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## Optimization of imaging systems containing metasurfaces using a ray-wave model

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**Abstract** – We describe a methodology for optimizing imaging performances of optical imaging systems containing both refractive optical elements and metasurfaces. The modelling of systems is done with a combination of geometrical and Fourier optics to take into account diffraction effects in the computation of the imaging performances. A surrogate model based on the local periodicity approximation is used to calculate the optical response of meta-atoms. System optimization is performed using an evolutionary strategy that takes into account both the distribution of meta-atoms on the metasurface and the geometry of refractive lenses.

### I. INTRODUCTION

Metasurfaces are of great interest in the design of imaging systems, as they offer a large number of degrees of freedom in a lightweight and compact component. One of their applications in this field is the correction of chromatic and monochromatic aberrations, which is conventionally achieved by adding extra lenses to imaging systems, at a cost in terms of weight and bulk.

Although very promising, metasurfaces are still difficult to include in optical systems due to the complexity of designing them in conjunction with more conventional optical elements such as mirrors or refractive lenses. One of the difficulty comes from the difference in modeling of classical optical elements, which is done with ray tracing, versus the modelling of metasurfaces which requires electromagnetic simulations. Another is the huge number of degree of freedoms ( $\sim 10^9$ ) needed to fully describe a centimeter-scale metasurface.

The goal of this paper is to describe a numerical methodology for accurately and rapidly simulating a centimeter-scale optical system containing a metasurface, and to show how this new simulation framework can be exploited to optimize such a system.

### II. SIMULATION FRAMEWORK

The methodology used in this work is similar to what has been presented in [1]. It is based on the coupling of the field tracing equations developed in [2] with the angular spectrum propagation method (ASPM) [3]. The model also uses the local periodicity approximation (LPA) to approximate the optical response of meta-atoms to a non-planar wavefront. A surrogate model for the transmission coefficient of meta-atoms is built from full-wave simulations to quickly obtain the transmitted field after the metasurface. It is based on linear-interpolation but other approximation techniques like cubic splines or artificial neural networks could be used. In Fig.1 we summarize the different steps of the algorithm. In terms of computing, a simulation of a system with a 5 mm entrance pupil and a lattice period of 300 nm for the metasurface is carried out in half a second on a cluster equipped with a Nvidia H100 NVL and uses around 60 GiB of memory.

### III. APPLICATION TO THE DESIGN OF AN EYEPiece

The imaging system chosen for our study is derived from the systems presented in [4]. The system we consider consists of three refractive elements and a metasurface attached to the last one, as shown in Fig. 2(c). The refractive lenses are made of a single material, N-BK7 glass, and the metasurface meta-elements are nanorods composed of TiO<sub>2</sub> on a silica substrate. The aim of the metasurface is to reduce the system's chromatic aberrations, while

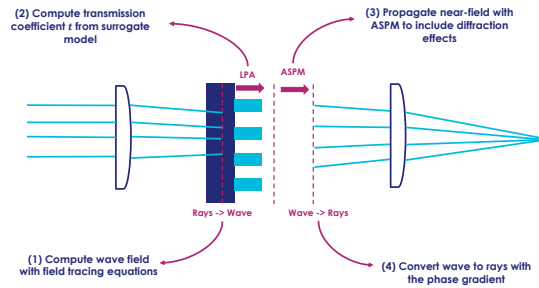


Fig. 1: Overview diagram of simulations steps involved in the ray-wave model

avoiding the use of additional lenses and materials that increases the system's cost and weight. Another advantage of using a metasurface is the reduction in the Petzval curvature of the system, to which the planar components do not contribute. The specifications of the target system are a focal length of 20 mm, less than 10% of distortion and a field of view of  $60^\circ$ .

The optimization of the imaging quality of the system is done in two stages: first we optimize it by modeling the metasurfaces with the generalized Snell's law [5]; then we take the optimum resulting from the first step for a second optimization with the ray-wave model. The benefits are twofold: firstly, we reduce the time needed to converge to an optimum, as ray tracing with the generalized Snell's law is less computationally expensive than the ray-wave model, and secondly, it helps us to reduce the computational cost, as a good design tends to illuminate only a small portion of the metalens, reducing the size of the computational window needed for ASPM calculations.

