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Broadband Reflectometry for Enhanced Diagnostics and Monitoring Applications

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To Davide, Federico and Francesca: the ones who motivate me every single day
Andrea

To my mother
Egidio

Foreword

One of the advantages of microwave techniques for diagnostics and monitoring applications is that microwave signals penetrate within dielectric structures and they are sensitive to the presence of interior flaws and interfaces. Broadband microwave techniques provide additional information either through incorporating finite range resolution or multi-frequency material characterization.

Microwave reflectometry is commonly implemented in a one-sided manner, which in turn makes it more attractive from practical point-of-view. The interest in broadband microwave reflectometry for materials diagnostics and for monitoring physical parameters of materials covers a broad realm of applications including: civil engineering and infrastructure, agriculture and medicine. Broadband microwave reflectometry is an area of engineering and science from which many publications have resulted over the years.

The authors of this monograph have expertly brought together information from many of such papers and by many investigators as well as their own. Of course, this monograph does not reflect all works in this field, nor does it answer all questions with respect to diagnosis and monitoring applications. However, it serves as an excellent summary of important broadband reflectometry approaches including the time domain reflectometry (TDR), the frequency domain reflectometry (FDR) and the TDR/FDR combined approaches. It is also important that their specific applications for the characterization of liquid materials, for monitoring of water content and for antenna measurements are considered in detail.

They include simultaneous measurement of the levels and the dielectric characteristics of liquid materials in layered media with consideration of measurement accuracy improvement using appropriate probe design, custom-made fixtures for calibration and a targeted optimization routine.

Another application I would like to mention focuses on moisture measurements and includes estimation of moisture content directly from TDR and through TDR/FDR combined approach. Though these methods and techniques are developed for soil measurements, they can also be applied for varieties of materials.

I believe this monograph will be useful to scientists, researchers and practitioners as well as students for future comprehensive studies, investigations and applications.

Rolla (MO),
February 2011

Prof. Sergey Kharkovsky
Missouri University of Science and Technology
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Preface

Monitoring and diagnostics are essential in many application fields: for the industry, for laboratory applications, as well as for countless other areas. Therefore, over the years, considerable research effort has been devoted to explore innovative technologies and methods that could guarantee increasingly reliable and accurate monitoring solutions. In this regard, electromagnetic methods have attracted great interest, also thanks to their vast potential for nondestructive testing. In particular, broadband microwave reflectometry (BMR) has established as a powerful tool for monitoring purposes; in fact, this technique can balance several contrasting requirements, such as the versatility of the system, low implementation cost, real-time response, possibility of remote control, reliability, and adequate measurement accuracy.

On such bases, the central topic of this book is the investigation of innovative BMR-based methods for monitoring applications. More specifically, throughout the book, the different approaches of this technique will be considered (i.e., time domain reflectometry - TDR, frequency domain reflectometry - FDR, and the TDR/FDR combined approach) and several applications will be thoroughly investigated. For each considered application, particular attention will be focused on innovative strategies and procedures that can be adopted to enhance the overall measurement accuracy. There are many application areas where TDR and FDR (or the combination of the two) have proved useful and promising. Therefore, it comes as no surprise that the applications considered herein are very diverse from each other and cover different fields. The present book is structured as follows.

In Chapt. 1, a brief overview of the contexts in which monitoring has assumed a paramount importance is given.

Chapt. 2 introduces the theoretical principles that are at the basis of BMR, and describes the parameters of interest in this technique. Furthermore, this chapter introduces to dielectric spectroscopy, which is one of the pivotal applications of BMR (in fact, as well known, many of the applications of BMR often descend from dielectric spectroscopy measurements).

In Chapt. 3, the TDR, FDR, and TDR/FDR combined approaches are thoroughly discussed, and the related advantages and shortcomings are addressed. In particular, some effective strategies for enhancing the accuracy of BMR measurements; all these strategies basically aim at compensating for the effect of systematic errors.

Chapt. 4 presents some innovative BMR-based solutions for the simultaneous monitoring of qualitative and quantitative characteristics of liquids. This is quite a broad application area, and the investigated applications cover diverse sectors: from the monitoring of stratified liquids (particularly useful for the industry of petrochemicals) to the analysis on edible liquids (useful, for example, for anti-adulteration control on vegetable oils).

Chapt. 5 is focused on the qualitative analysis of granular materials and on moisture measurements. This last application, which is particularly useful in soil science and agriculture, can be extended also to different areas. In fact, the qualitative status in the production of agrofoods, in the production of inert materials, and in the fertilizer industry (just to name a few of the investigated application fields) is strongly related to the amount of water content of these materials.

Finally, Chapt. 6 deals with the characterization of antennas through BMR. In particular, some useful guidelines for antenna characterization are presented. More specifically, the proposed procedures can help obtaining a higher measurement accuracy even when measurements are not performed in dedicated facilities (i.e., anechoic chambers).

In all the described procedures and methods, the ultimate goal is to endow them with a significant performance enhancement in terms of measurement accuracy, low cost, versatility, and practical implementation possibility, so as to unlock the strong potential of BMR.

Lecce (Italy),
February 2011

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Acronyms

AC	alternate current
AUT	antenna under test
BMR	broadband microwave reflectometry
DC	direct current
EM	electromagnetic
FD	frequency domain
FDC	frequency domain calibration
FFT	fast Fourier transform
FTIR	Fourier transform infrared
FDR	frequency domain reflectometry
GBNM	globalized bounded Nelder-Mead
ICM	independent capacitance measurement
IF	intermediate frequency
IFFT	inverse fast Fourier transform
LO	local oscillator
LUT	liquid under test
MUT	material under test
NMR	nuclear magnetic resonance
PCA	principal component analysis
RF	radio frequency
RFID	radio frequency identification
rmse	root mean square error
SMA	sub-miniature A
SNR	signal to noise ratio
SOL	short open load
SUT	system under test
TD	time domain

TDR	time domain reflectometry
TEM	transverse electromagnetic
TL	transmission line
TLM	transmission line method
TM	transverse magnetic
TSC	triple-short calibration
VNA	vector network analyzer
VSWR	voltage standing wave ratio

Chapter 1
Introduction

'Common sense is the collection of prejudices acquired by age eighteen'.
Albert Einstein

Abstract. This chapter introduces to broadband microwave reflectometry (BMR), which is the expression used in this book to indicate an electromagnetic technique used for monitoring and diagnostics purposes. The adjective *broadband* emphasizes the fact that the analysis can be carried out over a wide frequency range. A brief survey of the typical applications of BMR is also provided.

1.1 The Concept Behind This Book

Under the term *monitoring*, the Cambridge dictionary states the following definition

> to watch and check a situation carefully for a period of time in order to discover something about it.

Similarly, the word *diagnosis* indicates

> a judgment about what a particular illness or problem is, made after examining it.

Such broad, and yet unambiguous definitions seem to emphasize the urgency associated with the terms themselves [1]. As a matter of fact, now more than ever, 'keeping the situation under control', for cognitive or predictive purposes, is a transversal need in a number of interdisciplinary sectors, especially in industrial, environmental, civil, and agricultural areas. As a direct consequence, strict regulations have been enforced and guidelines have been issued that dictate specific standards (either qualitative or quantitative) that should be complied with, in order to ensure the suitability of the 'product' or of the 'process'. In this scenario, monitoring and diagnosis procedures are used for the optimization of process and for triggering possible corrective actions, or for checking the compliance of the product with pre-established quality standards.

In general, a monitoring program gathers data for several purposes, such as

- to draw comparisons against standard or target *status*;
- to make comparisons between different conditions or to conduct analyses;

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