A TUTORIAL ON MAJOR HARMONIC BALANCE SOFTWARE

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June 23, 1989

Introduction

we describe the use of Microwave Harmonica - a general purpose linear and nonlinear microwave circuit simulator

we also offer a brief comparison between Libra and Microwave Harmonica

Microwave Harmonica includes Super-Compact which performs linear simulations

nonlinear simulation is performed using harmonic balance method

Microwave Harmonica has a library of linear and nonlinear elements

Microwave Harmonica is capable of performing simulation and optimization of both linear and nonlinear circuits

The Harmonic Balance Method

Notation

$\mathbf{V}(k)$ contains external voltages of a linear subcircuit at harmonic k

$\mathbf{V}_t(k)$ contains both internal and external voltages of a linear subcircuit at harmonic k

$\bar{\mathbf{V}}$ contains real and imaginary parts of $\mathbf{V}(k)$ for all harmonics

$\wedge$ denotes adjoint quantities, e.g., $\hat{\mathbf{V}}(k)$

current vectors $\mathbf{I}(k)$, $\mathbf{I}_t(k)$, $\bar{\mathbf{I}}$ and $\hat{\mathbf{I}}(k)$ similarly defined

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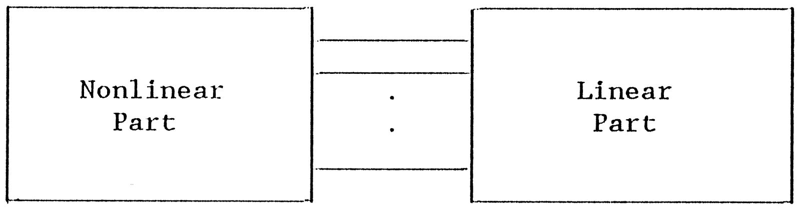
Harmonic Balance Simulation



time domain $\xleftrightarrow[\text{Transform}]{\text{Fourier}}$ frequency domain

harmonic balance equation

$$\bar{\mathbf{F}}(\bar{\mathbf{V}}) \triangleq \bar{\mathbf{I}}_{NL}(\bar{\mathbf{V}}) + \bar{\mathbf{I}}_{L}(\bar{\mathbf{V}}) = \mathbf{0}$$

where $\bar{\mathbf{I}}_{NL}(\bar{\mathbf{V}})$ and $\bar{\mathbf{I}}_{L}(\bar{\mathbf{V}})$ represent currents from the linear and the nonlinear parts, respectively

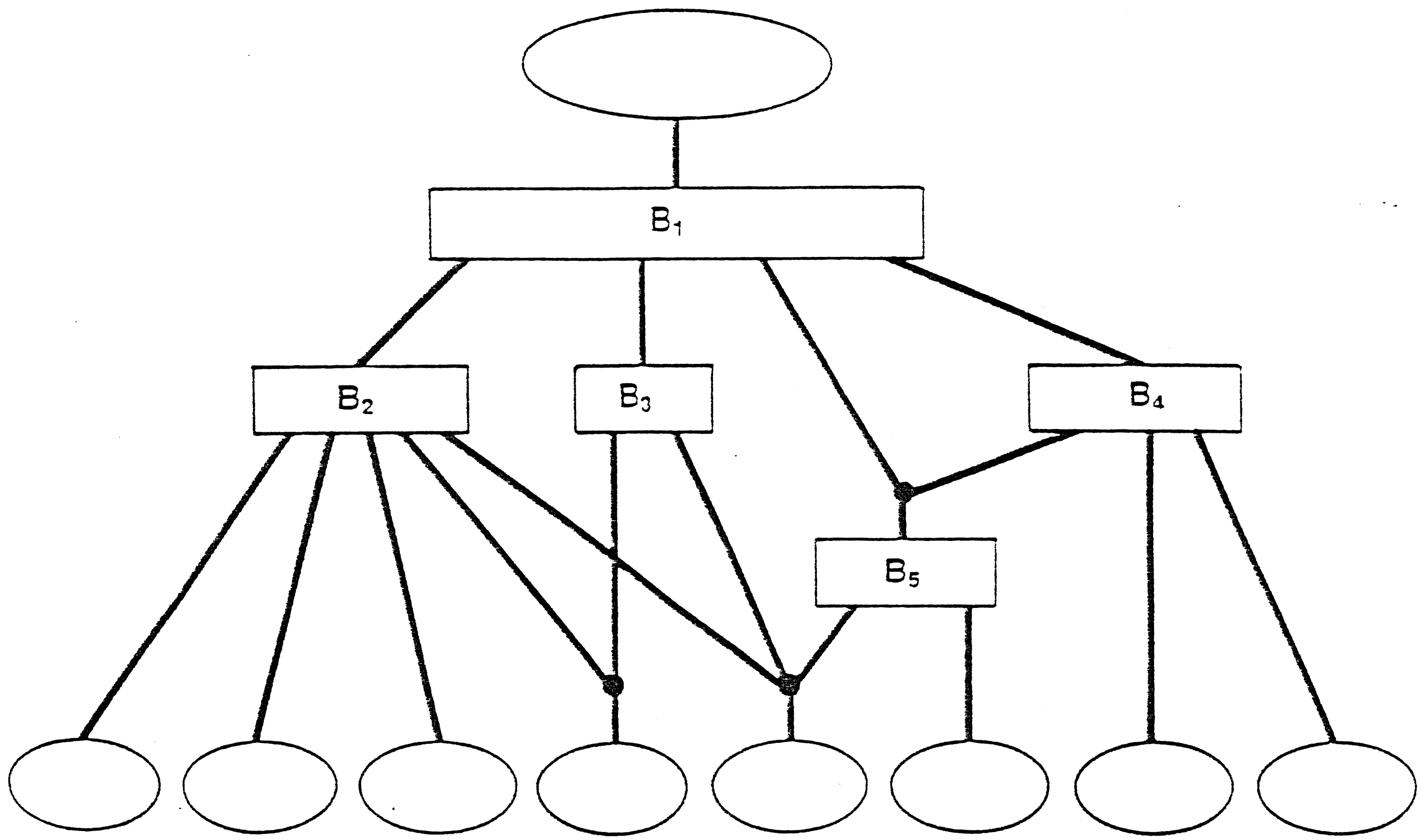


Fig. 1 An arbitrary circuit hierarchy. Each thick line represents a group of nodes. Each rectangular box represents a connection block for a subcircuit. Each bottom circular box represents a circuit element and the top circular box represents the sources and loads.

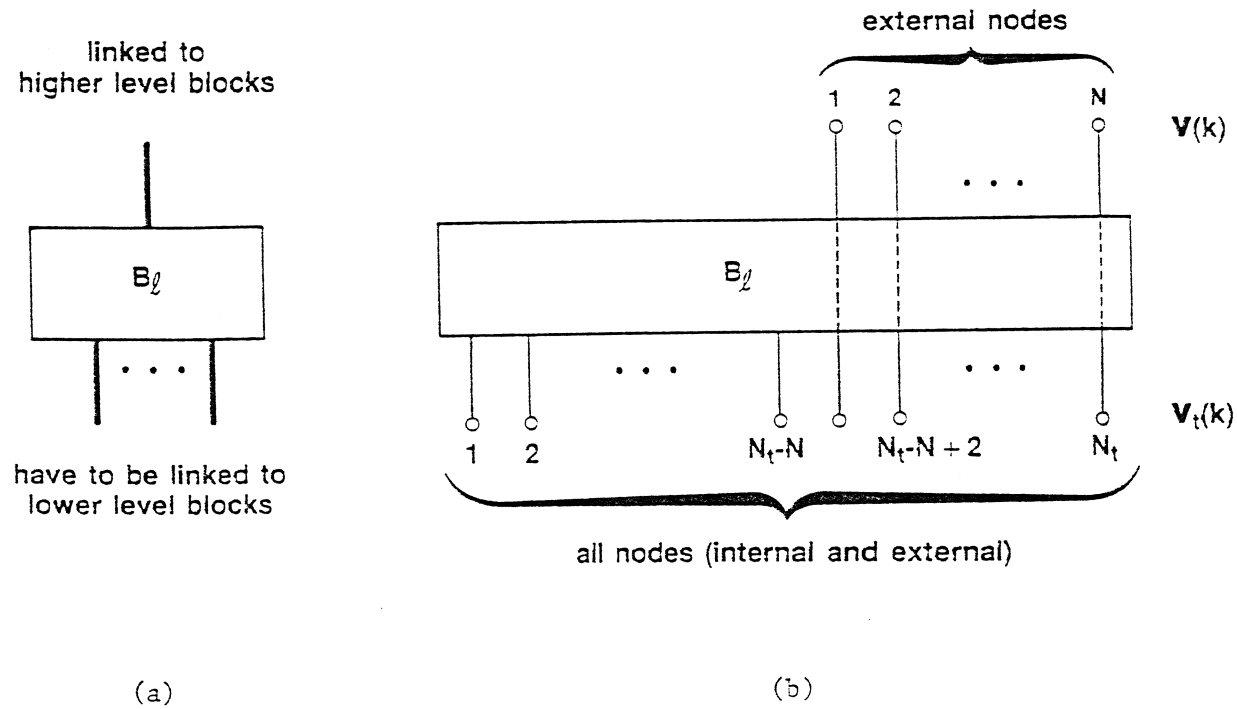


Fig. 2 A typical subcircuit connection block: (a) as seen from Fig. 1, (b) detailed representation of all the nodes of the subnetwork. Nodes at the top (bottom) of the rectangular box are the external (external and internal) nodes of the subnetwork.

