SAND2009-2664P

Control for an Optically Powered Firing Set Using Miniature Photovoltaic Arrays

Master of Science
Electrical Engineering
Thesis Presentation
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May 8, 2009

Acknowledgements

-Thesis Committee Members

-Sandia colleagues

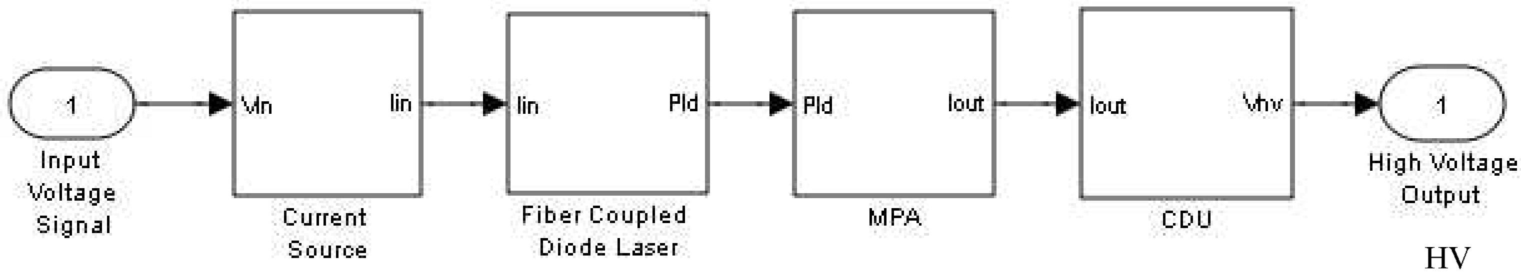
-Editor

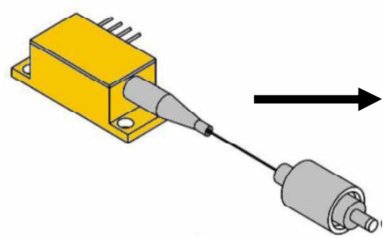
Thank You!

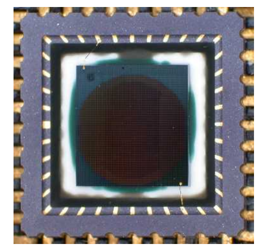
Thesis Presentation
Outline

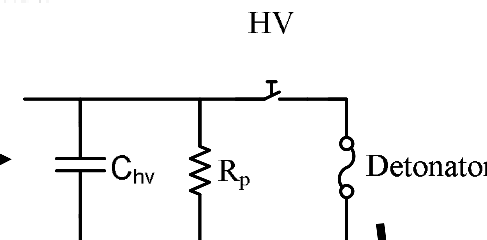
1. Objective & Requirements
2. Firing Set Design
3. Optical Powered FS Modeling
   1. Electrical
   2. Thermal
4. Optically Powered FS Verification
   1. Electrical
   2. Thermal
5. Control Solution
6. Recommendations
7. Conclusion

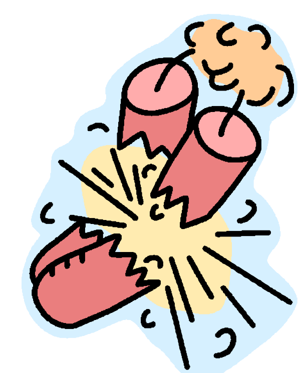
Background/Overview











Common Acronyms

MPA = Miniature Photovoltaic Array

CDU = Capacitive Discharge Unit

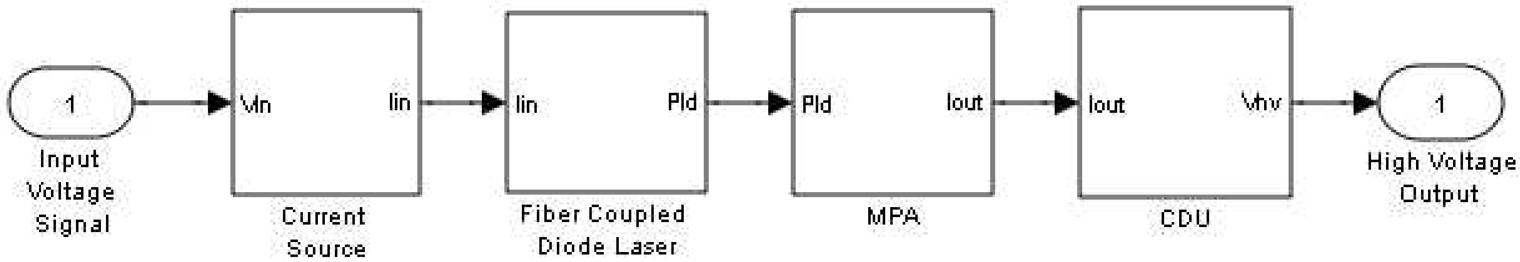
HV = High Voltage

LD = Diode Laser

FS = Firing Set

Objective

1. Control the HV output state of the CDU
2. Model the optically powered firing set (electrical, thermal, optical)
3. Minimize temperature of MPA and LD
4. Adjustment of HV output state



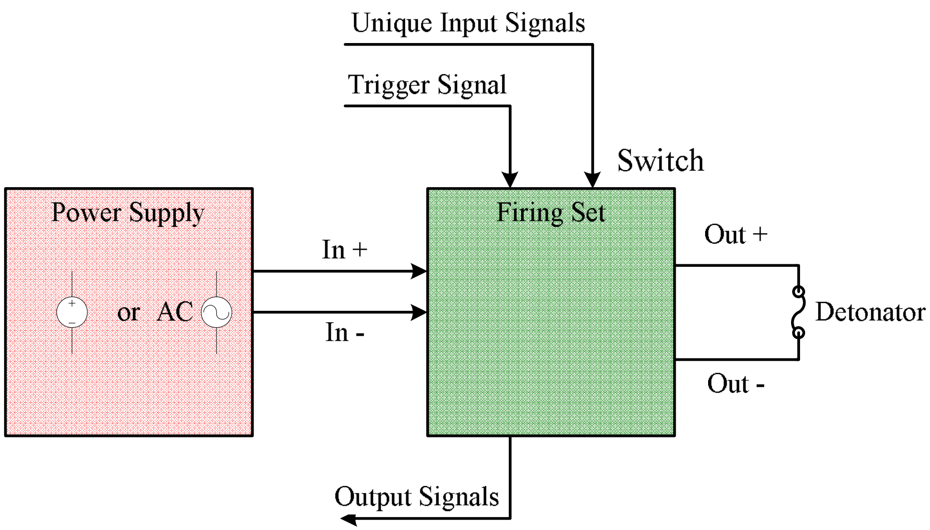
Requirements

- The system shall regulate the output voltage to a predetermined level of 1500 V with 3% regulation ripple (1525 V– 1475 V) and a rise time of less then 5 seconds.
- The system shall have the ability to adjust the output voltage level.
- The system shall regulate for a minimum of 5 seconds and a maximum of 30 seconds.
- The system shall minimize thermal heating of the MPA during regulation.
- The system shall minimize thermal heating of the 3 W fiber coupled laser diode during regulation.
- The number of electrical and mechanical components shall be minimized.

General Firing Set

What is a firing set?

