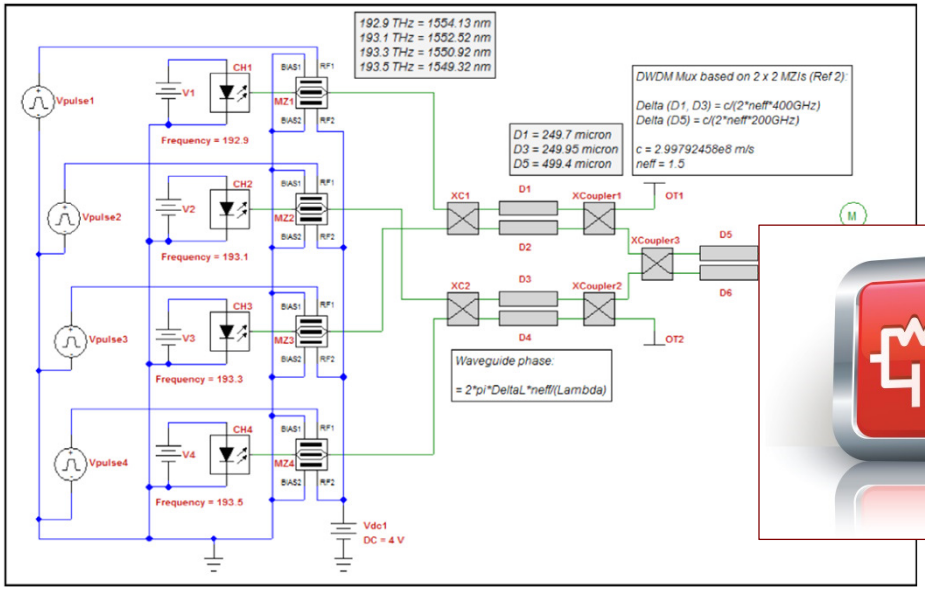

Optiwave
DESIGN SOFTWARE

OptiSPICE
Opto-Electronic Circuit Design Software

Silicon Depletion-Mode TW Modulator

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Nepean, ON, Canada
K2E 7X1

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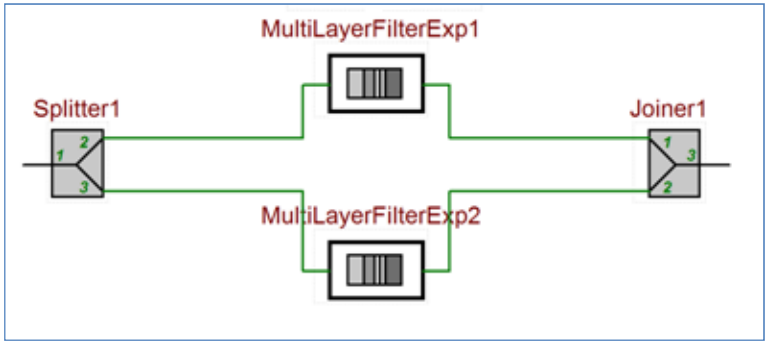
Introduction (MZM)

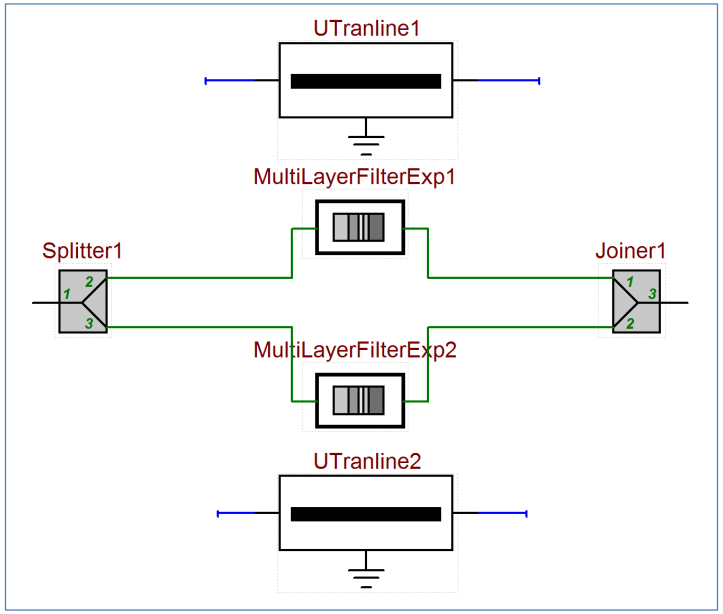
OptiSPICE
Opto-Electronic Circuit Design Software