Hierarchical Analysis

UPWARD analysis is to obtain the overall circuit matrix, e.g., Y matrix, for the linear part

DOWNWARD analysis is to obtain responses for the linear part at individual components, e.g., voltage or power for an element

TOP LEVEL analysis is to solve the harmonic balance equations for nonlinear networks

TOP LEVEL analysis is to solve the terminated circuit for linear networks

Top Level Simulation of Nonlinear Circuits

harmonic balance equation

$\overline{\mathbf{F}}(\overline{\mathbf{V}}) = 0$

Newton update

$\overline{\mathbf{V}}_{new} = \overline{\mathbf{V}}_{old} - \overline{\mathbf{J}}^{-1}\overline{\mathbf{F}}(\overline{\mathbf{V}}_{old})$

$\overline{\mathbf{J}}$ is the Jacobian matrix

the Newton solution provides the top level voltages V(k)

Downward Simulation of the Original Linear Network

consider a typical subcircuit

internal and external voltages $V_t(k)$ of the subcircuit can be computed from its external voltages $V(k)$ by

$$A(k) \begin{bmatrix} V_t(k) \\ I(k) \end{bmatrix} = \begin{bmatrix} 0 \\ V(k) \end{bmatrix}$$

$A(k)$ is the modified nodal admittance matrix of the subcircuit

$I(k)$ contains currents into the subcircuit from its external ports

$V_t(k)$, along with $I(k)$, is a solution to the subcircuit

Implementation

suppose subcircuits C1, C2 and C3 are directly connected to the subcircuit under consideration from below

then solution $V_t(k)$ contains internal and external voltages of the subcircuit under consideration

$V_t(k)$ also provides external voltages of the lower level subcircuits C1, C2, C3

the equation is used iteratively down the hierarchy until all desired voltages are found

Input File Syntax

circuit blocks

harmonic indices for excitation and outputs

- single tone case
- two tone case

frequency sweep and power sweep syntax

NVAR block

- DC state variables: fix or optimize
- AC state variables: fix or optimize

Nonlinear Device Models

device model covers the intrinsic part of the nonlinear models

users can describe FET parasitic or packaging effects using linear elements

user can define nonlinear device models through a subroutine

Linear Elements

the concept of primary and secondary elements

- primary elements - can be used to create subcircuits
- secondary elements - can be optimized

user can define linear elements through a subroutine

Control Options for HB Simulation

harmonic balance simulation is iterative

factors affecting convergence

- device operating in highly nonlinear regions
- excitation level very high
- insufficient number of harmonics considered
- accuracy specified is too small

convergence for diode circuits are usually slow - it is recommended not to use default control options

State Variable File

state variable solutions are automatically stored in the file *.VAR

management of the *.var file

- keep the file name consistent with that of the circuit file

- users are not encouraged to alter this file

Exploiting Sparse Simulator

subcircuits defined by primary circuits can be solved efficiently by the built-in sparse solver

DC Simulation

Microwave Harmonica requires that AC excitation should not be DC connected to bias ports

Frequency Sweep

small frequency step in frequency sweep will improve convergence

Microwave Harmonica Handles Frequency Degeneracy

if a frequency degeneracy occurs in a two tone case then one of the two exciting frequencies will be slightly perturbed

Libra and Microwave Harmonica
- A Brief Comparison

The comparison is mainly focused on the harmonic balance features of the two products

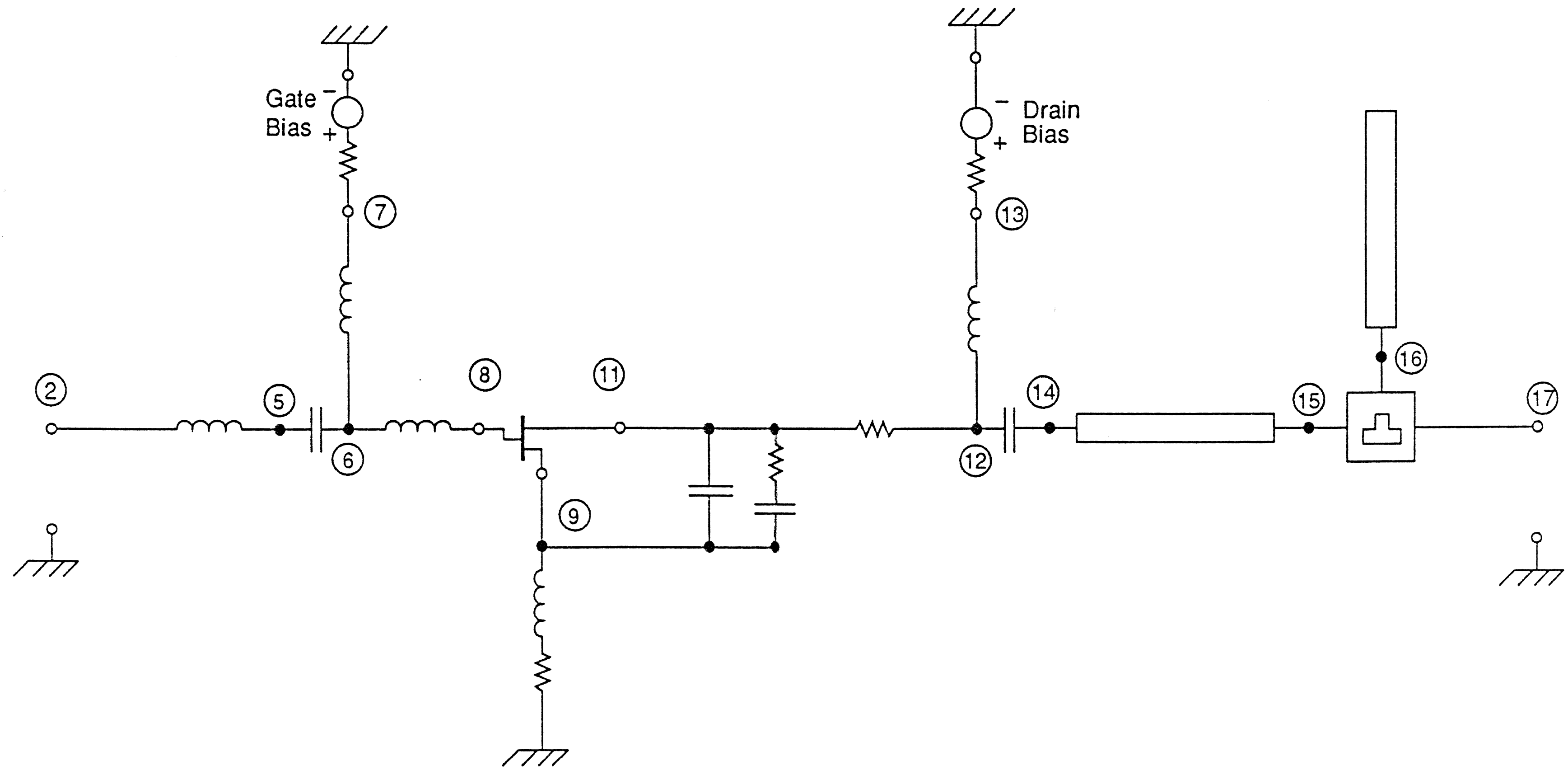


Fig. 2 Augmented linear subnetwork for the frequency doubler depicted in Fig. 1.

EXAMPLE 1

CIRCUIT FILE FOR MICROWAVE HARMONICA

```
*  EXAMPLE 1: STARTING OPTIMIZATION OF A FET FREQUENCY DOUBLER
NBLK
        SUBS EPSR=9.8                        ! *** DEFAULTS: H=.635E-3 SIGD=0 T=6E-6 ROC=3.85E-8 RHS=.15E-6
        SRLC  6  8   L=.16NH
  CAP1: PRLC  5  6   C=20PF                  ! *** SUCH A LABEL NOT AVAILABLE IN LIBRA
  IND1: SRLC  6  7   L=15NH                  ! *** SUCH A LABEL NOT AVAILABLE IN LIBRA
*
  SRLC 11  9  R=440   C=1.15PF
  PRLC 11  9  C=.12PF
  SRLC 11 12  R=2.153
  SRLC 9   0  R=1.144 L=0.07NH
  CAP1 12 14
  IND1 12 13
*
  SRLC  2   5               L=?.5NH  1NH   10NH?   Q=50       ! *** FREQUENCY INDEPENDENT QUALITY FACTOR Q
  MIC   14  15  0  0        P=?.5E-3 1.E-3 10.E-3? W=.1E-3
  MICO  16  0               P=?1.E-3 5.E-3 10.E-3? W=.635E-3
  TJUN  16  15 17  0  0  0  W1=.635E-3 W2=.1E-3  W3=.635E-3  X=1          ! *** X - DISPLACEMENT PARAMETER
*
  NFET  8  11  9                             ! *** MATERKA & KACPRZAK MODEL NOT AVAILABLE IN LIBRA
+ IDSS=6.E-2 VP0=-1.906 GAMA=-1.5E-2 E=1.8
+ SL=.676E-1 KG=1.1 T=7.E-12 SS=1.666E-3
+ IG0=.713E-5 AFAG=38.46 R10=3.5 KR=1.111
+ IB0=-.713E-5 AFAB=-38.46 C10=0.42E-12 K1=1.282
+ CF0=0.02E-12 KF=1.282 VBC=0. VDMX=10.0 NAME=MY_FET
*
  BIAS  7   0   V=FREE  R=100  NAME=GT_BIAS                   ! *** ONLY IDEAL DC SOURCES AVAILABLE IN LIBRA
  BIAS  13  0   V=FREE  R=100  NAME=DR_BIAS                   ! *** ONLY IDEAL DC SOURCES AVAILABLE IN LIBRA
*
  DOUBLER: 2PORT  2 0   17 0
END
FREQ
   HARM 4
   5GHZ
END
NEXC
   P1<H1>=2.E-3WATT                              ! *** ONLY FUNDAMENTAL FREQUENCY SOURCES AVAILABLE IN LIBRA
END
NOPT
   TG21<H2,H1>=2.5DB GT  W=.005
  + SP2<H2>   = 19DB GT  W=.005
END
NVAR                                              ! *** STATE VARIABLES NOT INITIALIZED IN LIBRA
  MY_FET VGS<H0>=-1.906 VGS<H1>=?.001 0?
   +  VDS<H0>=5.     VDS<H1>=?.001 0?
END
```

