Integrated lithography to prepare arrays of rounded nano-objects

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ABSTRACT

An integrated lithography method is presented to prepare rounded nano-objects with variable shape, in arrays with arbitrary symmetry and wavelength-scaled periodicity. Finite element method was applied to determine the near-field confinement under silver and gold colloid spheres' monolayers illuminated by circularly polarized beams possessing periodic intensity distribution, and to predict the shape of nano-objects, which can be fabricated on thin noble metal layers on glass substrates. It was shown that illumination by perpendicularly incident homogeneous beam results in hexagonal array of uniform nano-rings, while uniform nano-crescents appear due to single obliquely incident beam. Illumination of colloid sphere monolayers by interfering beams causes development of co-existent nano-rings and nano-crescents. It was demonstrated that the periodicity of complex patterns is determined by the wavelength and angle of incidence; the inter-object distance is controlled by the relative orientation of interference patterns with respect to colloid sphere monolayers; the nano-object size is determined by the wavelength, sphere diameter and material; while the near-field distribution sensitively depends on the direction of illumination by circularly polarized light. We present complex patterns of various rounded nano-objects that can be uniquely fabricated via Circular Integrated Interference and Colloid sphere Lithography (CIICL), and applied as plasmonic and meta-materials.

1. INTRODUCTION

Micro- and nano-scaled objects with arbitrary shape in variable patterns:
demand in recent nano-science and in practical nano-technological applications
for technologies, which make possible high resolution pattern fabrication at low cost

- classical scanning beam lithography methods [1]
- laser-based interference methods: parallel techniques, diffraction limited [2]
- laser induced self-organized processes: nano-scaled features generation [3]
- combination of interference lithography and self-organized processes [4]
- laser-based colloid-sphere lithography (LCSL): only hexagonal arrays of nano-objects [5, 6]
- control the near-field distribution applying obliquely incident beams [6, 7]
- metal colloid spheres: nano-scaled resolution, inter-particle coupling [8, 9]
- various patterns with non-hexagonal symmetry via colloid sphere lithography:
  - ➢ assembly process control by realizing chemical pre-treatment of colloid spheres [10]
  - ➢ application of templates to predefine the spheres' position [10, 11]
- integrated lithography method to produce wavelength-scaled periodic arrays with arbitrary symmetry, versatile nano-objects, control of coupling between metal spheres [12]

Circular Integrated Interference and Colloid sphere Lithography (CIICL):

- ✓ integration of classical interference lithography with colloid-sphere lithography
  high degree of freedom in complex pattern generation
- ✓ circularly polarized light
  fabrication of rounded objects

2. THEORETICAL METHODS

Illumination of colloid sphere monolayers by two circularly polarized beams possessing different lateral intensity distributions
Finite Element Method to determine the near-field enhancement under the colloid spheres

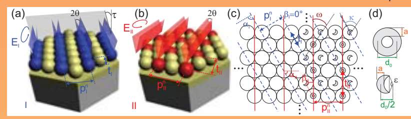
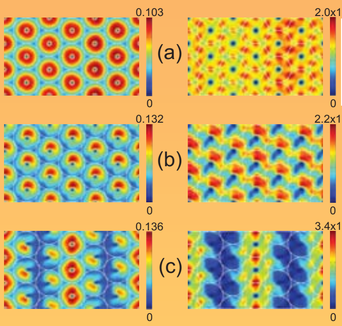


Figure 1. Illumination of hexagonal colloid sphere monolayers by two interfering circularly polarized beams in (a) CIICL-I geometry, where the angle of incidence (θ) and the tilt of the incidence plane (τ) is also indicated, and in (b) CIICL-II geometries. (c) The relative orientation of the plane of incidence (α), and the interference pattern (β), with respect to the (1, 0, 0) crystallographic direction in CIICL-I (blue) and in CIICL-II (red) geometries. The relative orientation of nano-objects with respect to the (1, 0, 0) direction (κ) and interference pattern (ω) is also indicated. (d) The size parameters of the rounded objects are: diameter (d_0), thickness (a), and gap-angle (ε).

3. RESULT AND DISCUSSION

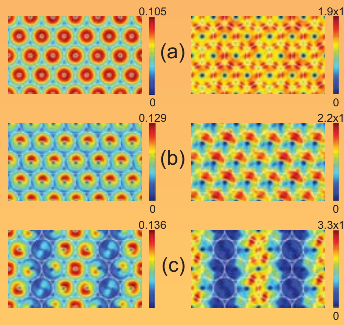
250 nm Ag spheres illuminated by 266 nm light in CIICL-I



266 nm → 250 nm Ag	θ=0°	θ=11.8°	CIICL-I (11.8°)	
Type	ring	crescent	ring	crescent
d_0	82	80	83	78
a	85	63	90	40
ε	-	140°	-	90°
ω	-	-	0°	120°
κ	-	105°	0°	120°
I	0.103	0.132	0.136	

Figure 2. Intensity distribution and Rh map under 250 nm Ag colloid spheres illuminated by 266 nm circularly polarized light: single (a) perpendicularly, (b) obliquely incident beams, and (c) two beams interfering in CIICL-I geometry. Size parameters are summarized in Table-2.

