Organic and Hybrid Photonic Crystals

Davide Comoretto

Editor

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To my Mother and my Father

Preface

The research field of *Photonic Crystals*, i.e., composite structures where materials possessing different refractive index are assembled into a highly ordered dielectric lattice with submicrometric periodicity, was founded in 1987 by the seminal papers by E. Yablonovitch and S. John published in the same volume of *Physical Review Letters* just 3 weeks one after the other. They provided the tools to rationalize the dielectric lattices optics within a new formalism that not only is able to extend their theoretical description but also becomes a source of inspiration for novel systems, structures, and applications.

As it was already observed in other research fields, the development of novel *Photonic Crystals* structures was based on the use of top-down approaches to impart the dielectric structure into inorganic insulators and semiconductors. Such techniques enable the fabrication of photonic structures possessing extraordinary precision and finely tailored properties for selected technological applications.

Several books that have been so far published in the field of *Photonic Crystals* are usually tuned to a specialist readership mainly composed of Physicists and Engineers. Even though colloidal chemists and block copolymer scientists provided important contributions to the field, a cultural and communication gap still exists between fundamental Physics and Chemistry, as well as other disciplines of potential interest to the *Photonic Crystals* field. For instance, novel organic and hybrid materials that are revolutionizing the field of electronics and sensing can hardly be nanostructured in the form of *Photonic Crystals* with top-down techniques. Furthermore, biomedical applications could greatly benefit from the developments of the field. In this respect, and in particular when organic and hybrid materials are used, the use of the bottom-up approach as well as the exploitation of the chemistry of the self-assembling process, widely exploited in *Nature*, provides an important step forward to the field. This book, ***Organic and Hybrid Photonic Crystals***, was conceived as a bridge between different communities in order to establish a common set of fundamental concepts and a language to be shared between Physicists, Chemists, Biologists, Engineers, and Material Scientists. This bridge has two main by-products: (1) it is a common playground where fundamental concepts from

different know-hows can be shared among all researchers, the language being adapted to allow a mutual understanding; (2) it shares important fundamental concepts thus becoming a possible educational tool for Ph.D. students or postdocs approaching this research field.

We are aware that the field of *Photonic Crystals* is still dominated by inorganic materials. However, the “flexibility” of both organic materials (in terms of mechanical properties and chemical tunability) and colloidal composites makes ***Organic and Hybrid Photonic Crystals*** promising for several applications and devices, avoiding the typical drawbacks of the inorganic world. For instance, the tunability provided by self-supporting structures, their flexibility, their controlled porosity, and their chemical functionalization are unprecedented for inorganic insulators or semiconductors. Moreover, the smart mixing of organic materials to selected inorganic ones (noble metals, semiconductors, quantum dots) allows the development of hybrid structures with enhanced properties and functionalities.

Last, but not least, the presence of photonic structures in *Nature* has been considered as a source of inspiration for novel devices. In particular, it has been highlighted in this book for biosensing applications and for the effects of phase separation in blends, which plays a major role in self-assembling processes.

The research field of ***Organic and Hybrid Photonic Crystals*** is intrinsically multidisciplinary, and it requires skills of fundamental optics, radiation-matter interaction, chemical properties of polymers and colloids, as well as photonic devices and biology. The contributors of the book have provided to colleagues from different disciplines the fundamental concepts used to develop ***Organic and Hybrid Photonic Crystals*** as well as main results reported in literature and future perspectives. The understanding of the different strategies pursued by chemists, physicists, engineers, material scientists, and biologists is then the tool to foster the development of the field and of its technological by-products.

