

MICROWAVE TRANSISTOR AMPLIFIERS

Analysis and Design



SECOND EDITION

Guillermo Gonzalez

Microwave Transistor Amplifiers Analysis And Design 2nd Edition International Edition

Inder Bahl



Microwave Transistor Amplifiers Analysis And Design 2nd Edition International Edition:

Practical RF Circuit Design for Modern Wireless Systems Rowan Gilmore, Les Besser, 2003 A practical approach to RF circuit design this volume covers nonlinear circuits and modelling RF transistor amplifiers oscillators and mixers

Low-Power Millimeter Wave Transmitters for High Data Rate Applications Khaled Khalaf, Vojkan Vidojkovic, John R. Long, Piet Wambacq, 2019-04-09 This book discusses low power techniques for millimeter wave transmitter IC Considerations for the front end design are followed by several implementation examples in the 60GHz band in CMOS down to 28nm technology Additionally the design and implementation details of digitally modulated millimeter wave polar transmitters are presented

HF-Leistungsverstärker in modernen Silizium- und Verbindungshalbleitern-Technologien Daniel Gruner, 2012-11-01 Kurzbeschreibung Diese Dissertation beschäftigt sich mit HF Leistungsverstärkern auf Basis moderner Transistortechnologien und verfolgt aktuelle Trends im Bereich Silizium und III V Verbindungshalbleiter Dies umfasst den Entwurf von innovativen HF Leistungstransistoren und Verstärkern Aspekte zur Charakterisierung und Aufbautechnik sowie den Vergleich zum aktuellen Stand von Wissenschaft und Technik Im ersten Teil richtet sich der Fokus auf MMIC Leistungsverstärker für 5 6 GHz WLAN Anwendungen Hierbei wird zunächst auf den Entwurf eines Push Pull PAs in einer 0 25 µm BiCMOS Technologie eingegangen Mit einer Betriebsspannung von lediglich 1 8 V zeigt dieser Verstärker ein breitbandiges Verhalten und erreicht im Frequenzbereich 5 6 2 GHz eine Sättigungsleistung von 24 dBm Der maximale Wirkungsgrad liegt bei 27 % PAE 18 % mit einer Verstärkung von typischerweise 9 dB Um diese Performance weiter zu verbessern wird eine innovative Transformer Combining Topologie vorgestellt Im Vergleich zum Push Pull Verstärker kann diese eine erhöhte Verstärkung 12 dB sowie einen exzellenten PAE Maximalwert von 23 % bei sonst ähnlichen Eigenschaften erzielen Als zweite Zielstellung wird die Steigerung der HF Leistungs Performance innerhalb moderner BiCMOS Technologien verfolgt In diesem Rahmen stehen die Analyse der Entwurf und die Evaluierung von LDMOS Transistoren für Anwendungen bis in den 6 GHz Bereich im Mittelpunkt Der Einfluss von Transistorgeometrie und Geometrie sowie auch der Stabilitätsnetzwerke wird unter Verwendung HF optimierter LDMOS Strukturen untersucht Die Evaluierung der Source Load Load Pull Messungen wird mit Hilfe mehrerer hybrider Verstärkermodule durchgeführt Als eine der ersten Veröffentlichungen kann diese Arbeit eine 6 GHz LDMOS Implementation in einer Standard BiCMOS Technologie mit einer Ausgangsleistung von mehr als 1 W und einem Wirkungsgrad über 40 % demonstrieren Der dritte Teil beschäftigt sich mit GaN Doherty Verstärkern für das 6 GHz Band Die Kombination von Doherty Konzept mit Strategien zur Harmonischen Terminierung einem auf Device Referenzebene optimierten Entwurf und der entwickelten Chip Wire Aufbautechnik erlaubt die Realisierung von einem der ersten 6 GHz Doherty Verstärker mit exzellenter Wirkungsgrad Leistungs sowie Linearitäts Performance Unter Verwendung zweier GaN Chip Transistoren kann eine maximale Ausgangsleistung von 41 5 dBm mit einem maximalen Wirkungsgrad von 63 % erreicht werden Im 6 dB Backoff Punkt wird dabei ein exzellenter Wirkungsgrad

