OptiSPICE

Model Library

Opto-Electronic Circuit Design Software

Version 5.2

Optiwave

OptiSPICE

Model Library

Opto-Electronic Circuit Design Software

Table of contents

Electrical Models Library

This section contains information on the following models

- Resistor Model
- Capacitor Model
- Inductor Model
- Lumped Transmission Line (U) Model
- Diode Model
- BJT Model
- MOSFET Model
- JFET Model
- MESFET Model
- Linear Network Element Model

Resistor Model

Syntax

```
.MODEL MODEL_NAME R <param1=val1> <param2=val2> ...
```

Parameters

Symbol and description	Default value	Units	Value range
R Resistance	0	ohm	[0, +INF[
C Parasitic capacitance connected from node 2 to ground	0	F	[0, +INF[
CRATIO Ratio of total parasitic capacitance allocated to input	0	-	[0, 1[
L The length of the resistor	1e-4	m	[0, +INF[
W The width of the resistor	1e-4	m	[0, +INF[
RAC AC resistance	0	ohm	[0, +INF[
RSH Sheet resistance	0	ohm/m^2	[0, +INF[
DW Width difference between the drawn width and actual width	0	m	]-INF, +INF[
DLR Length difference between the drawn length and actual length	1	m	]-INF, +INF[
SHRINK Shrink factor	1	-	[0, +INF[
COX Bottomwall capacitance of the resistor	3.453e-4	F/m^2	[0, +INF[

Symbol and description	Default value	Units	Value range
DI Relative dielectric constant	0	-	[0, +INF[
THICK Thickness of the dielectric	0	m	[0, +INF[
CAPSW Sidewall fringing capacitance	0	F	[0, +INF[
TC1 First order temperature coefficient	0	ohm/Deg, C	]-INF, +INF[
TC2 Second order temperature coefficient	0	ohm/Deg. C^2	]-INF, +INF[

Technical Background

Effective Resistance Calculation

If a wire resistance model is provided the effective resistance is calculated as follows. For non-zero values of *W*, *L*, and *RSH*, the effective resistance is expresses as

$$R_{eff} = \frac{L_{eff} \cdot RSH \cdot SCALE}{M \cdot W_{eff}} \quad (1)$$

where

- $L_{eff} = (L \cdot SHRINK - 2 \cdot DLR) \cdot SCALEM$
- $W_{eff} = (W \cdot SHRINK - 2 \cdot DW) \cdot SCALEM$

If any of *W*, *L*, and *RSH* are not given or defined with 0 value, then the effective resistance is expressed as

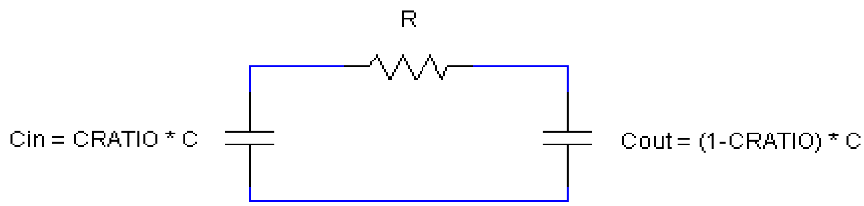
$$R_{eff} = \frac{R \cdot SCALE}{M} \quad (2)$$

For AC effective resistance calculation, *R* in the above equation is replaced by the element parameter *AC* or the model parameter *RAC* (in case of *AC* not given).

Parasitic Capacitance Calculation

In Wire RC model if parasitic capacitance *C* is given, input and output capacitance are determined by the *CRATIO* parameter as given by the following figure.

Figure 1 Input-output capacitance of Wire RC model



For non-zero values of *W*, and *L*, the effective parasitic capacitance is calculated as follows:

$$C_{eff} = M \cdot SCALE \cdot [L_{eff} \cdot W_{eff} \cdot COX + 2 \cdot (L_{eff} + W_{eff}) \cdot CAPSW] \quad (3)$$

If *COX* is not provided and *THICK* is non-zero, then for a non-zero *DI*, *COX* is calculated as

$$COX = \frac{DI \cdot \varepsilon_0}{THICK} \quad (4)$$

For zero *DI*, *COX* is calculated as

$$COX = \frac{DI \cdot \varepsilon_{0x}}{THICK} \quad (5)$$

where $\varepsilon_0 = 8.8542149e-12$ F/m and $\varepsilon_{0x} = 3.3453148e-11$ F/m.

In all other conditions (either of *W*, *L* or *THICK* is zero), the effective parasitic capacitance is calculated as

$$C_{eff} = C \cdot SCALE \cdot M \quad (6)$$

Resistor Temperature Equations

Resistance as a function of temperature can be expressed as:

$$R(T) = R(T_{nom}) \cdot (1 + TC1 \cdot DTEMP + TC2 \cdot DTEMP^2) \quad (7)$$

where T_{nom} : is the nominal temperature in Kelvin.

Notes:

Capacitor Model

Syntax

```
.MODEL MODEL_NAME C <param1=val1> <param2=val2> ...
```

Parameters

Symbol and description	Default value	Units	Value range
CAP Capacitance	0	F	[0, +INF[
L Length of the capacitor	0	m	[0, +INF[
W Width of the capacitor	0	m	[0, +INF[
CAPSW Sidewall fringing capacitance	0	F/m	[0, +INF[
COX Bottomwall capacitance	0	F/m^2	[0, +INF[
DI Relative dielectric constant	0	-	[0, +INF[
DEL Difference between the drawn width and the actual width or length	0	m	[0, +INF[
THICK Insulator thickness	0	m	[0, +INF[
SHRINK Shrink factor	1	-	[0, +INF[
TC1 First order temperature coefficient	0	1/degree C	]-INF, +INF[
TC2 Second order temperature coefficient	0	1/degree C^2	]-INF, +INF[

Technical Background

Capacitor equations include the calculation of effective capacitance and capacitance as a function of temperature.

If element capacitance is provided, the effective capacitance is calculated as follows:

$$C_{eff} = C \cdot SCALE(element) \cdot M \tag{1}$$

Otherwise, effective capacitance is calculated from effective width (*Weff*) and length (*Leff*), and *COX* values as follows:

$$C_{eff} = M \cdot SCALE(element) \cdot [L_{eff} \cdot W_{eff} \cdot COX + 2 \cdot (L_{eff} + W_{eff}) \cdot CAPSW] \tag{2}$$

where

$$W_{eff} = W_{scaled} - 2 \cdot DEL \tag{3}$$

$$L_{eff} = L_{scaled} - 2 \cdot DEL \tag{4}$$

W_{scaled} and L_{scaled} are the scaled width and length. If width and length are provided in Element, they are scaled by *.OPTION SCALE*. If not provided by element but provided in Model, then they are scaled by *.OPTION SCALM*.

If *COX* is not provided and *THICK* is not zero and *DI* not zero, then:

$$COX = \frac{DI \cdot \varepsilon 0}{THICK} \tag{5}$$

if *DI* is zero then:

$$COX = \frac{\varepsilon 0x}{THICK} \tag{6}$$

where $\varepsilon 0 = 8.8542149e-12$ F/m and $\varepsilon 0x = 3.3453148e-11$ F/m.

If only model capacitance (*CAP*) is provided, then:

$$C_{eff} = CAP \cdot SCALE(element) \cdot M \tag{7}$$

Capacitance as a function of temperature can be expressed as:

$$C(T) = C(T_{nom}) \cdot (1 + TC1 \cdot DTEMP + TC2 \cdot DTEMP^2) \quad (8)$$

where T_{nom} : is the nominal temperature in Kelvin.

Inductor Model

Syntax

```
.MODEL MODEL_NAME IntInd <param1=val1> <param2=val2> ...
```

Parameters

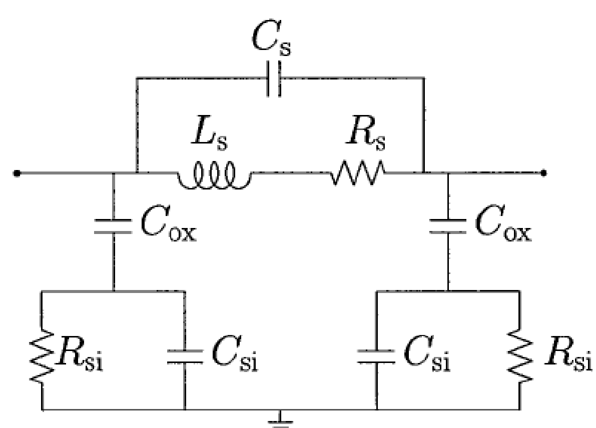
Symbol and description	Default value	Units	Value range
Silicon Type of substrate	1		1 - Silicon; 0 - III-V
f Operating frequency	1e9	Hz	[0, +INF[
rho Metal resistivity	2.651e-8	1/ohm	[0, +INF[
w Line width	29.7e-6	m	[0, +INF[
s Spacing	1.9e-6	m	[0, +INF[
dout Outer diameter	344e-6	m	[0, +INF[
tox Oxide thickness	4e-6	m	[0, +INF[
tmet Metal thickness	5e-6	m	[0, +INF[
n Number of turns	3.75	-	[0, +INF[
eox Oxide permittivity	1	-	[0, +INF[
mur Relative permeability	1	-	[0, +INF[
Csub Substrate cap/unit area	1.6e-3*1e-15/1e-12	uF/m^2	[0, +INF[

Symbol and description	Default value	Units	Value range
Gsub Substrate cond/unit area	14e-8/1e-12	xx/m^2	[0, +INF[
Type Type of spiral inductor	1	-	1 - Square, 2 - Hexogonal, 3 - Octogonal, 4- Circle
method Calculation method	1	-	1 - Modified Wheeler, 2 - Current Sheet, 3 - Fitted Monomial

Technical Background

The Inductor Model utilizes a lumped circuit approach (see Figure 1) to charactize the electrical charateristics of a spiral inductor [1]. Mathematial methods for calculating the inductance (L_s) of square, hexagonal, octagonal, and circular planar inductors are also included. These methods include the *Modified Wheeler, Current Sheet* and *Monomial* expressions [1].

Figure 1 Lumped circuit model for spiral inductor (obtained from Ref 1)



The physical model for the INDUCTOR model also includes the following calculations [2]:

Eddy current:

$$R_s = \frac{rho \cdot l}{w \cdot \delta \cdot (1 - e^{-(t/\delta)})}$$

$$\delta = \sqrt{\frac{2 \cdot rho}{2 \cdot \pi \cdot f \cdot \mu_r \cdot \mu_o}} \tag{1}$$

Feed-through capacitance:

$$C_s = n \cdot w^2 \cdot \frac{eox}{tox} \tag{2}$$

Oxide capacitance

$$C_{ox} = \frac{1}{2} \cdot l \cdot w \cdot \frac{eox}{tox} \tag{3}$$

Si substrate capacitance

$$C_{si} = \frac{1}{2} \cdot l \cdot w \cdot C_{sub} \tag{4}$$

Si substrate ohmic loss

$$R_{si} = \frac{2}{l \cdot w \cdot G_{sub}} \tag{5}$$

where *l* is the length of the Inductor coil (a calculated value)

Example

An Inductor L1 with model name “SiInductorModel” and a line-width of 29.7e-6, is defined as follows:

```
L1  1 0 SiInductorModel
.model SiInductorModel IntInd w = 29.7e-6
```

References

[1] S.S. Mohan, M.M Hershenson, S.P. Boyd, and T.H. Lee, *Simple Accurate Expressions for Planar Spiral Inductances,* IEEE Journal of Solid-State Circuits, Vol. 34, No. 10, October 1999

[2] C. Yue, “On-Chip Spiral Inductors forSilicon-Based Radio-Frequency Integrated CircuitsQuarles”, Center for Integrated Systems, Stanford University, CA *(http://www-smirc.stanford.edu/papers/Orals98s-cpyue.pdf, Accessed: 6 Aug 2014)*

Notes:

Lumped Transmission Line (U) Model

Lumped transmission line (U) model allows user to specify per unit length RLGC parameters for a lossy multi-conductor transmission line. It can support up to five conductor transmission lines.

Syntax

```
.MODEL MODEL_NAME U <param1=val1> <param2=val2> ...
```

Parameters

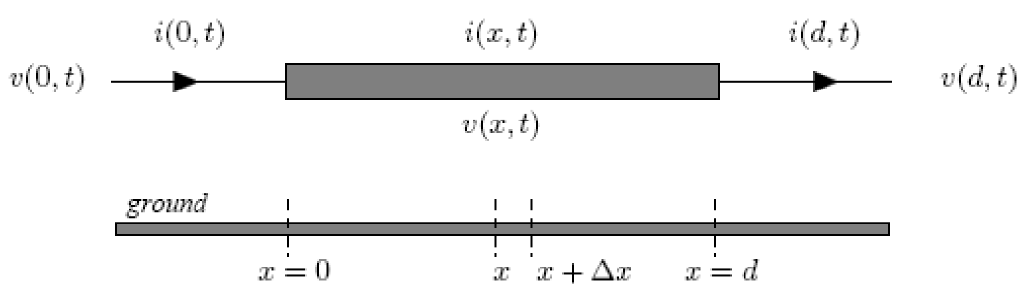
Symbol and description	Default value	Units	Value range
NL Number of conductors	1	-	[0, +INF[
RRR Reference plane resistance per meter	0	ohm/m	[0, +INF[
R*ii* (R11, R22, R33, ..., R55) Resistance of the i-th line per meter	0	ohm/m	[0, +INF[
L*ii* (L11, L22, L33, ..., L55) Self inductance of the i-th line per meter	0	H/m	[0, +INF[
L*ij* (L12, L13, .., L23, ..., L54) Mutual inductance between i-th and j-th line per meter	0	H/m	[0, +INF[
CR*i* (CR1, CR2, CR3, ..., CR5) Capacitance from i-th line to reference plane per meter	0	F/m	[0, +INF[
C*ij* (C12, C13, .., C23, ..., C54) Capacitance from i-th line to j-th line per meter	0	F/m	[0, +INF[
GR*i* (GR1, GR2, GR3, ..., GR5) Conductance from i-th line to reference plane per meter	0	S/m	[0, +INF[
G*ij* (G12, G13, .., G23, ..., G54) Conductance from i-th line to j-th line per meter	0	S/m	[0, +INF[
PNJMode Junction model to be used	SS_Jct		[SS_Jct, Full_Jct]

Symbol and description	Default value	Units	Value range
CJ Junction capacitance	0	F/m	[0, +INF[
RJ Junction resistance	0	ohm/m	[0, +INF[
RS Series resistance	0	ohm/m	[0, +INF[
JunctionModel Defines name of diode model when *PNJMode = Full_Jct*	*[Junction model name]*		

Technical Background

Transmission lines exhibit resistive, inductive, and capacitive effects at higher frequencies. Consider the transmission line system shown in Figure 1.

Figure 1 Transmission Line



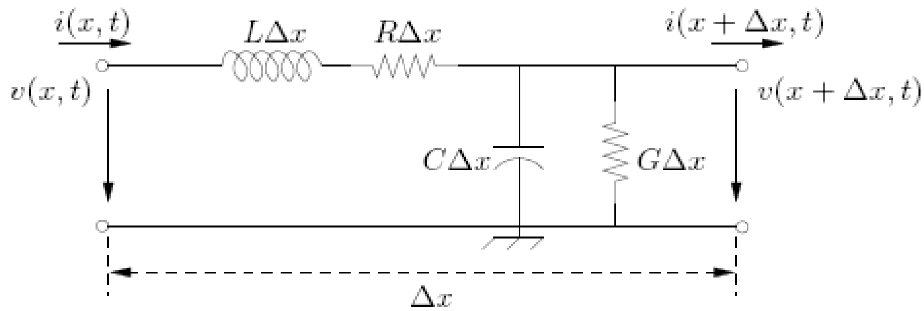
Telegrapher's equation describes the voltage and current of the transmission line as a function of distance and time.

$$\frac{\partial}{\partial x}v(x, t) = -R \cdot i(x, t) - L \cdot \frac{\partial}{\partial t}i(x, t) \tag{1}$$

$$\frac{\partial}{\partial x}i(x, t) = -G \cdot v(x, t) - C \cdot \frac{\partial}{\partial t}v(x, t) \tag{2}$$

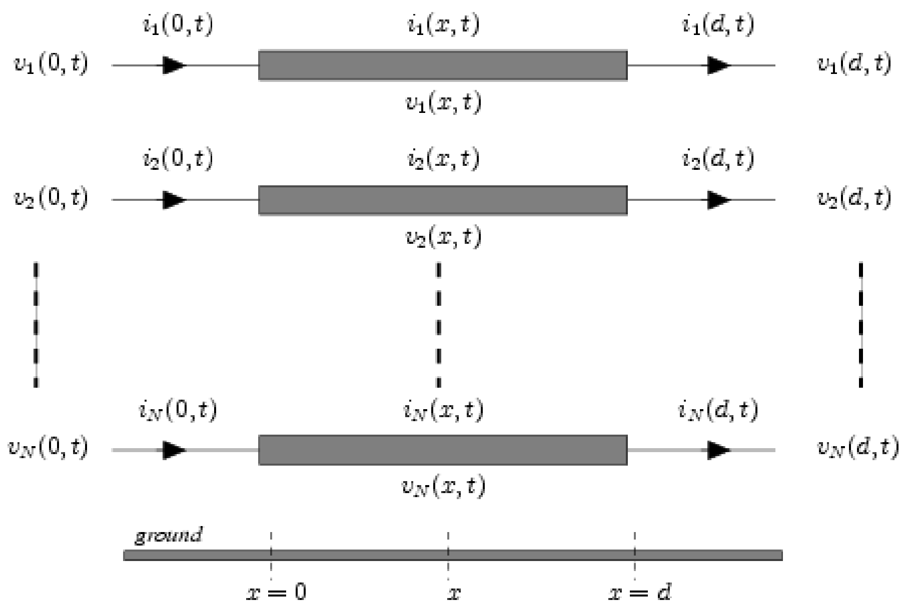
Telegrapher's equations can be approximated by dividing transmission lines into small segments and representing each segment using equivalent circuits so that they can be modeled by circuit simulators. An infinitesimal section of the transmission line with length Δx in Figure 1 can be represented using equivalent circuits as illustrated by the following Figure 2.

Figure 2 An infinitesimal section of the transmission line



In case of multi-conductor transmission line system (see Figure 3), mutual inductance, mutual capacitance, conductance are formed between adjacent lines.

Figure 3 Multi-conductor transmission line



The per-unit-length (p.u.l) parameters ($\boldsymbol{R}$, $\boldsymbol{L}$, $\boldsymbol{G}$, $\boldsymbol{C}$) become matrices and voltage-current variables become vectors represented by $\boldsymbol{v}$ and $\boldsymbol{i}$, respectively. The Telegrapher's equations for multi-conductor transmission line can be written as

$$\frac{\partial}{\partial x}\boldsymbol{v}(x,t) = -\boldsymbol{R}\cdot\boldsymbol{i}(x,t) - \boldsymbol{L}\cdot\frac{\partial}{\partial t}\boldsymbol{i}(x,t) \tag{3}$$

$$\frac{\partial}{\partial x}\boldsymbol{i}(x, t) = -\boldsymbol{G} \cdot \boldsymbol{v}(x, t) - \boldsymbol{C} \cdot \frac{\partial}{\partial t}\boldsymbol{v}(x, t) \tag{4}$$

The resistance p.u.l matrix can be defined as follows

$$\boldsymbol{R} = \begin{bmatrix} (r_0 + r_{11}) & r_0 & \dots & r_0 \\ r_0 & (r_0 + r_{22}) & \dots & r_0 \\ \dots & \dots & (r_0 + r_{kk}) & \dots \\ r_0 & r_0 & \dots & (r_0 + r_{NN}) \end{bmatrix} \tag{5}$$

where r_0 is reference plane resistance per unit length given by the parameter *RRR* and r_{11}, r_{22}, $\dots$, r_{NN} are resistance of each individual line per unit length given by the parameters *R11*, *R22*, ..., *R55*.

The inductance p.u.l matrix can be defined as follows

$$\boldsymbol{L} = \begin{bmatrix} l_{11} & l_{12} & \dots & l_{1N} \\ l_{21} & l_{22} & \dots & l_{2N} \\ \dots & \dots & l_{kk} & \dots \\ l_{N1} & l_{N2} & \dots & l_{NN} \end{bmatrix} \tag{6}$$

where the diagonal entries (l_{ii}) represents self inductance of k -th conductor per unit length, while the off-diagonal entries (l_{ij} , $i \neq j$) represents mutual inductance between conductor i and j per unit length. It has to be noted that $l_{ij} = l_{ji}$. The self inductance values are given by the model parameters *L11, L22, ..., L55* and mutual inductance values are given by *L12, L13, ..., L23, ... L54*.

The conductance p.u.l matrix can be defined as follows

$$\boldsymbol{G} = \begin{vmatrix} \sum_{i=1}^{N} g_{1i} & -g_{12} & \cdots & -g_{1N} \\ -g_{21} & \sum_{i=1}^{N} g_{2i} & \cdots & -g_{2N} \\ \cdots & \cdots & \sum_{i=1}^{N} g_{ki} & \cdots \\ -g_{N1} & -g_{N2} & \cdots & \sum_{i=1}^{N} g_{Ni} \end{vmatrix} \tag{7}$$

where g_{ii}, $i \in 1, 2, \ldots, N$, represents the conductance from i-th line to the reference plane per unit length, which are given by the parameters *GR1, GR2, ..., GR5*. The g_{ij}, $i \neq j$, entries represent the conductance between conductor i and j per unit length, which are given by the parameters *G12, G13, ..., G23, ..., G54*. It has to be noted that $g_{ij} = g_{ji}$.

The capacitance p.u.l matrix can be defined as follows

$$\boldsymbol{C} = \begin{vmatrix} \sum_{i=1}^{N} c_{1i} & -c_{12} & \cdots & -c_{1N} \\ -c_{21} & \sum_{i=1}^{N} c_{2i} & \cdots & -c_{2N} \\ \cdots & \cdots & \sum_{i=1}^{N} c_{ki} & \cdots \\ -c_{N1} & -c_{N2} & \cdots & \sum_{i=1}^{N} c_{Ni} \end{vmatrix} \tag{8}$$

where c_{ii}, $i \in 1, 2, \ldots, N$, represents the capacitance from i-th line to the reference plane per unit length, which are given by the parameters *CR1, CR2, ..., CR5*. The c_{ij}, $i \neq j$, entries represent the capacitance between conductor i and j per unit length, which are given by the parameters *C12, C13, ..., C23, ..., C54*. It has to be noted that $c_{ij} = c_{ji}$.

Junction model [2]

The junction model parameters can be used (*PNJMode*, *RS*, *CJ*, *RJ*) in addition to the regular RLCG transmission line parameters, to characterize traveling wave modulators (used in conjunction with electro-optic modulators). Either the small signal junction model (*PNJMode* = *SS_Jct*; Figure 4) or a full junction model (*PNJMode* = *Full_Jct*; Figure 5) can be defined. For the case of the full junction model a diode model must be defined using the model parameter *JunctionModel* = *"Diode Model Name".*

Figure 4 One section of the transmission line with a small signal junction model

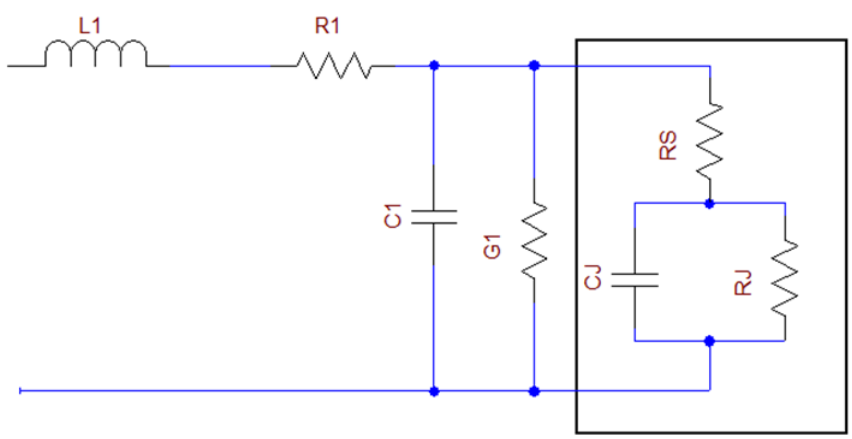
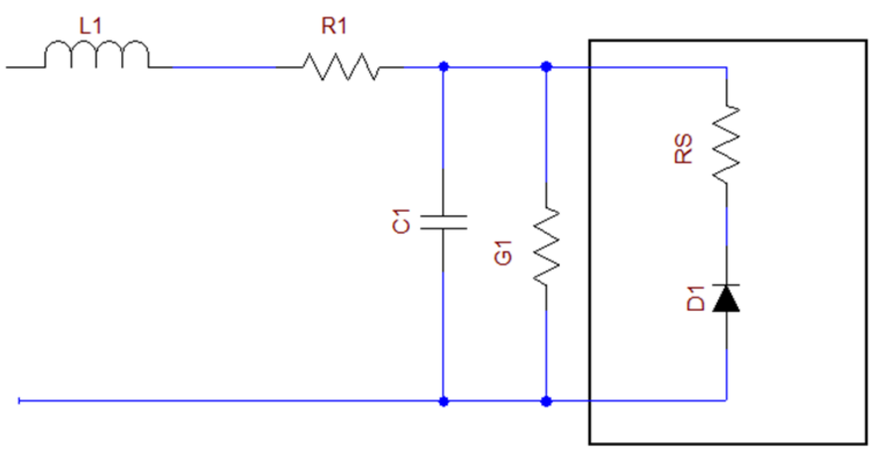
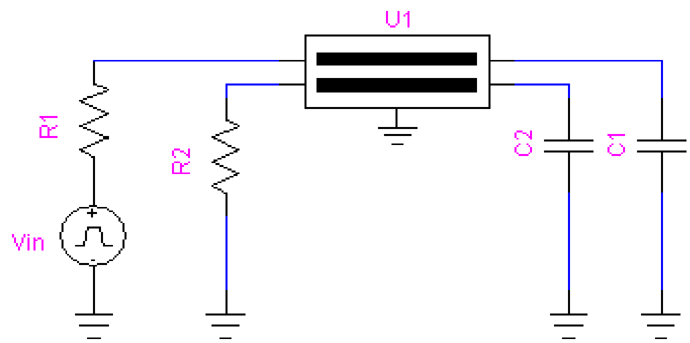


Figure 5 One section of the transmission line with full junction model



Example

Figure 6 Lossy two conductor transmission line example



The following example shows a netlist for the above circuit where a two conductor lossy transmission line is driven by a voltage pulse. The transmission line is descretized with 50 lumped segments.

```
* Two conductor lossy transmission line example
Vin in 0 PULSE (0 1 0 0.1N 0.1N 1N 2N)
R1 in 1 50
R2 2  0 30
C1 3  0 1.5e-12
C2 4  0 1.5e-12

* Transmission line element statement
* length = 10 cm and number of lumped segments = 50
U1 1 2 0 3 4 0 two_rlc l=0.1 LUMPS=50

* Transmission line model statement
.MODEL two_rlc U NL=2
+ Rrr=9.259259e-002 R11=9.351852e+000 R22=9.351852e+000
+ L11=8.461150e-007 L12=0 L22=8.461150e-007
+ Cr1=6.038600e-011 Cr2=6.038600e-011 C12=7.904400e-012

.TRAN 0.01N 20N
.MONITOR V 4
.END
```

References

[1] C.R. Paul, *Analysis of Multiconductor Transmission Lines*, 2nd ed, New York, NY: John Wiley & Sons Inc., 2008.

[2] K. Zhu, V. Saxena, W. Kuang, *Compact Verilog-A Modeling of Silicon Traveling-Wave Modulator for Hybrid CMOS Photonic Circuit Design*, IEEE 57th MWSCAS, 2014

Diode Model

Syntax

```
.MODEL MODEL_NAME D <param1=val1> <param2=val2> ...
```

Parameters

Symbol and description	Default value	Units	Value range
PJ Periphery of junction/junction outline	0	-	[0, +INF[
AREA Junction area	1	-	[0, +INF[
TLEV Temperature equation level selector	0	-	0,1,2
EG Energy gap	0	eV	[0, +INF[
LEVEL Diode model level selector	1	-	[0, +INF[
IK (IKF ,JBF) Forward-knee current	0	A	[0, +INF[
IKR (JBR) Reverse-knee current	0	A	[0, +INF[
RS Ohmic series resistance	0	Ohm	[0, +INF[
TRS Temperature coefficient of resistance	0.0	-	[0, +INF[
IBV (IB) Current at Breakdown voltage	1.0e-3	A	[0, +INF[
JSW (ISP) Sidewall saturation current	0	A	[0, +INF[
BV Reverse breakdown voltage	0	V	[0, +INF[

Symbol and description	Default value	Units	Value range
NBV Reverse breakdown voltage correction factor	1.0	V	]-INF, +INF[
CJP Zero-biased junction capacitance	0	F	[0, +INF[
TT Transit time	0	sec	[0, +INF[
FC Coefficient for forward-bias depletion capacitance	0.5	-	]-INF, +INF[
FCS Coefficient for forward-bias depletion periphery capacitance	0.5	-	]-INF, +INF[
NTUN Tunneling emission coefficient	90	-	]-INF, +INF[
JTUN Tunneling saturation current density	0	A/m^2	]-INF, +INF[
JTUNSW Sidewall tunneling saturation current	0	A/m	]-INF, +INF[
MJSW Periphery junction grading coefficient	0.33	-	]-INF, +INF[
PHP Periphery junction contact potential	0.8	V	]-INF, +INF[
KF Flicker noise coefficient	0	-	[0, +INF[
AF Flicker noise exponent	1.0	-	[0, +INF[
TTT1 First order temperature coefficient for TT	0	1/Deg. C	]-INF, +INF[
TTT2 Second order temperature coefficient for TT	0	1/(Deg. C)^2	]-INF, +INF[
TM1 First-order temperature coefficient for grading coefficient	0	1/Deg. C	]-INF, +INF[

Symbol and description	Default value	Units	Value range
TM2 Second-order temperature coefficient for grading coefficient	0	1/(Deg. C)^2	]-INF, +INF[
XTI Saturation-current temperature exponent	3.0	-	]-INF, +INF[
XTITUN Tunneling current temperature exponent	3.0	-	]-INF, +INF[
TCV Temperature coefficient for breakdown voltage	0	-	]-INF, +INF[
GAP1 First band gap (activation energy) correction factor	7.02e-4	eV/Deg. C	]-INF, +INF[
IS (JS) Saturation Current	1e-14	A or A/m2	[0, +INF[
CJO (CJ0) Zero-bias junction capacitance	0	F/m2	[0, +INF[
MJ (M ,EXA) Grading coefficient	0.5	-	]-INF, +INF[
PB (PHI ,VJ ,PHA) Junction area contract potential	0.8	-	[0, +INF[
DCAP Capacitor equation selector/assigner	2	-	1,2
N Emission coefficient	1	-	]-INF, +INF[
L Diode length	0	m	[0, +INF[
SHRINK Shrink factor	1.0	-	[0, +INF[
W Diode width	0	m	[0, +INF[
EF Forward critical electric field	1e8	V/cm	]-INF, +INF[

Symbol and description	Default value	Units	Value range
ER Reverse critical electric field	1e8	V/cm	]-INF, +INF[
JF Fowler-Nordheim forward current coefficient	1e-10	A/V^2	]-INF, +INF[
JR Fowler-Nordheim reverse current coefficient	1e-10	A/V^2	]-INF, +INF[
TOX Oxide thickness	100	m	[0, +INF[

Technical Background

There are three type of diode models are supported by OptiSPICE.

Three type of diode models are available to be selected by the *LEVEL* parameter.

- Junction model - *LEVEL = 1*
- Fowler-Nordheim diode model - *LEVEL* = *2*
- Geometric junction model - *LEVEL* = *3*

Junction model

The junction model represents the p-n semiconductor junction. The DC characteristics of the diode are determined by the parameters *IS, JSW,* and *N* in a forward bias operation. Reverse bias current is modeled by *IS*, *JSW*, *JTUN*, and *NTUN* and reverse bias breakdown current is modeled by *IS*, *JSW*, *BV*, *IBV*, *N*, *NTUN*, and *JTUN*. Parameters *IK* and *IKR* are used to model high-level injection.

Diffusion capacitance which is caused by injected minority carriers is modeled by the parameter *TT*. Depletion capacitance is modeled by parameters *CJO*, *PB*, *MJ*, *MJSW*, *PHP*, *FC*, and *FCS*. The parameter *DCAP* is used to select type of equation for depletion capacitance: if *DCAP* = 1, junction bottom area capacitance and junction periphery capacitance are calculated separately; if *DCAP* = 2, only total depletion capacitance is calculated. If *DCAP* is not given in the model statement, the *DCAP* value defined by *.OPTION* statement will be used.

Temperature has effects on energy gap, leakage current, breakdown voltage, contact potential, junction capacitance, and grading. The parameters *TLEV*, *EG*, *GAP1*, *XTI*, *XTITUN*, *TTT1*, *TTT2*, *TM1*, *TM2*, *TCV*, and *TRS* are used to model the temperature effects.

If noise simulation is performed, the flicker noise is modeled by the parameters *KF* and *AF*, while the thermal noise due to the series resistance *RS* also included.

Fowler-Nordheim diode

Fowler-Nordheim diodes have metal-insulator-semiconductor or semiconductor-insulator-semiconductor layers. Tunneling current flowing through the thin insulator is modeled by Fowler-Nordheim equations. Current through the diode when forward biased is defined as follows:

$$i_d = AREA \cdot JF \cdot \left(\frac{v_d}{TOX}\right)^2 \cdot e^{(-EF \cdot TOX)/TD} \tag{1}$$

where v_d is the voltage across the diode. The reverse bias current is defined as

$$i_d = -AREA \cdot JR \cdot \left(\frac{v_d}{TOX}\right)^2 \cdot e^{(ER \cdot TOX)/TD} \tag{2}$$

Capacitance C is defined as

$$C = AREA \cdot \frac{EOX}{TOX} \tag{3}$$

Geometric junction model

In geometric junction model is same as p-n junction model (*LEVEL =1*) except its geometric properties are scalable using scaling parameters *SCALM* and *SHRINK*. Effective area and junction periphery can be scaled as follows:

$$\begin{aligned} AREA_{eff} &= (AREA \cdot SCALM^2)/SHRINK^2 \\ PJ_{eff} &= (PJ \cdot SCALM)/SHRINK \end{aligned} \tag{4}$$

References

[1] Antognetti, P., and G. Massobrio. *Semiconductor Device Modeling with SPICE*, New York, NY: McGraw-Hill., 1988.

[2] Quarles, Thomas L., *Spice3 Version 3C1 Users Guide*, Memorandum No. UCB/ERL M89/42, University of California, Berkeley, Apr. 1989.

