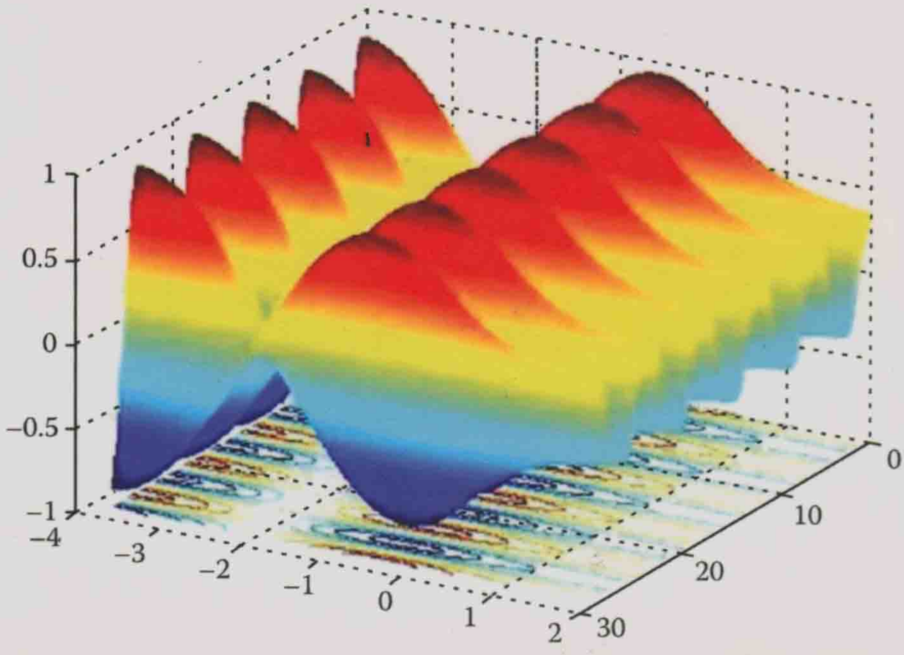
SECOND EDITION

ELECTROMAGNETICS OF TIME VARYING COMPLEX MEDIA

Frequency and Polarization Transformer



Dikshitulu K. Kalluri

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SECOND EDITION

ELECTROMAGNETICS OF TIME VARYING COMPLEX MEDIA

Frequency and Polarization Transformer

This book is dedicated

to my wife Kamala

and to my children Srinath, Sridhar, and Radha

Foreword to the First Edition

I am pleased to write a Foreword to this book by Professor D. K. Kalluri, for he has been a friend since I first became aware of his work in 1992. In that year, Professor C. S. Joshi of the University of California Los Angeles and coworkers were undertaking a series of experiments, based on ideas developed by a number of us theorists, to study the frequency shift of radiation by means of moving ionization fronts in plasmas. This work was closely related to that which Professor Kalluri had been doing for many years, and so we arranged for him to spend the summer of 1992 in Berkeley. In this way a fruitful collaboration, and a good friendship, was initiated. The transformation of an electromagnetic wave by an inhomogeneous medium has been discussed in many books. The Doppler effect, which is a frequency change due to a moving boundary, is also a standard topic in many books. However, the transformation of the frequency of an electromagnetic wave by a general time-varying medium is rarely discussed. The frequency change in a non-moving medium is contrary to the usual experience of wave change. Because of his background in electrical engineering and electromagnetics, Professor Kalluri could weave, in a unique way, this topic of current research interest into a book on Electromagnetics of Complex Media varying in space and time. By using simple ideal models, he has focused on the effect of the time-varying parameters in conjunction with one or more additional kinds of complexities in the properties of the medium, and thus made the subject more accessible. The reader can be assured that Professor Kalluri is highly competent to write this book, for he has contributed original research papers on the frequency shifting of electromagnetic radiation using a transient magnetized plasma. He has expertise, and many publications, dealing with moving media, the use of Laplace transforms to study the effect of boundaries on transient solution, the generation of a downshifted wave whose frequency may be controlled by the strength of a static magnetic field (transformation of a whistler wave), and the turning off of the external magnetic field (which showed that an original whistler wave is converted into a wiggler magnetic field). In short, the book that follows is written by a highly competent author who treats important subjects. I hope the reader will enjoy it as much as I have.

