400G DR4 硅光芯片设计培训

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光电子流片和软件培训 · Xia Men · 2023/08/15

http://picpalette.innolight.com:60000/

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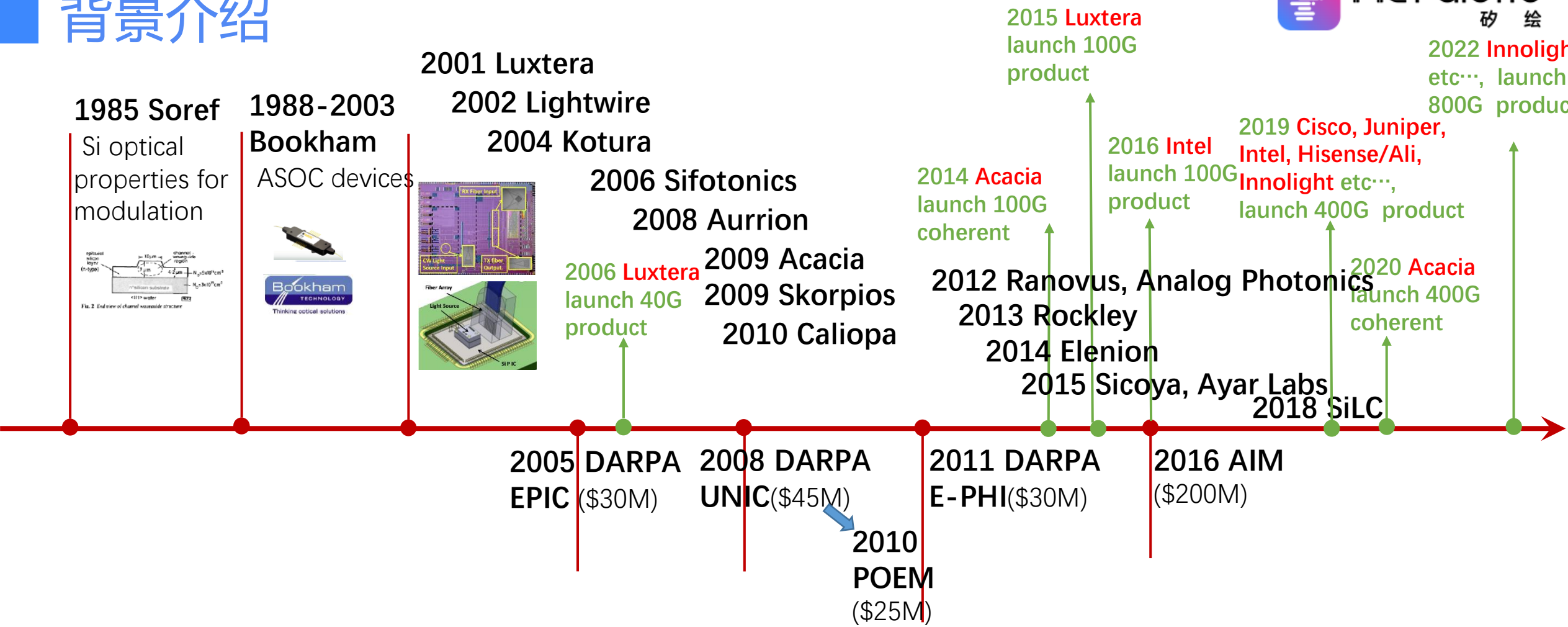
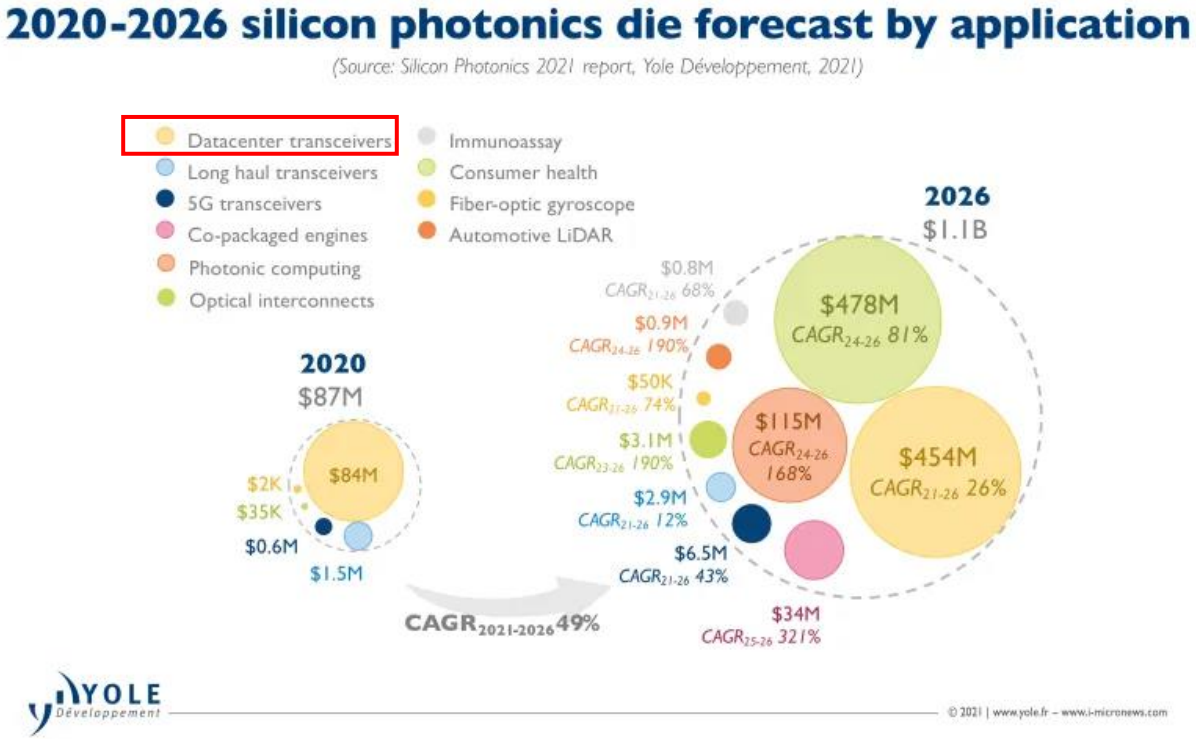
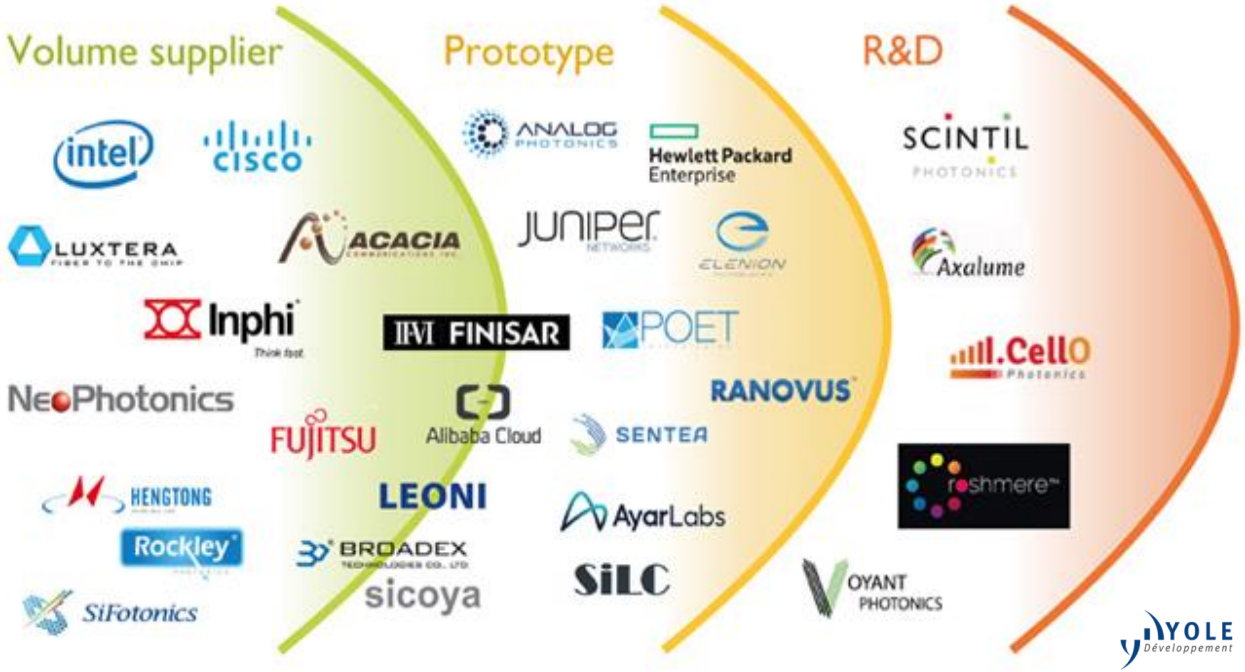
背景介绍



- Including US, governments funded billions of dollars in Si Photonics
  - Since 2002, EU funded FP6, FP7… with more than $580M
  - Japan funded JISSO with >$300M
  - And now, millions if not billions of $ on the way in China…

