu \)m for the 8-\( \mu \)m microlens at \( \lambda = 532 \) nm, as shown in Fig. 5a, c. Because their focusing effects are not the consequence of the wavefront engineering, 4-\( \mu \)m microlenses with 522- or 900-nm lattice spacing have nearly identical focal spots, which validates that the focal length depends mainly on the lens size and the working wavelength.

The focal spot is subject to the classical Rayleigh diffraction limit because the far-field focusing does not originate from the recovery of evanescent field [32] or super-oscillations [33]. Hence, the dependence of focal length on the operating wavelength can be expressed by a relationship derived from the Rayleigh-Sommerfeld (R-S) integral [18]. From Fig. 5b, d, we can see that the calculated optical field distributions by the R-S integral agree very well with the FDTD simulation results for both cases. However, the measurement results show a slight difference due to the various errors introduced during the fabrication procedure and optical measurement. It is worth noting that for the 4-\( \mu \)m case, the measurement deviation in contrast to the simulation is 8.3\%, compared to 1.1\% for the 8-\( \mu \)m case. In other words, the microlenses with a larger diameter are more insensitive to the normal errors.

Since the focusing performance is irrelevant to the wavefront engineering, the optical throughput of the focal spot depends on the SP-enhanced transmission through the subwavelength apertures [18]. When the results from Fig. 6 are compared with the transmission spectra from the different microlenses, the enhanced transmissions and the suppressed transmissions are present at different wavelengths depending on the lattice spacing. According to previous reports [34], the selective spectral response was discovered to be stemming from the combined effect of the propagating surface plasmon resonance (PSPR)
sustained at the metal/dielectric interface and the localized surface plasmon resonance (LSPR) around the nanoholes. As observed in Fig. 6c, the locations of the transmission dips, as implied by the circles, come up with a red shift along the $x$-coordinate axis as the lattice spacing increases, so it is with the transmission peaks. This endows the microlenses with unusual abilities to control the optical throughput at specific wavelengths and ensures microlenses being easily designed with a high-efficiency focusing. Figure 6a, b gives the field distributions of a 4-μm microlens for the case of $P = 400$ nm at the dip wavelength of 581 nm and the peak one of 681 nm, respectively. Except for a decrease in the focal length introduced by the increased wavelength, the intensity of the focal spot for the wavelength of 681 nm is almost 100 times more than that of $\lambda = 581$ nm.

II. Influences of random defects

Despite the fact that NSL is a highly parallel fabrication method to create large-area nanohole arrays in the microlenses and their arrays, one perceived problem of
this technique is that the defects are randomly distributed throughout the nanohole layer of the microlenses. The defects are nearly inevitable during the self-assembly process of nanospheres, which are normally thought to fundamentally limit the resolution and penetration depth of the optical methods. However, it is astonishing that defects offer an unusual alternative to conventional periodic structures to manipulate light. Some random defects are demonstrated to improve, rather than deteriorate the sharpness of the focus in a specific optical experiment [35, 36]. Therefore, the influence of defects spawned from our fabrication process on the focusing performance of microlenses studied here is essential for practical applications and the further research about random photonic crystals.

Apart from the abovementioned vacancies, dislocations, and multilayer defects that are generated from the self-assembly procedure of nanospheres, the shape deformation of nanoholes may also exist in the ultimate microlenses during the PS shrinkage and PS removal as a result of the imbalanced O₂ plasma etching. Therefore, these defects we considered can be classified as the form and position defects. To demonstrate the impact of the form defects on the focusing performance of microlenses, we present the microlenses with different out-of-roundness σ in the nanoholes when their common fill factor is 0.33 and the corresponding optical focusing images are given in Fig. 7a. Obviously, these focusing patterns for cases of σ = 0.4 and σ = 0.7 are almost the same except the slight variation of foci intensity. More obviously, as seen in Fig. 7a, the similar foci patterns in a₁, a₂, and a₃ indicate that the increased degree of deformation and the change of deformation direction impose negligible influence on the focusing properties of microlenses.