EXAMPLE 1

CIRCUIT FILE TRANSLATED TO THE LIBRA FORMAT

```
! EXAMPLE 1: STARTING OPTIMIZATION OF A FET FREQUENCY DOUBLER
! LIBRA FORMAT
DIM
   PWR  W                                            ! default dBm
   CUR  A                                            ! default mA
   VOL  V                                            ! EQUALS DEFAULT (can be omitted)
   FREQ GHZ                                          ! EQUALS DEFAULT (can be omitted)
   RES  OH                                           ! EQUALS DEFAULT (can be omitted)
   IND  NH                                           ! EQUALS DEFAULT (can be omitted)
   CAP  PF                                           ! EQUALS DEFAULT (can be omitted)
   LNG  MM                                           ! default MIL (meters not available)
VAR     ! similar to MICROWAVE HARMONICA labels
   CAP1 = 20.0
   IND1 = 15.0
CKT
   MSUB ER=9.8 H=.635 T=6E-3 RHO=1.58 RGH=.15E-3             ! all parameters must be specified in the
                                                             ! prescribed order; 1.58 = 3.85/2.44
   IND  6  8    L=.16
   CAP  5  6    C^CAP1
   IND  6  7    L^IND1
!  RES  11 12   R=2.153                              ! NOT NEEDED (included in the FET model)
!  SRC  11 9    R=440  C=1.15                        ! NOT NEEDED (included in the FET model)
!  CAP  11 9    C=0.12                               ! NOT NEEDED (included in the FET model)
!  RES  9  10   R=1.144                              ! NOT NEEDED (included in the FET model)
   IND  10 0    L=0.07
   CAP  12 14   C^CAP1
   IND  12 13   L^IND1
   INDQ 2  5    L # 0.5 1.0 10.0  Q=50  F=1  MOD=3           ! frequency independent quality factor Q
   MLIN 14 15   W=.1    L # 0.5 1.0 10.0
   MLOC 16             W=.635   L # 1.0 5.0 10.0
   MTEE 16 15 17       W1=.635  W2=.1  W3=.635               ! compare layout in LIBRA and MICROWAVE HARMONICA;
                                                             ! displacement parameter not available in LIBRA
! --------------------------------------
! Note: LIBRA does not support the Materka & Kacprzak model.  To solve this problem we may convert the Materka
!       & Kacprzak model to Curtice model and use it in the Libra circuit file and, if the models do not match
!       well, use the Curtice model in the MICROWAVE HARMONICA circuit file as well.  HarPE can be used to
!       convert one model to the other.  The parameters in the MODEL block in this circuit file may not match
!       the device described in the MICROWAVE HARMONICA circuit file.

   S2PA_A1  8  12  10  [MODEL=MY_FET]
! --------------------------------------
*  VS_G_BIAS  107  0   DC \ -1.906       ! only ideal DC sources are supported in LIBRA; optimization unclear
   RES        107  7   R=100             ! must be separated from the source
*  VS_D_BIAS  113  0   DC \ 5            ! only ideal DC sources are supported in LIBRA; optimization unclear
   RES        113  13  R=100             ! must be separated from the source
*  RES_RG     1    2   R=50
*  RES_RL     17   0   R=50
   DEF2P  2  17  DOUBLER
SOURCE
   DOUBLER P_INP_P  1  0  R=RES_RG  P^PWR  F^F1
MODEL
   MY_FET GAS MODEL=2   RS=1.144   RD=2.153     RG=0  RC=440   CRF=1.15P     &
              A0=0.065  A1=0.115   A2=0.059     A3=0.009                     &
              GAMMA=2   BETA=0.04  VDS0=2.0     VDSDC=2.0      RDS0=1250     &
              IS=1.E-9  N=1.5      CGD0=0.06P   CGS0=0.37P     CDS=0.12P
FREQ
   STEP  5
   NH  = 4
POWER
   STEP 2.E-3
FILEOUT                                              ! automatically done in MICROWAVE HARMONICA
   DOUBLER HB STATE EXAMPLE1.HBV
OUT                                                  ! interactively accessed in MICROWAVE HARMONICA
   DOUBLER PS_OUT_P 17  0   R=RES_RL   GR1
GRID                                                 ! interactively accessed in MICROWAVE HARMONICA
   RANGE   0 25 2.5
   GR1   -80 20 10
HBCNTL                                               ! interactively accessed in MICROWAVE HARMONICA
   RELTOL = 1E-6
   SAMPLE = 3.0
OPT  ! not clear what and how can be optimized; nonlinear optimization is announced for Libra 2.1
```

BRIEF COMPARISON OF LIBRA AND MICROWAVE HARMONICA

The comparison is mainly focused on the harmonic balance features. Libra V1.0 Users Manual (December, 1987) is used as the basis for evaluating Libra.

Microwave Harmonica is referred to as MH.

1. Optimization of Nonlinear Circuits

Libra: recently claimed for Libra 2.1 (in Microwave Journal May 1989)
MH: yes

2. Nonlinear Circuit Responses

Libra: power spectrum, waveform and spectrum of voltages and currents
MH: power spectrum, waveform and spectrum of voltages and currents

Libra: spectral density
MH: spectral purity, return loss, power added efficiency, transducer gain, transfer efficiency

3. Operating Frequencies of AC Sources

Libra: only at fundamental frequencies F1 and F2 (see p. 2-34)
MH: at fundamental, higher harmonics or intermodulating frequencies

4. Treatment of Mixer Case

Libra: spectrum defined by various intermodulating harmonics of the LO and RF frequencies
MH: spectrum efficiently defined by number of LO harmonics and number of side bands per LO harmonic

5. Unified Element Representation for Linear and Nonlinear Analysis

Libra: the syntax for linear and nonlinear elements is different; a star * must appear in front of elements relevant for harmonic balance; the names of such elements are mostly a mixture of internal keywords and user-specified character strings
MH: the syntax for linear and nonlinear elements is the same

6. Style of Outputs for Linear and Nonlinear Analysis

Libra: for linear outputs, user specifies response keyword and port number;
for nonlinear outputs, user specifies response keyword, node number and harmonic numbers
MH: for linear outputs, user specifies response keyword and port number;
for nonlinear outputs, user specifies response keyword, port number and harmonic numbers; also, interactive selection of the desired output is available

7. User's Access to State Variables

Libra: no access
MH: yes (user can specify bounds or fix some state variables)

8. User-Defined Nonlinear Elements

Libra: not clear
MH: yes (user can define his or her elements in a subroutine)

9. Built-in Models

Libra: diode; FET: Curtice model, Raytheon model, EEsof model; BJT
MH: diode; FET: Materka model, Curtice model; BJT

The following compares features similar in Libra and MH

10. Nonlinear Elements in Circuit Hierarchy

Libra: only at the highest hierarchy
MH: only at the highest hierarchy

11. Substrate Parameters Defined by a Special Element in Circuit Block

Libra: yes (the special element are MSUB, SSUB, SSSUB)
MH: yes (the special element is SUBS)

12. Ungrounded External Ports at the Top Circuit Hierarchy

Libra: allowed
MH: allowed

13. DC Sources

Libra: DC sources can be defined in either the circuit block or the source blocks (in CKT block or SOURCE block)
MH: DC sources can be defined in either the circuit block or the excitation block (in NBLK block or NEXC block)

14. AC Sources

Libra: AC sources can be defined in either the circuit block or the source block, but it is recommended to defined them in source block.
MH: AC sources are defined in the excitation block (NEXC block)

15. Saving and Reusing State Variable Solutions

Libra: yes (file .HBV)
MH: yes (file .VAR)

16. Harmonic Balance Control Variables (accuracy, number of iterations, etc.)

Libra: defined in circuit file
MH: accessed interactively; more parameters can be controlled