背景介绍



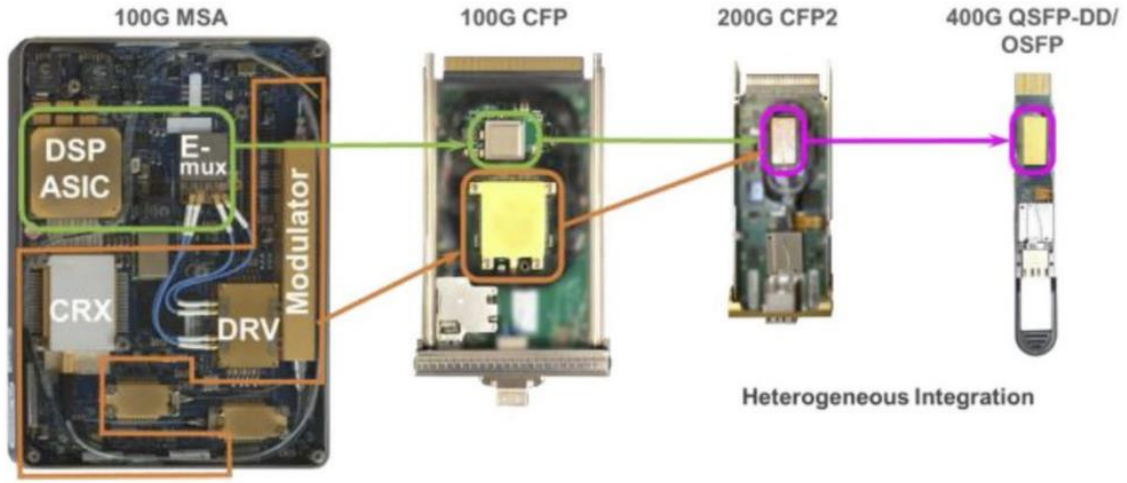


- 硅光芯片市场快速上升（CAGR~49%）
- 越来越多的公司加入到硅光芯片赛道中

背景介绍

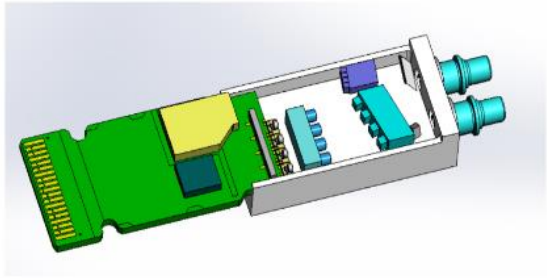
PIC Palette 矽 绘

相干模块

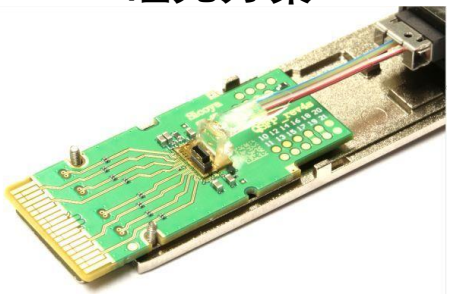


数通模块

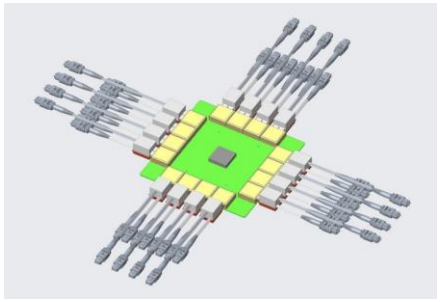
传统方案



硅光方案



CPO



Why Silicon Photonics?

优势

- ✓ 集成度、尺寸
- ✓ 封装成本
- ✓ 可靠性
- ✓ 量产能力
- ✓ 成本?

优势逐渐明显

400G 800G 1.6T 3.2T

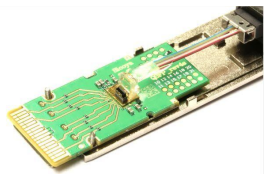
PSM CWDM 。。。

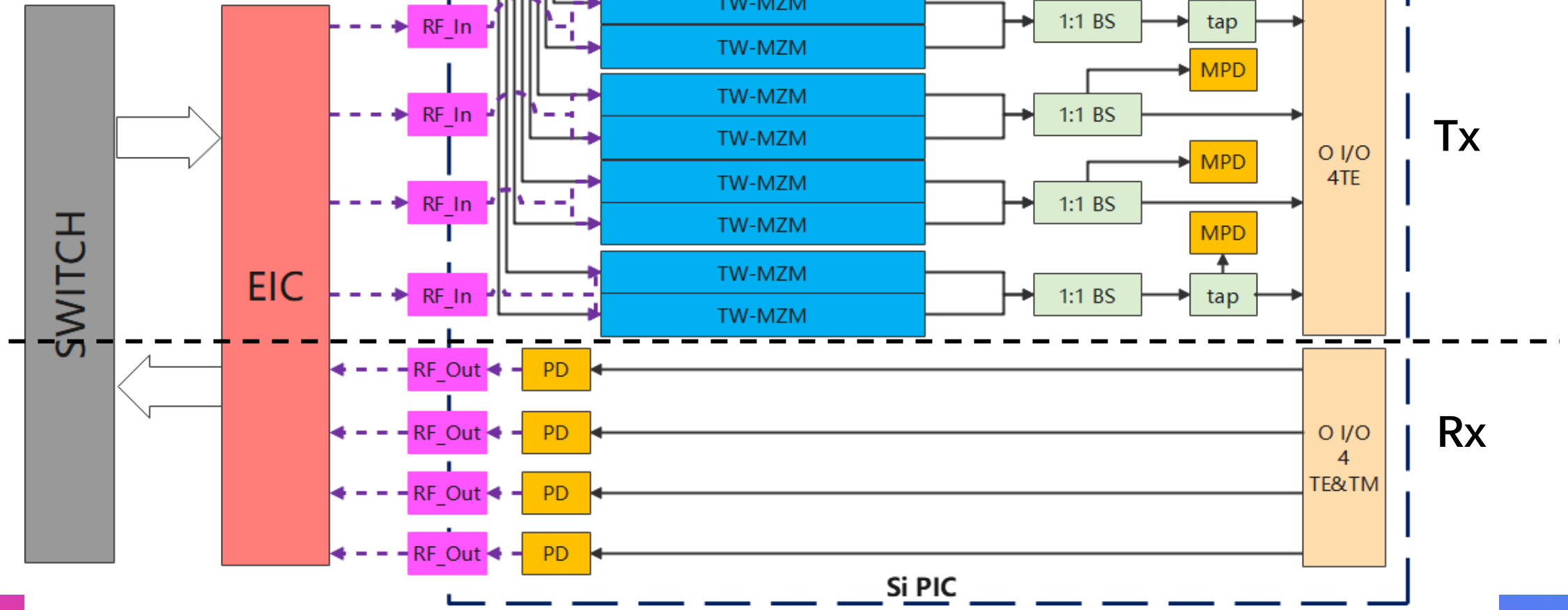
劣势

- 性能

400G光模块硅光芯片概述

有源器件	TW-MZM
	HS-PD/MPD
无源器件	EC
	Beam Splitter (BS)
	Tap
	Heater





400G光模块硅光芯片概述

PIC Palette 矽 绘

发射端性能指标

Table 124–6—400GBASE-DR4 transmit characteristics

Description	Value	Unit
Signaling rate, each lane (range)	53.125 ± 100 ppm	GBd
Modulation format	PAM4	—
Lane wavelength (range)	1304.5 to 1317.5	nm
Side-mode suppression ratio (SMSR), (min)	30	dB
Average launch power, each lane (max)	4	dBm
Average launch power, each lane[a] (min)	–2.9	dBm
Outer Optical Modulation Amplitude (OMA_{outer}), each lane (max)	4.2	dBm
Outer Optical Modulation Amplitude (OMA_{outer}), each lane (min)[b]	–0.8	dBm
Launch power in OMA_{outer} minus TDECQ, each lane (min)	–2.2	dBm
Transmitter and dispersion eye closure for PAM4 (TDECQ), each lane (max)	3.4	dB
Average launch power of OFF transmitter, each lane (max)	–15	dBm
Extinction ratio, each lane (min)	3.5	dB
$RIN_{21.4}OMA$ (max)	–136	dB/Hz
Optical return loss tolerance (max)	21.4	dB
Transmitter reflectance[c] (max)	–26	dB

[a] Average launch power, each lane (min) is informative and not the principal indicator of signal strength. A transmitter with launch power below this value cannot be compliant; however, a value above this does not ensure compliance.
[b] Even if the TDECQ < 1.4 dB, the OMA_{outer} (min) must exceed these values.
[c] Transmitter reflectance is defined looking into the transmitter.

接收端性能指标

Table 124–7—400GBASE-DR4 receive characteristics

Description	Value	Unit
Signaling rate, each lane (range)	53.125 ± 100 ppm	GBd
Modulation format	PAM4	—
Lane wavelengths (range)	1304.5 to 1317.5	nm
Damage threshold[a], each lane	5	dBm
Average receive power, each lane (max)	4	dBm
Average receive power, each lane[b] (min)	–5.9	dBm
Receive power (OMA_{outer}), each lane (max)	4.2	dBm
Receiver reflectance (max)	–26	dB
Receiver sensitivity (OMA_{outer}), each lane[c] (max)	–4.4	dBm
Stressed receiver sensitivity (OMA_{outer}), each lane[d] (max)	–1.9	dBm
Conditions of stressed receiver sensitivity test:[e]		
Stressed eye closure for PAM4 (SECQ), lane under test	3.4	dB
OMA_{outer} of each aggressor lane	4.2	dBm

[a] The receiver shall be able to tolerate, without damage, continuous exposure to an optical input signal having this average power level. The receiver does not have to operate correctly at this input power.
[b] Average receive power, each lane (min) is informative and not the principal indicator of signal strength. A received power below this value cannot be compliant; however, a value above this does not ensure compliance.
[c] Receiver sensitivity (OMA_{outer}), each lane (max) is informative and is defined for a transmitter with SECQ of 0.9 dB.
[d] Measured with conformance test signal at TP3 (see 124.8.9) for the BER specified in 124.1.1.
[e] These test conditions are for measuring stressed receiver sensitivity. They are not characteristics of the receiver.

