

Sustainable Manufacturing of Optical Metasurfaces with Engineered Optical Materials

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Abstract— Metasurfaces offer unprecedented control of amplitude, phase, and polarization while maintaining an ultrathin form factor. Despite these advantages, their reliance on nanoscale building blocks requires high resolution patterning. Conventional fabrication approaches such as electron beam lithography are based on direct writing, which suffers from low throughput and high cost, and is therefore not sustainable for large scale deployment. To address these limitations, we develop engineered optical materials that are fully compatible with nanoimprint lithography, enabling single step manufacturing of metasurfaces with scalable, low cost, and high throughput production. The first engineered optical material is a nanoparticle embedded resin, PER, created by dispersing high index nanoparticles into a resin to increase its effective refractive index while maintaining imprint compatibility. By choosing nanoparticles with appropriate optical properties, PERs can be tailored for different spectral ranges. TiO_2 PER provides high index performance in the visible region, ZrO_2 PER offers a wide bandgap and transparency in the ultraviolet, and Si PER enables high index operation in the near infrared. Using these PER, metasurfaces across a wide wavelength range can be produced in a single imprinting step. The second engineered optical material is a hybrid material in which a thin high index coating is deposited on the imprinted resin structures. This approach significantly increases the effective refractive index of the entire nanostructure. Depending on the target wavelength range, ZrO_2 hybrid materials are used for ultraviolet operation and TiO_2 hybrid materials are used for visible wavelengths. The third engineered optical material is a sol-gel based material that forms TiO_2 structures through thermal sintering after imprinting. This method is well suited for fabricating high index metasurfaces and allows control of the TiO_2 crystal phase, including anatase and rutile, by adjusting the curing temperature, thereby enabling high performance metasurface implementations. The fourth engineered optical material expands functionality by modifying either the matrix or the inclusions with functional species. Using polyvinyl alcohol as a humidity responsive matrix enables tunable metasurfaces, while hydroxypropyl cellulose allows fabrication of water soluble and environmentally friendly labels. Replacing the inclusions with quantum dots enables directional control of photoluminescence for active optical functionalities. All of these engineered optical materials can be replicated through wafer scale master molds fabricated by photolithography, enabling large area and high-volume production. Furthermore, nanoimprint lithography systems are being advanced from plate-to-plate configurations toward roll-to-plate and roll-to-roll systems, achieving higher yield, improved process automation, and increased throughput, bringing metasurface manufacturing closer to industrial scale. These mass producible metasurfaces are applicable to diverse technologies including VR/AR displays, 3D displays, 3D sensors, LiDAR, and compact imaging systems.

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