- Deliver high power signal to a detonator
- 3 Types
  1. Electrical
     1. CDU
     2. Cable Discharge
  2. Optical
     1. Optically Coupled
     2. Laser Ignition
     3. Laser Initiation
  3. Explosive
     1. Ferroelectric
     2. Slim loop Ferroelectric
     3. Ferromagnetic
     4. Compressed Magnetic Field
- Initiate detonator in a safe and reliable manner only when intended



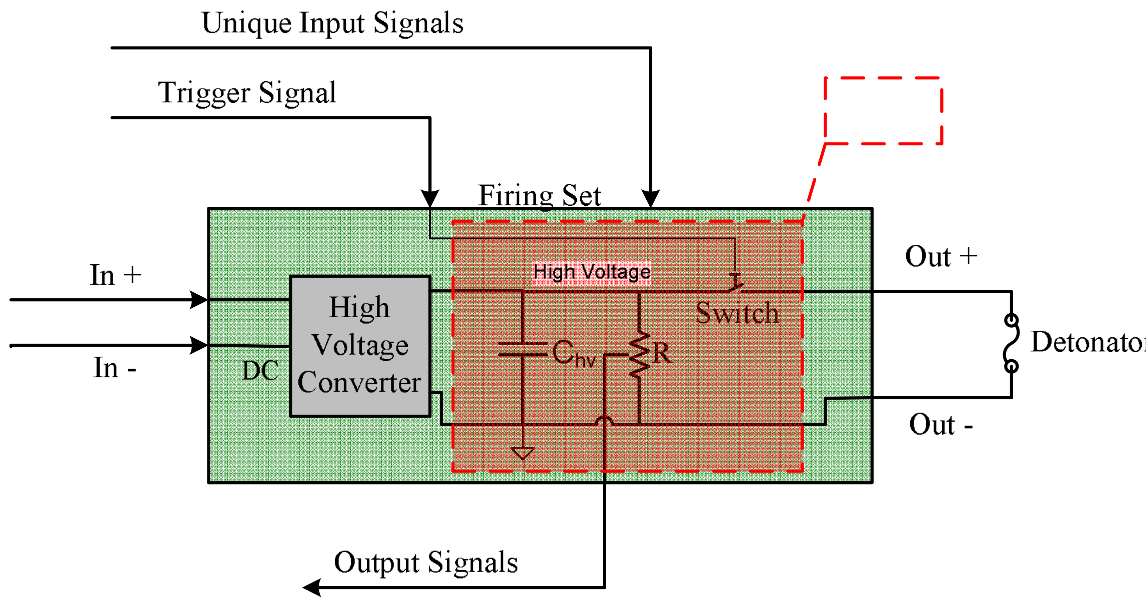
Electrical Firing Sets with CDU

Components

1. **HV Voltage Converter**
   1. **DC-to-DC**
      1. **Flyback converters**
      2. **Push-pull converters**
   2. **AC-to-DC**
2. **CDU**
   1. **HV capacitor**

$$E = \frac{1}{2} C V^2$$

   2. **Resistor**
   3. **HV switch**



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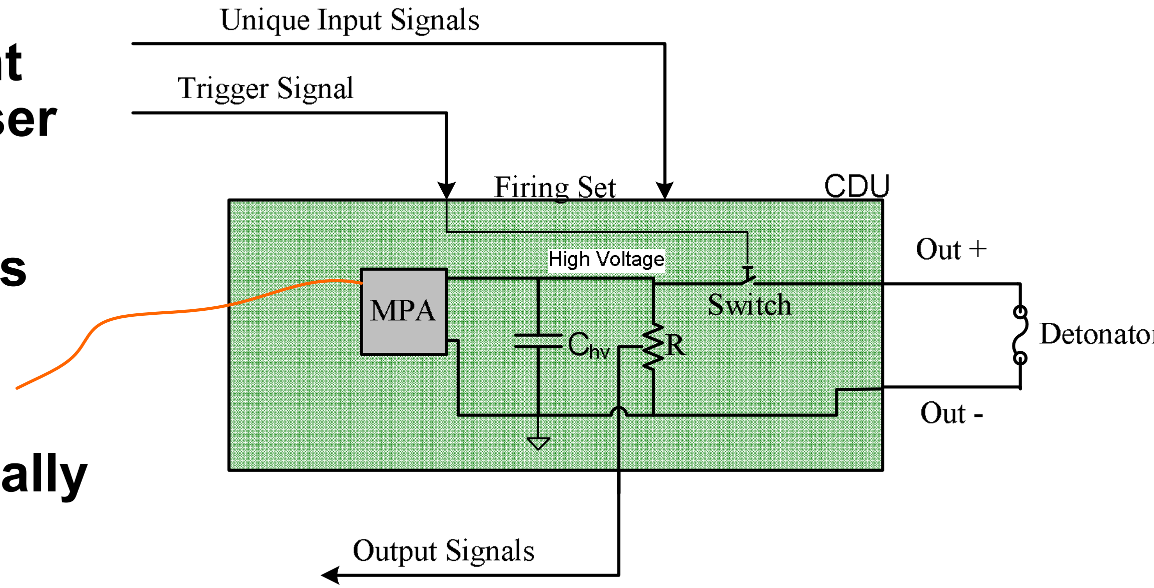
Optically Powered Firing Set

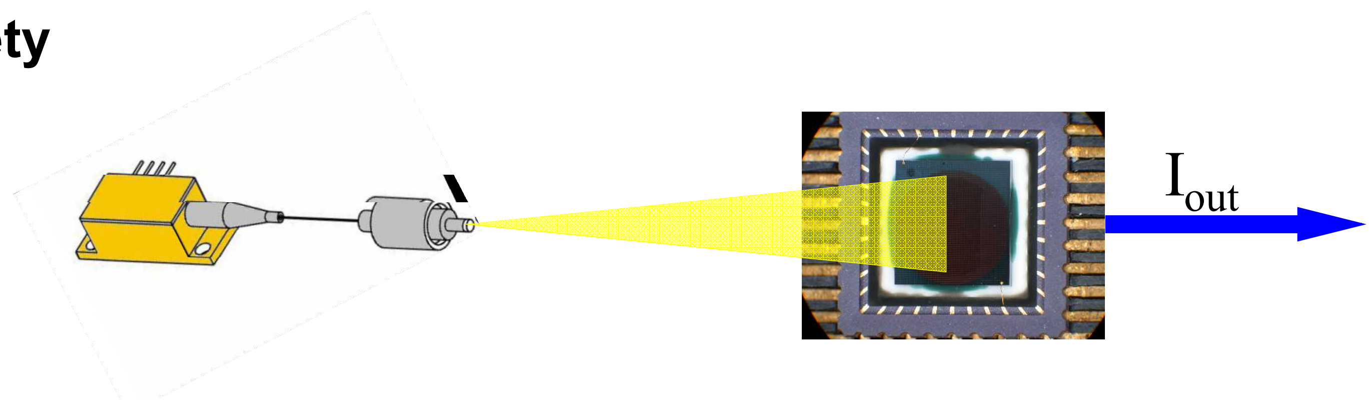
- **Power source is the light energy from the diode laser**

