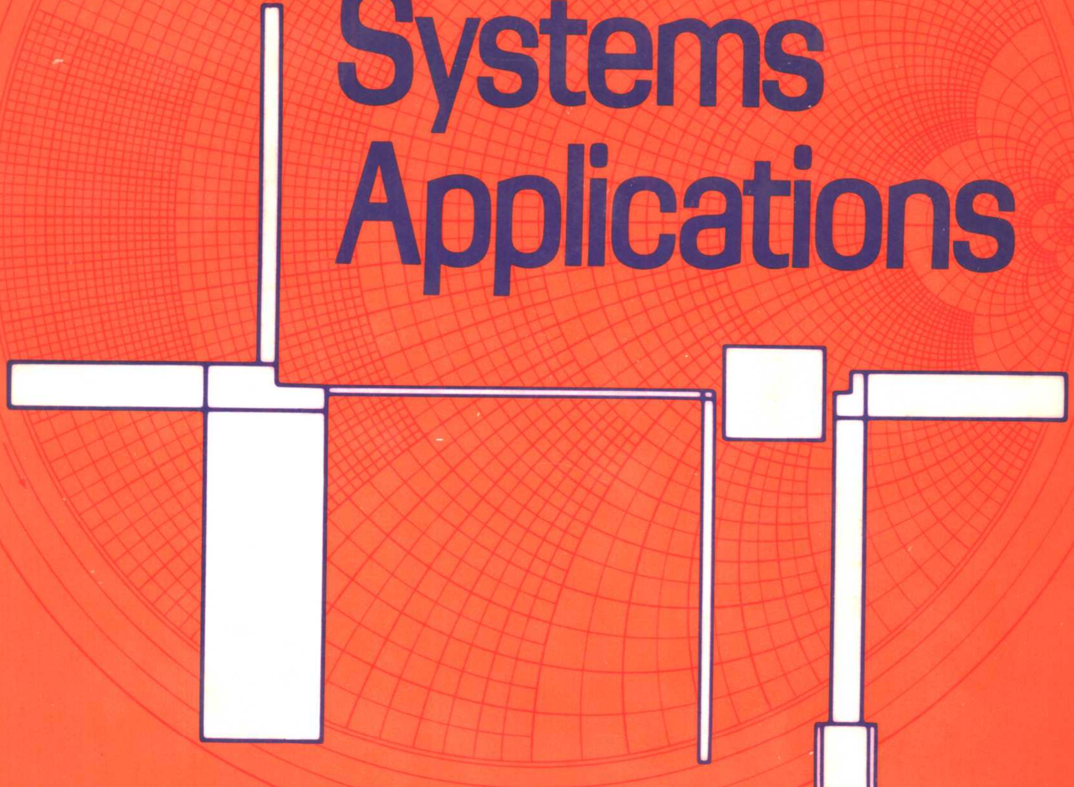
# Microwave Engineering and Systems Applications



Edward A. Wolff
Roger Kaul

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# Contributors

**J. Douglas Adam** (Chapter 10, co-author), Westinghouse Research Laboratories, Pittsburgh, Pennsylvania

**David Blough** (Chapter 22, co-author), Westinghouse Electric Co., Baltimore, Maryland

**Michael C. Driver** (Chapter 16), Westinghouse Research Laboratories, Pittsburgh, Pennsylvania

**Albert W. Friend** (Chapter 5), Space and Naval Warfare Systems Command, Washington, D.C.

**Robert V. Garver** (Chapters 6, 9, and 12; Chapter 10, co-author), Harry Diamond Laboratories, Adelphi, Maryland

**William E. Hosey** (Chapter 17; Chapter 22, co-author), Westinghouse Electric Co., Baltimore, Maryland

**Roger Kaul** (Chapters 2, 3, 4, 8, 11, 13, 14, 18, 19, 20, 21; Chapters 7, 15 co-author), Litton Amecom, College Park, Maryland (Presently at Harry Diamond Laboratories)

**David A. Leiss** (Chapters 7 and 15, co-author), EEsof Inc., Manassas, Virginia

# Preface

This book had its beginnings when Richard A. Wainwright, Cir-Q-Tel President, asked Washington area microwave engineers to create a course to interest students in microwave engineering and prepare them for positions industry was unable to fill. Five of these microwave engineers, H. Warren Cooper, Albert W. Friend, Robert V. Garver, Roger Kaul, and Edward A. Wolff, responded to the request. These engineers formed the Washington Microwave Education Committee, which designed and developed the microwave course. Financial support to defray course expenses was provided by Bruno Weinschel, President of Weinschel Engineering.

