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Design of Active and Passive Components for the Implementation of an Ultra-Broadband Wireless Communication System at 200 GHz

Dipl.-Ing.

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der Fakultät Elektrotechnik und Informationstechnik der
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Kurzfassung

Diese Forschungsarbeit untersucht die Eigenschaften und Grenzen von Schaltungen und kompletten Übertragungssystemen im Bereich sehr hoher Frequenzen um 200 GHz. Herausforderungen der Grundlagenforschung werden erörtert und ein umfassender Erkenntnisgewinn durch die Abdeckung eines breiten Spektrums von theoretischen Aspekten, Bauteilmodellierung und neuartigen Konzepten bis hin zu Machbarkeitsstudien anhand von Hardwarerealisierungen präsentiert. Eines der Hauptziele dabei ist eine hohe Bandbreite der einzelnen Komponenten zu erzielen. Um die vorgestellten Konzepte zu überprüfen, wird eine funktionsfähige Übertragungsstrecke durch systematische Anwendung neuartiger theoretischer und praktischer Ansätze in einer Vielzahl von Disziplinen realisiert. Einer der fortschrittlichsten SiGe BiCMOS Prozesse, mit einer f_{max} von bis zu 450 GHz, wird für die Implementierung verwendet. Optimierungen auf Layoutebene und bei der messtechnischen Charakterisierung wurden speziell für diese Technologie erarbeitet und tragen maßgeblich zur Gesamtleistung des Systems bei.
Es wird unter Anderem ein passives Verfahren vorgestellt zur Herstellung hocheffizienter 3D-On-Chip-Monopolantennen durch konventionelles Drahtbonden. Diese Technik wurde zudem für die direkte Verbindung von Schaltungen mit selbstentworfenen Hohlleitermodulen weiterentwickelt. Zusätzlich zu den passiven Lösungen sind bis zu 12 Chips aus 7 Einzeldesigns an der Montage des Demonstratoraufbaus beteiligt. Dazu gehören ein Sender und ein Empfänger mit 80 GHz HF-Bandbreite, ein 180 GHz Frequenzvervierfacher mit über 52 dB harmonischer Unterdrückung, ein Rauscharmer Verstärker mit 7.1 dB Rauschzahl, ein bei 15 dBm gesättigter Leistungsverstärker und ein Begrenzungsverstärker mit 25.4 THz Verstärkungs-Bandbreiten-Produkt. In Bezug auf die Hauptmetriken repräsentiert oder erweitert jeder dieser Blöcke dabei den aktuellen Standes der Technik. Zudem stehen die Simulationen und theoretischen Betrachtungen in exzellenter Übereinstimmung gegenüber den Messergebnissen.
Der Aufbau für die abschließende Machbarkeitsstudie besteht aus mehreren kompakten Modulen mit standardisierten koaxialen Schnittstellen und zeigt eine funktionsfähige drahtlose Verbindung über eine Entfernung von 1.5 m mit einer Datenrate von 60 Gbit/s für BPSK- und 40 Gbit/s für QPSK-Modulation. Eine Analyse der aufgetretenen Probleme, welche die maximal erreichte Leistung im QPSK Betrieb reduzieren, werden im Detail präsentiert und diskutiert. Verglichen mit dem Stand der Technik bietet dieses System eine der höchsten Symbolraten für BPSK in Kombination mit hoher Ausgangsleistung und großer Reichweite.

Abstract

This research thesis studies the properties and limits of circuits and complete transmission systems around very high frequencies at 200 GHz. Corresponding basic research challenges are discussed and profound knowledge gain is achieved by covering a wide range from theoretical aspects, device modeling and novel concepts up to feasibility studies by means of hardware implementations. The latter include interface, packaging and assembly issues, as well as approaches for the characterization in the laboratory. Here, one of the main goals is to achieve a high bandwidth for each individual component. To prove the presented concepts, a full functional link is realized by systematically applying novel theoretical and practical approaches to overcome existing problems in a variety of disciplines. One of the most advanced SiGe BiCMOS processes, with an f_{max} of up to 450 GHz, is used for the implementation. Optimizations at layout level and for the characterization procedure, are derived specifically for this technology, which contribute significantly to the overall achieved system performance.