Andrew M. Sessler
Berkeley, California

Preface

A simple electromagnetic medium is modeled by three electromagnetic parameters, permittivity (ε), permeability (μ), and conductivity (σ), all of which are positive scalar constants. A complex medium is one in which at least one of these parameters is not a positive scalar constant.

A number of excellent graduate-level books on the electromagnetics of inhomogeneous (space-varying) anisotropic (electromagnetic properties depend on direction of the fields) and dispersive complex media are available. Examples of such books include *Radio Wave Propagation in Ionosphere* by K. G. Budden, published by Cambridge University Press in 1966 and *Theory of Reflection* by John Lekhner, published by Martinus Nijhoff Publishers in 1987. Motivation for development of the theory, numerical simulation, and experimental work includes application in designing systems using (a) shortwave propagation in the ionosphere and (b) optics of anisotropic crystals. In all these studies the medium is assumed to have time-invariant but space-varying electromagnetic properties. The dominant effect of a system involving a time-invariant medium is conservation of the frequency of the signal, and the spatial variation of the medium induces a change in the wave number. The properties of the medium do change with time in these systems but very slowly compared to the period of the propagating wave, and the effects are of secondary importance. For example, the electron density profile in the ionosphere changes from night to day and hence the permittivity of the medium changes in time but the signal frequency is hardly affected by such a change. Hence the time-varying aspect of the medium is generally ignored.

With the availability of powerful ultrafast pulse sources, it is now possible to ionize a medium in a short time and thus change the permittivity of the medium in a time that is short compared to the period of the propagating wave. An idealization of this experimental situation is called flash ionization (sudden-switching) of the medium. The temporal electron density profile is approximated as a step profile with zero rise time. Across such a time discontinuity, the wave number k is conserved but induces a change in the frequency. This property can be used to create a frequency transformer. One can visualize a black box whose input frequency f_i is changed to an output frequency f_0 by the time-varying medium.

Part I of this edition, Theory: Electromagnetic Wave Transformation in a Time-Varying Magnetoplasma Medium, contains a slightly enhanced version of the entire first edition of the book. The time-varying medium, under consideration, continues to be mostly the magnetoplasma because, at this time, it is the only complex medium whose electromagnetic properties can be changed significantly by ionization or deionization of the plasma medium or by switching on or off the background magnetic field. The relative permittivity ε_p can be changed by orders of magnitude. All the misprints in the first edition have been corrected.

Part II, Numerical Simulation: FDTD for Time-Varying Medium, concentrates on the development of an important tool for numerical simulation of electromagnetic wave interaction based on the finite-difference time-domain (FDTD) technique. It is based on expressing the constitutive relation between the current density **J** and the electric field **E** in the time domain as an auxiliary differential equation. While Maxwell's equations are discretized, as usual, by using the central difference approximations, the auxiliary differential equation is solved exactly over a time step by assuming constant values of the plasma parameters $(\omega_p, \omega_b, \nu)$ at the center of the time step. The algorithm, called "exponential time-stepping" in the literature, is therefore valid for large values of the plasma parameters, and the limitation of the usual technique based on central difference approximation of the derivative of **J**, which severely restricts the values of $\omega_b \Delta t$ and $\nu \Delta t$, is mitigated. Location of **J** at the center of Yee's cube yields the leap-frog step-by-step algorithm. Appendix K, which is a reprint of the paper published in 1998, discusses this aspect in detail. The author believes that the modified FDTD used in this book is appropriate for the time-varying magnetoplasma medium, as evidenced by the successful simulations given in Part II as well as Part III.

The first two parts assume unbounded medium or simple boundaries with free space. For the practical case of a finite rise time of the ionization process, the frequency-transformed traveling waves can escape the time-varying medium through the boundary, before the full interaction with the time-varying medium takes place. The experimental difficulty of the generation of a large volume of uniform plasma in a short time can be mitigated if the plasma is bounded in a cavity. In a cavity, the switching angle ϕ_0 is another controlling parameter. The input parameters, including the parameters describing the polarization of the input wave and the system parameters of the switched magnetoplasma medium influence the frequencies and the phases of the output waves. Thus a switched magnetoplasma in a cavity acts like a generic frequency and polarization transformer.

