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Design Criteria for Highly Non-Paraxial Flat Lenses

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A new class of two-dimensional metamaterials (metasurfaces), called planar optical elements (POEs), can be classified as having a microscopic thickness ($\lesssim \lambda$), macroscopic transverse dimensions ($\gtrsim 100\lambda$), and being composed of an array of nanostructured light scatterers. The array is engineered to produce a desired collective response in the phase, polarization, and amplitude of the scattered optical wave. POEs can be found in broad range of micro- and nano-photonic technologies [1, 2]. For example, POEs have been built for use as waveplates in vortex beam generation [3], and for negative reflection and refraction [3,4]. For imaging purposes, the lens-type POE is referred to as a "flat lens", and an achromatic flat lens has recently been constructed [5]. In this paper, we pay attention to the general design criteria one should consider when constructing a flat lens.

Recent advances in fluorescence and near-field microscopies have enabled optical imaging with spatial resolution beyond the diffraction limit, and POEs may play an important role in the future of super resolution optical microscopy. We use numerical methods to directly integrate the scalar Kirchhoff diffraction integrals, without employing any analytic approximations, and explore what general characteristics of a flat lens produce the "tightest" possible point spread function.

For an aplanatic lens, which, given an axial plane wave as an input, will produce a spherical output wave, the resolution criterion is sometimes taken from Rayleigh, $0.61\lambda/NA$, and sometimes from Abbe, $\lambda/2NA$, where NA is the numerical aperture. In this paper, we show that there is a connection between these two resolution criteria. The former criterion is due to the Fraunhofer approximation, while the latter is due to heuristic arguments made early in the development of optical microscopy. In practice, all high- flat lenses are inherently nonparaxial (large diffraction angles), so the Rayleigh limit does not apply. By analyzing the results of our parametric study, we can make some general remarks about the resolution limit of an aplanatic, high- flat lens. Furthermore, we consider the effect of changing the response of the flat lens, from one which produces spherical waves (aplanatic) to one which produces the so-called "perfect" wave [6].

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