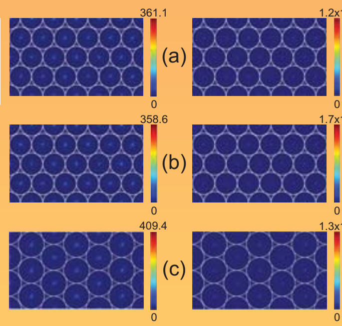
250 nm Ag spheres illuminated by 266 nm light in CIICL-II



266 nm → 250 nm Ag	θ=0°	θ=10.2°	CIICL-II (10.2°)	
Type	ring	crescent	ring	crescent
d_0	82	80	84	80
a	85	70	75	70
ε	-	130°	-	120°
ω	-	-	30°	120°
κ	-	120°	60°	150°
I	0.105	0.129	0.126	

Figure 3. Intensity distribution and Rh map under 250 nm Ag colloid spheres illuminated by 266 nm circularly polarized light: single (a) perpendicularly, (b) obliquely incident beams, and (c) two beams interfering in CIICL-II geometry. Size parameters are summarized in Table-3.

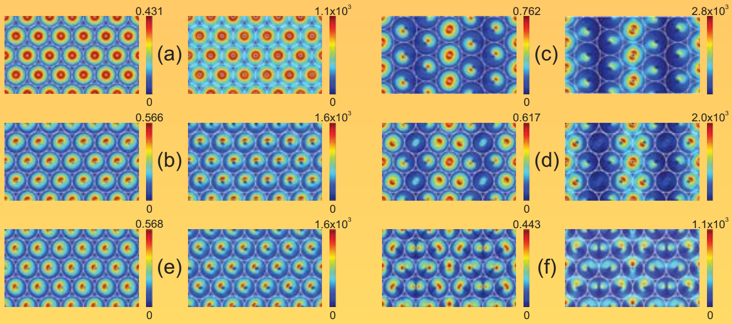
250 nm Ag spheres illuminated by 400 nm light in CIICL-II



400 nm → 250 nm Ag	θ=0°	θ=15.5°	CIICL-II (15.5°)	
Type	ring	crescent	ring	crescent
d_0	~10	-	~10	-
a	-	-	-	-
ε	-	-	-	-
ω	-	-	-	-
κ	-	-	-	-
I	361.106	358.647	409.381	

Figure 4. Intensity distribution and Rh map under 250 nm Ag colloid spheres illuminated by 400 nm circularly polarized light: single (a) perpendicularly, (b) obliquely incident beams, and (c) two beams interfering in CIICL-II geometry. Size parameters are summarized in Table-4.

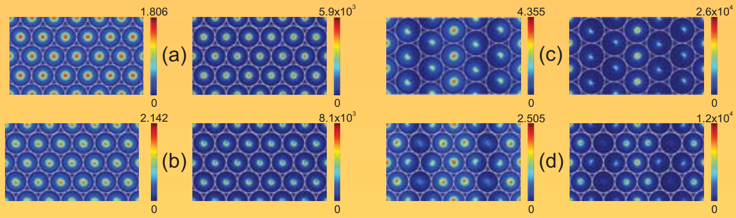
250 nm Au spheres illuminated by 400 nm light in CIICL-I and CIICL-II



400 nm → 250 nm Au	θ=0°	CIICL-I (17.9°)		θ=15.5°	CIICL-II (15.5°)		θ=15.5° rotated	CIICL-II (15.5°) tilted	
Type	ring	ring	crescent	crescent	ring	crescent	crescent	ring	crescent
d_0	51	44	50	55	54	50	50	49/37	48
a	66	55	30	66	70	45	32	88/43	47
ε	-	-	110°	170°	-	150°	160°	-	170°
ω	-	30°	120°	-	30°	120°	-	0°	30°/150°
κ	-	30°	120°	90°	60°	150°	30°	30°	60°/180°
I	0.431	0.762		0.566	0.617		0.568	0.662	

Figure 5. Intensity distribution and Rh map under 250 nm Au colloid spheres illuminated by 400 nm circularly polarized light: single (a) perpendicularly, (b) obliquely incident beams, two beams interfering in (c) CIICL-I and (d) CIICL-II geometry. The plane of light incidence is (e) rotated by α = 45° for obliquely incident single beam, and (f) tilted by τ = 45° for both two beams interfering in CIICL-II geometry. Size parameters are summarized in Table-5.