To explore the influences of position defects, we deviate the positions of nanoholes to different directions with a length δ. The deviation direction of each hole is randomly distributed from hole to hole and kept constant for each δ (see Fig. 7b). With the increase of δ, the nanoholes deviate from the perfectly close-packed state and become “more random.” Three similar focusing patterns of microlenses regarding different random positions of nanoholes, δ = 0, 50, and 100 nm, are obtained. Furthermore, it is observed that a slight decrease in foci intensity appears on the field profile with a more random nanohole array. Above all, it reveals that the form and position defects within microlenses play little effect on the focusing performance and mostly just modulate the foci intensity.

III. Focusing performance of microlens arrays

Figure 8 shows the fabricated 3 × 3 microlenses array with different spacings and the experimentally measured optical patterns under λ = 532 nm, as well as the broadband illumination. Note that the focal spots from microlenses with more dislocations in the array are weaker.

![Fig. 7](image_url)

**Fig. 7** a) Focal spots from microlenses are independent of the out-of-roundness error σ of nanoholes. The focusing properties do not show a clear change when σ = 0 (rounded nanoholes) in Fig. 5 is increased to a₁ σ = 0.4, a₂ σ = 0.7 with a horizontal distorted direction, and a₃ σ = 0.7 with a perpendicular distorted direction. b) Introduction of spatial randomness into the positions of nanoholes. Deviation directions are randomly different from hole to hole, but the deviation length δ is kept constant for each hole. The same focusing patterns are obtained when the deviation length b₁ δ = 0, b₂ δ = 50 nm, and b₃ δ = 100 nm.
than those from other microlenses in Fig. 8b. It is because the dislocation defects effectively reduce the number of nanoholes contributing to the optical interference pattern. Further, the results show excellent agreement with those obtained by the FDTD simulations that the defects mainly affect the foci intensity. In addition, the microlenses can focus the broadband white light (Fig. 8 (a2), and (b2)) due to the minimal chromatic aberration. The focal spots under the white light illumination have the similar lateral dimensions as those under a single wavelength, while the broadband focal length is approximately the average of the focal lengths at the SP-enhanced wavelengths. In addition, the focusing coupling effect in microlens array which we had analyzed in our previous research [37] emerges in the obtained focusing patterns as the regions C, D, and E flagged in Fig. 8 (b1) and (b2).

Conclusions
To sum up, we have demonstrated for the first time that the NSL technique as a highly parallel and low-cost method can be used to fabricate the metallic planar microlenses functioning over the entire visible spectrum. Supported by the simulated and experimental results, the focusing properties of microlenses can be explained by a combination of both optical interference and surface plasmon effects. Taking into consideration the lattice spacing and diameter of nanoholes, the microlenses can be tailored to provide high transmission at specific wavelengths. The focusing performance of microlenses from the perfect to the defective state is exploited by the FDTD method. Both the simulations and experiments clarify that the random defects in nanohole arrays simply affect the focusing efficiency of microlenses and the focusing coupling effect as predicted occurs under both the single wavelength and broadband illumination. The broadband focusing capability, miniaturized size, and versatile fabrication technique all together open a great potential for compact and inexpensive all-optical or opto-electronic devices such as photovoltaics [26], color filters [38], and refractive index sensing [39].

Abbreviations
3D: Three-dimensional; CCD: Charge-coupled device; FDTD: Finite-difference time-domain; FWHM: Full-width at half-maximum; LIL: Laser interference lithography; NA: Numerical aperture; NSL: Nanosphere lithography; PS: Polystyrene; SEM: Scanning electron microscope.
Funding
The work is financially supported by the National Natural Science Foundation of China (NSFC) (51375400, 51622509), the Specific Project for the National Excellent Doctoral Dissertations (201430), and the 111 Project (B13044).

Authors’ Contributions
The idea of the study was conceived by YY. PW carried out the numerical stimulation and wrote the manuscript. PW and XY performed the experiment. The idea of the study was conceived by YY. PW carried out the numerical stimulation and wrote the manuscript. PW and XY performed the experiment. The idea of the study was conceived by YY. PW carried out the numerical stimulation and wrote the manuscript. PW and XY performed the experiment.

