ELECTROMAGNETIC FIELDS AND WAVES

电磁场与电磁波

Robert R. G. Yang
Thomas T. Y. Wong

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Recommendation

It is the first book regarding electromagnetic fields and waves translated directly from a Chinese textbook in order to meet the requirement of bilingual teaching and learning in China. Recently, there are many textbooks about electromagnetics in domestic or international presses, but professor Yang's book is very different from all of them. This book expounds the behaviors of the electromagnetic fields based on Helmholtz's theorem for the vector fields, and reveals thoroughly the divergence and the curl properties of the electromagnetic fields. In addition, it provides a rigorous relationship between the sources and the fields. Furthermore, the author pays more attention to the introduction of electromagnetic waves and the development of some recently advanced technology in the book. Since Yang's book was published in 2003, it has been well received by the readers. I am sure that this English version will be welcome not only by Chinese teachers and students but by international readers also.

Weigan Lin 林为干

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Preface

(For English version)

This is an English translation of the textbook "Electromagnetic fields and electromagnetic waves", written by Rugui Yang and published by Higher Education Press in 2003. The initial translation was conducted by Robert R. G. Yang. Further review and revision of the translation was performed by Thomas T. Y. Wong. Professor Yang is with Southwest Jiaotong University of China, where he was the director of the Electromagnetics Institute. Professor Wong is with the Illinois Institute of Technology (IIT) in USA, where he is the director of the Microwave Laboratory and the chairman of the Electrical and Computer Engineering Department at IIT.

To facilitate bilingual teaching and learning, much effort has been devoted to preserving the original syntax as well as the style of presentation vested in the Chinese text, while being mindful of the intrinsic differences between the two languages.

The assistance in word processing provided by Ming Yan and Feng Gao, both doctoral students in electrical engineering at IIT, has been a significant contribution to the preparation of the revised manuscript.

Questions and comments on this book will be much appreciated. Readers are encouraged to visit the Website at http://lxy.swjtu.edu.cn/emi/books/emfw/emfw.asp.

Robert R. G. Yang

Thomas T. Y. Wong

June, 2005

Preface

This is a university-level textbook on electromagnetic fields and waves for undergraduate programs in electronic and information engineering, focusing on the basic properties of electromagnetic fields and waves, with emphasis on time-varying fields. With the rapid development of information technology, a thorough understanding of and familiarity with the properties of electromagnetic fields and waves, along with the relevant analytical tools and practical applications are expected for professionals working in the field of information technology. A course on electromagnetics is therefore an important part of the curriculum that forms the essential knowledge base for undergraduates majoring in information technology and electronic engineering.

As we know, a static charge gives rise to an effect that appears as a force acting on a charge body in the surrounding, within which an electric field is said to exist. Moving charges or electric currents lead to another kind of field, which results in forces acting on magnets and conductors carrying currents, referred to as a magnetic field. From these we see that the effects of both the electric field and the magnetic field are revealed as forces. As a result, the electric field and the magnetic field are both vector fields. If the magnitude and the location of the electric charge do not change with time, the electric field produced by the charge will also be constant over time. This kind of electric field is known as an electrostatic field. When the magnitude and the velocity of an electric charge in motion are kept constant so that the resultant electric current is steady, the magnetic field produced will be time independent and known as a steady magnetic field. If the charge and the current vary with time, the electric field and magnetic field they produce will be functions of time. It was found that time-varying electric field and magnetic field must co-exist and have definite relation to each other, leading to a time-varying electromagnetic field. The interaction between time-varying electric field and time-varying magnetic field results in an electromagnetic wave in space. When an electromagnetic wave travels, it transmits the energy of its source through the action of the electromagnetic field. On the other hand, electrostatic field and steady magnetic field are independent of each other, and may be investigated separately. Accordingly, the discussion in this book be-

gins with the electrostatic field, to be followed by the steady magnetic field, and then the time-varying electromagnetic field.

Although electromagnetic fields and waves are invisible (except for visible light), their existence can be inferred from the energy and momentum they carry. As is well known, light is a form of electromagnetic wave. The radiation pressure and the vast energy brought by sunlight show beyond any doubt electromagnetic fields and waves possess many qualities of wave motion found in various media. Among these qualities, forces and energy due to an electromagnetic field are the most important ones in its interaction with matters.

