Microwave Integrated Circuits

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I. KNEPPO

Slovak Institute of Metrology
Bratislava, Slovak Republic

J. FABIAN

Electrotechnical Institute of
the Slovak Academy of Sciences,
Bratislava, Slovak Republic

P. BEZOUŠEK
P. HRNÍČKO
M. PAVEL

Research Institute of
Radiotechnology
Pardubice, Czech Republic

SPRINGER-SCIENCE+BUSINESS MEDIA. B.V.

Published in co-edition with Ister Science Press Limited
Ister Science Press Limited, Staromestska 6, Bratislava, Slovak Republic

First edition 1994

Softcover reprint of the hardcover 1st edition 1994

ISBN 978-94-010-4535-3 ISBN 978-94-011-1224-6 (eBook)
DOI 10.1007/978-94-011-1224-6

A catalogue record for this book is available from the British Library

∞ Printed on permanent acid-free text paper, manufactured in accordance with ANSI/NISO Z39.48-1992 (Permanence of Paper).

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Contributors

P. Bezoušek

Research Institute of Radiotechnology, Pardubice, Czech Republic

J. Fabian

Electrotechnical Institute of the Slovak Academy of Sciences, Bratislava, Slovak Republic

F. Hrníčko

Research Institute of Radiotechnology, Pardubice, Czech Republic

I. Kneppo

Slovak Institute of Metrology, Bratislava, Slovak Republic

M. Pavel

Research Institute of Radiotechnology, Pardubice, Czech Republic

List of symbols

A) Physical quantities

a	waveguide width; parameter of the Richards' transformation; parameter of the coplanar line
b	waveguide height
B	parameter of the Richards' transformation
B_a, B_b	susceptance
c	light velocity in vacuum
C, C_c	capacitance, collector-base capacitance
d	distance of the lateral wall from the line
e	distance of the slot centre from the waveguide centre
$\mathbf{E}$	electric field intensity
$\mathbf{E}_0$	electric intensity before introducing losses
f	frequency
f_c	waveguide cut-off frequency
f_{cm}	m-th mode cut-off frequency
$f_{\max}$	maximum oscillation frequency of the transistor
f_n	normalization frequency
f_{stat}	limit frequency of using results of quasistatic methods
f_T	transit time cut-off frequency of a transistor
$F_{\min}$	minimum noise figure
g, g_m	normalized slot width, transconductans for $U_S = 0\,\text{V}$, respectively
g_i	values of prototype elements

G	conductivity
G_a	available power gain
$G(x,y;x',y')$	Green's function
h	substrate thickness
h_1	height of the dielectric layer under substrate
h_2	height of dielectric layer above substrate
h_{21e}	current gain of the transistor in common emitter configuration
$\mathbf{H}$	magnetic field intensity
$\mathbf{H}_0$	magnetic field intensity before introducing losses
I	longitudinal current in the strips; isolation attenuation
I_{dss}	drain current of transistor
I_L	transition attenuation (loss)
J	surface current density
$J_{xin}(\beta)$	Fourier image of the base function of the current density
k	wave number
k_c	equivalent dielectric constant at the limit frequency
k_e	equivalent dielectric constant
k, k_i, k', k_i'	moduli of elliptic integral
$K(k), K(k_i)$	complete elliptic integral of first type
$K'(k), K'(k_i)$	complementary elliptic integral of first type
l_i	length of the line segment
l_o	length of the capacity of the stub
l_r	resonator length
l_s	active segment length
L	inductance; coupling attenuation of a coupler
n	number of vertices of n-angle; filtre degree
n_j	normal line to the j-th part of the conductor
N	number of conductive strips
$N_n(kr)$	Bessel's function of second type of n-th order