Part III, Application: Frequency and Polarization Transformer—Switched Medium in a Cavity, discusses this application. The author believes that this is an important application emerging from the theories developed in Part I. In particular, it is shown that one can use this technique to transform from 2.45 GHz, an inexpensive source in a consumer product (microwave oven), to 300 GHz terahertz radiation with enhanced electric field. Appendix Q, which is a reprint of a recently published paper, discusses this aspect. The frequency transformer that accomplishes this transformation has a whistler wave as the input wave and the time-varying medium in the cavity is created by switching off the ionization source, thus converting the magnetoplasma medium in the cavity to free space.

The author is grateful to Professor Alexeff for volunteering to write a brief account of the experimental work done so far on this topic by his and other groups. The author would achieve his objective if this book helps to stimulate additional experimental work by many, including himself. When the third edition is published Part IV will grow, indicating the progress in experimental work. Experiments based on switching in a cavity can be done more easily and can bring more researchers with moderate laboratory equipment into the area. The author is planning such experiments based on a significantly improved and easier technique in development.

This edition starts with an overview of the material covered in the book on the frequency transformation effect of the time-varying magnetoplasma medium. It contains 14 chapters and 17 appendices. The appendices (except Appendix A) are reprints (with minor changes) of papers published by the author and his doctoral students. This collection at one place should help a new researcher of the area to have comprehensive access to the subject. Chapters 11 and 12 deal with the concepts and serve the purpose of giving an overall picture before digging into the deeper exposure in Appendices I through Q.

Preface to the First Edition

After careful thought I have developed two graduate courses in electromagnetics, each with a different focus. One of them assumes a simple electromagnetic medium, that is a medium described by scalar permittivity (ε), permeability (μ), and conductivity (σ). The geometrical effect due to the shape and size of the boundaries is the main focus. There are many excellent textbooks, for example, *Advanced Electromagnetics* by Constantine A. Balanis, published by John Wiley & Sons in 1989, to serve the needs of this course.

Recent advances in material science suggest that materials can be synthesized with any desired electromagnetic property. The optimum properties for a given application have to be understood and sought after. To facilitate developing such appreciation in our graduate students, I have developed another course called the "Electromagnetics of Complex Media." The focus here is to bring out the major effects due to each kind of complexity in the medium properties. The medium is considered complex if any of the electromagnetic parameters ε, μ, and σ are not scalar constants. If the parameters are functions of signal frequency, we have temporal dispersion. If the parameters are tensors, we have anisotropy. If the parameters are functions of position, we have inhomogeneity. A plasma column in the presence of a static magnetic field is at once dispersive, anisotropic, and inhomogeneous. For this reason, I have chosen plasma as the basic medium to illustrate some aspects of the transformation of an electromagnetic wave by a complex medium.

An additional aspect of medium complexity that is of current research interest arises out of the time-varying parameters of the medium. Powerful lasers that produce ultrashort pulses for ionizing gases into plasmas can permit fast changes in the dielectric constant of a medium. An idealization of this process is called the sudden creation of the plasma or the sudden switching of the medium. More practical processes require a model of a time-varying plasma with an *arbitrary rise time*.

The early chapters use a mathematical model that usually has one kind of complexity. The medium is often assumed to be unbounded in space or has a simple plane boundary. The field variables and the parameters are often assumed to vary in one spatial coordinate. This eliminates the use of heavy mathematics and permits the focus to be on the effect. The last chapter, however, has a section on the use of the finite-difference time-domain method for the numerical simulation of three-dimensional problems.

The main effect of switching a medium is to shift the frequency of the source wave. The frequency change is contrary to the usual experience of wave change we come across. The exception is the Doppler effect, which is a frequency change due to a moving boundary. The moving boundary is a particular case of a time-varying medium.

The primary title is to indicate that the book will serve the needs of students who study electromagnetics as a base for a number of disciplines that use "complex materials."

Examples are electro-optics, plasma science and engineering, microwave engineering, and solid-state devices. The aspects of "Electromagnetic Wave Transformation by a Complex Medium" that are emphasized in the book are the following:

1. Dispersive medium
2. Tunneling of power through a plasma slab by evanescent waves
3. Characteristic waves in an anisotropic medium
4. Transient medium and frequency shifting
5. Green's function for unlike anisotropic media
6. Perturbation technique for unlike anisotropic media
7. Adiabatic analysis for modified source wave

All the above topics use one-dimensional models.