- **High voltage converter is replace by the MPA.**

- **Power source is electrically isolated from CDU**

- **Enhanced Safety**





CDU Components

Mass

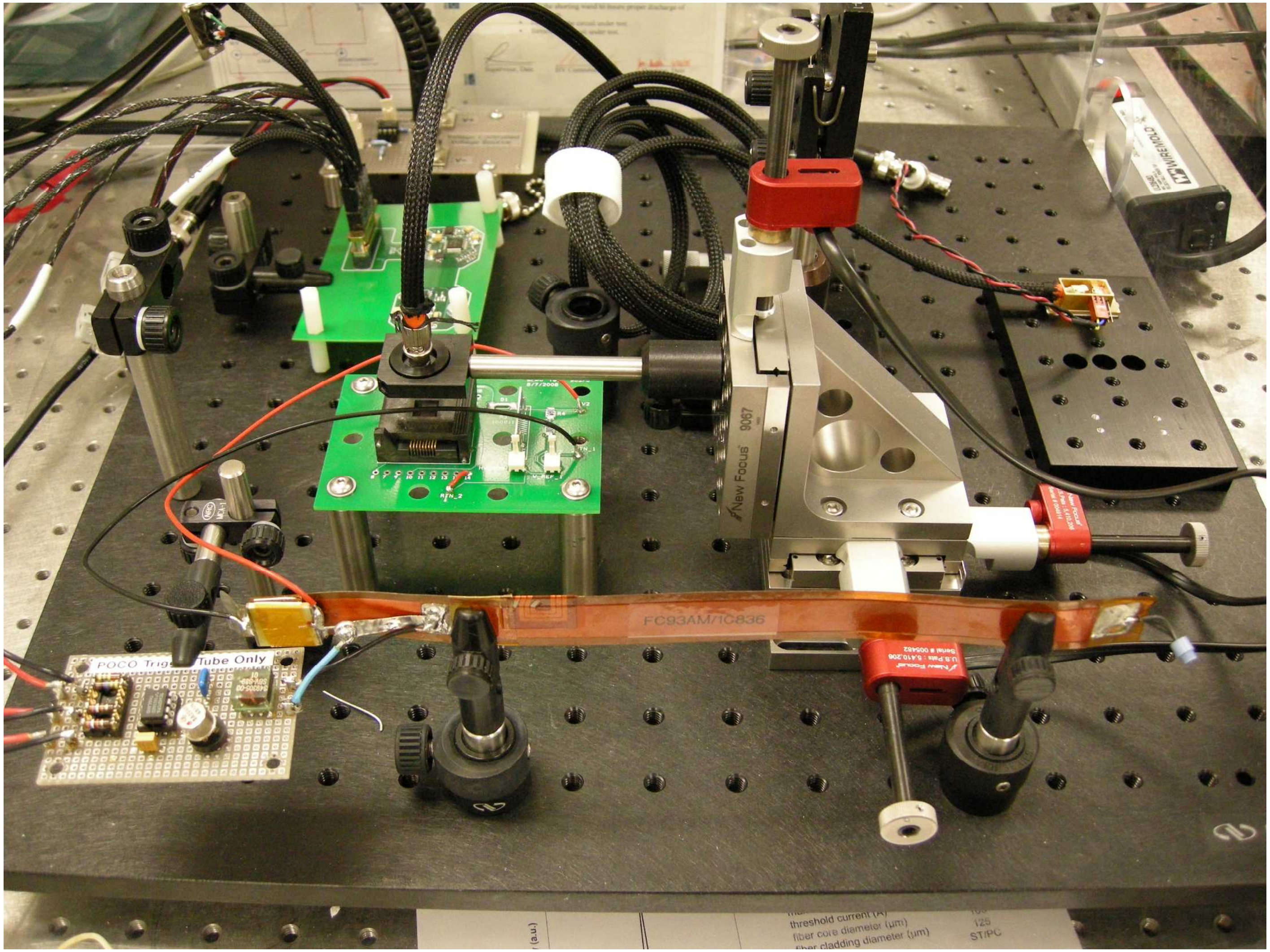
MPA = 0.45g

Small Flyback

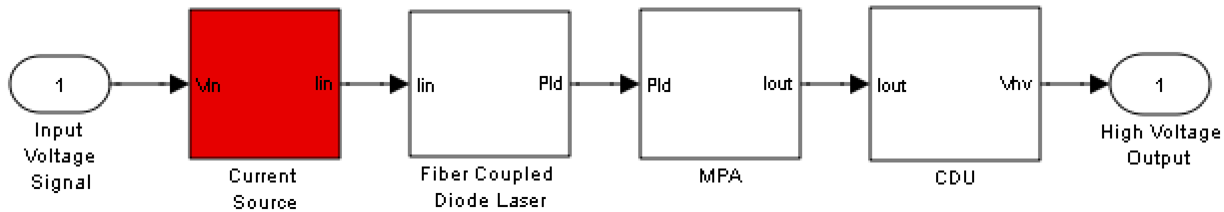
XFMR = 1.21g

Small Cap = 11.54g

Optically Powered Firing Set Experimental Setup



Electrical Modeling – Current Source



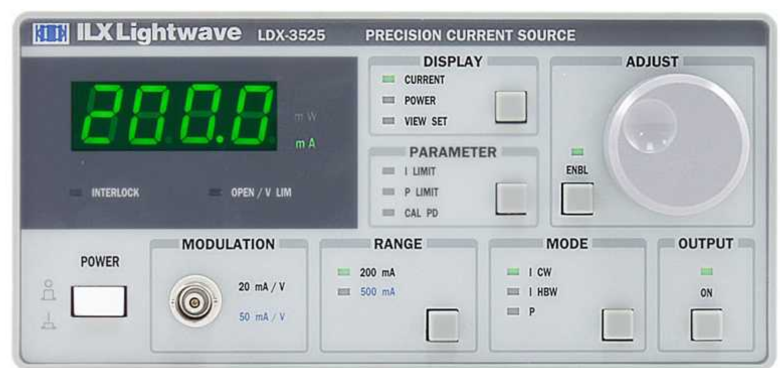
- **ILX Lightwave LDX-3565 Precision Current Source**

- **0 – 6 A**

- **Modulation Transfer function**

$$600\frac{mA}{V}$$

- **Transfer function accuracy ±10%**



Electrical Modeling
Semiconductor Physics

1. **Background**

- **Schrödinger's equation describes the motion of a particle**

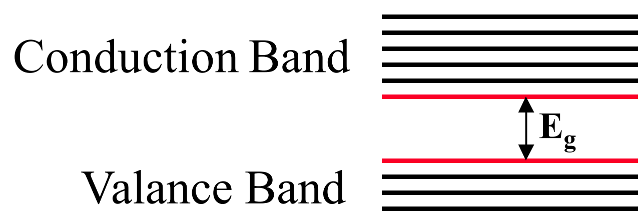
$$\frac{\hbar^2}{2m}\nabla^2\Psi + VZ = i\hbar\frac{\partial\Psi}{\partial t}$$

- **Solving it we can find the wave functions and energy levels of the system.**

2. **Each material has a distinct bandgap structure**

- **When bonds between atoms are formed to make a semiconductor, the uppermost energy levels of atoms each broaden into bands of levels. These bands are a collection of different electron energy levels.**

- **Bands in red dominate the electrical properties of the semiconductor**



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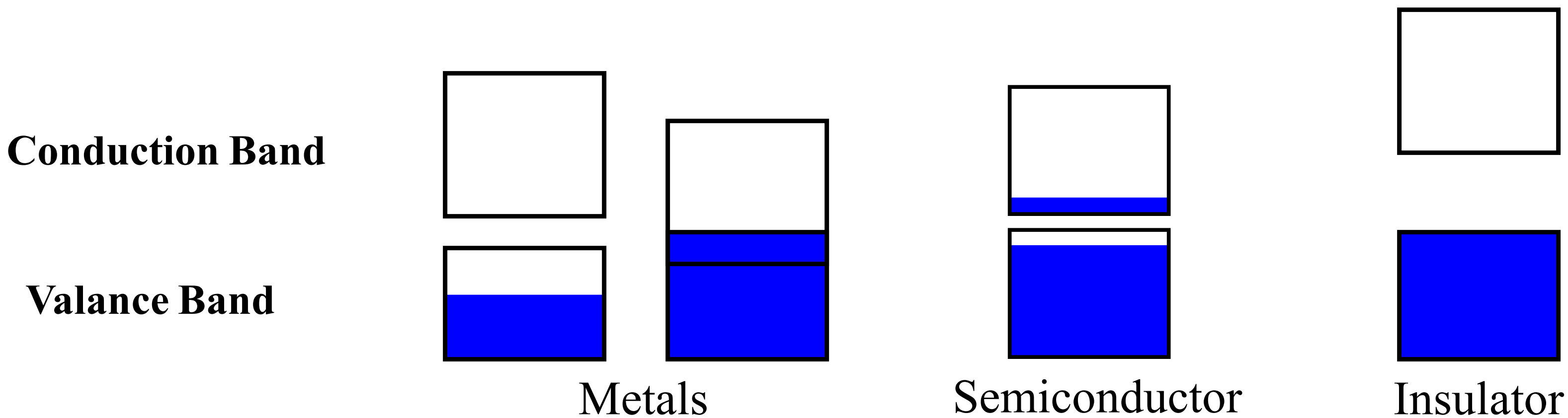
Electrical Modeling
Semiconductor Physics

