

OptiSPICE
Model Library

Version 1.1



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1 Introduction

OptiSPICE optical model library is designed to be compatible with SPICE engines such that optical and electrical components can be simulated simultaneously. This document describes the set of OptiSPICE optical models that are available directly in Tanner T-Spice simulation engine via a dynamically linked compact model library. For more information on news and product updates on this software integration package you can visit our website at the following link:

<https://optiwave.com/?p=54896>

2 Technical Background

2.1 Optical Signal Modeling

OptiSPICE optical models use slowly varying envelope approximation to model the behaviour of optical signals as they travel through various devices. Complex valued bidirectional optical signals are separated into individual channels with unique optical carrier frequencies.

$$E_o = Ee^{j2\pi f_c t} \quad (2.1.1)$$

High frequency (Thz) sinusoid signals are never directly simulated in the transient simulations. The carrier frequency is used to determine the reflection and transmission characteristics of frequency dependent optical devices.

2.2 Netlist Export Format

All the devices that are included in this package follow the same netlist export format.

OXXX SIG1 SIG2 SIG3 .. SIGN <DeviceType> <param1 = val> <param2 = val> ...

For example the netlist export for a laser with three ports would be,

OLaser1 OptOut Vmag Vphi laser ChanValue=193.2e12 ChanUnits=Hz

3 Optical Devices

3.1 Directional Coupler

Table 1: Port Order

Number	Signal Type	Description	Optional
1	Optical	-	No
2	Optical	-	No
3	Optical	-	No
4	Optical	-	No

Table 2: Parameters

Name	Symbol	Default Value	Units	Range
Device Type	IdealCoupler	-	-	-
Coupling Coefficient	couplingCoeff	0.5	-	[0,1]
Conjugate	conjFactor	-1	-	-1,1

An optical directional coupler is a device that physically couples two input signals and produces two output signals. The output fields are related to the input optical fields by the following matrix[1].

$$\begin{bmatrix} O_1 \\ O_2 \\ O_3 \\ O_4 \end{bmatrix} = \begin{bmatrix} 0 & 0 & \sqrt{1-c} & jp\sqrt{c} \\ 0 & 0 & jp\sqrt{c} & \sqrt{1-c} \\ \sqrt{1-c} & jp\sqrt{c} & 0 & 0 \\ jp\sqrt{c} & \sqrt{1-c} & 0 & 0 \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \end{bmatrix}$$

Where c is the coupling coefficient and p is -1 if the parameter conjugate is set to -1 (default), otherwise $p = 1$. The coupling coefficient stays the same for all the channels.

For this device, the inputs are mixed into each output and similarly in the reverse direction the outputs are mixed onto the inputs. However, there is no interference between the forward and reverse signals or between the channels of each set of propagating signals.

3.2 Laser

Table 3: Port Order

Number	Signal Type	Description	Optional
1	Optical	Laser Output	No
2	Electrical	Magnitude/Real/Power Input	No
3	Electrical	Phase/Imaginary Input	No
4	Electrical	Frequency Control Node	Yes

Table 4: Parameters

Name	Symbol	Default Value	Units	Range
Device Type	Laser	-	-	-
Channel Value	ChanValue	193.1	-	] 0,+INF [
Channel Units	ChanUnits	Thz	-	[Hz, KHz, MHz, GHz, THz]
Input Type	InputType	PowPhi	-	] Polar, Cartesian, PowPhi [

For the laser model, the complex valued optical output E is directly controlled by electrical port voltages V_1 and V_2 . The channel frequency (f_c) is set by using the parameters *channel value* and *channel units*. The channel frequency is used to determine the model behaviour of optical various devices such as [waveguide](#), [optical s-parameter](#) and [photodiode](#).

The following equations are used to generate the optical signal based on the *Input Type* parameter.