The course was given for several years to seniors at the Capitol Institute of Technology in Laurel, Maryland. It was also given to seniors at the University of Maryland in College Park, Maryland and was given as a continuing education course to practicing engineers on several successive weekends at the University of Maryland Adult Education Center. The students had studied electromagnetic theory, so the emphasis of the course was placed on engineering and the types of problems encountered by practicing engineers. Lengthy proofs were only referenced so that the application of microwave techniques could be emphasized.

Once the course was designed and available textbooks were examined, it appeared to the Committee that it would need its own textbook to give a balanced, systems oriented presentation of modern microwave engineering. The course made extensive use of expert guest lecturers, and the notes used by the course lecturers provide the basis for this book. The course lasted two semesters or three quarters. The students were given extensive opportunity to use the SUPER-COMPACT computer program for the design of their own microwave circuits. This text should provide the basics for a beginning microwave engineer, a reference book to the fundamentals of microwave engineering for practicing engineers, and a text for short-course classes.

This textbook is divided into four parts. Part I (Chapters 2–4) provides the motivation for studying microwaves and describes the three major systems that use microwaves: communications, radar, and electronic warfare. These chapters show the importance of system parameters, such as noise temperature, bandwidth, and circuit losses which the microwave engineer must consider in circuit design.

Part II (Chapters 5–17) provides information on the design of various microwave components used for microwave generation, transmission, control, and detection. The components discussed include transmission lines, transmission line components, filters, ferrites, antennas, diodes, amplifiers, oscillators, vacuum tubes, and monolithic microwave integrated circuits.

Part III (Chapters 18–20) presents the measurement techniques needed to verify the performance of the components fabricated for a microwave subsystem. If a laboratory accompanies this course, Part III can be studied after Chapter 6 and can be taught simultaneously with Part II.

Part IV (Chapters 21 and 22) describes the design procedures for interconnecting microwave components into receiver and transmitter subsystems. These subsystems are the major microwave parts of communications, radar, or electronic warfare systems. The subsystem performance dictates the system performance presented in Part I and depends on the capabilities of the components described in Part II.

The creation of a comprehensive text— including applications and requirements, components, circuits, measurements, and subsystems—within the bounds of a single book has made it necessary to present engineering relations and equations without always including their often lengthy derivations. When derivations are omitted, references are given to sources in the literature.

Numerous periodicals and books provide a source of additional material on microwaves. After World War II and the development of radar, the MIT Radiation Laboratory Series of books became the "Bible" and main source of educational material. Soon to follow was the IEEE (formerly IRE) Transactions on Microwave Theory and Techniques, which began in 1953. (A cumulative index was published in June 1981.) In 1958, Theodore S. Saad began publication of *The Microwave Journal.* This was followed in 1962 by Hayden's regular publication of *Microwaves* (in a square format) and in 1971 by Weber Publications' *Microwave System News.* Add to this the digests from the International Solid State Circuits Conferences, the International Microwave Symposium, the *IEEE Journal of Solid State Circuits*, selected issues of the *IEEE Transactions on Electron Devices*, and *Proceedings of the IEEE*, and you can fill more than 6 meters of bookshelf. In more recent years, there have also been European and Japanese publications that should be included in any comprehensive microwave library. In 1963, A. F. Harvey attempted to condense all of the useful microwave information into one encyclopedic book.* It served as a good starting point for any new research endeavors because the researcher was not forced to scan all the old journals. The *Advances in Microwaves* series, edited by Dr. Leo Young (published from 1966 to 1971), presents in-depth articles on numerous microwave subjects, and the two-volume *Microwave Engineers' Handbook*, edited by Theodore Saad (published in 1971), provides excellent reference material for practicing engineers. *Introduction to Microwave Theory and Measurement*, written by Algie L. Lance in 1964, has been the most popular course text. Because all these books are at least ten years old, they do not include modern developments (such as monolithic integrated circuits) and generally do not emphasize the systems aspects found in this textbook.

We acknowledge the contributions Melvin Zisserson made to many of the chapters. Patricia Campbell meticulously typed the manuscript.

EDWARD A. WOLFF
ROGER KAUL

*January, 1988*

* A. F. Harvey, *Microwave Engineering*, Academic Press, London, 1963.

