Computational Nanophotonics and Inverse Design

Simulation and Inverse Design of Nonlinear Nanostructured Materials

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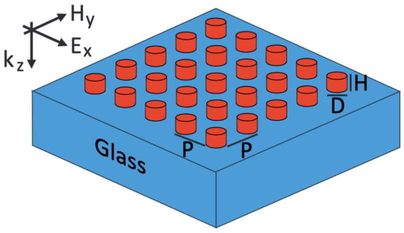

Figure 1: *Sketch of a metasurface on a substrate [5].*

In Short

- Large-scale simulations to engineer and tune the linear and nonlinear response of free-space and integrated optical metasurfaces.
- Inverse design of nanostructures, metasurfaces, and integrated optics via topology optimization for classical and quantum applications.

The past decade has seen a significant surge in nanophotonics research, which explores the interaction between light and matter at the nanoscale. This progress is facilitated by advancements in nanofabrication techniques like e-beam lithography, focused ion beam, and two-photon polymerization which, by allowing precise control at the nanoscale, enable the creation of complex nanostructures. Based on the physics of plasmonic and Mie-type resonances, metal and dielectric nanostructures can be engineered to manipulate light-matter interaction. When arranged in 2D and 3D lattices, these nanostructures form metasurfaces and metamaterials, respectively. This opens avenues for achieving optical properties that are not attainable in bulk materials. Researchers are exploring such nano-engineered materials to manipulate and dynamically adjust light properties in both linear and nonlinear regimes, for applications in imaging, biosensing, communications, optical computing, autonomous driving, and quantum technologies.

In this project, we tackle several modelling and design problems that require large-scale simulations and therefore high-performance computing. This includes the simulation and design of optical metasurfaces (see sketch in Fig. 1) exhibiting collective resonances [1]), tunable metamaterials [2], anapole nanostructures [3], hybrid nanocystals [4], integrated meta-waveguides, and tunable metasurfaces [5].

Metaheuristic methods are typically employed for design problems with a limited number of variables. However, these methods become computationally prohibitive for large-scale optimization problems and are practical only when a good initial design is known. In recent years, inverse design has emerged as a paradigm to efficiently explore large spaces of parameters and find new conceptual designs beyond conventional methods. These non-intuitive designs can offer solutions to complex optimization problems and unlock advanced functionalities. Gradient-based topology optimization based on the material distribution approach has been developed for a broad range of applications and is currently used in many fields, including electromagnetics.

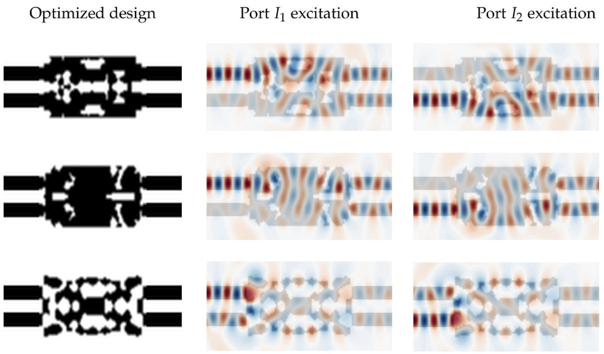

Figure 2: *Topology optimization of an integrated beam splitter with arbitrary phase at the output ports [6].*

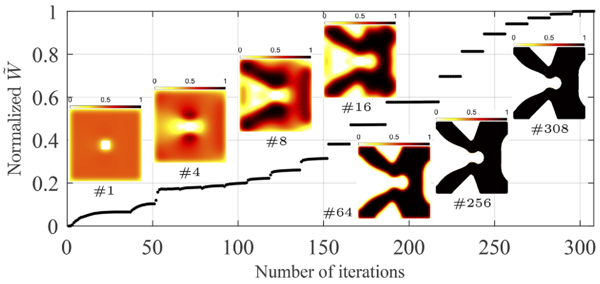

Figure 3: *Progressive optimization of the topology of a metallic (silver) nanoantenna. Black is metal, and white is vacuum [7].*

Within this project, we employed topology optimization methods to inverse design integrated optical circuits with advanced functionalities [6] (Fig. 2), and developed new time-domain topology optimization techniques. This includes techniques to optimize the topology of plasmonic nanostructures [7] (Fig. 3), a parallel algorithm to handle large-scale design volumes for the optimization of plasmonic and dielectric materials with arbitrary optical dispersion and anisotropy [8] (Fig. 4), and time-domain methods for the broadband maximization of absorption in dispersive nanostructures [9].

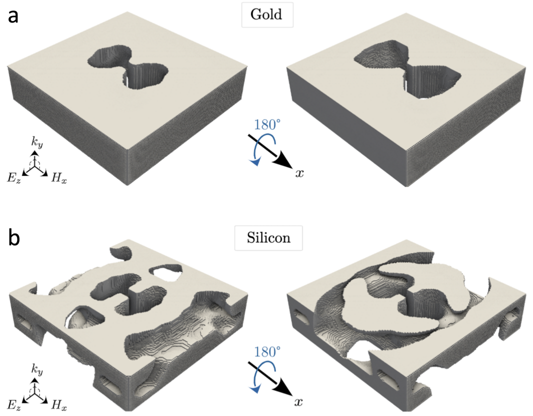

Figure 4: *Free-form 3D topology optimization of (a) gold and (b) silicon nanostructures for near-field enhancement [8].*

We will continue our research on the simulation and design of nanophotonic devices, and the development of inverse design techniques for several projects in the field of tunable metaphotonics, quantum technologies, and integrated optics. The computational complexity of the problems that our group is tackling requires access to high-performance computing. Our problems are large-scale for at least three reasons: (i) we are interested in realistic devices, so we need to simulate full metasurfaces/metamaterials in 3D, (ii) nanophotonic structures require a fine discretization to accurately describe the physics of nonlinear and nonlocal phenomena [10,11], and (iii) topology optimization requires hundreds of iterations to find the optimal design solution. Optical simulations and inverse design in this project will primarily be conducted using parallel in-house solvers based on the finite-difference time-domain (FDTD) method [8,12].

WWW

`https://www.hot.uni-hannover.de/en/research-groups/computationalphotonics`

More Information

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Project Partners

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