von 49 % erzielt

Description This work focuses on RF power amplifiers based on modern transistor technologies and investigates current trends in silicon as well as III V semiconductors This includes the design of innovative RF power devices and amplifiers characterization and assembling techniques as well as the comparison to other state of the art achievements The first part focuses on MMIC power amplifiers for WLAN applications in the 5.6 GHz range Based on a 0.25 μm BiCMOS technology a low voltage push pull power amplifier using integrated transformers is presented At a supply voltage of 1.8 V this fully integrated amplifier achieves a wideband performance showing a maximum output power of 24 dBm across 5.6 GHz A maximum efficiency of 27 % PAE 18 % is obtained with a small signal gain of typically 9 dB To further improve this performance an innovative transformer combining topology is developed Compared to the push pull amplifier this topology achieves an increased gain of 12 dB and an enhanced maximum PAE of up to 23 % with otherwise similar characteristics showing state of the art performance The RF power enhancement of Bi CMOS technologies is a second major aim of this work In this context the analysis design and evaluation of medium voltage LDMOS FETs for wireless applications up to 6 GHz is presented Using RF optimized NLD MOS transistors power devices of different sizes were fabricated in a standard 0.25 μm BiCMOS technology The influences of the finger geometry and the stabilization networks on the RF performance are studied Power evaluation of the LDMOS transistors is carried out by means of hybrid power amplifier modules As one of the first contributions this work shows a 6 GHz LDMOS implementation in a standard BiCMOS technology that achieves an output power of greater than 1 W with a drain efficiency of more than 40 % In the third part a harmonically tuned GaN Doherty amplifier targeted for vehicular applications at 6 GHz is presented The combination of the Doherty concept with harmonic tuning strategies an optimized design approach and the developed chip wire assembly technology results in one of the first Doherty amplifiers implemented for the 6 GHz frequency range with excellent efficiency output power and linearity performance Using two bare die GaN devices a maximum output power of 41.5 dBm with 63% peak drain efficiency is obtained At 6 dB output power back off an excellent drain efficiency of still 49 % can be achieved

Millimeter-Wave

Antennas: Configurations and Applications Jaco du Preez, Saurabh Sinha, 2016-06-20 This book comprehensively reviews the state of the art in millimeter wave antennas traces important recent developments and provides information on a wide range of antenna configurations and applications While fundamental theoretical aspects are discussed whenever necessary the book primarily focuses on design principles and concepts manufacture measurement techniques and practical results Each of the various antenna types scalable to millimeter wave dimensions is considered individually with coverage of leaky wave and surface wave antennas printed antennas integrated antennas and reflector and lens systems The final two chapters address the subject from a systems perspective providing an overview of supporting circuitry and examining in detail diverse millimeter wave applications including high speed wireless communications radio astronomy and radar The vast amount of information now available on millimeter wave systems can be daunting for researchers and designers entering the field This

book offers readers essential guidance helping them to gain a thorough understanding based on the most recent research findings and serving as a sound basis for informed decision making

Ultra Wideband Ranjit Gharpurey, Peter Kinget, 2008-03-06 Recent advances in wireless communication technologies have had a transformative impact on society and have directly contributed to several economic and social aspects of daily life. Increasingly the untethered exchange of information between devices is becoming a prime requirement for further progress which is placing an ever greater demand on wireless bandwidth. The ultra wideband UWB system marks a major milestone in this progress. Since 2002 when the FCC allowed the unlicensed use of low power UWB radio signals in the 3.1-10.6 GHz frequency band there has been significant synergistic advance in this technology at the circuits architectural and communication systems levels. This technology allows for devices to communicate wirelessly while coexisting with other users by ensuring that its power density is sufficiently low so that it is perceived as noise to other users. UWB is expected to address existing needs for high data rate short range communication applications between devices such as computers and peripherals or consumer electronic devices. In the long term it makes available spectrum to experiment with new signaling formats such as those based on very short pulses of radio frequency RF energy. As such it represents an opportunity to design fundamentally different wireless systems which rely on the bandwidth of the signals to enhance the data rate or which use the available bandwidth for diverse applications such as ranging and biomedical instrumentation

