SPICE Modeling for Mixed Electronic/Photonic VLSI

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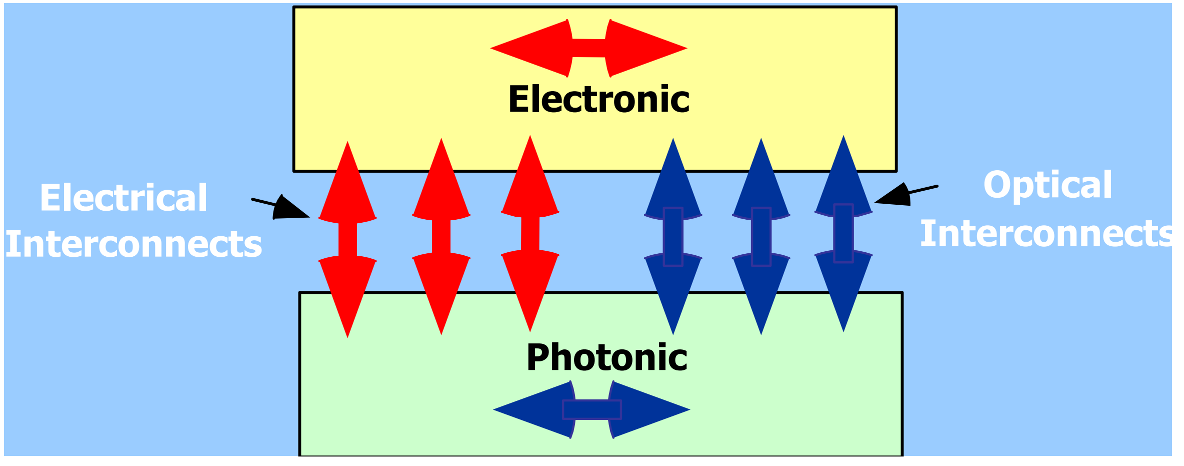


Talk Outline

- **Objectives and Tasks**
- **Key Accomplishments**
- **Models and Optoelectronic Circuit Simulation**
  - **VCSELs**
  - **PIN Photodiodes**
  - **MSM Structure**
  - **Photonic AIM-Spice**
  - **Optoelectronic Circuit Simulation**
- **Future Plans**
- **Conclusions**
- **List of Publications**

Objective and Tasks

Objective

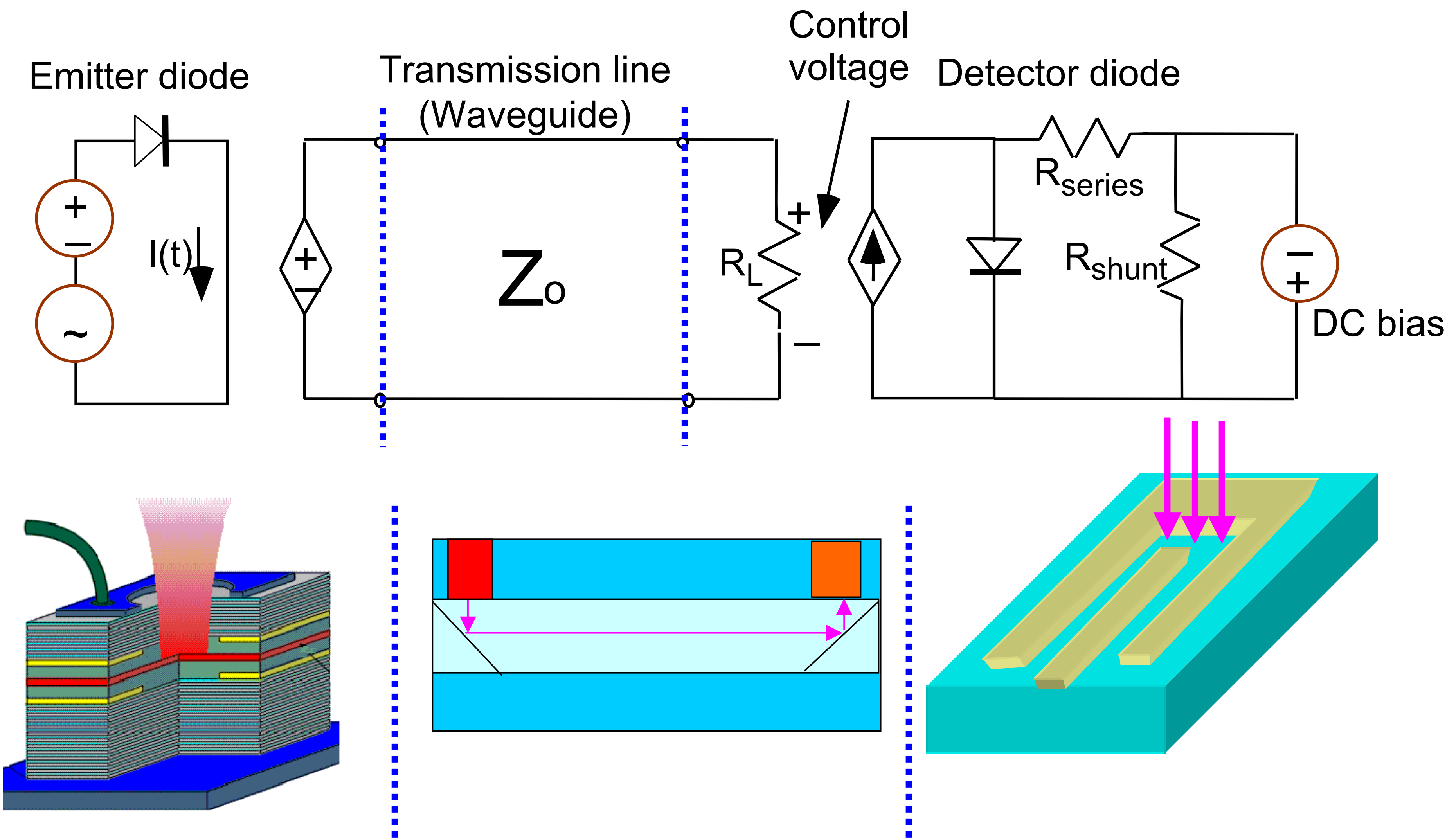
To develop CAD tools suitable for mixed electronic/photonic VLSI

Tasks

To develop a new generation of accurate and reliable models for photonic devices, describing the interrelations of optical and electrical inputs and outputs.
These models should be compatible with modern circuit simulators.

To develop a SPICE-type circuit simulator - Photonic SPICE - that will be enhanced to handle the added dimension represented by photonic signals, devices and interconnects.

Equivalent Circuit for Photonic SPICE



Key Accomplishments

VCSELs: **Self-consistent self-heating SPICE model available, including transient simulation**

Photodetectors: **SPICE model developed for MSM structures, PIN Photodiodes. Schottky Barrier Photodiode Model Developed.**

Optoelectronic AIM-Spice Developed

Model Requirements for Circuit Simulators

- *Physics Based*
- *Semi-analytical*
- *Convergence*
- *Ease of parameter extraction*
- *Compatibility with existing CAD tools*

Photonic SPICE Device and New Models

Devices: Emitters, Detectors, Interconnects

Models: -Photonic signals described in terms of electrical signals
-Analytical response functions expressed in terms of electrical equivalents, obeying the laws of circuitry imbedded in the circuit simulator
-Kirchhoff's current and voltage laws

Other issues:
-Interactions between optical and electronic devices (stray light effects)
-Power budget
-Self-heating
-Optical interconnects

Rate Equation for Electron Density for a VCSEL

$$\frac{dN}{dt} = \eta \frac{I}{qV} - \frac{N}{\tau_n} - \frac{A(N - N_{tr})S}{1 + \varepsilon S}$$

N: Electron density (10^{25} m^{-3}) V: Active region volume (10^{-20} m^3)

I: Injection current (1 mA) τ_n: Carrier lifetime (1ns)

S: Output photon density (10^{25} m^{-3})

Γ: Confinement factor (10^{-9}) A: Optical gain factor (10^{-21} m^3/s)

η: Current injection efficiency (0.5)

N_{tr}: Transparency carrier density (10^{23} m^{-3})

ε: Gain compression parameter (10^{-26} m^3)

(Typical parameter values are given in parenthesis)

Rate Equation for Photon Density for a VCSEL

$$\frac{dS}{dt} = \gamma \frac{\Gamma N}{\tau_n} - \frac{S}{\tau_p} + \frac{A(N - N_{tr})S}{1 + \varepsilon S}$$

γ: Coupling factor (0.01) τ_n: Carrier lifetime

N: Electron density (10^{25} m^{-3})

I: Injection current (1 mA) τ_p: Photon lifetime

S: Output photon density (10^{25} m^{-3})