Table 5: Laser Input Type Equations

Input Type	Equation
Polar	$O_1 = V_1 e^{jV_2}$
Cartesian	$O_1 = V_1 + jV_2$
PowPhi	$O_1 = \sqrt{V_1} e^{jV_2}$

3.3 LaserFC

Table 6: Port Order

Number	Signal Type	Description	Optional
1	Optical	Laser Output	No
2	Electrical	Magnitude/Real/Power Input	No
3	Electrical	Phase/Imaginary Input	No
4	Electrical	Frequency Control Node	No

Table 7: Parameters

Name	Symbol	Default Value	Units	Range
Channel Value	ChanValue	193.1	-	] 0,+INF [
Channel Units	ChanUnits	Thz	-	[Hz, KHz, MHz, GHz, THz]
Input Type	InputType	PowPhi	-	] Polar, Cartesian, PowPhi [

The basic operation of this laser is the same as the standard [laser](#) model with the exception of an additional port to control the channel frequency. The input voltage sets the channel frequency and it is affected by the *Channel Units* parameter. For example, if the frequency node voltage is 191.5 and the *Channel Units* parameter is Thz then the output channel frequency will be set to 191.5 Thz.

3.4 Mirror

Table 8: Port Order

Number	Signal Type	Description	Optional
1	Optical	-	No

Table 9: Parameters

Name	Symbol	Default Value	Units	Range
Reflection Coefficient	reflection	0.0	-	[0,1]
Phase Shift	phaseshift	0.0	Radians	] -INF,INF [

The *Reflection Coefficient* parameter sets the ratio of reflected and incident power and *Phase Shift* determines the phase of the reflected optical signal based on the following formula,

$$O_1 = I_1 \sqrt{R} e^{j\phi} \quad (3.4.1)$$

Phase shift and reflection are constant across all the channels that are incident to the mirror.

3.5 Terminator

The terminator functions the same way as the [Mirror](#) but its reflection and phase shift parameters are set to 0.

3.6 Optical Filter

Table 10: Port Order

Number	Signal Type	Description	Optional
1	Optical	Input	No
2	Optical	Output	No

Table 11: Parameters

Name	Symbol	Default Value	Units	Range
Filter Type	FilterType	Bessel	-	Bessel, Butterworth, Chebyshev
Filter Mode	FilterMode	Bandpass	-	Bandpass, Bandstop
Filter Order	FilterOrder	1	-	[1, 20]
Filter Bandwidth	FilterBW	10e9	Hz	] 0, +INF [
Center Frequency	fc	193.1e12	Hz	] 0, +INF [
Ripple Factor	rf	0.5	dB	] 0.0, +INF [

Optical filter applies bandpass or bandstop filters to all the incoming optical signals with varying channel frequencies. The user can select one of the three available filter types, Butterworth, Bessel, Chebyshev. The equations below describe the prototype lowpass transfer function for each filter type in Laplace domain. Bandpass and bandstop transfer functions are derived based on the lowpass prototype transfer functions.

For the following equations, n is the filter order and ω_c is the bandwidth of the lowpass filter.

Bessel Filter

The Reverse Bessel polynomials are described by the following function[2],

$$\theta_n(s) = \sum_{k=0}^n a_k s^k \quad (3.6.1)$$

Where,

$$a_k = \frac{(2n - k)!}{2^{n-k} k! (n - k)!} \quad (3.6.2)$$

The Lowpass Bessel filter is given by the following transfer function,

$$H(s) = \frac{\theta_n(0)}{\theta_n(s w_b / \omega_c)} \quad (3.6.3)$$

Where w_b is the 3dB bandwidth normalization factor.

$$w_b = \sqrt{(2N - 1) \ln(2)} \quad (3.6.4)$$

Butterworth Filter

The Butterworth polynomial is given by the following equation,

$$B(s) = \prod_{k=1}^n (s - s_k) / \omega_c \quad (3.6.5)$$

where each pole is described by,

$$s_k = \omega_c e^{j(2k+n-1)\pi} \quad (3.6.6)$$

$$H(s) = \frac{B(0)}{B(s)} \quad (3.6.7)$$

Chebyshev Filter

Poles of the Chebyshev filter are described by the following equation,

$$s_{pm} = \omega_c (-\sinh(\delta) \sin(\theta_m) + j \cosh(\delta) \cos(\theta_m)) \quad (3.6.8)$$

$$\delta = \frac{1}{n} \arcsin\left(\frac{1}{\epsilon}\right) \quad (3.6.9)$$

$$\theta_m = \frac{\pi}{2} \frac{2m-1}{n} \quad (3.6.10)$$

and the ripple factor is calculated by using the formula below,

$$\epsilon = \sqrt{10^{0.1r} - 1} \quad (3.6.11)$$

Chebyshev lowpass filter transfer function is given by,

$$H(s) = \frac{1}{2^{n-1} \epsilon} \prod_{m=1}^n \frac{1}{(s - s_{pm}) / \omega_c} \quad (3.6.12)$$