High Frequency and Microwave Engineering Ed da Silva, 2001-03-15 With the increased use of mobile phones and computer wireless techniques a need has developed for a book which provides students and industry with expertise in radio and microwave engineering. This important text has been written with these aims in mind. Provides a comprehensive course in radio and microwave engineering. Includes CD ROM containing the CAD package PUFF 2.1 for construction and evaluation of circuits and a comprehensive section on practical aspects of design. Written by an experienced author in a clear and easy to follow style. Contains a variety of examples and self test questions with model answers. The material covers transmission lines scattering parameters couplers amplifiers oscillators and phase locked loops in a novel way by introducing examples from daily life prior to the introduction of the theory. Microwave tools such as Smith charts scattering parameters and signal flow diagrams are dealt with thoroughly and are fully integrated in the numerous examples throughout the text and with PUFF. *High Frequency and Microwave Engineering* is intended as an advanced undergraduate text for students of electrical and communication engineering and is also eminently suitable for self study and as a manual for those in the industry wishing to update their engineering skills. Provides a comprehensive course in radio and microwave engineering. Contains many examples and self test questions with model answers

Fundamentals of RF and Microwave Transistor Amplifiers Inder Bahl, 2009-06-17 A Comprehensive and Up to Date Treatment of RF and Microwave Transistor Amplifiers. This book provides state of the art coverage of RF and microwave transistor amplifiers including low noise narrowband broadband linear high power high efficiency and high voltage. Topics covered include modeling analysis

design packaging and thermal and fabrication considerations Through a unique integration of theory and practice readers will learn to solve amplifier related design problems ranging from matching networks to biasing and stability More than 240 problems are included to help readers test their basic amplifier and circuit design skills and more than half of the problems feature fully worked out solutions With an emphasis on theory design and everyday applications this book is geared toward students teachers scientists and practicing engineers who are interested in broadening their knowledge of RF and microwave transistor amplifier circuit design Antennas and Propagation for Wireless Communication Systems Simon R.

Saunders,Alejandro A. Aragón-Zavala,2024-09-11 Comprehensive resource describing both fundamentals and practical industry applications of antennas and radio propagation employed in modern wireless communication systems The newly revised and thoroughly updated Third Edition of this classic and popular text Antennas and Propagation for Wireless Communication Systems addresses fundamentals and practical applications of antennas and radio propagation commonly used in modern wireless communication systems from the basic electromagnetic principles to the characteristics of the technology employed in the most recent systems deployed with an outlook of forthcoming developments in the field Core topics include fundamental electromagnetic principles underlying propagation and antennas basic concepts of antennas and their application to specific wireless systems propagation measurement modelling and prediction for fixed links macrocells microcells femtocells picocells megacells and narrowband and wideband channel modelling with the effect of the channel on communication system performance Worked examples and specific assignments for students are presented throughout the text with a solutions manual available for course tutors with a dedicated website containing online calculators and additional resources plus details of simple measurements that students can perform with off the shelf equipment such as their laptops and a Wi Fi card This Third Edition of Antennas and Propagation for Wireless Communication Systems has been thoroughly revised and updated expanding on and adding brand new coverage of sample topics such as Maxwell s equations and EM theory multiple reflections as propagation mechanisms and waveguiding HAPS High Altitude Platforms propagation design and noise considerations of earth stations macrocell models and cellular base station site engineering FSS frequency selective surfaces adaptive antenna theory developments massive and distributed MIMO in particular and how to process raw data related to channel measurements for mobile radio systems The techniques used in mobile systems spanning the latest 4G 5G and 6G technology generations A wider range of frequencies extending from HF VHF and UHF up to the latest millimetre wave and sub terahertz bands With comprehensive coverage of foundational subject matter as well as major recent advancements in the field Antennas and Propagation for Wireless Communication Systems is an essential resource for undergraduate and postgraduate students researchers and industry engineers in related disciplines **RF / Microwave Circuit Design for Wireless Applications** Ulrich L. Rohde,Matthias Rudolph,2013-01-07 Provides researchers and engineers with a complete set of modeling design and implementation tools for tackling the newest IC technologies Revised

and completely updated RF Microwave Circuit Design for Wireless Applications Second Edition is a unique state of the art guide to wireless integrated circuit design that provides researchers and engineers with a complete set of modeling design and implementation tools for tackling even the newest IC technologies It emphasizes practical design solutions for high performance devices and circuitry incorporating ample examples of novel and clever circuits from high profile companies Complete with excellent appendices containing working models and CAD based applications this powerful one stop resource Covers the entire area of circuit design for wireless applications Discusses the complete system for which circuits are designed as well as the device technologies on which the devices and circuits are based Presents theory as well as practical issues Introduces wireless systems and modulation types Takes a systematic approach that differentiates between designing for battery operated devices and base station design RF Microwave Circuit Design for Wireless Applications Second Edition is an indispensable tool for circuit designers engineers who design wireless communications systems and researchers in semiconductor technologies telecommunications and wireless transmission systems