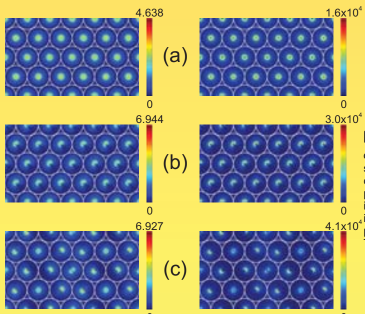
250 nm Au spheres illuminated by 532 nm light in CIICL-I and CIICL-II



532 nm → 250 nm Au	θ=0°	CIICL-I (24.2°)		θ=20.77°	CIICL-II (20.77°)	
Type	ring	ring	crescent	crescent	ring	crescent
d_0	30	27	30	33	29	32
a	34	31	16	18	34	21
ε	-	-	90°	180	-	210°
ω	-	30°	120°	-	120°	30°
κ	-	30°	120°	150°	150°	60°
I	1.806	4.355		2.142	2.505	

Figure 6. Intensity distribution and Rh map under 250 nm Au colloid spheres illuminated by 532 nm circularly polarized light: single (a) perpendicularly, (b) obliquely incident beams, two beams interfering in (c) CIICL-I and (d) CIICL-II geometry. Size parameters are summarized in Table-6.

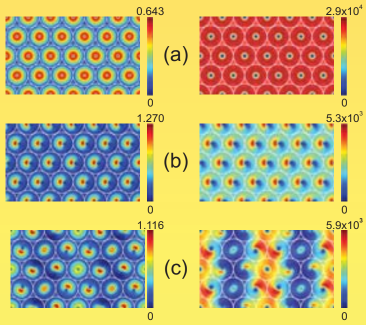
100 nm Au spheres illuminated by 532 nm light in CIICL-II



532 nm → 100 nm Au	θ=0°	θ=62.5°	CIICL-II (62.5°)	
Type	ring	crescent	ring	crescent
d_0	13	12	-	13
a	15	8	-	12
ε	-	180°	-	160°
ω	-	-	30°	135°
κ	-	60°	60°	165°
I	4.6	6.8	6.9	

Figure 7. Intensity distribution and Rh map under 100 nm Au colloid spheres illuminated by 532 nm circularly polarized light: single (a) perpendicularly, (b) obliquely incident beams, and (c) two beams interfering in CIICL-II. Size parameters are summarized in Table-7.

100 nm Au spheres illuminated by 400 nm light in CIICL-II



400 nm → 100 nm Au	θ=0°	θ=41.8°	CIICL-II (41.8°)	
Type	ring	crescent	ring	crescent
d_0	23	20	23	24
a	30	24	31	23
ε	-	150°	-	120°
ω	-	-	-	105°
κ	-	45°	-	135°
I	0.643	1.27	1.116	

Figure 8. Intensity distribution and Rh map under 100 nm Au colloid spheres illuminated by 400 nm circularly polarized light: single (a) perpendicularly, (b) obliquely incident beams, and (c) two beams interfering in CIICL-II. Size parameters are summarized in Table-8.

4. CONCLUSION

We introduce a circularly polarized integrated interference and colloid sphere lithography. This integrated lithography combines the advantages of two techniques, as the symmetry and periodicity of the wavelength-scaled interference modulation determines a periodic pattern, while the intensity concentration in the near-field of colloid-spheres occurs only within an area much smaller than the wavelength. The analysis of the resulted near-field distributions has shown that the *a* thickness and d_0 diameter of the nano-rings and nano-crescents as well as the gap-angle of the latter are determined by the wavelength and by the colloid spheres material and diameter together. The local intensity distribution is fundamentally influenced by the sphere material in specific spectral interval, illumination close to Fröhlich-condition results in extremely tight field confinement. The orientation of the non-rotationally symmetric objects with respect to the (1, 0, 0) direction and to the interference pattern is determined by the illumination direction of specific hexagonal colloid sphere monolayers. This orientation might be tuned by varying the azimuthal angle, incidence plane tilt, wavelength, and sphere diameter, while maintaining analogous period-to-diameter ratio in CIICL-II geometry.
The patterns of nano-rings and C-shaped objects are promising in several applications, as they strongly modify the spectral properties of thin metal films, and result in very strong near-field confinement. The size and the orientation of e.g. C-shaped objects can be varied along arrays with this technique, which is important in meta-material design.

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Applications

Fabrication of C-shaped aperture arrays [13]

Plasmonic materials for spectral engineering [14]

Meta-materials [15]

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