To the best of our knowledge, none of the books on photonic crystals published to date are easily readable by chemists, thus excluding a large part of such scientists from the field. Only reviews in Chemistry journals have been so far reported. In the same way, physicists are excluded from the know-how of the chemical tools to develop organic photonic crystal structures. From an engineering point of view, the interest is limited to the beautiful inorganic structures, while organics may provide structures unconceivable in the inorganic world. In addition, the biological approach should be a source of inspiration for novel applications. **The ambitious goal of this book is to become a melting pot of multidisciplinary knowledge in the field of Organic and Hybrid Photonic Nanostructures.**

The book is organized into three main parts:

- I. Introduction to Organic and Hybrid Photonic Crystal Properties
- II. Growth and Properties
- III. Chemistry and Physics of Photonic Crystals at Work

The three chapters in Part I provide the essential theoretical tools for understanding *Photonic Crystal* concepts thus allowing an easy reading of the following

Fig. 1 Scheme of *Organic and Hybrid Photonic Crystals*

chapters. Moreover, they introduce in a very elegant way the potential of organic materials in the field of photonics, from polymer to carbonaceous systems. Finally, photonic crystal structures in plants and animals are reviewed, being considered as hybrid nanostructured material systems, with inorganic and organic components and appropriate refractive index contrast. General principles of structure formation, the influence of disorder, and the achievable biological functions are elucidated through different examples. In the scheme of the book reported in Fig. 1, Part I constitutes the deep core.

Part II is composed of seven chapters and is devoted to the description of methods used to fabricate *Organic and Hybrid Photonic Crystals*, i.e., self-assembling, top-down, and melt or solution processing. Among self-assembling processes to obtain *Organic and Hybrid Photonic Crystals*, different approaches and materials are described, such as the engineering of spherical colloids in order to prepare opal-like structures, the use of sol-gel responsive systems, the supramolecular structure of liquid crystals or block copolymers, as well as Chemical Vapour Deposition (CVD). Top-down methods suitable for organic and hybrid materials are very different from those—time and energy consuming—used for inorganic materials. Indeed, nano-imprinting and holography are widely used, since they are very powerful, simple, and relatively cheap. When polymer materials are solution- or melt-processable, spin-coating and coextrusion are widely employed. The first is

efficient to engineer structures and materials over relatively wide areas, while the latter allows preparing very large area multilayered structures.

Part III is composed of 11 chapters and deals with different physical and technological issues. The role of light–matter interaction is described in these chapters with emphasis on fundamental issues such as strong coupling, energy transfer, and modification to the radiative recombination as well as to photonic applications, e.g., laser systems, photovoltaic heterostructures, and different kind of sensors (both chemical and biological). Moreover, specific features and opportunities provided by the smart mixing (engineering) of photonic crystal systems to plasmonic nanostructures are described.

We did not plan a technological section in the book, since different devices are permeating all chapters where they are described as proof-of-concept for different applications. For this reason, in each chapter, specific applications are reported discussing the role of materials and structures in improving device performances. A more detailed insight into the technological issues concerning the synthesis and specific applications of photonic nanostructures can be achieved taking advantage of the large number of references cited for each chapter.

Dimensionality of the *Organic and Hybrid Photonic Crystals* structures deserves a final comment. The processing techniques described in the book are mainly suitable to the preparation of one- and two-dimensional systems. Among 1D Photonic Crystals, the Distributed Bragg Reflector is easily achieved by spin-coating, coextrusion, CVD, as well as by self-assembling of liquid crystals and block copolymers. A variant of the DBR structure is the microcavity, where a periodicity defect is sandwiched between two multilayers. Nano-imprinting allows easily preparing 1D molded Distributed FeedBack structures. This technique should be extended to 2D and 3D photonic structures. However, the widely used 3D structure is the opal one, which is obtained by the self-assembling of monodisperse nanospheres and the inverse-opal one, as obtained upon infiltration by using opal templates. Face centered cubic and compact hexagonal structures can be easily obtained. Several examples are discussed in depth within the book. An additional opportunity for different 3D photonic crystal structures is provided by holographic lithography, where suitable patterns are obtained by laser beam interference into the photosensitive materials. 2D self-assembled structures obtained by both block copolymers and microsphere arrays are also briefly described.

In order to help the reader to approach different problems/materials/structures from different perspectives, an extended keyword list is provided allowing an easy cross-reference to different chapters. Additional more specific cross-references can be also found within each chapter.

Genova, Italy
12 January 2015

Davide Comoretto

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