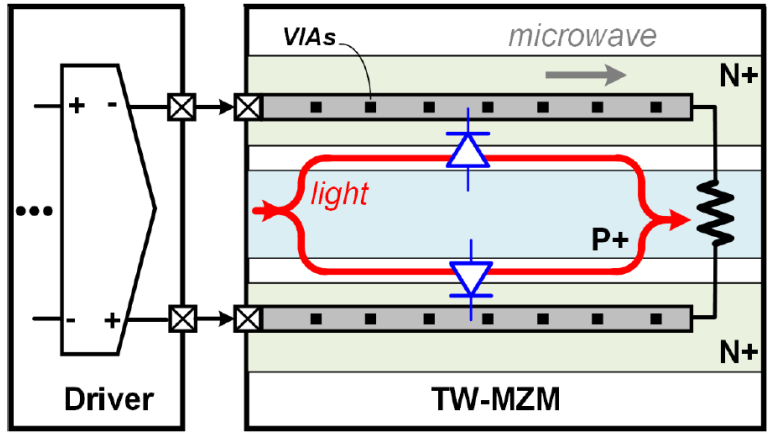
LD/EC/MZM/BS

EC/PD

IEEE Std 802.3bs™-2017

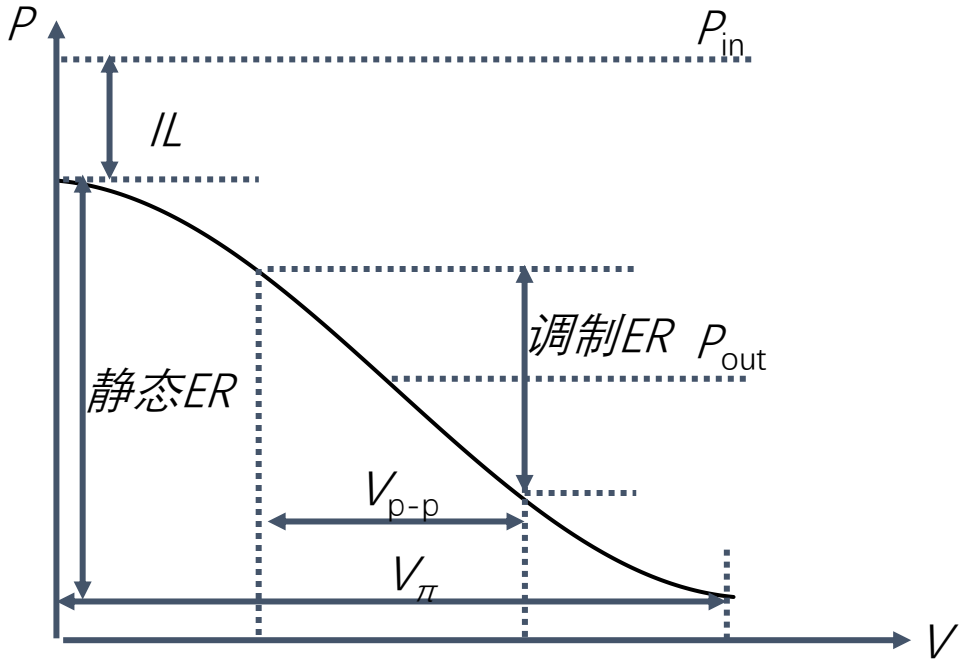
400G硅光器件——马赫曾德调制器（MZM）

马赫曾德调制器关键指标
1. 插入损耗 （IL）
2. 静态消光比 （ER）
3. 半波电压 （V_π）
4. 3dB带宽/频率响应 （BW）



Qi, Nan, et al. "Co-design and demonstration of a 25-Gb/s silicon-photonic Mach–Zehnder modulator with a CMOS-based high-swing driver." *IEEE Journal of Selected Topics in Quantum Electronics* 22.6 (2016): 131-140.

结构分解	设计要点
PN结	1. 离子注入分布； 2. 掺杂损耗； 3. 调制效率； 4. 静态R、C寄生参数；
（行波）电极	1. 行波电极寄生参数； 2. 光-电速度匹配； 3. 驱动阻抗匹配；

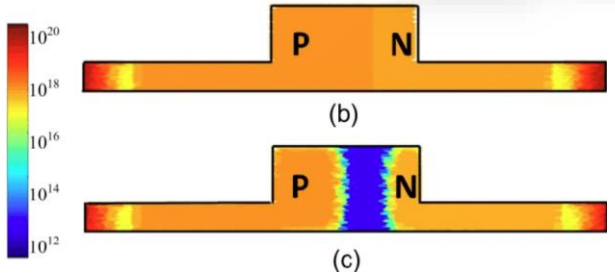


400G硅光器件——马赫曾德调制器（MZM）

结构分解	设计要点
PN结	1. 离子注入分布； 2. 掺杂损耗； 3. 调制效率； 4. 静态R、C寄生参数；
（行波）电极	1. 行波电极寄生参数； 2. 光-电速度匹配； 3. 驱动阻抗匹配；

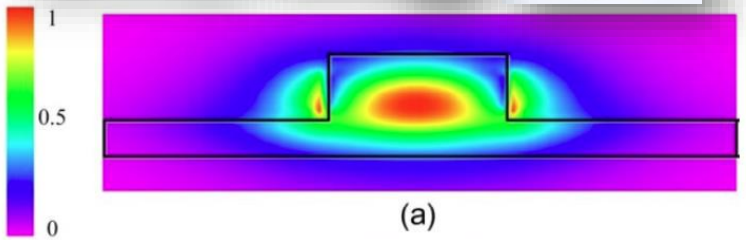
TCAD工艺仿真

Sentaurus TCAD　SILVACO　SYNOPSYS



光场仿真

Max-Optics 曼光　Photon Design　RSOFT synopsys　COMSOL MULTIPHYSICS

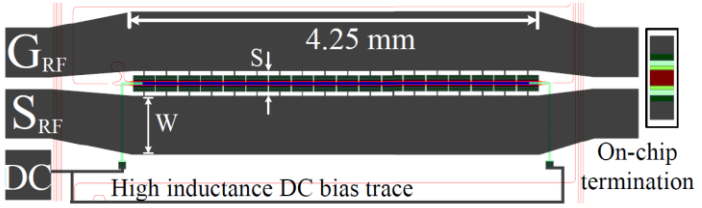


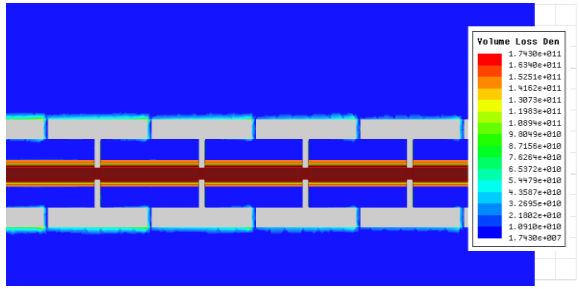
Ding, Jianfeng, et al. "Method to improve the linearity of the silicon Mach-Zehnder optical modulator by doping control." *Optics express* 24.21 (2016): 24641-24648.

电磁场仿真

Ansys ELECTRONICS DESKTOP

CST STUDIO SUITE
ELECTROMAGNETIC FIELD SIMULATION SOFTWARE





Patel, David, et al. "Design, analysis, and transmission system performance of a 41 GHz silicon photonic modulator." *Optics express* 23.11 (2015): 14263-14287.

$n_{g,o}$

n_{eff}

Z_c / Z_t

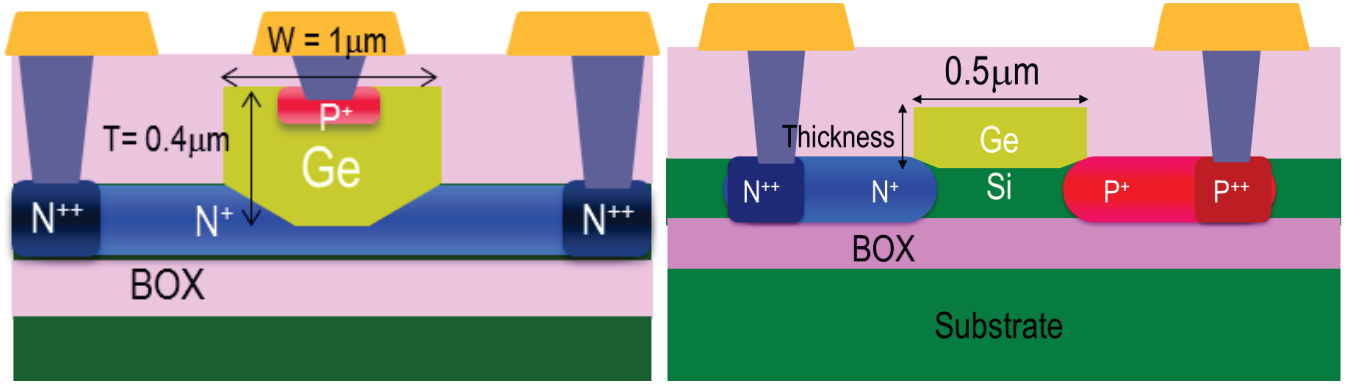
python　MATLAB

Advanced Design System　VPIphotonics DESIGN AUTOMATION

1. 插入损耗 （IL）
2. 半波电压 （V_π）
3. 3dB带宽/频率响应 （BW）

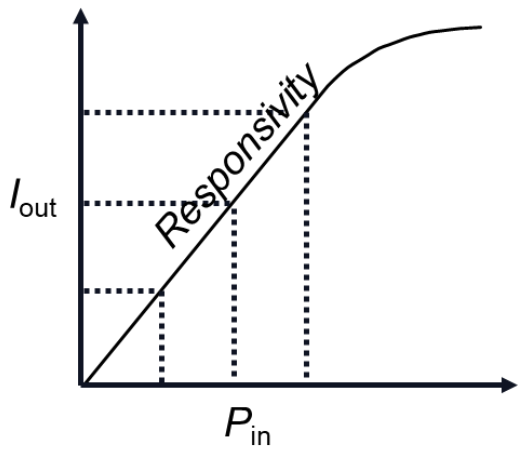
400G硅光器件——锗硅探测器

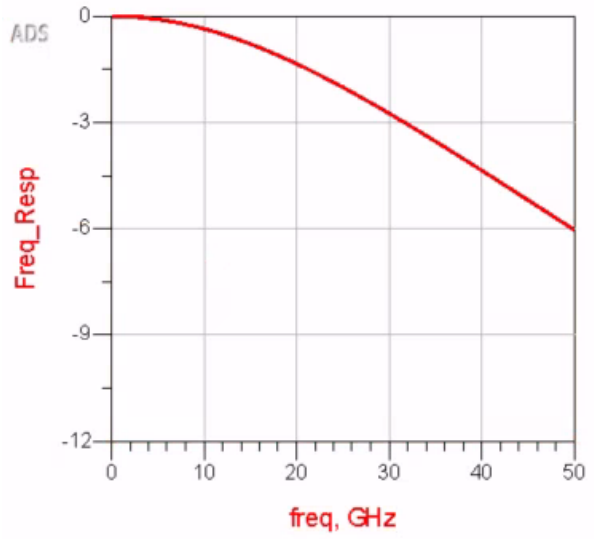
马赫曾德调制器关键指标
1. 响应度 （Resp.）
2. 偏振相关性
3. 暗电流 （I_d）
4. 3dB带宽/频率响应 （BW）
5. 大光下的线性特性



Chen, Hongtao. Advanced germanium pin and avalanche photodetectors for low-power optical interconnects. *Diss. Ghent University*, 2016.

