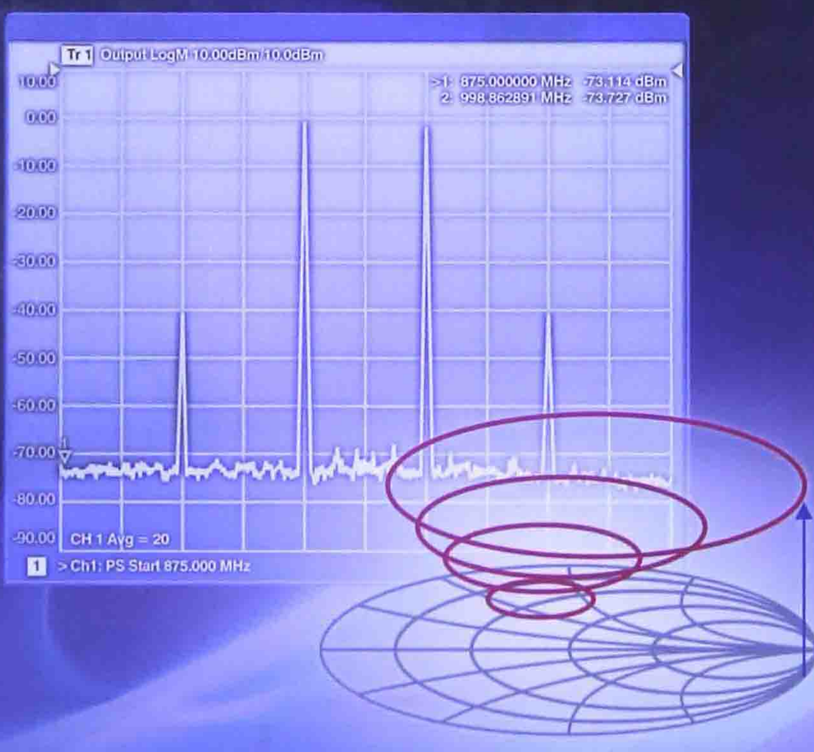
HANDBOOK OF

MICROWAVE COMPONENT MEASUREMENTS

WITH ADVANCED VNA TECHNIQUES



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To my dear wife Dana

Foreword

The electronics industry has undergone revolutionary changes in the past 20 years. System performance has significantly advanced, physical size of hardware has shrunk, quality and reliability have greatly improved and manufacturing costs have dramatically decreased. Underlying these advances has been the phenomenal growth in RF test and measurement capability. Modern-day RF test equipment has progressed to the point where it is not uncommon to measure signals below −100 dBm at milliseconds speed. Even more astounding is the ability to marry RF test capability with analysis software whereby test equipment can produce linear and non-linear models of the device under test to significantly improve the life of the design engineer, using this capability.

RF and microwave components have played an important role in this revolutionary change. Component size has shrunk, parasitics have been reduced, quality standards have greatly improved and costs have reduced ten-fold. At the same time, test fixtures and interconnects have improved to enable a higher level of precision during characterization and production measurement. In parallel with these advances, test equipment has improved to an extent where there has been a revolution in the capabilities to make precise and fast measurements of RF and microwave components. The success of a manufacturer of RF and microwave components is directly linked to the quality and capability of measuring component performance during the design, qualification and production phase of the product life cycle. From a practical point of view, the testing must be fast (1–2 seconds), the accuracy very precise (hundredths of a dB), with a high degree of repeatability. Each phase of the life cycle imposes its unique requirements for measurement accuracy and data collection.

During the design phase, full characterization of performance, including amplitude and phase, is a must in order to establish a reference for future production runs. So it becomes a necessary requirement to characterize and de-embed the test setup and test fixtures to isolate actual device performance. Fortunately, the modern vector network analyzer provides support in this regard. Consequently, the performance data obtained during the design phase becomes the gold standard for evaluating statistical variation obtained from future production lots; and these lots are accepted or rejected based on the statistical results, with sigma generally being the statistic most closely watched by the test or QA engineer to evaluate production lot acceptance.

When published specs are provided for a component, it is very important to understand that these specifications are simply markers which allow for a first impression or summary review of the component performance. However, only when performance data and performance graphs are provided for all parameters, including both amplitude and phase, would the "real" performance of the component be known. Furthermore, in characterizing components for use in customer evaluations, it is important to provide this data both within and outside the specified bandwidth. In non-linear components such as a frequency mixer, higher-order harmonics of the RF and LO signals are generated, and depending on the load impedance outside the specified frequency range, these higher-order harmonics can get reflected back into the mixer, causing an interaction between the desired signals and the unwanted harmonics. Fortunately, modern-day analyzers can make these harmonic measurements relatively quickly and easy.

