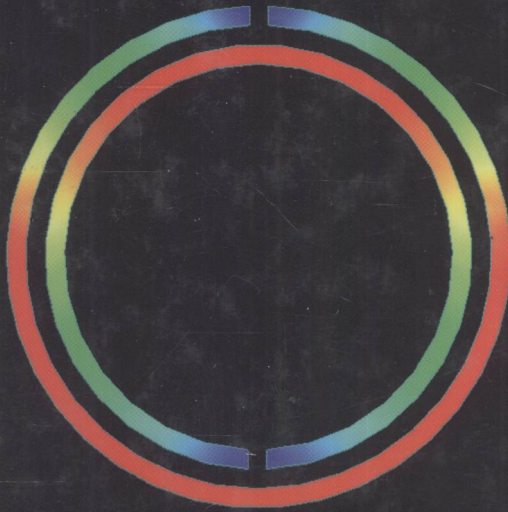


# Metamaterials with Negative Parameters

Theory, Design, and Microwave Applications



RICARDO MARQUÉS, FERRAN MARTÍN,  
and MARIO SOROLLA

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# **Metamaterials with Negative Parameters**



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*To our families*  
*Asunción, Ricardo Jr., Concepción and Ricardo Sr.*  
*Anna, Alba and Arnau*  
*Puri, Carolina and Viviana*  
*And also to the memory of Prof. Manuel Horno*

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# Preface

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Discovery consists of seeing what everybody has seen and thinking what nobody has thought.

Albert Szent-Gyorgyi

Classical electromagnetism is one of the best established theories of physics. Its concepts and theorems have been shown to be useful from the atomic to the cosmological scale; and they have been more successful in surviving to the relativistic and quantum revolutions than other classical concepts. It is well known for instance that Maxwell's equations were at the very basis of relativity and that Maxwell's electromagnetic theory was the first relativistic invariant theory. Concerning quantum mechanics, classical electromagnetism still provides the best foundations—together with quantum dynamics—for atomic and solid state physics. It is only in the domain of particle physics that classical electromagnetism needs to be reformulated as quantum electrodynamics. With regard to practical applications, classical electromagnetic theory is the basis of many well-known technologies, which strongly affect our ordinary lives, from power generation to wireless communications. It seems very difficult to add something conceptually new to such well-established theories and technologies.

However, during recent years, a new expression appeared in the universe of classical electromagnetic theory: *metamaterials*. From 2000 to 2007, the number of journal and conference papers related to metamaterials has grown exponentially; there has also been a multitude of special sessions, tutorials, and scientific meetings, all around the world, devoted to this new topic. Related to *metamaterials*, other topics appeared on the scene, such as *photonic crystals*, *negative refraction*, *left-handed media*, or *cloaking*, among others. But what is the reason and meaning behind this sudden explosion in the otherwise quiet waters of electromagnetism? In fact, nothing is new from the point of view of fundamental science in metamaterials. Throughout this book, it will be shown that metamaterials can be understood by using well-known theoretical tools, such as homogenization of effective media or elementary transmission line theories. In addition, many electrical and electronic

engineers have pointed out that almost all new applications arising from metamaterial concepts can be understood by using more conventional approaches, that is, without the need to invoke these metamaterial concepts. So, what is new in metamaterials?

Physicists usually try to explain how nature works, whereas engineers try to apply this knowledge to the design of new devices and systems, useful for certain applications. In our opinion, metamaterials are placed at an intermediate position between science and engineering—for this reason they are of interest to both physicists and engineers. Metamaterials are not “materials” in the usual sense: they cannot be found in nature (by the way, this is a very common definition of metamaterials). In fact, metamaterials are artificial structures (products of human ingenuity), designed to obtain controllable electromagnetic or optical properties. This includes the possibility to synthesize artificial media with properties not found among natural materials, such as negative refraction, among others. Within this scenario, it is evident that metamaterials may open many challenging objectives of interest to physicists and scientists in general. From the technological and engineering viewpoint, the interest in metamaterials is based on the possibility of designing devices and systems with new properties or functionalities, able to open up new fields of application or to improve existing ones. Although it has been argued that certain applications of metamaterials can be analyzed through conventional approaches, the key virtue of metamaterials is in providing new design guidelines for components and systems that are missing in conventional approaches. Other applications such as subdiffraction imaging are, however, genuine products of metamaterials. This intermediate position between physics and engineering is a relevant aspect and probably one of the main novelties of metamaterials. In order to highlight this multidisciplinary nature, in our opinion it is appropriate to refer to this new topic as metamaterials science and engineering.

Most metamaterials fall in one of two categories: *photonic or electromagnetic crystals* and *effective media*. The first category corresponds to structures made of periodic micro- or nano-inclusions whose period is of the same order as the signal wavelength. Therefore, their electromagnetic properties arise mainly from periodicity. Conversely, in effective media the period is much smaller than this signal wavelength. Hence, their electromagnetic properties can be obtained from a homogenization procedure. This book is mainly devoted to the second category, specifically to those metamaterials that can be characterized by a negative effective permittivity and/or permeability.

The first chapter is devoted to the analysis of the electrodynamics of continuous media with simultaneously negative dielectric permittivity and magnetic permeability. Chapter 2 is focused on the design of bulk metamaterials made of systems of individual metallic inclusions with a strong electric and/or magnetic response near its first resonance. The third chapter develops the transmission line approach for the design of metamaterials with negative parameters, including both the nonresonant and the resonant-type approaches. Chapter 4 is devoted to the analysis of some relevant microwave applications of the concepts developed in the previous chapters. Finally, in Chapter 5, some related and/or advanced topics, such as metasurfaces, magneto-inductive waves in metamaterial structures and subdiffraction imaging devices are developed.

This book is mainly directed towards the resonant-type approach to metamaterials because, obviously, it has been strongly influenced by the personal experience of the authors. However, our aim in writing this book has been to give a complete overview of the present state-of-the-art in metamaterials theory, as well as the most relevant microwave applications of metamaterial concepts. Indeed, our purpose has been twofold: to generate curiosity and interest for this emerging field by those readers not previously involved in metamaterials science and engineering and to provide useful ideas and knowledge to scientists and engineers working in the field.

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*Sevilla, Spain*  
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*Pamplona, Spain*  
*October 2007*

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R. M.  
F. M.  
M. S.

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