3.7 Optical Gain

Table 12: Port Order

Number	Signal Type	Description	Optional
1	Optical	-	No
2	Optical	-	No
3	Electrical	-	No
4	Electrical	-	No

Table 13: Parameters

Name	Symbol	Default Value	Units	Range
Gain Coefficient	g	1.0	-	[0, INF [

This device functions as a voltage dependent optical gain. The relationship between its input, output and control voltages are given by the following equation.

$$O_2 = g\sqrt{V_1 - V_2}I_1 \quad (3.7.1)$$

The gain is applied equally across all the channels passing through this device.

3.8 Optical PhaseShift

Table 14: Port Order

Number	Signal Type	Description	Optional
1	Optical	-	No
2	Optical	-	No
3	Electrical	-	No
4	Electrical	-	No

Table 15: Parameters

Name	Symbol	Default Value	Units	Range
Phase Coefficient	g	1.0	-	[0, INF [

This device functions as a voltage dependent optical phase shifter. The relationship between its input, output and control voltages are given by the following equation.

$$O_2 = e^{jg(V_1 - V_2)} I_1 \quad (3.8.1)$$

The optical phase shift is applied equally across all the channels passing through this device.

3.9 Photodiode

Table 16: Port Order

Number	Signal Type	Description	Optional
1	Optical	-	No
2	Electrical	-	No
3	Electrical	-	No

Table 17: Parameters

Name	Symbol	Default Value	Units	Range
Responsivity	responsivity	1.0	A/W	[0, INF [
Interpolation Type	interpType	Lin	-	Lin, Poly, Spline
Polynomial Order	polyOrder	3	-	[1,10]
Responsivity File	responsivityFile	-	-	-

The equation for the photodiode current can be derived in two steps. First, a total effective field value is calculated by multiplying the square root of the responsivity with the field value at each channel. These effective field values are added together to calculate the total effective field value.

$$E_T = \sum_{c=1}^n \sqrt{R(f_c)} E_c e^{j2\pi f_c} \quad (3.9.1)$$

Then the total effective power is calculated using the total effective field. This power is equivalent to the current that is generated by the photodiode.

$$I = P_T = |E_T E_T^*| \quad (3.9.2)$$

If the responsivity file is not used, a constant responsivity value is set by the *Responsivity* parameter is used across all the channels.

The responsivity file can be used to set the responsivity as a function of frequency in Thz. The responsivity file is composed of two space separated columns where the first column is frequency in Thz and the second column describes the responsivity in A/W. For example,

```
193.1  0.2
193.2  0.3
193.3  0.4
193.4  0.5
193.5  0.4
```

There are multiple interpolation schemes available for the responsivity file as the exact channel frequency used in the simulation may not be defined in the responsivity file. The interpolation scheme is set by the *Interpolation Type* parameter. While all the interpolation schemes can be used with noiseless data, only the polynomial fit is appropriate if significant noise is present.

3.10 S-Parameter N Port

Table 18: Port Order

Number	Signal Type	Description	Optional
1	Optical	-	No
2	Optical	-	Yes
3	Optical	-	Yes
\vdots	Optical	-	Yes
N	Optical	-	Yes

Table 19: Parameters

Name	Symbol	Default Value	Units	Range
S-Parameter File	sparamFile	-	-	-
S-Parameter File Format	SParam	SParam	-	SParam, OptiBPM

The following matrix is used to relate inputs from each port to the output at each port for each channel separately.