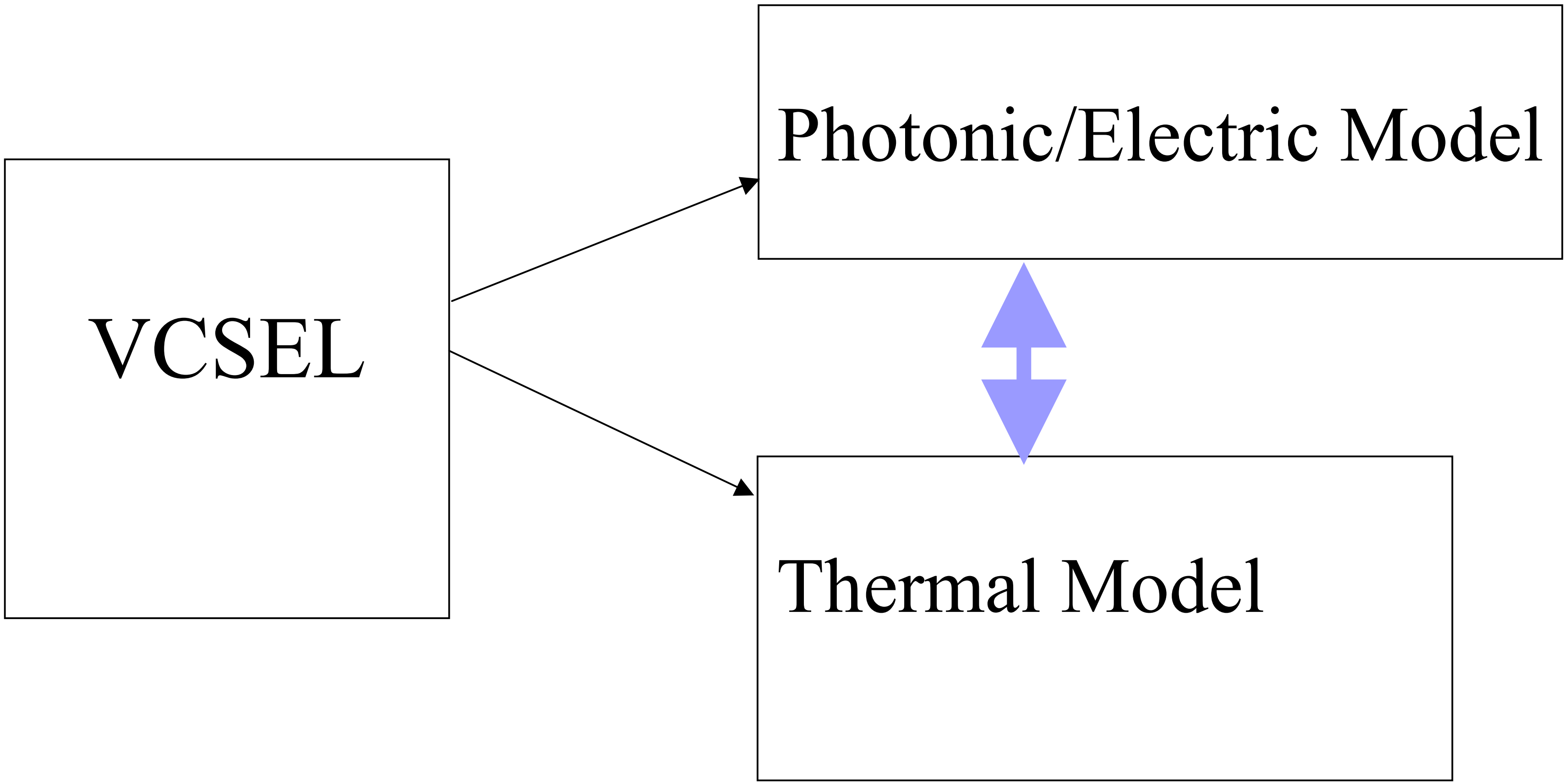
Γ: Confinement factor (10^{-9}) A: Optical gain factor (10^{-21} m^3/s)

η: Current injection efficiency (0.5)

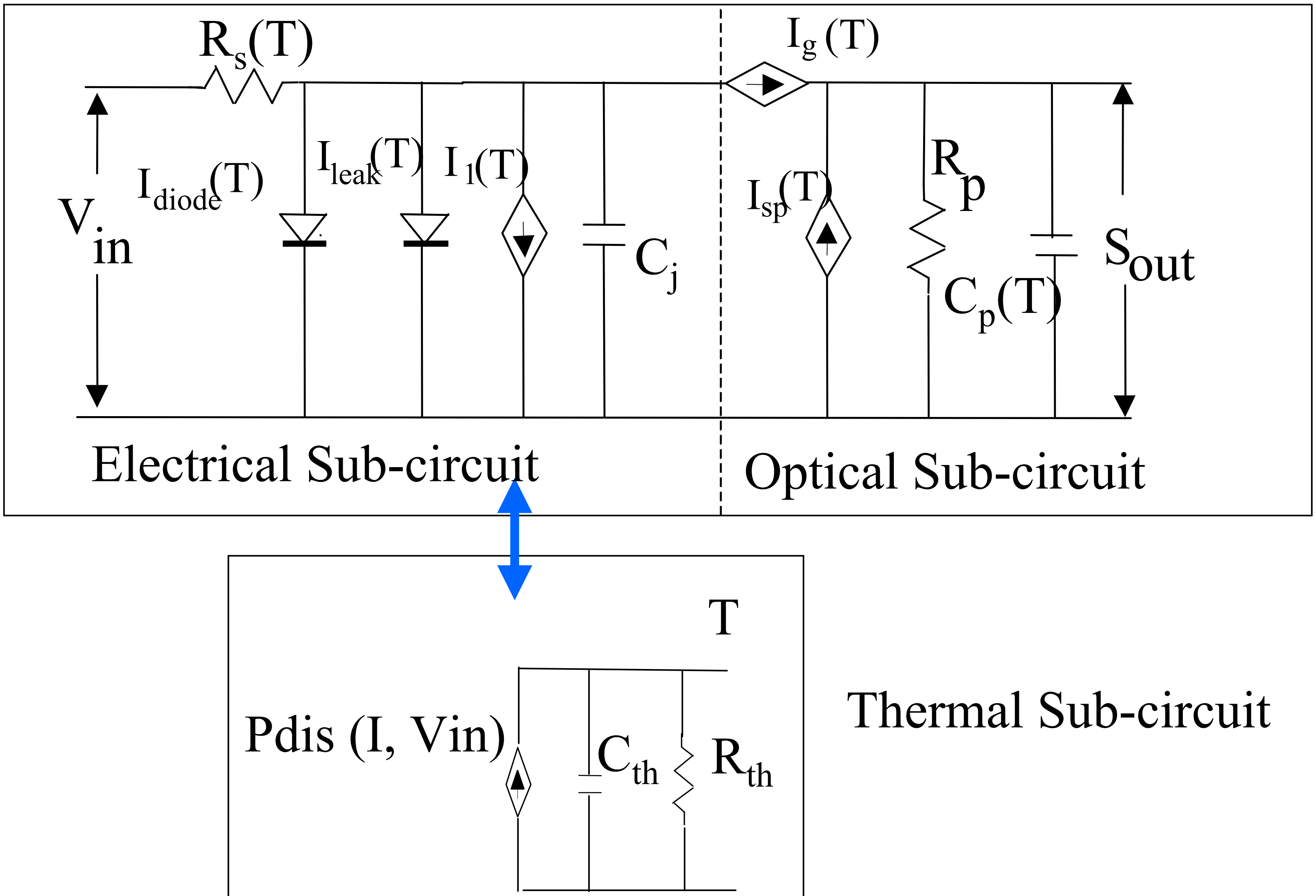
N_{tr}: Transparency carrier density (10^{23} m^{-3})

ε: Gain compression parameter (10^{-26} m^3)