Among others, a passive method is developed for creating high-efficiency 3D on-chip monopole antennas by means of conventional wire-bonding. This technique is further refined for packaging circuits directly into self-designed waveguide modules. In addition to the passive solutions, up to 12 chips from 7 individual designs are involved in the assembly of the test setup. This includes a transmitter and a receiver with 80 GHz RF bandwidth, a 180 GHz frequency quadrupler with more than 52 dB harmonic rejection, a low-noise amplifier with 7.1 dB noise figure, a power amplifier saturated at 15 dBm and a limiting amplifier with 25.4 THz gain-bandwidth product. In regard to the main metrics, each of these blocks represent or extends the current state-of-the-art. Additionally, the simulations and theoretical investigations are in excellent agreement with the measurement results.

The setup for the final feasibility study consists of several compact modules with standardized coaxial interfaces and shows an operational wireless link over a distance of 1.5 m with a data rate of 60 Gbit/s for BPSK and 40 Gbit/s for QPSK modulation. An analysis of the occurring issues, which reduced the maximum achieved performance in the QPSK mode are presented and discussed in detail, revealing further research potentials for the future. Compared to the state-of-the-art this system offers one of the largest symbol rates for BPSK in combination with high output power and large range.

Table of Contents

Symbols and Abbreviations

Mathematical and Physical Constants

Symbol	Value	Unit	Description
c_0	$2.997\,925 \cdot 10^8$	m/s	Speed of light in vacuum
γ	0.577 216	1	Euler–Mascheroni constant
e	2.718 282	1	Base of the natural logarithm
ε_0	$8.854\,188 \cdot 10^{-12}$	F/m	Permittivity of the vacuum
h	$6.626\,070 \cdot 10^{-34}$	Js	Planck constant
j	–	–	Imaginary unit ($j^2 = -1$)
k_B	$1.380\,649 \cdot 10^{-23}$	J/K	Boltzmann constant
μ_0	$1.256\,637 \cdot 10^{-6}$	H/m	Permeability of the vacuum
π	3.141 593	1	Circle constant
q	$1.602\,177 \cdot 10^{-19}$	C	Elementary charge
Z_0	376.7303	Ω	Characteristic impedance of the vacuum

General Equation Symbols

Symbol	Unit	Description
α, β	1/m	Attenuation / propagation factor of a wave
A	m^2	Area or aperture
B	Hz	Bandwidth
C	F	Capacitance
d	m	Distance or diameter
η	1 (%)	Efficiency
F	1	Noise factor
f	Hz	Frequency
G, L	1 (dB)	Gain / Loss factor; $L = G^{-1}$
Γ	1 (dB)	Reflection coefficient
I	A	Electric current
k	1	Proportionality factor
L	H	Inductance
λ	m	Wavelength
ω	rad/s	Angular frequency
φ	rad (°)	Absolute phase or phase shift
P	W (dBm)	Real power
Q	1	Quality factor
R	Ω	Resistance
ρ	Ωm	Specific resistivity; $\rho = \sigma^{-1}$
r, θ	*various*	Polar coordinates

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Symbol	Unit	Description
σ	S/m	Specific conductivity; $\sigma = \rho^{-1}$
τ	s	Time constant
T	K (°C)	Temperature
t	s	Time
V	V	Voltage
w, h, l	m	Width, height, length
x, y, z	*various*	Cartesian coordinates
Y	S	Admittance
Z	Ω	Impedance

Circuit parameters, which are only valid in a small-signal analysis, are distinguished by lower case symbols. For instance, R_b is the physical track resistance of the base contact in a BJT, while r_{be} is the small-signal base-emitter resistance in the linearized operating point.
Variables, which represent multiple values, such as groups, vectors or matrices, are printed in a bold style. For instance, **S** stands for the complete S-parameter matrix of an n-port.