Notes:

BJT Model

Syntax

NPN: `.MODEL MODEL_NAME NPN <param1=val1> <param2=val2> ...`

PNP: `.MODEL MODEL_NAME PNP <param1=val1> <param2=val2> ...`

Parameters

Symbol and description	Default value	Units	Value range
AREA Area scaling factor	1	m^2	[0, +INF[
BF (BFM) Ideal maximum forward beta	100	-	[0, +INF[
BR (BRM) Ideal maximum reverse beta	1	-	[0, +INF[
CBCP External base-collector parasitic capacitance	0	F	[0, +INF[
CBEP External base-emitter parasitic capacitance	0	F	[0, +INF[
CCSP External collector-substrate parasitic capacitance	0	F	[0, +INF[
IBC DC base-collector current	0	A	]-INF, +INF[
IBE DC base-emitter current	0	A	]-INF, +INF[
ISC B-C leakage saturation current	0	A	]-INF, +INF[
ISE B-E leakage saturation current	0	A	]-INF, +INF[
ISS Base-substrate saturation current	0	A	]-INF, +INF[

Symbol and description	Default value	Units	Value range
IS (JS) Transport saturation current	1e-16	A	]-INF, +INF[
NF Forward current emission coefficient	1.0	-	]-INF, +INF[
NR Reverse current emission coefficient	1.0	-	]-INF, +INF[
NE (NLE) B-E leakage current emission coefficient	1.5	-	]-INF, +INF[
NC (NLC) B-C leakage current emission coefficient	2	-	]-INF, +INF[
NS Substrate current emission coefficient	1.0	-	]-INF, +INF[
VAF (VA ,VBF) Forward early voltage	0	V	]-INF, +INF[
VAR (VB ,VRB ,BV) Reverse early voltage	0	V	]-INF, +INF[
IK (IKF ,JBF) Corner for forward beta high current roll-off	0	A	]-INF, +INF[
IKR (JBR) Corner for the reverse beta high current roll-off	0	A	]-INF, +INF[
SUBS Defines geometry of the transistor with respect to substrate: 1 - vertically oriented collector, base, and emitter; -1 - laterally (horizontally) oriented collector, base, and emitter	1	-	]-INF, +INF[
RB Zero bias base resistance	0	ohm	[0, +INF[
RBM Minimum base resistance at high currents	0	A	]-INF, +INF[
RE Emitter resistance	0	ohm	[0, +INF[
RC Collector resistance	0	ohm	[0, +INF[

Symbol and description	Default value	Units	Value range
IRB (JRB ,IOB) Current where base resistance falls halfway to its min value	0	A	]-INF, +INF[
XCJC (CDIS) Fraction of B-C depletion capacitance connected to internal base node	1.0	-	]-INF, +INF[
TF Ideal forward transit time	0	sec	[0, +INF[
ITF (JTF) High-current parameter for effect on TF	0	A	]-INF, +INF[
VTF Coefficient of dependency of TF on Vbc	0	V	]-INF, +INF[
XTF Coefficient for bias dependence of TF	0	-	]-INF, +INF[
TR Ideal reverse transit time	0	sec	[0, +INF[
XTB Forward and reverse beta temperature exponent	0	-	]-INF, +INF[
BV Reverse breakdown voltage	0	V	]-INF, +INF[
NBV Reverse breakdown correction factor	1.0	V	]-INF, +INF[
FC Coefficient for forward-bias depletion capacitance formula	0.5	-	[0, +INF[
FCS Coefficient for forward-bias depletion capacitance formula (periphery)	0.5	-	[0, +INF[
NTUN Tunneling emission coefficient	90	-	]-INF, +INF[
JTUN Tunneling saturation current	0	A	]-INF, +INF[
JTUNSW Sidewall tunneling saturation current	0	A	]-INF, +INF[

Symbol and description	Default value	Units	Value range
MJSW Grading coefficient (in terms of periphery)	0.33	-	]-INF, +INF[
PHP Periphery Junction contact potential	0.8	V	]-INF, +INF[
KF Flicker noise coefficient	0	-	]-INF, +INF[
AF Flicker noise exponent	1.0	-	]-INF, +INF[
TLEV Temperature equations selector	0	-	0, 1, 2
EG Energy gap for temperature effect on IS	0	eV	]-INF, +INF[
TTT1 First order temperature coefficient for transit time	0	-	]-INF, +INF[
TTT2 Second order temperature coefficient for transit time	0	-	]-INF, +INF[
TM1 Grading coefficient first-order temperature coefficient	0	-	]-INF, +INF[
TM2 Grading coefficient second-order temperature coefficient	0	-	]-INF, +INF[
XTI Temperature exponent for effect on transport saturation current (IS)	3.0	-	]-INF, +INF[
XTITUN The tunneling current temperature exponent	3.0	-	]-INF, +INF[
TCV Temperature coefficient of breakdown voltage	0	-	]-INF, +INF[
GAP1 First bandgap correction	7.02e-4	-	]-INF, +INF[
DCAP BJT capacitor equation selector	2	-	1, 2

Symbol and description	Default value	Units	Value range
CJE B-E zero-bias depletion capacitance	0	F	[0, +INF[
MJE (ME) B-E junction exponential factor	0.33	F	]-INF, +INF[
VJE (PE) B-E built-in potential	0.75	V	]-INF, +INF[
CJC B-C zero-bias depletion capacitance	0	F	[0, +INF[
MJC (MC) B-C junction exponential factor	0.33	-	]-INF, +INF[
VJC (PC) B-C built-in potential	0.75	V	]-INF, +INF[
CJS (CCS ,CSUB) Zero-bias collector-substrate capacitance	0	F	[0, +INF[
MJS (ESUB) Substrate junction exponential factor	0.500	-	]-INF, +INF[
VJS (PSUB) substrate junction built-in potential	0.75	V	]-INF, +INF[
IBV (IB) Current at breakdown voltage	1.0e-3	A	]-INF, +INF[

Technical Background

The BJT Model is used to represent bipolar junction transistors. OptiSPICE supports the following SPICE model versions for BJTs:

- Integral charge control model of Gummel and Poon [1, 2].
- Mextram 504 [3]
- Agilent HBT model [4]

In addition to the SPICE model, if substrate is provided, it supports vertical and lateral geometrical structure of the transistor device (with respect to the substrate) using the *SUBS* parameter. For a vertical orientation of collector, base, and emitter, *SUBS* is set to 1; for a lateral orientation *SUBS* is set to -1. Some of the diode model parameters are used to characterize the base-emitter and base-collector junctions.

Gummel and Poon model

To use the Gummel and Poon model in a BJT simulation (with model name “gp”), please use the following (for NPN and PNP BJT configurations):

```
.model gp <param1=val1> <param2=val2> ...
.model gp <param1=val1> <param2=val2> ...
```

Mextram model

To use the Mextram 504 model in a BJT simulation (with model name “mextram”), please use the following (for NPN and PNP BJT configurations):

```
.model mextram NPN level = 504 <param1=val1> <param2=val2> ...
.model mextram PNP level = 504 <param1=val1> <param2=val2> ...
```

Agilent model

To use the Agilent HBT model in a BJT simulation (with model name “agilent”), please use the following (for NPN and PNP BJT configurations):

```
.model agilent NPN level = 101 <param1=val1> <param2=val2> ...
.model agilent PNP level = 101 <param1=val1> <param2=val2> ...
```

References

[1] Quarles, Thomas L., Spice3 Version 3C1 Users Guide, Memorandum No. UCB/ERL M89/42, University of California, Berkeley, Apr. 1989

[2] H. K. Gummel and H. C. Poon, "An integral charge control model of bipolar transistors", Bell Syst. Tech. J., vol. 49, pp. 827–852, May–June 1970.

[3] http://www.nxp.com/models/simkit/bipolar-models/mextram.html

[4] http://cp.literature.agilent.com/litweb/pdf/ads2008/ccnld/ads2008/AgilentHBT_Model_%28Agilent_Heterojunction_Bipolar_Transistor_Model%29.html

MOSFET Model

MOSFET level 1, 2, BSIM3 (levels 8, 49, or 53), BSIM3SOI (level 70) and BSIM4 (levels 14 or 54) are supported by OptiSPICE. Level 1 and 2 parameters are listed here. For the BSIM model parameters refer to the URLs provided in Technical Background.

Syntax

n-channel: `.MODEL MODEL_NAME NMOS <param1=val1> <param2=val2> ...`

p-channel: `.MODEL MODEL_NAME PMOS <param1=val1> <param2=val2> ...`

Parameters

Symbol and description	Default value	Units	Value range
LEVEL Model index	1	-	1, 2
COX Oxide capacitance	3.453e-4	F/m	[0, +INF[
TOX Oxide thickness	1e-7	m	[0, +INF[
DELVTO Voltage threshold shift at zero bias	0	V	]-INF, +INF[
DELTA Width effect on threshold voltage	0	-	]-INF, +INF[
UCRIT Critical field for mobility degradation	10e3	V/cm	]-INF, +INF[
UTRA Transverse field coefficient for mobility	0	-	]-INF, +INF[
THETA Mobility modulation	0	-	]-INF, +INF[
VMAX Maximum drift velocity of carriers	0	m/s	[0, +INF[
ECRIT MOS critical electric drain field for mobility reduction	0.0	V/cm	]-INF, +INF[

Symbol and description	Default value	Units	Value range
NEFF Total channel-charge (fixed and mobile) coefficient	1.0	-	]-INF, +INF[
UEXP (F2) Critical field exponent in mobility degradation	0	-	]-INF, +INF[
NFS (FSS) Fast surface state density	0	1/cm^2	]-INF, +INF[
XJ Metallurgical junction depth	0	-	]-INF, +INF[
ETA Static feedback	1	-	]-INF, +INF[
GAMMA Bulk threshold parameter	0.527625	V^1/2	[0, +INF[
LAMBDA Channel-length modulation	0	1/V	]-INF, +INF[
NGATE Doping concentration of polysilicon gate	0	1/cm^3	[0, +INF[
TRS Source resistor temperature coefficient	0.0	-	]-INF, +INF[
VTO Zero-bias threshold voltage	0.0	V	]-INF, +INF[
CGBO (CGB0) Gate-bulk overlap capacitance per meter channel length	0	F/m	[0, +INF[
CGDO (CGD0) Gate-drain overlap capacitance per meter channel width	1.0E-12	F/m	[0, +INF[
CGSO (CGS0) Gate-source overlap capacitance per meter channel width	1.0E-12	F/m	[0, +INF[
CJ Zero-bias bulk junction bottom cap. per sq.-meter of junction area	579.11e-6	F/m^2	[0, +INF[

Symbol and description	Default value	Units	Value range
CJSW Zero-bias bulk junction sidewall cap. per meter of junction perimeter	0	F/m	[0, +INF[
CBS Zero-bias B-S junction capacitance	0	F	[0, +INF[
CBD Zero-bias B-D junction capacitance	0	F	[0, +INF[
CAPOP Meyer capacitance model selector	2	-	0, 1, 2
CF1 Modified Meyer control voltage for transition of gate-source capacitance from depletion region to weak inversion region for the gate source overalap capacitance (for CAPOP=2 only)	0.0	V	[0, +INF[
CF2 Modified Meyer control voltage for transition of gate-source capacitance from weak inversion to strong inversion region (for CAPOP=2 only)	0.1	V	[0, +INF[
CF3 Modified Meyer control for the gate-source capacitance and gate-drain capacitance transition from the saturation region to the linear region as a function of vds (for CAPOP=2 only)	1.0	-	[0, +INF[
CF4 Modified Meyer control for the contour of the gate bulk capacitance and gate-source capacitance smoothing factors	50	-	[0, +INF[
CF5 Modified Meyer control for the capacitance multiplier for gate-source capacitance in the saturation region	0.667	-	[0, +INF[
CGBEX Gate-bulk capacitance exponent	0.5	-	[0, +INF[
KF Flicker noise coefficient	0	-	]-INF, +INF[
AF Flicker noise exponent	1.0	-	]-INF, +INF[

Symbol and description	Default value	Units	Value range
IS (JS) Bulk junction saturation current	1e-14	A or A/m^2	]-INF, +INF[
JS Bulk junction saturation current	0	A/m^2	]-INF, +INF[
UO (U0) Surface mobility	0	cm^2/(V*sec)	[0, +INF[
KP Transconductance parameter	0	A/V^2	]-INF, +INF[
F1EX Grading coefficient for bulk junction bottom	0	-	]-INF, +INF[
RSH Drain and source diffusion sheet resistance	0	ohm/m^2	[0, +INF[
RD Drain ohmic resistance	0	ohm	[0, +INF[
RS Source ohmic resistance	0	ohm	[0, +INF[
RG Gate ohmic resistance	0	ohm	[0, +INF[
LMLT Gate length shrink factor	1.0	-	]-INF, +INF[
WMLT Gate width shrink factor.	1.0	-	]-INF, +INF[
BEX Temperature exponent for mobility parameter	-1.5	-	]-INF, +INF[
METO (MET0) Fringing field factor for gate-to-source and gate-to-drain overlap capacitance calculation	0	um	[0, +INF[
NSS Surface state density	0.0	1/cm^2	[0, +INF[
NSUB Substrate doping	1e15	1/cm^3	[0, +INF[
TPG Type of gate material	1.0	-	]-INF, +INF[

Symbol and description	Default value	Units	Value range
PHI Surface potential	0.576036	V	]-INF, +INF[
XL Channel length difference between the physical (wafer) length and the drawn reference length	0	m	[0, +INF[
LD Lateral diffusion	0	m	[0, +INF[
DEL Reduction of channel length	0.0	m	[0, +INF[
XW Channel width difference between the physical (wafer) width and the drawn reference width	0	m	[0, +INF[
WD Lateral diffusion into channel from bulk along the width	0.0	m	[0, +INF[
XTI Temperature exponent of saturation current	3.0	-	]-INF, +INF[
JSW (ISP) Saturation current from sidewall bulk junction	0	A/m	]-INF, +INF[
BV Breakdown voltage	0	V	]-INF, +INF[
NBV Reverse breakdown voltage correction factor	1.0	-	]-INF, +INF[
CJP Zero-bias bulk junction sidewall cap. per meter of junction perimeter	0	F/m	[0, +INF[
TT Transition time	0	sec	[0, +INF[
FC Coefficient for forward-bias depletion capacitance formula	0.5	-	]-INF, +INF[
FCS Coefficient for forward-bias depletion source capacitance formulae	0.5	-	]-INF, +INF[

Symbol and description	Default value	Units	Value range
NTUN Reverse tunneling non-ideality factor for source	90	-	]-INF, +INF[
JTUN Reverse tunneling non-ideality factor for junction area	0	-	]-INF, +INF[
JTUNSW Reverse tunneling non-ideality factor for junction area	0	-	]-INF, +INF[
MJSW Bulk junction sidewall grading coeff.	0.33	-	]-INF, +INF[
PHP Contact potential at bulk sidewall junction	0.8	V	]-INF, +INF[
TTT1 First order temperature coefficient for transit time	0	-	]-INF, +INF[
TTT2 Second order temperature coefficient for transit time	0	-	]-INF, +INF[
VNDS Reverse MOS diode current transition point	-1	V	]-INF, +INF[
NDS Reverse bias slope coefficient	1	-	]-INF, +INF[
TM1 First-order temperature coefficient for grading coefficient	0	-	]-INF, +INF[
TM2 Second-order temperature coefficient for grading coefficient	0	-	]-INF, +INF[
XTITUN Tunneling current temperature exponent	3.0	-	]-INF, +INF[
TCV Threshold voltage temperature coefficient	0	-	]-INF, +INF[
GAP1 First bandgap correction factor	7.02e-4	eV/Deg. C	[0, +INF[

Symbol and description	Default value	Units	Value range
MJ (M ,EXA) Bulk junction bottom grading coeff.	0.5	-	]-INF, +INF[
PB (PHA ,PHS ,PHD) Bulk junction potential	0.8	V	]-INF, +INF[
DCAP MOS diode model selector	2	-	0, 1, 2
N Emission Coefficient	1	-	]-INF, +INF[
IBV (IB) Current at breakdown voltage	1.0e-3	A	]-INF, +INF[
IK (IKF ,JBF) Forward knee current of MOS diode	0	A	]-INF, +INF[
IKR (JBR) Reverse knee current of MOS diode	0	A	]-INF, +INF[
TLEV Temperature equation selector/assigner	0	-	0, 1, 2
EG Activation Energy	0	eV	[0, +INF[

Technical Background

Levels 1 and 2

The level 1 and 2 of the MOSFET models are the level 1 and 2 of the SPICE MOSFET models [1]. The level 1 is the simple MOSFET model given by Shichman-Hodges [2]. The Level 2 provides an analytical one-dimensional model which incorporates most of the second-order effects of small-size devices. Meyer's gate capacitance model [3] is used for these levels. Based on parameter *CAPOP*, when *CAPOP = 0,* original Meyer's model is selected, when *CAPOP* is 1 or 2, a modified Meyer's model is used. Several HSPICE LEVEL 1 and 2 parameters are also supported in order to provide compatibility for HSPICE netlists. Diode parameters are used to model body-drain and body-source junctions.

BSIM models

Berkeley Short-channel IGFET Model (BSIM) developed by Berkeley's device group at University of California, Berkeley is used to accurately model the device physics of small-geometry MOS transistors. BSIM3 (level 8, 49, or 53) and BSIM4 (level 14 or 54) are supported by OptiSPICE. BSIM3 model parameter details are given in the BSIM3 Users' Manual from University of California, Berkeley at

http://www-device.eecs.berkeley.edu/~bsim/Files/BSIM3/ftpv330/Mod_doc/b3v33manu.tar

BSIM4 model parameters are given in the BSIM4 Users' Manual at

http://www-device.eecs.berkeley.edu/~bsim/Files/BSIM4/BSIM470/BSIM470_Manual.pdf

BSIMSOI model

BSIMSOI (level 70) is used to model MOS transistors manufactured with the Silicon-On-Insulator (SOI) technology. BSIMSOI V3.2 is supported by OptiSPICE. The model parameters are given in the BSIMSOI Users' Manual at

http://www-device.eecs.berkeley.edu/~bsim/Files/BSIMSOI/bsimsoi3p2.zip

References

[1] Vladimirescu, A. and S. Liu. *The simulation of MOS integrated circuits using SPICE2*, Memorandum No. UCB/ERL M80/7, University of California, Berkeley, Feb. 1980.

[2] Shichman, H and D. A. Hodges. "Modeling and simulation of insulated-gate field effect transistor switching circuits", IEEE Journal of Solid-State Circuits SC-3., pp. 285-289, 1968.

[3] J. E. Meyer, "MOS Models and Circuit Simulation", RCA Review, Vol. 32, March 1971

JFET Model

Syntax

n-channel: `.MODEL MODEL_NAME NJF <param1=val1> <param2=val2> ...`

p-channel: `.MODEL MODEL_NAME PJF <param1=val1> <param2=val2> ...`

Parameters

Symbol and description	Default value	Units	Value range
LEVEL JFET DC model selector	1	-	1, 2
AREA Global area scale factor	1	-	[0, +INF[
ACM Area calculation method	0	-	0, 1
ALIGN Misalignment of gate	0	m	[0, +INF[
L Channel length	0	m	[0, +INF[
W Channel width	0	m	[0, +INF[
LDEL Difference between drawn and actual device length	0	m	[0, +INF[
LDIF Distance of the lightly doped region ranging from the edge of the FET to heavily doped region	0	m	[0, +INF[
WDEL Difference between drawn and actual device width	0	m	[0, +INF[
HDIF Distance of the highly doped region ranging from source or drain contact to lightly doped region	0	m	[0, +INF[

Symbol and description	Default value	Units	Value range
RD Drain resistance	0	ohm	[0, +INF[
RS Source resistance	0	ohm	[0, +INF[
RG Gate resistance	0	ohm	[0, +INF[
RSH Sheet resistance for heavily doped region	0	ohm/m^2	[0, +INF[
RSHG Sheet resistance of gate	0	ohm/m^2	[0, +INF[
RSHL Sheet resistance for lightly doped region	0	ohm/m^2	[0, +INF[
BETA Transconductance parameter	1.0e-4	A/V^2	[0, +INF[
VTO (VT0) Threshold (pinch-off) voltage	-2	V	]-INF, +INF[
LAMBDA Channel length modulation parameter	0	1/V	]-INF, +INF[
LAM1 Channel length modulation gate voltage parameter	0	1/V	]-INF, +INF[
CGS (CGSO ,CGS0) Zero-bias gate-to-source junction capacitance	1.0E-12	F	[0, +INF[
CGD (CGDO ,CGD0) Zero-bias gate-to-drain junction capacitance	1.0E-12	F	[0, +INF[
GCAP Zero-bias gate capacitance used if CGS and CGD are not provided	0.0	ohm	[0, +INF[
CRAT Source fraction of gate capacitance	0.666	ohm	[0, +INF[
TRS Source resistor temperature coefficient	0.0	-	]-INF, +INF[

Symbol and description	Default value	Units	Value range
TRD Drain resistor temperature coefficient	0.0	-	]-INF, +INF[
TRG Gate resistor temperature coefficient	0.0	-	]-INF, +INF[
NLEV noise model level	1	-	1, 2, 3
GDSNOI Channel noise coefficient	1	-	]-INF, +INF[
TLEV Temperature equation level selector	0	-	0,1,2
EG Energy gap	0	eV	[0, +INF[
IK (IKF ,JBF) Forward-knee current	0	A	[0, +INF[
IKR (JBR) Reverse-knee current	0	A	[0, +INF[
IBV (IB) Current at Breakdown voltage	1.0e-3	A	[0, +INF[
JSW (ISP) Sidewall saturation current	0	A	[0, +INF[
BV Reverse breakdown voltage	0	V	[0, +INF[
NBV Reverse breakdown voltage correction factor	1.0	V	]-INF, +INF[
TT Transit time	0	sec	[0, +INF[
FC Coefficient for forward-bias depletion capacitance	0.5	-	]-INF, +INF[
FCS Coefficient for forward-bias depletion periphery capacitance	0.5	-	]-INF, +INF[

Symbol and description	Default value	Units	Value range
NTUN Tunneling emission coefficient	90	-	]-INF, +INF[
JTUN Tunneling saturation current density	0	A/m^2	]-INF, +INF[
JTUNSW Sidewall tunneling saturation current	0	A/m	]-INF, +INF[
MJSW Periphery junction grading coefficient	0.33	-	]-INF, +INF[
PHP Periphery junction contact potential	0.8	V	]-INF, +INF[
KF Flicker noise coefficient	0	-	[0, +INF[
AF Flicker noise exponent	1.0	-	[0, +INF[
TTT1 First order temperature coefficient for TT	0	1/Deg. C	]-INF, +INF[
TTT2 Second order temperature coefficient for TT	0	1/(Deg. C)^2	]-INF, +INF[
TM1 First-order temperature coefficient for grading coefficient	0	1/Deg. C	]-INF, +INF[
TM2 Second-order temperature coefficient for grading coefficient	0	1/(Deg. C)^2	]-INF, +INF[
XTI Saturation-current temperature exponent	3.0	-	]-INF, +INF[
XTITUN Tunneling current temperature exponent	3.0	-	]-INF, +INF[
TCV Temperature coefficient for breakdown voltage	0	-	]-INF, +INF[
GAP1 First band gap (activation energy) correction factor	7.02e-4	eV/Deg. C	]-INF, +INF[

Symbol and description	Default value	Units	Value range
IS (JS) Saturation Current	1e-14	A or A/m2	[0, +INF[
MJ (M ,EXA) Grading coefficient	0.5	-	]-INF, +INF[
PB (PHI ,VJ ,PHA) Junction area contract potential	0.8	-	[0, +INF[
DCAP Capacitor equation selector/assigner	2	-	1,2
N Emission coefficient	1	-	]-INF, +INF[

Technical Background

Junction Field Effect Transistor (JFET) model is derived from Shichman-Hodges model [1]. When *LEVEL = 1*, the DC characteristics are defined by the SPICE DC model [2], whereas when *LEVEL = 2*, a gate voltage dependent channel length modulation is also included. Gate-to-source and gate-to-drain junctions are modeled by diode model parameters.

The paramour *ACM* is used to define the gate area calculation method when gate width (*W*) and length (*L*) are given. When *ACM = 0*, the area becomes unitless and the effective area is defined by

$$Area_{eff} = \frac{W_{eff} \cdot M}{L_{eff}} \tag{1}$$

where

- $W_{eff} = (W + WDEL) \cdot SCALEM$
- $L_{eff} = (L + LDEL) \cdot SCALEM$
- M is the element multiplier (element parameter)

The effective drain, source, and gate series resistance can be given by

$$RD_{eff} = \frac{RD}{Area_{eff}} \tag{2}$$

$$RS_{eff} = \frac{RS}{Area_{eff}} \tag{3}$$

$$RG_{eff} = \frac{RG}{M^2} \cdot Area_{eff} \tag{4}$$

When *ACM = 1*, the physical area is computed and the effective area is given by

$$Area_{eff} = L_{eff} \cdot W_{eff} \cdot M \tag{5}$$

In this case (*ACM = 1*), if the *RD*, *RS*, and *RG* are given and being nonzero, their effective values are calculated as follows:

$$RD_{eff} = \frac{RD}{M} \tag{6}$$

$$RS_{eff} = \frac{RS}{M} \tag{7}$$

$$RG_{eff} = \frac{RG}{M} \tag{8}$$

Otherwise they are calculated based on the sheet resistance parameters as given by

$$RD_{eff} = RSH \cdot \frac{HDIF}{W_{eff} \cdot M} + RSHL \cdot \left(\frac{LDIF + ALIGN}{W_{eff} \cdot M}\right) \tag{9}$$

$$RS_{eff} = RSH \cdot \frac{HDIF}{W_{eff} \cdot M} + RSHL \cdot \left(\frac{LDIF - ALIGN}{W_{eff} \cdot M}\right) \tag{10}$$

$$RG_{eff} = RSHG \cdot \frac{W_{eff}}{L_{eff} \cdot M} \tag{11}$$

Based on the effective area, the effective saturation current can be calculated as follows

$$IS_{eff} = IS \cdot Area_{eff} \tag{12}$$

If both *L* and *W* are given, effective transconductance parameter can be given by

$$BETA_{eff} = BETA \cdot \frac{W_{eff} \cdot M}{L_{eff}} \tag{13}$$

Otherwise it is defined by

$$BETA_{eff} = BETA \cdot AREA \tag{14}$$

Drain-source current model

When *LEVEL = 1*, the drain-source current, I_{DS}, is defined for the three regions of operations, cut-off, saturation, and linear, as follows. In cutoff region where the gate-source voltage, $V_{GS} \leq VTO$, $I_{DS} = 0$. For saturation region, where $0 < V_{GS} - VTO \leq V_{DS}$, the current is given by

$$I_{DS} = BETA_{eff} \cdot (V_{GS} - VTO)^2 (1 + LAMBDA \cdot V_{DS}) \tag{15}$$

For linear region, where, $0 < V_{DS} < V_{GS} - VTO$, the current is given by

$$I_{DS} = BETA_{eff} \cdot V_{DS} \cdot [2(V_{GS} - VTO) - V_{DS}](1 + LAMBDA \cdot V_{DS}) \tag{16}$$

When *LEVEL* = *2*, both saturation and linear currents will include the effect from *LAM1* parameter. For the saturation region it can be given by

$$I_{DS} = BETA_{eff} \cdot V_{GST}^2 [1 + LAMBDA \cdot (V_{DS} - V_{GST})(1 + LAM1 \cdot V_{GS})] \tag{17}$$

where $V_{GST} = V_{GS} - VTO$. For a reverse biased saturation region, where $V_{GS} < 0$, the current can be given by

$$I_{DS} = BETA_{eff} \cdot V_{GST}^{2}\left[1 + LAMBDA \cdot (V_{DS} - V_{GST}) \cdot \frac{V_{GST}}{VTO}\right] \tag{18}$$

For linear region, it can be given by

$$I_{DS} = BETA_{eff} \cdot V_{DS} \cdot (2V_{GST} - V_{DS}) \tag{19}$$

Gate-to-source and gate-to-drain effective junction capacitances

If the parameter GCAP is given the effective junction capacitances are calculated as given by

$$CGS_{eff} = GCAP \cdot CRAT \cdot Area_{eff} \tag{20}$$

$$CGD_{eff} = GCAP \cdot (1 - CRAT) \cdot Area_{eff} \tag{21}$$

Otherwise, they are calculated as

$$CGS_{eff} = CGS \cdot Area_{eff} \tag{22}$$

$$CGD_{eff} = CGD \cdot Area_{eff} \tag{23}$$

Noise model

If drain, gate, and source series resistances are non-zero, thermal noise is calculated. In addition, channel noise due to the drain-source current is also calculated. The channel noise has thermal and flicker noises. If the parameter *NLEV* < *3*, thermal noise spectral density of the channel is given by

$$N_{chT} = \sqrt{\frac{8 \cdot K \cdot T \cdot gm}{3}} \tag{24}$$

where

- K is the Boltzmann constant
- K is the temperature in kelvin
- gm is the transconductance of the JFET

If *NLEV = 3*, the thermal noise spectral density for the channel is given by

$$N_{chT} = \frac{8 \cdot K \cdot T}{3} \cdot BETA_{eff} \cdot (V_{GS} - VTO) \cdot \frac{(1 + \alpha + \alpha^2)}{\alpha} \cdot GDSNOI \quad (25)$$

where $\alpha = 0$ for saturation region, $\alpha = 1 - V_{DS}/(V_{GS} - VTO)$.

The flicker noise of the channel is given by

$$N_{chF}(f) = \sqrt{\frac{KF \cdot (I_{DS})^{AF}}{f}} \quad (26)$$

where f is noise spectrum frequency.

References

[1] Shichman, H and D. A. Hodges. "Modeling and simulation of insulated-gate field effect transistor switching circuits", IEEE Journal of Solid-State Circuits SC-3., pp. 285-289, 1968.

[2] Quarles, Thomas L., *Spice3 Version 3C1 Users Guide*, Memorandum No. UCB/ERL M89/42, University of California, Berkeley, Apr. 1989.

MESFET Model

Syntax

n-channel: `.MODEL MODEL_NAME NMF <param1=val1> <param2=val2> ...`

p-channel: `.MODEL MODEL_NAME PMF <param1=val1> <param2=val2> ...`

Parameters

Symbol and description	Default value	Units	Value range
AREA Global area scale factor	1	-	[0, +INF[
RD Drain resistance	0	ohm	[0, +INF[
RS Source resistance	0	ohm	[0, +INF[
RG Gate resistance	0	ohm	[0, +INF[
BETA Transconductance parameter	1.0e-4	A/V^2	[0, +INF[
B Doping tail extending parameter	0.3	1/V	[0, +INF[
ALPHA Saturation voltage parameter	2	1/V	[0, +INF[
VTO (VT0) Threshold (pinch-off) voltage	-2	V	]-INF, +INF[
LAMBDA Channel length modulation parameter	0	1/V	]-INF, +INF[
CGS (CGSO ,CGS0) Zero-bias gate-to-source junction capacitance	1.0E-12	F	[0, +INF[
CGD (CGDO ,CGD0) Zero-bias gate-to-drain junction capacitance	1.0E-12	F	[0, +INF[
PB (PHI ,VJ ,PHA) Junction area contract potential	1	-	[0, +INF[

Symbol and description	Default value	Units	Value range
TRS Source resistor temperature coefficient	0.0	-	]-INF, +INF[
TRD Drain resistor temperature coefficient	0.0	-	]-INF, +INF[
TRG Gate resistor temperature coefficient	0.0	-	]-INF, +INF[
NLEV noise model level	1	-	1, 2, 3
GDSNOI Channel noise coefficient	1	-	]-INF, +INF[
TLEV Temperature equation level selector	0	-	0,1,2
EG Energy gap	0	eV	[0, +INF[
IK (IKF ,JBF) Forward-knee current	0	A	[0, +INF[
IKR (JBR) Reverse-knee current	0	A	[0, +INF[
IBV (IB) Current at Breakdown voltage	1.0e-3	A	[0, +INF[
JSW (ISP) Sidewall saturation current	0	A	[0, +INF[
BV Reverse breakdown voltage	0	V	[0, +INF[
NBV Reverse breakdown voltage correction factor	1.0	V	]-INF, +INF[
TT Transit time	0	sec	[0, +INF[
FC Coefficient for forward-bias depletion capacitance	0.5	-	]-INF, +INF[

Symbol and description	Default value	Units	Value range
FCS Coefficient for forward-bias depletion periphery capacitance	0.5	-	]-INF, +INF[
NTUN Tunneling emission coefficient	90	-	]-INF, +INF[
JTUN Tunneling saturation current density	0	A/m^2	]-INF, +INF[
JTUNSW Sidewall tunneling saturation current	0	A/m	]-INF, +INF[
MJSW Periphery junction grading coefficient	0.33	-	]-INF, +INF[
PHP Periphery junction contact potential	0.8	V	]-INF, +INF[
KF Flicker noise coefficient	0	-	[0, +INF[
AF Flicker noise exponent	1.0	-	[0, +INF[
TTT1 First order temperature coefficient for TT	0	1/Deg. C	]-INF, +INF[
TTT2 Second order temperature coefficient for TT	0	1/(Deg. C)^2	]-INF, +INF[
TM1 First-order temperature coefficient for grading coefficient	0	1/Deg. C	]-INF, +INF[
TM2 Second-order temperature coefficient for grading coefficient	0	1/(Deg. C)^2	]-INF, +INF[
XTI Saturation-current temperature exponent	3.0	-	]-INF, +INF[
XTITUN Tunneling current temperature exponent	3.0	-	]-INF, +INF[
TCV Temperature coefficient for breakdown voltage	0	-	]-INF, +INF[

Symbol and description	Default value	Units	Value range
GAP1 First band gap (activation energy) correction factor	7.02e-4	eV/Deg. C	]-INF, +INF[
IS (JS) Saturation Current	1e-14	A or A/m2	[0, +INF[
MJ (M ,EXA) Grading coefficient	0.5	-	]-INF, +INF[
DCAP Capacitor equation selector/assigner	2	-	1,2
N Emission coefficient	1	-	]-INF, +INF[

Technical Background

The Metal Semiconductor Field Effect Transistor (MESFET) model is based on the SPICE model which is derived from the GaAs FET model of Statz et al [1]. The channel current (drain-source current) is modeled by the parameters VTO, B, BETA, ALPHA, and LAMBDA. The drain-source current, I_{DS}, is defined for the three regions of operations, cut-off, saturation, and linear. In cutoff region where the gate-source voltage, $V_{GS} \leq VTO$, $I_{DS} = 0$. For saturation region, where $0 < V_{DS} \leq 3/ALPHA$, the current is given by

$$I_{DS} = \beta \cdot (V_{GS} - VTO)^2 \cdot \left[1 - \left(1 - ALPHA \cdot \frac{V_{DS}}{3}\right)^3\right] \cdot (1 + LAMBDA \cdot V_{DS}) \quad (1)$$

For linear region, where, $V_{DS} > 3/ALPHA$, the current is given by

$$I_{DS} = \beta \cdot (V_{GS} - VTO)^2 (1 + LAMBDA \cdot V_{DS}) \quad (2)$$

where β is given by

$$\beta = \frac{BETA}{1 + B \cdot (V_{GS} - VTO)} \quad (3)$$

Gate-to-source and gate-to-drain capacitances are modeled as total gate charge as a function of gate-drain and gate-source voltages using Statz model [1]. Parameters *CGS*, *CGD*, and *PB* are used for this total gate charge computation.