p	approximation coefficient; complex frequency; auxiliary constant
$P, P_{\max}$	power, maximum power
p	dipole moment
$P(f)$	correcting function
q	approximation coefficient, filling factor, number of transfer zeros
q_s	correction for screening
q_t	correction for the microstrip thickness
Q	charge on the strip
r	cylindrical coordinate
r_i	internal diameter of a radial stub
r_L	external diameter of a radial stub
R, R_0	resistance, terminating resistance
R'_b	equivalent substrate resistance
RL	return losses
R_s, R_{sj}	specific high frequency resistance, specific high frequency resistance of the j-th part of the conductor surface
s	slot width; curve enclosing the strip conductor
S	directivity, surface area
S_v	surface area of the conductor cross section
$S_{12}(j)$	transfer function
t	time, conductor thickness
u	normalized conductor width
U	voltage at the strip centre
U_{DS}	drain-source voltage
U_p, U_P	breakdown voltage, pinch-off voltage, respectively
v_f	phase velocity
v	wave velocity
V, V_1, V_2, V_3	potential of conductors
${}_kV^i_m$	input voltage pulse from direction m

${}_{k+1}V_n^r$	reflected voltage pulse in direction n
w	complex variable; conductor width
w'	corrected strip width
w_c, w_L, w_1, w_2	conductor width
w_{ef}	effective strip width
W	wave energy per unit length
x, x', x_b	parameter
x, x_i	Cartesian coordinate
x	charge coordinate
y, y_i	Cartesian coordinate
$\mathbf{y}$	unit vector in direction of y-axis
y'	charge coordinate
Y_0	characteristic admittance
Y_{0p}	characteristic admittance of a capacitive sub
z	Cartesian coordinate; complex variable
Z_i	input wave impedance
Z_T	input terminal impedance
Z_0, Z_{0A}	characteristic impedance
$Z_{0\infty}$	characteristic impedance for $f \to \infty$
$Z_0(kr)$	wave impedance of radial line
Z_{0e}, Z_{0o}	characteristic impedance of even and odd modes respectively
α	attenuation constant, current gain, relaxation constant
α_0	current gain at zero frequency
α_C	conductive losses of unit length line
α_d	attenuation constant of the TEM mode resulting from dielectric losses
α_D	dielectric losses of unit length line
α_i	vertex angle
α_r	centre angle of radial stub
α_l	temperature coefficient of the length expansivity

α_z	transformation parameter
α_{ε_r}	temperature coefficient of relative permitivity
β	phase constant, coefficient of voltage coupling
γ	propagation constant
Γ	reflection coefficient
Γ_e, Γ_o	reflection coefficient of even and odd modes, respectively
δ, δ_{ef}	loss angle, effective loss angle
δ_n	penetration depth
$\delta(x - x')$	δ-function
Δ	increment
$\varepsilon, \varepsilon(\omega)$	permittivity
ε_r	relative permittivity
ε_{ef}	effective permittivity
η_{add}	adding efficiency
Θ	cylindrical coordinate
Θ_i, Θ_L	angle
λ_g, λ_L	wave length in line
λ_c	cut-off wave length
μ, μ_0	permeability, permeability of vacuum
Π^e, Π^m	Hertz vector
ρ	charge density; triangular polar coordinate
τ_b, τ_c, τ_e	time of flight through the base, collector, emittor
τ_{ec}	total transistor delay
τ_{rc}	time constant of the collector
φ_d	differential phase shift
Φ, Φ_k	potential, potential on the surface of the k-th conductor
Φ_D	scalar dipole potential
ψ	angle
ω	angular frequency
ω'	cut-off angular frequency

B) Abbreviations

BFL	Buffered FET Logic
DCFL	Direct Coupled FET Logic
SDFL	Schottky Diode FET Logic
HEMT	High Electron Mobility Transistor
MODFET	MOdulation Doped FET
TEGFET	Two-dimensional Electron Gas FET
SDHT	Selective Doped Heterostructure Transistor
SISFET	Semiconductor Insulator Semiconductor FET
MESFET	MEtal Semiconductor FET
FET	Field Effect Transistor
MIC	Microwave Integrated Circuit
MMIC	Monolitic Microwave Integrated Circuit
SWR	Standing Wave Ratio
VSWR	Voltage Standing Wave Ratio
TEM	Transverse ElectroMagnetic (wave)