Selection of Special Equation Symbols

Symbol	Unit	Description
a_i, b_i	$\sqrt{W}$	Power waves entering / leaving port i of an n-port
BER	1	Bit error rate
$B_{3\,dB}$	Hz	3-dB bandwidth
δ_s	m	Skin depth
ε_r, μ_r	1	Relative permittivity / permeability
f_c	Hz	Center frequency
f_{free}	Hz	Frequency of a free running oscillator
f_{max}	Hz	Maximum oscillation frequency
f_t	Hz	Transit frequency
G_{max}	1 (dB)	Maximum available power gain
g_m	S	Small-signal transconductance
$\mathbb{I}_0(x)$	–	Modified Bessel function of the 0^{th}-order
I_c	A	Collector current
I_s	A	Reverse saturation current of a pn-junction diode
$I\|OP_{n\,dB}$	dBm	Input / output referred n-dB compression point
K	1	Small-signal stability factor
λ_0	m	Free space wavelength
$\mathscr{L}(f)$	dBc/Hz	Phase noise at carrier offset f
NF	dB	Noise figure; $NF = 10\log_{10} F$
P_{dc}	W	Average dc power consumption

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Symbol	Unit	Description
P_{sat}	W (dBm)	Saturated output power
S_{mn}	1 (dB)	Scattering parameter between port m and n ($S_{\mathrm{mn}} = \frac{b_{\mathrm{m}}}{a_{\mathrm{n}}}$)
$\tan\delta$	1	Loss tangent of a dielectric
t_{g}	s	Group delay
t_{p}	s	Period time ($f = t_{\mathrm{p}}^{-1}$)
V_{B}	V	Bias voltage
$V_{\mathrm{be\|ce}}$	V	Base / collector-emitter voltage
$V_{\mathrm{DD\|CC}}$	V	CMOS / bipolar positive supply voltage
V_{T}	V	pn-junction temperature voltage ($V_{\mathrm{T}} \approx 26\,\mathrm{mV}$ at 300 K)
V_{th}	V	CMOS threshold voltage
Z_0	Ω	Characteristic impedance

Acronyms and Abbreviations

Acronym	Description
ac, dc	Alternating / direct current
ADC, DAC	Analog-to-digital / digital-to-analog converter
BCB	Benzocyclobutene
BEOL	Back-end of line
BER[T]	Bit error rate [tester]
BiCMOS	Technology providing bipolar and CMOS components
BPF, HPF, LPF	Band-, high-, lowpass filter
BPSK, QPSK	Binary / quadrature phase-shift keying
CB, CE, CC	Common base, emitter, collector (bipolar transistors)
CG, CS, CD	Common gate, source, drain (MOSFET)
[C]MOS	[Complementary] metal-oxide-semiconductor
CM[RR]	Common mode [rejection ration]
CNC	Computerized numerical control (machining)
DR	Dynamic range
DUT	Device under test
EIRP	Equivalent isotropic radiated power
EM	Electromagnetic
ENIG, EPIG	Electroless nickel / palladium, immersion gold (surface finish)
FET	Field-effect transistor
FOM	Figure of Merit
FR-4	Flame Retardant class 4 (common grade of PCB materials)
GBWP	Gain-bandwidth product
[G]CPW	[Grounded] coplanar waveguide
HBT	Heterojunction bipolar transistor
HEMT	High-electron-mobility transistor
HICUM	High Current Model