Diode model parameters are used to model the gate-to-source and gate-to-drain junction currents.

Noise model is for the MESFET is same as that of JFET noise model, where thermal and flicker noise for the channel are calculated using *NLEV*, *GDSNOI*, *KF* and *AF* parameters. Thermal noise due to the drain, gate, and source series resistances are also calculated.

References

[1] Statz, H., Newman, P., Smith, I.W., Pucel, R.A., Haus, H.A., "GaAs FET device and circuit simulation in SPICE," Electron Devices, IEEE Transactions on , vol.34, no.2, pp. 160- 169, Feb 1987.

Linear Network Element Model

Syntax

```
.MODEL MODEL_NAME LNET <param1=val1> <param2=val2>...
```

Parameters

Symbol and description	Default value	Units	Value range
DEV_TYPE Device type to be modeled (H, Y, Z, G parameters)	G	-	G, H, Y, Z
IN_FORMAT Input format to be used (rpk/zpk/yfn/tstone): • rpk (pole residue format) • zpk (zero pole format) • yfn (transfer function format) • tstone (touchstone format) • basic filters (butter/bessel/chebyshev)	RPK	-	RPK, ZPK, YFN, TSTONE, FILTER
IN_FILE_S Name of input file (applied to rpk, zpk, yfn, tstone)	“input_file_name”	-	-
NLHSPORTS Defines the number of left-hand side ports	1	-	
NOrderL_I Defines the filter order. Used for the left hand side (high pass) if creating a bandpass or bandstop filter.	1	-	
NOrderH_I Defines the filter order (used for the right hand side (low pass) if creating a bandpass or bandstop filter. This parameter is ignored for highpass and lowpass filters.	1	-	
FCL Filter bandwidth (left) - used to defined the high pass position for bandpass and bandstop.	-	Hz	]-INF, +INF[
FCH Filter bandwidth (right) - used to define the low pass position for bandpass and bandstop. This parameter is ignored for highpass and lowpass filters.	-	Hz	

Symbol and description	Default value	Units	Value range
ALPHA Loss factor (dB)	0	dB	[
FTYPE Defines the filter type: • LOWPASS • HIGHPASS • BANDPASS • BANDSTOP	LOWPASS	-	LOWPASS, HIGHPASS, BANDPASS, BANDSTOP
UDF_TYPE_S Defines the filter shape/profile	butter	-	[butter, bessel, chebyshev]
RF Ripple factor (Chebyshev)	1	-	[

Technical Background

For each linear network element model (***Lnet***) model, the device type (*dev_type*) and input format (*in_format*) needs to be defined. If the model is not a basic filter then it also needs an input file (*in_file_s*) located in the same directory as the schematic or Netlist.

The available device types include:

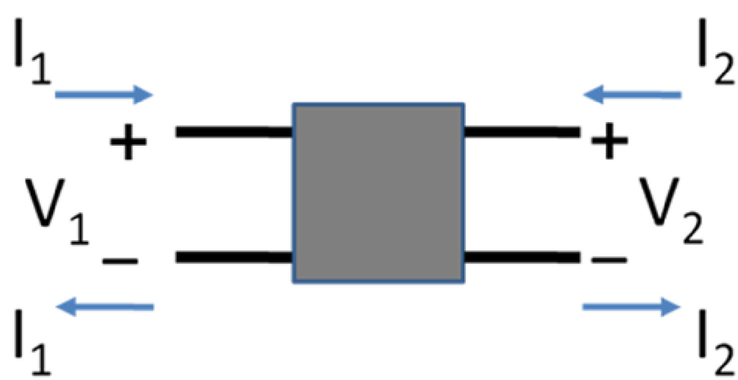
- ***dev_type = H***: H parameter, [V1 I2]' = [H][I1 V2]'
- ***dev_type = Y***: Y parameter, [I1 I2]' = [Y][V1 V2]'
- ***dev_type = Z***: Z parameter, [V1 V2]' = [Z][I1 I2]'
- ***dev_type = G***: G parameter, [I1 V2]' = [G][V1 I2]'

The input file is specified with the parameter *in_file_s* = "input_file_name" (rpk/zpk/yfn/tstone)

Each device can have an arbitrary number of ports so V and I are vectors. Every port is defined by a positive and a negative voltage and a current flowing through the device. The voltages and currents on the right hand side of the equation multiplying H/Y/Z/G parameters control the output.

The number of ports on the left hand side of the device are defined using *nlhsPorts*

Figure 1 Two port linear network element mode (Source: https://en.wikipedia.org/wiki/Two-port_network, Accessed 18 Oct 2016)



Input Formats

The recursive convolution algorithm is used to calculate the transient response of each pole/residue pair. All the input formats are converted to poles and residues before the simulation.

Pole Residue Format (in_format = RPK)

Each entry in the parameter matrix is defined by a set of poles (p) and residues (r) and a constant offset (k). Poles and residues can be complex numbers. The constant offset is a real number.

$$X_{mn} = \sum_{i=1}^{L} \frac{r_i}{(s - p_i)} + k \quad (1)$$

File format (RPK)

nports numports
begin m n
delay dt
begin_complex L
p1_real   p1_imag   r1_real r1_imag
…
pL_real   pL_imag   rL_real rL_imag
end

Example RPK file

nports 2
begin 1 1
delay 0
begin_const 1
2 0
end

begin 1 2
delay 0
begin_real 1
-3e9 -3e9
end

begin 2 1
delay 0
begin_complex 2
-5e9 -15e9 -25e9 0
-5e9 +15e9 -25e9 0
end

begin 2 2
delay 0

begin_const 1
8 0
end

Zero Pole Format (in_format = ZPK)

Each entry in the parameter matrix is defined by a set of poles (p) and zeros (z) and a constant multiplier (k). Poles and residues can be complex numbers. The constant multiplier is a non-zero real number

$$X_{mn} = k \cdot \frac{\prod_{i=1}^{L} s - z_i}{\prod_{j=1}^{K} s - p_j} \tag{2}$$

<u>File format (ZPK)</u>

nports numports
begin m n
delay dt
begin_real zeros L
z1
z2
.
zL
begin_real poles K
p1
p2
.
pK
begin_real k 1
k
end

<u>Example ZPK file</u>

nports 2

begin 1 1
begin_real zeros 2
1
4
begin_real poles 3
-2
-3
-5
begin_real k 1
1
end

begin 2 1
delay 1e-9
begin_real zeros 1
-2e9
begin_real poles 2
-1e10
-4e8
begin_real k 1
-4e9
end

begin 1 2
begin_real zeros -1
begin_real poles 2
-1e10
-4e8
begin_real k 1
-4e18
end

begin 2 2
begin_real zeros -1
begin_real poles 1
-1e10
begin_real k 1
-1e10
end

Transfer Function Format (in_format = YFN)

Each entry in the parameter matrix is defined by two sets of polynomial constants for numerator and denominator. 'a' and 'b' coefficients must be real.r

$$X_{mn} = k \cdot \frac{\sum_{i=0}^{L} a_i \cdot s^i}{\sum_{j=0}^{K} b_j \cdot s^j} \qquad (3)$$

File format (YFN)

nports numports

begin m n
delay dt
a0 a1 a2 … aL
b0 b1 b2 … bK
end

Example YFN file

nports 2

begin 1 1
delay 0
-3e9 -7e18
1 5e9 6e18
end

begin 1 2
delay 0
1
1 9e9
end

begin 2 1
delay 1e-9
-3e9 -7e18
1 5e9 6e18
end

begin 2 2
delay 0
1
1 9e9
end

Touchstone Format (in_format = TSTONE)

The user inputs frequency vs mag/phi or complex data. The vector fit algorithm is used to automatically generate poles and residues for the input.

For further information on the touchstone format please see:

https://ibis.org/touchstone_ver2.0/touchstone_ver2_0.pdf

Basic Filters (in_format = FILTER)

The user defines the filter model (Chebyshev, Butterworth, Bessel). The filter type can be low, high, band-pass or band-stop.

The filter parameters are as follows:

- ***NOrderL_i* = integer**: Filter order. Used for the left hand side for bandpass and bandstop
- ***NorderH_i = integer***: Filter order. Used for the right hand side for bandpass and bandstop. Ignored for highpass and lowpass filters
- ***FcL = double***: Filter bandwidth. Used for the left hand side for bandpass and bandstop)
- ***FcH = double***: Filter bandwidth. Used for the right hand side for bandpass and bandstop. Ignored for highpass and lowpass filters
- ***alpha = double***: Loss factor in dB

- ***ftype = LOWPASS/HIGHPASS/BANDPASS/BANDSTOP***)
- ***UDF_type_s = butter/bessel/chebyshev***
- ***rf = double***: Ripple factor for Chebyshev

Optoelectronic Models Library

This section contains information on the following models

Notes:

CWSOURCE Model

Syntax

Style	Form
OptiSPICE	`.MODEL MODEL_NAME CWSOURCE <param1=val1> <param2=val2> ...`

Parameters

Symbol and description	Default value	Units	Value range
CWSourceType Continuous wave source type	MAGPHI	-	MAGPHI, REALIMAG, POWPHI,
PolarCoeff Magnitude sharing coefficient for X and Y polarizations	1.0	-	[0, +INF[
ModeCoeff List of coefficients for the magnitude of each mode	-	-	[0, +INF[
Wavelength Wavelength	1550	nm	[0, +INF[
Frequency Center frequency	193.1	-	[0, +INF[
FrequencyUnit Frequency unit	THz	-	Hz, THz, nm,
FreqShift Carrier Frequency offset	FreqShift	-	[0, +INF[
GainCoeff Optical output field gain coefficient	1.0	-	[0, +INF[
PhaseCoeff Optical output field phase coefficient	1.0	-	]-INF, +INF[
RealEfieldCoeff Real part of the electric field coefficient	1.0	-	[0, +INF[
ImagEfieldCoeff Imaginary part of the electric field coefficient	1.0	-	[0, +INF[

Mode Shape Parameters

Symbol and description	Default value	Units	Value range
NumModes Number of modes	1	-	[1, +INF[
IsPolarized Set output is only X polarized (0) or both X and Y polarized (1)	0	-	0,1
ModeType Output mode type	GAUSSIAN_MODE	-	GAUSSIAN_MODE, FILE_MODE, BESSEL_0_MODE, BESSEL_1_MODE, HERMITE_GAUSSIAN_MODE, LAGUERRE_GAUSSIAN_MODE, UNIFORM_MODE
SigmaX (Rad) Horizontal spatial simulation window	50	um	[0, +INF[
SigmaY Vertical spatial simulation window	50	um	[0, +INF[
ModeFileList List of file names containing mode profile for each mode	-	-	-
ModeFile Name of the file that defines the mode profile for all modes if ModeFileList is not provided	-	-	-
LibDirectory Directory containing mode file	-	-	-
ModeSpotSize Mode spot size sets the size of the Gaussian modes (defined as the point where the Gaussian drops 2 standard deviations - 13% of the peak).	5	um^2	[0, +INF[
ModeSpotSizeY ModeSpotSizeY sets the size of the Gaussian mode for the y-axis. When set to 0, this value is equal to ModeSpotSize	0	um^2	[0, +INF[
ModeInvRadius Mode inverse radius	0	um	[0, +INF[

Symbol and description	Default value	Units	Value range
ModeIndexMList List of mode index M for each mode	-	-	[0, +INF[
ModeIndexNList List of mode index N for each mode	-	-	[0, +INF[
ModeIndexM If ModeIndexMList is not provided then this value is used as the mode index M for all modes	0	-	[0, +INF[
ModeIndexN If ModeIndexNList is not provided then this value is used as the mode index N for all modes	0	-	[0, +INF[
CacheModeShape Option to save the mode profile to a file	0	-	0,1
UseModeShapeCache Option to use already saved mode profile	0	-	0,1

Technical Background

The specification of how the optical output is determined by the input voltages is determined by the parameter *CWSourceType.*

MAGPHI: Voltage at input 1, V_1 , (must be positive) directly controls the magnitude of the output, and voltage at input 2, V_2 , directly controls the phase of the output according to:

$$E_{Out} = \alpha V_1 \exp(j\phi V_2) \qquad (1)$$

where

- α is the parameter *GainCoeff*
- ϕ is the parameter *PhaseCoeff.*

POWPHI: Voltage at input 1 V_1 (must be positive) directly controls the power of the output, and voltage at input 2 V_2 directly controls the phase of the output according to:.

$$E_{Out} = \sqrt{\alpha V_1} \exp(j\phi V_2) \qquad (2)$$

where

- α is the parameter *GainCoeff*
- ϕ is the parameter *PhaseCoeff.*

REALIMAG: Voltage at input 1 V_1 directly controls the real part of the output, and voltage at input 2 V_2 directly controls the imaginary part of the output according to:

$$E_{Out} = \alpha_{Real} V_1 + j\alpha_{Imag} V_2 \tag{3}$$

where

- α_{Real} is the parameter *RealEfieldCoeff*
- α_{Imag} is the parameter *ImagEfieldCoeff.*

The wavelength of the optical output is set by the *Wavelength* or *Frequency* parameters. With *FrequencyUnit* setting the units to be used for the *Frequency* parameter. *FrequencyShift* specifies a constant wavelength shift from the center frequency and is modeled as linearly increasing phase.

The parameter *NumModes* specifies the number of modes in the optical output signal. Power for each mode can be scaled by the parameter *ModeCoeff* as follows:

$$P_{out_i} = m_i \cdot P_{out} \tag{4}$$

where P_{out_i} is the power for mode *i*, P_{out} is the initial calculated output power for all modes, and m_i is the *i*-th value of the parameter *ModeCoeff*.

The source can either be singularly polarized (X) or have two polarizations (X,Y) by setting *isPolarized* to 0 or 1 respectively. If *isPolarized = 1*, the power is scaled by the parameter *PolarCoeff* as follows:

$$P_x = p \cdot P_{out}$$
$$P_y = (1 - p) \cdot P_{out} \tag{5}$$

where

- P_x is the power of the X polarized field
- P_y is the power of the Y polarized field
- p is the parameter *PolarCoeff*
- P_{out} is the initial calculated power for both polarization

The parameter *ModeType* determines the optical mode shapes of the output modes. The mode shapes are described below as a function of polar co-ordinates r and φ. Transformation of polar to rectangular co-ordinates can be given by

$$x = r\cos\varphi \qquad (6)$$
$$y = r\sin\varphi$$

The spatial window for the calculation of mode shape is defined in the X-Y plane such that

$$-\sigma_x \le x \le \sigma_x \qquad (7)$$
$$-\sigma_y \le y \le \sigma_y$$

where

- σ_x is the parameter *SigmaX*
- σ_y is the parameter *SigmaY.*

LAGUERRE_GAUSSIAN_MODE: The Laguerre-Gaussian mode is described as:

$$\psi_{m,n}(r,\varphi) = \left(\frac{2r^2}{w_o^2}\right)^{\left|\frac{n}{2}\right|} L_m^n\left(\frac{2r^2}{w_o^2}\right)\exp\left(\frac{r^2}{w_o^2}\right)\exp\left(j\frac{\pi r^2}{\lambda R_o}\right)\begin{cases}\sin(|n|\varphi),\ n \ge 0\\ \cos(|n|\varphi),\ n < 0\end{cases} \qquad (8)$$

where *m* and *n* represent the X and Y index that describe the azimuthal and radial indexes, respectively. *R* (1/*ModeInvRadius*) is the radius of curvature and w_0 (*ModeSpotSize*) is the spot size. $L_{n,m}$ is the Laguerre polynomial. The *m* and *n* values for each mode is given by the parameter *ModeIndexMList* and *ModeIndexNList* respectively. If these list parameters are not given, then corresponding parameter values given by *ModeIndexM* or *ModeIndexN* will be used to set same *m* or *n* values for all modes.

HERMITE_GAUSSIAN_MODE: The Hermite-Gaussian mode is described as:

$$\psi_{m,n}(r,\varphi) = H_m\left(\frac{\sqrt{2}x}{w_{ox}}\right)\exp\left(-\frac{x^2}{w_{ox}^2}\right)\exp\left(j\frac{\pi x^2}{\lambda R_{ox}}\right)H_n\left(\frac{\sqrt{2}y}{w_{oy}}\right)\exp\left(-\frac{y^2}{w_{oy}^2}\right)\exp\left(j\frac{\pi y^2}{\lambda R_{oy}}\right) \qquad (9)$$

where *m* and *n* represent the X and Y index that describe the mode dependencies for the X and Y-axis. *R* (1/*ModeInvRadius*) is the radius of curvature and w_0 (*ModeSpotSize*) is the spot size. H_m and H_n are the Hermite polynomials.

GAUSSIAN_MODE: The Gaussian mode is described as:

$$\psi(r, \varphi) = A_o e^{-\left(\frac{x^2}{\sigma_x^2} + \frac{y^2}{\sigma_y^2}\right)} \tag{10}$$

where

- A_o is the normalization constant
- σ_x is the parameter *SigmaX*
- σ_y is the parameter *SigmaY.*

FILE_MODE: Loads a mode shape from a file. Parameters *ModeFileList* is the list of mode profile file names for each mode and *LibDirectory* is the name of the folder where the file is located. If *ModeFileList* is not given, then all modes will use the same profile given by the file name by *ModeFile* parameter.

Following modes are radial modes where the mode function depends only on r .

BESSEL_0_MODE: The Bessel mode 0 is described as:

$$\psi_i(r) = \begin{cases} J_0\left(\frac{\alpha_i r}{\sigma_x}\right), r \le \sigma_x \\ 0, r > \sigma_x \end{cases} \tag{11}$$

where

- J_o is the Bessel function of the first kind with order 0
- $\alpha_i = J_0(i)$
- $i \in 0, 1, \ldots, N$
- N is the parameter *NumModes*
- σ_x is the parameter *SigmaX.*

BESSEL_1_MODE: The Bessel mode 1 is described as:

$$\psi_i(r) = \begin{cases} J_1\left(\frac{\beta_i r}{\sigma_x}\right), r \le \sigma_x \\ 0, r > \sigma_x \end{cases} \tag{12}$$

where

- J_1 is the Bessel function of the first kind with order 1
- $\beta_i = J_1(i)$
- $i \in 0, 1, \ldots, N$
- N is the parameter *NumModes*
- σ_x is the parameter *SigmaX.*

UNIFORM_MODE: The uniform mode is described as:

$$\psi_i(r) = \begin{cases} 1, r \le \sigma_x \\ 0, r > \sigma_x \end{cases} \quad (13)$$

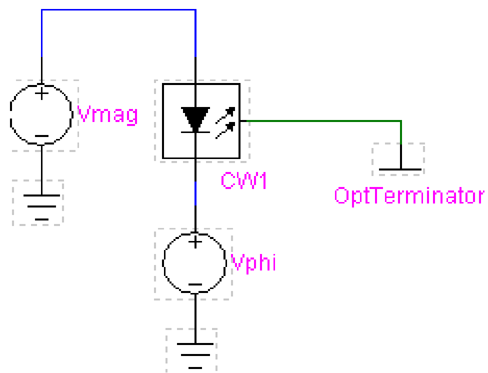
where

- $i \in 0, 1, \ldots, N$
- N is the parameter *NumModes*
- σ_x is the parameter *SigmaX.*

Examples

CW Source controlled by magnitude-phase input (MAGPHI)

Figure 1 CW Source example circuit



The following example shows a netlist where a CW Source is controlled by magnitude (represented by voltage source Vmag) and phase (Vphi).

```
* Controlling voltages Vmag and Vphi
Vmag 1 0 DC=2.0
Vphi 2 0 DC=1.570796

* CW source element CW1. First input is connected to Vmag.
* Second input is connected to Vphi.
* Third node is optical output and connected to mirror.
Osp CWSOURCE Name=CW1 Nodes=[1 2 3] MoName=CWMOD

* Mirror used as a optical terminator with reflection coefficient 0
Osp MIRROR Name=OptTerminator Nodes=[3] MoName=TerminatorMod Ref=0.0

* CW Souce model statement. Model name: CWMOD
.MODEL CWMOD CWSOURCE CWSourceType=MAGPHI
+ GainCoeff=1.0 PhaseCoeff=1.0

* Mirror model statement
.MODEL TerminatorMod MIRROR

* Monitor optical power of CW1
.MONITOR OptPower CW1 3 DIR=OUT

* Monitor optical phase of CW1
.MONITOR OptPhase CW1 3 DIR=OUT
```

```
* Transient simulation
.TRAN 0.001n 0.5n

.END
```

CW Source controlled by power-phase input (POWPHI)

The same above example with only exception where control is provided by voltages representing power and phase can be given by the following model statement.

```
.MODEL CWMOD CWSOURCE CWSourceType=POWPHI
+ GainCoeff=1.0 PhaseCoeff=1.0
```

CW Source controlled by real-imaginary input (REALIMAG)

The following example shows a CW source controlled by voltages representing real and imaginary values. Only changes to the netlist are shown below.

```
...
Vreal 1 0 DC=5
Vimag 2 0 DC=5
.....
.MODEL CWMOD CWSOURCE CWSourceType=REALIMAG
+ RealEfieldCoeff=1.0 ImagEfieldCoeff=1.0
...
```

Obtaining Laguerre-Gaussian mode shape output for CW Source

The default mode shape is Gaussian mode. Following example shows setting Laguerre-Gaussian mode to the first example and saving the mode shape to a file.

```
...
.MODEL CWMOD CWSOURCE ModeType = LAGUERRE_GAUSSIAN_MODE
+ CWSourceType=MAGPHI
+ GainCoeff=1.0 PhaseCoeff=1.0
...
* Save all optical mode shapes to files
.OPTION CacheAllModeShape = 1
...
```

Setting the global option parameter *CacheAllModeShape* to 1 saves all the mode shapes for all optical signals in files.

LASER Model

Syntax

Style	Form
OptiSPICE	.MODEL MODEL_NAME LASER <*param1=val1*> <*param2=val2*> ...

Parameters

Symbol and description	Default value	Units	Value range
PolarCoeff Magnitude sharing coefficient for X and Y polarizations	1.0	-	[0,1]
Wavelength (lambda) Wavelength	1550	nm	[0, +INF[
Frequency (f0) Center frequency	193.1	-	[0, +INF[
FrequencyUnit Frequency unit	THz	-	Hz, THz, nm
FreqShift Carrier frequency offset	FreqShift	-	[0, +INF[
ElecMode Electrical operation mode of the laser: as a diode (DIODE), voltage as a polynomial function of current (POLY_VI), or current as a polynomial function of voltage (POLY_IV)	DIODE	-	DIODE, POLY_VI, POLY_IV
AntiSym Option to invert the polynomial functions (POLY_VI or POLY_IV) on the negative axis	0	-	0,1
IVType Expression type for POLY_IV mode: direct expression of current (CURR) or indirect expression through resistance (RES)	RES	-	RES, CURR
coeff Polynomial coefficients (if ElecMode is POLY_VI or POLY_IV)	-	-	]-INF, +INF[

Symbol and description	Default value	Units	Value range
Toff Temperature offset	0	K	]-INF, +INF[
Tcoeff Temperature polynomial coefficients	-	-	]-INF, +INF[
IOffCoeff Temperature dependent offset current coefficients	-	-	]-INF, +INF[
v_g Group velocity	8.5e9	cm/s	]-INF, +INF[
n_g Effective index	8.5e9		]-INF, +INF[
NumModesLong Number of longitudinal modes	1		[0, +INF[
ChannelMode When SingleChan, all long modes will be contained within a single channel. When LongChan, all long modes will be split into separate channels.	SingleChan		SingleChan, LongChan
GAINS List of gain coefficient which is the product of differential gain and group velocity for each longitudinal mode	-	cm^3/s	]-INF, +INF[
TAUN Carrier lifetime	1	s	]-INF, +INF[
TAUP Photon lifetime	1	s	]-INF, +INF[
L Length of the laser cavity		cm	]-INF, +INF[
SetF0FromLength Sets the central channel frequency/lambda using the length. This finds a mode nearest to the input lambda parameter	0	cm	0, 1
LASERVOL Active layer volume	1	cm^3	[0, +INF[
EPSI Gain compression coefficient	0	cm^3	]-INF, +INF[

Symbol and description	Default value	Units	Value range
Qeff0 Quantum efficiency	0.2	-	[0,1]
KAPPAS Coefficient of gain to difference in emission stimulation	-	-	]-INF, +INF[
ETA Current-injection efficiency	1.0	-	]-INF, +INF[
GAMMAS List of mode confinement factor for each longitudinal mode	-	-	[0, +INF[
BETAS List of spontaneous emission factor for each mode	-	-	[0, +INF[
ALPHA Linewidth enhancement factor	5	-	]-INF, +INF[
NO (N0) Carrier density at transparency	0	1/cm^3	]-INF, +INF[
Rth Thermal resistance	0	K/W	[0, +INF[
Cth Thermal capacitance	0	J/K	[0, +INF[
PhaseNoise Enable phase noise	1	-	0,1
PhotonNoise Enable photon noise	1	-	0,1
CarrierNoise Enable carrier noise	1	-	0,1
DiodeNoise Enable diode noise	1	-	0,1

Diode Model Parameters

Symbol and description	Default value	Units	Value range
PJ PN junction periphery	0	m^2	[0, +INF[

Symbol and description	Default value	Units	Value range
AREA PN junction area	1	m^2	[0, +INF[
IK (IKF ,JBF) Forward knee current	0	A or A/m^2	]-INF, +INF[
IKR (JBR) Reverse knee current	0	A or A/m^2	]-INF, +INF[
RS Source ohmic resistance	0	ohm	[0, +INF[
TRS Source resistor temperature coefficient	0.0	-	]-INF, +INF[
IBV (IB) Current at breakdown voltage	1.0e-3	A	]-INF, +INF[
JSW (ISP) Saturation current from sidewall bulk junction	0	A/m	]-INF, +INF[
BV Breakdown voltage	0	V	]-INF, +INF[
NBV Emission coefficient at breakdown voltage	1.0	-	]-INF, +INF[
CJP Zero-bias bulk junction sidewall capacitance per meter of junction perimeter	0	F/m	[0, +INF[
TT Transition time	0	sec	[0, +INF[
FC Coefficient for forward-bias depletion capacitance formula	0.5	-	]-INF, +INF[
FCS Coefficient for forward-bias depletion periphery capacitance formulae	0.5	-	]-INF, +INF[
NTUN Reverse tunneling non-ideality factor for source	90	-	]-INF, +INF[
JTUN Reverse tunneling non-ideality factor for junction area	0	-	]-INF, +INF[

Symbol and description	Default value	Units	Value range
JTUNSW Reverse tunneling non-ideality factor for junction area	0	-	]-INF, +INF[
MJSW Bulk junction sidewall grading coefficients	0.33	-	]-INF, +INF[
PHP Contact potential at bulk sidewall junction	0.8	V	]-INF, +INF[
KF Flicker noise coefficient	0	-	]-INF, +INF[
AF Flicker noise exponent	1.0	-	]-INF, +INF[
TTT1 Transit time temperature coefficient 1	0	-	]-INF, +INF[
TTT2 Transit time temperature coefficient 2	0	-	]-INF, +INF[
VNDS Reverse current transition point	-1	V	]-INF, +INF[
NDS Reverse bias slope (coefficient)	1	-	]-INF, +INF[
TM1 First order temperature coefficient using in computing MJ	0	1/C	]-INF, +INF[
TM2 Second order temperature coefficient using in computing MJ	0	1/C^2	]-INF, +INF[
XTI Temperature exponent of saturation current	3.0	-	]-INF, +INF[
XTITUN Exponent for the tunneling current temperature	3.0	-	]-INF, +INF[
TCV Threshold voltage temperature coefficient	0	-	]-INF, +INF[
GAP1 Initial bandgap correction factor	7.02e-4	eV/C	]-INF, +INF[

Symbol and description	Default value	Units	Value range
IS (JS) Bulk junction saturation current	1e-14	A or A/m^2	]-INF, +INF[
CJO (CJ0) Zero-bias capacitance	0	F	[0, +INF[
MJ (M, EXA) Bulk junction bottom grading coefficient	0.5	-	]-INF, +INF[
PB (PHI, VJ, PHA) Bulk junction potential	0.8	V	]-INF, +INF[
DCAP Diode capacitor model selector	2	-	[0, +INF[
N Emission coefficient	1	-	]-INF, +INF[

Technical Background

Basic Dynamics

The modulation dynamics of the laser are modeled by coupled rate equations that describe the relationship between the carrier density $N(t)$, photon density $S(t)$, optical phase $\phi(t)$ and temperature $T(t)$ [1][2].

$$\frac{dN(t)}{dt} = \frac{\eta \cdot (I(t) - I_{off}(t))}{q \cdot V_a} - \frac{N(t)}{\tau_n} - g_0 \cdot (N(t) - N_0) \cdot \frac{1}{(1 + \varepsilon \cdot S(t))} \cdot S(t) + F_N(t) \tag{1}$$

$$\frac{dS(t)}{dt} = \Gamma \cdot g_0 \cdot (N(t) - N_0) \cdot \frac{1}{(1 + \varepsilon \cdot S(t))} \cdot S(t) - \frac{S(t)}{\tau_p} + \frac{\Gamma \cdot \beta \cdot N(t)}{\tau_n} + F_S(t) \tag{2}$$

$$\frac{d\phi(t)}{dt} = \frac{1}{2} \cdot \alpha \cdot \left[\Gamma \cdot g_0 \cdot (N(t) - N_0) - \frac{1}{\tau_p}\right] + F_\phi(t) \tag{3}$$

$$\frac{dT(t)}{dt} = \frac{1}{\tau_{th}}[T_0 + (I(t) \cdot V(t) - P_0)R_{th} - T(t)] \tag{4}$$

where

- g_0 is the gain slope constant, $g_0 = v_g \times a_0$

- a_0 is the active layer gain coefficient
- v_g is the parameter *Vg*
- ε is the parameter *EPSI*
- N_0 is the parameter *N0*
- β is any of the parameter in the list parameter *BETAS*
- Γ is any of the parameter in the list parameter *GAMMAS*
- V_a is the parameter *LASERVOL*
- τ_p is the parameter *TAUP*
- τ_n is the parameter *TAUN*
- α is the parameter *ALPHA*
- η is the parameter *ETA*
- T_0 is the ambient temperature in Kelvin
- P_O is the output power
- R_{th} is the parameter *Rth*
- τ_{th} is the thermal time constant
- $I(t)$ is the current through laser
- $I_{off}(t)$ is the temperature dependent offset current
- $V(t)$ is the time varying voltage difference between the node 1 and 2 of the laser
- $F_N(t)$, $F_S(t)$, and $F_\phi(t)$ are Langevin noise forces for carrier, photon, and phase noises respectively.

The time variations for the optical and laser chirp are given by [1]

$$P_0 = \frac{S \cdot V_a \cdot \eta_0 \cdot h \cdot v}{2 \cdot \Gamma\tau_p} \tag{5}$$

$$\Delta v = \frac{1}{2 \cdot \pi} \cdot \frac{d\phi}{dt} \tag{6}$$

where

- η_o is the parameter *Qeff0*

- ν is the optical frequency
- h is Planck's constant.

If the parameter *KAPPAS* is given in the model statement then the optical output power for each mode is calculated as follows:

$$P_0 = S \cdot \kappa \tag{7}$$

where κ is from the list parameter *KAPPAS*.

The wavelength of the optical output is set by the *Wavelength* or *Frequency* parameters. With *FrequencyUnit* setting the units to be used for the *Frequency* parameter. *FrequencyShift* specifies a constant wavelength shift from the center frequency and is modeled as linearly increasing phase.

Carrier, photon, and phase noises are added (if noise analysis is enabled in the simulation) when their corresponding *CarrierNoise*, *PhotonNoise*, and *PhaseNoise* parameters are set to 1 (default choice). These noise forces can be expressed using normalized Gaussian random processes [3][4]:

$$F_S(t) = \sqrt{\frac{2 \cdot \Gamma \cdot \beta \cdot N(t) \cdot S(t)}{\tau_n \cdot \Delta t}} \cdot x_S(t)$$

$$F_N(t) = \sqrt{\frac{2 \cdot N(t)}{\tau_n \cdot \Delta t}} \cdot x_N(t) - F_S(t) \tag{8}$$

$$F_\phi(t) = \sqrt{\frac{\Gamma \cdot \beta \cdot N(t)}{2 \cdot S(t) \cdot \tau_n \cdot \Delta t}} \cdot x_\phi(t)$$

where

- $x_S(t)$, $x_S(t)$, and $x_S(t)$ are normalized Gaussian random process
- Δt is the time step for discretization

For details on parameters related to optical mode shape please refer to the technical background for CW Source

Electrical Operation

The electrical operation of the device is determined by the parameter *ElecMode*. This parameter can be set to one of three values: *DIODE*, *POLY_VI*, or *POLY_IV*. If it is set to *DIODE* (default), the electrical model is that of a diode and diode model parameters can be used to specify its electrical characteristics.

The other two modes (*POLY_VI* and *POLY_IV*) define that a voltage/current or current/voltage relationship should be used. This relationship is specified by the list parameter *coeff* = $[p_0, p_1, p_2, \ldots, p_N]$, where N is the order of the polynomial. The values of this list specify polynomial coefficients in the form of

$$Y = p_0 + p_1 x(t) + p_2 x^2 + \ldots + p_N x^N \tag{9}$$

In *POLY_VI* mode, the voltage can be expressed as follows:

$$V(t) = p_0 + p_1 I(t) + p_2 I(t)^2 + \ldots + p_N I(t)^N \tag{10}$$

For a *POLY_IV* specification the parameter *IVType* can be set to either *RES* (default) or *CURR*. If *RES* is specified the polynomial specifies a non-linear resistor with

$$R(t) = p_0 + p_1 V(t) + p_2 V(t)^2 + \ldots + p_N V(t)^N \tag{11}$$

where $R(t)$ is the time varying resistance. If CURR is specified then

$$I(t) = p_0 + p_1 V(t) + p_2 V(t)^2 + \ldots + p_N V(t)^N \tag{12}$$

The *AntiSym* parameter can be used with the two polynomial modes to specify that the polynomial is inverted on the negative axis. This is most useful for the *POLY_IV* mode to avoid multi-valued convergence issues.