Block Diagram of VCSEL Equivalent Circuit



VCSEL Equivalent Circuit



Rensselaer

Thermal Equations

DARPA

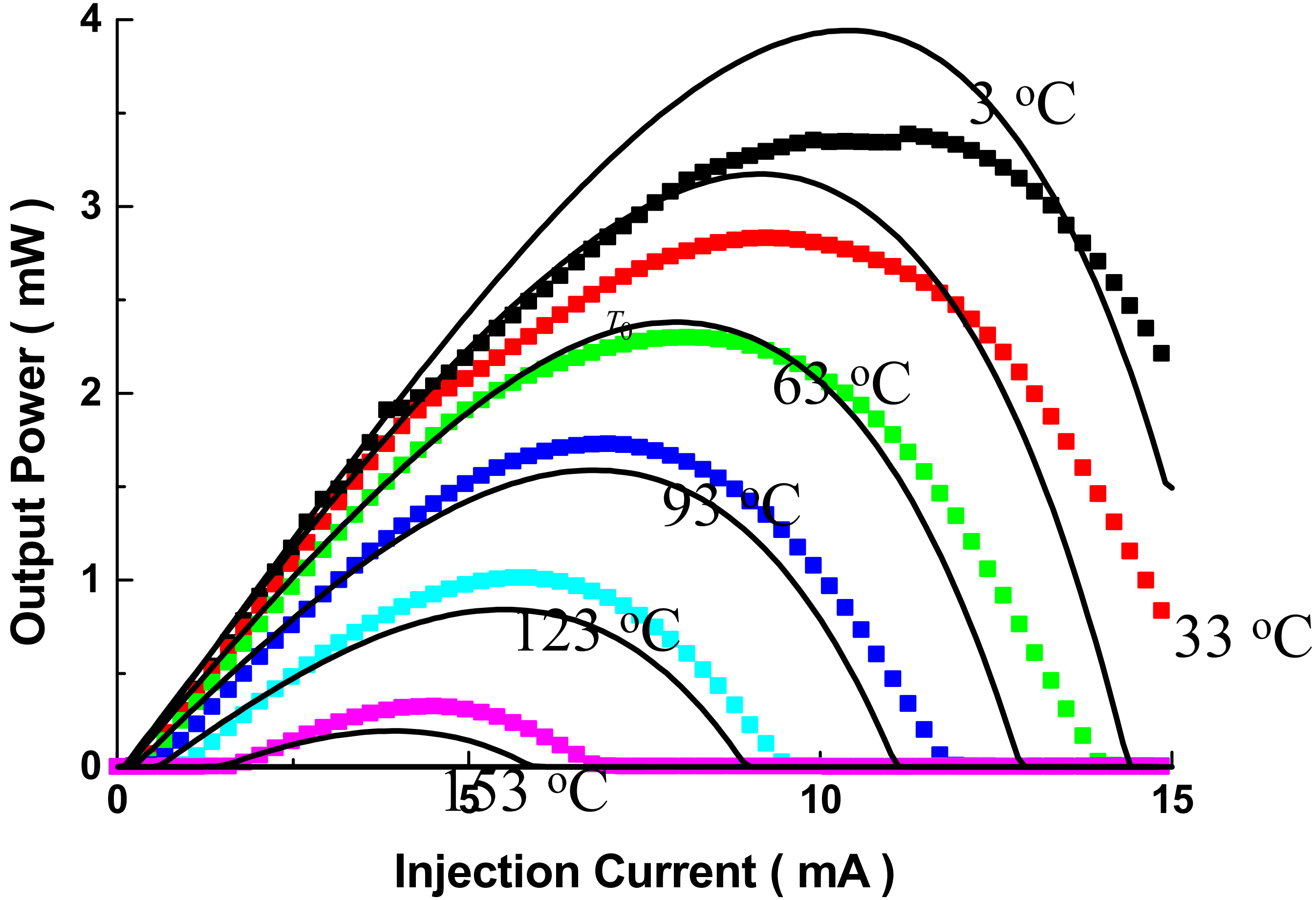
$$\eta(T) = \begin{cases} \eta_1 = \eta_0(1 - c_0 T + c_1 T^2) & \text{for } \eta_1 > 0.001 \\ 0 & \text{for } \eta_1 < 0.001 \end{cases}$$

$$A(T) = -A_0 arctg(-\frac{T - T_{trans}}{T_{\mathrm{lg}}}) + A_1$$

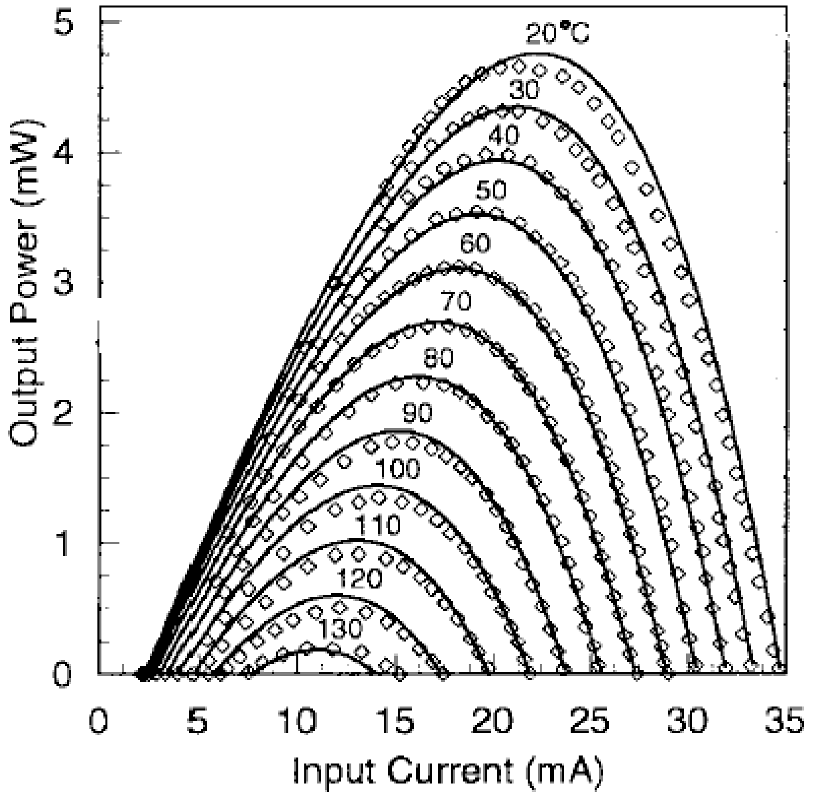
$$I_s(T) = I_s(T_0)\left(\frac{T}{T_0}\right)^{XTI/n} \exp\left(-\frac{qE_g(T_0)}{nkT}(1 - \frac{T}{T_0})\right)$$

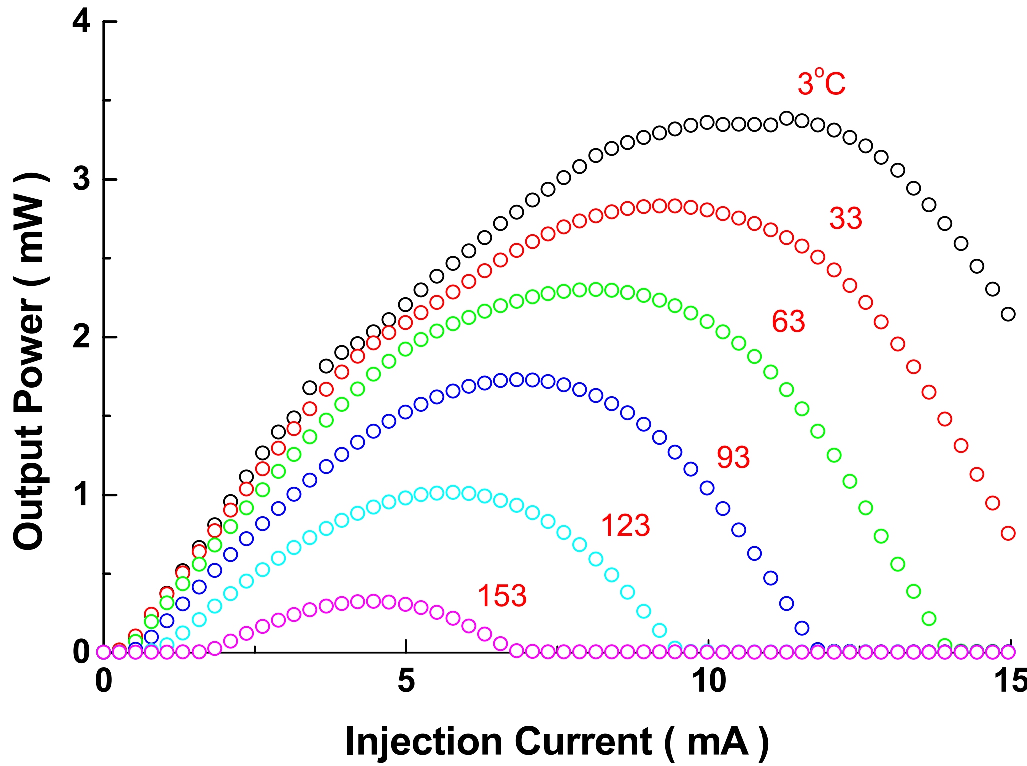
$$N = \frac{I_s \tau_n}{qV}(\exp(\frac{qVin}{nkT}) - 1)$$