结构分解	设计要点
吸收（响应度）	1. Si-Ge模式耦合； 2. Ge区域光场吸收；
带宽	1. R、C寄生参数； 2. 载流子渡越时间； 3. 大光入射时载流子对电场减弱作用。

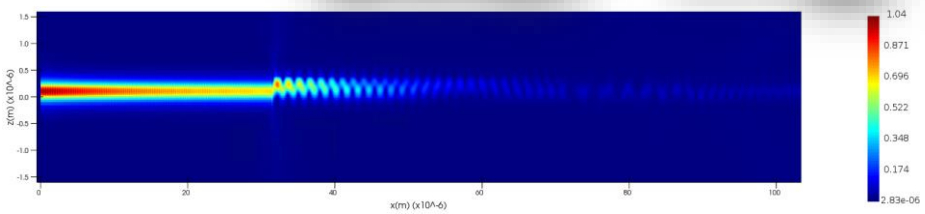




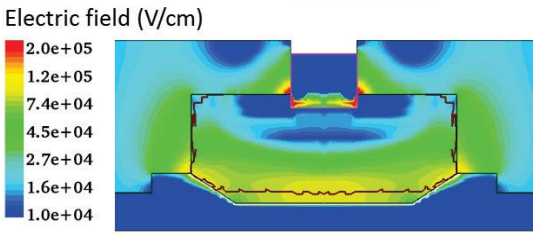
400G硅光器件——锗硅探测器

结构分解	设计要点
吸收（响应度）	1. Si-Ge模式耦合； 2. Ge区域光场吸收；
带宽	1. R、C寄生参数； 2. 载流子渡越时间； 3. 大光入射时载流子对电场减弱作用。

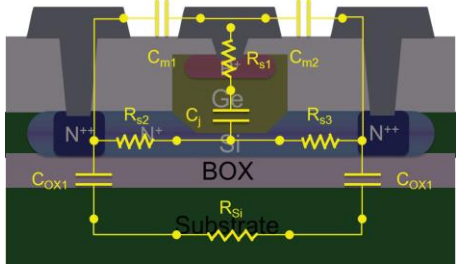
光场仿真



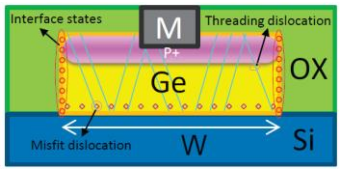
TCAD工艺仿真

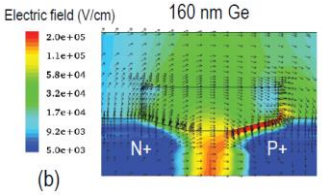


电路仿真



1. 响应度/偏振相关性
2. 3dB带宽/频率响应 （BW）





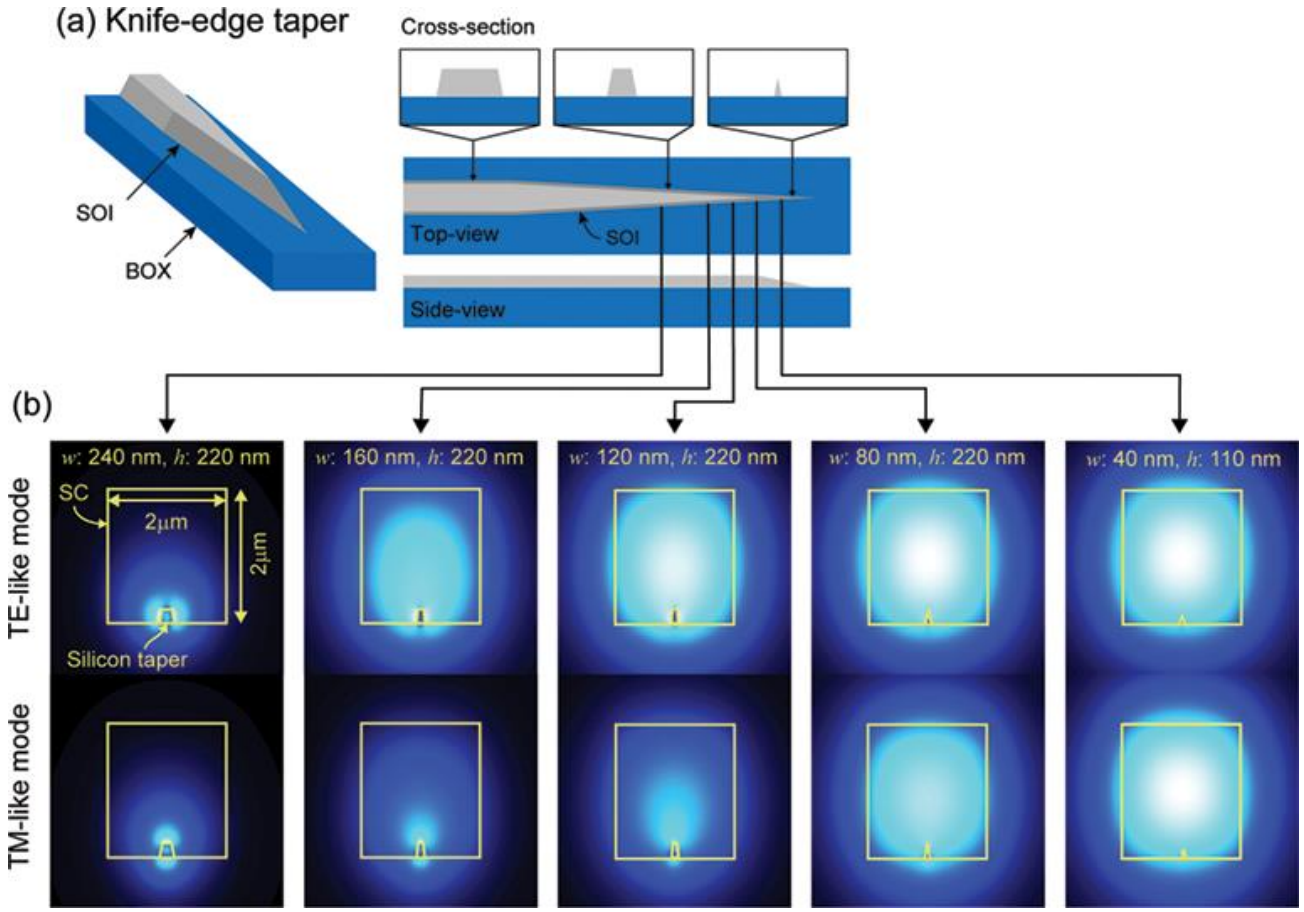
工艺强相关
3. 暗电流 （I_d）
4.大光下的线性特性

Chen, Hongtao. Advanced germanium pin and avalanche photodetectors for low-power optical interconnects. *Diss. Ghent University*, 2016.

400G硅光器件——边缘耦合器（EC）

边缘耦合器关键指标
1. 耦合模场大小 （MFD）
2. 插入损耗 （IL）
3. 偏振相关损耗 （PDL）
4. 回波损耗 （RL）

结构分解	设计要点
光纤耦合部分	1. 光纤-端面模式匹配; 2. 双偏振模式差异; 3. 端面反射处理;
模式渐变部分	1. 模式泄露损耗; 2. 模式失配损耗; 3. 传输损耗;



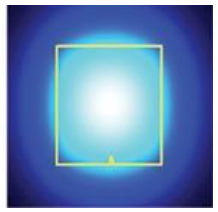
Mu, Xin, et al. "Edge couplers in silicon photonic integrated circuits: A review." *Applied Sciences* 10.4 (2020): 1538.