If the *ElecMode* = *Diode,* the *DiodeNoise* parameter enables (1 - default) or disables (0) noise to be added to the diode if noise analysis is enabled in the simulation.

Thermal Operation

Parameters *Rth* and *Cth* can be set to create a simple thermal sub-circuit for the device. However, the parameter *ExtTnode* can be used to specify an external temperature node to which an external thermal network can be attached.

This internal temperature is used within the electrical model. If a diode mode is specified, the temperature dependent diode equations are used (see Diode Model). The temperature dependence of the *POLY_VI* and *POLY_IV* electrical modes are specified by the polynomial list parameter *Tcoeff* =$[p_{T_0}, p_{T_1}, p_{T_2}, \ldots, p_{T_M}]$, where M is the order of the polynomial. For *POLY_VI* mode, the voltage can be expressed as follows:

$$V(t) = [p_0 + p_1 I(t) + p_2 I(t)^2 + \ldots + p_N I(t)^N] \cdot [p_{T_0} + p_{T_1} T_d + p_{T_2} T_d^{\ 2} + \ldots + p_{T_M} T_d^{\ M}] \quad (13)$$

where

- $T_d = T - T_{off}$
- T_{off} is the parameter *Toff* (offset temperature) in Kelvin
- $[p_0, p_1, p_2, \ldots, p_N]$ are given by the parameter *coeff*.

For *POLY_IV* mode, when *IVType* is *RES*, the resistance can be expressed as

$$R(t) = [p_0 + p_1 V(t) + p_2 V(t)^2 + \ldots + p_N V(t)^N] \cdot [p_{T_0} + p_{T_1} T_d + p_{T_2} T_d^{\ 2} + \ldots + p_{T_M} T_d^{\ M}] \quad (14)$$

When *IVType* is *CURR*, the current can be expressed as

$$I(t) = [p_0 + p_1 V(t) + p_2 V(t)^2 + \ldots + p_N V(t)^N] \cdot [p_{T_0} + p_{T_1} T_d + p_{T_2} T_d^{\ 2} + \ldots + p_{T_M} T_d^{\ M}] \quad (15)$$

The laser dynamics are temperature dependent indirectly through the thermal dependence of the electrical current and directly through the temperature dependent offset current, $I_{off}(t)$, defined as

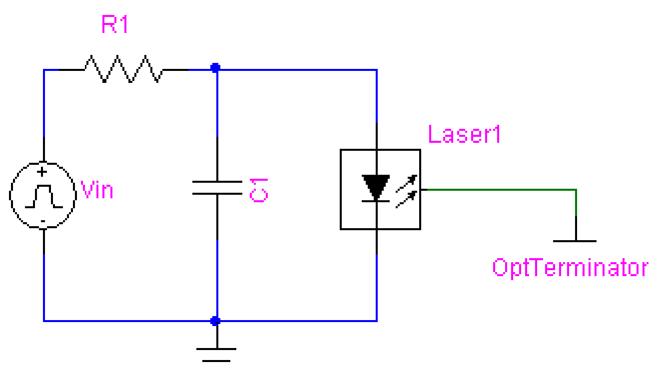
$$I_{off}(t) = p_{i_0} + p_{i_1} T_d + p_{i_2} T_d^{\ 2} + \ldots + p_{i_L} T_d^{\ L} \quad (16)$$

where polynomial coefficients are specified by the list parameter *IOffCoeff* as *IOffCoeff* = $[p_{i_0}, p_{i_1}, p_{i_2}, \ldots, p_{i_L}]$ where L order of the polynomial.

Examples

Laser with diode electrical mode

Figure 1 Laser example circuit



The following example shows a netlist for the above circuit where a laser diode is driven by a voltage pulse. The laser's electrical characteristics are defined by a diode model and the laser rate equation parameters are obtained from [1].

```
* Driving pulse voltage source
* Pulse 2-4 V, 0.2 ns rise and fall time,
* 0.2 ns pulse width and 1 ns period
Vin 1 0 PULSE 2 4 0.0 0.2ns 0.2ns 0.2ns 1n

* series resistance and shunt capacitance
R1 1 2 50
C1 2 0 50pF

* First node of the laser connected to voltage source,
* second node is connected to ground and the third optical
* node is connected to an optical terminator
Osp Laser Name=Laser1 Nodes=[2 0 3] MoName=LMOD Frequency=193.1
+ FreqShift=0.0 FrequencyUnit=THz

* Mirror is used as an optical terminator with zero reflection
Osp MIRROR Name=OptTerminator Nodes=[3] MoName=TerminatorMod Ref=0

* Laser model statement
.MODEL LMOD LASER
+ TAUN = 1ns  TAUP = 3ps
+ NumModes = 1 N0 = 1.0e+018  GAMMAS = 0.4
+ BETAS = 3e-5  EPSI = 5e-17  Qeff0 = 0.4
+ GAINS = 2.125e-6  LASERVOL = 1.5e-10  ALPHA = 5
```

```
* Laser's diode model parameters
+ level=1 BV = 3.5 N=1.3 IS=0.8e-4

* Mirror model statement
.MODEL TerminatorMod MIRROR

* Monitor current through laser
.MONITOR I Laser1 1

* Monitor optical power for laser output
.MONITOR OptPower Laser1 3 DIR=OUT POL=X

* Monitor optical chirp for laser output
.MONITOR OptChirp Laser1 3 DIR=OUT POL=X

.TRAN .01ps 1ns
.END
```

Laser with POLY_VI mode

The laser diode in the above example is replaced with a POLY_VI (voltage as a function of current).

```
.MODEL LMOD LASER
+ TAUN = 1ns  TAUP = 3ps
+ NumModes = 1 N0 = 1.0e+018  GAMMAS = 0.4
+ BETAS = 3e-5  EPSI = 5e-17  Qeff0 = 0.4
+ GAINS = 2.125e-6  LASERVOL = 1.5e-10  ALPHA = 5

* Electrical mode is POLY_VI
+ ElecMode = POLY_VI

* Coefficients for the polynomial function with order = 7
+ coeff = [2.254e9 -6.448e8  7.465e7 -4.488e6  1.496e5 -2.754e3
+           3.758e1 5.419e-2]
```

Laser with POLY_IV mode

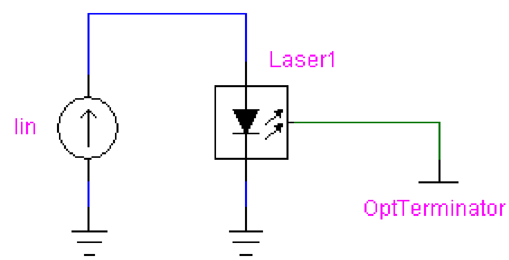
The laser diode model in the first example is replaced with a *POLY_IV* (current as a polynomial function of voltage). Current is directly expressed as function of voltage difference between the node 1 and 2, by defining *IVType* = *CURR*. The model statement is given below:

```
.MODEL LMOD LASER
+ TAUN = 1ns  TAUP = 3ps
```

```
+ NumModes = 1 N0 = 1.0e+018  GAMMAS = 0.4
+ BETAS = 3e-5  EPSI = 5e-17  Qeff0 = 0.4
+ GAINS = 2.125e-6  LASERVOL = 1.5e-10  ALPHA = 5

* Electrical mode POLY_IV and direct expression of current is used
+ ElecMode = POLY_IV  IVType = CURR

* Coefficients for the polynomial function with order = 7
+ coeff = [0.472 -1.647 2.165 -1.214 0.089 0.225 -0.014 0.0002]
```

Laser with thermal effects

Figure 2 Laser circuit exhibiting thermal effects



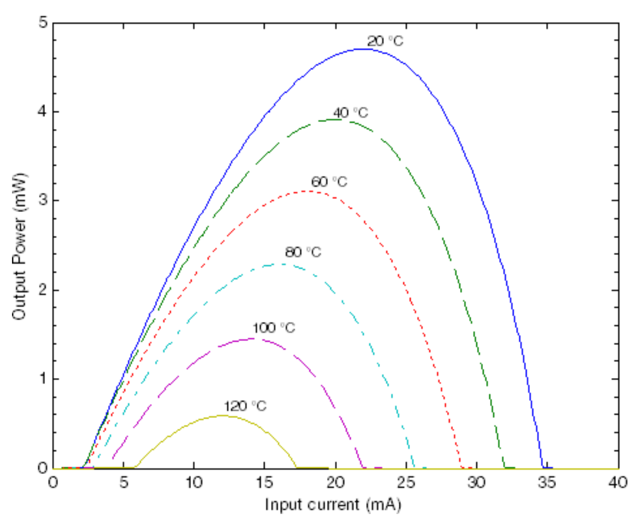
The following example shows a netlist for the above circuit. Laser power at different ambient temperature values are monitored for a DC sweep of the current source. The *ElecMode* of the laser is *POLY_VI* and the voltage-temperature dependence is described by the polynomial function as in (13). The temperature dependent offset current is also described by polynomial function as in (16). The laser rate equation parameters and the polynomial coefficients are obtained from [2].

```
* Circuit elements and connections
Iin 0 in 20mA
Osp LASER  Name=Laser1 Nodes = [in 0 laserout] MoName = Lvi
+ Wavelength = 863nm
Osp MIRROR Name=OptTerminator Nodes=[laserout] MoName=TerminatorMod

* Define the parameter AmbientTemp with default value 20
.param AmbientTemp = 20

* Set room temperature (parameterized using AmbientTemp)
.OPTION TNOM = AmbientTemp

* DC sweep of the current source from 0-40 mA (increment 0.1 mA)
* AmbientTemp parameter sweep from 20-120 (increment 20).
* DC sweep will be performed for each AmbientTemp value.
.dc Iin 0 40mA 0.1mA
```

```
+ sweep AmbientTemp 20 120 20

* Laser model statement
.Model Lvi LASER TAUN=5.0e-9 TAUP = 2.28e-12 N0 = 1.94e7
+ GAMMAS = 1.0 BETAS = 1e-6 EPSI = 0 KAPPAS = 2.6e-8
+ GAINS = 1.6e4  ElecMode = POLY_VI
+ coeff = [-4.296e9 6.683e8 -4.154e7 1.338e6 -2.439e4 275 1.721 ]
+ IOffCoeff = [1.022e-12 -2.531e-10 2.908e-7 -2.545e-5 1.246e-3 ]
+ Toff = 273.5 Rth = 2.6e3

* Optical terminator model statement
.model TerminatorMod MIRROR

* Monitor optical power
.MONITOR OptPower Laser1 3 DIR=OUT POL=X
.end
```

Figure 3 shows the simulation results for the optical power output at different ambient temperatures.

Figure 3 Simulation Results: Optical power output



References

[1] J. C. Cartledge and G. S. Burley, "The Effect of the Laser Chirping on Lightwave System Performance", J. Lightwave Technology, vol. 7, pp. 568-573, March 1989.

[2] P. V. Mena, J. J. Morikuni, S. M. Kang, A. V. Harton and K. W. Wyatt, "A Simple Rate-Equation-Based Thermal VCSEL Model", J. Lightwave Technology, vol. 17, pp. 865-872, May 1999.

[3] C. H. Henry, "Phase Noise in Semiconductor Lasers", J. Lightwave Technol., Vol. 4, No. 3, 1986, pp. 298-311.

[4] N. Schunk, K. Petermann, "Noise Analysis of Injection-Locked Semiconductor Injection Lasers", IEEE J. Quantum Electron., Vol. 22, No. 5, 1986, pp. 642-650.

MACHZEHNDER Model

Syntax

Style	Form
OptiSPICE	`.MODEL MODEL_NAME MACHZEHNDER <param1=val1> <param2=val2> ...`

Parameters

Symbol and description	Default value	Units	Value range
ExtinctionRatio Extinction ratio	20	-	]-INF, +INF[
SwitchBiasVoltage DC voltage required to turn the modulator from the OFF state to the ON state, or vice versa	4	V	]-INF, +INF[
SwitchRFVoltage RF voltage required to turn the modulator from the OFF state to the ON state, or vice versa	4	V	]-INF, +INF[
InsertionLoss The insertion loss of the Machzehdner interferometer	5	dB	[0, +INF[
ElecMode Electrical mode	RLC	-	DIODE, POLY_VI, POLY_IV, RLC
R Resistance in the RF circuit	0	ohm	[0, +INF[
L Inductance in the RF circuit	0	H	[0, +INF[
C Capacitance in the RF circuit	0	F	[0, +INF[
IVType Expression type for POLY_IV electrical mode	RES	-	RES, CURR
coeff Polynomial coefficients (if ElecMode is POLY_VI or POLY_IV)	-	-	]-INF, +INF[

Symbol and description	Default value	Units	Value range
AntiSym Option to invert the polynomial functions (POLY_VI or POLY_IV) on the negative axis	0	-	0,1
Rth Thermal resistance	0	K/W	[0, +INF[
Cth Thermal capacitance	0	J/K	[0, +INF[
Toff Temperature offset	0	K	]-INF, +INF[
Tcoeff Temperature polynomial coefficients	-	-	]-INF, +INF[

Diode Model Parameters

Symbol and description	Default value	Units	Value range
PJ PN junction periphery	0	m^2	[0, +INF[
AREA Area of the diode	1	m^2	[0, +INF[
IK (IKF, JBF) Forward knee current	0	A or A/m^2	]-INF, +INF[
IKR (JBR) Reverse knee current	0	A or A/m^2	]-INF, +INF[
RS Source ohmic resistance	0	ohm	[0, +INF[
TRS Source resistor temperature coefficient	0.0	-	]-INF, +INF[
IBV (IB) Current at breakdown voltage	1.0e-3	A	]-INF, +INF[
JSW (ISP) Saturation current from sidewall bulk junction	0	A/m	]-INF, +INF[
BV Breakdown voltage	0	V	]-INF, +INF[

Symbol and description	Default value	Units	Value range
NBV Emission coefficient at breakdown voltage	1.0	-	]-INF, +INF[
CJP Zero-bias bulk junction sidewall capacitance per meter of junction perimeter	0	F/m	[0, +INF[
TT Transition time	0	sec	[0, +INF[
FC Coefficient for forward-bias depletion capacitance formula	0.5	-	]-INF, +INF[
FCS Coefficient for forward-bias depletion source capacitance formula	0.5	-	]-INF, +INF[
NTUN Reverse tunneling non-ideality factor for source	90	-	]-INF, +INF[
JTUN Reverse tunneling non-ideality factor for junction area	0	-	]-INF, +INF[
JTUNSW Reverse tunneling non-ideality factor for junction area	0	-	]-INF, +INF[
MJSW Bulk junction sidewall grading coefficients	0.33	-	]-INF, +INF[
PHP Contact potential at bulk sidewall junction	0.8	V	]-INF, +INF[
KF Flicker noise coefficient	0	-	]-INF, +INF[
AF Flicker noise exponent	1.0	-	]-INF, +INF[
TTT1 Transit time temperature coefficient 1	0	-	]-INF, +INF[
TTT2 Transit time temperature coefficient 2	0	-	]-INF, +INF[

Symbol and description	Default value	Units	Value range
VNDS Reverse current transition point	-1	V	]-INF, +INF[
NDS Reverse bias slope (coefficient)	1	-	]-INF, +INF[
TM1 First order temperature coefficient using in computing MJ	0	1/C	]-INF, +INF[
TM2 Second order temperature coefficient using in computing MJ	0	1/C^2	]-INF, +INF[
XTI Temperature exponent of saturation current	3.0	-	]-INF, +INF[
XTITUN Exponent for the tunneling current temperature	3.0	-	]-INF, +INF[
TCV Threshold voltage temperature coefficient	0	-	]-INF, +INF[
GAP1 Initial bandgap correction factor	7.02e-4	eV/C	]-INF, +INF[
IS (JS) Bulk junction saturation current	1e-14	A or A/m^2	]-INF, +INF[
CJO (CJ0) Zero-bias capacitance	0	F	[0, +INF[
MJ (M ,EXA) Bulk junction bottom grading coefficient	0.5	-	]-INF, +INF[
PB (PHI ,VJ ,PHA) Bulk junction potential	0.8	V	]-INF, +INF[
DCAP Diode capacitor model selector	2	-	[0, +INF[
N Emission coefficient	1	-	]-INF, +INF[

Technical Background

Optical Operation

The Machzehnder structure consists of an input optical branch, which splits the incoming light into two arms, followed by two independent optical arms, which are subsequently recombined by the output optical branch. Application of an electrical signal to one of the optical arms controls the degree of interference at the output optical branch and therefore controls the output intensity.

The optical field at the output of the modulator is given by:

$$E_O(t) = \frac{E_{in}(t)}{10^{(I_L/20)}} \cdot (\gamma \cdot e^{(j \cdot \pi \cdot v_2(t)/V_{\pi RF} + j \cdot \pi \cdot v_{bias2}/V_{\pi DC})} + (1-\gamma) \cdot e^{(j \cdot \pi \cdot v_1(t)/V_{\pi RF} + j \cdot \pi \cdot v_{bias1}/V_{\pi DC})}) \quad (1)$$

where

- $E_{in}(t)$ is the input signal
- I_L is the parameter *InsertionLoss*
- $v_1(t)$ and $v_2(t)$ are the RF voltages at *CNodes* 1 and 2 respectively
- v_{bias1} and v_{bias2} are the DC bias voltages at *BNodes* 1 and 2 respectively
- $V_{\pi RF}$ is the parameter *SwitchRFVoltage*
- $V_{\pi DC}$ is the parameter *SwitchBiasVoltage*
- γ is the power splitting (combining) ratio of arm two for the input (output, respectively) Y-branch waveguide, and is given by

$$\gamma = \left(1 - \frac{1}{\sqrt{10^{e_r/10}}}\right)/2 \quad (1)$$

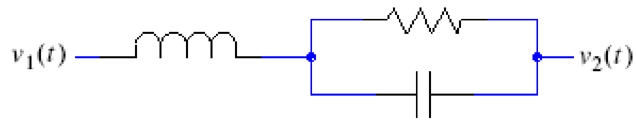
where e_r is the parameter *ExtinctionRatio.*

Electrical Operation

The electrical connection between RF voltage input nodes for the Machzehnder modulator is determined by the *ElecMode* parameter. This parameter can be set to one of three values: *DIODE*, *POLY_VI*, *POLY_IV* or *RLC*.

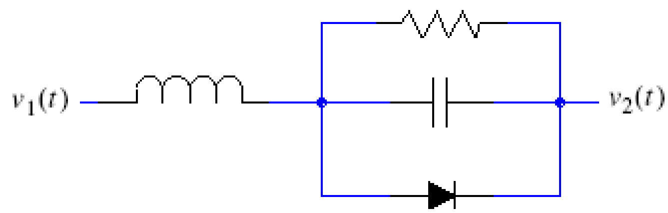
If set to *RLC* (default) the electrical model is simply a input inductor set by *L* in series with a resistor and capacitor (values set by *R* and *C*) in parallel as shown by Figure 1.

Figure 1 Machzehnder Electrical Mode: RLC



If set to *DIODE* the electrical model incorporates a spice diode in parallel with the *R* and *C* (see Figure 2) and any of the diode parameter can be used to specify its electrical characteristics.

Figure 2 Machzehnder Electrical Mode: DIODE



For *POLY_VI* and *POLY_IV* modes, the diode is replaced by a nonlinear elements whose current/voltage relationship are characterized by polynomial functions. For the details on polynomial functions see Electrical Operation of the Laser model.

Thermal Operation

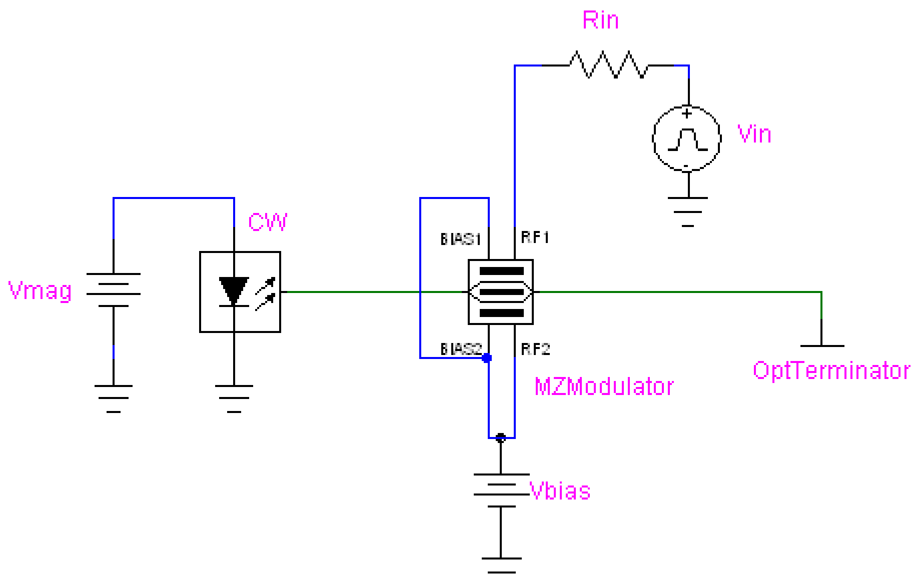
Electrical circuit elements connected between the RF input voltage nodes can have thermal effects.

Parameters *Rth* and *Cth* can be set to create a simple thermal sub-circuit for the device. However, the parameter *ExtTnode* can be used to specify an external temperature node to which an external thermal network can be attached.

This internal temperature is used within the electrical model. If a diode mode is specified, the temperature dependent diode equations are used. The temperature dependence of the *POLY_VI* and *POLY_IV* electrical modes are specified by the polynomial list parameter *Tcoeff*. For more detail on polynomial expression for *POLY_VI* and *POLY_IV* modes, see the section Thermal Operation of the Laser model.

Example

Figure 3 Machzehnder modulator example



The following example shows a netlist for the above circuit where an optical input from a continuous wave source is modulated by an electrical signal (pulse voltage) applied on the node *RF1* of the Machzehnder Modulator.

```
* Circuit elements and connections
Vmag magin 0 DC=0.5
Vbias bias 0 DC=4
Vin in 0 PULSE 0.0 4.0 1n 0.1n 0.1n 2n 0.0
Rin 1 in 100
Osp CWSOURCE Name=CW Nodes=[magin 0 cwout] MoName=CWmodel

* Machzehnder element
Osp MACHZEHNDER Name=MZModulator Nodes=[cwout mzout] CNodes=[1 bias]
+ BNodes=[bias bias] MoName=MZModel

Osp MIRROR Name=OptTerminator Nodes=[mzout] MoName=TerminatorMod

* Machzehnder model statement
.MODEL MZModel MACHZEHNDER
+ ExtinctionRatio=20 InsertionLoss=3
+ SwitchBiasVoltage=4 SwitchRFVoltage=4
+ ElecMode=RLC R=100k L=0 C=1pF

.MODEL CWmodel CWSOURCE CWSourceType=MAGPHI
```

```
.MODEL TerminatorMod MIRROR

* Monitor optical output power of the Machzehnder Modulator
.MONITOR OptPower MZModulator 2 DIR=OUT POL=X

.TRAN 0.01n 10n
.END
```

OPTELECABS Model

Syntax

Style	Form
OptiSPICE	`.MODEL MODEL_NAME OPTELECABS <param1=val1> <param2=val2> ...`

Parameters

Symbol and description	Default value	Units	Value range
GammaC Facet loss	0	-	]-INF, +INF[
taun_abs List of polynomial coefficients that determine the voltage dependent carrier lifetime	-	-	]-INF, +INF[
CoeffFile (DeviceFile) Name of the file containing measured characteristics of loss and chirp coefficient	-	-	-
ElecMode Electrical mode	RLC	-	DIODE, POLY_VI, POLY_IV, RLC
R Resistance in the RF circuit	0	ohm	[0, +INF[
L Inductance in the RF circuit	0	H	[0, +INF[
C Capacitance in the RF circuit	0	F	[0, +INF[
IVType Expression type for POLY_IV electrical mode	RES	-	RES, CURR
coeff Polynomial coefficients (if ElecMode is POLY_VI or POLY_IV)	-	-	]-INF, +INF[
Vmax Maximum voltage	1e50	V	]-INF, +INF[
Vmin Minimum voltage	-1e50	V	]-INF, +INF[

Symbol and description	Default value	Units	Value range
Imax Maximum current	1e50	A	]-INF, +INF[
Imin Minimum current	-1e50	A	]-INF, +INF[
AntiSym Option to invert the polynomial functions (POLY_VI or POLY_IV) on the negative axis	0	-	0,1
Rth Thermal resistance	0	K/W	[0, +INF[
Cth Thermal capacitance	0	J/K	[0, +INF[
Toff Temperature offset	0	K	]-INF, +INF[
Tcoeff Temperature polynomial coefficients	-	-	]-INF, +INF[

Diode Model Parameters

Symbol and description	Default value	Units	Value range
PJ PN junction periphery	0	m^2	[0, +INF[
AREA Area of the diode	1	m^2	[0, +INF[
IK (IKF ,JBF) Forward knee current	0	A or A/m^2	]-INF, +INF[
IKR (JBR) Reverse knee current	0	A or A/m^2	]-INF, +INF[
RS Source ohmic resistance	0	ohm	[0, +INF[
TRS Source resistor temperature coefficient	0.0	-	]-INF, +INF[
IBV (IB) Current at breakdown voltage	1.0e-3	A	]-INF, +INF[

Symbol and description	Default value	Units	Value range
JSW (ISP) Saturation current from sidewall bulk junction	0	A/m	]-INF, +INF[
BV Breakdown voltage	0	V	]-INF, +INF[
NBV Emission coefficient at breakdown voltage	1.0	-	]-INF, +INF[
CJP Zero-bias bulk junction sidewall capacitance per meter of junction perimeter	0	F/m	[0, +INF[
TT Transition time	0	sec	[0, +INF[
FC Coefficient for forward-bias depletion capacitance formula	0.5	-	]-INF, +INF[
FCS Coefficient for forward-bias depletion source capacitance formulae	0.5	-	]-INF, +INF[
NTUN Reverse tunneling non-ideality factor for source	90	-	]-INF, +INF[
JTUN Reverse tunneling non-ideality factor for junction area	0	-	]-INF, +INF[
JTUNSW Reverse tunneling non-ideality factor for junction area	0	-	]-INF, +INF[
MJSW Bulk junction sidewall grading coefficients	0.33	-	]-INF, +INF[
PHP Contact potential at bulk sidewall junction	0.8	V	]-INF, +INF[
KF Flicker noise coefficient	0	-	]-INF, +INF[
AF Flicker noise exponent	1.0	-	]-INF, +INF[

Symbol and description	Default value	Units	Value range
TTT1 Transit time temperature coefficient 1	0	-	]-INF, +INF[
TTT2 Transit time temperature coefficient 2	0	-	]-INF, +INF[
VNDS Reverse current transition point	-1	V	]-INF, +INF[
NDS Reverse bias slope (coefficient)	1	-	]-INF, +INF[
TM1 First order temperature coefficient using in computing MJ	0	1/C	]-INF, +INF[
TM2 Second order temperature coefficient using in computing MJ	0	1/C^2	]-INF, +INF[
XTI Temperature exponent of saturation current	3.0	-	]-INF, +INF[
XTITUN Exponent for the tunneling current temperature	3.0	-	]-INF, +INF[
TCV Threshold voltage temperature coefficient	0	-	]-INF, +INF[
GAP1 Initial bandgap correction factor	7.02e-4	eV/C	]-INF, +INF[
IS (JS) Bulk junction saturation current	1e-14	A or A/m^2	]-INF, +INF[
CJO (CJ0) Zero-bias capacitance	0	F	[0, +INF[
MJ (M, EXA) Bulk junction bottom grading coefficient	0.5	-	]-INF, +INF[
PB (PHI ,VJ ,PHA) Bulk junction potential	0.8	V	]-INF, +INF[
DCAP Diode capacitor model selector	2	-	[0, +INF[

Symbol and description	Default value	Units	Value range
N Emission coefficient	1	-	]-INF, +INF[

Technical Background

Optical Operation

Electro-Absorption Modulator (EAM) which is typically used to modulate a constant amplitude optical source to produce a bit stream. An EAM functions by applying a bias voltage to semiconductor ridge waveguide structure altering the carrier density (N) present in the structure. The complex index of refraction ($\bar{n} = n_r + jn_i$) of the waveguide is a function of number of carriers present and the applied electric field. Changing the applied bias thus produces a variation in both phase and amplitude of the propagating signal and can be used to suppress or modulate the input optical signal. The degree of modulation of the optical signal is directly related to the length of the waveguide. For an incident signal $E_i e^{j\phi_i}$ on a device characterized by a length L and wavevector k_0, where n_r and n_i are both functions of the applied bias V and N, we have for the propagation of a single optical signal through the waveguide, the following expression for the output field [1].

$$E_o e^{j\phi_o} = E_i e^{-k_0 L n_i} e^{j(\phi_i - k_0 L n_r)} \tag{1}$$

where $\Gamma = 2k_0 L n_i$ is a loss coefficient and output phase is $\phi_o = \phi_i - k_0 L n_r$. For an EAM, n_i and n_r are complicated functions of N and V. Typically, a device is characterized by measuring the attenuation and chirp as function of V and the incident optical power $S_i = E_i^2$. Using such measurements two parameters $\Gamma(V, N)$ (which defines the loss) and $\alpha(V, N)$ (a chirp coefficient) can be determined.

Using these parameters a physical model of the EAM can be specified [1]. An internal rate equation determines the number of photo-carriers:

$$\frac{dN}{dt} = \frac{\lambda}{hc} e^{-\Gamma_c} (1 - e^{-\Gamma(V, N) + 2\Gamma_c}) S_i - \frac{N}{\tau} \tag{2}$$

where λ is the optical wavelength, c the speed of light, h Planck's constant, Γ_c the fiber facet loss and the τ carrier lifetime. The magnitude and phase of the output field are determined by:

$$E_o(t) = E_i e^{-\Gamma/2}$$
$$\frac{d\phi_0}{dt} = \frac{\alpha(V,N)}{2} \cdot \frac{d\Gamma(V,N)}{dt} \quad (3)$$

The parameter *GammaC* set the facet loss (Γ_c). The parameter *taun_abs* is the list of polynomial coefficients that determine the voltage dependent carrier lifetime τ as

$$\tau = p_0 + p_1 V + p_2 V^2 + \ldots + p_L V^L \quad (4)$$

where

- $[p_0, p_1, p_2, \ldots, p_N]$ are the polynomial coefficients given by *taun_abs*
- V is the voltage difference between *CNodes* 1 and 2
- L is the order of the polynomial

The measured characteristics $\Gamma(V,N)$ and $\alpha(V,N)$ can be specified in a text file set by the parameter *DeviceFile*. The format of this file is:

- dimension of the matrix
- range of fitted carrier density
- range of fitted voltage
- matrix representing polynomial coefficients for $\Gamma(V,N)$ function
- matrix representing polynomial coefficients for $\alpha(V,N)$ function

The $\Gamma(V,N)$ and $\alpha(V,N)$ are evaluated in the form of

$$F(N,V) = \sum_{i=1}^{M} \sum_{j=1}^{K} A_{i,j} \cdot V^{(j-1)} \cdot N^{(i-1)} \quad (5)$$

where

- M is the fitted number of carriers
- K is the fitted number of voltages
- A is the coefficient matrix.

Electrical Operation

The electrical connection between the electrical input nodes (*CNodes*) for the Electro-Absorption Modulator is determined by the *ElecMode* parameter. This parameter can be set to one of three values: *DIODE*, *POLY_VI*, *POLY_IV* or *RLC* (same as that of Machzehnder Modulator). For more details see the section Electrical Operation of the Machzehnder model.

Thermal Operation

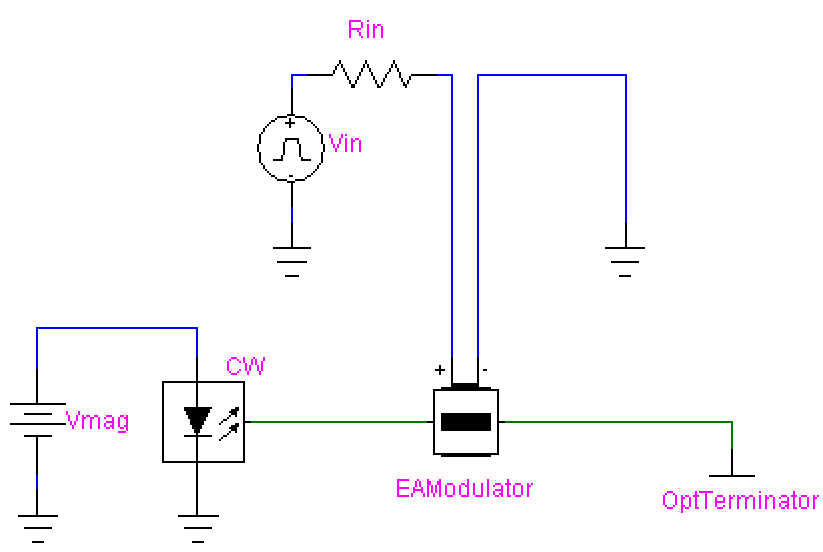
Electrical circuit elements connected between the RF input voltage nodes can have thermal effects.

Parameters *Rth* and *Cth* can be set to create a simple thermal sub-circuit for the device. However, the parameter *ExtTnode* can be used to specify an external temperature node to which an external thermal network can be attached.

This internal temperature is used within the electrical model. If a diode mode is specified, the temperature dependent diode equations are used. The temperature dependence of the *POLY_VI* and *POLY_IV* electrical modes are specified by the polynomial list parameter *Tcoeff*. For more detail on polynomial expression for *POLY_VI* and *POLY_IV* modes, see the section Thermal Operation of the Laser model.