Dr. Dunsmore has captured the essence of modern-day measurements. He provides a practical understanding of measurement capabilities and limitations. He provides a means for the test engineer to not only make measurements, but also to understand test concepts, anticipate measurement results and learn how to isolate and characterize the performance of the DUT, independent of potential errors inherent in the test environment. I am confident that this book will serve as a reference for understanding measurement methods, test block diagrams and measurement limitations so that correlation between the manufacturer and user would take place by using a common reference. This book has the potential to be an invaluable source to further the progress of the RF and microwave world.

Harvey Kaylie
President and Founder of Mini-Circuits

Preface

This book is a bit of mixture between basic and advanced, and between theoretical and practical. Unfortunately, the dividing lines are not particularly clear, and depend considerably upon the training and experience of the reader. While primarily a text about measurement techniques, there is considerable information about device attributes that will be useful to both a designer and a test engineer, as one purpose of device testing is to ascertain the attributes that do not follow the simplified models commonly associated with those devices. In practice, it is the unexpected responses that consume the majority of the time spent in test and troubleshooting designs, particularly related to active devices such as amplifiers and mixers.

The principal instrument for testing microwave components is the vector network analyzer (VNA), and recent advances have increased the test capabilities of this instrument to cover far more than simple gain and match measurements. As a designer of VNAs for more than 30 years, I have been involved in consulting on the widest range of microwave test needs from cell phone components to satellite multiplexers. The genesis and goal of this book is to provide to the reader a distillation of that experience to improve the quality and efficiency of the R&D and production test engineer. The focus is on modern test methods; the best practices have changed with changing instrument capability and occasionally the difference between legacy methods and new techniques is sufficiently great as to be particularly highlighted.

Chapter 1 is intended as an introduction to microwave theory and microwave components. The first half introduces characterization concepts common to RF and microwave work. Some important mathematical results are presented which are useful in understanding the results of subsequent chapters. The second half of Chapter 1 introduces some common microwave connectors, transmission lines and components, as well as providing some discussion of the basic microwave test instrumentation. This chapter is especially useful to engineers new to RF and microwave testing.

Chapter 2 provides a detailed look into the composition of common VNA designs along with their limitations. While this level of detail is not normally needed by the casual user, test engineers trying to understand measurement results at a very precise level will find it useful to understand how overall results are affected by VNA test configuration. While the modern VNA can make a wide range of measurements, including distortion, power and noise figure measurements, still the principal use is in measuring S-parameters. The second half of Chapter 2 illustrates many useful parameters derived from basic S-parameters.

Perhaps the most arcane aspect of using VNAs for test is the calibration and error-correction process. Chapter 3 is a comprehensive discussion of the error models for VNAs, calibration methods, uncertainty analysis and evaluation of calibration residuals. This chapter also introduces the idea of source and receiver power calibrations, about which, excluding this book, very little formal information is currently available. The chapter concludes with many practical aspects of VNAs that affect the quality of calibrated measurements.

Chapter 4 is likely the most mathematically rigorous, covering the very useful topic of time domain transforms used in VNAs. The topic of gating, its effects, and compensation methods is examined in particular. These first four chapters comprise the introductory material to microwave component measurements.

The remaining chapters are focused on describing particular cases for microwave component measurements. Chapter 5 is devoted to passive microwave components such as cables and connectors, transmission lines, filters, isolators and couplers. Best practices, and methods for dealing with common problems, are discussed for each component.

Chapter 6 is all about amplifier measurements, and provides the understanding needed for complete characterization. In particular, difficulties with measuring high gain and high power amplifiers are discussed, including pulsed RF measurements. Non-linear measurements such as harmonics and two tone intermodulation are introduced, and many of the concepts for distortion and noise measurements are equally valid whether using a spectrum analyzer or a modern VNA for the test receiver.

Chapter 7 extends the discussion of active device test to that of mixers. Because few engineers have experience with mixers, and they are often only superficially covered in engineering courses, the chapter starts with a detailed discussion of the modeling and characteristics of mixers and frequency converters. Measurement methods for mixers can be quite complicated, especially for the phase or delay response. Several key methods are discussed, with a new method of calibrating, using a phase reference, presented in detail for the first time. Besides the magnitude and phase frequency response, methods for measuring mixer characteristics versus RF and local oscillator power are presented, along with distortion and noise measurements. This chapter is required reading for any test engineer dealing with mixers or frequency converters.

Chapter 8 brings in the concept of differential and balanced devices, and provides complete details on the analysis and measurement methods for differential devices including non-linear responses, noise figure and distortion.

Chapter 9 provides a collection of very useful techniques and concepts for the test engineer, particularly with respect to test fixturing, including a complete discussion of creating in-fixture calibration kits.