- Mach Zehnder Modulator (MZM)
  - Phase shift is achieved from using Pockels Effect, Kerr, or carrier injection/depletion
  - Short and compact but requires higher voltage/power
  - Limited modulation speed (10-40 Gb/s)
- Building blocks
  - 1 Splitter
  - 1 Joiner
  - 2 Waveguides
- OptiSPICE Model
  - Explicit multilayer filter model is set up with a single layer
  - The change in the refractive index can be controlled by a voltage source
  - Can be configured as push-pull or asymmetric



Introduction (TW Modulator)

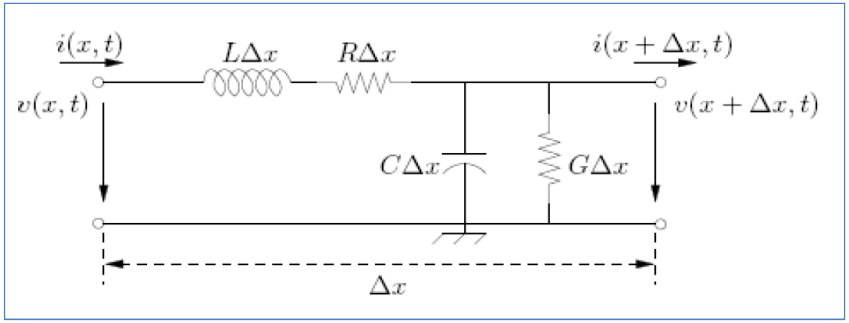
- Traveling Wave MZM
  - Modulation occurs the same way as MZM
  - Phase shift is achieved from using Pockels Effect, Kerr, or carrier injection/depletion
  - Longer device but uses lower voltage/power compared to regular MZM
  - Can achieve higher modulation speeds (~70 Gbit/s)
- Building blocks
  - 1 Splitter
  - 1 Joiner
  - 2 Transmission line electrodes
  - 2 Waveguides
- OptiSPICE Model
  - The waveguide consists of many layers with controllable refractive indexes
  - Each transmission line corresponds to a different metal contact connected to one of the waveguides
  - The waveguides and the transmission line models have the same length and the same number of sections
  - The refractive index of each layer is a function of the voltage in the corresponding section of the transmission line



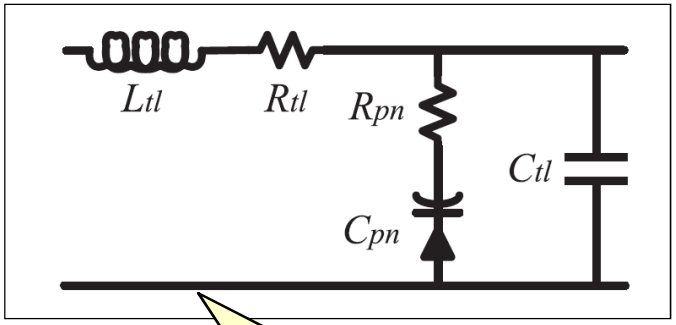
Si-TWM Model Overview

- Modified transmission line model for PN Junction
- Sectionalized modulator arms (MLF + TL)
- Δn α E in each section (can be nonlinear)

