Superresolution hidden in the far-field and spatial-spectral transformations

The diffraction limit is a physical law, which makes optical imaging of objects smaller than approximately half of the wavelength of light at macroscopic distances by means of classical optical techniques impossible. Other methods have been developed for microscopic imaging of very small objects, like the near field optical scanning microscopy (NSOM), fluorescence microscopy, stochastic optical reconstruction microscopy (STORM), as well as non-optical scanning microscopic methods. However, the recent works on interscale mixing microscopy report proof-of-principle results for the possibility of tricking the diffraction limit with purely optical methods. It appears possible to reconstruct the sub-wavelength information of a microscopic object using computational methods from an spectrally broadband measurement of far-field information. Another nanostructure such as a sub-wavelength grating must be attached to the measured one for the purpose of such an indirect measurement. The far-field contains intermixed information of the two objects, including some part which was prohibited to reach the far-field by the diffraction limit.

This project is aimed at investigating the possibility of restoring the image of sub-wavelength objects from a far-field measurement. We want to use a different accompanying nano-object than a grating, namely an artificial metal-dielectric photonic structure called hyperbolic metamaterial, and which has already been proposed for this purpose in a recent theoretical work. It has unusual anisotropic optical properties that make it similar to a metal or to a dielectric for certain directions of light propagation. Yet, in contrast to metals through which light can not propagate at all, and to dielectrics in which the diffraction limit holds, a hyperbolic metamaterial supports light propagation of extremely high spatial harmonics representing sub-wavelength information. It may be used to propagate and intermix light, and with a decoupling mechanism, for which we intend to use a layer of nanospheres, light may be released out of the metamaterial and further be transmitted with classical optical components.

Restoring the sub-wavelength object from an indirect measurement poses both optical and computational challenges. On the mathematical side, the recently developed theory of compressive sensing will help us solve the problem. It is helpful in the interpretation of indirect and incomplete measurements, which seem to lead to unsolvable ambiguous inverse problems. It makes use of the commonly existing unknown internal structure of the measured data, and of the related property of compressibility of data. The common experience of the possibility to compress computer files with almost any kind of previously uncompressed data is a practical argument for the applicability of this theory to various fields. In fact, it finds increased attention in many disciplines, including optics. Usually a compressive measurement requires a simpler hardware (such as a simpler and cheaper optical set-up) sufficient to conduct an indirect measurement, and much larger computational resources, a strategy which is nowadays economically justified.

We will conduct our measurements in set-ups which inherently make use compressive sensing techniques. These will be a spectrometer and a microscopic imaging spectrometer (similar to a camera with a large number of colour channels). We should note that the development of such (less expensive) hyperspectral and super-resolving imaging techniques is potentially important for numerous fields, for instance for bio-medical applications.

A significant part of the project is related to the development of the sampling and reconstruction methods for compressive measurements, as well as to rigorous electromagnetic modelling of light in a hyperbolic metamaterial. We intend to cover the data recovery for the spectrometer, imaging spectrometer as well as imaging spectrometer with spatial-spectral transformation (the thing done by the hyperbolic metamaterial) in a similar, gradually extended, compressive-sensing based framework. These optical set-ups will be also developed gradually, beginning with the modified spectrometer, through microscopic imaging spectrometer, and finally to include spatial-spectral transformations. Realization of this project aims at bringing first experimental results of super-resolving compressive imaging with a hyperbolic metamaterial.