Surface optical elements in transmissive and reflective mode : from diffractive structures to metasurfaces

English summary:

Metamaterials permit to generate new effective optical properties. Based on subwavelength structurations and possible local resonances, they permit to control the induced phaseshifts. Considering this phase response, a diffractive optical element (DOE) can be considered as an simplified archetype of metasurface asking for a rigourous design. Our research group has specific skills in the use and development of rigorous calculation methods applied to electromagnetism. These methods permit the modelling of micro-optical components taking into account the reflected light, the polarization and the wide angle propagation. These tools are compatible with the study of DOEs or metamaterials. These methods are named Radiation Spectrum Method (RSM), Finite Difference Time Domain (FDTD). We also use their coupling and work on their parallelisation. The proposed work will consist in including the propagator RSM 3D in an iterative algorithm permitting the design of DOEs working in taking into account the reflected light. These DOEs, called «sandwich» mix forward and backward waves for targeted uses. If necessary, the parallelisation of this new code will be undertaken. At least, these elements will be fabricated and characterized.

Supervisors:

- Philippe Gérard
  Current position: Ass. Professor at INSA Strasbourg

- Patrice Twardowski
  Current position: Ass. Professor at Télécom Physique Strasbourg.

They have a large experience in the design of diffractive optical elements (DOE) and in their fabrication by microlithographic processes. DOEs are archetypes of metasurfaces. The supervisor's team has developed in-house a rigorous Radiation Spectrum Method (RSM) and a Finite Difference Time Domain (FDTD) programs for electromagnetic problems particularly concerning subwavelength structures. Moreover, the IPP team possesses several types of commercial simulation software for rigorous electromagnetic simulation.

Research team and Lab:

ICube Lab, Photonics Instrumentation and Processes (IPP) team

The ICube laboratory brings together researchers of the University of Strasbourg, the CNRS (French National Center for Scientific Research), the ENGEES and the INSA of Strasbourg in the fields of engineering science and computer science, with imaging as the unifying theme.

With around 580 members, ICube is a major driving force for research in Strasbourg whose main areas of application are biomedical engineering and the sustainable development.
The IPP team groups together research activities in the field of the interaction between light and micro and nanostructured media, with the aim of extracting certain information or of modifying the material to give it a specific functionality. The application domains are measurement, instrumentation and laser processing.
Team website: http://icube-ipp.unistra.fr/

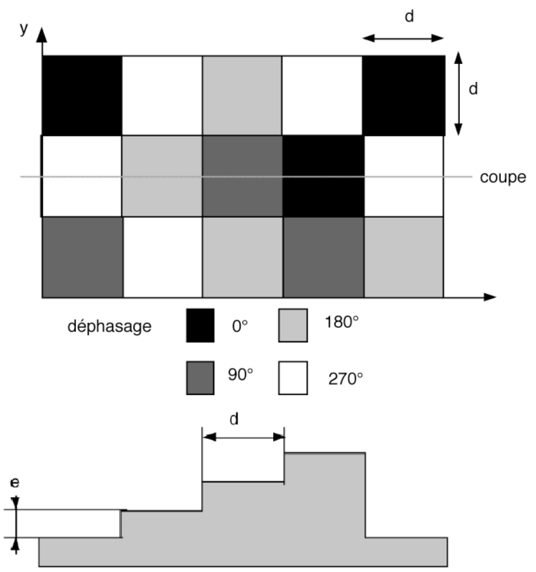
Strasbourg city:

At 1h40 from Paris, Strasbourg's 2000 year history has taken it from being a prosperous merchant city to its current position as capital of the peoples of Europe, from a centre for humanist thinking to a thriving hub of creators and entrepreneurs.
With its blend of cultures, innate tolerance, ecological awareness and embodiement of the European spirit, Strasbourg is a highly attractive, yet contemporary city. A multifaceted image, which is the basis of its originality.
Europe is alive here - the Europe which belongs to its citizens, is being constructed here to deal with the major issues currently facing our society, such as education, industrial modernisation, solidarity, the change in energy sources and eco-responsibility.
Strasbourg, inspired perhaps by the soaring steeple of its cathedral, is a city where culture and business combine to form fertile ground for our future development.
Extract from Strasbourg city website: http://www.en.strasbourg.eu/en/home-en/