$$\begin{bmatrix} O_1 \\ O_2 \\ \vdots \\ O_N \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} & \dots & S_{1N} \\ S_{21} & \ddots & & S_{2N} \\ \vdots & & \ddots & \vdots \\ S_{N1} & S_{N2} & \dots & S_{NN} \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ \vdots \\ I_N \end{bmatrix}$$

Time delay for each S-Parameter entry S_{mn} is defined by the group delay,

$$t_d = -\frac{d\phi(\omega)}{d\omega} \quad (3.10.1)$$

Where,

$$\phi = \text{atan}(S_{mn}) \quad (3.10.2)$$

The s-parameter file is used to describe the scattering matrix at each frequency individually. 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)

The first line of a Touchstone file describes the format of the input and the subsequent lines are used to describe the data. The specifications of this format have been extended for optical signals in OptiSPICE models. If the frequency unit is set to be m, mm, μm or nm then the input is assumed to be a function of wavelength instead of frequency. For optical s-parameters the touchstone format can only be used in s-parameter mode and a resistance does not have to be specified. Below a two port S-Parameter file example uses Thz as the frequency unit and real and imaginary components (RI) of the S-Parameter

entries,

THZ S RI

f_1 $S_{11}^r(f_1)$ $S_{11}^i(f_1)$ $S_{12}^r(f_1)$ $S_{12}^i(f_1)$ $S_{21}^r(f_1)$ $S_{21}^i(f_1)$ $S_{22}^r(f_1)$ $S_{22}^i(f_1)$

f_2 $S_{11}^r(f_2)$ $S_{11}^i(f_2)$ $S_{12}^r(f_2)$ $S_{12}^i(f_2)$ $S_{21}^r(f_2)$ $S_{21}^i(f_2)$ $S_{22}^r(f_2)$ $S_{22}^i(f_2)$

...

r and i superscripts are used to denote the real and imaginary parts of the S-Parameter entries.

3.11 Waveguide

Table 20: Port Order

Number	Signal Type	Description	Optional
1	Optical	-	No
2	Optical	-	No

Table 21: Parameters

Name	Symbol	Default Value	Units	Range
Length	length	40×10^{-6}	m	] 0,+INF [
Effective Refractive Index (Real Part)	RefIndexReal	2.4	-	] 0,+INF [
Effective Refractive Index (Imaginary Part)	RefIndexImag	0.0	-	] -INF,+INF [
Effective Index File	RefIndexFile	-	-	-
Frequency delay	FreqDelay	0	-	0, 1

The waveguide model is able to capture the time delay, phase shift and loss/gain of an optical signal travelling through a waveguide. The relationship between input and output optical signals for both forward and reverse travelling waves is given by the following formula.

$$O = I e^{-j(\frac{2\pi f n L}{c} - \phi)} \quad (3.11.1)$$

Where n is the complex valued effective index of the mode, L is the waveguide length, f is the channel frequency and c is the speed of light in vacuum.

The real part of the effective index is used to calculate the total phase shift and the imaginary part is used to calculate gain/loss.

$$n = n_r(f) + j n_i(f) \quad (3.11.2)$$

The time delay of the optical signal for an individual channel is then calculated based on the group index (n_g) and the length of the waveguide.

$$n_g = n_r + f \frac{dn_r}{df} \quad (3.11.3)$$

$$t_d = \frac{L n_g}{c} \quad (3.11.4)$$

An additional phase shift term (ϕ) is added to the waveguide equation (3.11.1) to capture

the time dependence of the channel frequency. This term is only used for time domain simulations.

$$\phi = 2\pi(f(t) - f(t - t_d))t \quad (3.11.5)$$

If the effective index is set up through the *RefIndex* parameters then it is assumed to be constant across all the frequencies.