1. **How are the bands filled?**



2. **Semiconductor band structure**

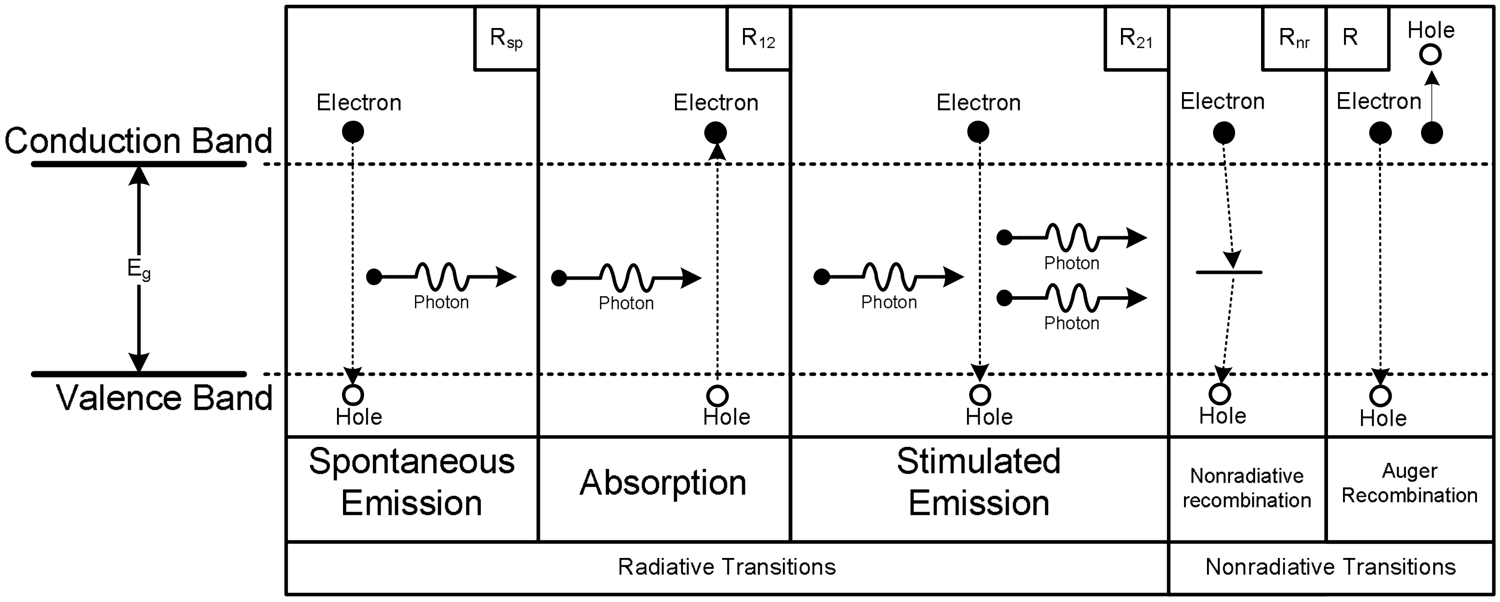
- **Valance band is almost completely filled**
- **Conduction is almost empty**
- **For analysis of practical laser operation we will assume single band for conduction and valance bands**

Electrical Modeling
Semiconductor Physics

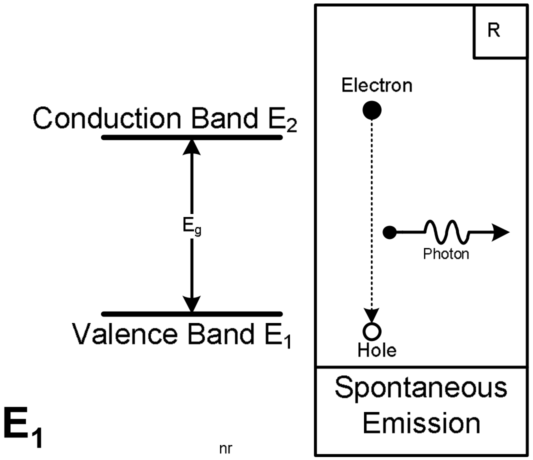
Electronic Transitions and interactions with light

1. **Spontaneous Emission**
2. **Absorption**
3. **Stimulated Emission**

Optical Fiber



Electrical Modeling
Semiconductor Physics



1. Spontaneous Emission

- **Recombination of electron-hole = emission of photon**
- **LED**
- **Emission random in direction, phase, time**
- **Need hole at E_1 and electron at E_2 simultaneously**
- **Transition rate is product of electron density at E_2 and E_1**

$$R_{sp} = AD(E_2)f(E_2,T)D(E_1)[1-f(E_1,T)]$$

Density of electronic states

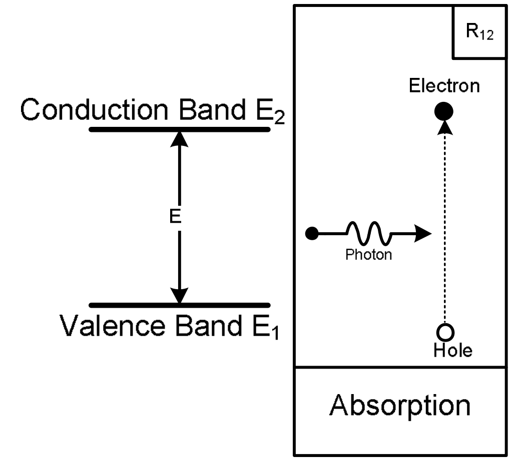
Fermi Function – probability that they are occupied by electrons

- **Simplified when emission happens in undoped active region**

$$R_{sp} = N^2 B$$

Bimolecular recombination coefficient

Electrical Modeling
Semiconductor Physics



2. Absorption

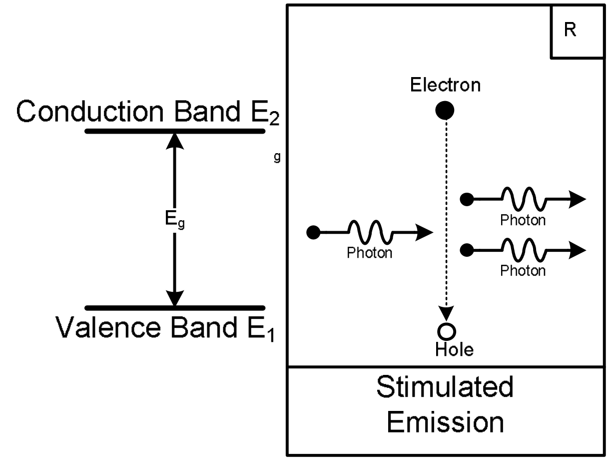
- Photon absorbed in semiconductor material
- Stimulates generation of an electron to the conduction band and leaving hole in valance band
- 3 particle process
- Transition rate is product of three densities

$$R_{12} = B_{12}\underbrace{D(E_2)\left[1 - f(E_2,T)\right]}_{\substack{\textbf{Density of non-occupied}\\ \textbf{states in conduction band}}}D(E_1)f(E_1,T)\rho(\hbar w)$$

Density of photons

Electrical Modeling
Semiconductor Physics

3. **Stimulated Emission**
   - **Photon disturbs the system and stimulates the recombination of an electron and hole.**
   - **New photon is generated with same phase and direction of incident photon**
   - **Net of 2 photons – called "optical amplification"**
   - **Transition rate product of three densities from 3 particles**



$$R_{21} = B_{21} D(E_1)\left[1 - f(E_1, T)\right] D(E_2) f(E_2, T) \rho(\hbar w)$$

Electrical Modeling
Semiconductor Physics

1. **Non-radiative transitions**
   - **Recombination at point defects, surfaces, and interfaces in active region**

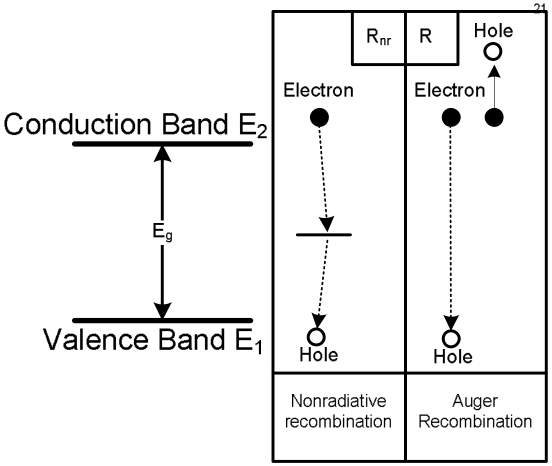
$$R_{nr1} = AN$$

   - **Auger recombination: electron to hole recombination energy is transferred to an electron in the form of kinetic energy**

