Preface

The present thesis has been written predominantly in the course of my activities as Research Associate (Oct. 2007 till Dec. 2013) at the Institute of Microwaves and Photonics (LHFT), Friedrich-Alexander University of Erlangen-Nuremberg, Germany.

Outline

The thesis is structured in six chapters, a summary and an appendix. The core statements of each chapter are introduced in the following. A German translation of the summary is included in an additional chapter.

Chapter 1 Synthetic Instruments introduces history and the **fundamental idea** of synthetic instruments. Block diagrams of synthetic and traditional instruments are shown and **critical millimeter-wave components** for synthetic automatic test systems are identified.

In **Chapter 2 Resistive Diode Frequency Multipliers** a complete **modelling procedure** for discrete **Schottky diodes** is illustrated, which includes the semiconductor and linear parts of the diode. One section deals with single tone large signal analysis of nonlinear circuits, as it is used by harmonic balance circuit simulators. Different diode configurations, optimum embedding impedances and the author's frequency **multiplier design flow** are explained. Experimental results are presented. These include an octave bandwidth frequency **tripler for 20 to 40 GHz**, five frequency multipliers for **50 / 60 to 110 GHz** and frequency multipliers for **D- and Y-band**. In addition, the design equations of Dolph-Chebyshev waveguide tapers and an uncertainty analysis of spectral power measurements above 50 GHz are outlined.

In the first section of **Chapter 3 Planar Directional Couplers and Filters**, the modal and nodal scattering and impedance network parameters of coupled transmission lines according to the **general waveguide circuit theory** (GWCT) are introduced. This analysis is based on results from 2D EM Eigenmode analysis. The second section deals with **backward wave directional couplers**. A synthesis procedure for nonuniform transmission line couplers is included. Theoretical and experimental investigations on backward wave couplers with dielectric overlay technique (stripline) and wiggly-line technique to equalize the even and odd mode phase velocities are presented. The third section is dedicated to **codirectional couplers**. Beside the synthesis procedure, simulated and measured results of various codirectional couplers on thin-film processed alumina are given. Couplers for planar integration require internal nonreflective impedance terminations. Several 50 Ω **terminations** based on nickel chrome (NiCr) sheet resistors are presented in section 3.4. It further includes simulation and measurement results of the author's DC to 110 GHz **attenuator series**. Equalized phase velocities are also beneficial for edge and broadside **coupled line bandpass filters (BPF)** to suppress the parasitic second passband. This is demonstrated in section 3.5 by applying wiggly-line technique to the first and last filter element of an edge coupled line BPF on 10 mil alumina.

Chapter 4 Triple Balanced Mixers presents the author's investigations on triple balanced mixers (TBM), which are the only mixers providing overlapping RF, LO and IF frequency ranges together with large IF bandwidth and enhanced RF large signal handling capability. The first section highlights major differences and similarities between frequency multipliers and mixers. This is followed by a section about analytical and numerical methods for mixer analysis. Different methods are listed together with their strengths and weaknesses. With the results of single tone large signal analysis (harmonic balance) as a starting point, **large signal / small signal (LSSS) mixer analysis** based on conversion matrices is derived. The minimum achievable conversion loss at different embedding impedances and also optimum embedding impedances are calculated for a simplified case, which includes nonzero diode series resistances. Different mixer configurations (SBM, DBM and TBM) are compared from a small signal analysis point of view and regarding the mixers' spurious tone behaviour, following a method from Henderson. A **planar TBM realization** on SiO_2 using commercial silicon crossed quad diodes is presented. The TBM operates from **1 to 45 / 50 GHz** at RF / LO and achieves at least 20 GHz IF bandwidth. Simulation and measurement results of the component are presented. Measurement results of the TBM within an automatic test system front end module are included.

The first section of **Chapter 5 Power Detectors** introduces theoretical foundations. Expressions for detector current β and voltage sensitivity γ, and the upper $\Delta P_{\mathrm{sq}}, P_{\mathrm{USL}}$ and lower boundary $P_{\mathrm{NEP}}, P_{\mathrm{TSS}}$ of the square law dynamic range are derived. This is followed by a section which compares common detector architectures. Two planar ultra-wideband power detector designs operating from **1 to 40 GHz** and **60 to 110 GHz** are presented. The detectors are part of the signal generator frequency extension modules, described in chapter 6, to realize monitoring of the output power level and automatic level control (ALC).

Chapter 6 Integrated Front End Assemblies presents two signal generator frequency extension modules for the output frequency ranges **20 to 40 GHz** and **60 to 110 GHz**. Such source modules are required in automatic test systems to provide internal local oscillator signals and high frequency stimulus. Although many necessary functionalities are available as microwave monolithic integrated circuits (MMIC), hybrid realization is preferred to combine the advantages of both, thin-film processed alumina Al_2O_3 or quartz SiO_2 and MMIC technology. Components from the preceding sections are utilized within the source modules.

The **Appendix Filter Synthesis** includes equations for synthesis of Chebyshev lowpass (LPF) and bandpass filters (BPF) in a very compact form. The filters are either based on **g** parameters of a lowpass prototype filter or **G** parameters of a prototype quarterwave transformer.