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Acronym	**Description**
HR	Harmonic rejection
IC	Integrated circuit
IEEE	Institute of Electrical and Electronics Engineers
IF	Intermediate frequency
ILO	Injection-locked oscillator
InP	Indium phosphide (technology)
I-Q	inphase / quadrature (modulation type)
ISI	Inter-symbol interference
ISIG	Immersion silver, immersion gold (surface finish)
LA	Limiting amplifier
LDO	Low dropout (dc regulator)
LNA	Low noise amplifier
LO	Local oscillator
LSB, USB	Lower / upper sideband
MAG, MSG	Maximum available / stable (power) gain
MIM	Metal-insulator-metal (capacitor)
[ML-]TRL	[Multiline] through-reflect-line (calibration)
MMIC	Monolithic microwave integrated circuit
mmW	Millimeter-Wave
NF	Noise figure
OP	Operating point
op-amp	Operation amplifier
PA	Power amplifier
PAE	Power-added efficiency
PAM[n]	Pulse-amplitude modulation [with n symbols]
PCB	Printed circuit board
PDK	Process development kit
PLL	Phased-locked loop
PP	Push-push (doubler topology)
PRBS[n]	Pseudo-random binary sequence [of length n]
PTFE	Polytetrafluoroethylene (also known as Teflon)
QAM[n]	Quadrature amplitude modulation [with n symbols]
RF	Radio frequency
RMS	Root-mean-square
SSB, DSB	Single- / double-sideband
SE	Single-ended
SFDR	Spurious-free dynamic range
SiGe	Silicon-Germanium (technology)
SMD, SMT	Surface-mount device / technology
SNR, SIR, SINR	Signal-to-noise / interference / interference-and-noise-ratio
SOI	Silicon-on-insulator
SOLT	short-open-load-through (calibration)

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Acronym	Description
TE, TM, TEM	Transverse electric / magnetic / electromagnetic (mode)
TL	Transmission line
TRL, TRM	Through-reflect-line / match (calibration)
RX, TX, TRX	Receiver, transmitter, transceiver
VBIC	Vertical Bipolar Inter-Company model
VCO	Voltage controlled oscillator
VGA	Variable gain amplifier
VGC	Variable gain combiner
VM	Vector modulator
VNA	Vector network analyzer
WR-n	Identifier for rectangular waveguides of around $\frac{n}{100}$ inch width

Common Named Concepts

Name	Reference	Description
Colpitts oscillator	[Col27]	Class of oscillator topologies, implemented with capacitive voltage-divider feedback
Friis' equation	[Fri44]	Equation for calculating the total noise figure of a cascade of passive and active two-ports
Gilbert cell	[Gil68]	Active double-balanced up- or down-conversion mixer, implemented with transistors
Lange coupler	[Lan69]	Passive 90° hybrid coupler, implemented with interdigitated coupled transmission lines
Marchand balun	[Mar44]	Passive broadband balun, implemented with coupled transmission lines
Mason's invariant	[Mas54]	Metric for the unilateral gain of a two-port, often used to determine $f_{\max}$ of a transistor
Miller effect	[Mil19]	Effect, that an inverting amplifier increases the effective capacitance between its in- and output
Wilkinson divider	[Wil60]	Passive power divider, implemented with transmission lines and lumped resistors

1. Introduction

This thesis presents the scientific advancements that were achieved in the area of ultra-broadband mm-wave communication systems over a period of 5 years, beginning in October 2014. The overall goal was the realization of a complete wireless transceiver system, operating in a band around 200 GHz, which is able to handle signals with data rates up to 100 Gbit/s. The main research activity was carried out at the Chair of Circuit Design and Network Theory of the Faculty of Electrical and Computer Engineering at the Technical University of Dresden. Most of the results have been produced within the framework of publicly funded projects, most notably "Automatic Impedance Matching" (AIM) and "Highly Adaptive Energy-Efficient Computing" (HAEC) by the German Research Foundation (DFG; Deutsche Forschungsgesellschaft) and Agent3D Hertz by the German Federal Ministry of Education and Research (BMBF; Bundesministerium für Bildung und Forschung).

Motivation

Transceiver systems operating in the mm-wave region allow wireless communication with data rates above 100 Gbit/s, otherwise only achievable with wired or optical links. In recent years, realizations in III/V and silicon-based semiconductor technologies have been introduced [Boe14]. However, the previous realizations in silicon, which are excellently suited for mass production, have comparatively high noise figures, low transmission powers and low available bandwidth. This offers a variety of possibilities for innovative approaches. The achievable power levels are limited mainly by the low breakdown voltages in modern semiconductor processes and by the high resistive losses at mm-waves. The achieved bandwidth of previous realizations is limited mostly by the amplifiers used. The simultaneous application of advanced matching network structures can further increase the performance [Fri14].