The effective index can also be set up as a function of wavelength from a text file by using *RefIndexFile* parameter. The file needs to be configured as space separated file with three (third column is optional) columns, wavelength in μm , real part of the effective index and imaginary part of the effective index. For example,

1.50	2.5675	-0.0015
1.51	2.5569	-0.0021
1.52	2.5462	-0.0028

3.12 Waveguide Crossing

Table 22: Port Order

Number	Signal Type	Description	Optional
1	Optical	-	No
2	Optical	-	No
3	Optical	-	No
4	Optical	-	No

Table 23: Parameters

Name	Symbol	Default Value	Units	Range
S11	S11	0.001	-	] 0,+INF [
S21	S21	0.01	-	] 0,+INF [
S31	S31	0.98	-	] 0,+INF [
S41	S41	0.01	-	] 0,+INF [
Input Type	InputType	powPhi	-	PowPhi, Polar, Cartesian

This device models the transmission, reflection and the leakage of an optical signal as it goes through a waveguide crossing. It uses the following S-Parameter matrix to calculate the response of the waveguide crossing. This model assumes constant S-Parameter coefficient across all the channels.

$$\begin{bmatrix} O_1 \\ O_2 \\ O_3 \\ O_4 \end{bmatrix} = \begin{bmatrix} S_{11} & S_{41} & S_{31} & S_{21} \\ S_{21} & S_{11} & S_{41} & S_{31} \\ S_{31} & S_{21} & S_{11} & S_{41} \\ S_{41} & S_{31} & S_{21} & S_{11} \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \end{bmatrix}$$

Complex valued S-Parameter entries can be set up either as a single value or as a vector with two entries. For example, for a reflection coefficient with magnitude 0.01 and phase of 0.5 radians the S_{11} and InputType parameters can be set as,

$$S_{11} = "0.01 0.5"$$

$$InputType = Polar$$

3.13 WG Phase Shifter

Table 24: Port Order

Number	Signal Type	Description	Optional
1	Optical	-	No
2	Optical	-	No
3	Electrical	-	No
4	Electrical	-	No

Table 25: Parameters

Name	Symbol	Default Value	Units	Range
Length	length	40×10^{-6}	m	] 0,+INF [
Effective Refractive Index (Real Part)	ReffIndexReal	2.4	-	] 0,+INF [
Effective Refractive Index (Imaginary Part)	RefIndexImag	0.0	-	] -INF,+INF [
Effective Index File	ReffIndexFile	-	-	-
Frequency delay	FreqDelay	0	-	0, 1
Effective Index Delta (Real Part)	dnRealdv	0.0	-	-
Effective Index Delta (Imaginary Part)	dnImagdv	0.0	-	-

The waveguide phase shifter model uses the [waveguide](#) model as a basis. It extends the equation of the effective index (3.11.2) such that it can be controlled by voltage nodes.

$$n = n + \Delta n_r(V) + j\Delta n_i(V) \quad (3.13.1)$$

Both real ($\Delta n_r(V)$) and imaginary ($\Delta n_i(V)$) parts of the voltage controlled refractive index functions are described by a polynomial equation.

$$n_{r/i}(V) = a_0V^0 + a_1V^1 + \dots + a_kV^k \quad (3.13.2)$$

The polynomial coefficients (descending order) can be set up using the real and imaginary parts of the effective index delta parameters as a vector.

$$dnRealdv = "a_k \ a_{k-1} \ \dots \ a_1 \ a_0"$$

For example, a 3rd order polynomial can be set as the following,

$$dnRealdv = "0.01 \ -0.53 \ 1.5 \ 0.1"$$

3.14 Y-Branch

Table 26: Port Order

Number	Signal Type	Description	Optional
1	Optical	-	No
2	Optical	-	No
3	Optical	-	No

Table 27: Parameters

Name	Symbol	Default Value	Units	Range
Split Ratio	SplitRatio	0.5	-	[0, 1]

A y-branch can be used as a splitter or joiner. It uses the following matrix equation to set up the relationship between the input and the output ports.

$$\begin{bmatrix} O_1 \\ O_2 \\ O_3 \end{bmatrix} = \begin{bmatrix} 0 & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ \sqrt{c} & 0 & 0 \\ \sqrt{1-c} & 0 & 0 \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix}$$

By default the splitting ratio is set up as 50 percent power in each arm; however this can be changed by using the *Split Ratio* parameter.

References

- [1] Keiser, G., *Optical Fiber Communications*, McGraw-Hill, Higher Education (2000).
- [2] Giovanni Bianchi and Roberto Sorrentino, *Electronic filter simulation & design*. McGraw-Hill Professional (2007). pp. 31–43