Preface

Nanophotonics is a burgeoning branch of modern optics. It promises to revolutionize many fields of physics and engineering since it is commonly understood as an enabling technology. It has impact on the evolution of science in general by supporting it with new and refined tools, e.g. novel microscopic techniques as used in biology or medicine; but allows foremost also for the implementation of applications that were unimaginable just some time ago, e.g. cloaking devices that conceal objects from external observers. Most notably, the key ability that makes nanophotonics such unique is to provide means to steer the propagation and the distribution of electromagnetic fields on length scales much smaller than the wavelength by relying on suitably tailored nanomaterials. To observe significant interactions, resonances are exploited in many cases that are evoked due to specific material properties, dimensions, symmetries, and geometrical arrangements of the involved constituents; or a combination thereof.

The technology, both in experiment and theory, to achieve and to describe nanomaterials relies in many cases on the periodic arrangement of an identical unit cell. That seems to be advantageous since it allows to eliminate scattering losses, to simulate the optical response by taking into account only a single unit cell and appropriate boundary conditions, it allows to simplify the fabrication that is accomplished in most cases by means of top-down technologies, and it permits to detect a noticeable signal from fabricated systems in the far-field by measuring quantities that are linked to an ensemble of many unit cells and not just to the response of an individual constituent. All these aspects were instrumental in the development of materials that drove the evolution of nanophotonics, but it constitutes nowadays also an obstacle that hinders its further progress. For example, it is difficult to imagine that with top-down technologies it will be possible to fabricate nanooptical devices that exploit the peculiarities of light propagation in the bulk material and not just the interaction of light with a frequency selective surface. It is difficult to imagine that a true localization of light in spatial domains significantly smaller than the wavelength using a spatially extended source can be achieved with a periodic structure that likely leads to a periodic localization in space or, as a last example, in the field of metamaterials were it is the aim to tailor effective properties as probed by an external source, it will be difficult to achieve an isotropic material response. The periodicity at which the unit cells are usually arranged in space will be similarly probed by the external source and it will leave its signature.

To overcome such limitation and to implement new functionalities, the field of *amorphous nanophotonics* is just about to emerge. The *Leitmotif* here is to exploit self-organization mechanisms that rely on bottom-up approaches for the fabrication of nanooptical systems. In result, the structures are predominantly characterized by a deterministic unit cell with tailored geometries; but the spatial arrangement of many of these unit cells forming the material is not controlled with arbitrary precision. Instead of a periodic tiling, the structures appear either amorphous or random. The goal of amorphous nanophotonics along with some explanations is illustrated at a selected example in Fig. 1. Detrimental for the immediate use of such structures in applications is the lack of a sufficiently developed language in which we can discuss on theoretical grounds the optical properties of such system, is the lack of a technology to fabricate amorphous nanophotonical systems and a lack of methods to access in an actual experiment the properties of systems alike. However, the promise of major applications with groundbreaking impact, as outlined also in depth in this book, constitutes a strong motivation to explore this field.

Since major efforts were already devoted in the past to close this gap and to establish a language in which we can access, discuss and explore amorphous nanophotonic systems, this book is intended to make the case for scientists working on or are even just interested in this field. Selected contributors to this book have been collaborating in the Nanogold project funded under the FP7 of the European Union, a project that brought together material scientists that explore bottom-up methods for the fabrication of new nanomaterials and physicists working in the field of metamaterials, to merge both streams and to advance both fields. Many more colleagues well beyond the people involved in this project contributed finally to this book to make it bold and sound.

This book is understood as a seminal reference as well as the inaugural document in which the stage is set for the field of amorphous nanophotonics. It aims at covering aspects that enable scientists to enter and work efficiently in this field and gives indications on perspective applications. The book is roughly divided into four sections; each containing a different number of chapters.

The first section contains two chapters. They provide a broader overview over selected subjects from either an experimental or a theoretical point of view, respectively. The first chapter, written by Alastair Cunningham and Thomas Bürgi, provides a detailed overview over experimental means for the bottom-up organization of metallic nanoparticles. Although not all amorphous nanostructures rely on metallic nanoparticles, their use is often preferred since the localized surface plasmon polariton they sustain guarantees a significant light matter interaction. It is moreover a prominent constituent where the isolated unit cell already sustains a strong response. However, by arranging these metallic nanoparticles by various methodologies spatially in a suitable manner, a response does emerge that is not observed in the individual element. This experimentally oriented chapter is complemented by a chapter written from a theoretical perspective by Filiberto Bilotti and Sergei