Transmission line model



*Modified Transmission Line Model**

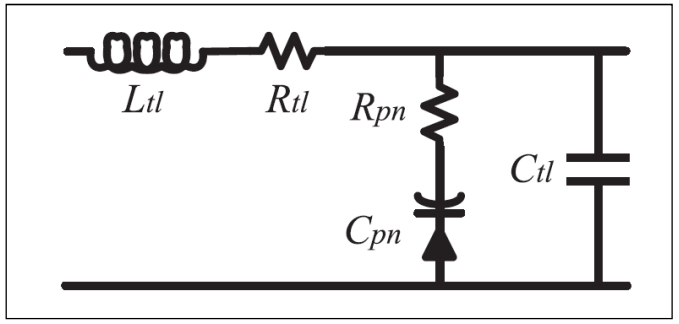


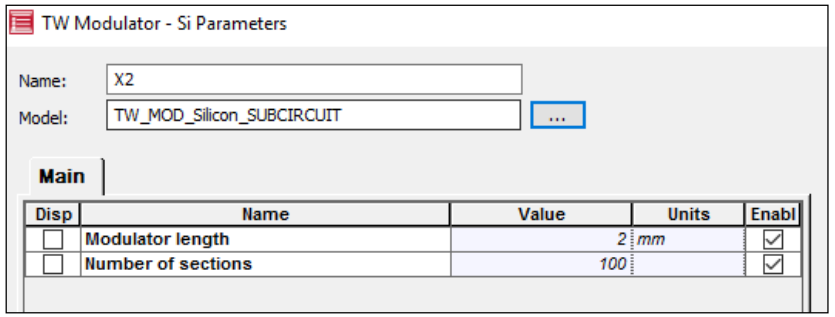
Single sections connected to a single layer of a multilayer filter

**K. Zhu, V. Saxena and W. Kuang, "Compact Verilog-A modeling of silicon traveling-wave modulator for hybrid CMOS photonic circuit design," 2014 IEEE 57th International Midwest Symposium on Circuits and Systems (MWSCAS), College Station, TX, 2014, pp. 615-618.*

Parameters

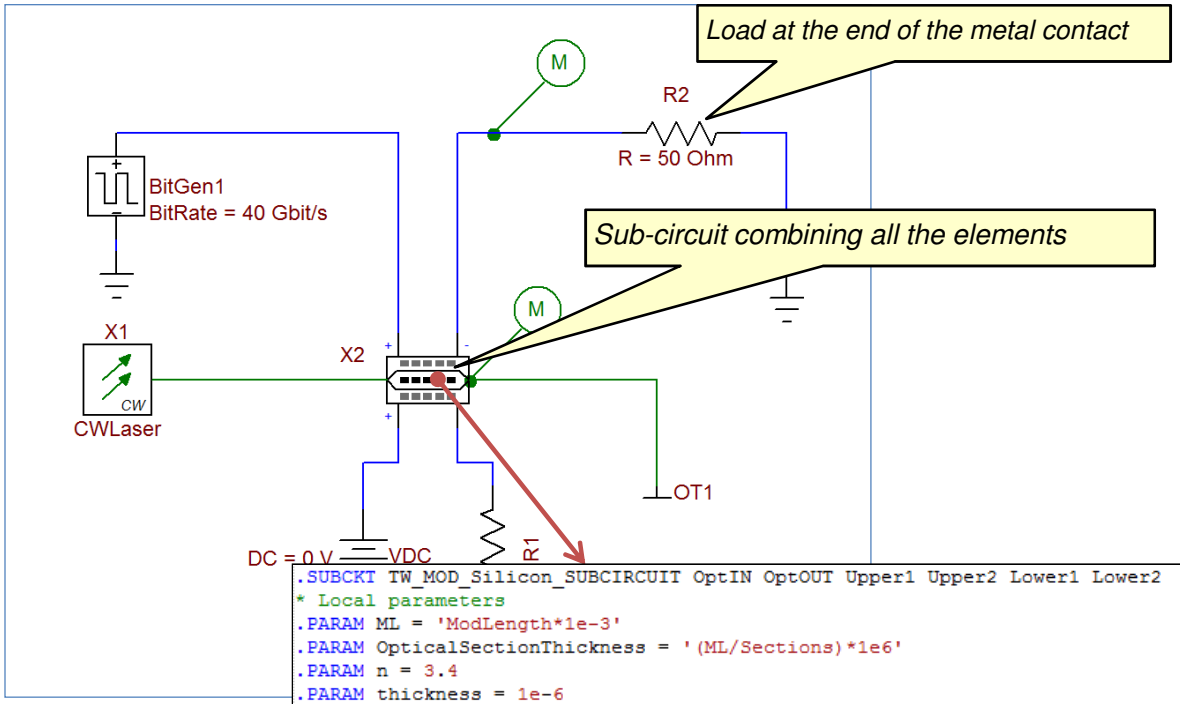
- Transmission line (model parameters)
  - 100 Sections (*Number of sections*)
  - Rtl = 2kohm/m
  - Ctl = 120 pf/m
  - Ltl = 500 nH/m
  - RS = 13e-3 ohm*m
  - CJ = 186 pf/m @(-3V Reverse Bias)
  - d = 2 mm (*Modulator length*)
- Transmission line (calculated parameters)
  - R0 = re(Z0) = 43 ohm @ 40 Ghz
  - neff = 3.4@ 40 Ghz
  - v = 8.8174e+07 m/s @ 40 Ghz