# Major Symbols, Abbreviations, and Acronyms

| | |
|---|---|
| A | ampere |
| $A$ | amplitude, antenna area, area |
| $A_e$ | antenna effective area |
| $A_{eu}$ | unity gain antenna effective area |
| $A_v$ | video pulse amplitude |
| AC | alternating current |
| AFC | automatic frequency control |
| AM | amplitude modulation |
| ANA | automatic network analyzer |
| $B$ | magnetic flux density |
| $B_{IF}$ | intermediate frequency bandwidth |
| $B_n$ | noise bandwidth |
| $B_S$ | source susceptance |
| BIT | built-in test |
| BPF | bandpass filter |
| BPSK | binary phase shift keyed |
| BPT | bipolar transistor |
| BW | bandwidth |
| b | bit |
| $C$ | camouflage factor, capacitance, coupling factor |
| $C_c$ | case capacitance |
| $C_{dg}$ | drain-gate capacitance |

| | |
|---|---|
| $C_{ds}$ | drain-source capacitance |
| $C_f$ | fringe capacitance |
| $C_j$ | junction capacitance |
| $C_p$ | package capacitance |
| $C_u$ | capacitance per unit length |
| $C_V$ | voltage coupling ratio |
| CAD | computer-aided design |
| CC-TWT | cavity-coupled traveling wave tube |
| CDMA | code division multiple access |
| CFA | crossed field amplifier |
| C/N | carrier-to-noise ratio |
| CSL | central spectrum line |
| CW | continuous wave |
| $c$ | velocity of light |
| $D$ | diameter, directivity |
| DC | direct current |
| DR | dynamic range |
| DSO | dielectric stabilized oscillator |
| DUT | device under test |
| $d$ | diameter |
| dB | decibel |
| dBc | decibels above carrier |
| dBm | decibels above 1 mW |
| dBW | decibels above 1 W |
| **E** | electric field vector |
| $E_b$ | energy per bit |
| $E_g$ | energy gap |
| $E_i$ | incident voltage |
| $E_r$ | reflected voltage |
| $E_t$ | transmitted voltage |
| ECCM | electronic counter-countermeasures |
| ECM | electronic countermeasures |
| EIRP | effective isotropic radiated power |
| EMC | electromagnetic compatibility |
| EMI | electromagnetic interference |
| ESM | electronic support measures |
| EW | electronic warfare |
| $e$ | electron charge |
| F | Farad |

| | |
|---|---|
| $F$ | focal length, noise figure |
| $F_{min}$ | minimum noise factor |
| $F_n$ | noise factor |
| FDMA | frequency division multiple access |
| FET | field-effect transistor |
| FIT | fault isolation test |
| FM | frequency modulation |
| FPA | final power amplifier |
| FSK | frequency shift keyed |
| $f$ | frequency |
| $f_c$ | carrier frequency |
| $f_{diff}$ | difference frequency |
| $f_{if}$ | intermediate frequency |
| $f_{in}$ | input frequency |
| $f_{lo}$ | local oscillator frequency |
| $f_{op}$ | operating frequency |
| $f_{out}$ | output frequency |
| $f_{res}$ | resonant frequency |
| G | Gauss, giga- |
| $G$ | conductance, gain |
| $G_A$ | available power gain |
| $G_a$ | antenna gain |
| $G_r$ | receiver antenna gain |
| $G_S$ | source conductance |
| $G_T$ | transducer power gain |
| $G_t$ | transmitter antenna gain |
| GaAs | gallium arsenide |
| g | gram |
| $g_m$ | transconductance |
| **H** | magnetic field vector |
| H | Henry |
| $H_c$ | coercive force |
| HEMT | high electron mobility transistor |
| HVPS | high voltage power supply |
| Hz | Hertz |
| $h$ | height, Planck's constant |
| $I$ | current, isolation |
| IF | intermediate frequency |
| IFM | instantaneous frequency measurement |

| | |
|---|---|
| IGFET | insulated gate field-effect transistor |
| IL | insertion loss |
| Im | imaginary part of complex number |
| IMD | intermodulation distortion |
| IMN | input matching network |
| IMPATT | impact ionization avalanche transit-time |
| IPA | intermediate power amplifier |
| $i$ | current |
| **J** | current density vector |
| JFET | junction field-effect transistor |
| J/S | jammer-to-signal ratio |
| K | Kelvin |
| $K$ | perveance |
| $k$ | Boltzmann's constant, kilo-, wave number |
| **k** | unit vector in propagation direction |
| $L$ | inductance, length, loss |
| $L_p$ | package inductance |
| $L_{system}$ | system loss |
| $L_w$ | wire inductance |
| LNA | low noise amplifier |
| LO | local oscillator |
| LVPS | low voltage power supply |
| M | mega- |
| $M_s$ | saturation magnetization |
| MESFET | metal-semiconductor field-effect transistor |
| MIC | microwave integrated circuit |
| MMIC | monolithic microwave integrated circuit |
| MOCVD | metalorganic chemical vapor deposition |
| MODFET | modulation-doped field-effect transistor |
| MOPA | master oscillator power amplifier |
| MOS | metal-on-semiconductor |
| MSG | maximum signal gain |
| MTI | moving target indicator |
| m | meter, milli- |
| $m$ | modulation index |
| $m_e$ | electron mass |
| $N$ | noise, number |
| $N_B$ | number of pulses |
| $N_i$ | input noise power |