Competing Interests
The authors declare that they have no competing interests.

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References
1. Lucchetti L, Tasseva J (2012) Optically recorded tunable microlenses based on dye-doped liquid crystal cells. Appl Phys Lett 100:181111
2. Katz Y, Ferber Y, Perano JR, Hubbard RF, Sprangle P, Zigler A (2013) Boron nitride plasma micro lens for high intensity laser pre-pulse suppression. Opt Express 21:5077–85
3. De AF, Patrini M, Das G, Maksymov I, Galli M, Bushinaro L, Andreani LC, Di FE (2008) A hybrid plasmonic-photonic nanodevice for label-free detection of a few molecules. Nano Lett 8:2321–7
4. Kang D, Pang C, Kim SM, Cho HS, Um HS, Choi YW, Suh KY (2012) Shape-controllable microlens arrays via direct transfer of photoreactive polymer droplets. Adv Mater 24:1709–15
5. Kanzhiro O, Hiyoshi K, Tjendewo L, Kazuno N, Takefumi Y, Toru N (2011) Retinal image contrast obtained by a model eye with combined correction of chromatic and spherical aberrations. Biomed Opt Express 2:1443–57
6. Moghim MJ, Fernandes J, Kancher A, Jang H (2015) Micro-Fresnel-zone-plate array on flexible substrate for large field-of-view and focus scanning. Sci Rep 5:15861
7. Lee MK, Kuo KH (2007) Single-step fabrication of Fresnel microlens array on sapphire substrate of flip-chip gallium nitride light emitting diode by focused ion beam. Appl Phys Lett 91:051111
8. Fang N, Lee H, Sun C, Zhang X (2005) Sub-diffraction-limited optical imaging with a silver superlens. Science 308:534–7
9. Yao J, Lee AP, Gray SK, Moore JS, Rogers JA, Nuzzo RG (2010) Functional nanostructured plasmonic materials. Adv Mater 22:1102–10
10. Barnes WL, Dereux A, Ebbes CW (2004) Surface plasmon subwavelength optics. Nature 424:824–30
11. Vergelders L, Catssyse PB, Yu Z, White JS, Barnard ES, Brongersma ML, Fan S (2009) Plane lenses based on nanoscale slit arrays in a metallic film. Nano Lett 9:235–8
12. Lin L, Goh XM, Mcguinness LP, Roberts A (2010) Plasmonic lenses formed by two-dimensional nanometric cross-shaped aperture arrays for Fresnel-region focusing. Nano Lett 10:1936–40
13. Huang K, Liu H, Garciavidal FJ, Hong M, Luk’Yanchuk B, Teng J, Qiu CW (2015) Ultrahigh-capacity non-periodic photon sieves operating in visible light. Nat Commun 6:7059
14. Chen X, Chen M, Mehmoond MQ, Wen D, Yue F, Qiu CW, Zhang S (2015) Longitudinal multilayer metal films for circulary polarized light. Adv Opt Mater 3:120–4
15. Yu Y, Zappe H (2011) Effect of lens size on the focusing performance of plasmonic lenses and suggestions for the design. Opt Express 19:9434–44
16. Zhu Y, Yuan W, Yu M, Diao J (2013) Metallic planar lens formed by coupled width-variable nanolenses for superfocusing. Opt Express 23:20124–31
17. Yu Y, Zappe H (2012) Theory and implementation of focal shift of plasmonic lenses. Opt Lett 37:1592–4
18. Gao H, Hyun JK, Lee MH, Yang JC, Lauhon LJ, Odom TW (2010) Broadband plasmonic microlenses based on patches of nanoholes. Nano Lett 10:4111–6
19. Bloomstein TM, Marchant MF, Deneault S, Hardy DE, Rothschild M (2006) 22-nm immersion interference lithography. Opt Express 14:6434–43
20. Uesawa F, Katsumata M, Ogawa K, Takeuchi K, Omori S, Yoshizawa M, Kawahara H (2004) Lithography of choice for the 45-nm node: new medium, new wavelength, or new beam. Proc SPIE 5377:34–45