P-I Curves for Different Temperatures

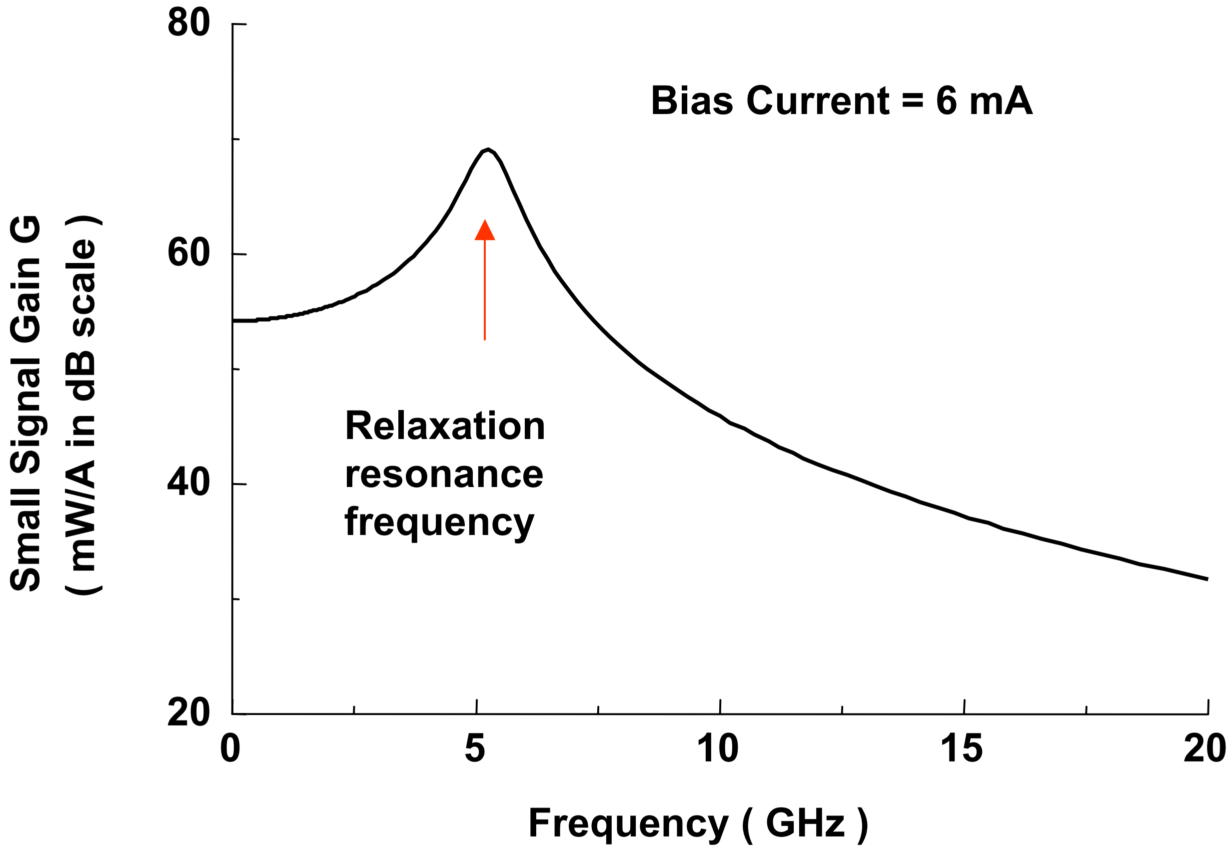


P-I Curves for Different VCSELs





Small Signal Analysis Results



$$G \equiv \left| \frac{dP}{dI} \right|$$

P-- optical output power

I -- input current

Transient Analysis Results

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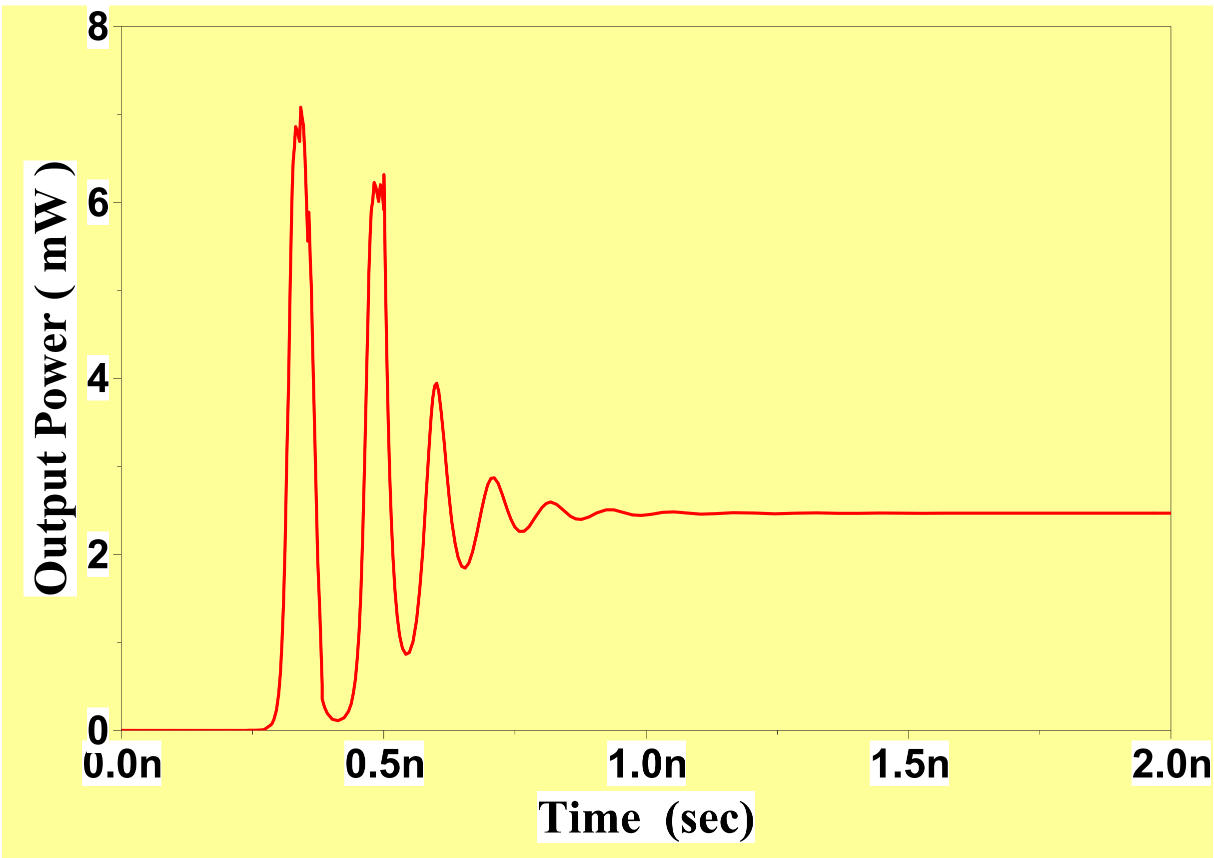
DARPA



Rise time = 0.5ns

Good convergence!

Preliminary Parameter Extraction

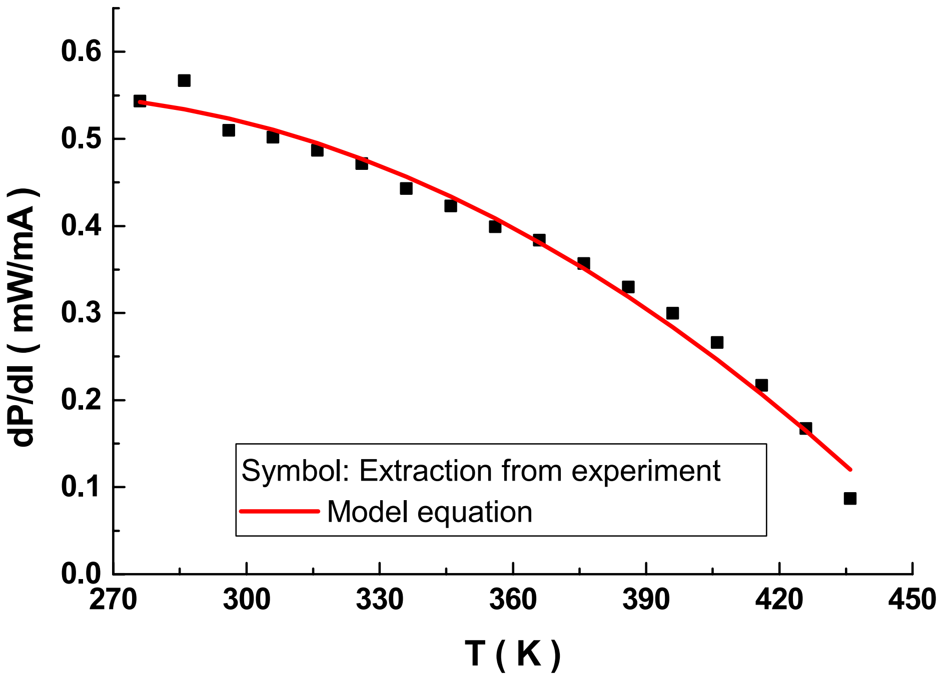
If self-heating is not considered, we can extract the gain and injection efficiency by measuring the threshold current (I_{th}) and the slope dP/dI from P-I curve.