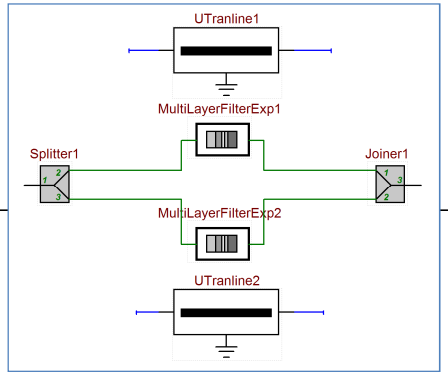




- Multilayer filter (model parameters)
  - n = 3.4 (Refractive index)
  - d = 2 mm (*Modulator length*)
  - 100 ML filter layers (*Number of sections*)
- Multilayer filter (calculated parameters)
  - v = c/n = 8.8174e+07 m/s
  - Vpi =1.3 V

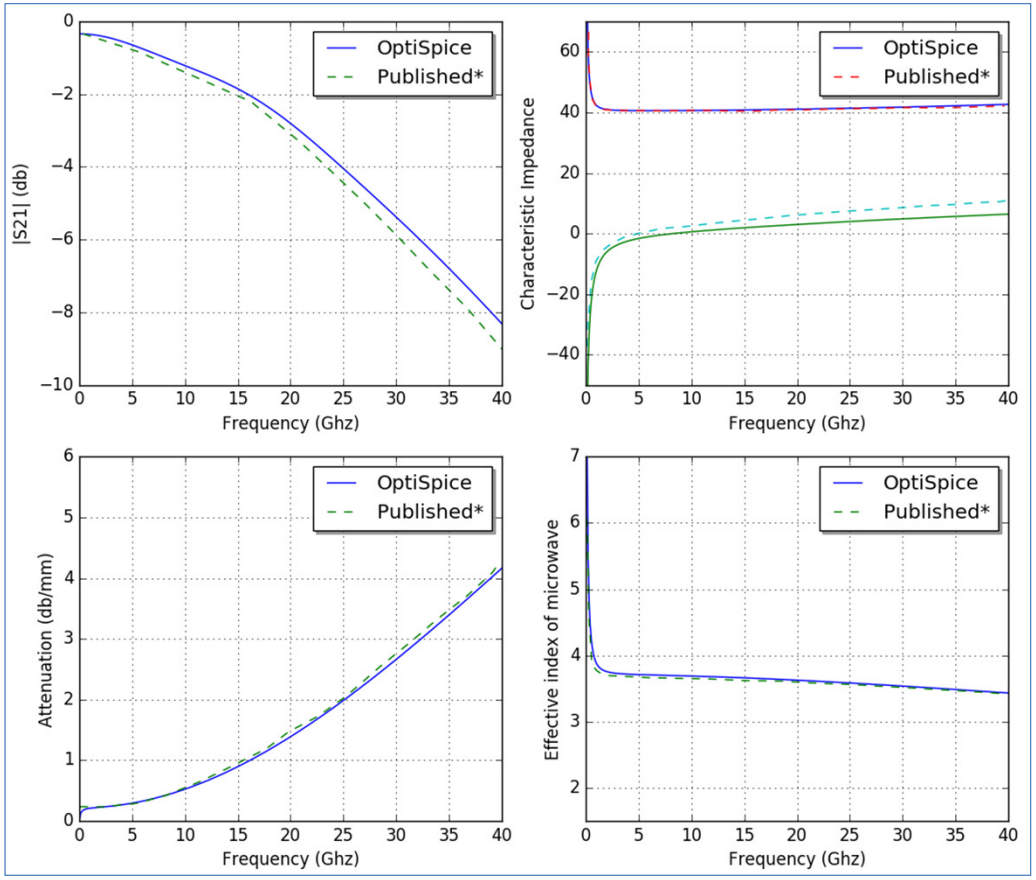
OptiSPICE TWM circuit






```
.SUBCKT TW_MOD_Silicon_SUBCIRCUIT OptIN OptOUT Upper1 Upper2 Lower1 Lower2
* Local parameters
.PARAM ML = 'ModLength*1e-3'
.PARAM OpticalSectionThickness = '(ML/Sections)*1e6'
.PARAM n = 3.4
.PARAM thickness = 1e-6
.PARAM r = '15e-12/thickness'
.PARAM rn = 'r*n*n*n'
* TW Mod optical building blocks
Osp JOINER Name=Joiner1 Nodes=[ WGUpperOUT WGLowerOUT OptOUT ] MoName=JOINER_MODEL SplitRatio=0.5
Osp SPLITTER Name=OptFork1 Nodes=[ OptIN WGUpperIN WGLowerIN ] MoName=OPTFORK_MODEL SplitRatio=0.5
Osp MULTILAYERFILTER Name=WaveguideLower Nodes=[ WGLowerIN WGLowerOUT ] MoName=MULTILAYERFILTEREXP_MODEL_LOWER FilterCnodes=[] I