17. FET Parasitics

Libra: topology fixed internally; parameters are defined within FET model
MH: arbitrarily defined by the user as ordinary linear elements

```
!  Example  testm.ckt
!  Optimization to fit S-parameter and DC bias measurement data.
!  Model used: Built-in Materka and Kacprzak model.
!
Expression
  GDS_MODEL = 1./440.
END
Model

   Extrinsic2     1 2 3 4 5
            LG:    0.16NH
            RG:    0
            RD:    2.153
            LD:    0
            RS:    1.144
            LS:    0.07NH
            GDS:   GDS_MODEL
            CX:    1.15PF
            CDS:   0.12PF  ;

   FETM      1 2 3                       ! Materka FET model
             IDSS:    6.e-2
             VPO:      -1.906              GAMMA:  -1.5E-2
             E:         1.8
        !     KE:        0
             SL:        .676E-1
             KG:        1.1              TAU:  7PS
             SS:        1.666E-3
             IGO:       .713E-5
             ALPHAG:    38.46
             IBO:       -0.713E-5
             ALPHAB:    -38.46               VBC:  0
             R10:      3.5
             KR:        1.111              C10:  0.42PF
             K1:        1.282
        !     C1S:       0.0048PF
             CF0:   0.02PF
             KF:        1.282 ;
    2POR  4  5;
end

Data
! S-parameter measurement data

#include "spar_1.dat"
end

Sweep
! HB simulation

!  FREQ: 0.2GHZ 6GHZ 10GHZ  PIN: 5DBM   VG: -0.673  VD: 4;
!  FREQ: 6GHZ  PIN: from -15DBM to 10DBM step=5DBM VG: -0.673  VD: 4;

! S-parameter simulation
```

```
  FREQ: from 2GHZ to 20GHZ STEP=2GHZ  VG: 0 -1 -2     VD: 2  4;

! DC IV simulation

  VG: 0.5 0 -0.5 -1  -1.5  -2  VD: FROM 0 TO 4 STEP=0.25;
end

Specification

 FREQ: from 2GHZ to 18GHZ step=3GHZ  MS11 PS11 MS21 PS21 MS12 PS12 MS22 PS22;
 VG: 0 -1.74 -3.1  VD: 4  ID 50;  ! weighting factor for ID is 50
end
```

```
!  Example  testc.ckt
!  optimization to fit S-parameter and DC data.
!  Model used: Built-in Curtice and Ettenberg cubic model.
!

Expression
  GDS_MODEL = 1./440.
END

Model
   Extrinsic2     1 2 3 4 5
            LG:    0.16NH
            RG:    0
            RD:    2.153
            LD:    0
            RS:    1.144
            LS:    0.07NH
            GDS:   GDS_MODEL
            CX:    1.15PF
            CDS:   0.12PF  ;

   FETC  1 2 3                        ! Curtice FET model
          A0:    ?0  0.0644434  0.3?      A1:     ?0.0544248 ?
          A2:    ? -0.00359251 ?           A3:   ? -0.00928337 ?
          GAMMA:  ? 1.00546 ?                BETA: ?-2  0.0529885  2?
          VDSO:    3
          IS:     ? 3.53605e-06 ?             N:    ?  1.18411 ?
          CGSO:  ? 0.380929PF ?             CGDO: ? 0.0184392PF ?
          FC :    ?  0.760981 ?               GMIN: ? 1.25927e-07 ?
          VBI:    ?  1.20067 ?              VBR:   10.0;

   2POR  4  5;
end

Data


! simulated DC IV data

#include "test_s1.dat"
#include "test_s2.dat"
#include "test_s3.dat"
#include "test_s4.dat"
#include "test_s5.dat"
#include "test_s6.dat"

#include "test_dc.dat"
end

Sweep
! S-parameter simulation

  FREQ: from 2GHZ to 20GHZ STEP=2GHZ  VG: 0 -1 -2     VD: 2  4;
```

```
! DC IV simulation

  VG: 0.5 0 -0.5 -1  -1.5  -2  VD: FROM 0 TO 4 STEP=0.25;

end

Specification
  FREQ: from 2GHZ to 20GHZ step=3GHZ  MS11 PS11 MS21 PS21 MS12 PS12 MS22 PS22;

 VG: 0.5 0 -1 -2 VD: 0.5  2  4  ID 20;
end
```

```
!  Example  testr.ckt
!  optimization to fit S-parameter and DC data.
!  Model used: Built-in Raytheon (Statz et al.) model.
!

Expression
  GDS_MODEL = 1./440.
END

Model
   Extrinsic2      1 2 3 4 5
            LG:     0.16NH
            RG:     0
            RD:     2.153
            LD:     0
            RS:     1.144
            LS:     0.07NH
            GDS:    GDS_MODEL
            CX:     1.15PF
            CDS:    0.12PF  ;

   FETR     1 2 3
            ALPHA =? 1.2031 ?               BETA  = ? 0.0136191 ?
            VTO = ? -1.99521   ?               THETA = ? 0.000240122 ?
            LAMBDA = ? 0.0391735 ?
            TAU:  7PS
            IS:     ? 3.18301e-06 ?                N:     ?  1.31133 ?
            CGSO:  ? 0.389679PF ?              CGDO: ? 0.0203977PF ?
            FC :    ?  0.723868 ?               GMIN: ? 1.27192e-07 ?
            VBI:    ?  1.19925 ?               VBR:   10.0;

   2POR  4  5;
end

Data


! simulated DC IV data

#include "test_s1.dat"
#include "test_s2.dat"
#include "test_s3.dat"
#include "test_s4.dat"
#include "test_s5.dat"
#include "test_s6.dat"

#include "test_dc.dat"
end

Sweep
! S-parameter simulation

  FREQ: from 2GHZ to 20GHZ STEP=2GHZ  VG: 0 -1 -2     VD: 2  4;
```

```
! DC IV simulation

  VG: 0.5 0 -0.5 -1  -1.5  -2  VD: FROM 0 TO 4 STEP=0.25;

end

Specification
  FREQ: from 2GHZ to 20GHZ step=3GHZ  MS11 PS11 MS21 PS21 MS12 PS12 MS22 PS22;

 VG: 0.5 0 -1 -2 VD: 0.5  2  4  ID 20;
end
```

file: tutorial.Dat

Data for Materka model

```
! DC Data (I-V Characteristics)
!
 PARAMETER VG=0.5V;
 FORMAT VD(V) ID(mA);
        0.0000      -113.5730
        0.2500       -13.7797
        0.5000        33.5464
        0.7500        49.3960
        1.0000        60.6714
        1.2500        67.8620
        1.5000        72.0954
        1.7500        74.5267
        2.0000        75.9763
        2.2500        76.9250
        2.5000        77.6272
        2.7500        78.2101
        3.0000        78.7354
        3.2500        79.2328
        3.5000        79.7172
        3.7500        80.1951
        4.0000        80.6694

 PARAMETER VG=0V;
 FORMAT VD(V) ID(mA);
        0.0000        -0.0063
        0.2500        13.3452
        0.5000        25.1776
        0.7500        34.9614
        1.0000        42.5600
        1.2500        48.1533
        1.5000        52.1063
        1.7500        54.8335
        2.0000        56.7065
        2.2500        58.0144
        2.5000        58.9612
        2.7500        59.6825
        3.0000        60.2654
        3.2500        60.7641
        3.5000        61.2121
        3.7500        61.6291
        4.0000        62.0276

 PARAMETER VG=-0.5V;
 FORMAT VD(V) ID(mA);
        0.0000         0.0002
        0.2500         5.7430
        0.5000        11.1542
        0.7500        16.0296
        1.0000        20.2521
        1.2500        23.7882
        1.5000        26.6704
```

1.7500	28.9730
2.0000	30.7892
2.2500	32.2145
2.5000	33.3356
2.7500	34.2255
3.0000	34.9432
3.2500	35.5345
3.5000	36.0337
3.7500	36.4668
4.0000	36.8520

PARAMETER VG=-1V;
FORMAT VD(V) ID(mA);

0.0000	0.0001
0.2500	2.0512
0.5000	4.0552
0.7500	5.9550
1.0000	7.7077
1.2500	9.2865
1.5000	10.6806
1.7500	11.8922
2.0000	12.9328
2.2500	13.8196
2.5000	14.5726
2.7500	15.2122
3.0000	15.7572
3.2500	16.2250
3.5000	16.6304
3.7500	16.9858
4.0000	17.3017

PARAMETER VG=-1.5V;
FORMAT VD(V) ID(mA);

0.0000	-0.0000
0.2500	0.3979
0.5000	0.8007
0.7500	1.2003
1.0000	1.5889
1.2500	1.9605
1.5000	2.3108
1.7500	2.6367
2.0000	2.9372
2.2500	3.2125
2.5000	3.4631
2.7500	3.6913
3.0000	3.8989
3.2500	4.0885
3.5000	4.2617
3.7500	4.4214
4.0000	4.5692

PARAMETER VG=-2V;
FORMAT VD(V) ID(mA);