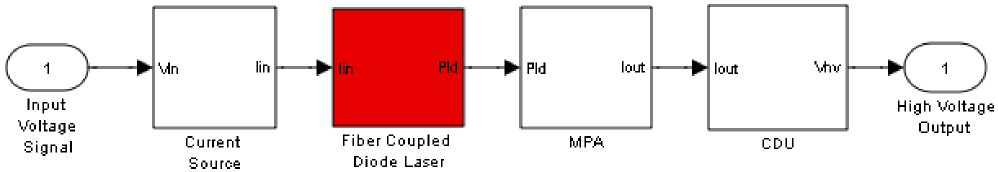
$$R_{nr2} = CN^3$$

   - **Total effect**

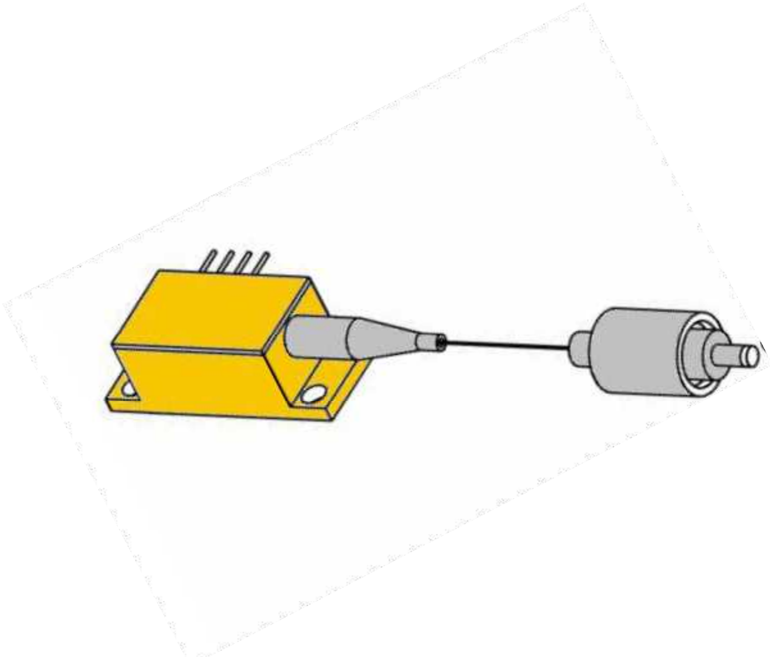
$$R_{nr} = AN + CN^3$$



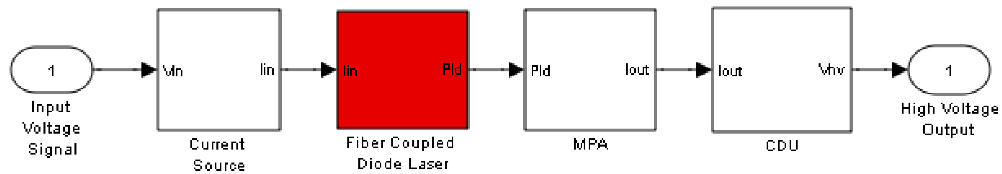
Electrical Modeling – Diode Laser General Info



- 3 Watt Jenoptik & Unique Mode
  - 808 nm
  - Fiber coupled
  - 3 W at 4.3 A
  - Broad area edge-emitting

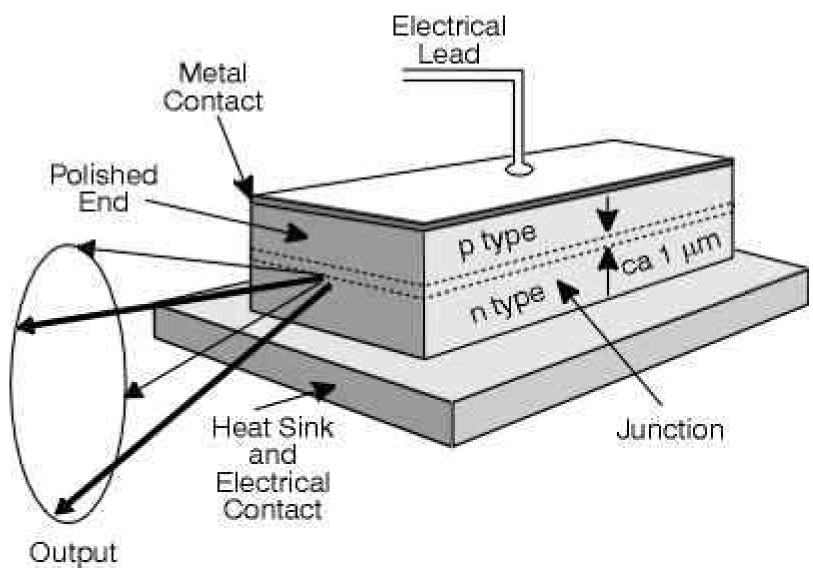


Electrical Modeling – Diode Laser Operation

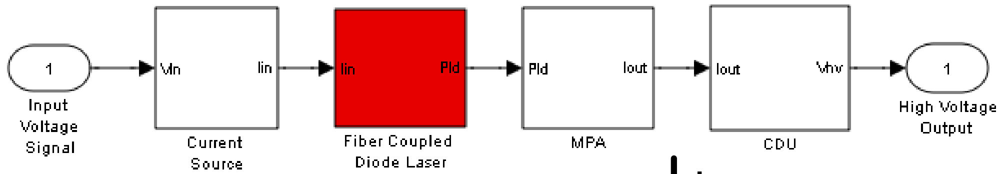


Laser Diode Operation

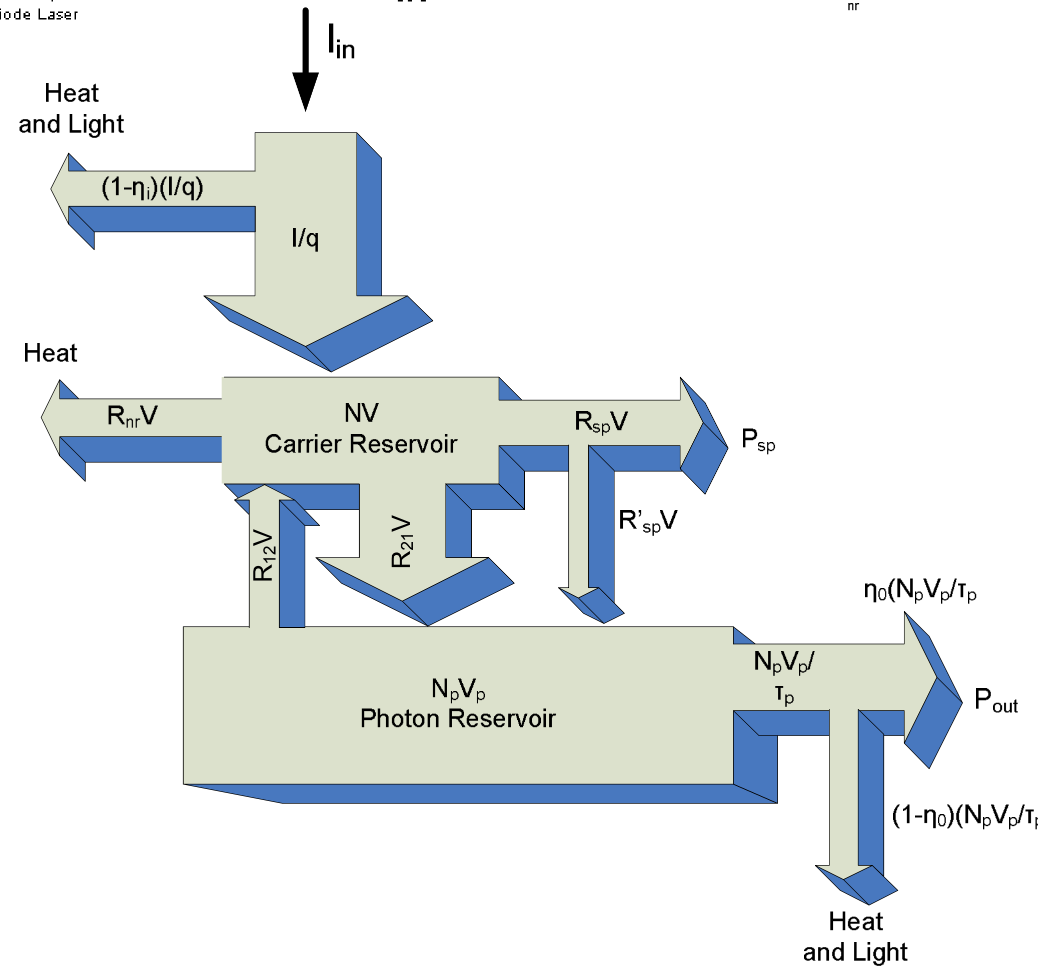
1. Forward bias → Emission of photons (Stimulated Emission)
2. Optical Waveguide and resonator