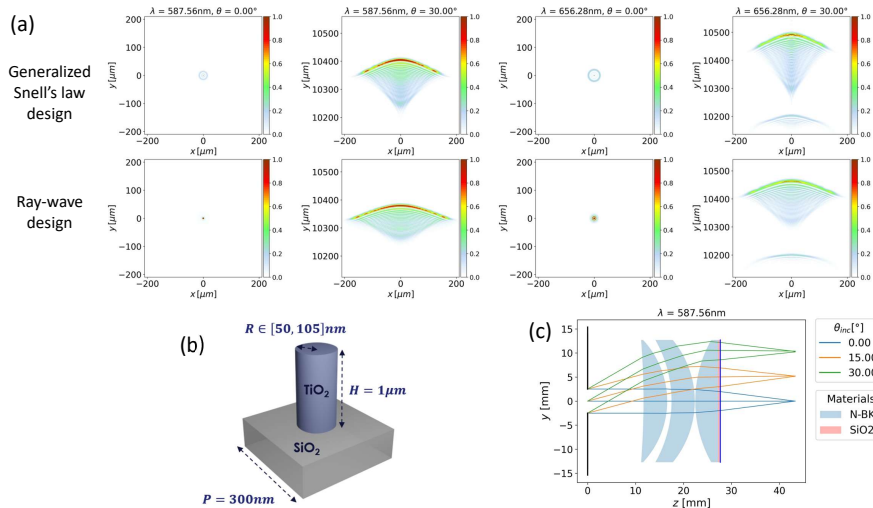


Fig. 2: (a) Point spread functions of the design obtained from optimizations using generalized Snell's law and the ray wave model. All intensities shown in the graphs are normalized by the maximum intensity of the generalized Snell's law design. (b) Representation of the geometry of meta-atoms used. (c) Optimized system after the optimization using the ray-wave model. The blue line in the figure represents the presence of nanostructures on the surface.

The optimization algorithm used in both stages is CMA-ES [6], as it has been proven to be very efficient to optimize ill-conditioned objective functions as the ones observed in the design of optical systems [7]. The optimization variables for the refractive lenses of the systems are their curvatures, their thicknesses and the air

gaps between them. For the parametrization of the geometrical repartitions of meta-atoms we use a reference phase function parametrized with even polynomials terms:  $\varphi_{\text{ref}}(\rho) = \sum_i^N A_i (\frac{\rho}{R_{\text{MS}}})^{2i}$ , where  $R_{\text{MS}}$  is the radius of the metalens,  $N$  is the number of polynomial coefficients,  $\rho$  is the distance from the center of the metasurface and the coefficients  $A_i$  are optimization parameters. The geometry of the meta-atoms is chosen so that a meta-atom placed at a distance  $\rho$  from the center of the meta-lens induces a phase shift  $\varphi_{\text{ref}}(\rho)$  at a nominal wavelength  $\lambda_d$  and at normal incidence. This parametrization has the benefits to describe the repartitions of meta-atoms with a few parameters (in our study we use 5 polynomial terms) and to explore only repartitions with a continuous phase profile at  $\lambda_d = 587$  nm. The imaging quality of the system is quantified with the room mean square (RMS) of the spot size during the 1<sup>st</sup> optimization step. It is equal to  $\sqrt{\frac{1}{N_{\text{rays}}} \sum_{k=1}^{N_{\text{rays}}} (x_k - \bar{x})^2 + (y_k - \bar{y})^2}$  where  $(x_k, y_k)$  is the positions of rays at the image plane and  $(\bar{x}, \bar{y})$  is their centroid.

For the 2<sup>nd</sup> optimization we maximize the mean intensity of the field inside a circle centered at the position of the wanted focus point and with a radius equal to half the RMS spot size.

The optimum found with the ray-wave model has an increase in mean intensity within the RMS spot size circle of a factor of 3 at normal incidence at the wavelengths considered (586 nm and 656 nm) compared with the design obtained using generalized Snell's law alone. For the other incidences, the two designs perform similarly. We believe that the lack of improvement at non-normal incidences is due to the absence of chromatic dispersion control with meta-atoms used, making it difficult to correct chromatic aberrations at all incidences.

#### IV. CONCLUSION

We have shown that by using the ray-wave model proposed with the CMA-ES algorithm, we can obtain an eyepiece design with improved image quality compared to a design found with generalized Snell's law. To improve the results obtained, a more complex geometry of meta-atoms than the one used should be considered in order to have better control over chromatic dispersion.

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