0.0000	-0.0000

0.2500	-0.0000
0.5000	0.0000
0.7500	0.0000
1.0000	0.0000
1.2500	0.0000
1.5000	0.0000
1.7500	0.0000
2.0000	0.0000
2.2500	0.0001
2.5000	0.0000
2.7500	0.0001
3.0000	0.0000
3.2500	0.0001
3.5000	0.0001
3.7500	0.0001
4.0000	0.0000

```
! Small-Signal S-Parameters
!
 PARAMETER VG=0V VD=2V;
 FORMAT FREQ(GHZ) MS11 PS11(DEG) MS21 PS21(DEG) MS12 PS12(DEG) MS22 PS22(DEG);
     1.00  0.9900    -15.00  4.1207   165.26  0.0063    87.51  0.4291     -9.27
     3.00  0.9369    -43.64  3.7996   140.53  0.0180    85.00  0.4187    -17.12
     5.00  0.8638    -69.20  3.3642   118.13  0.0281    85.32  0.4178    -26.06
     7.00  0.7994    -91.45  2.9327    98.71  0.0377    88.17  0.4225    -34.62
     9.00  0.7545   -110.91  2.5593    81.73  0.0485    92.03  0.4327    -42.86
    11.00  0.7296   -128.15  2.2492    66.54  0.0616    95.43  0.4480    -50.91
    13.00  0.7217   -143.62  1.9912    52.65  0.0776    97.59  0.4674    -58.84
    15.00  0.7271   -157.66  1.7716    39.70  0.0966    98.31  0.4898    -66.71

! Small-Signal S-Parameters
!
 PARAMETER VG=-0.5V VD=2V;
 FORMAT FREQ(GHZ) MS11 PS11(DEG) MS21 PS21(DEG) MS12 PS12(DEG) MS22 PS22(DEG);
     1.00  0.9942    -12.13  3.0760   166.81  0.0056    88.49  0.4162     -9.16
     3.00  0.9533    -35.74  2.9100   144.62  0.0162    87.34  0.4081    -16.67
     5.00  0.8897    -57.76  2.6716   123.59  0.0258    88.15  0.4096    -25.62
     7.00  0.8243    -77.96  2.4088   104.59  0.0350    91.02  0.4154    -34.34
     9.00  0.7696    -96.51  2.1591    87.52  0.0454    94.85  0.4259    -42.74
    11.00  0.7307   -113.72  1.9354    72.04  0.0580    98.32  0.4407    -50.91
    13.00  0.7078   -129.79  1.7381    57.82  0.0736   100.57  0.4593    -58.91
    15.00  0.6993   -144.86  1.5621    44.56  0.0923   101.32  0.4808    -66.80

! Small-Signal S-Parameters
!
 PARAMETER VG=-1V VD=2V;
 FORMAT FREQ(GHZ) MS11 PS11(DEG) MS21 PS21(DEG) MS12 PS12(DEG) MS22 PS22(DEG);
     1.00  0.9956    -10.41  2.1191   167.44  0.0052    87.54  0.5525     -8.63
     3.00  0.9632    -30.88  2.0326   146.68  0.0148    84.97  0.5412    -15.76
     5.00  0.9092    -50.50  1.9080   126.39  0.0226    85.08  0.5397    -24.34
     7.00  0.8480    -69.10  1.7596   107.55  0.0292    89.02  0.5415    -32.75
     9.00  0.7908    -86.77  1.6067    90.26  0.0366    95.90  0.5474    -40.89
    11.00  0.7439   -103.71  1.4590    74.39  0.0470   103.04  0.5576    -48.83
    13.00  0.7100   -120.04  1.3196    59.74  0.0618   107.96  0.5715    -56.65
    15.00  0.6895   -135.78  1.1879    46.12  0.0809   109.98  0.5881    -64.42

! Small-Signal S-Parameters
!
 PARAMETER VG=-1.5V VD=2V;
 FORMAT FREQ(GHZ) MS11 PS11(DEG) MS21 PS21(DEG) MS12 PS12(DEG) MS22 PS22(DEG);
     1.00  0.9966     -9.21  1.0998   167.65  0.0050    86.19  0.7272     -8.37
     3.00  0.9713    -27.48  1.0663   147.72  0.0139    81.36  0.7125    -15.29
     5.00  0.9266    -45.39  1.0198   127.83  0.0202    79.51  0.7090    -23.76
     7.00  0.8715    -62.85  0.9594   109.05  0.0239    83.64  0.7075    -32.21
     9.00  0.8145    -79.92  0.8903    91.63  0.0277    95.19  0.7085    -40.46
    11.00  0.7621    -96.71  0.8162    75.63  0.0358   109.33  0.7124    -48.53
    13.00  0.7184   -113.28  0.7392    61.02  0.0506   118.45  0.7189    -56.48
    15.00  0.6855   -129.61  0.6604    47.76  0.0716   121.31  0.7271    -64.33

! Small-Signal S-Parameters
```

```
!
PARAMETER VG=-2V VD=2V;
FORMAT FREQ(GHZ) MS11 PS11(DEG) MS21 PS21(DEG) MS12 PS12(DEG) MS22 PS22(DEG);
    1.00  0.9976     -8.31  0.0048     85.68  0.0048     85.68  0.8138     -8.29
    3.00  0.9785    -24.92  0.0133     79.94  0.0133     79.94  0.7993    -15.07
    5.00  0.9427    -41.55  0.0189     76.82  0.0189     76.82  0.7981    -23.62
    7.00  0.8944    -58.22  0.0213     80.22  0.0213     80.22  0.7977    -32.35
    9.00  0.8388    -74.96  0.0230     94.55  0.0230     94.55  0.7975    -41.05
   11.00  0.7813    -91.80  0.0300    114.44  0.0300    114.44  0.7971    -49.61
   13.00  0.7272   -108.72  0.0457    125.84  0.0457    125.85  0.7964    -58.01
   15.00  0.6804   -125.61  0.0682    128.10  0.0682    128.10  0.7950    -66.18
```

Data for Curtice model

```
! DC Data (I-V Characteristics)
!
 PARAMETER VG=0.5V;
 FORMAT VD(V) ID(mA);
        0.0000       -88.7760
        0.2500        -3.4374
        0.5000        22.3196
        0.7500        37.7115
        1.0000        50.5700
        1.2500        60.5621
        1.5000        67.8117
        1.7500        72.7602
        2.0000        75.9659
        2.2500        77.9477
        2.5000        79.1153
        2.7500        79.7602
        3.0000        80.0773
        3.2500        80.1918
        3.5000        80.1823
        3.7500        80.0972
        4.0000        79.9660

 PARAMETER VG=0V;
 FORMAT VD(V) ID(mA);
        0.0000         0.0000
        0.2500        13.0354
        0.5000        24.8927
        0.7500        34.9460
        1.0000        42.8978
        1.2500        48.7941
        1.5000        52.9311
        1.7500        55.7114
        2.0000        57.5253
        2.2500        58.6884
        2.5000        59.4294
        2.7500        59.9041
        3.0000        60.2129
        3.2500        60.4197
        3.5000        60.5642
        3.7500        60.6706
        4.0000        60.7539

 PARAMETER VG=-0.5V;
 FORMAT VD(V) ID(mA);
        0.0000         0.0035
        0.2500         7.4314
        0.5000        14.1644
        0.7500        19.7929
        1.0000        24.1821
        1.2500        27.4269
        1.5000        29.7468
```

1.7500	31.3866
2.0000	32.5575
2.2500	33.4197
2.5000	34.0837
2.7500	34.6235
3.0000	35.0866
3.2500	35.5024
3.5000	35.8897
3.7500	36.2601
4.0000	36.6207

PARAMETER VG=-1V;
FORMAT VD(V) ID(mA);

0.0000	0.0036
0.2500	2.6750
0.5000	5.1785
0.7500	7.3260
1.0000	9.0548
1.2500	10.3993
1.5000	11.4392
1.7500	12.2595
2.0000	12.9317
2.2500	13.5088
2.5000	14.0269
2.7500	14.5105
3.0000	14.9757
3.2500	15.4319
3.5000	15.8855
3.7500	16.3407
4.0000	16.7994

PARAMETER VG=-1.5V;
FORMAT VD(V) ID(mA);

0.0000	0.0037
0.2500	1.4568
0.5000	2.7520
0.7500	3.7922
1.0000	4.5584
1.2500	5.0871
1.5000	5.4354
1.7500	5.6577
2.0000	5.7967
2.2500	5.8826
2.5000	5.9352
2.7500	5.9681
3.0000	6.0098
3.2500	6.0742
3.5000	6.1637
3.7500	6.2797
4.0000	6.4226

PARAMETER VG=-2V;
FORMAT VD(V) ID(mA);

0.0000	0.0038

0.2500	1.4568
0.5000	2.7521
0.7500	3.7922
1.0000	4.5585
1.2500	5.0873
1.5000	5.4355
1.7500	5.6577
2.0000	5.7967
2.2500	5.8826
2.5000	5.9352
2.7500	5.9673
3.0000	5.9867
3.2500	5.9985
3.5000	6.0058
3.7500	6.0102
4.0000	6.0128

```
! Small-Signal S-Parameters
!
 PARAMETER VG=0V VD=2V;
 FORMAT FREQ(GHZ) MS11 PS11(DEG) MS21 PS21(DEG) MS12 PS12(DEG) MS22 PS22(DEG);
     1.00  0.9940   -13.96  3.6413   168.72  0.0065    87.11  0.4501    -9.10
     3.00  0.9615   -41.14  3.4342   150.39  0.0186    83.94  0.4392   -16.81
     5.00  0.9111   -66.46  3.1320   133.11  0.0286    83.49  0.4364   -25.80
     7.00  0.8597   -89.44  2.7945   117.82  0.0376    86.24  0.4366   -34.45
     9.00  0.8172  -110.10  2.4711   104.47  0.0476    90.79  0.4407   -42.68
    11.00  0.7869  -128.63  2.1822    92.79  0.0605    95.04  0.4484   -50.58
    13.00  0.7682  -145.28  1.9317    82.52  0.0767    97.63  0.4593   -58.23
    15.00  0.7590  -160.24  1.7168    73.42  0.0962    98.30  0.4726   -65.68

! Small-Signal S-Parameters
!
 PARAMETER VG=-0.5V VD=2V;
 FORMAT FREQ(GHZ) MS11 PS11(DEG) MS21 PS21(DEG) MS12 PS12(DEG) MS22 PS22(DEG);
     1.00  0.9960   -12.01  3.5763   169.54  0.0060    86.78  0.5472    -8.70
     3.00  0.9680   -35.60  3.4136   152.88  0.0170    82.98  0.5334   -16.11
     5.00  0.9220   -58.10  3.1744   136.68  0.0256    82.08  0.5273   -24.78
     7.00  0.8709   -79.16  2.8911   121.91  0.0326    85.43  0.5233   -33.09
     9.00  0.8247   -98.73  2.6031   108.67  0.0402    92.18  0.5228   -40.96
    11.00  0.7883  -116.86  2.3323    96.85  0.0512    99.27  0.5264   -48.49
    13.00  0.7630  -133.63  2.0876    86.27  0.0668   104.00  0.5337   -55.77
    15.00  0.7483  -149.10  1.8702    76.79  0.0866   105.75  0.5440   -62.91

! Small-Signal S-Parameters
!
 PARAMETER VG=-1V VD=2V;
 FORMAT FREQ(GHZ) MS11 PS11(DEG) MS21 PS21(DEG) MS12 PS12(DEG) MS22 PS22(DEG);
     1.00  0.9975   -10.61  2.3881   170.26  0.0057    86.26  0.6381    -8.51
     3.00  0.9797   -31.65  2.3087   155.17  0.0159    81.69  0.6235   -15.72
     5.00  0.9488   -52.17  2.1945   139.99  0.0234    79.88  0.6175   -24.35
     7.00  0.9118   -71.96  2.0491   125.67  0.0284    83.36  0.6126   -32.79
     9.00  0.8752   -90.89  1.8886   112.44  0.0335    92.88  0.6101   -40.86
    11.00  0.8438  -108.90  1.7258   100.35  0.0427   104.40  0.6107   -48.58
    13.00  0.8198  -125.93  1.5685    89.38  0.0584   112.11  0.6146   -56.04
    15.00  0.8038  -141.95  1.4211    79.52  0.0801   114.72  0.6213   -63.31

! Small-Signal S-Parameters
!
 PARAMETER VG=-1.5V VD=2V;
 FORMAT FREQ(GHZ) MS11 PS11(DEG) MS21 PS21(DEG) MS12 PS12(DEG) MS22 PS22(DEG);
     1.00  0.9997    -9.48  0.0055    85.26  0.0055    85.27  0.7798    -8.35
     3.00  0.9973   -28.44  0.0152    78.79  0.0152    78.79  0.7661   -15.23
     5.00  0.9927   -47.42  0.0216    74.42  0.0216    74.42  0.7654   -23.87
     7.00  0.9864   -66.37  0.0238    76.16  0.0238    76.16  0.7658   -32.69
     9.00  0.9789   -85.20  0.0241    90.68  0.0241    90.68  0.7665   -41.47
    11.00  0.9708  -103.71  0.0307   115.20  0.0307   115.20  0.7673   -50.11
    13.00  0.9624  -121.69  0.0492   128.97  0.0492   128.97  0.7677   -58.57
    15.00  0.9540  -138.87  0.0767   130.76  0.0767   130.76  0.7675   -66.81
```