More information about the thesis subject:

A diffractive optical element (EOD) is a component that applies the laws of Fourier optics. It can operate in the transmissive or reflective mode. It is made of a micro structured surface presenting thickness variations at the scale of a few wavelengths. Illuminated by a coherent light source it permits to obtain an arbitrary laser beam forming. We make classically the distinction between Fourier and Fresnel elements depending wheter the field is reconstrucuted is observed at the infinite or at fixed distance.

The metasurfaces permit the realisation of optical components. In this case, we replace diopters and lenses by diffraction grating with subwavelength period. We obtain an effective medium that presents an alternative solution for the realisation of lenses. We have used this solution to design a component combining the function of a beam concentrator and wavelength splitter for photovoltaic cells [1].



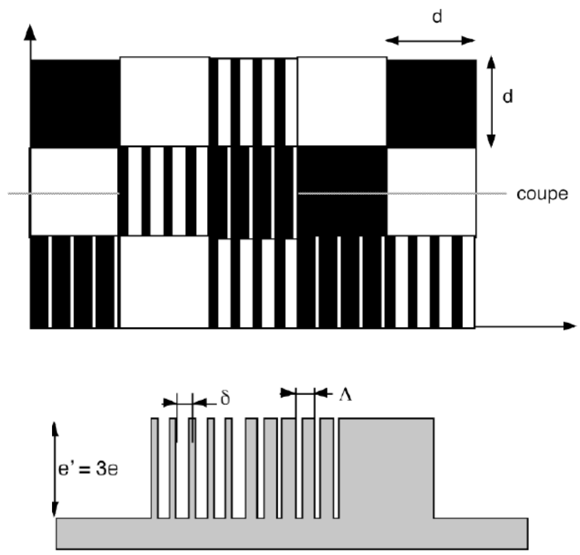


Figure 1: **illustration of the effective medium technique as an elementary case of metamaterial**

The Radiation Spectrum Method (RSM) [2] belongs to the family of the Beam Propagation Methods (BPM). It makes use of a modal approach where the other BPM tools make use of finite differences schemes. This method has initially been developed for the domain of integrated optics. The geometry of the component is first discretized in a succession of straight waveguides sections. The transverse electric and magnetic fields distributions of the excitating wave are projected on the forward and backward eigenmodes of the first straigth waveguide section. The eigenmodes are the guided modes, the radiation modes and the evanescents modes. Due to the modal nature of the method, the propagation of the forward and backward modes over the whole length of the straigth waveguide section is straightforward. The field at the end of this section serves as the excitation field for the new coming straight waveguide section. The current version of the RSM calculation kernel is limited to arbitrary geometries for 2D lossless waveguides. There exists also a 3D version accelerated with fast Fourier transforms and limited to plane waves projection. In oppositon to the Angular Spectrum Method (ASM) the projection occurs both on the forward and backward plane waves.

The Finite Difference Time Domain method (FDTD) proceeds with a meshing of the space and a discretization in time of all the electric and magnetic field components. It applies an explicite finite differences scheme on the Maxwell's equations. The main advantage of the method is its level of generality. Furthermore, it is relatively easy to operate extensions on the main algorithm to take into account new physical effects such as no-linearity, dispersion, periodic boundary conditions.

The high memory resources and calculation times are the two drawbacks of the method. We have at disposal in our laboratory the commercial software FDTD Solutions and several versions of 2D FDTD written en C langage. These codes have been used for the study of gratings of slits on metallic substrates, typical example of geometry presenting plasmonic effects. Another use concerns DOEs with subwavelength gratings [3], [4]. We also have access to a parallel FDTD version developed in our group with the MPI (Message Passing Interface) standard for computers with shared memory.