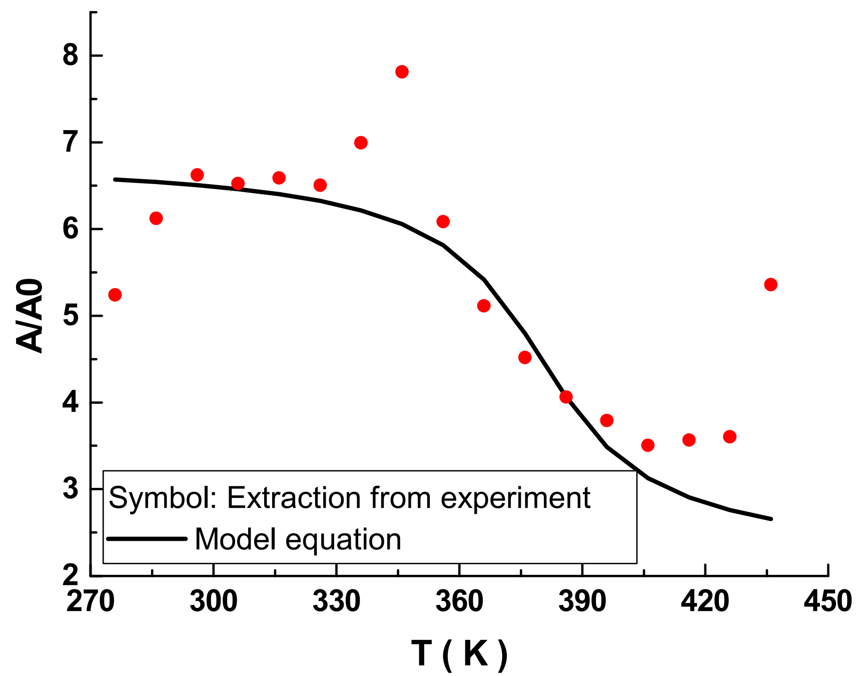
$$I_{th} = \frac{1}{\eta \tau_p \tau_n A}$$

$$\frac{dP}{dI} \propto \eta \tau_p$$

From these equations we can extract the temperature dependence of *A (optical gain factor)* and η (current injection efficiency) , assuming all the other parameters are temperature independent

Parameter Extraction Results





Model Advantages

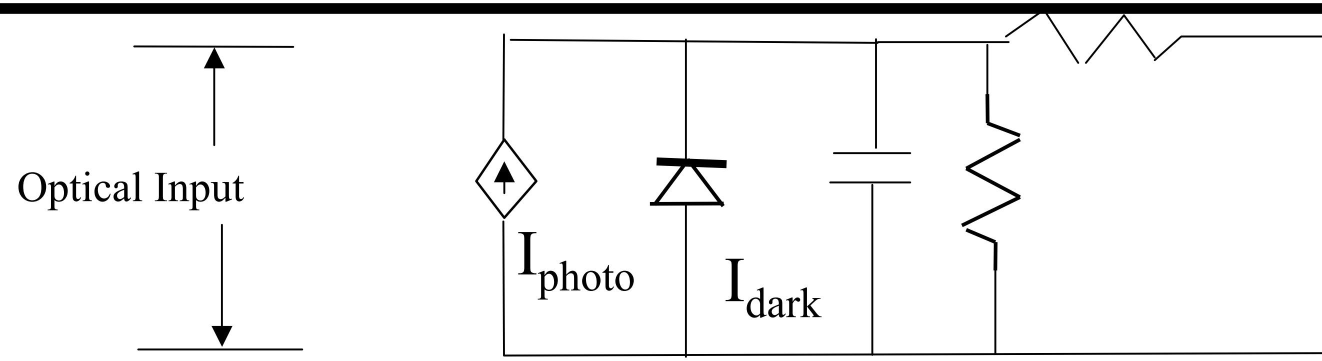
- Ease of parameter extraction

- Integration into SPICE source code -- good convergence and calculation speed

Possible Improvements

- Multiple-mode simulation
- Spatial hole burning effect
- Stray light/cross talk effect modeling and simulation
- Parasitic Effects
- Comparison of transient simulation with experimental data

MSM model for Photonic SPICE



Electrical Sub-circuit

$$I_{total} = I_{dark} + I_{photo}$$

$$I_{dark} = I_{e0}\exp\left(-\frac{\phi_B}{V_t}\right)\exp\left(\sqrt{\frac{qV}{\alpha\pi d\varepsilon\varepsilon_0 V_t^{\,2}}}\right) + I_{t0}\exp\left(-\frac{B_1}{V}\right)$$

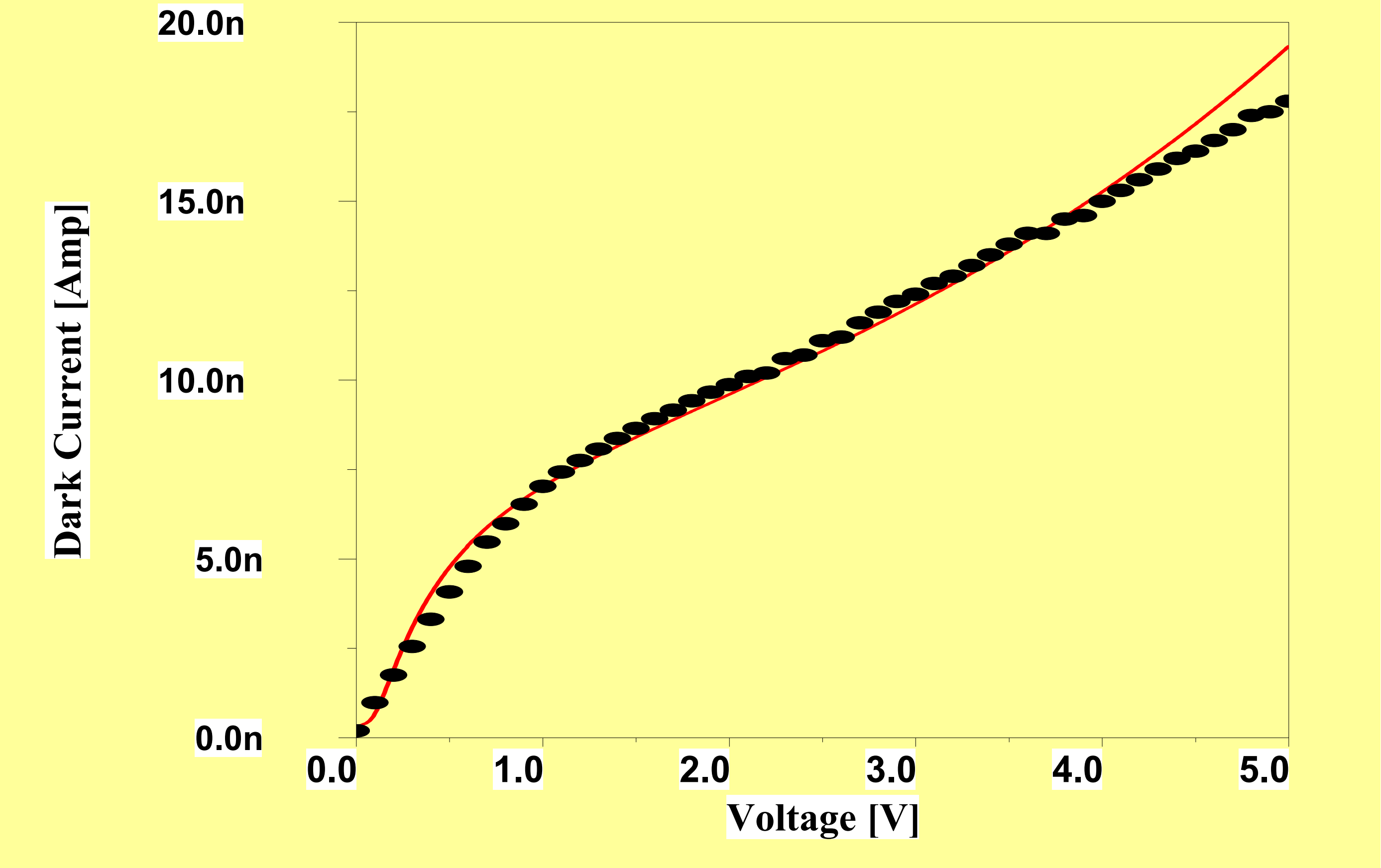
$$I_{photo} = I_{ph}\left[A\exp\left(-\frac{B_2}{V}\right)+1\right], V \geq V_{FB}$$

$$I_{photo} = I_{ph}A\exp\left(-\frac{B_2}{V}\right) + I_0\left[\exp\left(\frac{qV(2V_{FB}-V)}{nkT}\right)-1\right], V < V_{FB}$$

$$I_{ph} \propto Input\ Light\ Density$$

See *A. Xiang, W. Wohlmuth, P. Fay, S. Kang, I. Adesida, “Modeling of IinGaAs MSM Photodetector for Circuit-Level Simulation”, Journal of Lightwave Technology, Vol. 14, No. 5, May 1996, 716-723.*