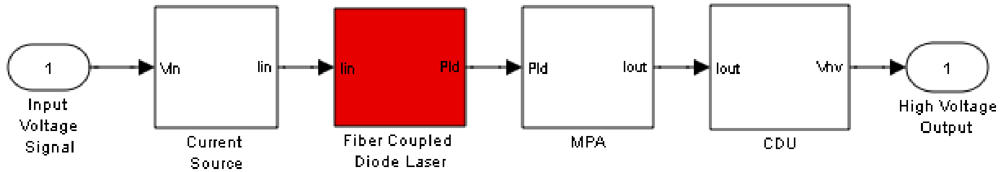
Electrical Modeling – Diode Laser Rate Equation Beginnings



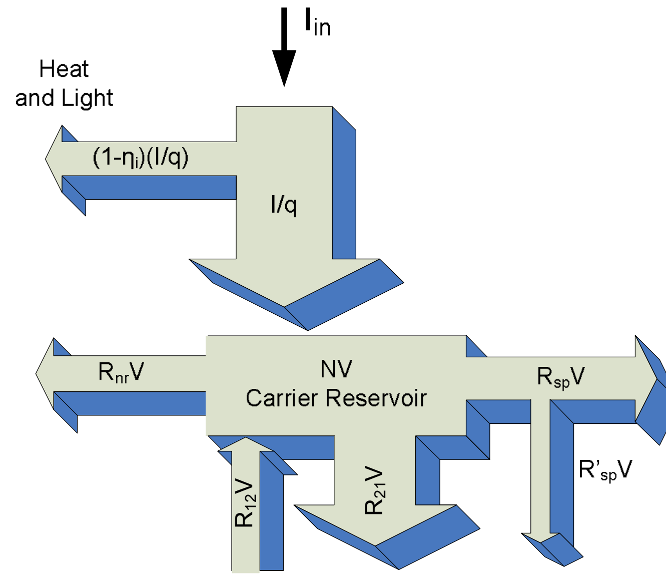
- Reservoir model will be used
- Time variations in N and N_p.
- N = carrier density
- N_p= photon density
- Arrows represent number of particles flowing per unit time
- Rate equations can be made by setting the time rate of change to equal rates going into minus rates leaving reservoir



Electrical Modeling – Diode Laser Rate Equation



1. **Carrier rate equation (single mode model)**
   - **No carrier leakage (R_l)**
   - **η_i = injection efficiency**
   - **V = volume of carrier reservoir**



$$V\frac{dN}{dt}=\frac{\eta_i I_{in}}{q}-(R_{sp}+R_{nr})V-(R_{21}-R_{12})V$$

- **Approximations**

$$(R_{sp}+R_{nr})=\left(BN^2\right)+AN+CN^3\approx\frac{N}{\tau}$$

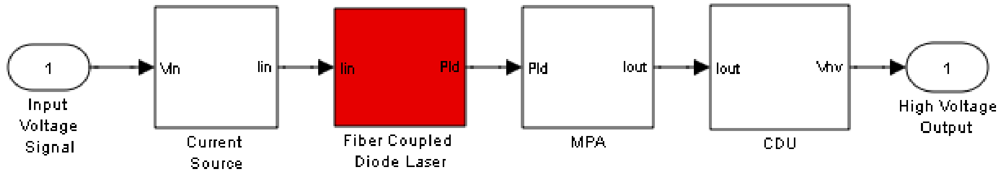
Carrier Decay Process

$$g=\frac{1}{N_p}\frac{dN_p}{dz}=\frac{1}{v_g N_p}\frac{dN_p}{dt}=\frac{(R_{21}-R_{12})}{v_g N_p}\therefore(R_{21}-R_{21})=gv_g N_p$$

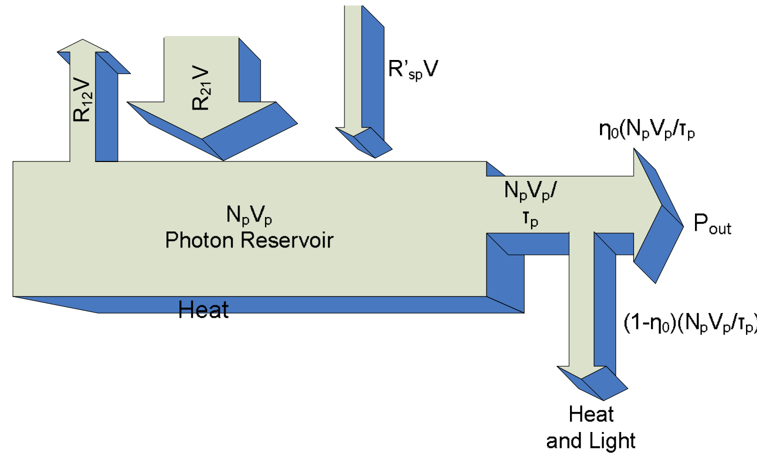
$$g=g_o\ln\left(\frac{N+N_s}{N_{tr}+N_s}\right)$$

$$\boxed{\frac{dN}{dt}=\frac{\eta_i I_{in}}{qV}-\frac{N}{\tau}-v_g g_o\ln\left(\frac{N+N_s}{N_{tr}+N_s}\right)}$$

Electrical Modeling – Diode Laser Rate Equation



2. Photon rate equation



$$V_p \frac{dN_p}{dt} = (R_{21} - R_{12})V - \frac{N_p V_p}{\tau_p} + R'_{sp} V$$

- **Divide out volumes**
- **Approximations**

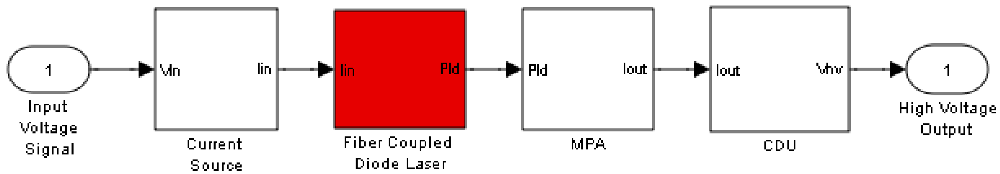
$$g = \frac{1}{N_p}\frac{dN_p}{dz} = \frac{1}{v_g N_p}\frac{dN_p}{dt} = \frac{(R_{21} - R_{12})}{v_g N_p} \therefore (R_{21} - R_{21}) = g v_g N_p$$

$$\Gamma = \frac{V}{V_p}$$

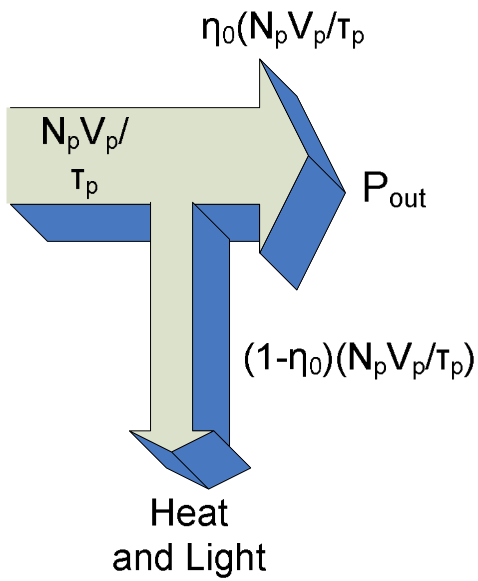
$$g = g_o \ln\left(\frac{N + N_s}{N_{tr} + N_s}\right)$$

$$\boxed{\frac{dN_p}{dt} = \left[\Gamma v_g g_o \ln\left(\frac{N + N_s}{N_{tr} + N_s}\right) - \frac{1}{\tau_p}\right] N_p + \Gamma R'_{sp}}$$