Examples

Figure 1 Electro-Absorption Modulator



The following example shows a netlist for the above circuit where an optical input from a continuous wave source is modulated by an electrical signal (pulse voltage) applied on the node Control node (CNodes) of the Electro-Absorption Modulator. The measured characteristics $\Gamma(V, N)$ and $\alpha(V, N)$ are given in the file Device.pol.

```
* Circuit elements and connections
Vmag magin 0 DC=0.32
Vin in 0 PULSE -1.5 0.0 1ns 0.4ns 0.4ns 2ns 4ns
Rin in 1 100
Osp CWSOURCE Name=CW Nodes=[magin 0 absin] MoName=CWModel

* Electro-Absorption Modulator (EAM) element
Osp OPTELECABS Name=EAModulator Nodes=[absin absout]
+ CNodes=[1 0] MoName=absmodel

Osp MIRROR Name=OptTerminator Nodes=[ absout ] MoName=TerminatorMod

* EAM model statement
.MODEL absmodel OPTELECABS GammaC = 4.16
+ taun_abs = [469.06p 1002.35p 962.14p 411.89p 79.57p 5.69p]
+ DeviceFile = Device.pol
+ R=100k C=2e-12

.MODEL CWmodel CWSOURCE
.MODEL TerminatorMod MIRROR

* Monitor input and output optical power
.MONITOR OptPower CW 3 DIR=OUT POL=X
.MONITOR OptPower EAModulator 2 DIR=OUT POL=X

.TRAN 0.01n 20n
.END
```

Device file containing measured characteristics of $\Gamma(V, N)$ and $\alpha(V, N)$

The device file Device.pol used in this example is given below. Any line starts with the '*' character is a comment.

```
* Coefficient matrix dimension
2 6

* Range of fitted carriers density values
51760.8 819626
```

```
* Range of fitted voltage
-2 0

* Gamma parameter coefficients
0.89562 -0.203093 -5.28616 -9.32171 -11.1176 -2.46292
3.43546e-4 -3.38207e-3 1.60636e-3 2.13946e-3 9.38282e-4 1.31759e-3

* Alpha parameter coefficients
0.978684 2.85313 2.49325 -5.71624 -9.38647 -3.49438
6.5574e-5 -1.54271e-3 -4.59328e-3 -2.39697e-3 -1.2671e-3 0.0747592e-3
```

The first line specifies the coefficient matrix dimension which is number of fitted carrier density values (number of rows) times number of fitted voltage values (number of columns). In the second line, the range of fitted carrier density values are given. Third line specifies the range of fitted voltage. Following these lines Gamma and Alpha coefficient matrices are given. These matrices must be entered such that each line corresponds to a row entry while each single value in a line corresponds to a column.

References

[1] N. Cheng, John C. Cartledge, “Measurement-Based Model for MQW Electroabsorption Modulators”, Journal of Lightwave Technology, VOL. 23, NO. 12, December 2005, pp. 4265-4269.

OPTPHASEDELAY Model

Syntax

Style	Form
OptiSPICE	.MODEL MODEL_NAME OPTPHASEDELAY <*param1=val1*> <*param2=val2*> ...

Parameters

Symbol and description	Default value	Units	Value range
PhaseDelays List of phase delay values for each mode	-	rad	[0, +INF[
a (Gain) Optical phase delay gain	1	-	]-INF, +INF[

Technical Background

This element adds a phase shift to the optical field as given by

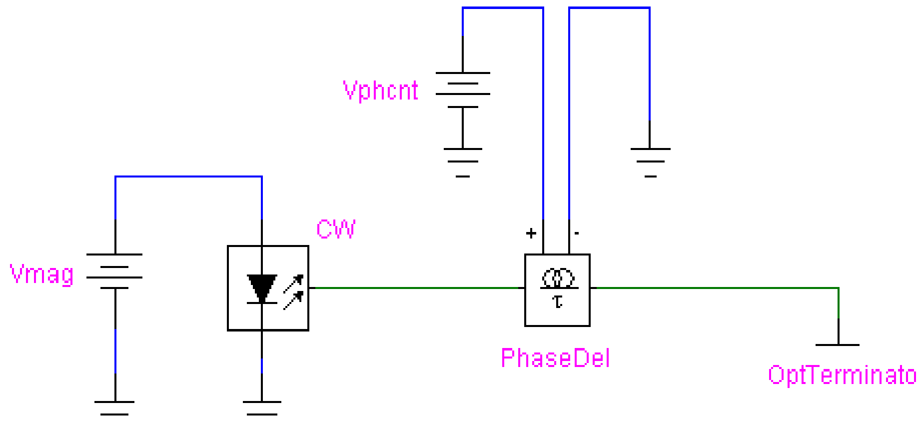
$$\phi_{out_i} = \phi_{in_i} + a(V_1 - V_2) + \phi_i \tag{1}$$

where

- ϕ_{out_i} is the phase of the output for i th mode
- ϕ_{in_i} is the phase of the input field for i th mode
- a is the parameter *a*
- V_1, V_2 are the control node voltages
- ϕ_i is the i th value (corresponds to the i th mode) in the list parameter *PhaseDelays* which is specified as *PhaseDelays* = $[\phi_1, \phi_2, \phi_3, \ldots, \phi_N]$

Example

Figure 1 Optical Phase Delay



The following example shows a netlist for the above circuit where a phase delay is applied through the Phase Delay element.

```
* Circuit elements and connections
Vmag magin 0 0.5
Osp CWSOURCE Name=CW Nodes=[magin 0 phin] MoName=CWmodel

* Phase delay element
Osp OPTPHASEDELAY Name=PhaseDel Nodes=[phin phout] CNodes=[cnt 0]
+ MoName=PhaseDelModel

* Voltage source connected to the control node of the
* phase delay element (adds a phase delay = pi/2)
Vphcnt cnt 0 1.570796

Osp MIRROR Name=OptTerminator Nodes=[phout] MoName=TerminatorMod

* Phase delay model statement
.MODEL PhaseDelModel OPTPHASEDELAY a=1.0

.MODEL CWmodel CWSOURCE
.MODEL TerminatorMod MIRROR

* Monitor input and output optical power
.MONITOR OptPhase CW 3 DIR=OUT POL=X
.MONITOR OptPhase PhaseDel 2 DIR=OUT POL=X

.TRAN 0.01n 5n
```

```
.END
```

PHOTODIODE Model

Syntax

Style	Form
OptiSPICE	`.MODEL MODEL_NAME PHOTODIODE` *<param1=val1> <param2=val2>* ...

Parameters

Symbol and description	Default value	Units	Value range
PDType Type of photodiode	LINEAR	-	LINEAR, PIN, APD
PDEFF Basic responsivity of the photodetector	1	A/W	[0+, +INF[
Eta External quantum efficiency	0.8	1/s	[0+, +INF[
FreqDomainModel Frequency domain filter model type	IntCap	-	IntCap, APDModel, PINModel
Vn Electron velocity	0	m/s	[0, +INF[
Vp Hole velocity	0	m/s	[0, +INF[
DepWidth Depletion width	0.88	m	[0, +INF[
AbsWidth Absorption width	0.88	m	[0, +INF[
Alpha Absorption coefficient	0	1/m	[0, +INF[
Tau_m Characteristic avalanche time constant	0	s/rad	[0, +INF[
Gain (M,APDGain) Avalanche gain (set to one for no avalanche phenomena)	1	-	[0, +INF[

Symbol and description	Default value	Units	Value range
Eh Emission rate for holes trapped at the heterojunction interface	0	1/s	[0, +INF[
Cext External parallel junction capacitance	0	F	[0, +INF[
L Series inductance	0	H	[0, +INF[
RShunt Parallel junction resistance	0	ohm	[0, +INF[
RS (RSeries) Series resistance	0	ohm	[0, +INF[
DiodeNoise Enable diode noise	0	-	0,1
CarrierNoise Enable carrier noise	1	-	0,1
PhotonNoise Enable photon noise	0	-	0,1
NoiseModel Photodiode noise model type	Gaussian	-	Gaussian, Poisson, WMC
IonRatio Ionization ratio of holes to electrons for WMC noise	0.88	-	[0, +INF[
Rth Thermal resistance	0	K/W	[0, +INF[
Cth Thermal capacitance	0	J/K	[0, +INF[

Diode Model Parameters

Symbol and description	Default value	Units	Value range
PJ PN junction periphery	0	m^2	[0, +INF[
AREA PN junction area	1	m^2	[0, +INF[

Symbol and description	Default value	Units	Value range
IK (IKF ,JBF) Forward knee current	0	A or A/m^2	]-INF, +INF[
IKR (JBR) Reverse knee current	0	A or A/m^2	]-INF, +INF[
TRS Source resistor temperature coefficient	0.0	-	]-INF, +INF[
IBV (IB) Current at breakdown voltage	1.0e-3	A	]-INF, +INF[
JSW (ISP) Saturation current from sidewall bulk junction	0	A/m	]-INF, +INF[
BV Breakdown voltage	0	V	]-INF, +INF[
NBV Emission coefficient at breakdown voltage	1.0	-	]-INF, +INF[
CJP Zero-bias bulk junction sidewall capacitance per meter of junction perimeter	0	F/m	[0, +INF[
TT Transition time	0	sec	[0, +INF[
FC Coefficient for forward-bias depletion capacitance formula	0.5	-	]-INF, +INF[
FCS Coefficient for forward-bias depletion periphery capacitance formulae	0.5	-	]-INF, +INF[
NTUN Reverse tunneling non-ideality factor for source	90	-	]-INF, +INF[
JTUN Reverse tunneling non-ideality factor for junction area	0	-	]-INF, +INF[
JTUNSW Reverse tunneling non-ideality factor for junction area	0	-	]-INF, +INF[

Symbol and description	Default value	Units	Value range
MJSW Bulk junction sidewall grading coefficients	0.33	-	]-INF, +INF[
PHP Contact potential at bulk sidewall junction	0.8	V	]-INF, +INF[
KF Flicker noise coefficient	0	-	]-INF, +INF[
AF Flicker noise exponent	1.0	-	]-INF, +INF[
TTT1 Transit time temperature coefficient 1	0	-	]-INF, +INF[
TTT2 Transit time temperature coefficient 2	0	-	]-INF, +INF[
VNDS Reverse current transition point	-1	V	]-INF, +INF[
NDS Reverse bias slope (coefficient)	1	-	]-INF, +INF[
TM1 First order temperature coefficient using in computing MJ	0	1/C	]-INF, +INF[
TM2 Second order temperature coefficient using in computing MJ	0	1/C^2	]-INF, +INF[
XTI Temperature exponent of saturation current	3.0	-	]-INF, +INF[
XTITUN Exponent for the tunneling current temperature	3.0	-	]-INF, +INF[
TCV Threshold voltage temperature coefficient	0	-	]-INF, +INF[
GAP1 Initial bandgap correction factor	7.02e-4	eV/C	]-INF, +INF[
IS (JS) Bulk junction saturation current	1e-14	A or A/m^2	]-INF, +INF[

Symbol and description	Default value	Units	Value range
CJO (CJ0) Zero-bias capacitance	0	F	[0, +INF[
MJ (M ,EXA) Bulk junction bottom grading coefficient	0.5	-	]-INF, +INF[
PB (PHI ,VJ ,PHA) Bulk junction potential	0.8	V	]-INF, +INF[
DCAP Diode capacitor model selector	2	-	[0, +INF[
N Emission coefficient	1	-	]-INF, +INF[

Technical Background

Photodetectors are modeled using an electrical diode and a photo-current which is proportional to the optical intensity at the input. The relationship of the photo-current to the optical intensity is given by a frequency domain filter response [1] that is synthesized into a circuit.

The basic photo responsivity of the diode is determined by the parameter *PDEFF*. If *PDEFF* is not given, while *Eta* (external quantum efficiency which defines the ratio between number of electrons generated and the number of photons absorbed per unit time) is given, the basic responsivity can be calculated as follows

$$R_{ph} = \frac{\eta q}{h\nu} \tag{1}$$

where

- R_{ph} is the basic responsivity
- η is the parameter *Eta*
- $h\nu$ is the photon energy per unit time, where h is the Planck's constant and ν is the optical frequency
- q is the elementary charge.

The parameter *PDType* specifies the type of diode to be used:

- *LINEAR* - No diode model used and no current filter is used. Simple linear relationship between the photocurrent, $i_{ph}(t)$, and the optical power, $P_o(t)$, given by $i_{ph}(t) = PDEFF \cdot P_o(t)$.
- *PIN* - Includes electrical diode model. The photocurrent generated is $i_{ph}(t) = PDEFF \cdot P_o(t)$ plus the plus effects due to the transit time of electrons and holes. Here no avalanche phenomena (*Gain* or *M* = 1) is used.
- *APD* - Includes electrical diode model. The photocurrent generated is $i_{ph}(t) = PDEFF \cdot P_o(t)$ plus the effects due to the transit time of electrons and holes. Avalanche phenomena (*Gain* or *M* > 1) is used here.

For the PIN and APD cases the photo current can be given by [1]

$$i_{ph}(t) = \frac{q}{W}[v_n N(t) + v_p P(t) + v_n N_s(t)] \tag{2}$$

where

- v_n and v_p are the parameters *Vn* and *Vp* respectively
- $N(t)$, $P(t)$, and $N_s(t)$ are the numbers of mobile primary electrons, primary holes, and secondary electrons in the depletion region respectively.
- W is the parameter *DepWidth*
- q is the elementary charge.

For PIN diode, only effects from primary holes and electrons are included. Complete formulation of $N(t)$, $P(t)$, and $N_s(t)$ are given in [1]. The parameters *Vn*, *Vp*, *Tau_m*, *Gain*, *AbsWidth*, *DepWidth*, *Alpha*, and *Eh* are used in modeling these equations.

This photo-current is then placed in parallel with a diode unless *LINEAR* mode is used. This configuration with addition of series resistance (parameter *RS*), a parallel resistance (parameter *Rshunt*), a series inductance (parameter *L*) and an parallel capacitance (parameter *Cext*) forms the electrical photo-diode model.

If the parameter *FreqDomainModel* is set to *IntCap*, only the intrinsic diode capacitance and *Rs*, *Rshunt*, *Cext* and *L* are present. If set to *PINModel* or *APDModel,* the filter is inserted implementing the frequency response equations given in [1].

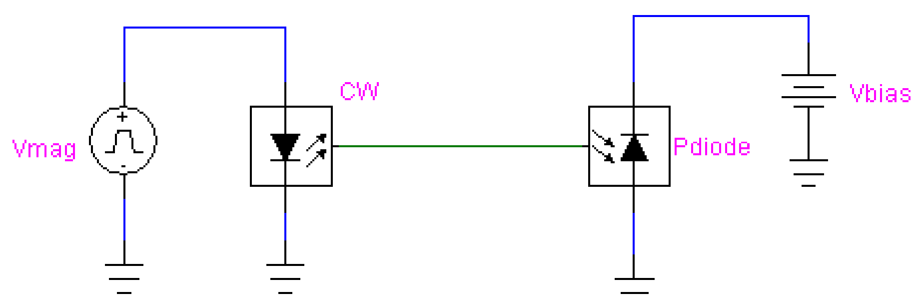
The noise is generated from three possible sources: diode noise which uses the diode noise model, carrier noise, and photon noise. Parameters *DiodeNoise*, *CarrierNoise*, and *PhotonNoise* determine if the above noise sources are to be enabled or disabled. Carrier noise can be described by three possible models: Gaussian, Poisson, and WMC (probability density function given by Webb, McIntyre, and Conradi) [2][3][4]. The parameter *NoiseModel*, which can be set to either *Gaussian*, *Poisson*, or *WMC*, determines the type of carrier noise model to be used.

Thermal Operation

Parameters *Rth* and *Cth* can be set to create a simple thermal sub-circuit for the device. However, the parameter *ExtTnode* can be used to specify an external temperature node to which an external thermal network can be attached. This internal temperature is used within the electrical model. If a diode model is specified the temperature dependent diode equations are used.

Examples

Figure 1 Photodiode circuit



In this circuit, a CW Source is connected to a Photodiode. The Photodiode is reverse biased using a DC bias source, Vbias. Linear, PIN, and APD diode models are used for the Photodiode model in the following examples.

Linear model

The netlist given below for the above circuit includes a linear model.

```
* Circuit elements and connections
Vmag magin 0 PULSE 0.0 0.5 0.0 0.1ns 0.1ns 0.8ns 2ns
Osp CWSOURCE Name=CW Nodes=[magin 0 pdin] MoName=CWMOD

* Photodiode element statement
Osp PHOTODIODE Name=Pdiode Nodes=[pdin 0 bias] MoName=PDModel
```

```
* Bias source
Vbias bias 0 5

* Photodiode model statement responsivity = 1 A/W
.MODEL PDModel PHOTODIODE  PDType = LINEAR PDeff = 1

.MODEL CWMod CWSOURCE

* Monitor optical power input and photodiode current
.MONITOR OptPower CW 3 DIR=OUT POL=X
.MONITOR I Pdiode 3

.TRAN 0.001ns 2ns
.END
```

PIN model

The Photodiode model statement for the linear case can be replaced with the following PIN diode model:

```
.MODEL PDModel PHOTODIODE  PDType = PIN
+ PDeff = 1 FreqDomainModel = PINModel
+ Vn = 7e4 Vp = 4.8e4 alpha = 1.15e6 tau_m = 2.6526e-12
+ DepWidth = 2.7e-6 AbsWidth = 2.7e-6
+ Cext = 0.1p RS = 50 L = 0.3n
```

APD model

In the following model statement, avalanche phenomena is included with the avalanche gain of 40. Also carrier noise are enabled and the noise model type is set to WMC.

```
.MODEL PDModel PHOTODIODE  PDType = APD
+ PDeff = 1 FreqDomainModel = APDModel
+ Vn=7e4 Vp=4.8e4 alpha=1.15e6 tau_m=2.6526e-12
+ DepWidth=2.7e-6 AbsWidth=2.0e-6
+ xt = 0.7e-6 eh = 0.25e12 Gain = 40
+ Cext = 0.1p RS = 50 L = 0.3n
+ CarrierNoise = 1 NoiseModel = WMC IonRatio = 0.88
```

References

[1] Campbell, J.C., Johnson, B.C., Qua, G.J., and Tsang, W.T., "Frequency response of InP/InGaAsP/InGaAs avalanche photodiodes", J. Lightwave Technology, Vol. 7, pp. 778-784, May 1989.

[2] Tang, J.T.K.and Letaief, K.B., "The use of WMC distribution for performance evaluation of APD optical communication systems", IEEE Trans. on Commun., Vol. 46, No. 2, 1998, pp. 279-285.

[3] Baker, K.R, "On the WMC density as an inverse Gaussian probability density", IEEE Trans. on Commun., Vol. 44, No. 1, 1996, pp. 15-17.

[4] Ascheid, G., "On the generation of WMC-distributed random numbers", IEEE Trans. on Commun., Vol. 38, No. 12, 1990, pp. 2117 - 2118.

LED Model

Syntax

Style	Form
OptiSPICE	`.MODEL MODEL_NAME LED <param1=val1> <param2=val2> ...`

Parameters

Symbol and description	Default value	Units	Value range
Frequency (f0) Center frequency	193.1	-	[0, +INF[
Bandwidth 3-dB bandwidth	6	-	[0, +INF[
FrequencyUnit Frequency unit	THz	-	Hz, THz, nm
PolarCoeff Magnitude sharing coefficient for X and Y polarizations	1.0	-	[0,1]
ModeCoeff List of coefficients for the magnitude of each mode	-	-	[0, +INF[
ElecMode Electrical operation mode of the LED: as a diode (DIODE), voltage as a polynomial function of current (POLY_VI), or current as a polynomial function of voltage (POLY_IV)	DIODE	-	DIODE, POLY_VI, POLY_IV
AntiSym Option to invert the polynomial functions (POLY_VI or POLY_IV) on the negative axis	0	-	0,1
IVType Expression type for POLY_IV mode: direct expression of current (CURR) or indirect expression through resistance (RES)	RES	-	RES, CURR
coeff Polynomial coefficients (if ElecMode is POLY_VI or POLY_IV)	-	-	]-INF, +INF[

Symbol and description	Default value	Units	Value range
Toff Temperature offset	0	K	]-INF, +INF[
Tcoeff Temperature polynomial coefficients	-	-	]-INF, +INF[
IOffCoeff Temperature dependent offset current coefficients	-	-	]-INF, +INF[
ETA Current-injection efficiency	1.0	-	]-INF, +INF[
Rth Thermal resistance	0	K/W	[0, +INF[
Cth Thermal capacitance	0	J/K	[0, +INF[
DiodeNoise Enable diode noise	1	-	0,1

Diode Model Parameters

Symbol and description	Default value	Units	Value range
PJ PN junction periphery	0	m^2	[0, +INF[
AREA PN junction area	1	m^2	[0, +INF[
IK (IKF ,JBF) Forward knee current	0	A or A/m^2	]-INF, +INF[
IKR (JBR) Reverse knee current	0	A or A/m^2	]-INF, +INF[
RS Source ohmic resistance	0	ohm	[0, +INF[
TRS Source resistor temperature coefficient	0.0	-	]-INF, +INF[
IBV (IB) Current at breakdown voltage	1.0e-3	A	]-INF, +INF[

Symbol and description	Default value	Units	Value range
JSW (ISP) Saturation current from sidewall bulk junction	0	A/m	]-INF, +INF[
BV Breakdown voltage	0	V	]-INF, +INF[
NBV Emission coefficient at breakdown voltage	1.0	-	]-INF, +INF[
CJP Zero-bias bulk junction sidewall capacitance per meter of junction perimeter	0	F/m	[0, +INF[
TT Transition time	0	sec	[0, +INF[
FC Coefficient for forward-bias depletion capacitance formula	0.5	-	]-INF, +INF[
FCS Coefficient for forward-bias depletion periphery capacitance formulae	0.5	-	]-INF, +INF[
NTUN Reverse tunneling non-ideality factor for source	90	-	]-INF, +INF[
JTUN Reverse tunneling non-ideality factor for junction area	0	-	]-INF, +INF[
JTUNSW Reverse tunneling non-ideality factor for junction area	0	-	]-INF, +INF[
MJSW Bulk junction sidewall grading coefficients	0.33	-	]-INF, +INF[
PHP Contact potential at bulk sidewall junction	0.8	V	]-INF, +INF[
KF Flicker noise coefficient	0	-	]-INF, +INF[
AF Flicker noise exponent	1.0	-	]-INF, +INF[

Symbol and description	Default value	Units	Value range
TTT1 Transit time temperature coefficient 1	0	-	]-INF, +INF[
TTT2 Transit time temperature coefficient 2	0	-	]-INF, +INF[
VNDS Reverse current transition point	-1	V	]-INF, +INF[
NDS Reverse bias slope (coefficient)	1	-	]-INF, +INF[
TM1 First order temperature coefficient using in computing MJ	0	1/C	]-INF, +INF[
TM2 Second order temperature coefficient using in computing MJ	0	1/C^2	]-INF, +INF[
XTI Temperature exponent of saturation current	3.0	-	]-INF, +INF[
XTITUN Exponent for the tunneling current temperature	3.0	-	]-INF, +INF[
TCV Threshold voltage temperature coefficient	0	-	]-INF, +INF[
GAP1 Initial bandgap correction factor	7.02e-4	eV/C	]-INF, +INF[
IS (JS) Bulk junction saturation current	1e-14	A or A/m^2	]-INF, +INF[
CJO (CJ0) Zero-bias capacitance	0	F	[0, +INF[
MJ (M, EXA) Bulk junction bottom grading coefficient	0.5	-	]-INF, +INF[
PB (PHI, VJ, PHA) Bulk junction potential	0.8	V	]-INF, +INF[
DCAP Diode capacitor model selector	2	-	[0, +INF[

Symbol and description	Default value	Units	Value range
N Emission coefficient	1	-	]-INF, +INF[

Technical Background

In the Light Emitting Diode (LED) model,the mean of the optical power is a function of the current through diode. The conversion of the current into optical power is described by the responsivity of the LED

$$P = \eta \cdot h \cdot f \cdot \frac{i(t)}{q} \tag{1}$$

where

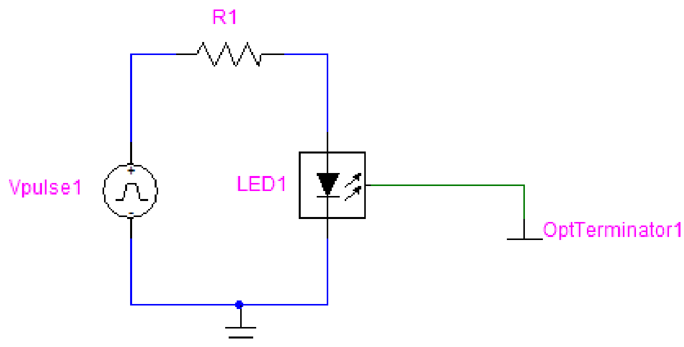
- η is the quantum efficiency given by parameter Eta
- f is the emission frequency
- q is the electron charge
- $i(t)$ is the current through diode.

To simulate LED, transient noise simulation must be enabled since the emitted photons have random phases and the device is an incoherent optical source.

By default, electrical operation is modeled as semiconductor diode, properties of which are defined by the diode model parameters. Current-voltage relationship of the LED can also be expressed as a polynomial function if the parameter *ElecMode* is set to *POLY_VI*, or *POLY_IV*. For more details on electrical and thermal operations, see the sections Electrical Operation and Thermal Operation of the Laser model.

Example

Figure 1 LED example



The netlist for the above circuit is given as follows:

```
* Circuit elements
Vpulse1 1 0 PULSE 0.0 5 0.2n 0.05n 0.05n 0.15n 0.512n
R1 1 2 50

* LED element statement
Osp LED Name=LED1 Nodes=[ 2 0 LO ] MoName=LED_MODEL
+ Frequency=193.1 Bandwidth=6 FrequencyUnit=THz

Osp MIRROR Name=OptTerminator1 Nodes=[ LO ] MoName=TERMINATOR_MODEL

* LED model statement
.MODEL LED_MODEL LED IsPolarized = 1
+ ETA = 0.05 DiodeNoise = 0 PolarCoeff = 0.5

.MODEL TERMINATOR_MODEL MIRROR IsPolarized = 1

* Trnasient simulation - noise simulation enabled
.TRAN 0.015625p 1.024n NoiseSim=1 MaxBandwidth=6.4e+013

.MONITOR I LED1 1
.MONITOR OptFields LED1 3 DIR=OUT

.END
```

Optical Models Library

This section contains information on the following models

- OPTGAIN Model
- XCOUPLER Model
- SMFIBER Model
- MMFIBER Model
- FREESPACE Model
- OCONN Model
- MIRROR Model
- OPTCHANNELFILTER Model
- OPTFFT Model
- OMNIOCONN Model
- MULTILAYERFLITER (WAVEGUIDE) Model
- OPTRING Model
- OPTISYSINOPT Model
- OPTAMPM Model

Notes:

OPTGAIN Model

Syntax

Style	Form
OptiSPICE	`.MODEL MODEL_NAME OPTGAIN <param1=val1> <param2=val2> ...`

Parameters

Symbol and description	Default value	Units	Value range
Gain (FwdGain) Power gain factor (port 1 to port 2)	1	-	[0, +INF[
Atten (FwdAtten) Power loss factor (port 1 to port 2)	1	-	[0, +INF[
RevGain Power gain factor (port 2 to port 1)	1	-	[0, +INF[
RevAtten Power loss factor (port 2 to port 1)	1	-	[0, +INF[
GaindB (FwdGaindB) Power gain in dB (port 1 to port 2)	0	dB	]-INF, +INF[
AttendB (FwdAttendB) Power loss in dB (port 1 to port 2)	0	dB	]-INF, +INF[
RevGaindB Power gain in dB (port 2 to port 1)	0	dB	]-INF, +INF[
RevAttendB Power loss in dB (port 2 to port 1)	0	dB	]-INF, +INF[
NoiseFigure Determines the amplifier noise figure (port 1 to port 2)	0	dB	]-INF, +INF[
RevNoiseFigure Determines the amplifier noise figure (port 2 to port 1)	0	dB	]-INF, +INF[
PhaseShift (FwdPhaseShift) Phase shift (port 1 to port 2)	0	rad	]-INF, +INF[

Symbol and description	Default value	Units	Value range
RevPhaseShift Phase shift (port 2 to port 1)	0	rad	]-INF, +INF[

Technical Background

The OPTGAIN model is used to specify the parameters of an optical gain/attenuation element. The attenuation or gain of the element can be specified by using *Gain/Atten/RevGain/RevAtten* and corresponding dB parameters (*GaindB, AttendB*, etc.). The dB parameters take high priority over its corresponding *Gain/Atten* parameters. Therefore, if corresponding dB parameters is given, gain/attenuation is calculated from it in the form of $10^{x/10}$.

If both gain and attenuation parameters are given, the resultant gain is given by

$$G = \frac{g_0}{\alpha_0} \quad (1)$$

where

- G is the resultant gain
- g_0 is the gain given by *Gain* or *GaindB* parameter
- α_0 is the attenuation given by *Atten* or *AttendB* parameter.

Noise spectral density at output is calculated as follows

$$S = (G \times 10^{Nf/10} - 1) \cdot h\nu \quad (2)$$

where

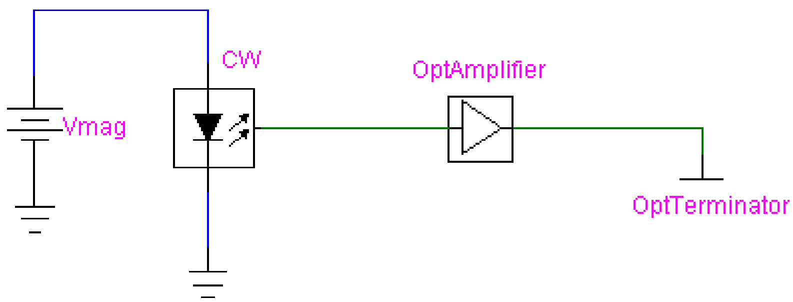
- Nf is the noise figure in dB. The parameter *NoiseFigure* is used for output at port 2 (forward), while *RevNoiseFigure* is used for output at port 1
- h is the Planck's constant and ν is the frequency of the propagating signal

Phase shifts for forward and reverse waves can be given using *PhaseShift* and *RevPhaseShift* parameters.

Examples

Optical Gain

Figure 1 Optical amplifier example

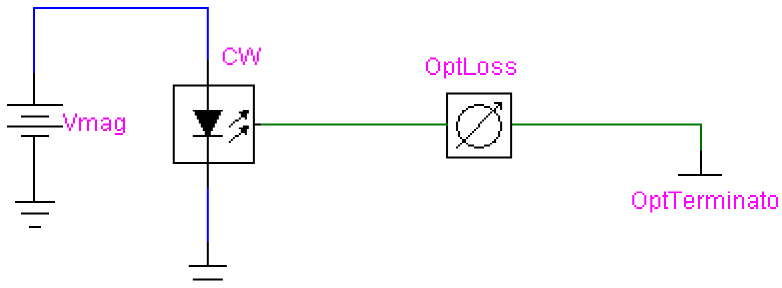


The following example shows a netlist for the above circuit where input of a CW Source is amplified (10 dB) using an optical gain element.

```
* Circuit elements and connections
Vmag magin 0 0.05
Osp CWSOURCE Name=CW Nodes=[magin 0 ampin] MoName=CWmodel

* Optical Gain element statement
Osp OPTGAIN Name=OptAmplifier Nodes=[ampin ampout] MoName=AmpModel

Osp MIRROR Name=OptTerminator Nodes=[ampout] MoName=TerminatorMod

* Optical Gain model statement
.MODEL AmpModel OPTGAIN GaindB=10 NoiseFigure=4
+ RevNoiseFigure=-100 RevGaindB=-100

.MODEL CWmodel CWSOURCE
.MODEL TerminatorMod MIRROR

* Monitor input and output optical power
.MONITOR OptPower CW 3 DIR=OUT POL=X
.MONITOR OptPower OptAmplifier 2 DIR=OUT POL=X

.TRAN 0.01ns 5ns NoiseSim=1 MaxBandwidth=1e12
.END
```

Optical Loss

Figure 2 Optical loss example



A netlist is given for the above circuit where a 3-dB loss is applied to the CW Source output.

```
* Circuit elements and connections
Vmag magin 0 0.5
Osp CWSOURCE Name=CW Nodes=[magin 0 lossin] MoName=CWmodel

* Optical Gain element statement
Osp OPTGAIN Name=OptLoss Nodes=[lossin lossout] MoName=LossModel

Osp MIRROR Name=OptTerminator Nodes=[lossout] MoName=TerminatorMod

* Optical Gain model statement. 3 dB attenuation specified
.MODEL LossModel OPTGAIN AttendB=3

.MODEL CWmodel CWSOURCE
.MODEL TerminatorMod MIRROR

* Monitor input and output optical power
.MONITOR OptPower CW 3 DIR=OUT POL=X
.MONITOR OptPower OptLoss 2 DIR=OUT POL=X

.TRAN 0.01ns 5ns
.END
```

XCOUPLER Model

Syntax

Style	Form
OptiSPICE	`.MODEL MODEL_NAME XCOUPLER <param1=val1> <param2=val2> ...`

Parameters

Symbol and description	Default value	Units	Value range
C Coupling coefficient	0.5	-	]-INF, +INF[
Conjugate Conjugate	1	-	0,1

Technical Background

The XCOUPLER model is used to specify the parameters of an cross-coupler element. An optical cross-coupler is a device that physically couples two input signals and produces two output signals. The output fields are related to the input fields by [1],

$$\begin{bmatrix} E_{o_1} \\ E_{o_2} \end{bmatrix} = \begin{bmatrix} \sqrt{1-c} & jp\sqrt{c} \\ jp\sqrt{c} & \sqrt{1-c} \end{bmatrix} \begin{bmatrix} E_{i_1} \\ E_{i_2} \end{bmatrix} \tag{1}$$

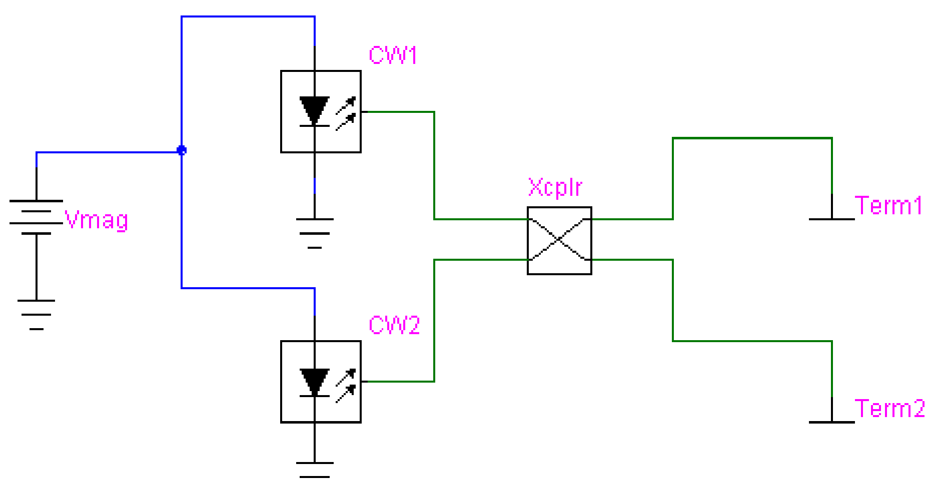
where c is the parameter *C* and p is -1 if the parameter *Conjugate* is set to 1 (default), otherwise $p = 1$.

Therefore, for this device, the inputs are mixed into each output and conversely for the reverse direction, the outputs are mixed onto the inputs. However, there is no interference between the forward and reverse signals or between the modes of each set of propagating signals.

