URSI GASS 2021, Rome, Italy, 28 August - 4 September 2021

Metasurfaces for nano-optical sensing

A. Femius Koenderink*[(1)], Ruslan Röhrich[(1,2)], Tom A.W. Wolterink[(1)], Robin D. Buijs[(1)], Nick J. Schilder[(1)], and Ewold Verhagen[(1)]
(1) Center for Nanophotonics, AMOLF, Science Park 104, 1098 XG Amsterdam, The Netherlands, e-mail: f.koenderink@amolf.nl
(2) ARCNL, Science Park 110, 1098 XG Amsterdam, The Netherlands

Optical metasurfaces consisting of metal or dielectric nanoscatterers are widely studied due to their ability to control optical fields at the nanoscale. These metasurfaces are optical elements that are engineered to shape reflected and transmitted optical fields, giving rise to a variety of applications such as flat optics, vector beam generation or sub-wavelength focusing. Here, we investigate the potential of employing metasurfaces for nano-optical sensing and imaging with subwavelength resolution. The idea is to exploit complex light scattering from a metasurface, programmable illmunination, and finally retrieval of spatial information of a sample from far-field scattering images.

Obtaining nanoscale spatial information without real-space imaging, but instead by analysis of diffraction patterns is already a valuable tool in metrology. For instance, in the semiconductor industry the alignment of printed layers is analysed by socalled diffraction-based overlay metrology, performed on grating structures that are placed on the wafer specifically for the purpose. The aim is to retrieve the nanoscale lateral shift between two gratings from their far-field scattering profile. In our work we ask the questions how you optimally choose the "target" if you generalize from a grating to a metasurface, how you would optimally choose the illumination, for instance allowing for wavefront shaping, and how to retrieve information from far-field observables, such as angle-resolved radiation patterns.

As a first scenario we consider retrieving the position of a localized object in a nanophotonic structure with superresolution, though without making any real space image. We present a platform-agnostic method for retrieving spatial information from just far-field diffraction patterns, exploiting that light scattering in a structure of resonant nanostructures can yield radiation patterns that depend very strongly on geometry due to near-field interactions. As a proof-of-principle demonstration, we apply this to experimental data in which we determine the position of a point-like cathodoluminescence light source relative to a bullseye antenna with deep sub-wavelength accuracy by imaging only angle-resolved radiation patterns. We present an inversion technique based on singular value decomposition of calibration data, and show the capability to localize light source with deeply sub-diffractive resolution, surpassing $\lambda/50$.

As a second scenario we ask how to optimally tailor metasurface geometries to obtain nanoscale spatial information. In particular we investigate how well different 2D antenna array designs, ranging from periodic, to deterministic aperiodic perform as overlay error sensors in diffraction-based overlay metrology. By moving away from simple periodic gratings, the diffraction patterns become very rich in features. These deterministic diffraction, or speckle, patterns in principle giving the opportunity to encode spatial information more effectively than is possible in just a few diffraction orders. However, this increase in the number of information channels comes at the expense of diffraction efficiency into each channel. Using a stochastic optimization algorithm we analyse optimal geometries for enhanced position sensitivity in far-field scattering.

Finally, as a step towards near-field imaging of nanoscale samples, we discuss the idea of freely programming the spatial structure of the optical near field above a strongly scattering metasurface by tailoring incident wavefronts, as is possible by wavefront shaping through a spatial light modulator. Through optimization of the illumination field, we find that it is possible to selectively light up individual or multiple resonant nano-antennas, even if the antennas are identical, and at sub-diffractive spacings, too small to resolve within the diffraction limit. Moreover, we show that it is possible to light up patterns matching the complete Hadamard basis on small sub-diffractive grids of scatterers. This demonstrates how metasurfaces enable selective generation of complex sub-diffractive field patterns that could form an optimal basis for spatially-resolved sensing at the nanoscale.