400G硅光器件——边缘耦合器（EC）

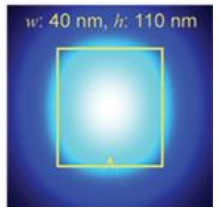
结构分解	设计要点
光纤耦合部分	1. 光纤-端面模式匹配; 2. 双偏振模式差异; 3. 端面反射处理;
模式渐变部分	1. 模式泄露损耗; 2. 模式失配损耗; 3. 传输损耗;

Mode overlap 计算

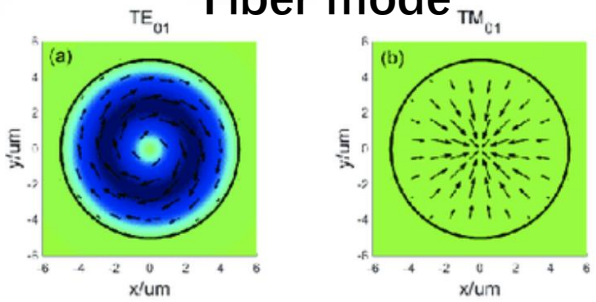
TE Mode



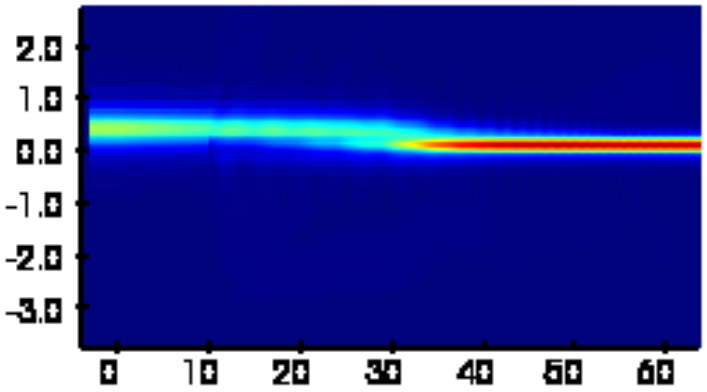
TM Mode



Fiber mode



光场传输仿真



$$\eta = \frac{\left|\int E_1^* E_2 \mathrm{d}A\right|^2}{\int |E_1|^2 \mathrm{d}A \int |E_2|^2 \mathrm{d}A}$$

边缘耦合器关键指标

1. 插入损耗 （IL）
2. 偏振相关损耗 （PDL）
3. 回波损耗 （RL）

400G硅光器件——Heater

1:1 Heater 关键指标
1. 插入损耗 （IL）
2. π相移功耗（P_π）
3. 响应时间（τ）

结构分解	设计要点
波导区域	1. 插入/传输损耗
加热区域	1. 加热效率； 2. 截面电流密度；
Under cut	1. 对后续工艺的影响； 2. 对芯片可靠性的影响；

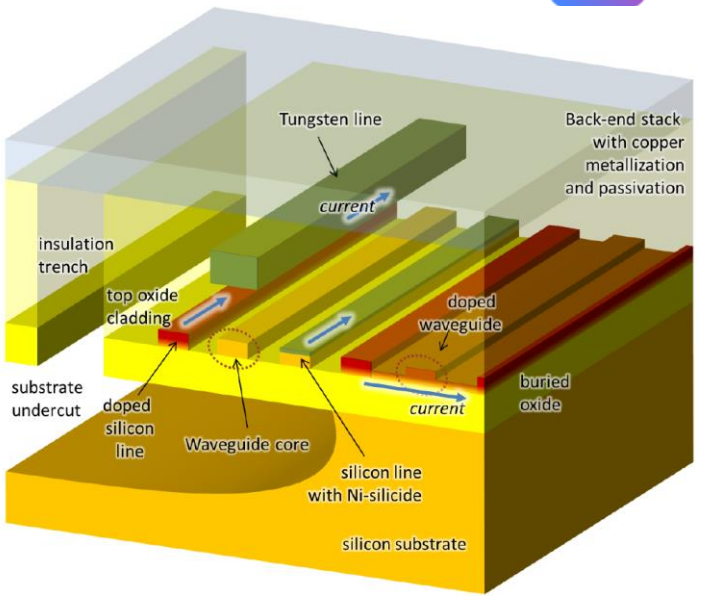


TABLE I. HEATER PERFORMANCE COMPARISON

Heater type	Efficiency [mW/π]	Line Resistivity [Ω/μm]	Heating τ 1/e [μs]	Cooling τ 1/e [μs]
Without Insulation				
Doped silicon	20.4	293	21.3	66.0
Silicide	22.5	27.3	19.1	75.8
Tungsten	23.4	1.1	38.2	45.11
Doped waveguide	21.9	N/A*	43.4	39.8
With Insulation				
Doped silicon	1.42	317	151	217
Silicide	1.49	28.0	188	218
Tungsten	1.42	1.3	198	227
Doped waveguide	1.30	N/A*	236	156

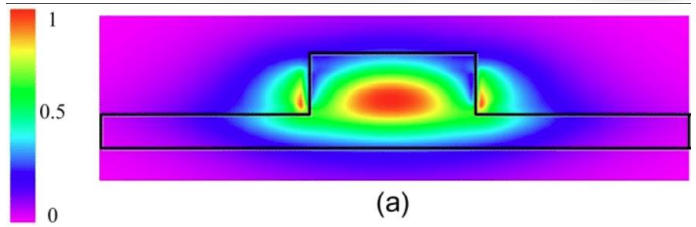
* in-waveguide heaters have a line conductivity

Masood, Adil, et al. "Comparison of heater architectures for thermal control of silicon photonic circuits." 10th International Conference on Group IV Photonics. IEEE, 2013.

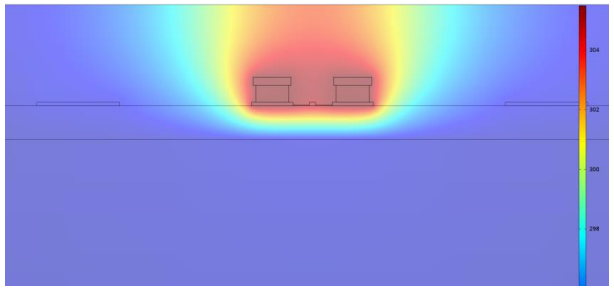
400G硅光器件——Heater

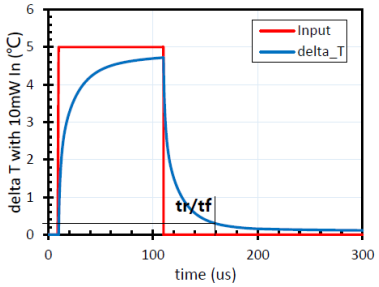
结构分解	设计要点
波导区域	1. 插入/传输损耗
加热区域	1. 加热效率； 2. 截面电流密度；
Under cut	1. 对后续工艺的影响； 2. 对芯片可靠性的影响；

光场仿真



热仿真
瞬态仿真





1. 插入损耗 （IL）

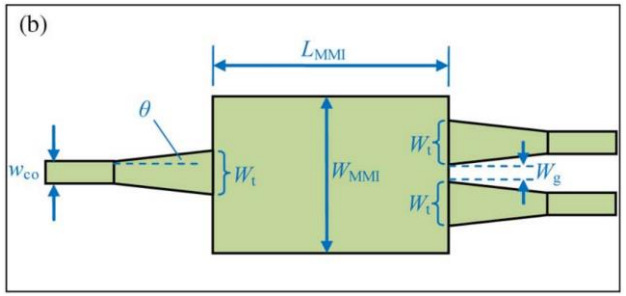
2. π相移功耗（P_π）
3. 响应时间（τ）

400G硅光器件——1:1 Beam Splitter

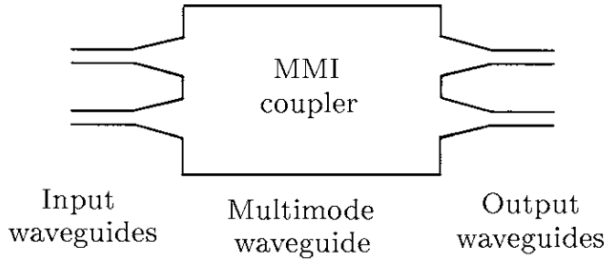
PIC Palette 矽 绘

1:1 Beam Splitter关键指标

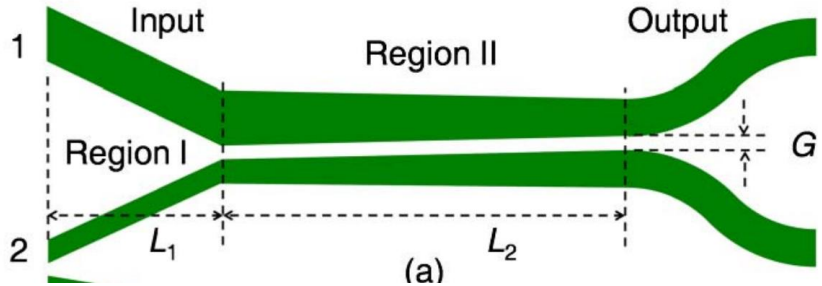
1. 插入损耗 （IL）
2. 分光一致性 （IMB）→ ER
3. 回波损耗 （RL）



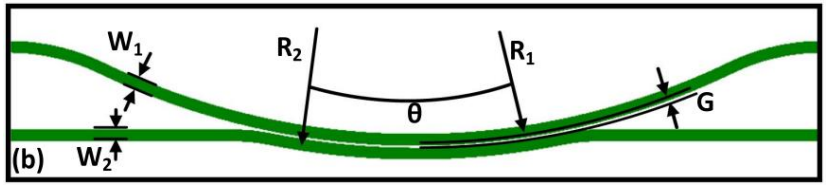
Sheng, Zhen, et al. "A compact and low-loss MMI coupler fabricated with CMOS technology." *IEEE Photonics Journal* 4.6 (2012): 2272-2277.



Hong-Zhen, Wei, et al. "Silicon-on-insulator based 2× 2 multimode interference coupler with large tolerance." *Chinese Physics Letters* 18.2 (2001): 245.



Xing, Jiejiang, et al. "Silicon-on-insulator-based adiabatic splitter with simultaneous tapering of velocity and coupling." Optics letters 38.13 (2013): 2221-2223.