The XCOUPLER model can also be used to model waveguide crossing devices. Please see the *Waveguide Crossing* device description in the Optical Devices Libary

Example (Xcoupler)

Figure 1 Cross coupler example



The following example shows a netlist for the above circuit where inputs of a cross-coupler are connected to two CW Sources and outputs are connected to optical terminator.

```
* Circuit elements and connections
Vmag magin 0 0.5
Osp CWSOURCE Name=CW1 Nodes=[magin 0 cw1out] MoName=CWmodel
Osp CWSOURCE Name=CW2 Nodes=[magin 0 cw2out] MoName=CWmodel

* Cross-coupler element
Osp XCOUPLER Name=Xcplr Nodes=[cw1out cw2out xcplrout1 xcplrout2]
+ MoName=XCouplerModel

* Optical terminators
Osp MIRROR Name=Term1 Nodes=[xcplrout1] MoName=TerminatorMod
Osp MIRROR Name=Term2 Nodes=[xcplrout2] MoName=TerminatorMod

* Cross-coupler model statement
.MODEL XCouplerModel XCOUPLER C=0.5 Conjugate=1

.MODEL CWmodel CWSOURCE
.MODEL TerminatorMod MIRROR

* Monitor ouput optical power and phase for the cross-coupler
.MONITOR OptPower Xcplr 3 DIR=OUT POL=X
.MONITOR OptPhase Xcplr 3 DIR=OUT POL=X
.MONITOR OptPower Xcplr 4 DIR=OUT POL=X
.MONITOR OptPhase Xcplr 4 DIR=OUT POL=X

.TRAN 0.01n 5n
.END
```

Reference

[1] Keiser, G., [*Optical Fiber Communications*], McGraw-Hill, Higher Education (2000).

SMFIBER Model

Syntax

Style	Form
OptiSPICE	`.MODEL MODEL_NAME SMFIBER <param1=val1> <param2=val2> ...`

Parameters

Symbol and description	Default value	Units	Value range
Attenuation Fiber attenuation in dB/km	0.1	dB/km	[0, +INF[
Dispersion Dispersion per km	2	ps/nm/km	[0, +INF[
Slope Dispersion slope per km	0.075	ps/nm^2/km	]-INF, +INF[
Wavelength Reference wavelength or frequency	1550	-	[0, +INF[
WavelengthUnit Wavelength/frequency unit	nm	-	Hz, THz, nm
n2 Nonlinear index of refraction	2.6e-20	m^2/W	]-INF, +INF[
Aeff Effective area	80	um^2	[0, +INF[
SignalBW Signal bandwidth for Split-step Fourier computation	50e9	Hz	]-INF, +INF[
NumZSteps Discretization steps in space	50	-	[0, +INF[
ChanCoupling Multiple channel coupling mode	NO	-	NO, XPM, MERGED
ForceDelayZero Option to minimize the signal delay	0	-	0,1

Symbol and description	Default value	Units	Value range
tstonefile Touchstone file name that define an optical filter at the output	-	-	-

Technical Background

The SMFIBER model is used to specify the parameters of a single mode non-linear fiber element. The fiber is modeled using the non-linear Schrodinger Equation which is derived from Maxwell's equations [1],

$$\frac{\partial E}{\partial z} + \alpha E + i\frac{\beta_2(\omega_0)}{2}\frac{\partial^2 E}{\partial T^2} - \frac{\beta_3(\omega_0)}{6}\frac{\partial^3 E}{\partial T^3} = i\gamma |E|^2 E \quad (1)$$

where

- E is the electric field envelope.
- α is the parameter *Attenuation*.
- ω_0 is the reference frequency of the signal related to the parameter *Wavelength* through $\omega_0 = 2\pi c/\lambda_0$ with c being the light speed in vacuum if the parameter *WavelengthUnit* is *nm*, otherwise ω_0 is given by *Wavelength*.
- T is the time variable in a frame of reference moving at the group velocity of the pulse.
- β_2 and β_3 are the first and the second Group Velocity Dispersion (GVD) parameters, respectively. These are related to the model parameters *Dispersion* (D) and *Slope* (S) as given by:

$$D = \frac{d\beta_1}{d\lambda} = -\frac{2\pi c}{\lambda^2}\beta_2$$

$$\beta_3 = \left(\frac{\lambda}{2\pi c}\right)^2(\lambda^2 S + 2\lambda D),\ S = \frac{dD}{d\lambda} \quad (2)$$

- γ is the non-linearity factor given by

$$\gamma = \frac{\omega_0 n_2}{cA_{eff}}$$

where n_2 is the parameter *n2* and A_{eff} is the parameter *Aeff*

Equation 1 can be reduced to a dimensionless form and be solved using symmetrized split-step Fourier method [1][2].

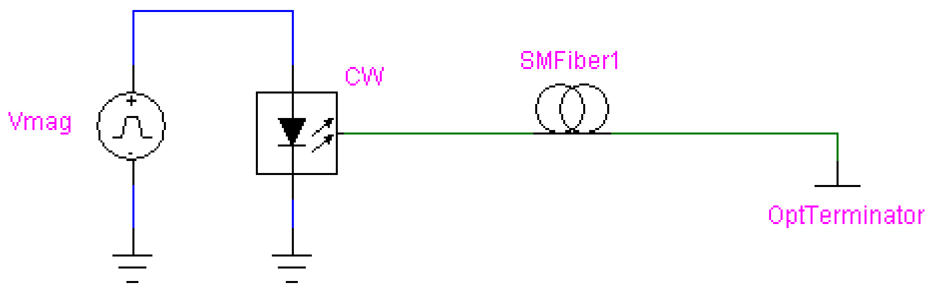
The signal bandwidth modeled is set by *SignalBW* and the number discretization steps in space along the fiber by *NumZSteps*.

If the fiber is being simulated with multiple channels present a number of modes can be selected by specifying the parameter *ChanCoupling*. The default mode of *NO* simulates completely independent channels with no coupling at all. If *ChanCoupling* is set to *XPM* individual channels are simulated but cross-phase modulation is included. If *ChanCoupling* is set to *MERGED* a single large channel is created encompassing all input channels full coupling (including three wave mixing) is modeled. For this case the channels will be re-created at the output of the fiber by dividing up the merged output signal in the frequency domain. If it is wished an optical filter defined by a *tstonefile* can be applied at the output of each channel (shifted to be centered on each channel).

If it is wished to remove the long delay associated with the fiber *ForceDelayZero* can be set to minimize (but not eliminate due to numerical constraints) the signal delay in the fiber.

Examples

Figure 1 Single mode fiber example

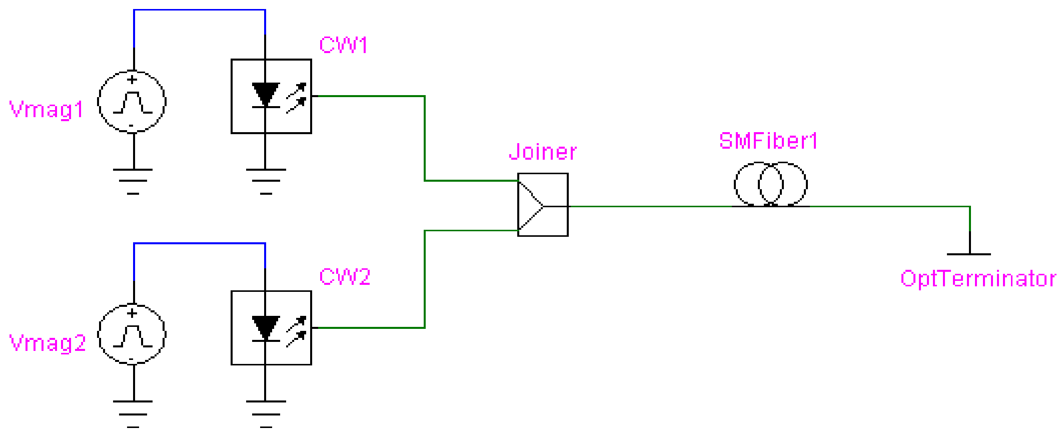


The netlist for the above circuit containing a single-mode fiber is given below:

```
* Circuit elements and connections
Vmag magin 0 PULSE 0.0 0.5 0.0 0.2ns 0.2ns 5ns
Osp CWSOURCE Name=CW Nodes=[magin 0 fibin ] MoName=CWMod

* SMFIBER element with length of 2 km
Osp SMFIBER Name=SMFiber1 Nodes=[fibin fibout] MoName=SMFiberMod
+ Length = 2

Osp MIRROR Name=OptTerminator Nodes=[fibout] MoName=TerminatorMod

* SMFIBER model statement.
* ForceDelayZero is set in order to observe
* fiber output with less simulation time
.MODEL SMFiberMod SMFIBER Attenuation = 0.5
+ Dispersion = 4.5 Slope = 0.01 n2 = 2.6e-20
+ ForceDelayZero=1 SignalBW=200g NumZSteps=100

.MODEL CWMod CWSOURCE
.MODEL TerminatorMod MIRROR

.MONITOR OptPower CW 3 DIR=OUT POL=X
.MONITOR OptPhase CW 3 DIR=OUT POL=X
.MONITOR OptPower SMFiber1 2 DIR=OUT POL=X
.MONITOR OptPhase SMFiber1 2 DIR=OUT POL=X

.TRAN 0.01ns 50ns
.END
```

Single mode fiber with channel coupling

Figure 2 Single mode fiber with two channel coupling



In this example, two channels (two CW Sources with different wavelengths) are connected as inputs for the single-mode fiber. A joiner is used to input two different channels as a single input into the fiber. Channel coupling is set to *MERGED* so that a single large channel is created encompassing the two input channels and two channels are re-created at the output. Netlist is given below:

```
* Circuit elements and connections
Vmag1 magin1 0 PULSE 0.0 0.5 0.0 0.2ns 0.2ns 5ns
Vmag2 magin2 0 PULSE 0.0 0.5 4ns 0.5ns 0.5ns 10ns

Osp CWSOURCE Name=CW1 Nodes=[magin1 0 jin1 ] MoName=CWMod
+ Frequency=1550 FrequencyUnit=nm
Osp CWSOURCE Name=CW2 Nodes=[magin2 0 jin2 ] MoName=CWMod
+ Frequency=1550.05 FrequencyUnit=nm

Osp JOINER Name=J1 Nodes=[jin1 jin2 fibin]
+ MoName=JoinerModel SplitRatio=0.5

* SMFIBER element with length of 50m
Osp SMFIBER Name=SMFiber1 Nodes=[fibin fibout] MoName=SMFiberMod
+ Length = 0.05

Osp MIRROR Name=OptTerminator Nodes=[fibout] MoName=TerminatorMod

* SMFIBER model statement.
.MODEL SMFiberMod SMFIBER Attenuation = 0.5
+ Dispersion = 4.5 Slope = 0.01
```

```
+ ForceDelayZero=1 SignalBW=200g NumZSteps=50
+ Wavelength=1550 WavelengthUnit=nm
+ ChanCoupling=MERGED

.MODEL JoinerModel OMNIOCONN
.MODEL CWMod CWSOURCE
.MODEL TerminatorMod MIRROR

* Monitor input and output power and phase
.MONITOR OptPower J1 3 DIR=OUT POL=X
.MONITOR OptPhase J1 3 DIR=OUT POL=X
.MONITOR OptPower SMFiber1 2 DIR=OUT POL=X
.MONITOR OptPhase SMFiber1 2 DIR=OUT POL=X

.TRAN 0.01ns 100ns
.END
```

For channels with cross-phase modulation only, the model statement is:

```
.MODEL SMFiberMod SMFIBER Attenuation = 0.5
+ Dispersion = 4.5 Slope = 0.01
+ ForceDelayZero=1 SignalBW=200g NumZSteps=50
+ Wavelength=1550 WavelengthUnit=nm
+ ChanCoupling=XPM
```

For an optical filter (specified by a Touchstone file) need to be applied at the output for each channel (shifted to be centered on each channel), an example of model statement is:

```
.MODEL SMFiberMod SMFIBER Attenuation = 0.5
+ Dispersion = 4.5 Slope = 0.01
+ ForceDelayZero=1 SignalBW=200g NumZSteps=50
+ Wavelength=1550 WavelengthUnit=nm
+ ChanCoupling=MERGED tstonefile=Filter.s2p
```

References

[1] G. P. Agrawal, "Nonlinear fiber optics", Academic press, 3rd edition, 2001.

[2] M. Lax, J. H. Batteh and G. P. Agrawal, Journ. Appl. Phys. 52 , 109, (1981).

MMFIBER Model

Syntax

Style	Form
OptiSPICE	.MODEL MODEL_NAME MMFIBER *<param1=val1>* *<param2=val2>* ...

Parameters

Symbol and description	Default value	Units	Value range
FiberModeShapeMode Special mode shape formats for multi-mode fiber	UseModeShape	-	UseModeShape, UseOSLibrary, UseCamLibrary, SpecifiedCoupling
DELAYS List of modal delays	-	sec	[0, +INF[
PhaseDelays List of phase delay for each mode	-	rad	]-INF, +INF[
RelativeDelay Relative delay enable	0	-	0,1
Atten Fiber attenuation	1.0	- or dB/km	[0, +INF[
AttenByMode Fiber attenuation by mode	-	- or dB/km	[0, +INF[
AttenIndB Option for setting attenuation: dB/km (1) or liner with distance (0)	0	-	0,1
SpecifiedCoupling List of power coupling coefficient for each mode	-	-	]-INF, +INF[

Technical Background

The MMFIBER model is used to specify the parameters for a multi-mode linear fiber element.

The basic model of the multi-mode fiber is a set of bi-directional optical signals contained within optical channels defined by a carrier frequency. Each signal is subject to a modal and phase delay defined by the two list parameters *Delays = [D0 D1 .. Dn]* and *PhaseDelay = [P0 P1 .. Pn]* where each element of the list corresponds to a mode [1]. Basic mode shape details can be set by the mode parameters (for on mode parameters see the technical background for CWSOURCE model). Delays are specified in seconds and phase delays in radians.

An attenuation for all modes can also be specified by the parameters *Atten.* Attenuation can also be specified per mode using the parameter *AttenByMode = [A0 A1 ... An]*. Attenuation can either be linear with distance (when *AttenIndB = 0)* or dB/km (when *AttenIndB = 1*).

Complex mode shapes (typically obtained by mode solvers) and attributes, such as effective index and modal delays, can also be used by setting the parameter *FiberModeShapeMode* which can be set to the following values:

- *UseModeShape*: this is the default choice. In this mode, the mode shapes can only be given using regular mode shape parameters, and modal and phase delay are given using *Delays* and *PhaseDelay* as discussed above.
- *UseOSLibrary*: allows user to load spatial mode shapes and propagation attributes using OptiSPICE Multimode library format. The library files can be generated by MM Fiber Parameter Extractor, a standalone software provided with OptiSPICE suite.
- *UseCamLibrary*: allows user to load multi-mode fiber measurements of modal delays and power-coupling coefficients using the Cambridge file format.
- *SpecifiedCoupling*: If the mode shape of the fiber are specified then the coupling parameters between adjacent elements will handled by an optical connector (see OCONN model). However, if a specified coupling is wanted the list parameter *SpecifiedCoupling = [R0 R1 ... Rn]* can be used to set the reflectivity of each mode.

The parameter *RelativeDelay* provides the option whether the differential modal delay is absolute or relative by setting 0 or 1 respectively. In case of relative modal delay (*RelativeDelay = 1*), it subtracts off the minimum modal delay present.

OptiSPICE Multimode Library format (*UseOSLibrary*)

The set of files which can be generated by MM Fiber Parameter Extractor specify list of wavelengths propagating and for each wavelength a set of mode properties such as current mode index, radial and azimuthal index, effective index, and group delay.

Three types of files are used in this library format. The first file is the one that should be provided as the parameter *ModeFile* and the directory is given by the parameter *LibDirectory*. The extension of the file must be *'.dat'* and it should be defined as *Modefile* = *filename* where the *filename* is the file name without extension '*.dat*'. This file specify with the list of wavelengths and for each wavelength corresponding spatial mode file name and delay file name. For example, for two wavelengths (820 and 1550 nm) the format of the file is:

```
820         library_000M.dat      library_000D.dat
1550        library_001M.dat      library_001D.dat
```

The format of the spatial mode file is the following: for each spatial mode a unique file ID is provided, the current mode index, the number of modes in the file, the number of mesh point in the X and Y dimensions and the spatial width of the X and Y dimensions, for example:

```
a4c44f9abe840f593272eebee973e556d374f5f1 0 59 200 200 100 100
1.831372912911e-015 0 1.831372912911e-015 0 1.831372912911e-015 0 ...
....
```

The format of the delay file is the following: for each line the mode index is provided, the number of modes in the file, the radial and azimuthal index of the mode, the effective index and the modal delay, for example:

```
0    59    0    1    1.413448035957    4.717264101503e-009
1    59    0    2    1.411942906443    4.717269452002e-009
```

Cambridge file format (*UseCamLibrary*)

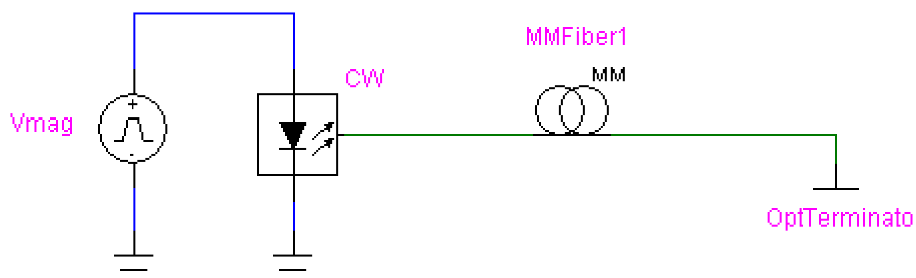
Cambridge file provides for each mode involved the modal delay and the power coupling coefficient. Delays are provided based on the fiber length and the reference length. The reference length is defined to be 300 meters. Total delay should be calculated based on the fiber length and the reference length.

The format of the delay file is the following: first column is the mode group, second is the modal delay for the reference length (300 m) in nano-seconds and the third is power coupling coefficient. Comments start with '%'. Following is a portion of a Cambridge file:

```
% Modal delays and coefficients at 1300 nm in 300 m of 62.5 um MMF
%
% LP mode-group order, modal delay (ns), power-coupling coefficient
3             0.000000000000       0.000000083051
4             0.605922367923       0.000000987835
5             0.346593814440       0.000014554609
6             0.579316736394       0.000092136456
7             0.428864723915       0.000537053394
```

Examples

Figure 1 MMFIBER example



The netlist for the above circuit containing a multi-mode fiber of length 10 m is given below:

```
* Circuit elements and connections
Vmag magin 0 PULSE 0.0 0.5 0.0 0.1ns 0.1ns 2ns 5ns
Osp CWSOURCE Name=CW Nodes=[magin 0 fibin ] MoName=CWMod

* MMFIBER element with length of 10 m
Osp MMFIBER Name=MMFiber1 Nodes=[fibin fibout] MoName=MMFiberMod
+ Length=0.01

Osp MIRROR Name=OptTerminator Nodes=[fibout] MoName=TerminatorMod

* MMFIBER model statement
* Mode type: Hermite Gaussian, number of modes = 3
* Each mode has different modal delay, phase delay and attenuation
```

```
.MODEL MMFiberMod MMFIBER
+ ModeType = HERMITE_GAUSSIAN_MODE NumModes = 3
+ AttenByMode = [10 12 15] AttenIndB = 1
+ Delays = [50.0n 50.5n 51.0n]
+ PhaseDelays = [0.78 .30 .13]

.MODEL CWMod CWSOURCE
.MODEL TerminatorMod MIRROR

.MONITOR OptPower CW 3 DIR=OUT POL=X
.MONITOR OptPhase CW 3 DIR=OUT POL=X
.MONITOR OptPower MMFiber1 2 DIR=OUT POL=X
.MONITOR OptPhase MMFiber1 2 DIR=OUT POL=X

.TRAN 0.01ns 100ns
.END
```

Model using OptiSPICE Multimode Library

For a multi-mode fiber, for which the spatial modes and propagation attributes were specified by OptiSPICE Multimode Library (obtained using MM Fiber Parameter Extractor stored in a file called Library.dat in the directory LibDir), the model statement is:

```
.Model MMFiberMod MMFIBER FiberModeShapeMode = UseOSLibrary
+ ModeFile = Library LibDirectory = LibDir
```

Model using Cambridge file format

For a multi-mode fiber, for which the modal delay and the power coupling coefficient were specified by a Cambridge file (file: CamLib.txt, directory: LibDir), the model statement is:

```
.Model MMFiberMod MMFIBER FiberModeShapeMode = UseCamLibrary
+ ModeFile = CamLib.txt LibDirectory = LibDir
```

Model using Specified Coupling

Model statement for a multi-mode fiber with Specified Coupling coefficients is:

```
.Model MMFiberMod MMFIBER FiberModeShapeMode = SpecifiedCoupling
+ NumModes = 3 DELAYS = [3.00e-6 3.00025e-6 3.00035e-6]
+ SpecifiedCoupling = [0.5 0.3 0.2]
```

References

[1] P. Pepeljugoski, S. E. Golowich, A. J. Ritger, P. Kolesar, A. Risteski “Modeling and Simulation of Next-Generation Multimode Fiber Links”, Journal of Lightwave Technology, Vol. 21, No. 5, pp. 1242--1255, May 2003.

FREESPACE Model

Syntax

Style	Form
OptiSPICE	.MODEL MODEL_NAME FREESPACE <*param1=val1*> <*param2=val2*> ...

Parameters

Symbol and description	Default value	Units	Value range
FSEType Freespace element type	FFT	-	DIRECT, FFT
Ref Power return loss (port 1 to port 1)	0	-	[0, +INF[
RevRef Power return loss (port 2 to port 2)	0	-	[0, +INF[
RefdB Power return loss (port 1 to port 1) in dB	100	-	[0, +INF[
RevRefdB Power return loss (port 2 to port 2) in dB	100	dB	[0, +INF[
D Free space distance between elements. When f_lens is non-zero, D is equal to the distance between the input element plan and the lens plane.	1	m	[0, +INF[
Use Cache Option to use previously cached mode shape	0	-	0,1
f_lens Controls the focal point of the convex lens. The lens operation is only enabled if this value is non zero, otherwise the free space propagation	0	m	[0, +INF[
D2 The free space distance from the lens plane to the end element plane. This parameter is only used if f_lens is set to a non-zero value.	0	m	[0, +INF[

Symbol and description	Default value	Units	Value range
aperture_type Defines whether a rectangular or circular aperture will be applied to the diffracted wave	NO_APERTURE	-	[NO_APERTURE, RECTANGULAR, CIRCULAR
lx_aperture The x dimension of the rectangle aperture. If x > lx_aperture or x < -lx_aperture nothing passes through	0	um	[0, +INF[
ly_aperture The y dimension of the rectangle aperture. If y > ly_aperture or y< -ly_aperture nothing passes through	0	um	[0, +INF[
r_aperture Radius of the circular aperture	0	um	[0, +INF[
CacheElement Option to cache (save) mode shape to a file	0	-	0,1
XOff Defines the amount of translation of the mode shape in the X-direction	0	um	]-INF, +INF[
YOff Defines the amount of translation of the mode profile in the Y-direction	0	um	]-INF, +INF[
XTilt Defines the amount of rotation of the mode profile around the X-axis	0	rad	]-INF, +INF[
YTilt Defines the amount of rotation of the mode profile around the Y-axis	0	rad	]-INF, +INF[

Technical Background

The FREESPACE model is used to specify the parameters of a freespace element. Freespace device represents the optical connection formed between two devices with possibly different mode structures where a region of free-space is present at the interface. In this situation the input mode shapes ($\hat{I}_i(x, y)$) undergo diffraction as they travel to the output device. The diffracted input mode can be determined from the Fresnel diffraction equation which is a function of geometry and the carrier wavelength [1]

$$\hat{D}_i(r, z_0) = \frac{k}{j2\pi z}\iint \hat{I}_i(r', 0)e^{jk\frac{(r-r')^2}{2z}} dr' d\phi \tag{1}$$

where $\hat{D}_i(r, z_0)$ represents the field component due to the i th input mode $\hat{I}_i$ of the input device. The diffraction distance is z and k is the wave number of the optical field. It should be noted that these field components are no longer orthonormal due to the diffraction process.

These diffracted fields can then summed and the resultant field distribution ($\hat{D}_t(r, z_0)$) formed.

$$\hat{D}_t(r, z_0) = \sum_i \hat{D}_i(r, z_0) \tag{2}$$

This diffracted field will then excite the modes of the output device $\hat{O}_i(x, y)$. The excitation of the output modes by the input modes can therefore be represented by a set of coefficients $\bar{S}_{ij}$ calculated by an overlap integral,

$$\bar{S}_{ij} = \iint \hat{O}_i(r)\hat{D}_j(r, r')drdr' \tag{3}$$

This resultant field is then used to excite the output devices modes using overlap integrals to determine the power distribution between modes (see OCONN model for details on overlap integrals).

The amount of reflected power can be set by using the parameters *Ref/RevRef/RefdB/RevRefdb* with the phase shifts of the reflected components set by *PhaseShift/RevPhaseShift*.

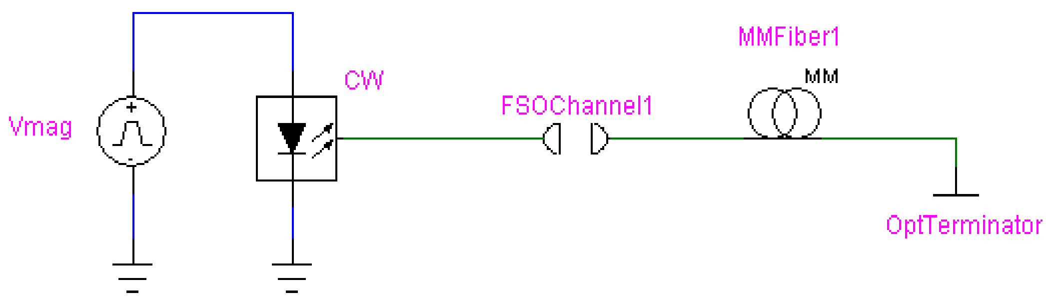
The parameter *D* sets the distance between the two elements in meters.

The parameter *FSEType* can be used to specify the type of numerical method used to determine the diffraction. If set to *DIRECT* a direct numerical integration is used which can be slow. If set to *FFT* restrictions are placed on the diffracted mode shape resolution but is much quicker to calculate. If *CacheElement* is set the calculation of the diffraction will be stored between simulations and reused if possible and *UseCache* is set to 1.

The parameters *Xoff* and *Yoff* specify an offset in a position of the mode-shapes of the two connecting elements. Parameters *Xtilt* and *YTilt* specify a tilt angle between the modes.

Examples

Figure 1 FREESPACE example



In this example, a FREESPACE element with the name FSOChannel1 is connected between a CW Source and a multi mode fiber. The distance of the freespace is 100 microns. The netlist of this circuit is given below:

```
* Circuit elements and connections
Vmag magin 0 PULSE 0.0 0.5 0.0 0.1ns 0.1ns 2ns 5ns
Osp CWSOURCE Name=CW Nodes=[magin 0 fsein] MoName=CWMod

* Freespace element statement. Distance = 100 um
Osp FREESPACE Name=FSOChannel1 Nodes=[fsein fseout] MoName=FseMod
+ D=100u

Osp MMFIBER Name=MMFiber1 Nodes=[fseout fibout]
+ MoName=FiberMod Length=1e-3
Osp MIRROR Name=OptTerminator Nodes=[fibout] MoName=TerminatorMod

* Freespace model statement.
* Direct numerical integration is used to determine the diffraction.
* If element shape is already cached from previous simulation,
* option to use those are enabled.
.MODEL FseMod FREESPACE FSEType=Direct

.MODEL CWMod CWSOURCE
.MODEL FiberMod MMFIBER
.MODEL TerminatorMod MIRROR
```

```
* Monitor input and output power and phase to the FREESPACE element
.MONITOR OptPower CW 3 DIR=OUT POL=X
.MONITOR OptPhase CW 3 DIR=OUT POL=X
.MONITOR OptPower FSOChannel1 2 DIR=OUT POL=X
.MONITOR OptPhase FSOChannel1 2 DIR=OUT POL=X

* Option to cache modeshapes of all element is enabled
.OPTION CacheAllModeShapes=1

.TRAN 0.01ns 5ns
.END
```

Since the *FSEType* is *Direct* in this example, the simulation will be slow. For faster results it should be changed to *FFT* as given below, however the accuracy is not guaranteed in this method.

```
.MODEL FseMod FREESPACE FSEType=FFT
```

References

[1] M. Born, E. Wolf, “Principles of Optics: Electromagnetic Theory of Propagation, Interference and Diffraction of Light”, Cambridge University Press, Cambridge, UK, 1964.

OCONN Model

Syntax

Style	Form
OptiSPICE	`.MODEL MODEL_NAME OCONN <param1=val1> <param2=val2> ...`

Parameters

Symbol and description	Default value	Units	Value range
OconnType Type of optical connection	LINEAR	-	LINEAR, SPECIFIED, COMPLEX,
Ref Power return loss (port 1 to port 1)	0	-	[0, +INF[
RevRef Power return loss (port 2 to port 2)	0	-	[0, +INF[
RefdB Power return loss (port 1 to port 1) in dB	100	dB(W)	]-INF, +INF[
RevRefdB Power return loss (port 2 to port 2) in dB	100	dB(W)	]-INF, +INF[
PhaseShift (FwdPhaseShift) Phase shift (port 1 to port 2)	0	rad	]-INF, +INF[
RevPhaseShift Phase shift (port 2 to port 1)	0	rad	]-INF, +INF[
RefPhaseShift Phase shift (port 1 to port 1)	pi/2	rad	]-INF, +INF[
RevRefPhaseShift Phase shift (port 2 to port 2)	pi/2	rad	]-INF, +INF[
Gain (FwdGain) Power gain factor (port 1 to port 2)	1	-	[0, +INF[
RevGain Power gain factor (port 2 to port 1)	1	-	[0, +INF[

Symbol and description	Default value	Units	Value range
Atten (FwdAtten) Power loss factor (port 1 to port 2)	1	-	[0, +INF[
RevAtten Power loss factor (port 2 to port 1)	1	-	[0, +INF[
GaindB (FwdGaindB) Power gain in dB (port 1 to port 2)	0	dB	]-INF, +INF[
RevGaindB Power gain in dB (port 2 to port 1)	0	dB	]-INF, +INF[
AttendB (FwdAttendB) Power loss in dB (port 1 to port 2)	0	dB	]-INF, +INF[
RevAttendB Power loss in dB (port 2 to port 1)	0	dB	]-INF, +INF[
XOff Defines the amount of translation of the mode shape in the X-direction	0	um	]-INF, +INF[
YOff Defines the amount of translation of the mode profile in the Y-direction	0	um	]-INF, +INF[
XTilt Defines the amount of rotation of the mode profile around the X-axis	0	rad	]-INF, +INF[
YTilt Defines the amount of rotation of the mode profile around the Y-axis	0	rad	]-INF, +INF[
UseCache Use cache	0	-	0,1
CacheElement Cache element	0	-	0,1
PolarMode Preset polarization modes that set appropriate Jones Matrix values.	None	-	None, X, Y, A45, Am45, LeftCir, RightCir, QWPX, QWPY, HWPX, HWPY, Angle
PolAngle Polarization rotation angle	0	rad	]-INF, +INF[

Symbol and description	Default value	Units	Value range
JonesMatrix List of Jones Matrix values	-	-	]-INF, +INF[
IsoMode Isolation mode type	FWD	-	FWD, REV

Technical Background

The OCONN model is used to specify the parameters of an optical element used to connect two other elements, but can also be used as general element to specify gain, attenuation and polarization effects.

When an OCONN element is connected between two elements with differing mode shapes, the mode shapes of the two elements will be used to calculate the mode mixing for signals traveling between the two elements using overlap integrals as given by:

$$\bar{C}_{ij} = \iint \hat{I}_i(x,y)\hat{O}_j(x,y)dxdy \quad (1)$$

where

- $\hat{I}_i(x,y)$ is the input device mode shape for i th mode
- $\hat{O}_j(x,y)$ is the output device mode shape for j th mode
- $\bar{C}_{ij}$ forms a matrix of complex coefficients that relates the input and output complex envelops for each mode such that $\bar{E}_{out_j} = \bar{C}_{ij}\bar{E}_{in_i}$.

  Note: An OCONN element will be automatically inserted internally by OptiSPICE with default parameters when two elements with different mode shapes are directly connected.

The amount of reflected power can be set by using the parameters *Ref/RevRef* and corresponding dB parameters. Attenuation or gain can be introduced by using *Gain/Atten/RevGain/RevAtten* and corresponding dB parameters. Phase shifts for transmitted signals can be set using *PhaseShift/RevPhaseShift* (if only *PhaseShift* is set then it is applied in both directions). Phase shifts for reflected signals can be set by *RefPhaseShift/RevRefPhaseShift*.

For isolator (OPTISO) element, if *IsoMode* is set to *FWD* then the optical isolator with a forward gain of one and a reverse gain of zero and if it is set to *REV* then the forward gain is set to zero and reverse gain is set to one.

The parameters *Xoff* and *Yoff* specify an offset in a position of the mode-shapes of the two connecting elements. Parameters *Xtilt* and *YTilt* specify a tilt angle between the modes.