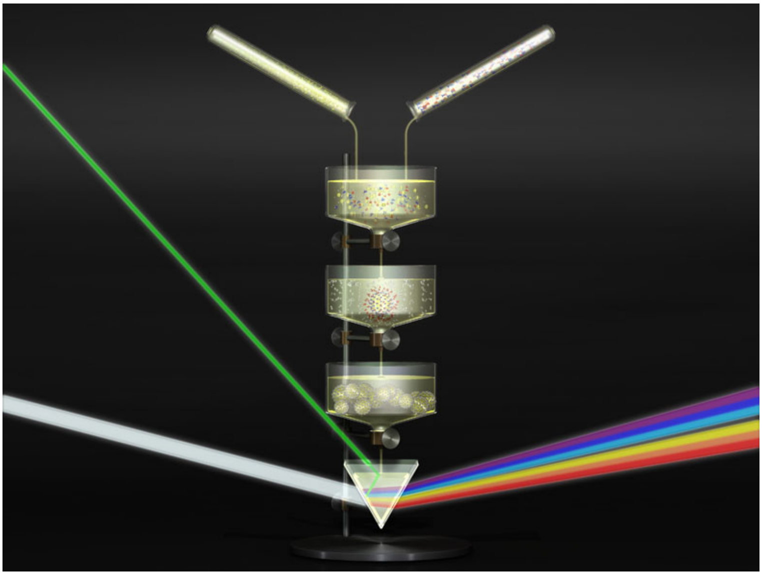

Fig. 1 Conceptual idea of how bottom-up nanofabrication techniques are used to fabricate an amorphous metamaterial; a referential example for a system from the field of amorphous nanophotonics. In this artistic view the process goes from the top to the bottom. Each stage represents a different lengths scale and should be seen as different magnification. In a first step, suitable ingredients on a molecular or nanometric scale are combined according to a chemical receipt. It leads to the formation of a unit cell that may possess a complicated geometry that can, however, be well controlled. In the present example, metallic nanoparticles decorate a dielectric core particle. The scattering response of such structure is dominated by a magnetic dipole, a response not available in nature. The geometry of this basic unit cell is the last item that can be controlled with high precision. The fabrication in solution allows for the realization of large scale quantities, i.e. an entire material is available immediately, but it comes at the expense that the arrangement of these meta-atoms in space cannot be controlled anymore. The resulting structure will be amorphous. This however, brings also a lot of advantages which are beneficially exploited. The available material, e.g., is isotropic since no directional preference exists. An isotropic material with a negative index of refraction, as achievable in principle, would be the Holy Grail that can be used in many applications. Detrimental would be only, as indicated in the figure as well, that the strongly dispersive nature would only allow for the observation of this effect at a narrow frequency range; although concepts exist to extend this spectral domain. With the present state-of-the-art we are not yet at the bottom part of this figure, but a majority of steps in this direction were already successfully gone. The documentation of this progress is one of the purposes of this book

Tretyakov. There, a broader overview on possible applications is given that base on amorphously arranged metallic nanoparticles. Emphasis in this chapter is put on metamaterials but eventually the possibilities for applications well beyond are equally documented.

The second section contains three chapters that discuss issues concerning the theoretical and numerical analysis of amorphous nanophotonical systems. If, in stark contrast to periodic structures, the constituents are no longer periodically arranged in space, novel approaches have to be put in place. Therefore, the first chapter in this section, written by Ari Sihvola and Henrik Wallén, gives an overview over homogenization techniques for amorphous nanomaterials. The insights documented in this chapter enable scientists to replace conceptually their complicated structured amorphous materials by a homogeneous one preserving its electromagnetical properties. Although, such homogenization techniques clearly have their limitations, as discussed in depth in the chapter, they allow to consider amorphous materials in the design of functional devices. The impact of such contribution cannot be estimated high enough. The second chapter in this section, written by Stefan Mühlig and Carsten Rockstuhl, outlines an approach to discuss properties of amorphous nanophotonical materials on the base of the scattering response of its constituents. The main ingredient is the expansion of the rigorously calculated scattered field into electromagnetic multipoles. Such analysis allows for a profound discussion of what properties will emerge in the bulk amorphous media. If only a few multipoles contribute, e.g. the electric and/or the magnetic dipole, homogenization methods as introduced in the previous chapter can be applied. For constituents that do not obey this requirement, i.e. where the scattering response is dominated by a multitude of multipoles, the computational strategy as discussed in depth in the third chapter of this section, written by Vassilios Yannopapas, Alexandros G. Vanakaras, and Demetri J. Photinos, can be used to explore the nanooptical system. There, it is described how the T-matrix of an individual constituent, i.e. a matrix containing information on how an arbitrary incident field is scattered into the far-field, is calculated and how it is used in a subsequent analysis of the optical properties of a media made from many such constituents. The technique they describe permits to hierarchically treat amorphous nanophotonical materials where, in analogy to Fig. 1, the view of the description is successively narrowed.