CMOS Front Ends for Millimeter Wave Wireless Communication Systems Noël Deferm, Patrick Reynaert, 2015-03-23 This book focuses on the development of circuit and system design techniques for millimeter wave wireless communication systems above 90GHz and fabricated in nanometer scale CMOS technologies The authors demonstrate a hands on methodology that was applied to design six different chips in order to overcome a variety of design challenges Behavior of both actives and passives and how to design them to achieve high performance is discussed in detail This book serves as a valuable reference for millimeter wave designers working at both the transistor level and system level

CMOS Low Noise Amplifiers for Single and Multiband Applications: A Comprehensive Design Approach Norlaili Mohd Noh, Farshad Eshghabadi, Arjuna Marzuki, 2023-10-11 This book provides comprehensive knowledge aimed at practicing integrated circuit design engineer or researcher to learn and design a low noise amplifier LNA for single and multiband applications The content is structured in a way so that even a beginner can follow the design method easily This book features the following characteristics different types of LNA designs with key building blocks are discussed and detailed analysis is given for each LNA design which covers from the fundamental and principal knowledge to the justification of the design approach Detailed design approaches are using 180 nm and 130nm CMOS technologies purposely presented in this manner to give exposure to the design of LNA under different technologies The LNAs in this book are designed for GSM WCDMA and WLAN standards but the same method can be used for other frequencies of operation Comprehensive analyses on the extreme or corner condition effects are highlighted Besides detailed derivation of equations relating to the parameters of the LNA s performance metrics help LNA designers in understanding how the performance metrics of the LNA can be optimized to meet the desired specification Electromagnetic analyses using Sonnet an electromagnetic tool able to replace the conventional post layout simulation with resistance and capacitance parasitic extraction for more accurate frequency performance prediction are presented The electromagnetic method is

proposed to be used in the LNA design as it can accurately predict the LNA's performance before tape out for first pass fabrication MATLAB codes are provided to generate important S parameters and noise figure values

Compressive Sensing Based Algorithms for Electronic Defence Amit Kumar Mishra,Ryno Strauss Verster,2016-12-22 This book details some of the major developments in the implementation of compressive sensing in radio applications for electronic defense and warfare communication use It provides a comprehensive background to the subject and at the same time describes some novel algorithms It also investigates application value and performance related parameters of compressive sensing in scenarios such as direction finding spectrum monitoring detection and classification

RF and Microwave Circuits, Measurements, and Modeling Mike Golio,Janet Golio,2018-10-08 Highlighting the challenges RF and microwave circuit designers face in their day to day tasks RF and Microwave Circuits Measurements and Modeling explores RF and microwave circuit designs in terms of performance and critical design specifications The book discusses transmitters and receivers first in terms of functional circuit block and then examines each block individually Separate articles consider fundamental amplifier issues low noise amplifiers power amplifiers for handset applications and high power power amplifiers Additional chapters cover other circuit functions including oscillators mixers modulators phase locked loops filters and multiplexers New chapters discuss high power PAs bit error rate testing and nonlinear modeling of heterojunction bipolar transistors while other chapters feature new and updated material that reflects recent progress in such areas as high volume testing transmitters and receivers and CAD tools The unique behavior and requirements associated with RF and microwave systems establishes a need for unique and complex models and simulation tools The required toolset for a microwave circuit designer includes unique device models both 2D and 3D electromagnetic simulators as well as frequency domain based small signal and large signal circuit and system simulators This unique suite of tools requires a design procedure that is also distinctive This book examines not only the distinct design tools of the microwave circuit designer but also the design procedures that must be followed to use them effectively