The element can also be used to set the polarization filtering. The parameter *PolarMode* can set an appropriate Jones Matrix for a number of preset modes. Jones Matrix is a 2 × 2 matrix that describes polarizing components as given by:

$$\begin{bmatrix} E_{out_x} \\ E_{out_y} \end{bmatrix} = \begin{bmatrix} J_{11} & J_{12} \\ J_{21} & J_{22} \end{bmatrix} \begin{bmatrix} E_{in_x} \\ E_{in_y} \end{bmatrix} \tag{2}$$

Following are the preset polar modes:

- *None* - no polarization filtering, $J = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$
- *X*: linear polarizer with X axis transmission, $J = \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix}$
- *Y*: linear polarizer with Y axis transmission, $J = \begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix}$
- *A45*: linear polarizer with transmission at 45° with X axis, $J = \frac{1}{2}\begin{bmatrix} 1 & 1 \\ 1 & 1 \end{bmatrix}$
- *Am45*: linear polarizer with transmission at -45° with X axis, $J = -\frac{1}{2}\begin{bmatrix} 1 & 1 \\ 1 & 1 \end{bmatrix}$
- *LeftCir*: left circular polarizer, $J = \frac{1}{2}\begin{bmatrix} 1 & -j \\ j & 1 \end{bmatrix}$
- *RightCir*: right circular polarizer, $J = \frac{1}{2}\begin{bmatrix} 1 & j \\ -j & 1 \end{bmatrix}$
- *QWPX*: Quarter-wave plate, fast X axis, $J = e^{j\pi/4}\begin{bmatrix} 1 & 0 \\ 0 & j \end{bmatrix}$
- *QWPY*: Quarter-wave plate, fast Y axis, $J = e^{j\pi/4}\begin{bmatrix} 1 & 0 \\ 0 & -j \end{bmatrix}$
- *HWPX*: Half-wave plate, fast X axis, $J = \begin{bmatrix} j & 0 \\ 0 & -j \end{bmatrix}$

- *HWPY*: Half-wave plate, fast Y axis, $J = \begin{bmatrix} -j & 0 \\ 0 & j \end{bmatrix}$

- *Angle*: linear polarizer with transmission at θ radians with X axis, where θ is given by the parameter *PolAngle.*

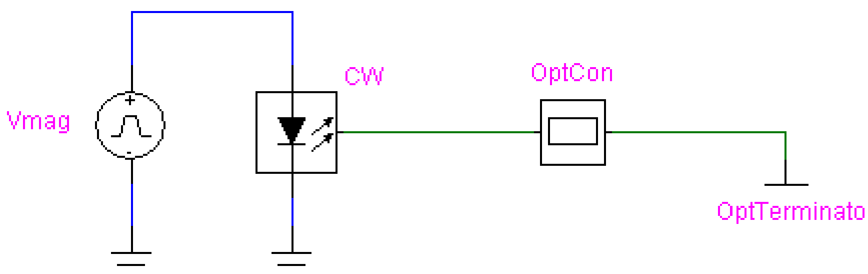
$$J = \begin{bmatrix} cos^2(\theta) & \cos(\theta)\sin(\theta) \\ \sin(\theta)\cos(\theta) & sin^2(\theta) \end{bmatrix}$$

In addition to preset modes, Jones Matrix can be set explicitly using *JonesMatrix* parameter as *[Re(J11) Im(J11) Re(J12) Im(J12) .... Re(J22) Im(J22)]*.

Examples

Optical connector with return loss

Figure 1 OCONN with return loss



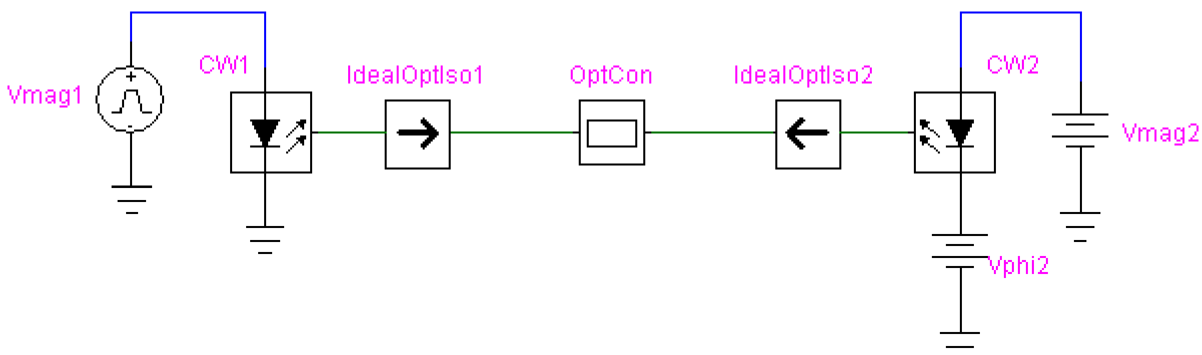
In this example the optical connector is used to apply a return loss (reflection) and a phase shift in the returned signal. The netlist of this circuit is given below.

```
* Circuit elements and connections
Vmag magin 0 PULSE 0.0 0.5 0.0 0.1ns 0.1ns 2ns 5ns
Osp CWSOURCE Name=CW Nodes=[magin 0 cwout] MoName=cwmodel

* OCONN element statement
Osp OCONN Name=OptCon Nodes=[cwout oconnout] MoName=oconnmod

Osp MIRROR Name=OptTerminator Nodes=[oconnout] MoName=TerminatorMod

* OCONN model with return loss of 10 dB and return phase shift of pi/4
.MODEL oconnmod OCONN RefdB=10 RefPhaseShift=0.785398

.MODEL cwmodel CWSOURCE
```

```
.MODEL TerminatorMod MIRROR
* Monitor power and phase of OCONN at Port 1 (in both direction)
.MONITOR OptPower OptCon 1 DIR=IN POL=X
.MONITOR OptPhase OptCon 1 DIR=IN POL=X
.MONITOR OptPower OptCon 1 DIR=OUT POL=X
.MONITOR OptPhase OptCon 1 DIR=OUT POL=X

.TRAN 0.01ns 5ns
.END
```

Optical connector with forward and reverse return loss

Figure 2 OCONN with forward and reverse return loss



This example illustrates an optical connector having both forward and reverse return loss. Ideal optical isolators are used to ensure CW Sources only transmit the power in one direction and do not receive any power back. These optical isolator elements (OPTISO) also use OCONN model. The netlist of this circuit is given below.

```
* Circuit elements and connections
Vmag1 mag1in 0 PULSE 0.0 1.0 0.0 0.1ns 0.1ns 3ns 5ns
Osp CWSOURCE Name=CW1 Nodes=[mag1in 0 cw1out] MoName=cwmodel
Vmag2 mag2in 0 1.0
Vphi2 phi2in 0 1.570796
Osp CWSOURCE Name=CW2 Nodes=[mag2in phi2in cw2out] MoName=cwmodel

* Optical isolator (OPTISO) element statement
Osp OPTISO Name=IdealOptIso1 Nodes=[cw1out oconnpt1] MoName=isomodel
Osp OPTISO Name=IdealOptIso2 Nodes=[cw2out oconnpt2] MoName=isomodel

* OCONN element statement
Osp OCONN Name=OptCon Nodes=[oconnpt1 oconnpt2] MoName=oconnmod
```

```
* OCONN model for optical connector
* 10 and 3 dB of return losses at port 1 and 2 respectively
.MODEL oconnmod OCONN Ref=0.1 RevRef=0.5
+ RefPhaseShift=1.570796 RevRefPhaseShift=1.570796

* OCONN model for optical isolator
.MODEL isomodel OCONN IsoMod=FWD

.MODEL cwmodel CWSOURCE

* Monitor output power and phase of OCONN at port 1 and 2
.MONITOR OptPower OptCon 1 DIR=OUT POL=X
.MONITOR OptPhase OptCon 1 DIR=OUT POL=X
.MONITOR OptPower OptCon 2 DIR=OUT POL=X
.MONITOR OptPhase OptCon 2 DIR=OUT POL=X

.TRAN 0.01ns 5ns
.END
```

Polarizer

The OCONN can be used as a polarizer. Circuit in Figure 1 is can be used as a polarizer example with the change of OCONN model in the netlist. For a linear polarizer with transmission at 45° with horizontal (*PolarMode* = *A45*), the OCONN model in the first example can be replaced by the following model:

```
.MODEL oconnmod OCONN PolarMode=A45
```

For a user set angle of transmission with horizontal ($\pi/3$ rad), corresponding model statement is given by:

```
.MODEL oconnmod OCONN PolarMode=Angle PolarAngle=1.0471976
```

To enter Jones Matrix directly to describe a polarizer with $J = \frac{1}{2}\begin{bmatrix} 1 & -j \\ j & 1 \end{bmatrix}$, corresponding model statement is given by:

```
.MODEL oconnmod OCONN JonesMatrix = [ 0.5 0 0 -0.5 0 0.5 0.5 0]
```

MIRROR Model

Syntax

Style	Form
OptiSPICE	`.MODEL MODEL_NAME MIRROR <param1=val1> <param2=val2> ...`

Parameters

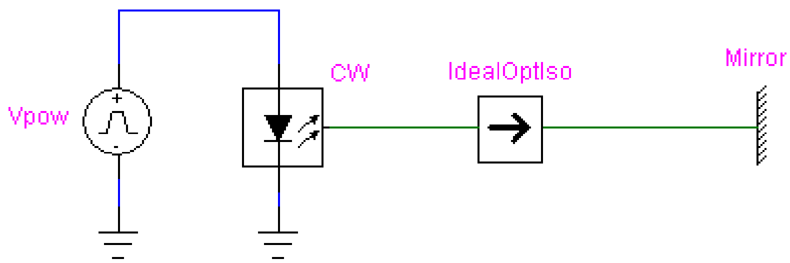
Symbol and description	Default value	Units	Value range
Ref Reflection	1	-	[0, +INF[
RefdB Reflection in dB	100	dB	]-INF, +INF[
PhaseShift Phase shift of the reflected wave	0	rad	]-INF, +INF[

Technical Background

The mirror simply reflects all incident modes and channels of whatever polarity is incident from the input element. The parameters *Ref* and *RefdB* set the value of the reflected power. The parameter *PhaseShift* sets the phase shift of the reflected wave. The mirror model can be used as an optical terminator with *Ref = 0*.

Example

Figure 1   Mirror example



Following is the netlist for the above circuit containing a mirror with a reflection coefficient of 0.5, and phase shift of $\pi/4$ rad.

```
* Circuit elements and connections
Vpow powin 0 PULSE 0.0 0.5 0.0 0.1ns 0.1ns 2ns 5ns
Osp CWSOURCE Name=CW Nodes=[powin 0 cwout] MoName=cwmodel
Osp OPTISO Name=IdealOptIso Nodes=[cwout mirrorin] MoName=isomodel

* Mirror element statement
Osp MIRROR Name=Mirror Nodes=[mirrorin] MoName=MirrModel

* Mirror model statement
.MODEL MirrModel MIRROR Ref = 0.5 PhaseShift = 0.785398

.MODEL cwmodel CWSOURCE CWSourceType=POWPHI
.MODEL isomodel OCONN IsoMod=FWD

* Monitor mirror input and output power and phase
.MONITOR OptPower Mirror 1 DIR=BOTH POL=X
.MONITOR OptPhase Mirror 1 DIR=BOTH POL=X

.TRAN 0.01ns 10ns
.END
```

OPTCHANNELFILTER Model

Syntax

Style	Form
OptiSPICE	`.MODEL MODEL_NAME OPTCHANNELFILTER <param1=val1> <param2=val2> ...`

Parameters

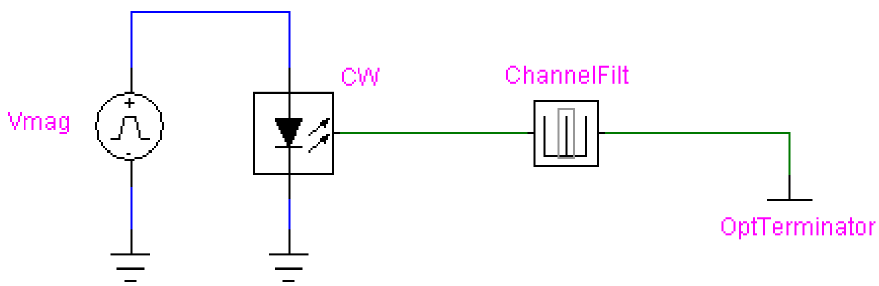
Symbol and description	Default value	Units	Value range
PassBandMode Passband mode selection to define the way center frequencies and bandwidths to be entered	ListOfBands	-	ListOfBands, CenterFreqAndBW, CenterFreqAndConstBW
PassBands List of pass bands to be entered according to the PassBandMode	-	-	[0, +INF[
Bandwidth Set a constant bandwidth for all center frequencies (If PassBandMode is CenterFreqAndConstBW)	50	-	-
FrequencyUnit Frequency unit	THz	-	Hz, THz, nm,
BandwidthUnit Bandwidth unit	nm	-	Hz, GHz, nm,

Technical Background

The OPTCHANNELFILTER model is used to specify the parameters for an idealized optical filter. Such an element can be used to completely block particular optical channels. The passed carrier frequencies are defined by the parameters *PassBandMode*, *PassBands*, and *BandWidth*. If *PassBandMode* = *ListOfBands*, the list parameter *PassBands* = *[f1 f2 f3 f4 .. fn-1 fn]* defines n/2 pass bands defined from *f1* to *f2*, *f3* to *f4* and so on. If *PassBandMode* = *CenterFreqAndConstBW* then *PassBands* = *[f1 f2 f3 f4 .. fn-1 fn]* defines *n* pass bands centered on *f1, f2, .. fn* with a bandwidth given by parameter *BandWidth*. If *PassBandMode* = *CenterFreqAndBW* then *PassBands = [f1 bw1 f2 bw2 .. fn bwn]* defines *n* pass bands centered on *f1, f2, .. fn* with a bandwidth given by *bw1, bw2 .. bwn*.

Examples

Figure 1 Optical Channel Filter



The following netlist is given for the above circuit where input channels are filtered by the Optical Channel Filter. In this example, CW source is simulated with several wavelengths (1300 - 1800 nm) using parameter sweep of wavelength. The channel filter allows only 1400 - 1550 nm and 1600 - 1700 nm.

```
* Define parameter WavLen to be used as a parametric
* wavelength for the input to the channel filter
.param WavLen = 1300

* Perform transient including the sweeping of the parameter WaveLen
* from 1300 to 1800 nm (increment of 100 nm)
.TRAN 0.01ns 60ns sweep WavLen 1300 1800 100

* Circuit elements and connections
Vmag magin 0 PULSE 0.0 0.5 0.0 0.1ns 0.1ns 2ns 5ns

* CW Source with parametric wavelength
Osp CWSOURCE Name=CW Nodes=[magin 0 chin] MoName=CWMod
+ Frequency = WavLen FrequencyUnit = nm

* Channel filter element statement
Osp OPTCHANNELFILTER Name=ChannelFilt Nodes=[chin chout]
+ MoName=ChanFilterModel

Osp MIRROR Name=OptTerminator Nodes=[chout] MoName=TerminatorMod

* Channel filter model statement
* Allows wavelengths from 1400-1550 nm and 1600-1700 nm
```

```
.MODEL ChanFilterModel OPTCHANNELFILTER
+ PassBandMode = ListOfBands
+ PassBands = [1400 1550 1600 1700] FrequencyUnit = nm

.MODEL CWMod CWSOURCE
.MODEL TerminatorMod MIRROR

* Monitor input and output power
.MONITOR OptPower CW 3 DIR=OUT POL=X
.MONITOR OptPower ChannelFilt 2 DIR=OUT POL=X

.END
```

As expected, from the results it can be noticed that wavelengths of 1300 nm and 1800 nm are blocked by the Channel Filter.

The example model statement when Channel Filter is specified by *PassBandMode* = *CenterFreqAndConstBW* can be given by:

```
* Allows channel 1400 - 1500 nm and 1600 - 1700 nm
.MODEL ChanFilterModel OPTCHANNELFILTER
+ PassBandMode = CenterFreqAndConstBW
+ PassBands = [1450 1650] FrequencyUnit = nm
+ Bandwidth = 100 BandwidthUnit = nm
```

The example model statement when Channel Filter is specified by *PassBandMode* = *CenterFreqAndBW* can be given by:

```
* Allows channel 1395 - 1405 nm and 1590 - 1610 nm
.MODEL ChanFilterModel OPTCHANNELFILTER
+ PassBandMode = CenterFreqAndBW
+ PassBands = [1400 10 1600 20] FrequencyUnit = nm BandwidthUnit = nm
```

OPTFFT Model

Syntax

Style	Form
OptiSPICE	`.MODEL MODEL_NAME OPTFFT <param1=val1> <param2=val2> ...`

Parameters

Symbol and description	Default value	Units	Value range
Frequency Output filter coefficients with specific center frequency	193.1	-	]0,+INF[
FilterFreqShift Frequency shift from center frequency value	0	-	]0,+INF[
SignalBW Bandwidth of envelope of the filter input signal	0.05	-	]0,+INF[
ExclusionBW Exclusion bandwidth to exclude any channels not inside this bandwidth.	-1	-	]0,+INF[
FrequencyUnit Frequency unit	THz	-	Hz, THz, nm
FilterType Filter transfer characteristics type	BESSEL	-	BESSEL, BUTTERWORTH
FilterBW 3 dB filter bandwidth	10	GHz	]0,+INF[
FilterIL Insertion loss of the filter	0	dB	[0,+INF[
FilterOrder Order of the function	1	-	1,2,3, ...
FilterFile Filename with the measured data	-	-	-
FileFreqUnit Determines the frequency unit of the file with the measurements	Hz	-	Hz, GHz, THz, m, nm

Symbol and description	Default value	Units	Value range
FileFormat Determines the format of the file with the measurements	POWERPHASE	-	POWERPHASE, REALIMAG
FilePowScale Determines whether the measured data is in linear scale or in dB	LINEAR	-	LINEAR, DB
Tstonefile Touchstone file name containing two port S-parameters for the optical filter	-	-	-

Technical Background

The OPTFFT performs Fast Fourier Transform (FFT) on the incoming optical signal so that it can be used as an optical filter. The transfer function for the filter can be given in two forms: (1) user defined behavioral type for the filter transfer characteristics and (2) measured filter response given by a file.

The parameter *Frequency* sets the center frequency of the filter, with *FilterFreqShift* specifying shift from this value. The *SignalBW* parameter sets the bandwidth of envelope which sets the sampling time for FFT (this bandwidth should be larger then filter width and input signal bandwidth). The parameter *ExclusionBW* excludes any channels not inside this bandwidth (centered around the center frequency of the filter). The excluded channels do not propagate to the other elements. The default value of -1 for *ExclusionBW* means no channels are excluded by default. Frequency unit for these parameters are set by *FrequencyUnit* parameter, which can be set to Hz, THz, or nm.

Filter transfer characteristics of the behavioral filters are defined the type of the filter (*FilterType*), 3-dB bandwidth (*FilterBW*), insertion loss (*FilterIL*), and the order of the filter (*FilterOrder*). Filter types of *BESSEL* and *BUTTERWORTH* are the supported user defined behavioral filter types.

For the measured filter, the input file (*FilterFile*) is formatted containing frequency and filter measurement. The parameter *FileFreqUnit* determines the frequency or wavelength unit of the first item. It can be in Hz, THz, m, or nm. According to the parameter *FileFormat*, the second item can either contain power and phase (*POWERPHASE*) or real and imaginary (*REALIMAG*). If the format is *POWERPHASE*, the power can either be in linear scale or in dB defined by the parameter *FilePowScale*. The phase is specified in radians.

Power-phase format (assuming frequency unit is in THz and linear scale)

193.10	0.0	0.0
193.11	0.01	1.571
193.12	0.02	2.094
...	...	...

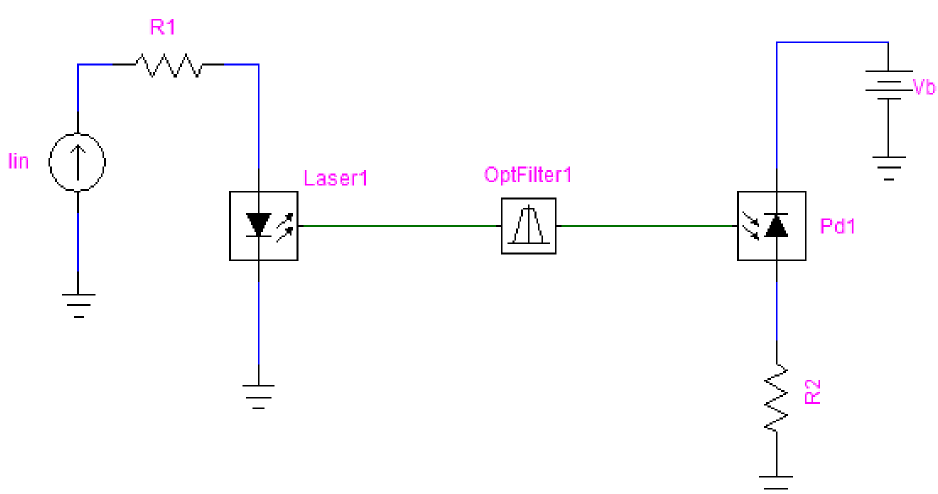
Real-imaginary format

193.10	0.0	0.0
193.11	-2.04e-6	0.010
193.12	-0.010	0.017
...	...	...

Measured filter can also be expressed using two port S parameters given by Touchstone file format. The parameter *Tstonefile* defines the name of the Touchstone file.

Example

Figure 1 Optical filter (OPTFFT)



The following netlist is given for the above circuit where output from the laser, which exhibits noise, is filtered by the optical filter, OptFilter1. The output of the filter is connected to a photodiode to be converted into electrical signal.

```
* Elements before optical filter
Iin 0 1 PULSE 100m 122m 0.0 0.2n 0.2n 0.4n 1.2n
R1 1 2 50
Osp Laser Name=Laser1 Nodes=[ 1 0 Lin ] MoName=CML Frequency=193.1
+ FrequencyUnit=THz

* OPTFFT element statement
Osp OPTFFT Name=OptFilter1 Nodes=[ Lin Lout ] MoName=Filter_Model

* Elements after optical filter
Osp PHOTODIODE Name=Pd1 Nodes=[ Lout Vout Bias ] MoName=PD_Model
Vb Bias 0 2
R2 Vout 0 2.5k

* OPTFFT model statement
* Signal bandwidth is set to 0.5 THz
* Filter is a Bessel type filter (order 2) with 7GHz 3-dB bandwith
.MODEL Filter_Model OPTFFT
+ Frequency=193.1237 FrequencyUnit=THz SignalBW=0.5
+ FilterType=BESSEL FilterBW=7 FilterOrder=2

* Other model statements
.MODEL CML LASER
+ LASERVOL = 1.5e-010 Vg = 8.5e+009 Qeff0 = 0.4
+ GAINS = 2.125e-6 N0 = 1.0e+018 GAMMAS = 0.4
+ TAUN = 1.5e-009 TAUP = 4e-012 BETAS = 30e-006
+ EPSI = 49.99999999999999e-018 ALPHA = 3
+ PHASENOISE = 1 PHOTONNOISE = 1 CARRIERNOISE = 1

.MODEL PD_Model PHOTODIODE PDeff=0.1

* Perform transient analysis by enabling noise
.TRAN 1p 6n NoiseSim=1 MaxBandwidth=1e12

* Signals to monitor
.MONITOR I Laser1 1
.MONITOR OptFields Laser1 3 DIR=OUT Format=CMPLX
.MONITOR OptFields OptFilter1 2 DIR=OUT Format=CMPLX
.MONITOR V Vout

.END
```

OMNIOCONN Model

Syntax

Style	Form
OptiSPICE	`.MODEL MODEL_NAME OMNIOCONN <param1=val1> <param2=val2> ...`

Parameters

Symbol and description	Default value	Units	Value range
LossType Loss types	CONST_LOSS	-	CONST_LOSS, UNITY
SubType Define whether the element type is general multi-port or 2 to 1 splitter or joiner	MULTI_PORT	-	MULTI_PORT, SPLITTER, JOINER,
SplitRatio Power split ratio	0.5	-	[0, +INF[
InputFilters List of input filter model (OPTFFT) names for each input port	-	-	-
OutputFilters List of output filter model (OPTFFT) names for each output port	-	-	-
InputOptFilterModel Single input filter model (OPTFFT) name for all input ports	-	-	-
OutputOptFilterModel Single input filter model (OPTFFT) name for all output ports	-	-	-
InputFiltersCF List of center frequencies to be applied as channel filers for each input port	-	-	]-INF, +INF[
OutputFiltersCF List of center frequencies to be applied as channel filers for each output port	-	-	]-INF, +INF[

Symbol and description	Default value	Units	Value range
InputFiltersBW List of corresponding bandwidth for each input channel filter	-	-	[0, +INF[
OutputFiltersBW List of corresponding bandwidth for each output channel filter	-	-	[0, +INF[
InputCenterFiltersLambda0 If InputFiltersBW is not provided, defines the center frequency value to be used as an initial value for the input ports (center frequency of first input port will be set to this value)	1550	-	[0, +INF[
InputDeltaFiltersLambda Incremental center frequency value for subsequent input ports (from input port 2)	0	-	[0, +INF[
OutputCenterFiltersLambda0 If OutputFiltersBW is not provided, defines the center frequency value to be used as an initial value for the output ports (center frequency of first output port will be set to this value)	1550	-	[0, +INF[
OutputDeltaFiltersLambda Incremental center frequency value for subsequent output ports (from output port 2)	0	-	[0, +INF[
InputFilterConstBW If InputCenterFiltersLambda0 is used to specify the center frequencies, this parameter set a constant bandwidth for all input ports	0	-	[0, +INF[
OutputFilterConstBW If OutputCenterFiltersLambda0 is used to specify the center frequencies, this parameter set a constant bandwidth for all output ports	0	-	[0, +INF[
FrequencyUnit Frequency unit for the channel filters	THz	-	Hz, THz, nm

Technical Background

The OMNIOCONN model is used to specify the parameters of an optical multi-port connector elements. This element passes every input signal (in either direction) to every output.

This element can either be a simple splitter or joiner with a 2 to 1 transition, or a general multi-port connector. If the element statement is defined as Osp SPLITTER or Osp JOINER, then it is a splitter or a joiner respectively. If the element statement is defined as Osp OMNIOCONN, then according to the model parameter *SubType*, it can either be a splitter (*SubType = SPLITTER*), joiner (*SubType = JOINER*), or a general multi-port connector (*SubType = MULTI_PORT*, default choice).

For splitter and joiner, then the input and output nodes are given using *Nodes* parameter, while for a general multi-port element, input and output nodes are given by *InputNodes* and *OutputNodes* parameters respectively.

If *LossType* is set to *UNITY,* each input signal is passed through all output nodes and each output signal is passed through all input nodes without change in power. As the power is simply duplicated in each port, the power is not conserved in this *LossType*.

If the *LossType* is set to *CONST_LOSS* (default choice), constant loss is applied to each signal. The power splitting has two cases: 1) if the number of output ports are two, the power is splitted to port 1 and 2 such that

$$P_{o1} = SplitRatio \cdot P_{in}$$

$$P_{o2} = (1 - SplitRatio) \cdot P_{in} \tag{1}$$

where P_{o1} and P_{o2} are the powers at the output port 1 and 2 respectively and P_{in} is the input power; 2) if the number of output ports are more than two, the input power will be splitted equally among for N output ports ($1/N$ of the input power in each output port).

In a joiner, power is joined such that

$$P_{out} = \left(\sqrt{\frac{P_{i1}}{N}} + \sqrt{\frac{P_{i2}}{N}} + \ldots + \sqrt{\frac{P_{iN}}{N}}\right)^2 \tag{2}$$

where P_{i1}, P_{i2}, ..., P_{iN} are the power from input ports 1, 2, ..., *N* and P_{out} is the joined power at the output port. A splitter can act as a joiner if all output ports are used as inputs and input port is used as an output, and vice versa, a joiner can act as a splitter if input and output ports are swapped.

For a general multi input/output device the power splitting factor is determined by $1/\sqrt{NM}$, where N and M are number of input and output ports respectively.

Input and output optical filters can be specified for the element. Using the list parameter *InputFilters = [M0 M1 ... Mn]* a set of optical filter model names can be specified (see OPTFFT) and a filter will be inserted at each input. If the keyword *NO* is used for a model name, then no filter will be inserted. Likewise the parameter *OutputFilters = [M0 M1 ... Mn]* can be used to specify filters on the outputs. The parameters *InputOptFilterModel* and *OutputOptFilterModel* can be used to place the same filter on each input or output respectively.

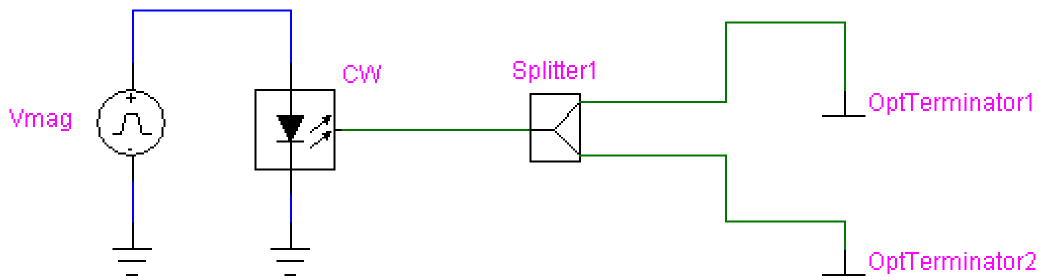
Alternatively, channel filters (see OPTCHANNELFILTER) can be placed on each input or output by specifying center frequencies and bandwidths. Individual center frequencies and bandwidths can be specified by the list parameters *InputFiltersCF*, *OutputFilterCF*, *InputFiltersBW*, and *OutputFiltersBW*.

Instead of specifying individual center frequencies for each port, *InputCenterFiltersLambda0* and *OutputCenterFiltersLambda0* can be used to set an initial center frequency with an increment in the center frequency for each input/output set by *InputDeltaFiltersLambda* and *OutputDeltaFiltersLambda*. In this situation the bandwidth should be set by *InputFilterConstBW* and *OutputFilterConstBW*.

Examples

Splitter

Figure 1 Splitter example



This example shows a power splitter that splits 80% of the power to the first output port and 20% to the second. The netlist is given as follows:

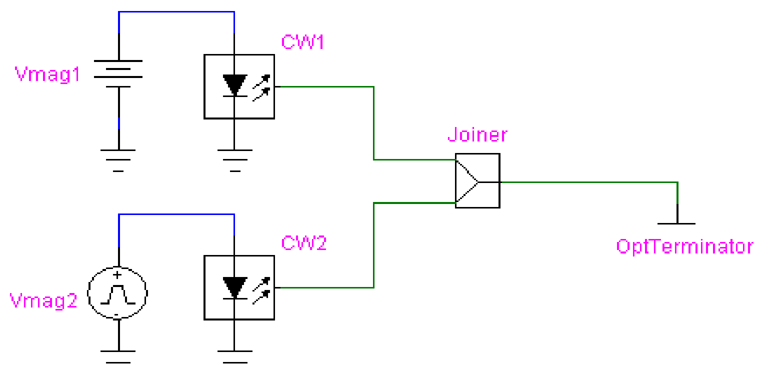
```
* Circuit elements and connections
Vmag magin 0 PULSE 0.0 0.5 0.0 0.2ns 0.2ns 5ns
Osp CWSOURCE Name=CW Nodes=[magin 0 in] MoName=CWMod
* Splitter defined as an OMNIOCONN element
Osp OMNIOCONN Name=Splitter1 Nodes=[in out1 out2] MoName=SplitterModel

Osp MIRROR Name=OptTerminator1 Nodes=[out1] MoName=TerminatorMod
Osp MIRROR Name=OptTerminator2 Nodes=[out2] MoName=TerminatorMod

* OMNIOCONN model statement.
* SubType is set as splitter with a split ratio of 0.8.
* This split ratio will split 80% of the input power to the first
* output port and 20% to the second port
.MODEL SplitterModel OMNIOCONN SubType = SPLITTER SplitRatio = 0.8

.MODEL CWMod CWSOURCE
.MODEL TerminatorMod MIRROR

* Monitor input and two of the splitter's output port power
.MONITOR OptPower CW 3 DIR=OUT POL=X
.MONITOR OptPower Splitter1 2 DIR=OUT POL=X
.MONITOR OptPower Splitter1 3 DIR=OUT POL=X

.TRAN 0.01ns 60ns
.END
```

If the splitter is defined with the *LossType* of *UNITY*, then each output port will produce the same power equal to the power of the CW Source. The model statement for such a splitter is given by:

```
.MODEL SplitterModel OMNIOCONN SubType = SPLITTER LossType = UNITY
```

Joiner

Figure 2 Joiner example



In this example optical input from two CW sources (with same wavelengths) are connected to a joiner. First CW Source produces a constant power of 0.25W while the second one produces a pulse waveform with peak power of 0.25W. The joiner with the default *SplitRatio* of 0.5 produces a peak output of 0.5W and a minimum power of 0.125W. The netlist for the above circuit is given below:

```
* Circuit elements and connections
Vmag1 magin1 0 DC=0.5
Vmag2 magin2 0 PULSE 0.0 0.5 0.0 0.1ns 0.1ns 2ns 5ns
Osp CWSOURCE Name=CW1 Nodes=[magin1 0 jin1 ] MoName=CWMod
Osp CWSOURCE Name=CW2 Nodes=[magin2 0 jin2 ] MoName=CWMod

* Joiner is defined as an OMNIOCONN element
Osp OMNIOCONN Name=Joiner Nodes=[jin1 jin2 jout] MoName=JoinerModel

Osp MIRROR Name=OptTerminator Nodes=[jout] MoName=TerminatorMod

* OMNIOCONN model statement for Joiner
.MODEL JoinerModel OMNIOCONN SubType=Joiner

.MODEL CWMod CWSOURCE
.MODEL TerminatorMod MIRROR
```

```
* Monitor joiner output power
.MONITOR OptPower Joiner 3 DIR=OUT POL=X

.TRAN 0.01ns 20ns
.END
```

Multi-port connector

Following netlist shows an example of a one input and three output multi-port OMNIOCONN. The optical power input from a CW Source is split such that equal power (1/3 of the input power) is produced at each output port.

```
* Circuit elements and connections
Vmag powin 0 PULSE 0.0 0.6 0.0 0.2ns 0.2ns 5ns
Osp CWSOURCE Name=CW Nodes=[powin 0 in] MoName=CWMod

* OMNIOCONN element statement
Osp OMNIOCONN Name=multiportcon InputNodes=[in]
+ OutputNodes=[out1 out2 out3] MoName=MultiPortModel

Osp MIRROR Name=OptTerminator1 Nodes=[out1] MoName=TerminatorMod
Osp MIRROR Name=OptTerminator2 Nodes=[out2] MoName=TerminatorMod
Osp MIRROR Name=OptTerminator3 Nodes=[out3] MoName=TerminatorMod

* OMNIOCONN model statement.
.MODEL MultiPortModel OMNIOCONN

.MODEL CWMod CWSOURCE CWSourceType=POWPHI
.MODEL TerminatorMod MIRROR

* Monitor optical power output in CW source and
* three of the output ports of multi-port connector
.MONITOR OptPower CW 3 DIR=OUT POL=X
.MONITOR OptPower multiportcon 2 DIR=OUT POL=X
.MONITOR OptPower multiportcon 3 DIR=OUT POL=X
.MONITOR OptPower multiportcon 4 DIR=OUT POL=X

.TRAN 0.01ns 60ns
.END
```

Placing optical filters and channel filters

The following model statement is an example where input and output filters (OPTFFT models) are placed for the multi-port connector. The filters are placed on the input port and first and second ports of the output.

```
.MODEL MultiPortModel OMNIOCONN
+ InputFilters = [inFilterModel]
+ OutputFilters = [outFilterModel1 NO outFilterModel3]
```

where optical filter models are specified as:

```
.MODEL inFilterModel OPTFFT tstoneFile = FilterIn.s2p
.MODEL outFilterModel1 OPTFFT tstoneFile = FilterOut1.s2p
.MODEL outFilterModel3 OPTFFT tstoneFile = FilterOut3.s2p
```

In the following model statement, channel filters are included for the input and output ports.

```
.MODEL MultiPortModel OMNIOCONN FrequencyUnit = nm
+ InputFiltersCF = [1550] InputFiltersBW = [100]
+ OutputFilterCF = [1550 1560 1570] OutputFiltersBW = [4 4 4]
```

The equivalent model of the above can also be specified using *InputCenterFiltersLambda0* and *OutputCenterFiltersLambda0*. For the three output ports an increment in the center frequency for each output port is set by *OutputDeltaFiltersLambda*.

```
.MODEL MultiPortModel OMNIOCONN FrequencyUnit = nm
+ InputCenterFiltersLambda0 = 1550
+ InputFilterConstBW = 100
+ OutputCenterFiltersLambda0 = 1550 OutputDeltaFiltersLambda = 10
+ OutputFilterConstBW = 4
```

MULTILAYERFLITER (WAVEGUIDE) Model

Syntax

Style	Form

OptiSPICE	`.MODEL MODEL_NAME MULTILAYERFILTER <param1=val1>`
	`+ <param2=val2> ...`
	`.MODEL MODEL_NAME WAVEGUIDE <param1=val1> <param2=val2> ...`

Parameters

Symbol and description	Default value	Units	Value range
FilterType Defines whether the filter is implicit or explicit. When the filter is set to explicit, the transmission and reflection coefficients are calculated for every time step, thus time delay and electrical bandwidth effects are captured (Note: For a large number of layers, the calculation time of this FilterType will increase significantly) When the filter is set to implicit, the filter is static - the transmission and reflection coefficients are only calculated for the channel wavelength operating point (no electrical bandwidth effects are captured). This FilterType will generally run more quickly that the Explicit filter type.	Implicit	-	Implicit, Explicit
Thickness List of layer thickness. Length of list defines number of layers	-	um	]0, +INF[
N0 Index at the start of the filter - external to layers. If set to zero index will match filter for all modes/channels.	1.0	-	]0, +INF[
NF Index at the end of the filter - external to layers. If set to zero index will match filter for all modes/channels.	1.0	-	]0, +INF[
N0List List of indexes by mode at the start of the filter - external to layers	-	-	]0, +INF[

Symbol and description	Default value	Units	Value range
NFList List of indexes by mode at the end of the filter - external to layers	-	-	]0, +INF[
InputType Sets the way in which the lists parameters (Index, Atten, AlphaT, BetaT, AlphaV, and BetaV) are interpreted. MultiLayer - list values are specified by layer; SingleLayer - list values are specified by mode	MultiLayer	-	MultiLayer, SingleLayer
Index (Neff) List of indexes - should be n long (where n is number of layers or modes)	-	-	]0, +INF[
Atten List of attenuation - should be n long (where n is number of layers or modes)	-	-	]0, +INF[
TotalAtten If Atten is not given the total attenuation is distributed equally among the layers	1.0	-	]0, +INF[
AlphaV (dNdV) List by layer or mode of derivative of index with respect to voltage	-	1/V	]-INF, +INF[
BetaV (d2NdV2) List by layer or mode of second derivative of index with respect to voltage	-	1/V^2	]-INF, +INF[
AlphaT (dNdT) List by layer or mode of derivative of index with respect to temperature	-	1/K	]-INF, +INF[
BetaT (d2NdT2) List by layer or mode of second derivative of index with respect to temperature	-	1/K^2	]-INF, +INF[
AlphaL (dLdV) List by layer of derivative of layer length with respect to voltage	-	um/V	]-INF, +INF[
BetaL List by layer of second derivative of layer length with respect to voltage	-	um/V^2	]-INF, +INF[
Length Waveguide length	1.0	um	]0, +INF[

Symbol and description	Default value	Units	Value range
MaxOptLen List by layer or mode for maximum possible optical length	0.0	um	]0, +INF[
DefLambda Unless channel wavelength is known from the source (laser,cw), this wavelength value is used to calculate the filter characteristics.	1550	nm	]0, +INF[
ParaFile Name of the file to describe the parameters for a multilayer-multimode-multichannel filter	-	-	-
TilingNum The TilingNum can be used to define periodic multilayer structures. For example if TilingNum=3 and Thickness = [0.1 0.2], the following periodic structure will be created: [0.1 0.2 0.1 0.2 0.1 0.2]. The same operation will be performed for the parameters Index, Atten, AlphaT, BetaT, AlphaV, and BetaV.	1	-	[1, +INF[
Apo_Type Type of apodization to apply to filter (Gaussian, Cosine). By default the Apo_Type is not active (None).	None	-	[Gaussian, Cosine, None]
Apo_del_N Maximum change in the refractive index (for Gaussian and Cosine)	0.0	-	-
Apo_sigma Standard deviation of the apodization profile (for Gaussian)		-	-

Technical Background

This model characterizes a multi-layer thin film interference where the interference is often exploited to produce filtering in optical systems. A multilayer structure consisting of layers of material of differing optical index will produce a complex series of interfering waves formed by the reflection at and transmission through each interface. The interference in a series of layers can be simulated in two ways in OptiSPICE.