Electrical Modeling – Diode Laser
Final Rate Equation



Total Model



$$\frac{dN}{dt} = \frac{\eta_i I_{in}}{qV} - \frac{N}{\tau} - v_g g_o \ln\left(\frac{N+N_s}{N_{tr}+N_s}\right)$$

$$\frac{dN_p}{dt} = \left[\Gamma v_g g_o \ln\left(\frac{N+N_s}{N_{tr}+N_s}\right) - \frac{1}{\tau_p}\right] N_p + \Gamma R'_{sp}$$

$$P_{ld} = \eta_o h\nu \frac{N_p V_p}{\tau_p}$$

Energy per photon at a specific λ

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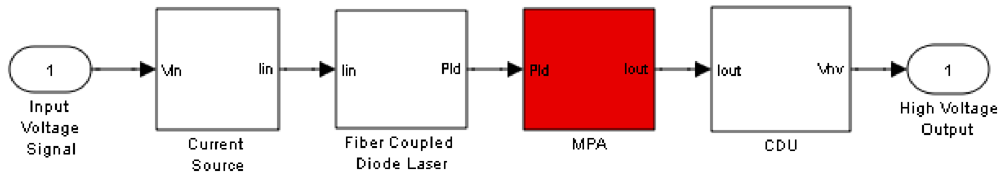
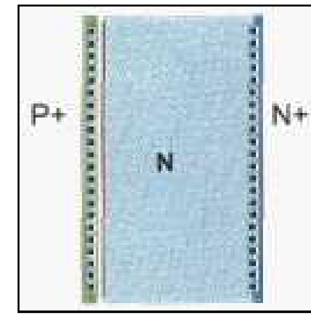
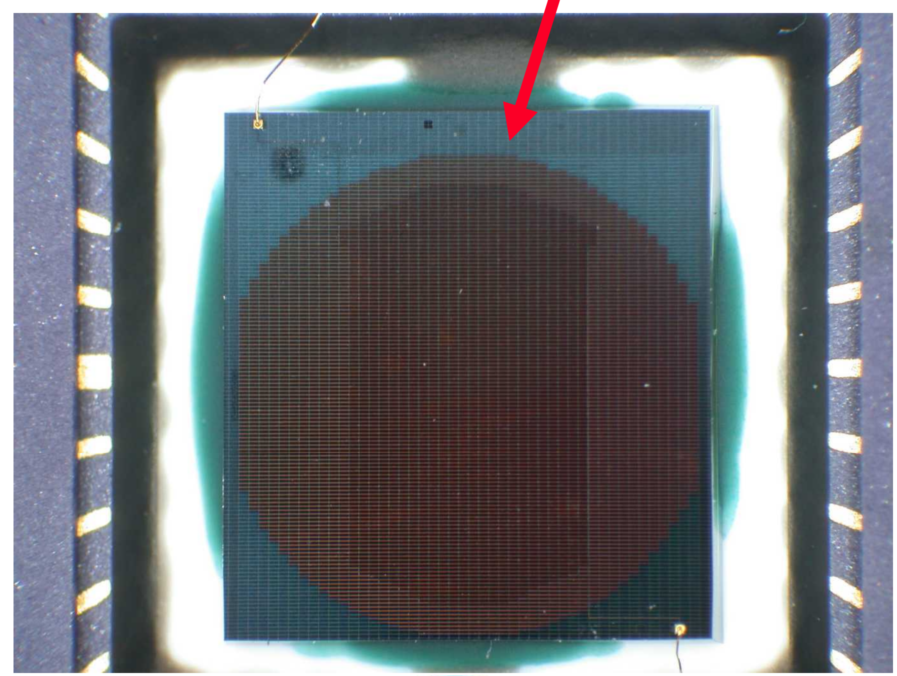
Electrical Modeling – MPA
General Info



1 Cell



x 2400



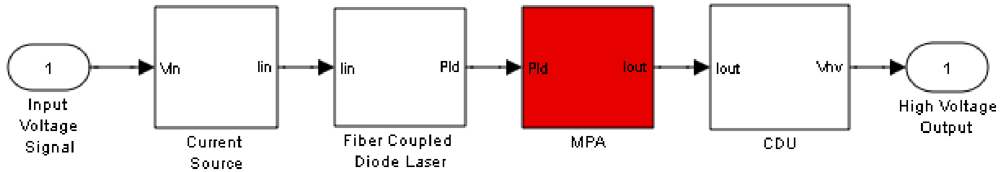
Miniature Photovoltaic Array

- Series connected silicon photovoltaic array
- Built at Sandia National Laboratories' Microelectronics Development Lab (MDL)
- Use Silicon-On-Insulator (SOI) technology

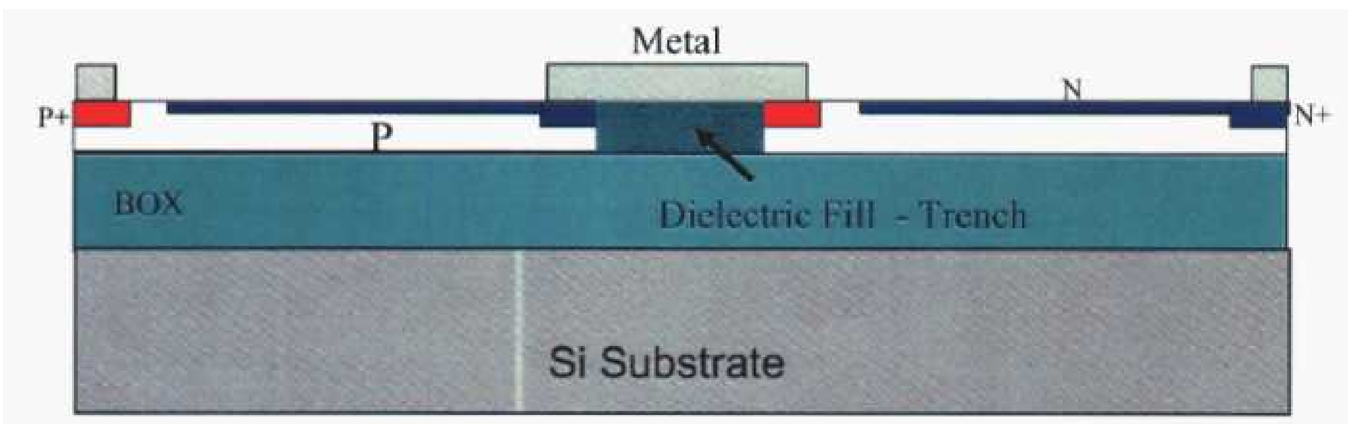
How does it work?

- Current is generated when illuminated by light source

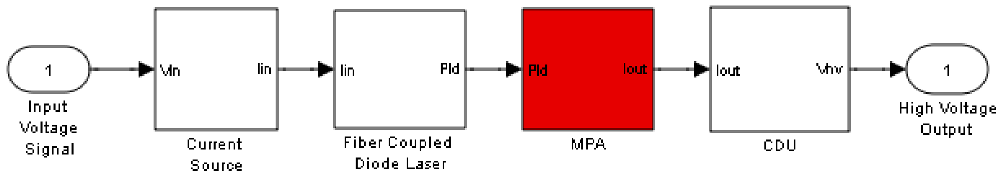
Electrical Modeling – MPA
General Info



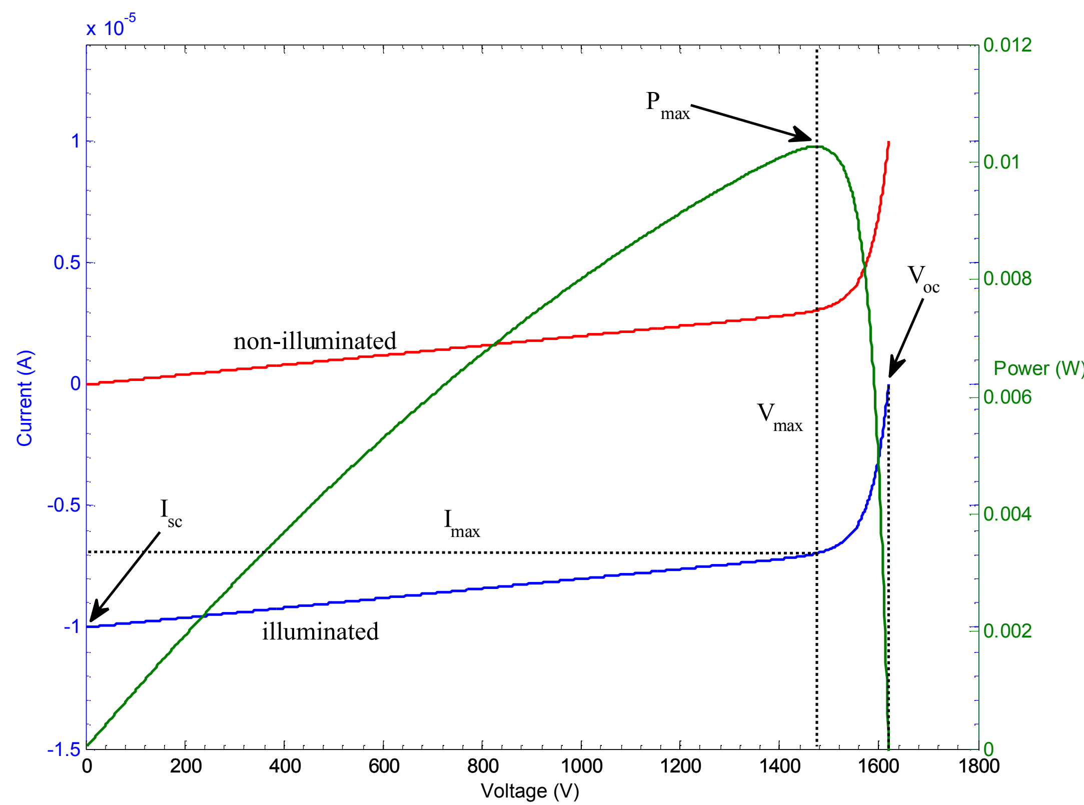
- **Uses the principle of absorption to generate current**
- **Minority Carrier Device**
- **Metal Grid structure is used to provide pathway for electrons**