It is well known that the existence and transmission of electromagnetic waves need not rely on any medium. Specifically, when an electromagnetic wave travels through a vacuum, it is said to propagate in "free space". In the presence of matter, an electromagnetic field gives rise to polarization and magnetization, which in turn lead to secondary fields which will modify the original field distribution. This is the interaction between the field and matters. To facilitate study of the subject, we first introduce electromagnetic fields in free space, after which the electromagnetic field in matter will be discussed.

We know that static electric charges produce electrostatic fields, and moving electric charges or electric currents give rise to magnetic field, in addition to electric field. Hence, electric charges and currents are sources for electromagnetic fields. It should be pointed out that they are the only sources for producing electromagnetic fields. Up to now, no magnetic charge or magnetic current of significance has been found to exist in nature. Nevertheless, the introduction of magnetic charges and currents in the analysis of electromagnetic fields can prove to be beneficial sometimes, although these must be treated as fictitious entities. Investigation on the relation between the field and its source is a fundamental subject in electromagnetic theory. We will introduce a number of mathematical equations to describe the relationship between the field and the source, as well as between the field and the media.

Nowadays the fundamental laws governing electromagnetic phenomena are well known. However, the path mankind took to accumulate the knowledge on electromagnetic field has been laborious and has spanned over a long period of time. The ability of a piece of amber to attract small items after it had been rubbed was discovered by the Greeks in 600 B. C. The attractive force between a magnet and iron was noted by the Chinese in 300 B. C. Early in the first century, the compass was invented and it was among the four great inventions in ancient China. Thereafter, the magnetic field

of the earth was discovered. In 1785, French scientist Charles Augustin de Coulomb (1736—1806) discovered Coulomb's law based on his observation in experiments. It gives the relationship between the force experienced by two small charged objects and the distance between them. In 1820 Danish scientist Hans Christian Oersted (1777—1851) discovered the magnetic field produced by an electric current. In the same year, French scientist Andre Marie Ampere (1775—1836) determined the force between two electric currents. Michael Faraday (1791—1867), a British scientist, discovered the phenomenon of electromagnetic induction in 1831 and put forth the law of electromagnetic induction, which states that a time-varying magnetic field must give rise to an electric field. In 1873, British scientist James Clerk Maxwell (1831—1879) postulated the displacement current, which provided the link between a time-varying electric field and a magnetic field. He put on a firm mathematical foundation the laws governing an electromagnetic field. They are known today as the famous Maxwell's equations. These equations state that a time-varying electric field produces magnetic field and vice versa. Maxwell further predicted the existence of electromagnetic waves, which was demonstrated in 1887 by the experiment conducted by German physicist Heinrich Rudolph Hertz (1875—1894). On this foundation, around the end of the 19th century, Popov in Russia and Marconi in Italy invented the technology to transmit information using electromagnetic waves, paving the way for the subsequent development of modern wireless communications, broadcasting, radar, remote control, microwave sensing, wireless networks and local area networks, satellite positioning, optical communications and other information technologies. The wide applications of these new technologies further enhance the development of electromagnetic theory. The availability of high performance and high speed computers and large memory capacity not only made the calculations encountered in obtaining the solutions to many problems in electromagnetics possible, but also gave rise to new methods to compute electromagnetic fields and waves. This gave birth to computational electromagnetics, which is an important branch of modern electromagnetics.

Electromagnetic fields are vector fields. To investigate the properties of electromagnetic fields, vector operators and analysis are often used. Therefore, the essential concepts, theorems, formulas and application of vector analysis are summarized in Chapter 1. The static electric fields are introduced in Chapter 2. Boundary value problems in electrostatics are discussed in Chapter 3. Chapter 4 is on steady electric current fields. Chapter 5 covers steady magnetic fields. Electromagnetic induction is discussed in Chapter 6. Chapter 7 is on time-varying electromagnetic fields. Plane

electromagnetic waves are introduced in Chapter 8. Guided electromagnetic waves are discussed in Chapter 9. The principles of electromagnetic radiation are discussed in Chapter 10. In terms of categorization, Chapter 1 provides a solid mathematical foundation, Chapters 2,3,4 and 5 cover static fields, and Chapter 7,8,9 and 10 are on time-varying fields. The relationship between electric and magnetic fields is brought out by the law of electromagnetic induction in Chapter 6. Finally, in the Appendices one finds the symbols, units and dimensions of physical quantities, decimal multiples and submultiples and their prefixes, vector identities, orthogonal coordinate systems, δ-functions, Bessel functions, Legendre functions, and a list of frequency bands and their utilizations.