The Electrical Engineering Handbook,Second Edition Richard C. Dorf,1997-09-26 In 1993 the first edition of The Electrical Engineering Handbook set a new standard for breadth and depth of coverage in an engineering reference work Now this classic has been substantially revised and updated to include the latest information on all the important topics in electrical engineering today Every electrical engineer should have an opportunity to expand his expertise with this definitive guide In a single volume this handbook provides a complete reference to answer the questions encountered by practicing engineers in industry government or academia This well organized book is divided into 12 major sections that encompass the entire field of electrical engineering including circuits signal processing electronics electromagnetics electrical effects and devices and energy and the emerging trends in the fields of communications digital devices computer engineering systems and biomedical engineering A compendium of physical chemical material and mathematical data completes this comprehensive resource Every major topic is thoroughly covered

and every important concept is defined described and illustrated Conceptually challenging but carefully explained articles are equally valuable to the practicing engineer researchers and students A distinguished advisory board and contributors including many of the leading authors professors and researchers in the field today assist noted author and professor Richard Dorf in offering complete coverage of this rapidly expanding field No other single volume available today offers this combination of broad coverage and depth of exploration of the topics The Electrical Engineering Handbook will be an invaluable resource for electrical engineers for years to come

Highly Efficient CMOS Power Amplifiers at C- and S-Band for Low Supply Voltages Jörg Carls, 2009

Advanced Silicon MMICs for mm-Wave Automotive Radar Front-Ends Alexander Kravets, 2015-06-12 This work presents a high linearity automotive radar front end at 77 GHz in 0.25 μ m SiGe technology The passive elements were realized using thin film microstrip lines A detailed transformer balun synthesis procedure was developed The realized passive baluns rat race and transformer show excellent commonmode rejection ratios exceeding 30 dB and low losses of 2.5 dB On the active side a low gain high linearity single stage common emitter LNA was realized The selected topology allowed finer trade off between linearity and sensitivity of the front end compared to multi stage LNA solutions For the mixer a low voltage supply high linearity low noise double balanced concept was employed It uses AC coupling between the two stages which allowed an independent optimization of transconductance core sizing and bias The transconductance was designed for best noise performance while the core was chosen for maximum linearity A high fidelity two channel receiver was realized using these circuit components which achieved a performance comparable to the published state of the art results in SiGe Single sideband noise figure better than 16.5 dB 1 dB compression point exceeding 12 dBm while consuming moderate 82 mA DC current from a 1.6 V supply for both channels

Microwave Circuit Design Using Linear and Nonlinear Techniques George D. Vendelin, Anthony M. Pavio, Ulrich L. Rohde, 2005-10-03 The ultimate handbook on microwave circuit design with CAD Full of tips and insights from seasoned industry veterans Microwave Circuit Design offers practical proven advice on improving the design quality of microwave passive and active circuits while cutting costs and time Covering all levels of microwave circuit design from the elementary to the very advanced the book systematically presents computer aided methods for linear and nonlinear designs used in the design and manufacture of microwave amplifiers oscillators and mixers Using the newest CAD tools the book shows how to design transistor and diode circuits and also details CAD's usefulness in microwave integrated circuit MIC and monolithic microwave integrated circuit MMIC technology Applications of nonlinear SPICE programs now available for microwave CAD are described State of the art coverage includes microwave transistors HEMTs MODFETs MESFETs HBTs and more high power amplifier design oscillator design including feedback topologies phase noise and examples and more The techniques presented are illustrated with several MMIC designs including a wideband amplifier a low noise amplifier and an MMIC mixer This unique one stop handbook also features a major case study of an actual anticollision radar transceiver which is compared in detail against

CAD predictions examples of actual circuit designs with photographs of completed circuits and tables of design formulae

Analog Circuit Design Willy M.C. Sansen, Johan Huijsing, Rudy J. van de Plassche, 2013-03-09 This new book on Analog Circuit Design contains the revised contributions of all the tutorial speakers of the eight workshop AACD Advances in Analog Circuit Design which was held at Nice France on March 23 25 1999 The workshop was organized by Yves Leduc of TI Nice France The program committee consisted of Willy Sansen K U Leuven Belgium Han Huijsing T U Delft The Netherlands and Rudy van de Plassche T U Eindhoven The Netherlands The aim of these AACD workshops is to bring together a restricted group of about 100 people who are personally advancing the frontiers of analog circuit design to brainstorm on new possibilities and future developments in a restricted number of fields They are concentrated around three topics In each topic six speakers give a tutorial presentation Eighteen papers are thus included in this book The topics of 1999 are X DSL and other communication systems RF MOST models Integrated filters and oscillators The other topics which have been covered before are 1992 Operational amplifiers A D Converters Analog CAD 1993 Mixed mode A D design Sensor interfaces Communication circuits 1994 Low power low voltage design Integrated filters Smart power 1995 Low noise low power low voltage design Mixed mode design with CAD tools Voltage current and time references vii viii 1996 RF CMOS circuit design Bandpass sigma delta and other data converters Translinear circuits 1997 RF A D Converters Sensor and actuator interfaces Low noise oscillators PLL s and synthesizers 1998 I Volt electronics Design and implementation of mixed mode systems Low noise amplifiers and RF power amplifiers for telecommunications