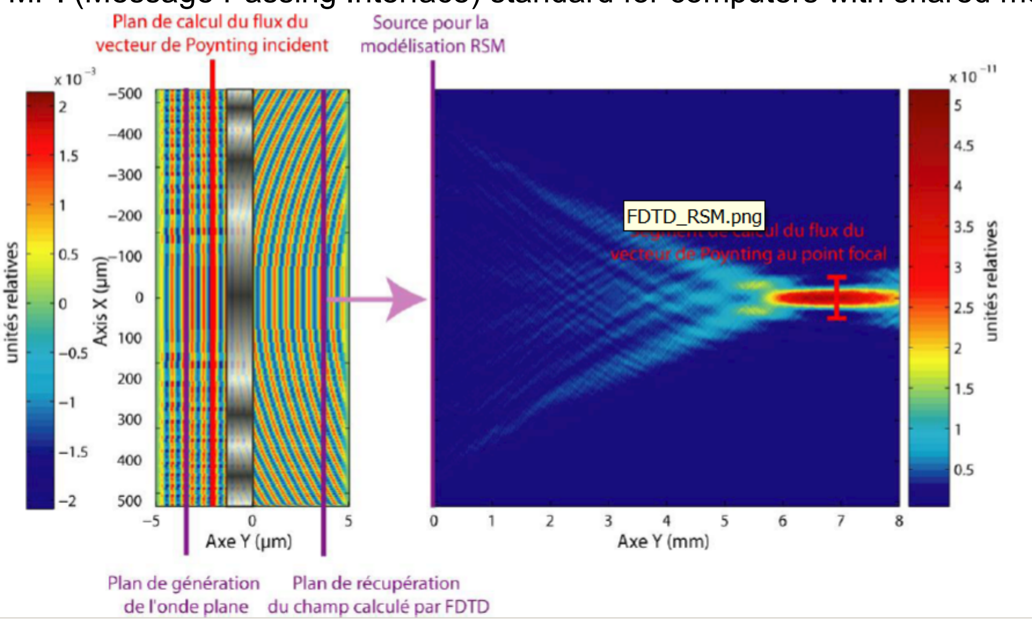


Figure 2: **FDTD/RSM combining to compute a Fresnel Lens using the effective medium theory.**

The proposed work in this thesis will be based on the tools ASM, RSM, FDTD to conceive new diffractive optical elements. The FDTD tool could be used to simulate metasurfaces. The tool RSM 3D plane waves will be used to design DOEs for which the combination of the incident and reflected field play a big role for the calculated of the reconstructed field. An experimental validation will be realised.

Publications :

[1] Albarazanchi A. et al., "Smart multifunction diffractive lens experimental validation for future PV cell applications", Opt. Express , 24 (2), pp 139–145 (2016).

[2] P. Gérard, P. Benech, D. Khalil, R. Rimet, S. Tedjini, “Towards a full vectorial and modal technique for the analysis of integrated optics structures : the Radiation Spectrum Method (RSM)”, Optics Communications , Vol 140, july 1997, pp 128-145.

[3] V. Raulot, P. Gérard, B. Serio, M. Flury, P. Meyrueis, “Comparison of the behavior of subwavelength lens in TE and TM polarization allowing some non standard functions”, Optics Letters, Vol. 36, n°7, april 2011, pp 1194-1196.

[4] V. Raulot, P. Gérard, B. Serio, M. Flury, B. Kress, P. Meyrueis, “Modeling of the angular tolerancing of an effective medium diffractive lens using combined finite difference time domain and radiation spectrum method algorithms”, Optics Express, vol. 18, n°. 17, August 2010, p 17974-17982.

[5] G. N Nguyen, K. Heggarty, P. Gérard, “Computationally efficient scalar nonparaxial modeling of optical wave propagation in the far-field”, Applied Optics, Vol. 53, n°10, pp 2196-2205.

[6] J. Yang, P. Twardowski, P. Gérard, W. Yu, and J. Fontaine, "Chromatic analysis of harmonic Fresnel lenses by FDTD and angular spectrum methods," Appl. Opt. 57, 5281-5287 (2018)