Simulation Results for Steady State Analysis



Dark Current Simulation versus Experiment

Simulation Results for Steady State Analysis

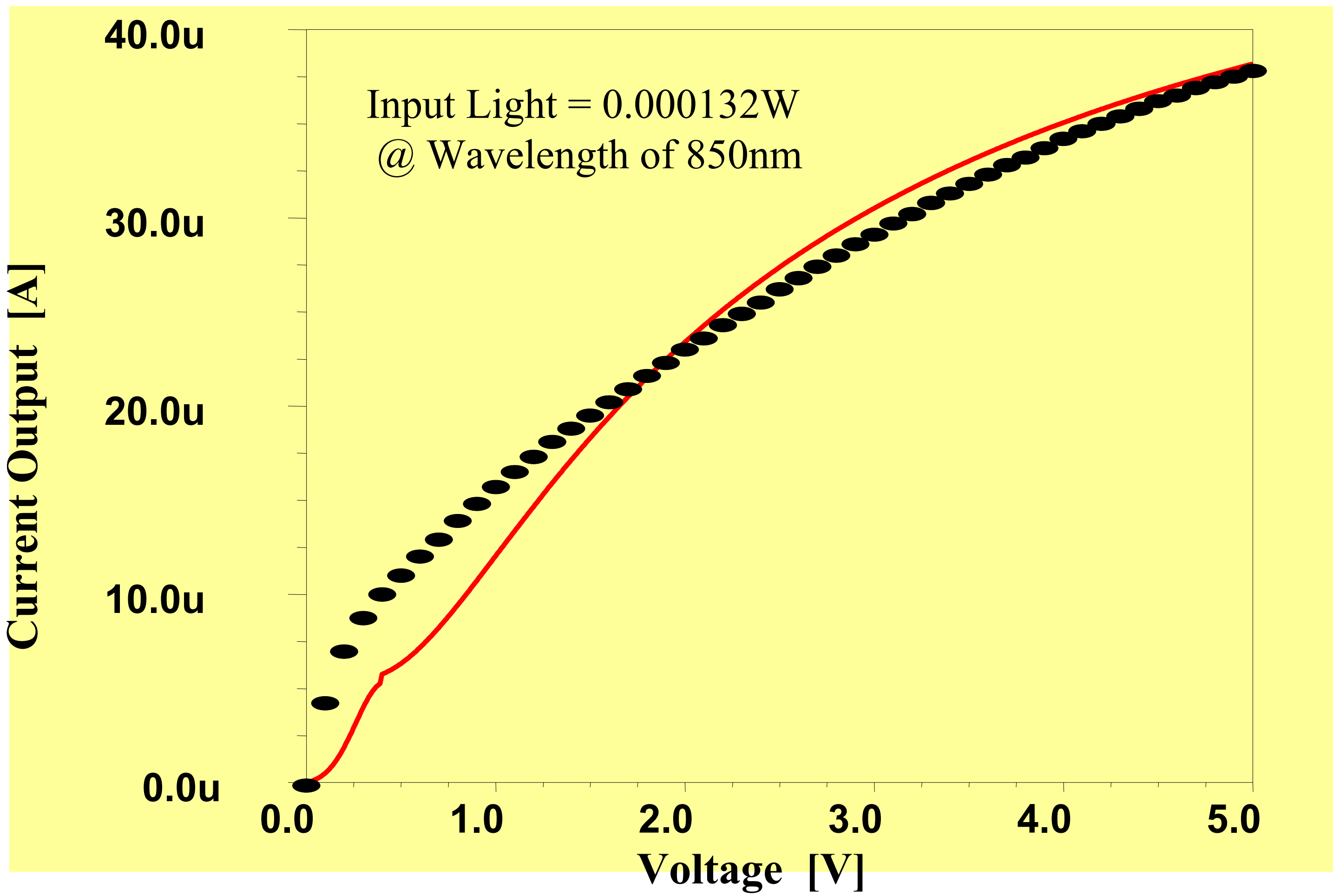


Photo Current Simulation versus Experiment

Parameters of the MSM structure

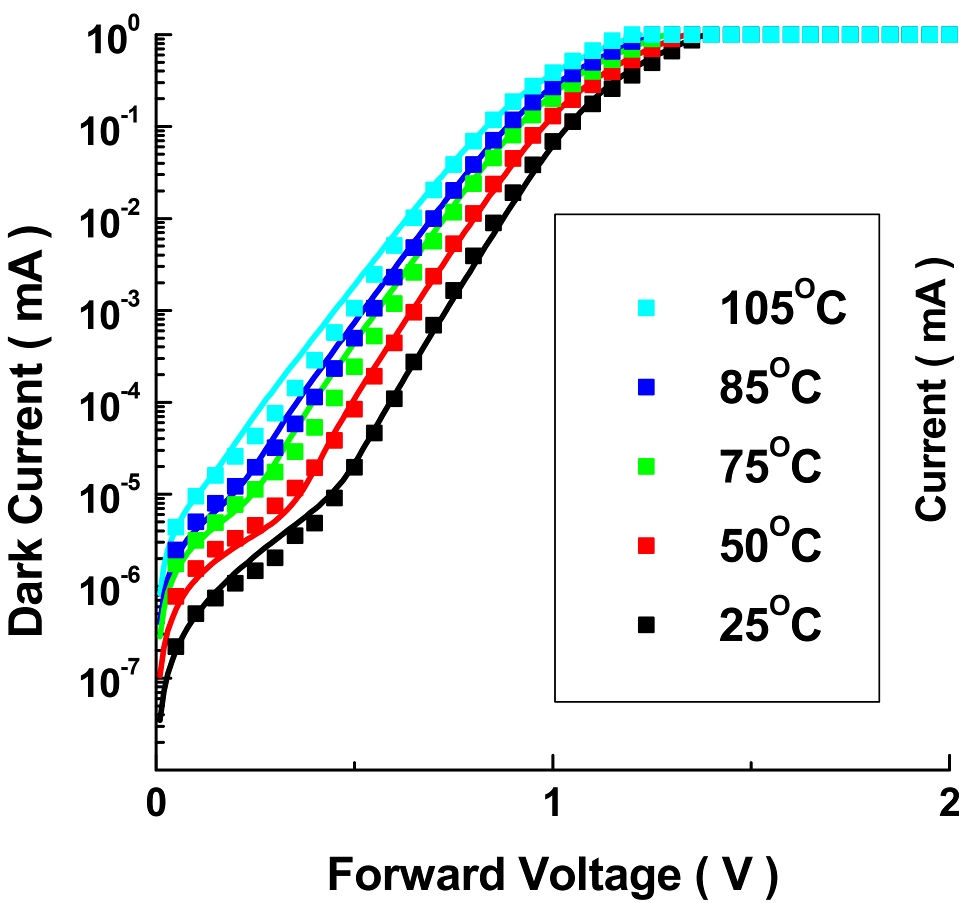
Notation	Parameters	Unit	Values in the model
I_{e0}	Saturation Current	A	3.5×10^{5}
$\alpha\varepsilon$	α is barrier lowering factor, ε is mixed relative permittivity	-	1.2
n	Potential Barrier Coefficient	V	1.65
d	Finger Spacing	m	2.5×10^{-6}
I_{t0}	Tunneling Current Factor	A	7.9×10^{-9}
B_1	Fitting Parameter	V	0.3567
B_2	Fitting Parameter	V	2
I_0	Fitting Parameter	A	1.2×10^{-7}
A	Fitting parameter	-	9
V_{FB}	Flat Band Voltage	V	0.4
ϕ_B	Potential Barrier	V	0.9
R	Responstivity = I_{ph}/P_{in}	A/W	0.04