21. Dong J, Liu J, Kang G, Xie J, Wang Y (2014) Pushing the resolution of photolithography down to 15 nm by surface plasmon interference. Sci Rep 4:5618
22. Zhang X, Ma X, Fei D, Zhao P, Liu H (2011) A biosensor based on metallic plasmonic crystals for the detection of specific bioaffinities. Adv Funct Mater 21:4219–27
23. Kostiarek A, Kandulski W, Glaczynska H, Giersig M (2005) Fabrication of nanoscale rings, dots, and rods by combining shadow nanosphere lithography and annealed polystyrene nanosphere masks. Small 1:349–44
24. Law S, Yu L, Rosenberg A, Wasserman D (2013) All-semiconductor plasmonic nanoantennas for infrared sensing. Nano Lett 13:4560–74
25. Lee SA, Hong SK, Park JK, Lee S (2014) Vertically oriented, three-dimensionally tapered deep-subwavelength metallic nanohole arrays developed by photofluidization lithography. Adv Mater 26:5251–8
26. Menezes JW, Ferreira JS, Santos MIL, Cescato L, Brolo AG (2010) Large-area fabrication of periodic arrays of nanoholes in metal films and their application in biosensing and plasmonic-enhanced photovoltaics. Adv Funct Mater 20:9818–24
27. Cataldo S, Zhao J, Neubrech F, Frank B, Zhang C, Braun PV, Giessen H (2012) Hole-mask colloidal nanolithography for large-area low-cost metamaterials and antenna-assisted surface-enhanced infrared absorption substrates. ACS Nano 6:979–85
28. Lerond T, Proust J, Yockelle-Kleirve H, Gerard D, Plain J (2011) Self-assembly of metallic nanoparticles into plasmonic rings. Appl Phys Lett 99:231109
29. Hall AS, Friesen SA, Mallouk TE (2013) Wafer-scale fabrication of plasmonic crystals from patterned silicon templates prepared by nanosphere lithography. Nano Lett 13:2623–7
30. Xu H, Liu X, Su G, Zhang B, Wang D (2012) Electrostatic repulsion-controlled formation of polydopamine-gold Janus particles. Langmuir 28:13060–5
31. Huang K, Ye H, Teng J, Yeo SP, Luk’Yanchuk B, Qiu CW (2013) Optimization-free superoscillatory lens using phase and amplitude masks. Laser Photonics Rev 8:152–7
32. Merlin R (2007) Radiationless electromagnetic interference: evanescent-field lenses and perfect focusing. Science 317:927–9
33. Roy T, Rogers ET, Yuan G, Zholudev N (2014) Point spread function of the optical needle super-oscillatory lens. Appl Phys Lett 100:231109
34. Duempelmann L, Casari D, Luu-Dinh A, Gallinet B, Novotny L (2015) Color rendering plasmonic aluminum substrates with angular symmetry breaking. ACS Nano 9:12383–91
35. Tatton TA, Norris DJ (2002) Device physics: definitive promise in photonics. Nature 416:685–6
36. Yan Q, Wang L, Zhao XS (2007) Artificial defect engineering in three-dimensional colloidal plasmonic crystals. Adv Funct Mater 17:3695–706
37. Yu Y, Ping W, Zhu Y, Diao J (2016) Broadband metallic planar microlenses in an array: the focusing coupling effect. Nanoscale Res Lett 11:109
38. Wang L, Ng R, Dinh AC, Jiali M, Yu Y, Yang JK (2016) Large area plasmonic color palettes with expanded gamut using colloidal self-assembly. ACS Photon 3:627–33
39. Cheng K, Wang S, Cui Z, Li Q, Dai S, Du Z (2012) Large-scale fabrication of plasmonic gold nanohole arrays for refractive index sensing at visible region. Appl Phys Lett 100:253101

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