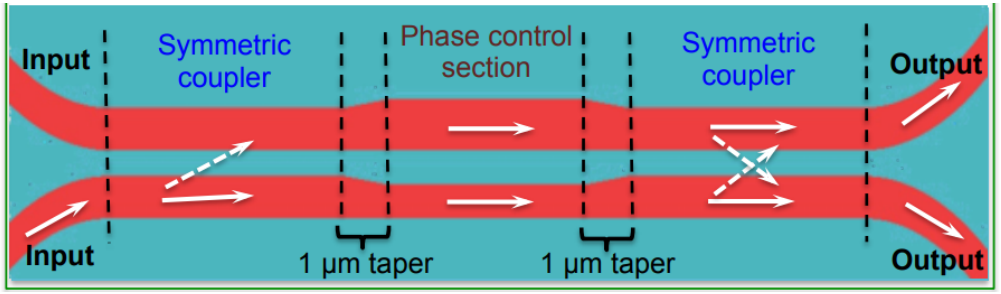


Chen, Sitao, et al. "Low-loss and broadband 2× 2 silicon thermo-optic Mach–Zehnder switch with bent directional couplers." Optics letters 41.4 (2016): 836-839.

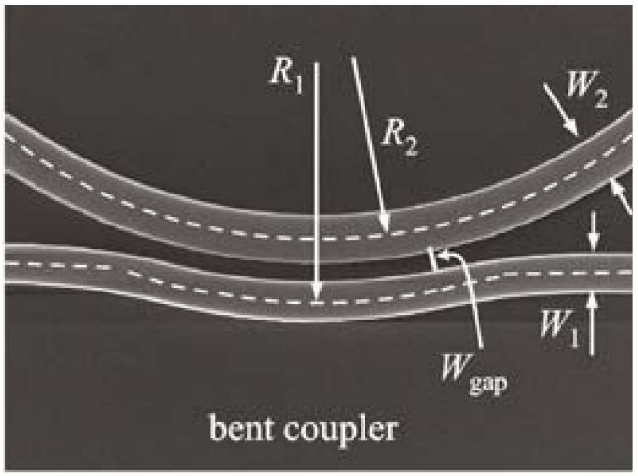
400G硅光器件——Tap

1:1 Tap 关键指标
1. 插入损耗 （IL）
2. 分光比 （Tap ratio）

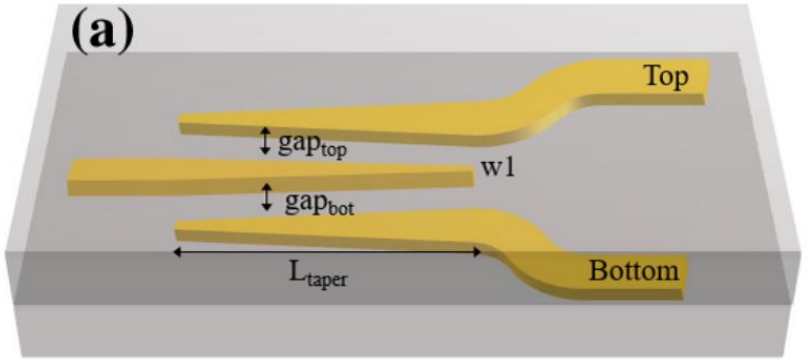
对于无源器件设计有一点很重要：
容差分析



Lu, Zeqin, et al. "Broadband silicon photonic directional coupler using asymmetric-waveguide based phase control." Optics express 23.3 (2015): 3795-3808.



Dai, Daoxin, and Shipeng Wang. "Asymmetric directional couplers based on silicon nanophotonic waveguides and applications." Frontiers of Optoelectronics 9 (2016): 450-465.



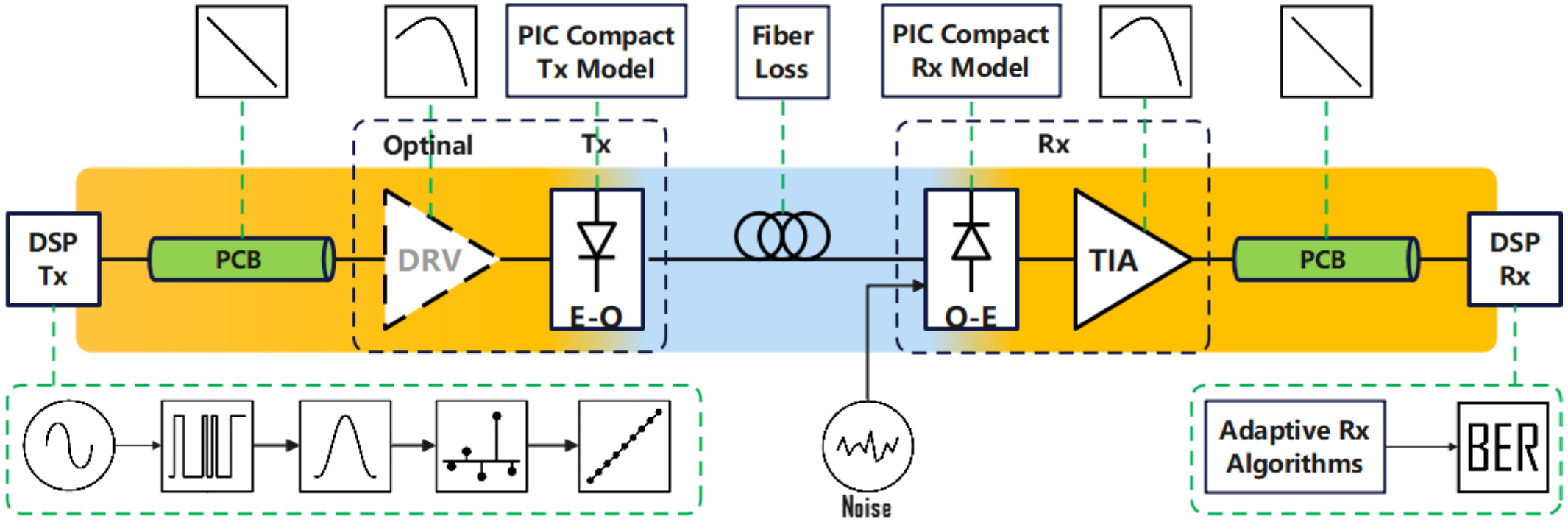
Zhu, Junbo, et al. "Compact, broadband, and low-loss silicon photonic arbitrary ratio power splitter using adiabatic taper." Applied Optics 60.2 (2021): 413-416.

400G硅光器件——无源器件仿真器

PIC Palette 矽 绘

方法	速度	准确性	典型器件	软件
FDTD	●	★	MMI/DC/Crossing	Max-Optics 曼光 Photon Design RSOFT SYNOPSYS
EME	★	▲	MMI/EC/PSR	Max-Optics 曼光 Photon Design
2D-FDTD	★	●	MRM/GC	Max-Optics 曼光
BPM	★	▲	DC	RSOFT SYNOPSYS
FDTD+TMM	▲	★	PSR	Max-Optics 曼光 Photon Design RSOFT SYNOPSYS
Coupled Mode Theory	★	●	MMI/DC/EC/PSR	MATLAB python

单波100Gbps 系统仿真简介——Schematic



Link model in ADS， including：

1. Basic DSP Tx & Rx Model
2. SNP model PCB Loss
3. SNP model for commercial DRV and TIA
4. Compact models for PIC, including Modulator, PD, Laser, and Passive devices
5. Fiber and connections loss