Osp MULTILAYERFILTER Name=WaveguideUpper Nodes=[ WGUpperIN WGUpperOUT ] MoName=MULTILAYERFILTEREXP_MODEL_UPPER FilterCnodes=[] I
* TW Mod electrical building blocks
U1 Upper1 0 Upper2 0 U_MODEL_1TR L=ML LUMPS=Sections
U2 Lower1 0 Lower2 0 U_MODEL_2TR L=ML LUMPS=Sections
.MODEL OPTFORK_MODEL OMNIOCONN SubType = Splitter
.MODEL JOINER_MODEL OMNIOCONN SubType = Joiner
.MODEL MULTILAYERFILTEREXP_MODEL_UPPER MULTILAYERFILTER FilterType = Explicit Index = [n] Thickness = [OpticalSectionThickness]
+ N0 = n NF = n AlphaV = [rn] MaxOptLen = 12 TilingNum = Sections
.MODEL MULTILAYERFILTEREXP_MODEL_LOWER MULTILAYERFILTER FilterType = Explicit Index = [n] Thickness = [OpticalSectionThickness]
+ N0 = n NF = n AlphaV = [rn] MaxOptLen = 12 TilingNum = Sections
.MODEL U_MODEL_1TR U  PNJMode=SS_Jct NL=1 RRR=0.0 R11=2e3 L11=500e-9 CR1=120e-12 GR1=0 RS = 13e-3 CJ = 186.87e-12
.MODEL U_MODEL_2TR U  PNJMode=SS_Jct NL=1 RRR=0.0 R11=2e3 L11=500e-9 CR1=120e-12 GR1=0 RS = 13e-3 CJ = 186.87e-12
.ENDS TW_MOD_Silicon_SUBCIRCUIT
```