1

Introduction

In general, the origin of the development of microwave circuits dates back to 1930, when microwave systems were introduced, advantageously implemented by waveguide parts. In attempts to provide the efficient transfer of the microwave power from the supply into the waveguide transmission line, considerable effort was developed in the field of the analysis of microwave circuits. Works by P. H. Smith (Smith, 1969) as a designer of graphic means for solving problems of transmission lines are well known. World War II accelerated the progress of the development of microwave procedures, which have found their application in the radar technique. This was a period of the origination of the hybrid T-element and of the first directional coupler and these parts immediately found their use in practice. The classic methods of solving the circuits led to a change from relationships for the voltage and current and impedance and admittance matrices to terms as transmitted and reflected waves, which resulted to a concept of scattering matrices. This opened possibilities of solving multiport networks. In this period, the waveguide and coaxial technique represented elements of microwave circuits and they complemented each other by their characteristics. The waveguide technique was used for its capability to transmit higher powers at low losses. Resonators based on cavity waveguides achieved high quality coefficients Q. In contrast to this, the coaxial technique offered a wide frequency range due to the absence of dispersion effects. The 1950s were characterized by an origin of special applications of two-conductor lines, as for example the strip line (Barret and Barnes, 1951). The advantage was taken of the feature that the characteristic impedance of the line can be easily controlled by the width of the middle strip, usually produced by the photo-etching technology on the copperclad dielectric substrate. This technology also found a wider application in the production of directional couplers and power dividers.

The microstrip is a further type of line occurring after that, however, due to larger loss per unit length resulting from radiation and due to its low dielectric constant ($\varepsilon = 2.5$) of the originally considered substrates, it did not find wide use in the microwave technique at that time. This, however, simultaneously initiated the development for a further period.

In the 1960s, a revival of microstrip lines actually occurred. This was also facilitated by the discovery of the elegant analysis of microstrip structures by Wheeler, 1964, which was based on the conformal representation. The new methods and technologies initiated a rapid development in the use of microstrip lines. The abilities of planar microwave transmission structures, rapid development of microwave semiconductor elements, technique of thin layers and photolithography resulted in a development of a new field of the technology — microwave integrated circuits (MIC). We can tell that these circuits mean an extension of the technology of hybrid integrated circuits into microwave frequencies.

The integrated technology plays an important role in the current microwave technique and it represents a key factor in the successful development of the microwave technique and in their penetration into different regions of the science and technology, into electronics for investment as well as consumption purposes. This technology presents a basic assumption of the economically efficient implementation of modern high-frequency systems with excellent technical and operational parameters, high reliability, resistance and stability, which are compact and in comparison with the preceding waveguide systems also characterized by smaller size and weight.

The high-productivity production of microwave integrated circuits and microwave systems on the integrated technological basis with low losses corresponding to the rejection of products and exceeding of allowances desired, is tightly related to a high level of theoretical as well as experimental methods of the microwave integrated circuit design. A wide base of the knowledge, method of the analysis and synthesis and of checked procedures is an ultimate requirement here, since the integrated structure allows at most for minimum repair interventions into the physically accomplished circuits in order that it could be unnecessary to adjust or alter unsuitable and, due to an imprecise design, deflected values of electric parameters of the integrated circuit. This factor is even more remarkably manifested in the series and mass production of a certain type of the microwave integrated circuit, where the lowest losses considerably affect the economy of the whole production.

The purpose of the authors of the present book is to yield to an expert reader as much information as possible on theoretical methods of analysis and synthesis of microwave elements and circuits produced by the integrated technology. The material arranged in the book is to a considerable extent a result of the research and development works of the authors, and it was also experimentally checked by the authors. The book presents material sufficient for providing its use as a practical handbook for experts in the research, designers of integrated circuits in industry and also as an auxiliary text for students at technical universities. However, the authors are aware that the current rapid development of the microwave integrated technology cannot be completely described in the monograph.