! Small-Signal S-Parameters

!

PARAMETER VG=-2V VD=2V;

FORMAT FREQ(GHZ) MS11 PS11(DEG) MS21 PS21(DEG) MS12 PS12(DEG) MS22 PS22(DEG);

1.00	0.9997	-8.72	0.0052	85.52	0.0052	85.51	0.7798	-8.34
3.00	0.9977	-26.20	0.0145	79.59	0.0145	79.59	0.7661	-15.18
5.00	0.9937	-43.80	0.0208	75.53	0.0208	75.53	0.7654	-23.79
7.00	0.9881	-61.54	0.0231	77.05	0.0231	77.05	0.7657	-32.59
9.00	0.9812	-79.39	0.0233	90.59	0.0233	90.59	0.7665	-41.33
11.00	0.9734	-97.22	0.0290	115.34	0.0290	115.34	0.7672	-49.96
13.00	0.9651	-114.83	0.0463	130.66	0.0463	130.66	0.7677	-58.40
15.00	0.9564	-131.96	0.0732	133.30	0.0732	133.30	0.7675	-66.62

Data for Raytheon model

```
! DC Data (I-V Characteristics)
!
 PARAMETER VG=0.5V;
 FORMAT VD(V) ID(mA);
        0.0000       -74.4389
        0.2500         2.4488
        0.5000        24.1092
        0.7500        38.1360
        1.0000        49.8242
        1.2500        59.2855
        1.5000        66.6622
        1.7500        72.1443
        2.0000        75.9748
        2.2500        78.4518
        2.5000        79.9286
        2.7500        80.8089
        3.0000        81.5121
        3.2500        82.2121
        3.5000        82.9120
        3.7500        83.6111
        4.0000        84.3099

 PARAMETER VG=0V;
 FORMAT VD(V) ID(mA);
        0.0000         0.0000
        0.2500        12.4408
        0.5000        22.9887
        0.7500        31.7500
        1.0000        38.8412
        1.2500        44.3957
        1.5000        48.5672
        1.7500        51.5335
        2.0000        53.4998
        2.2500        54.7005
        2.5000        55.3987
        2.7500        55.8807
        3.0000        56.3439
        3.2500        56.8068
        3.5000        57.2692
        3.7500        57.7310
        4.0000        58.1924

 PARAMETER VG=-0.5V;
 FORMAT VD(V) ID(mA);
        0.0000         0.0031
        0.2500         7.5083
        0.5000        13.7528
        0.7500        18.8369
        1.0000        22.8650
        1.2500        25.9477
        1.5000        28.2035
        1.7500        29.7610
```

2.0000	30.7598
2.2500	31.3514
2.5000	31.6997
2.7500	31.9709
3.0000	32.2399
3.2500	32.5087
3.5000	32.7774
3.7500	33.0459
4.0000	33.3140

PARAMETER VG=-1V;
FORMAT VD(V) ID(mA);

0.0000	0.0033
0.2500	3.5176
0.5000	6.4011
0.7500	8.7144
1.0000	10.5185
1.2500	11.8754
1.5000	12.8493
1.7500	13.5070
2.0000	13.9187
2.2500	14.1584
2.5000	14.3033
2.7500	14.4268
3.0000	14.5502
3.2500	14.6735
3.5000	14.7966
3.7500	14.9199
4.0000	15.0428

PARAMETER VG=-1.5V;
FORMAT VD(V) ID(mA);

0.0000	0.0034
0.2500	0.9057
0.5000	1.6414
0.7500	2.2274
1.0000	2.6805
1.2500	3.0180
1.5000	3.2575
1.7500	3.4172
2.0000	3.5155
2.2500	3.5725
2.5000	3.6080
2.7500	3.6396
3.0000	3.6712
3.2500	3.7029
3.5000	3.7345
3.7500	3.7662
4.0000	3.7977

PARAMETER VG=-2V;
FORMAT VD(V) ID(mA);