Annotations

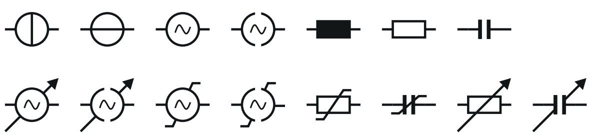
- The author tried to be compatible with guidelines for submission of articles to the IEEE Transactions on Microwave Theory and Techniques, regarding presentation of content and also syntax.
- Column vectors **X** and matrices **X** are shown in bold face typing.
- The subscripts $\mathbf{X}^{\mathrm{T}}, X^{\star}, \mathbf{X}^{\mathrm{H}}$ denote the matrix or vector transposition, complex conjugation and the Hermitian adjoint, respectively.
- Real and complex quantities are not distinguished.
- The letters $\alpha, \beta, \epsilon, \gamma, \sigma, P$ and p have different meanings throughout the thesis, which are believed to be clear from context.
- Per unit length network parameters are often marked with apostrophes. Within this work, the symbols R, L, C, G are used for the conventional equivalent network parameters **and** also for the distributed ones.
- The letter j is used for the imaginary unit, whereas the complex current is denoted by i.
- The frequency f and angular frequency $\omega = 2\pi f$ are both called frequency in the continuous text.
- The following frequency range abbreviations and designations for rectangular waveguides WR are used throughout this work.

band abbrev.	frequency range [GHz]	EIA band design.	internal dim. [mm]	TE_{10} cut-off freq. [GHz]
V	50 to 75	WR-15	3.759 × 1.880	40
E	60 to 90	WR-12	3.099 × 1.549	48
W	75 to 110	WR-10	2.540 × 1.270	59
F	90 to 140	WR-8	2.032 × 1.016	74
D	110 to 170	WR-6	1.651 × 0.826	91
G	140 to 220	WR-5	1.295 × 0.648	116
Y	170 to 260	WR-4	1.092 × 0.546	137
J	220 to 325	WR-3	0.864 × 0.432	174

EIA = The Electronic Industries Alliance, www.ecianow.org

An almost uniform labeling from V- to G-band is well-established in industry, which is not the case for the letters used for WR-4 to WR-3. Especially H-band is often used instead of J-band and many designations for the rarely used Y-band can be found.

- The following symbols denote DC current and voltage sources, AC current and voltage sources, lumped elements (inductors, resistors, capacitors), variable sources (arrow), nonlinear sources, nonlinear resistors and capacitors, variable resistors and capacitors.



- In physics, the notational operator $[\star]$ gives the unit of the physical quantity $\star$, to which it is applied. In this sense $[f]$ = GHz would be a correct application. Anyway, it is common practice to write [GHz]. The latter is used in all labels of Figures and Table captions throughout this work.
- The complex, frequency dependent permittivity $\epsilon(\omega)$ and conductivity $\sigma(\omega)$ cover the intrinsic bulk material properties. Whereas the effective conductivity $\sigma_{\text{eff}} = \sigma(\omega) + j\omega\epsilon(\omega)$ and effective permittivity $\epsilon_{\text{eff}}(\omega) = \sigma_{\text{eff}}/j\omega$ include both effects. The utilized definition of $\epsilon(\omega)$ includes the permittivity constant ϵ_0. This leads to the

following derived expressions of the intrinsic wave impedance Z_w and propagation coefficient γ.

$$Z_\mathrm{w} = \sqrt{\frac{\mu(\omega)}{\epsilon_\mathrm{eff}(\omega)}} = \sqrt{\frac{j\omega\mu(\omega)}{\sigma_\mathrm{eff}}} = \frac{j\omega\mu(\omega)}{\gamma}$$

$$\gamma = \frac{j\omega\mu(\omega)}{Z_\mathrm{w}} = \sqrt{j\omega\mu_0} \cdot \sqrt{\sigma_\mathrm{eff}}$$

- The letters v, i are used for voltage and current time domain waveforms, whereas the letters V, I are used for the corresponding DC and spectral components in the frequency domain. Small- and large-signal quantities are not distinguished.
- In general, frequency domain variables belong to the complex double sided Fourier series. Some derivations are expressed more suitable by complex single sided Fourier series. In both cases, the same symbol $\circ\!\!-\!\!\bullet$ for time to frequency domain mapping is used.
- Presented simulation data is based on the software tools Agilent ADS, Ansys HFSS, Ansys Designer and CST Microwave Studio.
- A complete list of utilized measurement instruments is given in the following. The presented measurement data underlies the accuracy of these instruments.

manufacturer	**instruments**
signal generators	Ag E8257D, R&S SMF100A, SMZ-90, An MG3694C
spectrum analyzers	Ag N9030A PXA, R&S FSW43, FSEK30
harmonic mixers	Ag M1970V, M1970W, R&S FS-Z75, FS-Z90, SAM-110, SAM-140, SAM-170, SAM-220
power detectors	Ag V8486A, W8486A, R&S NRP-Z55, NRP-Z57, NRP-Z58, VDI Erickson PM4
network analyzers	Ag N5247A, N5251A, R&S ZVA50, ZVA110

Ag = Agilent Technologies, www.home.agilent.com,
An = Anritsu GmbH, www.anritsu.com,
R&S = Rohde & Schwarz GmbH & Co. KG, www.rohde-schwarz.com,
VDI = Virginia Diodes Inc., www.vadiodes.com.

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