The following topics are covered briefly: (1) chiral media; (2) surface waves; and (3) periodic media. The topics that are not covered include (1) nonlinear media; (2) parametric instabilities; and (3) random media. I hope to include these topics in the future in an expanded version of the book to serve a two-semester course or to give a choice of topics for a one-semester course.

Problems are added at the end of the book for the benefit of those who would like to use the book as a textbook. The background needed is a one-semester undergraduate electromagnetics course that includes a discussion of plane waves in a simple medium. With this background, a senior undergraduate student or a first-year graduate student can easily follow the book. The solution manual for the problems is available.

The secondary title of the book emphasizes the viewpoint of frequency change and is intended to draw the attention of new researchers who wish to have a quick primer into the theory of using magnetoplasmas for coherent generation of tunable radiation. I hope the book will stimulate experimental and additional theoretical and numerical work on the remarkable effects that can be obtained by the temporal and spatial modification of magnetoplasma parameters. A large part of the book contains research published by a number of people, including the author of this book, in recent issues of several research journals. Particular attention is drawn to the reprints given in Appendices B through H. The book also contains a number of unpublished results.

The RMKS system of units is used throughout the book. The harmonic time and space variations are denoted by $\exp(j\omega t)$ and $\exp(-jkz)$, respectively.

Acknowledgments

The acknowledgments for this edition should be read along with the acknowledgments of the first edition since I continue to interact with most of those in that list. However, in the last few years there are two doctoral graduates who worked on time-varying media and shared with me the excitement of exploring this area of research. They are Dr. Monzurul Eshan and Dr. Ahmad Khalifeh. My present doctoral students Sebahattin Eker and Jinming Chen are deeply involved in this research. They are coauthors of some of the publications that are included in the appendices. Their help is thankfully acknowledged.

I am grateful to Professor Igor Alexeff of the University of Tennessee for writing Chapter 13 on experimental work.

A very special thanks to Jinming, who in his last semester of doctoral work undertook the task of critically reviewing the manuscript and used his considerable computer skills to format the text and figures to the specified standard.

Nora Konopka and Catherine Giacari at CRC encouraged me to submit a proposal for the second edition instead of publishing a separate research monograph on the Frequency and Polarization Transformer. The second edition has thus become a comprehensive work on Time-Varying Media. They along with other members of the team at CRC, Ashley Gasque and Kari Budyk, connected with bringing this book into its final shape, deserve my special thanks.

Acknowledgments to the First Edition

I am proud of my present and past doctoral students who have shared with me the trials and tribulations of exploring a new area of research. Among them, I would particularly like to mention Dr. V. R. Goteti, Dr. T. T. Huang, and Mr Joo Hwa Lee. A very special thanks to Joo Hwa, who in his last semester of doctoral work undertook the task of critically reviewing the manuscript and used his considerable computer skills to format the text and figures to the specified standard. I am grateful to the University of Massachusetts Lowell for granting the sabbatical during the spring of 1996 for the purpose of writing this book. The support of my research by Air Force Office of Scientific Research and Air Force Laboratories during 1996–1997 is gratefully acknowledged. I am particularly thankful to Dr. K. M. Groves for acting as my Focal Point at the Laboratory and for contributing to the research. The encouragement of my friends and collaborators, Professor Andrew Sessler of the University of California, and Professor Igor Alexeff of the University of Tennessee helped me a great deal in doing my research and writing this book.

My peers with whom I had the opportunity to discuss research of mutual interest include Professors A. Baños, Jr., S. A. Bowhill, J. M. Dawson, M. A. Fiddy, O. Ishihara, C. S. Joshi, T. C. Katsoules, H. H. Kuehl, S. P. Kuo, M. C. Lee, W. B. Mori, E. J. Powers, Jr., T. C. K. Rao, B. Reinisch, G. Sales, B. V. Stanic, N. S. Stepanov, D. Wunsch, and B. J. Wurtele and Drs. V. W. Byszewski, S. J. Gitomer, P. Muggli, R. L. Savage, Jr., and S. C. Wilks. The anonymous reviewers of our papers also belong to this group. I wish to recognize this group as having played an important role in providing us with the motivation to continue our research.

My special thanks go to Dr. Robert Stern at CRC for waiting for the manuscript and, once submitted, processing it with great speed.