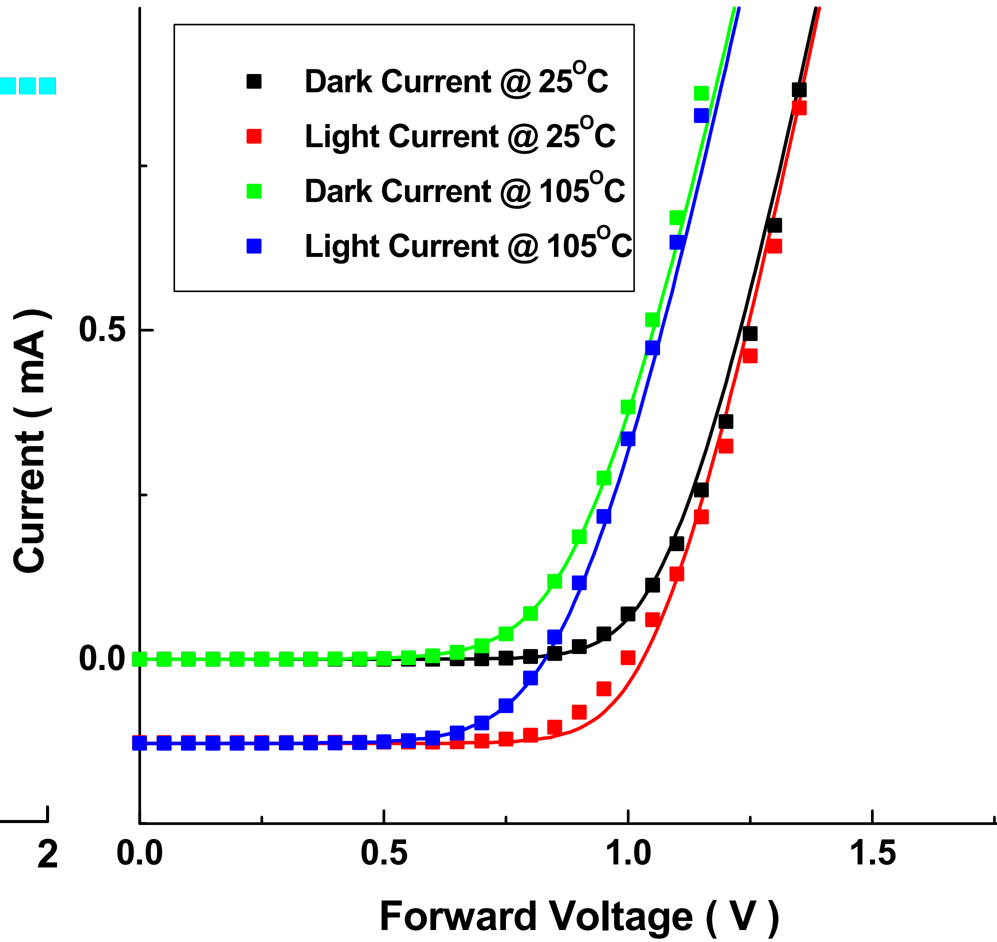
Temperature Model for PIN Photodiode

$$I_{sr}(T) = I_{sr}(T0)\left(\frac{T}{T0}\right)^{xti2} \exp\left(\frac{E_g}{2kn_{r2}}\left(\frac{1}{T0} - \frac{1}{T}\right)\right)$$

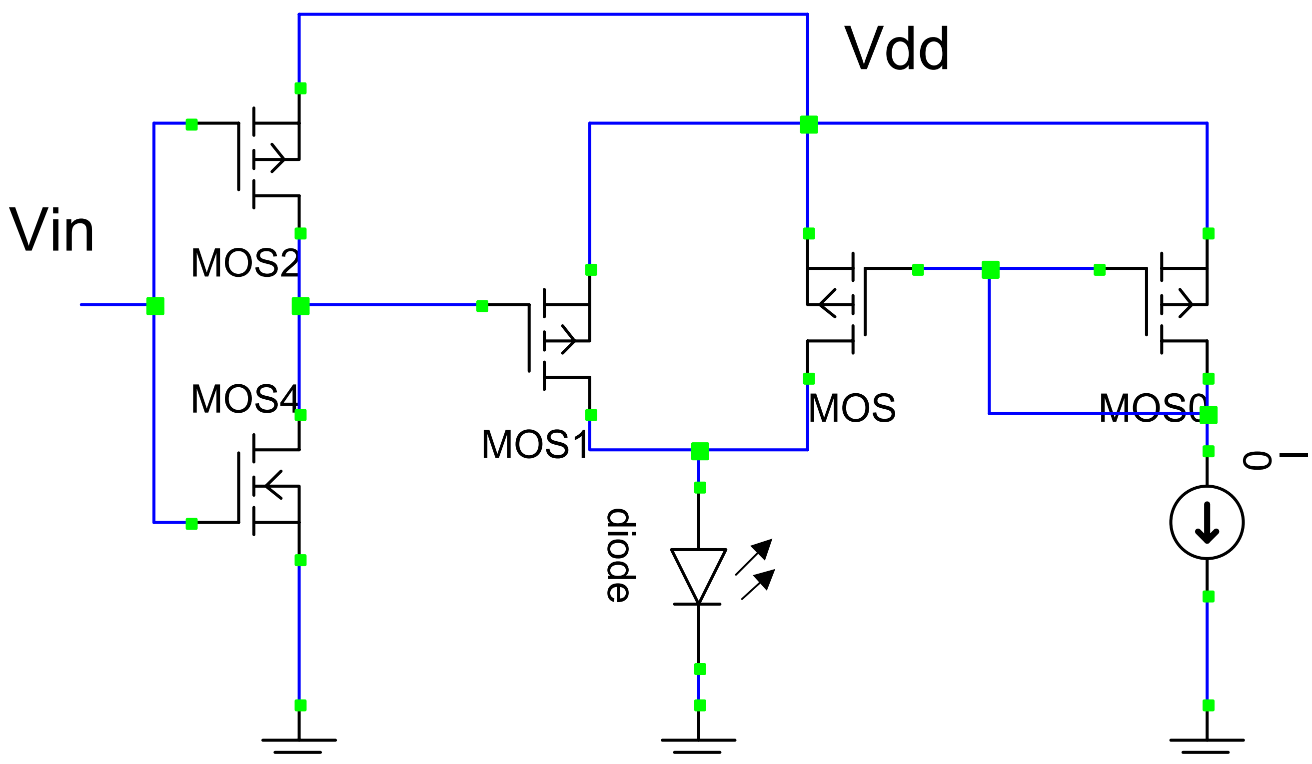
$$n_r(T) = n_r(T0)\left(\frac{T}{T0}\right)^{xti2}$$