Acknowledgments

Many of my colleagues assisted in the development and review of this book and I would like to acknowledge their help here. Henri Komrij, my R&D manager, has been a great supporter from the initial concept, as well as Greg Peters, VP and general manager of the Components Test Division. Many R&D engineers in our lab contributed to the review of the manuscript and their expertise in each field is sincerely appreciated: Keith Anderson, Dara Sarislani, Dave Blackham, Ken Wong, Shinya Goto, Bob Shoulders, Dave Ballo, Clive Barnett, Cheng Ning, Xin Chen, Mihai Marcu and Loren Betts. They did an excellent job and any remaining errors are entirely and regrettably my own.

Many of the new methods and techniques presented here rely on the difficult and precise implementation of measurement methods and algorithms and I'd like to thank our software design team, Johan Ericsson, Sue Wood, Jim Kerr, Phil Hoard, Jade Hughes, Brad Hokkanen, Niels Jensen, Raymond Taylor, Dennis McCarthy, Andy Cannon, Wil Stark, Yu-Chen Hu, Zhi-Wen Wong and Yang Yang, as well as their managers, Sean Hubert, Qi Gao and Dexter Yamaguchi for all their help over the years in implementing in our products many of the functions described here.

Finally I would like to remember here Dr. Roger Pollard, who as my Ph.D. adviser at University of Leeds and as a colleague during his sabbaticals at HP and Agilent Technologies, provided advice, mentoring and friendship; he will be greatly missed.

Joel P. Dunsmore
Sebastopol, CA

List of Acronyms

ACPL	adjacent channel power level
ACPR	adjacent channel power ratio
ADC	analog-to-digital-converter
AFR	automatic fixture removal
ALC	automatic level control
AM	amplitude modulated
APE	automatic port extension
arb	arbitrary-waveform generator
ATF	A-receiver transmission forward
ATS	automated test system
balun	BALanced-UNbalanced transformer
BTF	B-receiver transmission forward
BW	bandwidth
CMRR	common mode rejection ratio
CPW	coplanar waveguide
CSV	comma separated values
DANL	displayed average noise level
dBc	dB relative to the carrier
DDS	direct-digital synthesizer
DFT	discrete Fourier transform
DUT	device under test
DUTRNPI	DUT relative noise power incident
Ecal	electronic-calibration
EM	electromagnetic
ENR	excess noise ratio
ERC	enhanced response calibration
EVM	error vector magnitude
FBAR	film bulk acoustic resonator
FCA	frequency-converter application
FN	fractional-N
FOM	frequency offset mode
FPGA	field-programmable gate array
GCA	gain compression application
GPIO	general-purpose input/output

GUI	graphical user interface
IBIS	input output buffer information specification
IDFT	inverse discrete Fourier transform
IF	intermediate frequency
IFFT	inverse fast Fourier transform
IFT	inverse Fourier transform
IIP	input intercept point
IM	intermodulation
IMD	intermodulation distortion
IM3	third-order IM product
IP3	third-order intercept point
IMD	intermodulation distortion
IPwr	input power
KB	Kaiser-beta
LNA	low-noise amplifier
LO	local oscillator
LTCC	low-temperature cofired-ceramic
LVDS	low voltage differential signaling
MMIC	monolithic microwave integrated circuit
MUT	mixer under test
NF	noise figure
NFA	noise figure analyzer
NOP	normal operating point
NVNA	non-linear vector network analyzer
OPwr	output power
PAE	power added efficiency
PCB	printed circuit board
PIM	passive intermodulation
PMAR	power-meter-as-receiver
QSOLT	quick short open load thru
RBW	resolution bandwidth
RRF	reference-receiver forward
RMS	root-mean-square
RNPI	relative noise power incident
RTF	reference transmission forward
SA	spectrum analyzer
SAW	surface acoustic wave
SCF	source calibration factor
SE	single-ended
SMC	scalar mixer calibration
SMT	surface mount technology
SMU	source measurement unit
SNA	scalar network analyzer
SOLR	short open load reciprocal
SOLT	short open load thru
SRF	self-resonant frequency

SRL	structural return loss
SSB	single sideband
SSPA	solid-state power amplifier
STF	source transmission forward
SYSRNPI	system relative noise power incident
TD	time domain
TDR	time-domain reflectometer
TDT	time-domain transmission
TEM	transverse-electromagnetic
TOI	third-order intermodulation
TR	transmission/reflection
TRL	thru reflect line
TRM	thru reflect match
TVAC	thermal vacuum
TWT	traveling wave tube
UT	unknown thru
VCO	voltage-controlled oscillator
VMC	vector mixer/converter
VNA	vector network analyzer
VSA	vector signal analyzer
VSWR	voltage standing wave ratio
YIG	yttrium-iron-garnet
YTO	YIG-tuned-oscillator

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