Wiley Series in Microwave and Optical Engineering

Kai Chang, Series Editor

Fundamentals of Microwave Photonics

Vincent J. Urick Jr.
Jason D. McKinney
Keith J. Williams

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A comprehensive resource to designing and constructing analog photonic links capable of high RF performance

Fundamentals of Microwave Photonics provides a comprehensive description of analog optical links from basic principles to applications. The book is organized into four parts. The first begins with a historical perspective of microwave photonics, listing the advantages of fiber optic links and delineating analog versus digital links. The second section covers basic principles associated with microwave photonics in both the RF and optical domains. The third focuses on analog modulation formats—starting with a concept, deriving the RF performance metrics from basic physical models, and then analyzing issues specific to each format. The final part examines applications of microwave photonics, including analog receive-mode systems, high-power photodiodes applications, radio astronomy, and arbitrary waveform generation.

- Covers fundamental concepts including basic treatments of noise, sources of distortion and propagation effects
- Provides design equations in easy-to-use forms as quick reference
- Examines analog photonic link architectures along with their application to RF systems

A thorough treatment of microwave photonics, *Fundamentals of Microwave Photonics* will be an essential resource in the laboratory, field, or during design meetings.

The authors have more than 55 years of combined professional experience in microwave photonics and have published more than 250 associated works.

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WILEY SERIES IN MICROWAVE AND OPTICAL ENGINEERING

KAI CHANG, Editor
Texas A&M University

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For Cindy, Amanda and Vicki

PREFACE

This volume provides what we believe to be a thorough treatment of the microwave photonics field, sometimes referred to as RF or analog photonics. The intended audience ranges from an advanced undergraduate student in engineering or physics to experts in the field. The treatment is fundamental in nature and could be used in an advanced undergraduate or graduate-level course to introduce students to microwave photonics. Although a problem set is not included, there are instances throughout where an inventive instructor could devise assignments. It is our hope that seasoned veterans of the field will find this book most useful for a variety of reasons. We have tried to provide as much of the basic underlying physics as is possible in a work of this size. Sometimes, this information can be lost in a field as applied as microwave photonics. Plots that give bounds on performance for a variety of scenarios abound. A thorough list of references is provided for each chapter, including original sources where applicable. Design equations in easy-to-use forms are provided throughout and are intended for quick reference. Indeed, we plan to keep this volume readily accessible in the laboratory, in the field, or during design meetings.

We intended for this book to flow continuously from the first to the last page and believe we have succeeded in this endeavor. Beginners in the field are encouraged to read continuously, as the later chapters build on foundations laid in the earlier ones. Those more experienced in the field should find that navigation of the individual chapters is readily

achievable. Chapter 1 gives an introduction to microwave photonics and stands on its own, pointing to later chapters where more detail is provided. Chapter 2 describes the radio-frequency metrics that are most important to quantifying performance of microwave photonics systems and is largely divorced from optics. Chapters 3 through 5 provide fundamental treatments of noise, distortion, propagation, and fiber nonlinearities as they pertain to microwave photonics. These three chapters do not concentrate on any single modulation mechanism but rather are intended to provide a generalized treatment. Specific modulation and corresponding demodulation techniques are covered in Chapters 6 through 8, using the material in the previous four chapters. In Chapter 6, intensity modulation with direct detection employing an external Mach–Zehnder modulator is detailed. This technique is arguably the most prevalent today and therefore receives the most thorough treatment. Phase modulation is covered in Chapter 7 but with slightly less detail. Complete but relatively brief analyses of numerous other modulation formats are conducted in Chapter 8. Chapter 9 is concentrated on high power photodetectors. System and subsystem applications are covered in Chapter 10, which also describes some of the present trends in the field.

We ourselves acquired a more complete knowledge of many topics while writing this book and the work inspired many new concepts. We sincerely hope the same is true for all who pick up this volume.

VINCENT URICK
JASON MCKINNEY
KEITH WILLIAMS
Washington, DC, April 2014

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This book was written as a private work, and as such, the opinions expressed in this book are those of the authors and do not reflect the official position of the US Naval Research Laboratory (NRL), the US Navy, or the US Government. That being said, this work would not have been possible without the support of NRL throughout our careers. The work environment provided at NRL has made it possible to make steady progress in developing a thorough understanding, both experimental and theoretical, of microwave photonics technology. This would not have happened without the support of the management at NRL, specifically the Superintendents and Branch Heads who were instrumental in supporting our ability to make progress in this important technology area. Those individuals include Dr. Francis Klemm, Dr. Thomas Giallorenzi, Dr. John Montgomery, Dr. Joseph Weller, Dr. Ronald Esman, Mr. Michael Monsma, and Dr. Don Northam. We would also like to acknowledge those staff at NRL, both past and present, who have contributed to the development of microwave photonics.

We are indebted to the countless colleagues and collaborators that we have had the pleasure to work with over the years. The citations in the text name many of those who have inspired us but some are deserving of special mention. Firstly, Dr. Frank Bucholtz at NRL has provided significant insight into the analysis and understanding of analog optical links. His work is cited where applicable but his

contributions to our progress go well beyond those instances. Professor Nicholas Frigo of the US Naval Academy Physics Department assisted with the development of sections pertaining to polarization effects. Mr. Carl Villarruel, NRL (retired), has spent countless hours discussing the technical fine points of microwave photonics with us, particularly in areas concerning optical fiber effects. Dr. Preetpaul Devgan of the US Air Force Research Laboratory stimulated important concepts pertaining to modulation formats. Dr. Andrew Kowalevicz from Raytheon Company inspired useful viewpoints on optical fields in various media. Dr. Marcel Pruessner at the NRL provided valuable feedback on silicon integration for microwave photonics applications. Dr. Olukayode Okusaga, US Army Research Laboratory, gave insight into the subtitles of optoelectronic oscillators. Mr. Bill Jacobs, US Space and Naval Warfare Systems Command, provided alternative views on applications of microwave photonics and also assisted with professional responsibilities while this book was being written. We acknowledge Dr. Thomas Clark Jr. at Johns Hopkins Applied Physics Laboratory for discussing aspects of multioctave millimeter-wave photonics and signal processing. Finally, we wish to thank all the ambitious students we have instructed and those we have mentored for allowing us to pass on what we have learned. It is in those instances when one realizes that you don't truly understand something until you can teach it to someone else, a concept that was reinforced tenfold while writing this book.

Beyond the mainly professional acknowledgements mentioned previously, there are numerous individuals who have influenced us in profound ways. This work would have never come to be if it weren't for our parents and families. Our wives and children were supportive during the writing process, making numerous concessions along the way. We are forever grateful to our parents, Vincent Urick Sr., Susanne Urick, Dwight McKinney, Deborah McKinney, and Gertrude Williams. They nurtured intellectual curiosity in us and instilled a work ethic that was required to complete this book. Paul Urick, an old-time farmer from Pennsylvania, and Norman Zlotorzynski, a kind man who survived Omaha Beach in 1944, always provided inspiration when it was needed most. They both passed away while this book was being written and would like to have seen the completed work.

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