PIN Photodiode Model

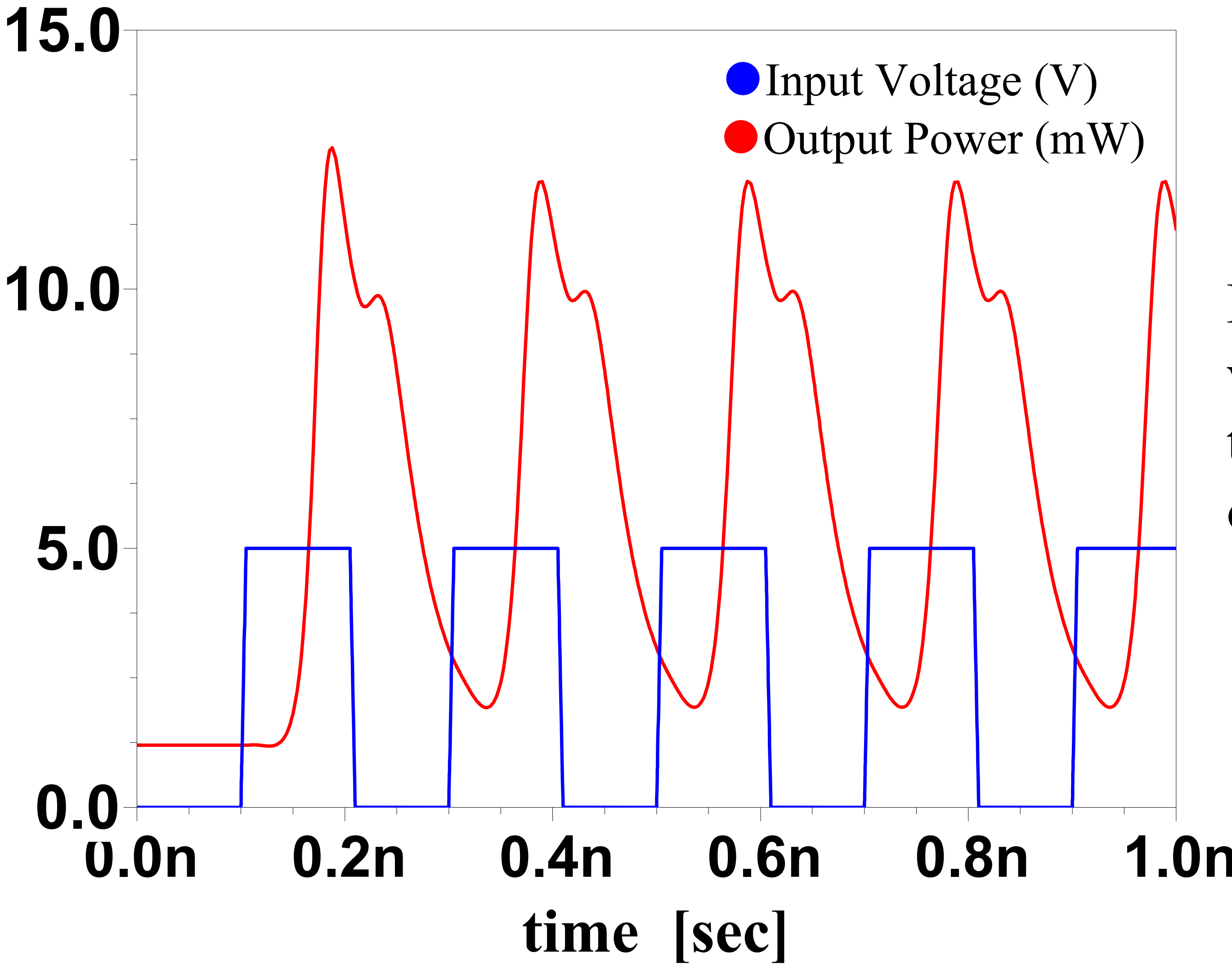




Laser Driver Circuit

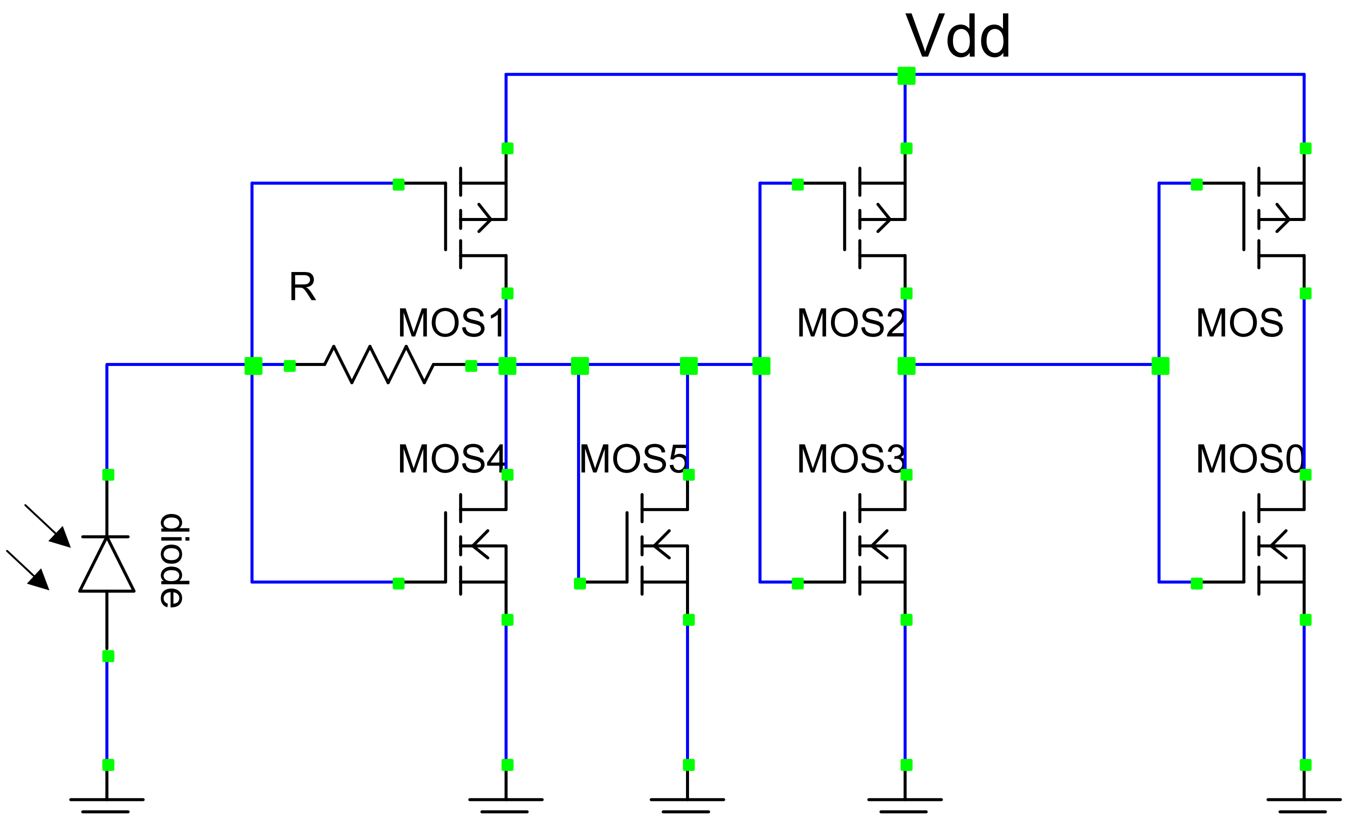


Simulation Results

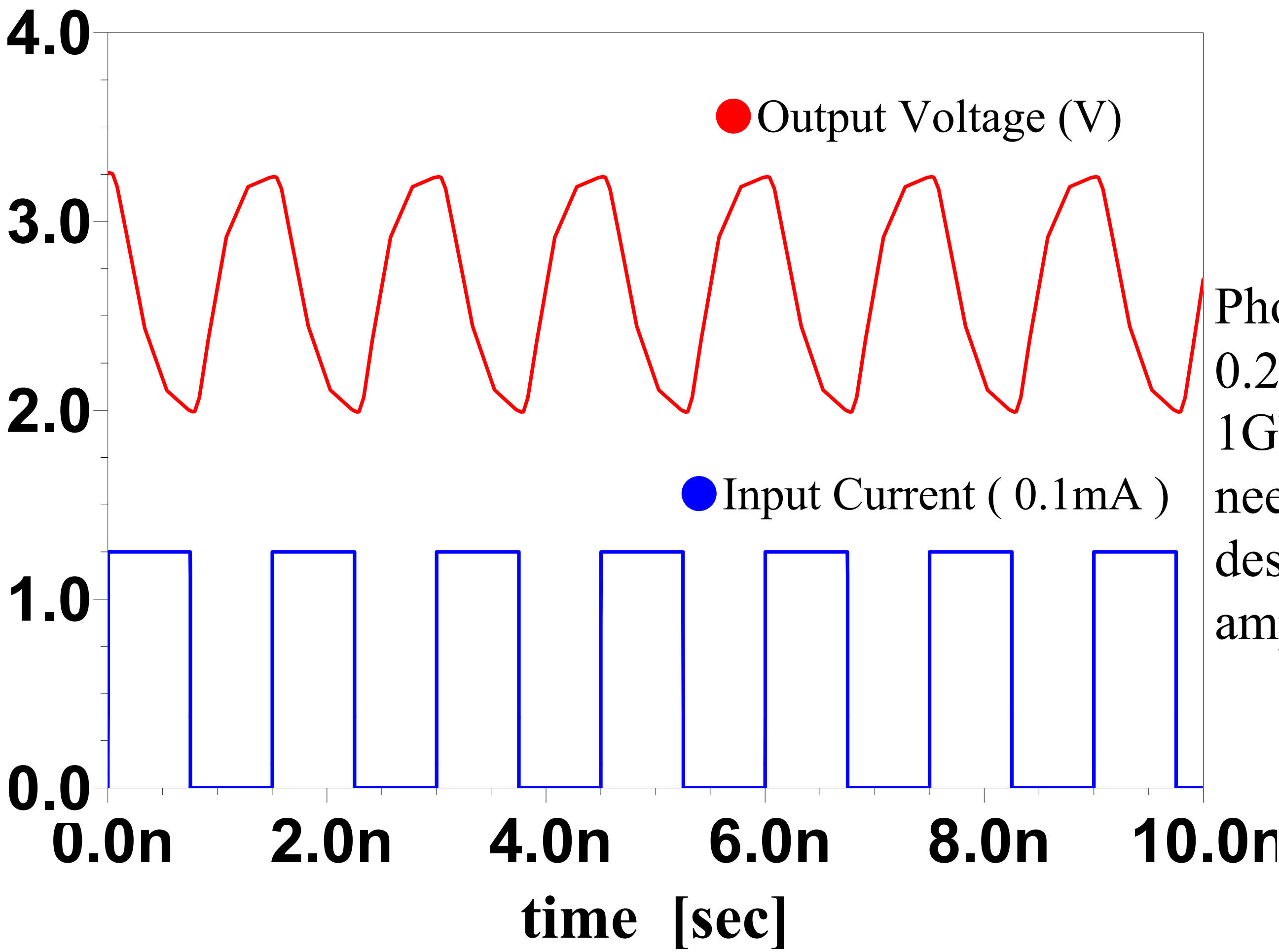


Driver circuit built with 0.25µm CMOS technology, laser operation at 5Gb/s

Optical Receiver Circuit



Receiver Circuit Simulation Results



Photodiode capacitance:0.5p
0.25µm CMOS technology
1Gb/s speed -- improvemen
needed, more effort on the design of transimpedance amplifier

Conclusions

•VCSEL model for Photonic SPICE has been developed. Both pulsed and continuous-wave operation can be simulated, and show satisfactory agreement with experimental results.

•Photo detector MSM model has been developed. Its steady-state behavior has been simulated.

•PIN photodiode model for temperature range up to 100^{o}C

•Laser driver and optical receiver circuits simulated to test the models

Future Work

- Parameter extraction and model maintenance & improvement for optoelectronic VLSI testability, characterization and design optimization
- Photonic SIM-Spice CAD tool validation for mixed electronic/photonic circuits.
- Waveguide simulation, including waveguides on silicon and incorporation into photonic AIM-Spice.
- Stray light/cross talk effect modeling and simulation

Publications

[1]. J. Deng, M. S. Shur, T. A. Fjeldly, S. Baier, "CAD Tools and Optical Device Modeling for Mixed Electronic/Photonic VLSI", International Journal of High Speed Electronics and Systems, Vol. 10, No. 1 (2000), 299-308

[2]. J. Deng, M. S. Shur, T. A. Fjeldly, S. Baier, T. Ytterdal, SPICE Modeling for Mixed Electronic/Photonic VLSI, accepted abstract for URSI 1999

[3]. J. Deng, M. S. Shur, T. A. Fjeldly, S. Baier, T. Ytterdal, SPICE Modeling for Mixed Electronic/Photonic VLSI, accepted extended abstract for SRC Techcon 2000

[4]. A paper for optical circuits simulation is in preparation