| | |
|---|---|
| $N_o$ | output noise power |
| NF | noise figure |
| n | nano- |
| **n** | unit normal vector |
| Oe | Oersted |
| OMCVD | organometallic chemical vapor deposition |
| OMT | orthomode transducer |
| $P_{ant}$ | power at antenna |
| $P_{avg}$ | average power |
| $P_D$ | power dissipated |
| $P_{DC}$ | direct-current power, input power |
| $P_{in}$ | incident power, input power |
| $P_L$ | load power |
| $P_{LIM}$ | limited power |
| $P_n$ | noise power |
| $P_{out}$ | output power |
| $P_r$ | received power |
| $P_T$ | transmitter output power |
| $P_t$ | transmitter output power |
| PCU | protection and control unit |
| $PD_{inc}$ | incident power density |
| $PD_{rec}$ | received power density |
| $PD_{rerad}$ | reradiated power density |
| $PD_t$ | transmitted power density |
| PIN | p-i-n semiconductor |
| PM | phase modulation |
| PMS | port modeling and synthesis |
| PPM | periodic permanent magnet |
| PPM-TWT | periodic permanent magnet traveling wave tube |
| PRF | pulse repetition frequency |
| PSK | phase shift keyed |
| p | pico- |
| $Q$ | resonance factor |
| $Q_{rad}$ | radiation resonance factor |
| QPSK | quadrature phase shift keyed |
| $R$ | range, resistance |
| $R_b$ | bit rate |
| $R_d$ | drain resistance |
| $R_{ff}$ | far field range |

| | |
|---|---|
| $R_{in}$ | input resistance |
| $R_j$ | junction resistance |
| $R_L$ | load resistance |
| $R_{max}$ | maximum range |
| $R_p$ | parallel resistance |
| $R_{rad}$ | radiation resistance |
| $R_s$ | series resistance, source resistance |
| Re | real part of complex number |
| RF | radio frequency |
| RWR | radar warning receiver |
| rms | root mean square |
| $S$ | signal, surface |
| $S_i$ | input signal power |
| $S_{min}$ | minimum detectable signal |
| $S_o$ | output signal power |
| $S_{11}$ | $S$-parameter |
| $S_{12}$ | $S$-parameter |
| $S_{21}$ | $S$-parameter |
| $S_{22}$ | $S$-parameter |
| SAW | surface acoustic wave |
| SCPC | single channel per carrier |
| SI | international system of units |
| SMA | subminiature connector |
| S/N | signal-to-noise ratio |
| SOJ | stand-off jammer |
| SSJ | self-screening jammer |
| STC | sensitivity time control |
| s | second |
| $s$ | distance |
| $T$ | temperature, transmission coefficent |
| $T_A$ | antenna temperature |
| $T_c$ | Curie temperature |
| $T_{eq}$ | equivalent noise temperature |
| $T_i$ | input temperature |
| $T_j$ | junction temperature |
| $T_m$ | modulation period |
| $T_o$ | reference temperature |
| $T_p$ | pulse period |
| $T_R$ | round trip time delay |