The small wavelengths at frequencies around 200 GHz also allows the direct integration of compact antenna structures. One possibility are antenna arrays, which achieve a high directivity by beam steering. This allows for longer ranges and better user separation. In the last years some circuit realizations were presented, which allow a suitable driving of such antenna arrays in the frequency range above 100 GHz. These phased-array chips consist of 4 to 16 individual control elements, whereby the antennas are partly integrated [Rie20a]. Due to the lower circuitry complexity, realizations in which the directional characteristic can only be set in discrete steps are more efficient.

If only a fixed point-to-point connection is required, the use of high-gain antennas, for example based on a combination of a horn and lens, is more suitable. The direct advantage is the significantly reduced circuit complexity and the high achievable distances, demonstrated up to over 800 m at 240 GHz [Kal15]. The frequency band around 200 GHz is particularly interesting for local networks with very high data throughput, for example between mobile base stations. A comparison of the free space path loss to the atmospheric attenuation for different relative humidity (RH) values is shown up to 500 GHz in Fig. 1.1 [Int13].

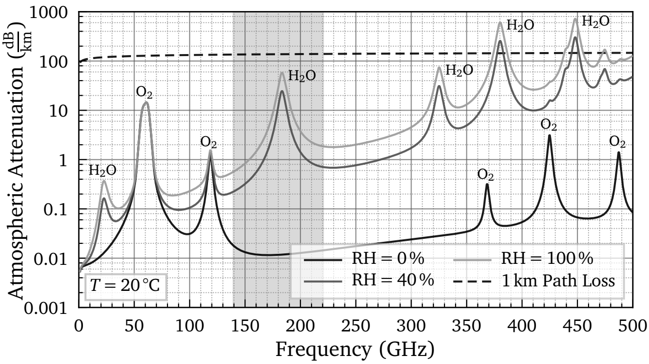

Fig. 1.1 – Free space path loss for 1 km and normalized atmospheric attenuation in dry and humid air with corresponding absorbing molecules annotated [Int13]

A local maximum can be observed around 180 GHz, which is caused by the water content in the air. While the general free space path loss follows a square law, meaning a doubling of the distance only leads to an increase of 6 dB, the atmospheric loss is multiplicative. For distances above a few 100 m, the attenuation increases significantly. This leads to an effective isolation of independent transceiver pairs and allows a denser placement of the infrastructure. The high attenuation above 500 GHz also indicates that no terrestrial long-range communication is feasible in this range, independent of future advances in mm-wave and sub-THz technology. However, this does not apply to space applications such as inter-satellite links.

Structure of the Thesis

The thesis can be roughly divided into three parts. First, a general introduction to the technology used is given in chapter 2, with insights into some of the problems encountered that are relevant to most of the subsequent implementations. This includes a small-signal evaluation of the transistor performance and the analysis of different approaches for an accurate calibration of measurements. The following chapters 3 to 6 present individual solutions and single circuit components for mm-wave applications. The subsections are grouped logically, instead of being sorted chronologically, and cover passive structures, broadband amplifiers, frequency generation and auxiliary blocks. This form of presentation may lead to some inevitable inconsistencies in regard of applied methods or techniques mentioned in later sections that handle earlier designs. Finally, chapter 7 describes the design, assembly and commissioning of the 200 GHz wireless link setup, which reuses many of the previous integrated circuits directly. A modular approach was followed, in which individual components can also be used later as general laboratory equipment. Problems that occurred during the final test phase, which could not be solved completely, are examined in detail and possible solutions for the future are evaluated.

The chapters covering the individual circuits follow a similar structure in general. A short introduction to possible applications of the respective component is given, followed by a discussion of the novel or special aspects of the design implementation. The measurement results are then compared with the simulation predictions and the overall performance is assessed. If applicable, a comparison to the state-of-the-art is made.

The last chapter gives the conclusion and presents once again the relevant results and an outlook on future applications of mm-wave systems. The appendix contains the bibliography, with the list of own publications, sorted chronologically and grouped by periodicals, conference submissions and co-authorship. A curriculum vitae summarizes the academic and professional career so far, with a personal acknowledgment as last words.