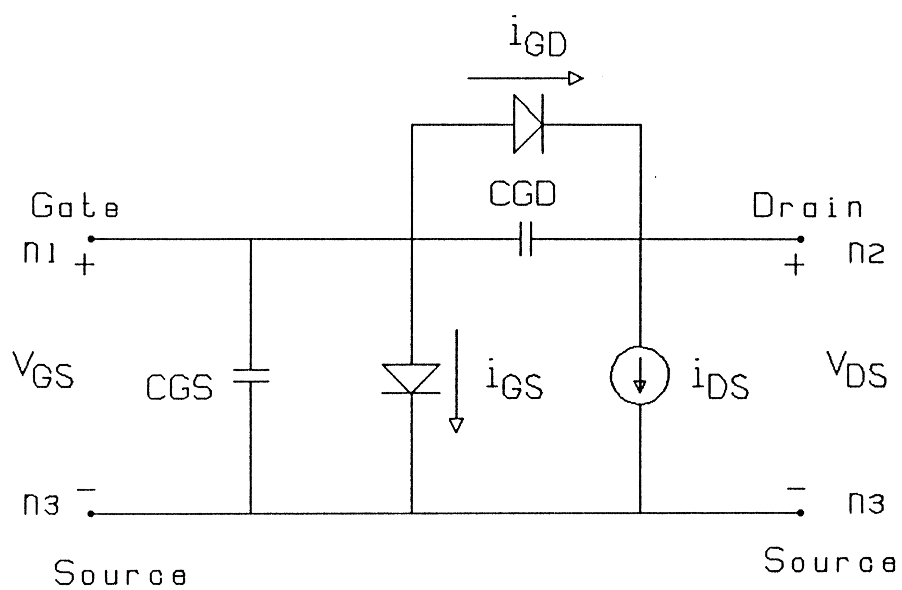
0.0000	0.0035
0.2500	0.0036

0.5000	0.0037
0.7500	0.0038
1.0000	0.0038
1.2500	0.0039
1.5000	0.0039
1.7500	0.0040
2.0000	0.0041
2.2500	0.0041
2.5000	0.0042
2.7500	0.0041
3.0000	0.0041
3.2500	0.0043
3.5000	0.0041
3.7500	0.0041
4.0000	0.0043

```
! Small-Signal S-Parameters
!
 PARAMETER VG=0V VD=2V;
 FORMAT FREQ(GHZ) MS11 PS11(DEG) MS21 PS21(DEG) MS12 PS12(DEG) MS22 PS22(DEG);
     1.00  0.9935    -14.39  3.5868   166.12  0.0071    86.69  0.4305     -9.49
     3.00  0.9597    -42.12  3.3618   142.77  0.0200    82.85  0.4196    -17.73
     5.00  0.9115    -67.35  3.0448   121.00  0.0307    81.70  0.4174    -27.02
     7.00  0.8681    -89.63  2.7098   101.62  0.0399    83.71  0.4202    -35.78
     9.00  0.8388   -109.21  2.4032    84.38  0.0497    87.77  0.4287    -44.07
    11.00  0.8251   -126.54  2.1369    68.83  0.0618    92.17  0.4427    -52.06
    13.00  0.8252   -142.04  1.9074    54.54  0.0772    95.52  0.4612    -59.88
    15.00  0.8362   -156.10  1.7060    41.21  0.0963    97.21  0.4833    -67.61

! Small-Signal S-Parameters
!
 PARAMETER VG=-0.5V VD=2V;
 FORMAT FREQ(GHZ) MS11 PS11(DEG) MS21 PS21(DEG) MS12 PS12(DEG) MS22 PS22(DEG);
     1.00  0.9961    -12.33  3.1466   166.88  0.0067    85.67  0.6016     -8.81
     3.00  0.9694    -36.39  2.9920   145.23  0.0185    80.01  0.5853    -16.47
     5.00  0.9286    -58.90  2.7720   124.37  0.0272    77.39  0.5776    -25.18
     7.00  0.8884    -79.52  2.5231   105.26  0.0331    79.67  0.5738    -33.39
     9.00  0.8584    -98.31  2.2799    87.86  0.0386    86.98  0.5762    -41.12
    11.00  0.8421   -115.49  2.0564    71.90  0.0472    96.65  0.5851    -48.59
    13.00  0.8393   -131.33  1.8542    57.07  0.0613   104.56  0.5999    -55.97
    15.00  0.8482   -146.03  1.6693    43.12  0.0814   108.70  0.6192    -63.39

! Small-Signal S-Parameters
!
 PARAMETER VG=-1V VD=2V;
 FORMAT FREQ(GHZ) MS11 PS11(DEG) MS21 PS21(DEG) MS12 PS12(DEG) MS22 PS22(DEG);
     1.00  0.9973    -10.91  2.3390   167.46  0.0063    84.99  0.7224     -8.58
     3.00  0.9785    -32.39  2.2508   147.14  0.0175    78.15  0.7041    -15.96
     5.00  0.9483    -52.99  2.1268   127.03  0.0251    73.98  0.6949    -24.56
     7.00  0.9163    -72.44  1.9764   108.14  0.0289    75.39  0.6882    -32.80
     9.00  0.8902    -90.73  1.8179    90.58  0.0312    85.02  0.6866    -40.61
    11.00  0.8741   -107.93  1.6610    74.25  0.0371   100.88  0.6911    -48.12
    13.00  0.8691   -124.16  1.5091    58.98  0.0510   113.79  0.7013    -55.53
    15.00  0.8743   -139.51  1.3617    44.58  0.0731   119.35  0.7161    -62.97

! Small-Signal S-Parameters
!
 PARAMETER VG=-1.5V VD=2V;
 FORMAT FREQ(GHZ) MS11 PS11(DEG) MS21 PS21(DEG) MS12 PS12(DEG) MS22 PS22(DEG);
     1.00  0.9985     -9.82  1.2561   167.94  0.0061    84.72  0.7923     -8.45
     3.00  0.9881    -29.34  1.2235   148.68  0.0168    77.41  0.7748    -15.59
     5.00  0.9704    -48.51  1.1803   129.22  0.0239    72.15  0.7682    -24.21
     7.00  0.9500    -67.18  1.1224   110.56  0.0265    72.30  0.7629    -32.71
     9.00  0.9316    -85.28  1.0532    92.97  0.0265    83.06  0.7603    -40.91
    11.00  0.9183   -102.77  0.9755    76.50  0.0305   105.18  0.7615    -48.86
    13.00  0.9114   -119.62  0.8908    61.17  0.0454   122.37  0.7665    -56.66
    15.00  0.9108   -135.77  0.8004    46.96  0.0701   127.75  0.7743    -64.39
```

```
! Small-Signal S-Parameters
!
 PARAMETER VG=-2V VD=2V;
 FORMAT FREQ(GHZ) MS11 PS11(DEG) MS21 PS21(DEG) MS12 PS12(DEG) MS22 PS22(DEG);
     1.00  0.9997    -8.95  0.0059    90.26  0.0058    84.84  0.8138    -8.36
     3.00  0.9975   -26.88  0.0162    79.55  0.0161    77.69  0.7993   -15.26
     5.00  0.9934   -44.91  0.0232    73.19  0.0230    72.04  0.7981   -23.92
     7.00  0.9876   -63.03  0.0255    72.05  0.0251    71.26  0.7978   -32.76
     9.00  0.9806   -81.18  0.0244    82.56  0.0239    82.29  0.7977   -41.55
    11.00  0.9729   -99.23  0.0275   108.84  0.0271   109.35  0.7975   -50.21
    13.00  0.9646  -116.97  0.0436   128.37  0.0434   128.89  0.7969   -58.69
    15.00  0.9562  -134.12  0.0705   132.58  0.0705   132.89  0.7955   -66.94
```

FETC Curtice and Ettenberg FET model FETC



FETC Curtice and Ettenberg FET model FETC

Keywords Defaults

Keywords		Defaults
A0	Cubic fit i_{DS} equation coefficient	0
A1	Cubic fit i_{DS} equation coefficient	0
A2	Cubic fit i_{DS} equation coefficient	0
A3	Cubic fit i_{DS} equation coefficient	0
GAMMA	Hyperbolic tangent function parameter	0
BETA	Coefficient for pinch-off change with respect to v_{DS}	0
VDS0	v_{DS} at which A0, A1, A2 and A3 were evaluated	0
TAU	Transit time under gate	0
IS	Gate junction saturation current (diode model)	1.0E-14
N	Gate-drain and gate-source emission coefficient (diode model)	1.0
CGD0	Zero-bias gate-drain junction capacitance (diode model)	0
CGS0	Zero-bias gate-source junction capacitance (diode model)	0
FC	Coefficient for forward bias used in capacitance equation (diode model)	0.5
GMIN	Linear conductance associated with the Schottky junctions	1.0E-12
VBI	Built-in gate potential	0.8
VBR	Gate junction reverse bias breakdown voltage or drain gate reverse bias breakdown voltage with v_{DS}=0	$+\infty$

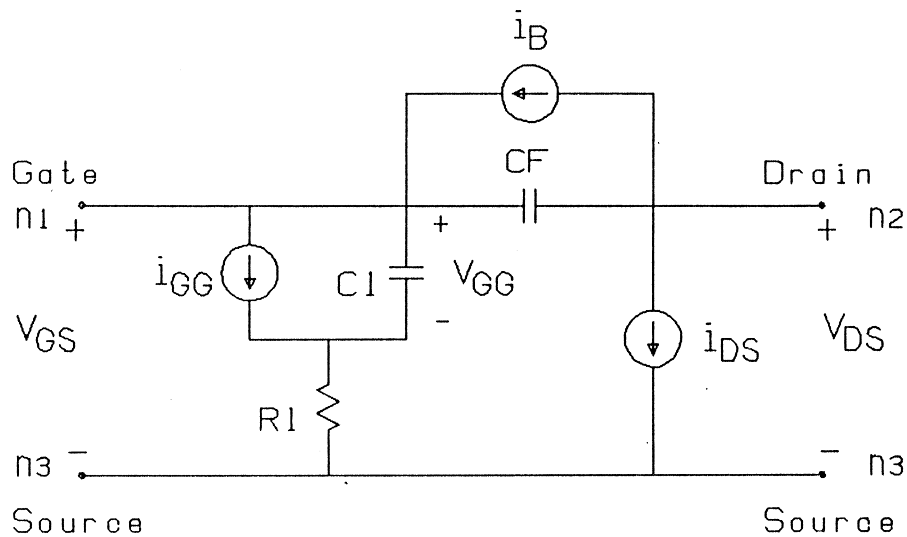
Form

```
FETC n1 n2 n3 [A0=x1] [A1=x2] [A2=x3] [A3=x4]
        [GAMMA=x5] [BETA=x6] [VDS0=x7] [TAU=x8]
        [IS=x9] [N=x10] [CGD0=x11] [CGS0=x12] [FC=x13]
        [GMIN=x14] [VBI=x15] [VBR=x16];
```

Example

```
FETC 2 4 3 A0=.065 A1=.115 A2=.059 GAMMA=2 VDS0=2 IS=3.7NA;
```

FETM Materka and Kacprzak FET model FETM



FETM — Materka and Kacprzak FET model — FETM

Keywords

Keywords		Defaults
IDSS	Drain saturation current for v_{GG}=0	6.0E-2
VP0	Pinch-off voltage for v_{DS}=0	-2.0
GAMMA	Voltage-slope parameter of pinch-off voltage	0
E	Constant part of the exponent defining the dependence of saturation drain current on gate voltage	2.0
KE	Parameter describing the dependence of the exponent on gate voltage	0
SL	Slope of the v_{GG}=0 drain characteristic in the linear region	6.0E-2
KG	Parameter defining the dependence on gate voltage of the drain characteristics slope in the linear region	0
TAU	Channel transit-time delay	0
SS	Slope of the v_{GG}=0 drain characteristic in the saturation region	0
IG0	Saturation current of gate Schottky barrier	0
ALPHAG	Slope factor of gate conduction current	38.696
IB0	Channel breakdown current for v_{DS}-v_{GS}=VBC	0
ALPHAB	Slope factor of breakdown current	0
VBC	Channel breakdown voltage	+∞
R10	Intrinsic channel resistance for zero gate voltage	3.5
KR	Voltage slope factor of intrinsic channel resistance	0
C10	Gate Schottky-barrier capacitance for v_{GG}=0	4.0E-4
K1	Voltage-slope parameter of gate capacitance	1.25
C1S	Parasitic additional constant component of the gate capacitance	0
CF0	Feedback capacitance for v_{DS}=v_{GS}	2.0E-5
KF	Voltage-slope parameter of feedback capacitance	0