单波100Gbps 系统仿真简介——Schematic

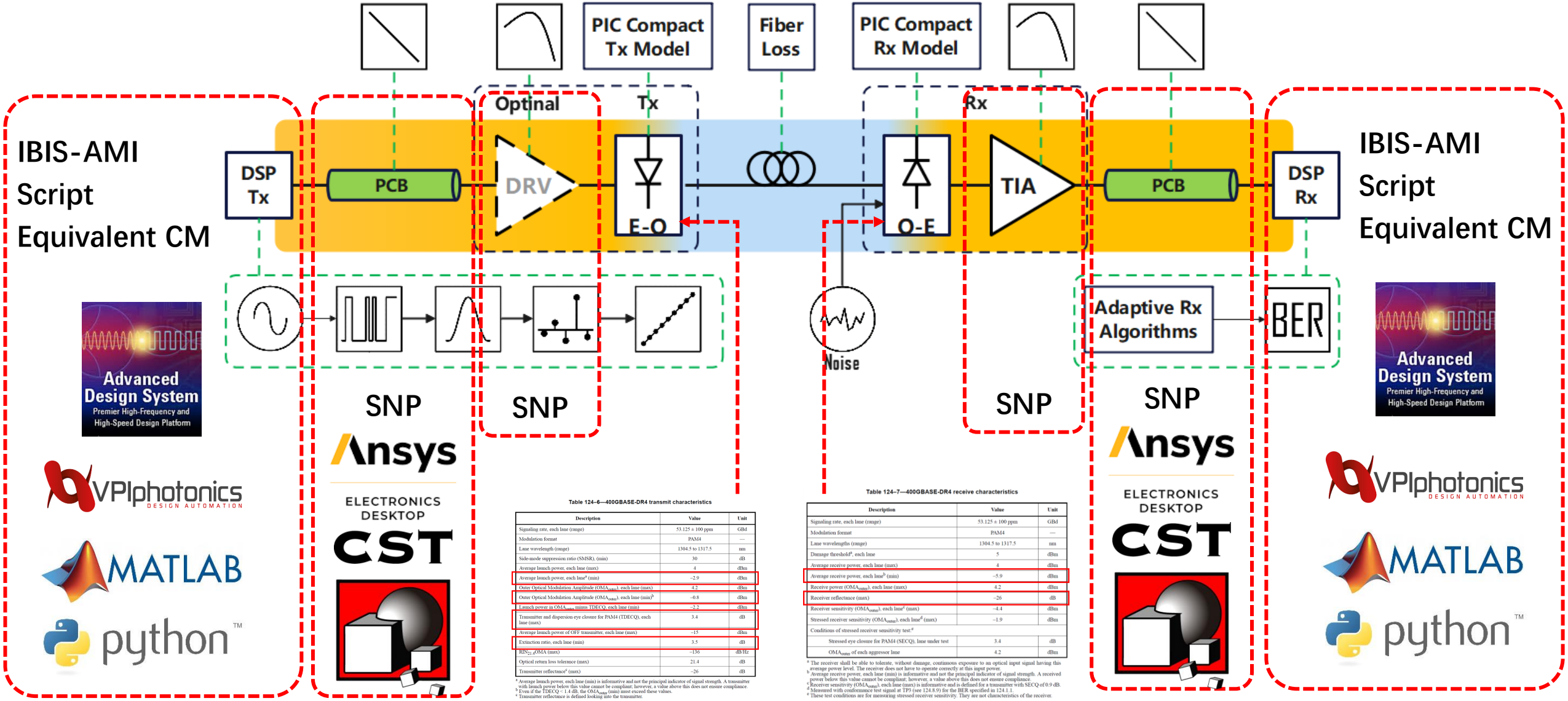


Table 124–6—400GBASE-DR4 transmit characteristics

Description	Value	Unit
Signaling rate, each lane (range)	53.125 ± 100 ppm	GBd
Modulation format	PAM4	—
Lane wavelength (range)	1304.5 to 1317.5	nm
Side-mode suppression ratio (SMSR), (min)	30	dB
Average launch power, each lane (max)	4	dBm
Average launch power, each lane[a] (min)	−2.9	dBm
Outer Optical Modulation Amplitude (OMA_{outer}), each lane (max)	4.2	dBm
Outer Optical Modulation Amplitude (OMA_{outer}), each lane (min)[b]	−0.8	dBm
Launch power in OMA_{outer} minus TDECQ, each lane (min)	−2.2	dBm
Transmitter and dispersion eye closure for PAM4 (TDECQ), each lane (max)	3.4	dB
Average launch power of OFF transmitter, each lane (max)	−15	dBm
Extinction ratio, each lane (min)	3.5	dB
$RIN_{21.4}OMA$ (max)	−136	dB/Hz
Optical return loss tolerance (max)	21.4	dB
Transmitter reflectance[c] (max)	−26	dB

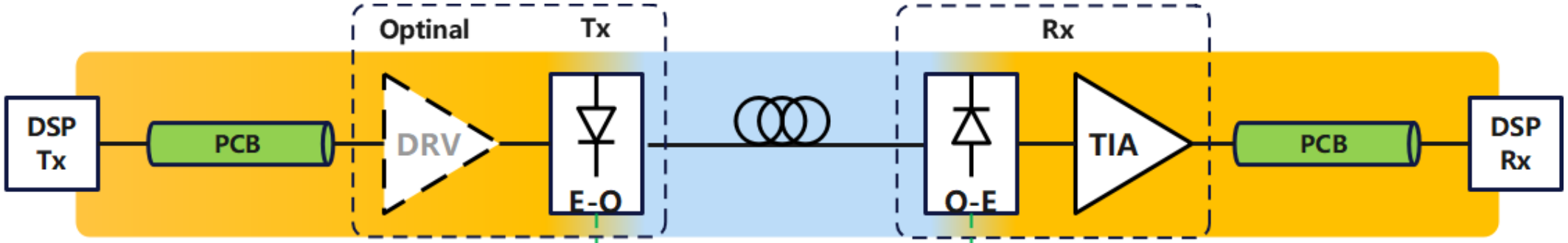
[a] Average launch power, each lane (min) is informative and not the principal indicator of signal strength. A transmitter with launch power below this value cannot be compliant; however, a value above this does not ensure compliance.
[b] Even if the TDECQ < 1.4 dB, the OMA_{outer} (min) must exceed these values.
[c] Transmitter reflectance is defined looking into the transmitter.

Table 124–7—400GBASE-DR4 receive characteristics

Description	Value	Unit
Signaling rate, each lane (range)	53.125 ± 100 ppm	GBd
Modulation format	PAM4	—
Lane wavelengths (range)	1304.5 to 1317.5	nm
Damage threshold[a], each lane	5	dBm
Average receive power, each lane (max)	4	dBm
Average receive power, each lane[b] (min)	−5.9	dBm
Receive power (OMA_{outer}), each lane (max)	4.2	dBm
Receiver reflectance (max)	−26	dB
Receiver sensitivity (OMA_{outer}), each lane[c] (max)	−4.4	dBm
Stressed receiver sensitivity (OMA_{outer}), each lane[d] (max)	−1.9	dBm
Conditions of stressed receiver sensitivity test:[e]		
Stressed eye closure for PAM4 (SECQ), lane under test	3.4	dB
OMA_{outer} of each aggressor lane	4.2	dBm

[a] The receiver shall be able to tolerate, without damage, continuous exposure to an optical input signal having this average power level. The receiver does not have to operate correctly at this input power.
[b] Average receive power, each lane (min) is informative and not the principal indicator of signal strength. A received power below this value cannot be compliant; however, a value above this does not ensure compliance.
[c] Receiver sensitivity (OMA_{outer}), each lane (max) is informative and is defined for a transmitter with SECQ of 0.9 dB.
[d] Measured with conformance test signal at TP3 (see 124.8.9) for the BER specified in 124.1.1.
[e] These test conditions are for measuring stressed receiver sensitivity. They are not characteristics of the receiver.

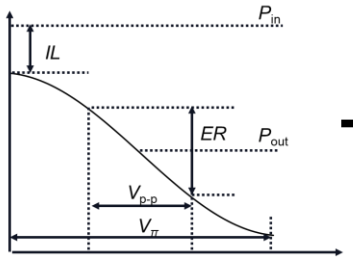
单波100Gbps 系统仿真简介——PIC Compact Model



PIC Compact Tx Model

Tx Compact Model

1. MZM Loss, *V*π, frequency response.
2. Laser Power
3. Coupling Efficiency
4. Passive Loss and ER



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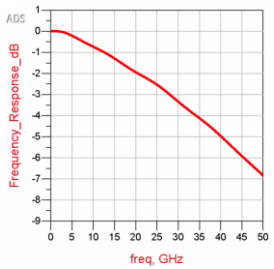
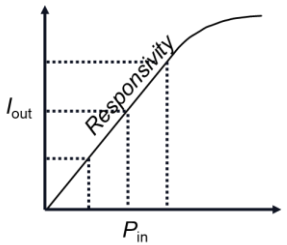


PIC Compact Rx Model

Rx Compact Model

1. PD Responsivity, frequency response
2. Coupling Efficiency
3. PD Noise



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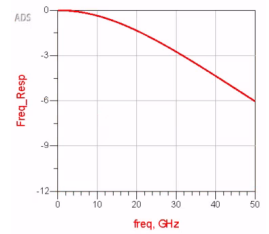
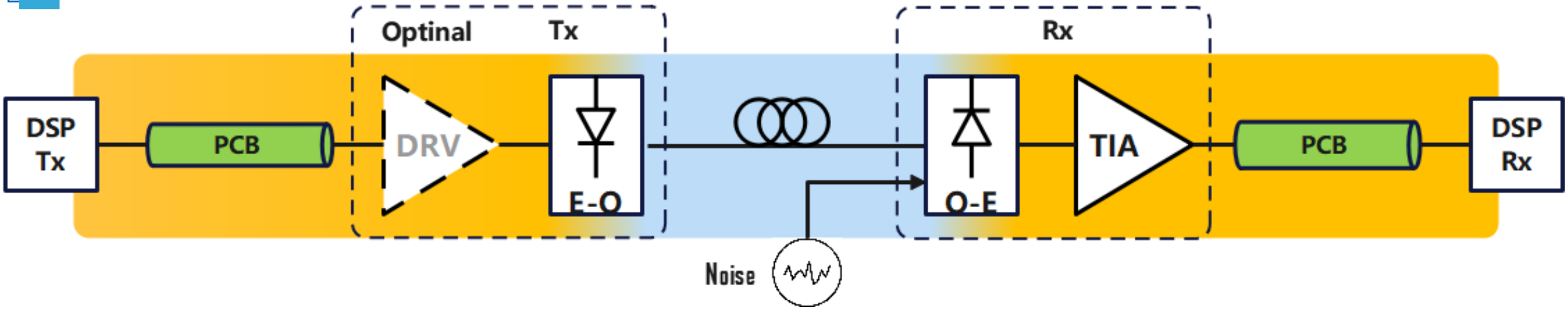
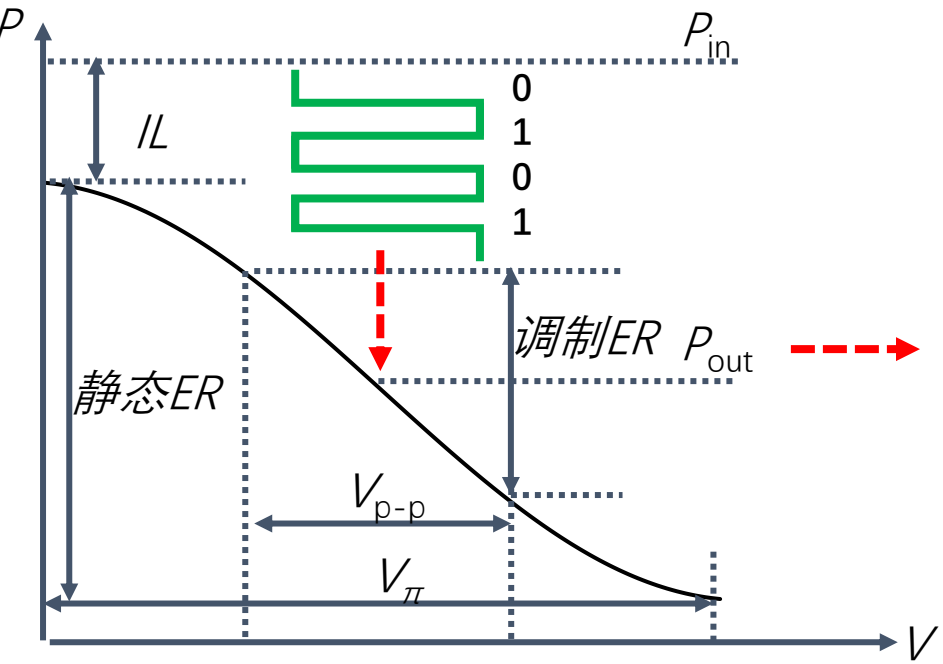