From the above we can see that this book is well endowed with contents on time-varying electromagnetic fields. At the same time, practical applications of electromagnetic theory are illustrated along with natural electromagnetic phenomena. To enhance the student's ability to analyze and solve problems and to consolidate the understanding of the basic theory, numerous examples are included with the discussion, while a considerable number of review questions and problems are placed at the end of each chapter.

The S. I. system of units is employed in this book. In electromagnetics, the four basic quantities are length (in meters), mass (in kilograms), time (in seconds), and electric current (in Amperes). For time-harmonic electromagnetic field, the time convention adopted is $e^{j\omega t}$.

There are a number of textbooks on electromagnetic fields and waves published in China and overseas. They may be placed in two categories according to the approach of presentation and the arrangement of the contents. In one approach, often referred to as the inductive method, Coulomb's law is first introduced. This is followed by the Biot-Savart law, Faraday's law, electrostatic fields, steady magnetic fields, and time-varying electromagnetic fields. The scope of discussion evolves from specialized topics to encompassing theory. This traditional method of presentation starts at a basic level and is easier to comprehend. However, the student may be bored as there is substantial overlap of the topics in the early sections with the ones found in a physics course on electricity and magnetism. At the same time, the sequential exposition of the basic laws requires considerable time, resulting in compression of the discussions on time-varying fields. The other approach may be called the deductive method. It starts from the Maxwell's equations and time-varying fields are introduced at an early stage. The static field is considered as a special case of the

dynamic field. The presentation completes with the discussion on static fields. The development is from the general to the specific. This approach reduces the contents on static fields while placing more emphasis on time-varying fields. However, the early exposition may be at too high a level for the student to comprehend. In 1985, the renowned expert of electromagnetic theory, Professor Xichun Huang of Xi'an Jiaotong University proposed that the Helmholtz's theorem, which accounts for a vector field in terms of its divergence and curl, should be the starting point for the discussion of electromagnetic theory. This approach avoids repetition of contents in physics courses, while setting the level of discussion within the reach of most students. Furthermore, it provides a vigorous treatment of the relationship between the source and the field, as well as the analysis and properties of electromagnetic fields. Based on the idea of Professor Xichun Huang, Professor Wenbing Wang, Professor Xiyuan Zhang and the author jointly wrote the lecture notes titled "Electromagnetic fields and waves." After they were classtested twice, the author developed the notes into formal curriculum. In textbook form it was published by Xi'an Jiaotong University Press in 1989, after being taught several times and further revised.

This new edition is revised from the one published in 1989, with all the essential components retained. However, with the expansion of the undergraduate curriculum, the time devoted to an individual subject has been reduced. As a result, discussions on transmission lines, the equivalence principle, and geometrical optics have been deleted. At the same time, new applications of electromagnetic fields and waves in information technology have been incorporated with the discussions.

In revising this book, Drs. Yunlin Liu and Mingxi Wang, professors at Southwest Jiaotong University, assisted in editing the solutions to the exercises. In addition, graduate students Zhengtao Guan, Kaiyan Chen, and Shuangwen Zhang worked through all the problems given at the end of each chapter, along with all the computations involved. Mr. Wenbing Wang, professor at Xi'an Jiaotong University, reviewed the revised manuscript and provided many valuable suggestions, which substantially enhanced the quality of this book. The author offers these individuals his heartfelt appreciation for their contributions to the book.

The author further expresses his gratitude to the editors of Higher Education Press for their substantial effort in editing and publishing this work.

The author welcomes suggestions for correction of any error that is bound to exist, as well as constructive comments to further improve the presentation.

The Website for this book is

http://lxy.swjtu.edu.cn/emi/books/emfw/emfw.asp

It is furnished with an interactive forum to facilitate exchange of ideas on teaching and learning. Readers' participation is most welcome. Announcements concerning this book are being made on the Website on a regular basis.

Rugui Yang
Southwest Jiaotong University
Chengdu, Sichuan
May 1, 2002

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