Chapter 2 deals with the analysis of passive circuit elements starting from transmission lines of different types and their MIC applications. The second part considers discontinuities, their characteristics and applications in the MIC. In the third part, the problems of lumped elements are analysed.

Chapter 3 concerns semiconductor circuit elements such as Schottky diodes, varactor diodes, PIN diodes and transistors (bipolar, MESFET, HEMT).

Chapter 4 considers the basic circuits. The first part is aimed at methods of MIC synthesis with the use of the matrix approach. In the second part, basic linear circuits are analysed (non-reflecting load, resonators, attenuators, etc.) and the last part describes basic active and non-linear circuit (detectors, mixers, oscillators and amplifiers).

Chapter 5 includes the problems of measuring and testing. The first part considers measuring methods from the metrological standpoint. In the second part, the problems of the measuring set (test fixture and probes) are analysed and in the third part, calibration approaches are discussed. The last part considers the noise measurments.

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2

Analysis of passive circuit elements

F. Hrníčko and M. Pavel

2.1 TRANSMISSION LINES FOR MICROWAVE INTEGRATED CIRCUITS

In the microwave integrated circuits (MICs) special types of lines are used that, in general, are formed by means of diverse configurations of conducting strips on different substrates. The latter are represented by various types of lines such as microstrip, coplanar, slotlines or transmission lines on suspended or multi-layer substrates as well as coupled lines. For some important types of lines accurate solutions for quasi-static approximations were obtained, whereby the line's dispersion was determined with the use of a series of numerical methods that for the purpose of computer aided design can be approximated by closed relationships and vice versa the relationships for the synthesis can also be obtained.

2.1.1 Basic characteristics of homogeneous transmission lines

Basic component of the MIC is formed by homogeneous transmission lines enabling transmission of the electromagnetic field energy from the generator to the load or they stand as a part of a distributed circuit design. Usually, strip conductors located in definite places at dielectric sheets interfaces are used. Further, we shall confine ourselves just to the structures showing longitudinal uniformity. Transverse dimensions of such a line are independent of the coordinate along the direction of propagation. Basic parameters of the line are found using CAD-approximations or more tedious analytical methods from its dimensions in the transverse plane.

In the transmission lines used in the MICs, various types of waves can be excited. Apart from the waves propagating along the interface formed by the dielectric substrates waves can also be induced that are radiated into surrounding space. We try to suppress such unwanted waves by a suitable choice of transverse line dimensions and in the way the circuit is fed.

Transmission lines structure can be classified as *open*, *side-open* or *closed*. This classification says in what type of space the electromagnetic energy is propagating. By computation, various numerical solutions of the field are obtained differing both by their character and formal description. Open MIC lines are not resistant against perturbations and they, themselves can become a source of disturbation if the transverse dimensions of the structure are chosen improperly. On the other side, the improper transmission of information on the lines in closed structures is not affected by external fields. Most popular transmission lines in open structures are microstrip, coplanar waveguide, coplanar strips, slotline, suspended microstrip line, and some other lines. These types of lines, as a rule are enclosed in conductive boxes whose effect can either be neglected under the assumption of the properly selected size. In the other case the closed transmission structure should be investigated. To the closed structures the lines belong such as stripline, suspended stripline, finline etc. In many cases the closed structure transmission line problem can be analysed as a side-open one advantageously.

Transverse arrangement of some transmission lines for MICs are depicted in Fig. 2.1. In the following chapters the brief description of their properties, the way and limits of their application and accurate closed-form equations are given. They are most often achieved by many parameter curve fitting of precise analytical results. Some of the analytical methods are presented in Chapter 2.1.8 (or in the Appendix). More precise elaborating of those methods lies beyond the scope of this book.

Practically speaking, what we are interested in is the propagation along the transmission lines mentioned in the above. It is necessary to determine the distribution of the intensity of both the electric and magnetic field for the propagation mode under study. It can be achieved by solving the wave equations under definite boundary conditions.

Multiconductor transmission lines enable purely TEM or non-