单波100Gbps 系统仿真简介——Tx Design



Balance the *Vpi*, *IL* and *frequency response* by turning length/implant/impedance…



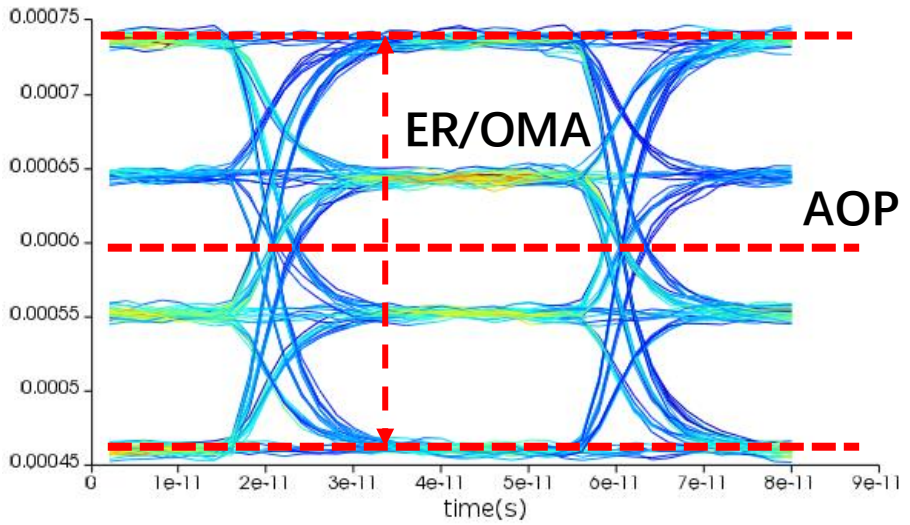


Table 124–6—400GBASE-DR4 transmit characteristics

Description	Value	Unit
Signaling rate, each lane (range)	53.125 ± 100 ppm	GBd
Modulation format	PAM4	—
Lane wavelength (range)	1304.5 to 1317.5	nm
Side-mode suppression ratio (SMSR) (min)	30	dB
Average launch power, each lane (max)	4	dBm
Average launch power, each lane (min)[a]	-2.9	dBm
Outer Optical Modulation Amplitude (OMA_{outer}), each lane (max)	4.2	dBm
Outer Optical Modulation Amplitude (OMA_{outer}), each lane (min)[b]	-0.8	dBm
Launch power in OMA$_{outer}$ minus TDECQ, each lane (min)	-3.5	dBm
Transmitter and dispersion eye closure for PAM4 (TDECQ), each lane (max)	3.4	dB
Average launch power of OFF transmitter, each lane (max)	-30	dBm
Extinction ratio, each lane (min)	3.5	dB
RIN$_{17.4}$OMA (max)	-136	dB/Hz
Optical return loss tolerance, each lane (min)	21.4	dB
Transmitter reflectance[c] (max)	-26	dB

[a] Average launch power, each lane (min) is informative and not the principal indicator of signal strength. A transmitter with launch power below this value cannot be compliant; however, a value above this does not ensure compliance.
[b] Even if the TDECQ < 1.4 dB, the OMA_{outer} (min) must exceed these values.
[c] Transmitter reflectance is defined looking into the transmitter.

AOP(min) -2.9 dBm

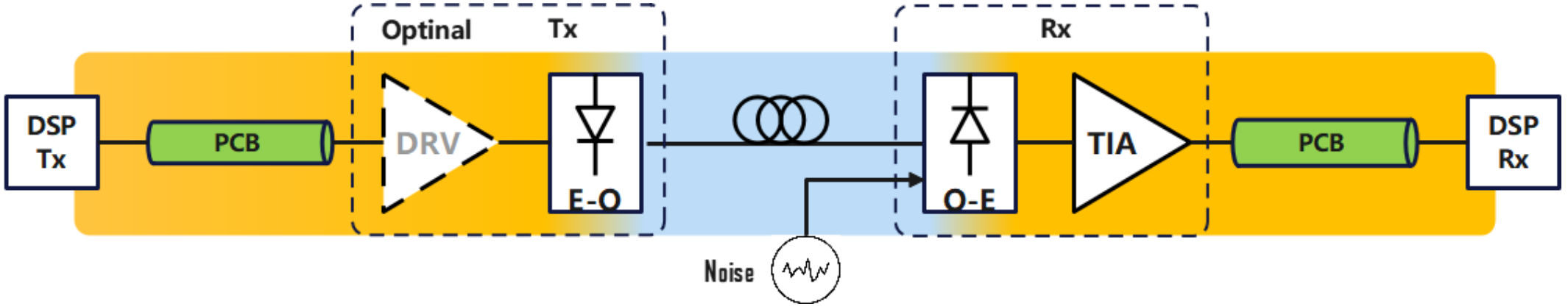
OMA(min) -0.8 dBm

ER 3.5 dB

TDECQ 3.4 dB

TDECQ is the optical power penalty of the measured optical transmitter compared to an ideal transmitter.

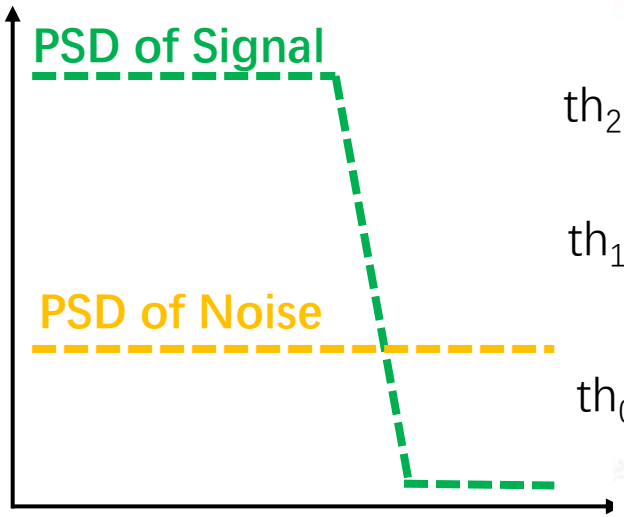
单波100Gbps 系统仿真简介——Rx Design



Choosing the proper bandwidth to get the best SNR!

Rx Noise source

1. Laser
2. PD
   - *Shot Noise*
   - *Thermal Noise*
   - *Dark Current Noise*
3. Crosstalk
4. TIA
5. ADC



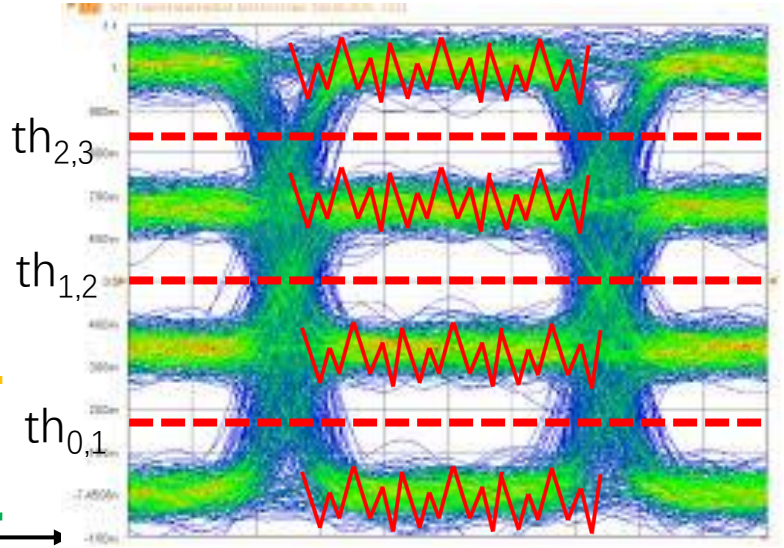


Table 124–7—400GBASE-DR4 receive characteristics

Description	Value	Unit
Signaling rate, each lane (range)	53.125 ± 100 ppm	GBd
Modulation format	PAM4	—
Lane wavelengths (range)	1304.5 to 1317.5	nm
Damage threshold[a], each lane	5	dBm
Average receive power, each lane (max)	4	dBm
Average receive power, each lane[b] (min)	–5.9	dBm
Receive power (OMA_{outer}), each lane (max)	4.2	dBm
Receiver reflectance (max)	–26	dB
Receiver sensitivity (OMA_{outer}), each lane[c] (max)	–4.4	dBm
Stressed receiver sensitivity (OMA_{outer}), each lane[d] (max)	–1.9	dBm
Conditions of stressed receiver sensitivity test[e]		
Stressed receiver sensitivity for PAM4 (SECQ), link budget	3.4	dB
OMA_{outer} of each aggressor lane		dBm

ARP(min) -5.9 dBm

RL (max) -26 dB

[a] The receiver shall be able to tolerate, without damage, continuous exposure to an optical input signal having this average power level. The receiver does not have to operate correctly at this input power.
[b] Average receive power, each lane (min) is informative and not the principal indicator of signal strength. A received power below this value cannot be compliant; however, a value above this does not ensure compliance.
[c] Receiver sensitivity (OMA_{outer}), each lane (max) is informative and is defined for a transmitter with SECQ of 0.9 dB.
[d] Measured with conformance test signal at TP3 (see 124.8.9) for the BER specified in 124.1.1.
[e] These test conditions are for measuring stressed receiver sensitivity. They are not characteristics of the receiver.

PIC Palette 矽 绘

感谢您的关注

Thank you for attention!

吴昊

浙江 杭州

扫一扫上面的二维码图案，加我为朋友。

hao.wu@innolight.com

http://picpalette.innolight.com:60000/