Finally, I am most thankful to my wife Kamala for assisting me with many aspects of writing the book and to my children Srinath, Sridhar, and Radha for standing by me, encouraging me, and giving up their share of my time for the sake of research.

Author

Dikshitulu K. Kalluri, PhD, is professor of Electrical and Computer Engineering at the University of Massachusetts, Lowell. Born in Chodavaram, India, he received his B.E. degree in electrical engineering from Andhra University, India; a DII Sc degree in high-voltage engineering from the Indian Institute of Science in Bangalore, India; earned a master's degree in electrical engineering from the University of Wisconsin, Madison, and his doctorate in electrical engineering from the University of Kansas, Lawrence.

Dr. Kalluri began his career at the Birla Institute, Ranchi, India, advancing to the rank of professor, heading the Electrical Engineering Department, then serving as (dean) assistant director of the Institute. He has collaborated with research groups at the Lawrence Berkeley Laboratory, the University of California Los Angeles, the University of Southern California, and the University of Tennessee, and has worked for several summers as a faculty research associate at Air Force Laboratories. Since 1984, he has been with the University of Massachusetts Lowell, where he is coordinator of the doctoral program and co-director of the Center for Electromagnetic Materials and Optical Systems (CEMOS). As part of the center, he recently established the Electromagnetics and Complex Media Research Laboratory.

Dr. Kalluri, a fellow of the Institute of Electronic and Telecommunication Engineers and a member of Eta Kappa Nu and Sigma Xi, has published many technical articles and reviews.

*Overview**

0.1 Introduction

This book deals with time-varying *complex media* and their applications. Some of these complexities are nonhomogeneity, dispersion, bi-isotropy, anisotropy, and combinations thereof. Medium complexity is expressed through constitutive relations. A comprehensive and rigorous presentation of constitutive relations for various kinds of complex media is given in Ref. [1].

An additional aspect of medium complexity that is of current research interest [2] arises out of the time-varying parameters of the medium. Transformation of the frequency of an electromagnetic wave (EMW) by a general time-varying medium is rarely discussed in books on electromagnetics, even though the Doppler effect (a frequency change due to a moving medium) is a standard topic in many books. The moving-medium problem is a particular case of a time-varying medium.

The frequency change in a nonmoving medium is contrary to usual experiences. The book deals with frequency shifts of several orders of magnitude that can be achieved by adding the complexity of time-varying parameters on top of the complexity of an anisotropic medium—in particular, the magnetoplasma medium. A time-varying magnetoplasma medium can act as a frequency transformer with a large frequency transformation ratio of the frequency of the output wave to the input wave (frequency upshifting) or a very small frequency transformation ratio (frequency downshifting). This remarkable effect is discussed in Part I (Theory: Electromagnetic Wave Transformation in a Time-Varying Magnetoplasma Medium) of the book by using simple ideal models for the geometry of the problem as well as constitutive relations of the magnetoplasma medium. The subject thus becomes more accessible and the focus is on the effect rather than on the achievement of high accuracy in the results. Accurate results can be obtained by using the finite-difference time-domain (FDTD) method for the numerical simulation of three-dimensional problems [3], which is discussed in Part II (Numerical Simulation: FDTD for Time-Varying Medium) of this book.

* © SPIE Sections 0.1 through 0.7 are based on a chapter written by Kalluri, titled 'Frequency-shifts induced by a time-varying magnetoplasma medium' pp. 245–266, in the book *Introduction to Complex Mediums for Optics and Electromagnetics*, edited by Weighlhofer, W. S. and Lakhtakia, A., SPIE, Bellington, WA, USA, 2003. With permission.

The chapter is organized as follows. Section 0.2 discusses the effect of a temporal discontinuity as opposed to a spatial discontinuity in the properties of the medium, and provides a simple explanation for the frequency shift caused by a temporal discontinuity. Section 0.3 discusses constitutive relations for a time-varying plasma medium. The sudden switching of an unbounded plasma medium is considered in Section 0.4. Section 0.5 deals with the more realistic problem of switching a plasma slab, and Section 0.6 discusses applications of frequency-shifting research that are under development. Section 0.7 explains the theory of wave propagation in a time-varying magnetoplasma medium and the possibility of effecting a big change in the relative permittivity of the medium by changing the ionization level or the background magnetic field. Such a big change in the relative permittivity leads to a large frequency shift. Section 0.8 provides an overview of Part III (Application: Frequency and Polarization Transformer—Switched Medium in a Cavity) and Section 0.9 provides an overview of Part IV (Experiments).