Wideband Low Noise Amplifiers Exploiting Thermal Noise Cancellation Federico Bruccoleri, Eric Klumperink, Bram Nauta, 2006-03-30 Low Noise Amplifiers LNAs are commonly used to amplify signals that are too weak for direct processing for example in radio or cable receivers Traditionally low noise amplifiers are implemented via tuned amplifiers exploiting inductors and capacitors in resonating LC circuits This can render very low noise but only in a relatively narrow frequency band close to resonance There is a clear trend to use more bandwidth for communication both via cables e g cable TV internet and wireless links e g satellite links and Ultra Wideband Band Hence wideband low noise amplifier techniques are very much needed Wideband Low Noise Amplifiers Exploiting Thermal Noise Cancellation explores techniques to realize wideband amplifiers capable of impedance matching and still achieving a low noise figure well below 3dB This can be achieved with a new noise cancelling technique as described in this book By using this technique the thermal noise of the input transistor of the LNA can be cancelled while the wanted signal is amplified The book gives a detailed analysis of this technique and presents several new amplifier circuits This book is directly relevant for IC designers and researchers working on integrated transceivers Although the focus is on CMOS circuits the techniques can just as well be applied to other IC technologies e g bipolar and GaAs and even in discrete component technologies

Advanced Microwave RF Antennas and Circuits Ofer Aluf, 2025-09-26 This book describes a new concept in analyzing RF Microwave circuits which includes RF Microwave antennas The analysis is based on nonlinear

dynamics and chaos models and shows comprehensive benefits and results All conceptual RF microwave circuits and antennas are innovative and can be broadly implemented in engineering applications The presentation fills the gap of analytical methods for microwave RF antennas and circuit s analysis concrete examples and geometric examples The microwave RF antennas and circuits analysis is developed systematically starting with basic microwave RF circuits and antennas differential equations and their bifurcations followed by fixed points analysis limit cycles Basin of Attraction BOA and Stability Stability switching Additionally the book discusses RFID Antennas systems design and analysis RF amplifiers basic and advance topics design methods This book is aimed at electrical and electronic engineers RF and microwave engineers students and researchers in physics as well It is aimed for research institutes in the area of high power Laser and Target chamber interaction which need to design and use Moebius loop antennas for detecting the created EMP It is also aimed for research institutes in the areas RF Microwave Magnetic Resonance Imaging MRI Electron paramagnetic resonance EPR Nuclear magnetic resonance NMR or electron spin resonance ESR spectroscopy and Electromagnetism and gives good comprehensive in RF and Microwave systems This second edition includes new chapters about Moebius loop magnetic antennas and Magnetic Resonance Imaging MRI RF coils systems which both are analyzed and simulate for stability and stability switching This second edition includes a new appendix about Transmission lines and matching networks Antennas systems and Oscillation systems fundamental and main parameters Unique features of the book are its emphasis on practical and innovative microwave RF engineering applications These include microwave RF circuits and antennas in a variety topological structures RFID ICs and antennas microstrips circulators cylindrical RF network antennas Tunnel Diode TD bipolar transistors field effect transistors FETs IMPATT amplifiers Small Signal SS amplifiers Bias T circuits PIN diode circuits power amplifiers oscillators resonators filters N turn antennas dual spiral coils antennas Helix antennas linear dipole and slot array Moebius loop magnetic antennas Magnetic Resonance Imaging MRI RF coils systems and Hybrid trans linear circuit Many examples are presented in this book and it is also ideal for intermediate level courses at graduate level studies It is also ideal for engineer who has not had formal instruction in nonlinear dynamics but who now desires to fill the gap between innovative microwave RF circuits and antennas and advance mathematical analysis methods

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