The third section contains two chapters which are devoted to the introduction of experimental means to measure in a quantitative sense the optical properties of amorphous systems. The first of these two chapters, written by Christian Helgert and Thomas Pertsch, discusses far-field characterization techniques. There, emphasis is put on the question how the amorphous character of the sample contributes to the measurable spectra. The discussion of the impact in the far-field is complemented by a chapter from Worawut Khunsin and Ralf Vogelgesang, which focuses on the near-field characterization. It is the intention to suggest that most notably the combination of both approaches provides a comprehensive picture on the optical properties of amorphous systems and how they can be used in potential applications.

This aspect, what to do actually with amorphous nanooptical systems, is discussed from a multitude of perspectives in the fourth section. It contains six further chapters. In the chapter from Keiichi Edagawa it is concisely shown under which conditions purely dielectric amorphous nanostructures do possess a photonic band gap. For frequencies inside such band gap, the propagation of electromagnetic fields is suppressed. However, it is not just the complete suppression but also the light diffusion and the ability to localize light in tiny spatial domains that are strongly affected, and actually enabled, by amorphous photonic materials. In the chapter that follows, written by Hui Cao and Heeso Noh, it is then shown how the localization of light in dielectric amorphous materials, once infiltrated with a suitable gain media, can be used to set-up novel lasers. Contrary to ordinary lasers where the light is spatially confined by mirrors forming a cavity, the formation of the cavity is promoted only by the amorphous material. In this chapter, among others, numerical and experimental results are nicely fused to provide a comprehensive picture. Applications of amorphous dielectric materials are not just found in technological devices made by mankind, but are also found in nature. The ability of amorphous nanostructures to strongly affect the visual appearance, i.e. the color an object possesses, was beneficial in the process of evolution. It led for example to their integration into the skin of various biological systems. A broad overview on this subject is given in the chapter by Stephen Luke and Peter Vukusic. A common theme that will be highlighted in this chapter is the ability of naturally occurring amorphous nanostructures to appear white, i.e. all wavelengths are scattered on a comparable strength. This ability, to strongly scatter the light of all wavelengths, is equally discussed in a chapter that follows but with a completely different point of view. This chapter, written by Franz Joseph Haug, details the scattering properties of amorphously textured surfaces with critical features down to a few tens of nanometers and their application in a thin-film solar cell to enhance the absorption of light. This is an application of paramount importance since any share of light that is additionally absorbed, promotes a higher efficiency of the solar cell. And since a solar cell cannot be optimized in its operation for just a single wavelength, the ability of these textured surface to strongly scatter the light at nearly all wavelengths is particularly important; explaining actually the success such textures do have already in commercial devices.

And to avoid the impression that only amorphous nanophotonical materials made from dielectrics are used in applications, the last two chapters in this fourth section are devoted to the use of structure containing metallic amorphous nanomaterials. In the chapter written by Roberto Caputo and co-workers from the University of Calabria, they detail how to make systems containing metallic nanoparticles integrated into self-organized soft materials active, i.e. they do change their properties upon an external stimulus. This paves the way, as outlined in this chapter, for applications such as tunable perfect absorbers and for novel sensor concepts; and their potentially use in a range of other innovative devices in diverse fields such as opto-electronics or opto-fluidics. In a final chapter Jose Dintinger and Toralf Scharf will detail the application and use of nanoparticle cluster matter to create artificial electromagnetic response with application to thin film optical devices.

It is our sincere hope that with the broad overview over all aspects related to the field of amorphous nanophotonics, we provide the necessary stimulus to significantly advance the entire field in the mid- and long-term. Our sincere thank goes at first to all the colleagues that have contributed to this book. Without their support and their passion for amorphous nanophotonics, this book and this field would not be where it is today. We would also like to thank our colleagues at Springer that supported us in all stages of the preparation of this book and its careful edition; most notably Dr. habil. Claus E. Ascheron. We would like to thank the European Union that funded some of the research in the project Nanogold that found its way into that book.

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