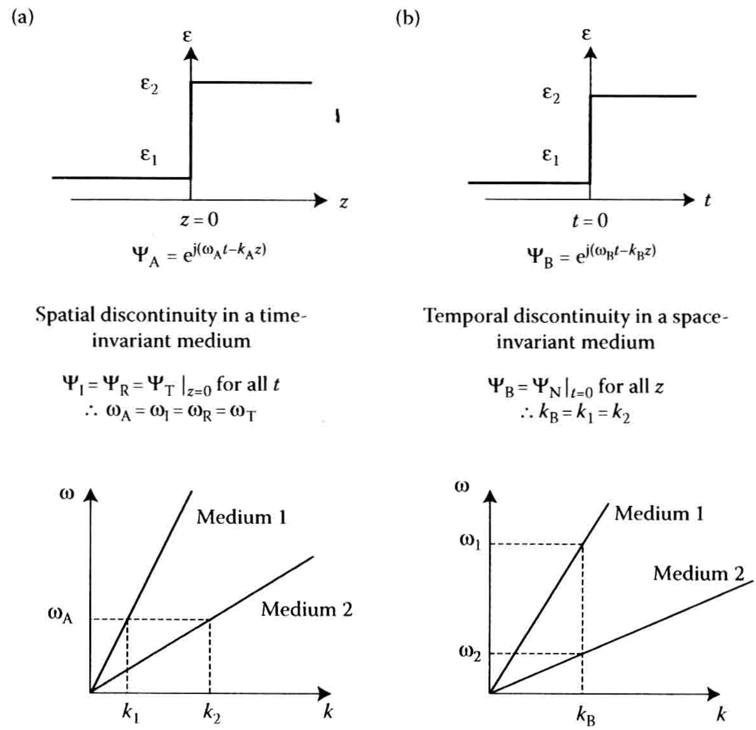

FIGURE 0.1 Comparison of the effects of temporal and spatial discontinuities.

0.2 Frequency Change due to a Temporal Discontinuity in Medium Properties

Let us consider normal incidence on a spatial discontinuity in the dielectric properties of a medium, of a plane wave propagating in the z-direction. The spatial step profile of the permittivity ε is shown at the top of Figure 0.1a.

The permittivity suddenly changes from ε_1 to ε_2 at $z = 0$. Let us also assume that the permittivity profile is time invariant. The phase factors of the incident, reflected, and transmitted waves are expressed as $\psi_A = e^{j(\omega_A t - k_A z)}$, where A = I for the incident wave, A = R for the reflected wave, and A = T for the transmitted wave. The boundary condition of the continuity of the tangential component of the electric field at z = 0 *for all t* requires

$$\omega_I = \omega_R = \omega_T = \omega_A. \tag{0.1}$$

This result can be stated as follows: the frequency ω is conserved across a spatial discontinuity in the properties of the electromagnetic medium. As the wave crosses from one medium to the other in space, the wave number k changes as dictated by the change in the phase velocity, not considering absorption here. The bottom part of Figure 0.1a illustrates this aspect graphically. The slopes of the two straight lines in the ω–k diagram are the phase velocities in the two media. Conservation of ω is implemented by drawing a horizontal line, which intersects the two straight lines. The k values of the intersection points give the wave numbers in the two media.

A dual problem can be created by considering a temporal discontinuity in the properties of the medium. Let an unbounded medium (in space) undergo a sudden change in its permittivity at $t = 0$. The continuity of the electric field at $t = 0$ now requires that the phase factors of the wave existing before the discontinuity occurs, called a source wave, must match with phase factors, Ψ_N, of the newly created waves in the altered or switched medium, when $t = 0$ is substituted in the phase factors. This must be true for all values of z. Thus comes the requirement that k is conserved across a temporal discontinuity in a spatially invariant medium. Conservation of k is implemented by drawing a vertical line in the ω–k diagram, as shown in the bottom part of Figure 0.1b. The ω values of the intersection points give the frequencies of the newly created waves [4–7].

0.3 Time-Varying Plasma Medium

Any plasma is a mixture of charged particles and neutral particles. The mixture is characterized by two independent parameters for each of the particle species. These parameters are particle density N and temperature T. There is