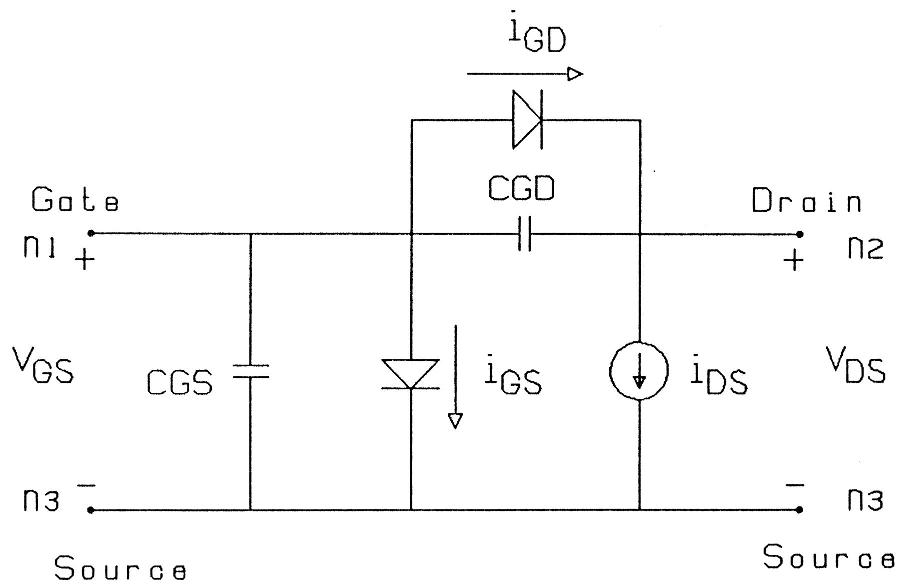
Form

```
FETM n1 n2 n3 [IDSS=x1] [VP0=x2] [GAMMA=x3] [E=x4] [KE=x5]
        [SL=x6] [KG=x7] [TAU=x8] [SS=x9] [IG0=x10] [ALPHAG=x11]
        [IB0=x12] [ALPHAB=x13] [VBC=x14] [R10=x15] [KR=x16]
        [C10=x17] [K1=x18] [C1S=x19] [CF0=x20] [KF=x21];
```

Example

```
FETM 2 4 3 IDSS=6.E-2 VP0=-1.9 SL=.0676 R10=3.5
           C10=.42PF K1=1.282 CF0=.02PF;
```

FETR Raytheon FET model FETR



FETR Raytheon FET model FETR

Keywords / Defaults

Keywords		Defaults
ALPHA	Hyperbolic tangent function parameter	0
BETA	Transconductance parameter	0
LAMBDA	Channel length modulation parameter	0
THETA	Transconductance parameter for large v_{GS}	0
VT0	Threshold voltage	-2.0
TAU	Transit time under gate	0
IS	Gate junction saturation current (diode model)	1.0E-14
N	Gate-drain and gate-source emission coefficient (diode model)	1.0
CGD0	Zero bias gate-drain junction capacitance (diode model)	0
CGS0	Zero bias gate-source junction capacitance (diode model)	0
FC	Coefficient for forward bias used in the capaciatance equation (diode model)	0.5
GMIN	Linear conductance associated with the Schottky junctions	1.0E-12
VBI	Built-in gate potential	0.8
VBR	Gate junction reverse bias breakdown voltage or drain gate reverse bias breakdown voltage with v_{DS}=0	+∞

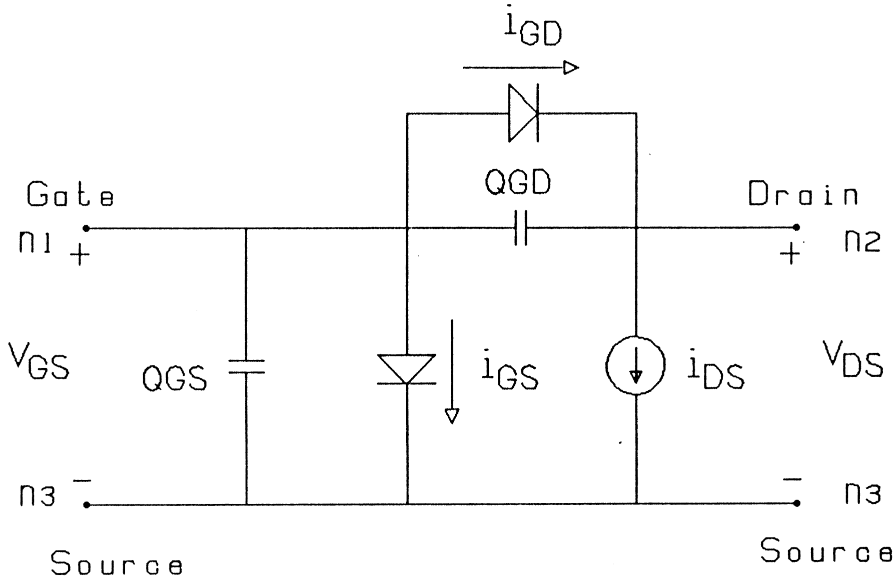
Form

```
FETR n1 n2 n3 [ALPHA=x1] [BETA=x2] [LAMBDA=x3]
              [THETA=x4] [VT0=x5] [TAU=x6] [IS=x7]
              [N=x8] [CGS0=x9] [CGD0=x10] [FC=x11]
              [GMIN=x12] [VBI=x13] [VBR=x14];
```

Example

```
FETR 2 4 3 BETA=0.02 VT0=-1.2 IS=3.7NA;
```

FETU1 **User-definable FET model 1** **FETU1**



FETU1 User-definable FET model 1 FETU1

Keywords / Defaults

Keyword	Description	Default
TAU	Transit time under gate	0
IGS	Gate-source current	0
IDS	Drain-source current	0
IGD	Gate-drain current	0
QGS	Gate-source capacitor charge	0
QGD	Gate-drain capacitor charge	0

Form

```
FETU1 [TAU=x1] [IGS=x2] [IDS=x3] [IGD=x4] [QGS=x5] [QGD=x6];
```

Example

```
FETU1 TAU=3PS IGS=Igs_user IDS=Ids_user IGD=Igd_user
      QGS=Qgs_user QGD=Qgd_user;
```

where Igs_user, Ids_user, Igd_user, Qgs_user and Qgd_user are labels which are user-defined in the EXPR block.

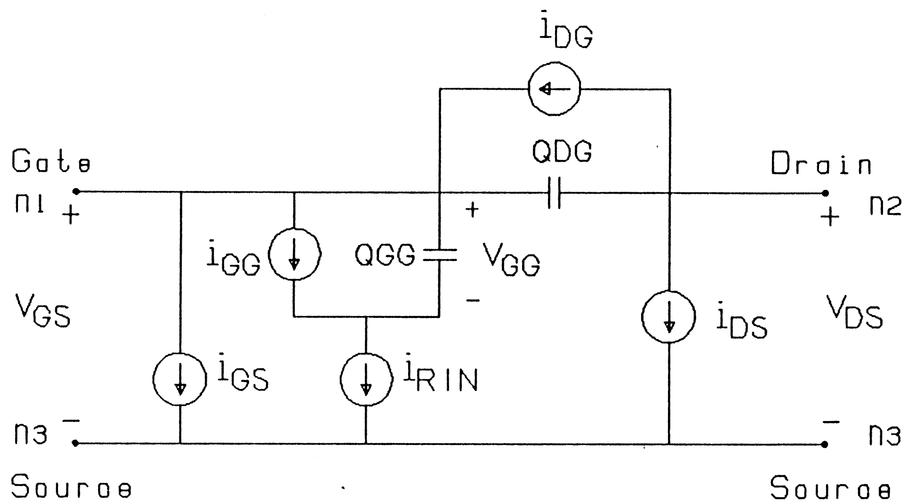
The Model

The internal variables available are fundamental frequency FFREQ, bias voltages VG, VD, instantaneous voltages VGS_T, VDS_T and delayed instantaneous voltage VGS_TAU.

IGS, IGD, QGS and QGD can be functions of FFREQ, VG, VD, VGS_T and VDS_T.

IDS can be a function of FFREQ, VG, VD, VGS_T, VDS_T and VGS_TAU.

FETU2 User-definable FET model 2 FETU2



FETU2 User-definable FET model 2 FETU2

Keywords / Defaults

Keyword	Description	Default
TAU	Transit time under gate	0
IGS	Gate-source current	0
IDS	Drain-source current	0
IDG	Drain-gate current	0
IGG	Gate current	0
IRIN	Component of source current	0
QGG	Gate capacitor charge	0
QDG	Drain-gate capacitor charge	0

Form

```
FETU1  [TAU=x1]  [IGS=x2]  [IDS=x3]  [IDG=x4]  [IGG=x5]
       [IRIN=x6]  [QGG=x7]  [QDG=x8];
```

Example

```
FETU1  TAU=3PS  IGS=Igs_user  IDS=Ids_user  IDG=Idg_user
       IGG=Igg_user  IRIN=Irin_user  QGG=Qgg_user  QDG=Qdg_user;
```

where Igs_user, Ids_user, Idg_user, Igg_user, Irin_user, Qgg_user and Qdg_user are labels which are user-defined in the EXPR block.

The Model

The internal variables available are fundamental frequency FFREQ, bias voltages VG, VD, instantaneous voltages VGS_T, VDS_T, VGG_T and delayed instantaneous voltage VGS_TAU.

IGS, IDG, IGG, IRIN, QGG and QDG can be functions of FFREQ, VG, VD, VGS_T, VDS_T and VGG_T.

IDS can be a function of FFREQ, VG, VD, VGS_T, VDS_T, VGG_T and VGS_TAU.