| | |
|---|---|
| $T_{rcvr}$ | receiver noise temperature |
| TDMA | time division multiple access |
| TDR | time domain reflectometer |
| TE | transverse electric wave |
| TEGFET | two-dimensional electron gas field-effect transistor |
| TEM | transverse electromagnetic wave |
| TM | transverse magnetic wave |
| TRF | tuned radio frequency |
| TV | television |
| TWT | traveling wave tube |
| $t$ | time |
| $t_o$ | pulse width |
| $t_r$ | rise time |
| $t_{rise}$ | rise time |
| UHF | ultra high frequency |
| V | Volt |
| $V$ | velocity, voltage, volume |
| $V_B$ | breakdown voltage |
| $V_{gs}$ | gate-source voltage |
| $V_I$ | incident voltage |
| $V_{max}$ | maximum voltage |
| $V_{min}$ | minimum voltage |
| $V_R$ | reflected voltage |
| $V_{sat}$ | saturation voltage |
| $V_T$ | transmitted voltage |
| VCO | voltage controlled oscillator |
| VHF | very high frequency |
| VHSIC | very high speed integrated circuit |
| VPE | vapor phase epitaxy |
| VSWR | voltage standing wave ratio |
| VTO | voltage tuned oscillator |
| $v$ | velocity, voltage |
| W | Watt |
| $W_{eff}$ | effective width |
| Wb | Weber |
| $w$ | width |
| $X$ | reactance |
| $X_{in}$ | input reactance |
| $X_j$ | junction reactance |

| | |
|---|---|
| $X_L$ | load reactance |
| XMTR | transmitter |
| $x$ | distance |
| $\mathbf{x}$ | unit vector in $x$ direction |
| $Y$ | admittance |
| $Y_{in}$ | input admittance |
| $Y_o$ | characteristic admittance |
| YIG | yttrium iron garnet |
| YTF | YIG tuned filter |
| $\mathbf{y}$ | unit vector in $y$ direction |
| $Z$ | impedance |
| $Z_{in}$ | input impedance |
| $Z_L$ | load impedance |
| $Z_o$ | characteristic impedance, wave impedance |
| $Z_{oe}$ | even mode characteristic impedance |
| $Z_{oo}$ | odd mode characteristic impedance |
| $Z_{out}$ | output impedance |
| $Z_S$ | source impedance |
| $Z_T$ | terminating impedance |
| $Z_w$ | branch line characteristic impedance |
| $\mathbf{z}$ | unit vector in $z$ direction |
| $\alpha$ | attenuation |
| $\alpha_c$ | conductive attenuation |
| $\beta$ | phase constant |
| $\Gamma$ | reflection coefficient |
| $\Gamma_g$ | generator reflection coefficient |
| $\Gamma_{in}$ | input reflection coefficient |
| $\Gamma_L$ | load reflection coefficient |
| $\Gamma_l$ | load reflection coefficient |
| $\Gamma_{out}$ | output reflection coefficient |
| $\Gamma_S$ | source reflection coefficient |
| $\Gamma_T$ | termination reflection coefficient |
| $\gamma$ | complex propagation constant, gyromagnetic ratio |
| $\Delta$ | matrix determinant |
| $\delta$ | insertion loss, skin depth |
| $\epsilon$ | permittivity |
| $\epsilon_{eff}$ | effective permittivity |
| $\epsilon_o$ | free space permittivity |

| | |
|---|---|
| $\epsilon_r$ | relative permittivity |
| $\eta$ | efficiency, electron charge/mass ratio, isolation |
| $\theta$ | angle, helix pitch angle |
| $\theta_B$ | Bragg angle |
| $\theta_T$ | thermal resistance |
| $\lambda$ | wavelength |
| $\lambda_c$ | cutoff wavelength |
| $\lambda_g$ | waveguide wavelength |
| $\lambda_o$ | free space wavelength |
| $\mu$ | micro-, permeability, cathode to electrode voltage ratio |
| $\mu_c$ | cathode to electrode cutoff voltage ratio |
| $\mu_o$ | free space permeability |
| $\mu_r$ | relative permeability |
| $\rho$ | efficiency, radiation efficiency, VSWR |
| $\sigma$ | conductivity, radar cross-section, standard deviation |
| $\sigma^o$ | radar cross-section per unit area |
| $\tau$ | pulse width |
| $\phi$ | angle, depression angle, work function |
| $\chi_m$ | magnetic susceptibility |
| $\omega$ | angular frequency |
| $\nabla$ | del operator |

## COMMONLY-USED CONSTANTS

$k = 1.38 \times 10^{-23}$ Joule/°K

$kT = 4 \times 10^{-21}$ Watts/Hertz when $T = 290$ °K

$c = 3 \times 10^8$ m/s

$\mu_0 = 4\pi \times 10^{-7}$ Henry/m

$\epsilon_0 = 8.85 \times 10^{-12}$ Farad/m

$m_e$ = electron mass = $9.1 \times 10^{-31}$ kg

$e$ = electron charge = $1.6 \times 10^{-19}$ Coulombs

$h$ = Planck's constant = $6.6 \times 10^{-34}$ Joule seconds

$Z_0$ = intrinsic impedance of free space = 377 ohms

# Contents