High-Throughput Fabrication of TiO_2-based Metalenses with Absolute Efficiencies Over 80% and Relative Efficiencies Over 90%

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Planar metalenses, waveguides, and diffractive optics are enabling for augmented reality (AR), light field displays, compact precision imaging and 3D sensors but are challenging to fabricate in a cost effective and scalable manner. Unlike the well-established and mature Si fabrication technology available for metalenses in the infrared, metalenses operating in the visible range have faced significant hurdles for fabricating subwavelength structures and high aspect-ratio features with precise control over the shape and sidewall roughness.

Recently, our group developed a new method enabling the fabrication of all-inorganic TiO_2 structures via additive manufacturing using nanoimprint lithography (NIL). We demonstrated that metalenses can be directly printed using stamps in a fast, scalable, and cost-effective pathway.[1-2] In our NIL-based approach, we fabricate all inorganic, high refractive index structures using a TiO_2 nanocrystal (NC)-based dispersion ink. Here we extended our work by reformulating our TiO_2 NC-based ink using mixtures of sized-controlled TiO_2 nanoparticles of different diameters, which enables more efficient packing, higher refractive index, and less shrinkage during imprinting. As shown in Figure 1, this strategy yields lenses with refractive indices as high as 1.97 and absolute and relative efficiencies >80% and >90%, respectively. Our results reveal that this simple, additive manufacturing-based approach can produce high-efficiency metalenses comparable to or more efficient than metalenses fabricated using a subtractive manufacturing platform.

References:

[1] Einck, V.J.; Torfeh, M; McClung, A; Jung, DE; Mansouree, M; Arbabi, A; Watkins, JJ. "Scalable Nanoimprint Lithography Process for Manufacturing Visible Metasurfaces Composed of High Aspect Ratio TiO 2 Meta-Atoms" ACS Photonics 2021, 8 (8), 2400–2409.

[2] Jung, DE; Howell, IR; Einck, VJ; Arisoy, F.D.; Verrastro, L.D.; McClung, A; Arbabi, A; Watkins, JJ "Refractive Index Tuning of All-Inorganic TiO2 Nanocrystal-Based Films and High Aspect Ratio Nanostructures Using Atomic Layer Deposition: Implications for High-Throughput Fabrication of Metalenses" ACS Applied Nanomaterials, 2023, 6, 3, 2009–2019.

(a)

Design	Row/ Column	C1	C2	C3	C4	C5	C6	C7	C8	C9	Ave.	St.Dev.
-20 nm	R1	*46.8	70.2	70.8	68.9	67.1	67.7	68.3	70.2	70.2	69.2	1.4
-10 nm	R2	70.8	73.2	69.5	70.8	70.8	71.4	72.0	73.8	73.8	71.8	1.5
0 nm	R3	73.8	72.6	72.6	75.7	75.7	75.1	71.4	71.4	70.2	73.2	2.0
+10 nm	R4	72.0	72.0	75.7	77.5	74.5	72.6	72.6	74.5	72.0	73.7	2.0
+20 nm	R5	69.5	72.6	79.4	75.7	72.0	72.6	76.3	78.8	78.2	75.0	3.5
-20 nm	R6	68.9	73.8	70.8	70.8	70.8	73.2	73.2	74.5	73.8	72.2	1.9
-10 nm	R7	72.6	76.3	73.8	70.8	72.0	75.1	76.3	76.3	72.0	73.9	2.2
0 nm	R8	75.7	78.2	73.2	72.0	72.6	77.5	78.2	76.9	72.6	75.2	2.6
+10 nm	R9	79.4	79.4	70.2	70.2	73.2	77.5	81.2	79.4	71.4	75.8	4.5
Total 80 lenses								90.4% (relative)			73.4	3.1

Efficiency ≥ 70% Efficiency ≥ 75% Efficiency ≥ 77% Efficiency ≥ 80%

(b)

Design	Rows	Ave.	St.Dev.
-20 nm	R1 & R6	69.1	6.3
-10 nm	R2 & R7	72.8	2.2
0 nm	R3 & R8	74.5	2.4
+10 nm	R4 & R9	75.1	3.6
+20 nm	R5	74.6	3.5

(c)

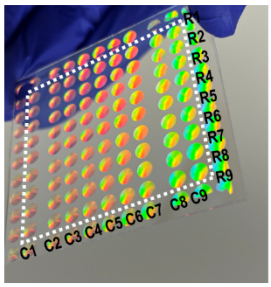

Figure 1. (a) The absolute focusing efficiencies of 81 lenses across 5 different design and (b) their average and standard deviation for each design in (c) one calcined metalens imprint prepared from a blended ink of size-controlled TiO_2 particles.