If the filter is simply a stack of material layers it is possible to model the effect of the entire stack with a single optical scattering element and the multilayer nature of the element is captured implicitly in terms of mode mixing matrices for transmission ($\hat{T}$) and reflection ($\hat{R}$) for each channel [1], [2]. This type of filter is called an implicit filter and index of refraction for each layer of this filter is static.

However, if it is needed, the physical structure can be simulated explicitly as series of optical scattering elements with a $\hat{\boldsymbol{T}}$ and $\hat{\boldsymbol{R}}$ using Snell's Law for each interface and a signal delay modeling the propagation through the thickness of the layer. This type of filter is called an explicit filter. This explicit formulation is useful when the index of refraction is time varying and dependent on system variables.

This model can also act as a waveguide model since it supports multi-mode multi-channel device with a specified effective index (and therefore phase shift/time delay/attenuation) for each mode of each channel.

Implicit filter

For an implicit implementation of optical filter a well developed theory for optical coatings can be used [3]. This theory starts from a fundamental application of Maxwell's equations to determine a characteristic matrix $\hat{\boldsymbol{M}}$ which describes the propagation of light through a layer of material. This matrix is defined as

$$\hat{\boldsymbol{M}} = \begin{bmatrix} \cos\phi & \dfrac{j \cdot \sin\phi}{n} \\ j \cdot n \cdot \sin\phi & \cos\phi \end{bmatrix} \tag{1}$$

where the signal delay through the layer is given by,

$$\phi = \frac{2\pi}{\lambda} nd \tag{2}$$

with d being the layer thickness, n the layer index, and λ the optical wavelength. can be shown that multiple layer structures can be described by single characteristic matrix given by [3]

$$\hat{\boldsymbol{M}} = \begin{bmatrix} \hat{M}_{11} & \hat{M}_{12} \\ \hat{M}_{21} & \hat{M}_{22} \end{bmatrix} = \hat{\boldsymbol{M}}_1 \hat{\boldsymbol{M}}_2 \hat{\boldsymbol{M}}_3 \ldots \hat{\boldsymbol{M}}_m \tag{3}$$

where $\hat{\boldsymbol{M}}_i$ is the characteristic matrix of the i-th layer.

Using the matrix $\hat{\boldsymbol{M}}$, the complex coefficients for transmission $\hat{t}$ and reflection $\hat{r}$ can be defined for the entire filter stack

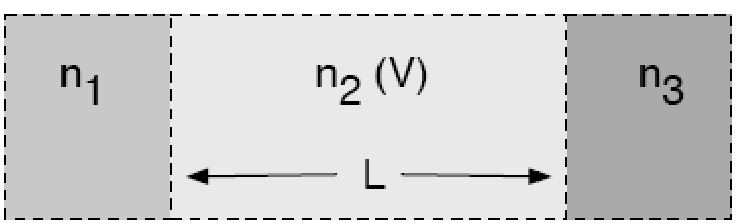
$$\hat{t} = \frac{2n_0}{n_0\hat{M}_{11} + jn_0n_s\hat{M}_{12} + j\hat{M}_{21} + n_s\hat{M}_{22}}$$
$$\hat{r} = \frac{n_0\hat{M}_{11} + jn_0n_s\hat{M}_{12} - j\hat{M}_{21} - n_s\hat{M}_{22}}{n_0\hat{M}_{11} + jn_0n_s\hat{M}_{12} + j\hat{M}_{21} + n_s\hat{M}_{22}} \quad (4)$$

where n_0 is the index of the first layer and n_0 the index of the final layer. Using these quantities the mode mixing matrices for transmission $\hat{\boldsymbol{T}}$ and reflection $\hat{\boldsymbol{R}}$ of an optical scattering element used to model the filter can be created in the same manner as for the simple interface above.

Explicit filter

The use of an implicit filter is limited to situations where the filter configuration is not subject to changes during operation and the channel carrier frequencies are fixed. A variety of optical filters can be fabricated which allow active control of the transmission and reflection characteristics. A simple implementation of such a device is shown in Figure 1. This structure is a simple three layer filter with a variable optical length for the middle layer; either the physical length L or the optical index n could be a function of the applied voltage, V.

Figure 1 Explicit filter



The optical length L and the he optical index n for a specific layer can be expressed as a function of applied layer voltage and temperature as given by

$$dT = T - T_{cir}$$
$$dV = V_1 - V_2$$
$$n = n_i + \alpha_V \cdot dV + \beta_V \cdot dV^2 + \alpha_T \cdot dT + \beta_T \cdot dT^2 \quad (5)$$
$$L = d + \alpha_L \cdot dV + \beta_L \cdot dV^2$$

where

- T is the temperature of the filter and T_{cir} is the circuit temperature
- V_1 and V_2 are the pair of voltages controlling the specific layer
- α_V is from the list parameter *AlphaV* corresponding to the specific layer
- β_V is from the list parameter *BetaV* corresponding to the specific layer
- α_T is from the list parameter *AlphaT* corresponding to the specific layer
- β_T is from the list parameter *BetaT* corresponding to the specific layer
- α_L is from the list parameter *AlphaL* corresponding to the specific layer
- β_L is from the list parameter *BetaL* corresponding to the specific layer.

Multi-layer/multi-channel/multi-mode filter

The properties for a multi-layer/multi-channel/multi-mode filter can be defined by a text file (name of the file is given by the parameter *paraFile*) where a value of the parameter can be specified for each mode of each channel for each layer. The format of the file is given as follows:

```
Layers Num_of_layers Channels Num_of_channels Modes Num_of_modes
Channels: ch0_wavelength ch1_wavelength ch2_wavelength ...

N0:
Channel channel_number
Mode mode_number N0_value

Layer layer_number:
Channel channel_number
Mode mode_number Index Atten AlphaT AlphaV BetaT BetaV
```

```
NF:
Channel channel_number
Mode mode_number NF_value
```

Comments (starting with '*' or '#' character) and new lines can be placed anywhere in the file. First entry must specify number of layers, number of channels, and number of modes. In second entry, all the channel wavelengths must be listed separated by a space. Third entry is for the *N0* parameter and the values for each mode of each channel must be entered in order for all modes and channels. Channel and mode numbers are entered from 0 to $N-1$ and 0 to $M-1$, where N and M are the number of modes and number of channels respectively. As the next entries, the parameters *Index*, *Atten*, *AlphaT*, *AlphaV*, *BetaT*, and *BetaV* are entered for each mode of each channel for each layer in order (from layer number 0 to $L-1$, where L is the number of layers). Finally the parameter *NF* is entered the same way as of *N0*. An example of this file is provided in the Examples section.

NOTE: The ***Multilayer Filter Input File Editor*** (under the Tools menu) can be used to automatically create the parameter text file.

Apodization

Apodization can be applied to the index profile of the ML filter (the filter requires at least two layers). Two profile are available: *Gaussian* and *Cosine*. For the Gaussian profile the change in the j^{th} layer is calculated as follows:

$$A_j = \Delta n \cdot e^{-\log(2) \cdot \left(\frac{j/N - 1/2}{\sigma}\right)^2} \tag{6}$$

where Δn is the maximum change in the refractive index (*Apo_del_N*) and σ is the standard deviation (*Apo_sigma*).

For the *Cosine* profile the change in the j^{th} layer is calculated as follows:

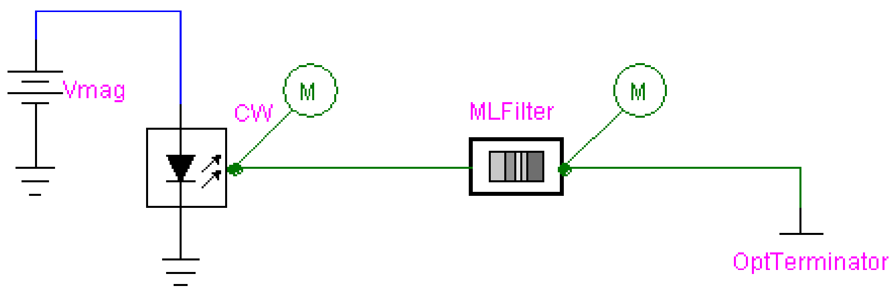
$$A_j = \frac{\Delta n}{2} \cdot \left(1 + \cos\left(\pi \cdot \left(\frac{j}{N} - \frac{1}{2}\right)\right)\right) \tag{7}$$

Examples

Implicit filter

The following is a channel filtering example using an implicit type filter.

Figure 2 Multilayer filter example



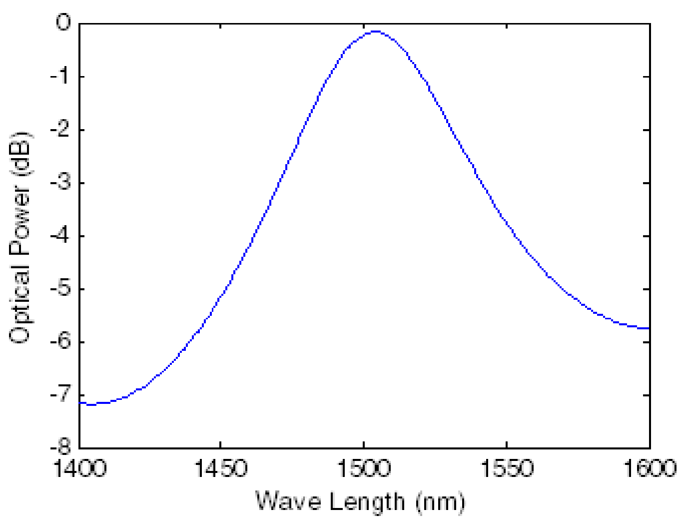
In this example, the output power of the multilayer filter is monitored for different values of wavelength. An operating point analysis is performed with the parametric sweep of the CW Source wavelength. The netlist for this example is given below.

```
* Circuit elements and connections
Vmag magin 0 1
Osp CWSOURCE Name=CW Nodes=[magin 0 lin] MoName=CWMod lambda = lam

* Multilayer filter element statement
Osp MULTILAYERFILTER Name=MLFilter Nodes=[lin lout] MoName=FilterImp

Osp MIRROR Name=OptTerminator Nodes=[lout] MoName=TerminatorMod

* Implicit multilayer model statement
.MODEL FilterImp MULTILAYERFILTER N0=1.0 NF=1.5
+ Thickness = [0.25 0.25 0.25 0.25 0.25 0.25]
+ Index = [3.5 4.5 3.5 4.5 3.5 4.5]

.MODEL CWMod CWSOURCE
.MODEL TerminatorMod MIRROR

.PARAM lam = 1550

* Perform opeating point analysis at various lambda values
.OP SWEEP lam 1400 1600 1

* Monitor filter input and output power
.MONITOR OptPower MLFilter 1 DIR=IN POL=X
```

```
.MONITOR OptPower MLFilter 2 DIR=OUT POL=X

.END
```

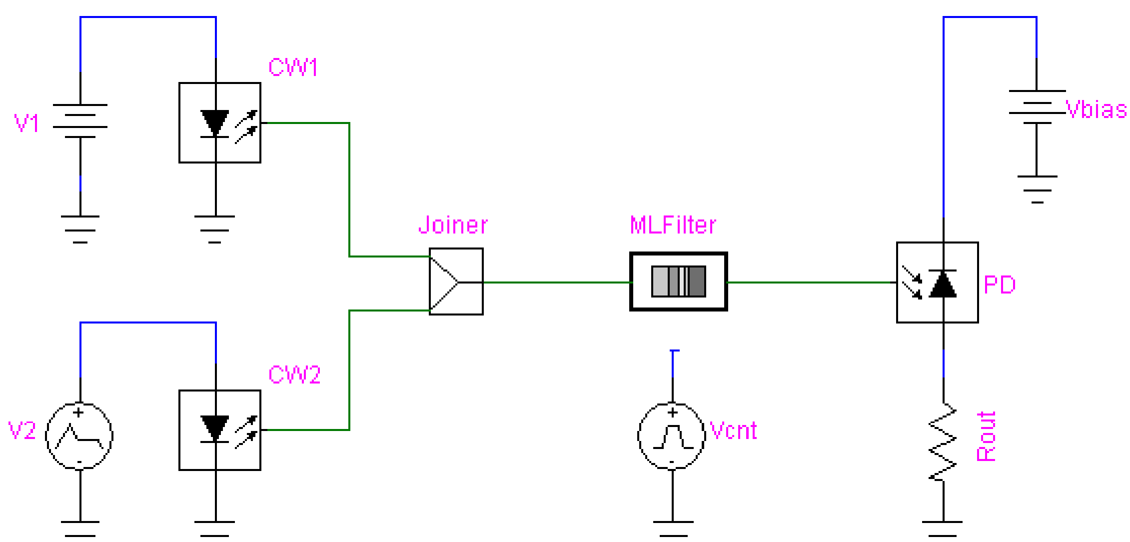
Figure 3 shows the filter output power in dB.

Figure 3 Filter output power



Explicit filter

Figure 4 Explicit filter example



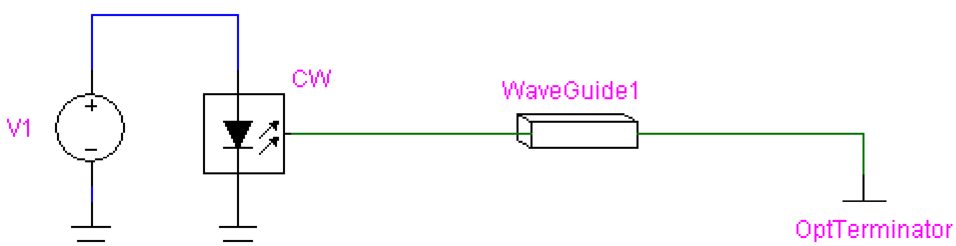
In the above circuit an explicit multilayer filter is utilized to perform a dynamic channel filtering according to the control voltage applied to one of its layer. Input from CW sources CW1 and CW2 with different wavelengths are connected to the multilayer filter through a 2 to 1 joiner. The multilayer filter has 11 layer and the 6-th layer is controlled by a voltage generated by a pulse voltage source Vcnt. The filter is designed such that when Vcnt remains 0V it transmits channel 1 and when it switch to a certain voltage it transmit channel 2. The netlist for the above circuit is given below.

```
* Parameter definitions
.PARAM na=1.0
.PARAM ns=3.5
.PARAM lambda0=1550
.PARAM lambdaSi='1550/ns'
.PARAM lambda2='lambda0+5'
.PARAM lambda2Si='lambda2/ns'
.PARAM ds='21*lambdaSi/4.0*1e-3'
.PARAM da='5*lambda0/4.0*1e-3'
.PARAM dg='2*lambda0/4.0*1e-3'
.PARAM dn=0.0283 dl='.0277/Na*dg'
.PARAM moptl='dg*na*2'
.PARAM ch1Lambda = 1550.04
.PARAM ch2Lambda = 1555.34

* Circuit elements and connections
V1 Mag1 0 100m
Osp CWSOURCE Name=CW1 Nodes=[Mag1 0 l1] MoName=CWMod lambda = ch1Lambda
V2 Mag2 0 PWL 0 200m 14n 200m 17n 400m 19n 400m 23n 200m 50n 200m
Osp CWSOURCE Name=CW2 Nodes=[Mag2 0 l2] MoName=CWMod lambda = ch2Lambda
Osp SPLITTER Name=Joiner Nodes=[j1 l1 l2] MoName=splittermodel

* Layer controlling voltage source
Vcnt cnt 0 pulse 0 dn 8n 2n 2n 16n 70n

* Multilayer filter element (11 layers).
* Layer 6 is controlled by voltage at node cnt
Osp MultiLayerFilter Name=MLFilter Nodes=[j1 o1] MoName=FilterEx
+ FilterCnodes=[{0 0} {0 0} {0 0} {0 0} {0 0} {cnt 0} {0 0} {0 0}
+ {0 0} {0 0} {0 0}]

Osp PHOTODIODE Name=PD Nodes=[ o1 Vout bias ] MoName=PDMOD
Vbias bias 0 2
Rout Vout 0 100
```

```
* Multilayer model statement
.Model FilterEx MultiLayerFilter FilterType=Explicit N0=na NF=na
+   Thickness = [ds da ds da ds dg ds da ds da ds ]
+   Index = [ns na ns na ns na ns na ns na ns ]
+   dNdV = [0 0 0 0 0 1 0 0 0 0 0 ]  MaxOptLen=[moptl]

.MODEL CWMod CWSOURCE
.MODEL PDMOD PHOTODIODE PDeff=1
.MODEL splittermodel SPLITTER

.TRAN 0.01n 35n

.MONITOR V Mag1
.MONITOR V Mag2
.MONITOR OptPower Joiner 1 DIR=OUT POL=X ChannelLambda = ch1Lambda
.MONITOR OptPower Joiner 1 DIR=OUT POL=X ChannelLambda = ch2Lambda
.MONITOR OptPower MLFilter 2 DIR=OUT POL=X ChannelLambda = ch1Lambda
.MONITOR OptPower MLFilter 2 DIR=OUT POL=X ChannelLambda = ch2Lambda
.MONITOR V Vout

.END
```

Waveguide

Figure 5 Waveguide example



In the above circuit a CW source with four modes is connected to a waveguide that has different indexes and attenuations for each mode. The netlist is given below.

```
* Circuit elements and connections
V1 Mag1 0 DC = 1 pwl 0 .1 1p .1 1.1p 1.0 2.1p 1.0 2.2p .1
Osp CWSOURCE Name=CW Nodes = [Mag1 0 lin] MoName = CWmodel

* Waveguide filter element statement
Osp WaveGuide  Name=WaveGuide1 Nodes = [lin lout] MoName=WGmodel
```

```
Osp MIRROR Name=OptTerminator Nodes=[lout] MoName=TerminatorMod

* Waveguide model statement
* This model is defined as a signle layer and therefore Index and Atten
* parameters are defined for each mode.
.MODEL WGmodel WaveGuide InputType=SingleLayer
+ Length=1000 N0=1.1 NF=1.1 NumModes = 4
+ ModeType = BESSEL_0_MODE Index=[1.1 1.2 1.3 1.4]
+ Atten=[1.0 .8 .6 .4]

.MODEL CWmodel CWSOURCE NumModes = 4 ModeCoeff = [.35 .2 .15 .10]
+ ModeType = BESSEL_0_MODE

.MODEL TerminatorMod MIRROR

.TRAN 0.01p 10p

.MONITOR OptPower CW 3 DIR=OUT  POL=TE
.MONITOR OptPower WaveGuide1 2 DIR=OUT POL=TE

.END
```

Multi-layer/multi-channel/multi-mode filter

Following model statement defines a multilayer/multi-channel/multi-mode filter whose properties are defined by a file name FlterSpec.txt.

```
.MODEL MLFileModel MultiLayerFilter
+ ParaFile = FilterSpec.txt Thickness = [ 100 120 100]
```

The file FlterSpec.txt is given below.

```
* Filter spec for multi mode filter

Layers 3 Channels 2 modes 2

Channels: 1558 1560

N0:
Channel 0
Mode 0 1.1
Mode 1 1.2
Channel 1
```

```
Mode 0 1.3
Mode 1 1.4

* Index atten dNdT dNdV d2NdT2 d2NdV2
Layer 0:
Channel 0
Mode 0  1.1 0.9 .01 .02 .0001 .002
Mode 1  1.2 0.85 .01 .02 .0001 .002
Channel 1
Mode 0  1.15 0.96 .01 .02 .0001 .002
Mode 1  1.26 0.87 .01 .02 .0001 .002

Layer 1:
Channel 0
Mode 0  1.5 1.0 .01 .02 .0001 .002
Mode 1  1.4 .95 .01 .02 .0001 .002
Channel 1
Mode 0  1.6 .92 .01 .02 .0001 .002
Mode 1  1.5 .95 .01 .02 .0001 .002

Layer 2:
Channel 0
Mode 0  1.1 0.9 .01 .02 .0001 .002
Mode 1  1.2 0.85 .01 .02 .0001 .002
Channel 1
Mode 0  1.15 0.96 .01 .02 .0001 .002
Mode 1  1.26 0.87 .01 .02 .0001 .002

NF:
Channel 0
Mode 0 1.15
Mode 1 1.25
Channel 1
Mode 0 1.35
Mode 1 1.45
```

References

[1] T. Tamir, *Guided-Wave Optoelectronics*. Berlin: Springer=Verlag, 1995.

[2] C.L. Chen, *Foundations for Guided-Wave Optics*. Wiley, 2006.

[3] A. Thelen, *Design of Optical Interference Coatings*. New York, USA: McGraw-Hill, 1989.

OPTRING Model

Syntax

Style	Form
OptiSPICE	.MODEL MODEL_NAME OPTRING <*param1=val1*> <*param2=val2*> ...

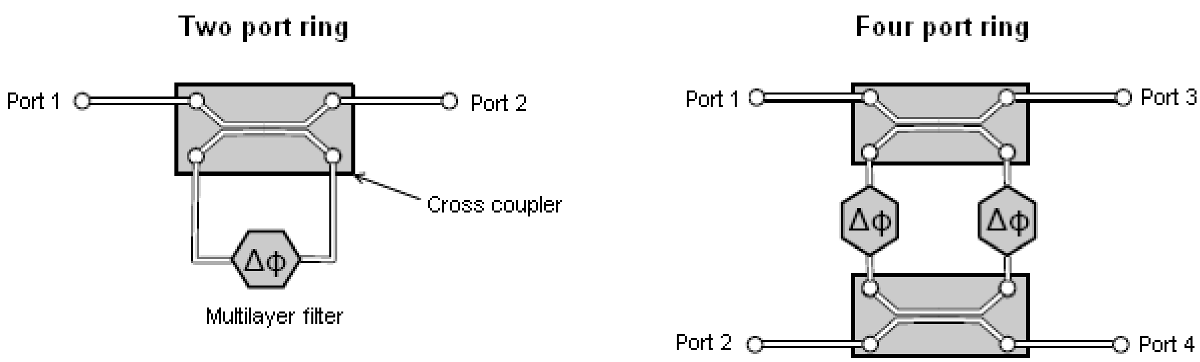
Parameters

Symbol and description	Default value	Units	Value range
Radius Radius of ring resonator	10	um	[0, +INF[
XC_model (XC_model1) Model name for the first cross coupler	-	-	-
XC_model2 Model name for the second cross coupler (only required for a four port ring resonator)	-	-	-
RingModel Name of the explicit multilayer model representing the ring	-	-	-

Technical Background

The ring resonator is a two or four port ring comprised of one/two cross-couplers and one/two explicit multilayer filters as given below by Figure 1.

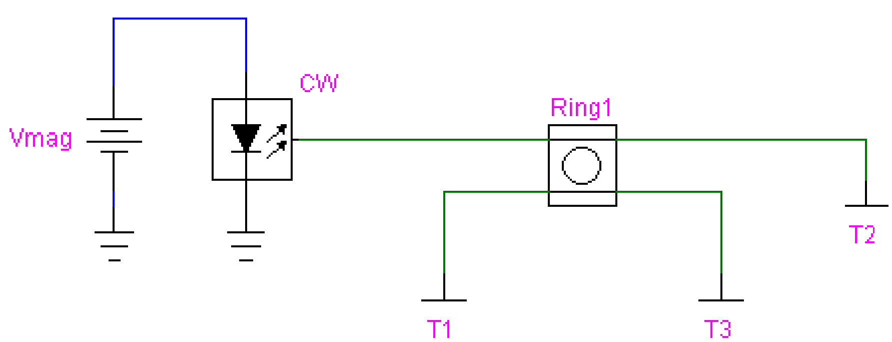
Figure 1 Ring resonator illustration



The explicit multilayer filters provide the capability to have a time varying signal delay that depends on the temperature and voltage.

Examples

Figure 1 Ring resonator example



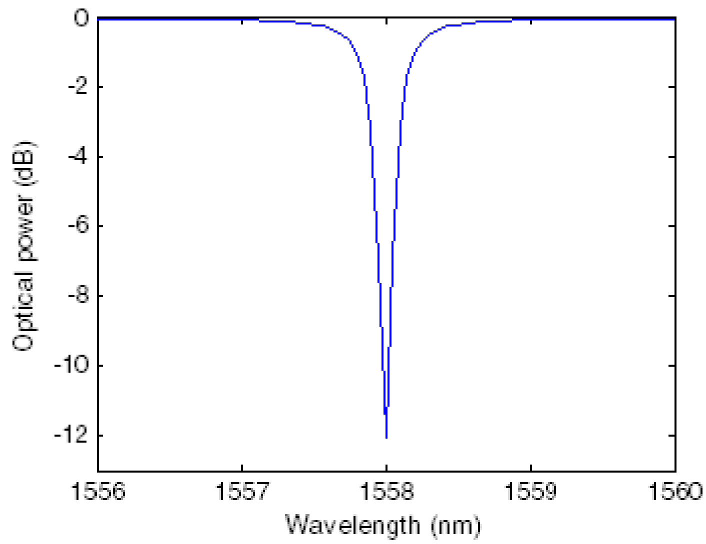
In this example, the output power of a four port ring resonator is monitored for different values of wavelength. An operating point analysis is performed with the parametric sweep of the CW Source wavelength. The netlist for this example is given below.

```
* Circuit elements and connections
Vmag magin 0 1
Osp CWSOURCE Name=CW Nodes = [magin 0 lin] MoName=CWMod lambda = lam

* Ring element statement
```

```
Osp OptRing Name=Ring1 Nodes = [lin lout1 lout2 lout3] MoName = RingMod

Osp MIRROR Name=T1 Nodes=[lout1] MoName=TerminatorMod
Osp MIRROR Name=T2 Nodes=[lout2] MoName=TerminatorMod
Osp MIRROR Name=T3 Nodes=[lout3] MoName=TerminatorMod

* Ring model statement
.MODEL RingMod OPTRING XC_model1 = XcoupMod XC_model2 = XCoupMod
+ RingModel = RingFilter Radius = r

* Cross-coupler model statement
.MODEL XCoupMod XCOUPLER Conjugate=0 c = cval

* Multilayer filter model statement
.MODEL RingFilter MultiLayerFilter FilterType=Explicit
+ N0 = 3 NF = 3 Index = [3] TotalAtten= gain

.MODEL CWMod CWSOURCE
.MODEL TerminatorMod MIRROR

* Parameter definition
.PARAM cval = 0.02
.PARAM gain = '1-cval'
.PARAM gain2 = '1.0'
.PARAM r ='(1+1.19e-4)*10'
.PARAM lam = 1550

* Perform opeating point analysis at various lambda
.OP SWEEP lam 1556 1560 0.05

* Monitor filter output power on each port of the ring
.MONITOR OptPower Ring1 1 DIR=IN POL=X
.MONITOR OptPower Ring1 2 DIR=OUT POL=X
.MONITOR OptPower Ring1 3 DIR=OUT POL=X
.MONITOR OptPower Ring1 4 DIR=OUT POL=X

.END
```

Figure 2 shows the filter output power in dB at port 3 (through port).

Figure 2 Ring output at port 3



OPTISYSINOPT Model

Syntax

Style	Form
OptiSPICE	.MODEL MODEL_NAME OPTISYSINOPT <*param1=val1*> <*param2=val2*> ...

Parameters

Symbol and description	Default value	Units	Value range
Frequencies (f0s) List of center frequencies by channel	-	-	[0, +INF[
FrequencyUnit Frequency unit	THz	-	Hz, THz, nm

Technical Background

The OPTISYSINOPT model is generated by OptiSystem for the OPTISYSINOPT optical input element in older to perform OptiSystem - OptiSPICE co-simulation. Generated model is written to a text file and included in the netlist using '.INCLUDE' statement. This model defines the all property of the generated optical signal such as channel frequencies, mode profiles and polarization details.

OPTAMPM Model

Syntax

Style	Form
OptiSPICE	`.MODEL MODEL_NAME OPTAMPM <param1=val1> <param2=val2> ...`

Parameters

Symbol and description	Default value	Units	Value range
TStoneInput When set to 1 the input file format is assumed to be Touchstone	1	-	[0,1]
BPMInput When set to 1 the input file format is assumed to be the OptiBPM scattering data (“data.s”) format	0	-	-
in_file_s Name of input data file (Touchstone or “.s”)	‘Filename’	-	-
InputPorts_i Number of input ports (left-hand side of component)	1	-	-

Technical Background

Touchstone/OptiBPM input files define a device with n inputs and m output ports.

Touchstone file

This file is generated by the user (either numerically, analytically or experimentally) and should be setup in accordance with the Touchstone file format (see https://ibis.org/touchstone_ver2.0/touchstone_ver2_0.pdf)

It models the scattering of the electric field from a port to all the outputs including reflections using a gain/loss factor and a phase shift:

$$\begin{bmatrix} O_1 \\ \dots \\ O_{n+m} \end{bmatrix} = \begin{bmatrix} S_{1,1} & \dots & S_{1,n+m} \\ \dots & \dots & \dots \\ S_{n+m,1} & \dots & S_{n+m,n+m} \end{bmatrix} \cdot \begin{bmatrix} I_1 \\ \dots \\ I_{n+m} \end{bmatrix} \quad (1)$$

OptiBPM File

OptiBPM can provide scattering data information for a variety of optical devices and can be used as a compact model generator for OptiSPICE simulations (the input read in by OptiSPICE is the “data.s” scattering data file produced by OptiBPM). It models the loss/gain and phase shift of the electric field from input ports to output ports:

$$\begin{bmatrix} O_1 \\ \dots \\ O_m \end{bmatrix} = \begin{bmatrix} T_{1,1} & \dots & T_{1,n} \\ \dots & \dots & \dots \\ T_{m,1} & \dots & T_{m,n} \end{bmatrix} \cdot \begin{bmatrix} I_1 \\ \dots \\ I_n \end{bmatrix} \quad (2)$$

Optiwave
7 Capella Court
Ottawa, Ontario, K2E 7X1, Canada

Tel.: 1.613.224.4700
Fax: 1.613.224.4706

E-mail: support@optiwave.com
URL: www.optiwave.com