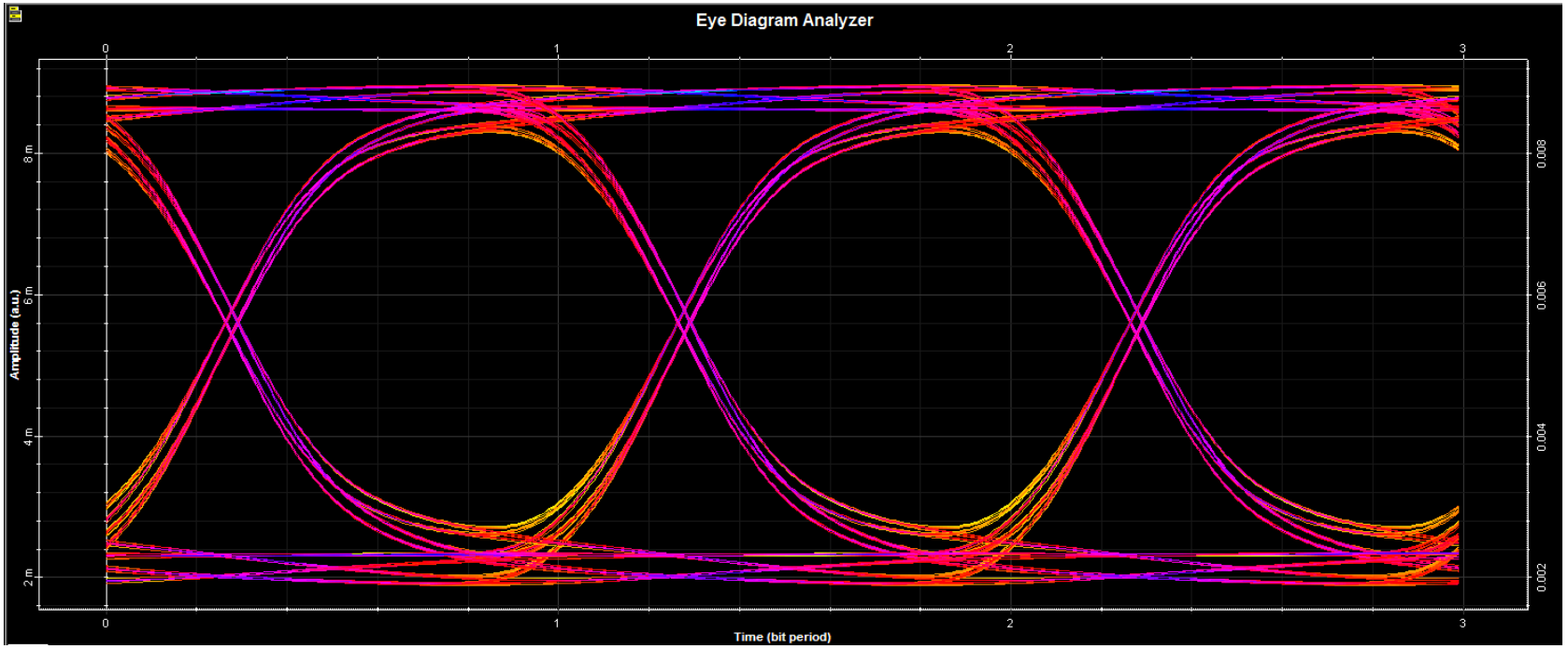
Transmission line characteristics



** Hao Xu, Xianyao Li, Xi Xiao, Zhiyong Li, Yude Yu and Jinzhong Yu, "Demonstration and Characterization of High-Speed Silicon Depletion-Mode Mach–Zehnder Modulators," in IEEE Journal of Selected Topics in Quantum Electronics, vol. 20, no. 4, pp. 23-32, July-Aug. 2014.*

Optical eye results

Eye diagram results for traveling wave modulator simulation (Ref design: TWMZM_Silicon.osch)



Velocity mismatch simulation

- In this simulation the refractive index of the waveguide was increased to reduce the velocity of the electric field
- As the velocity mismatch becomes more severe the change in the refractive index and the electric field traveling in the waveguide do not overlap long enough
- The reduced overlapping time decreases the total amount of phase shift accumulated by the traveling electric field, therefore the extinction ratio gets smaller

OptiSPICE simulation showing velocity mismatch in the traveling wave modulator (Ref design: TWMZM_Silicon_VelocityMismatch.osch)