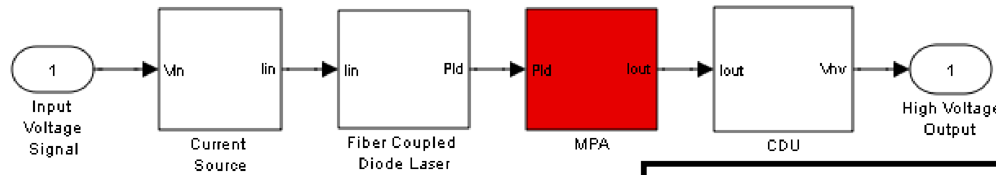
Electrical Modeling – MPA Operation



1. **Device is illuminated**
2. **High current / Low voltage**
3. **Low current / High voltage**



Electrical Modeling – MPA Characteristic Equation



1. **Single Exponential Model of p-n junction - single cell**

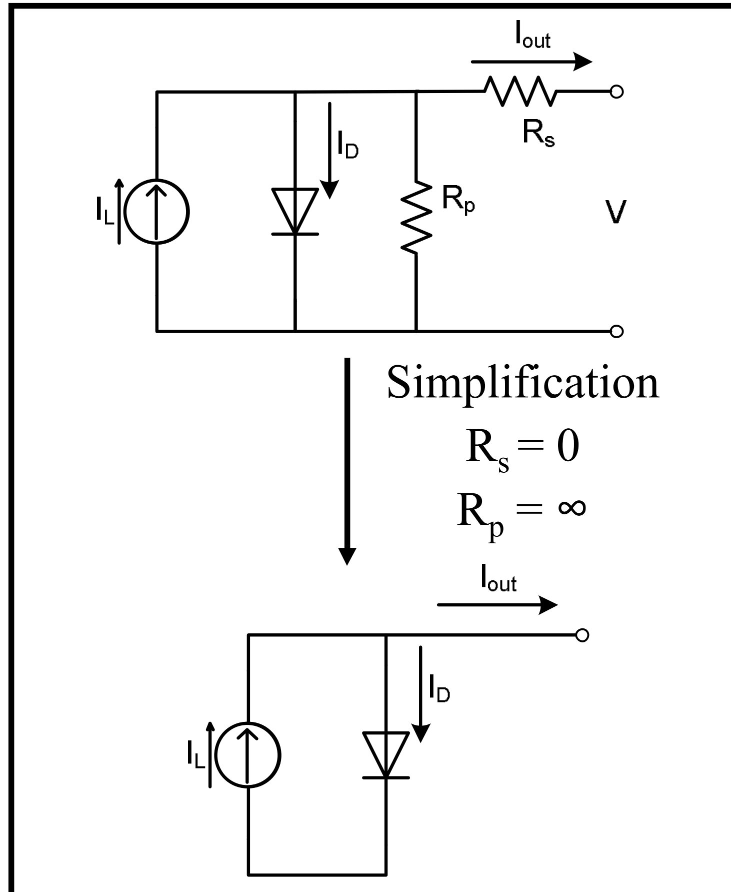
$$I_{OUT} = I_L - I_D$$

- **Shockley ideal diode equation**

$$I_D = I_o\left(e^{\frac{eV_d}{nkT}} - 1\right)$$

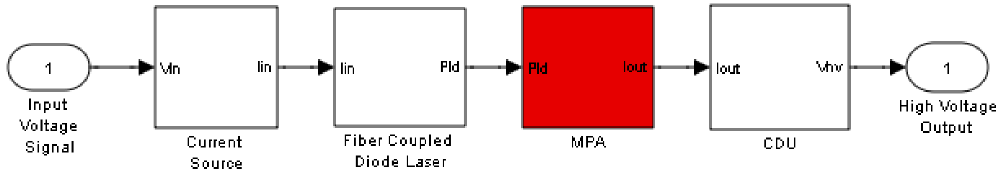
- **Output equation**

$$I_{OUT} = I_L - I_O\left(e^{\frac{eV}{nkT}} - 1\right)$$



Single Exponential Model

Electrical Modeling – MPA Characteristic Equation



2. Double Exponential Model of p-n junction - single cell (backup)

- **Provides better current voltage characteristics of solar cells**

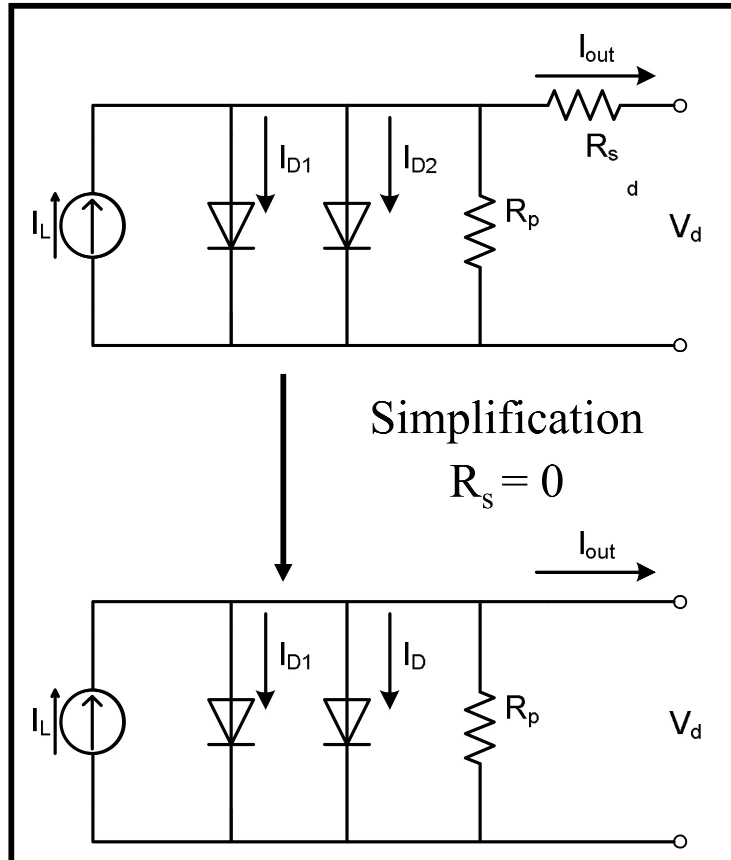
$$I_{OUT} = I_L - I_{D1} - I_{D2}$$

- **Output Equation**

$$I_{OUT} = I_L - I_{O1}\left(e^{\frac{eV_d}{n_1 kT}} - 1\right) - I_{O2}\left(e^{\frac{eV_d}{n_2 kT}} - 1\right) - \frac{V_d}{R_p}$$

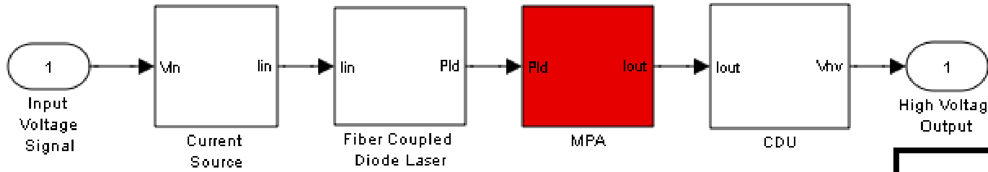
Saturation current due to diffusion mechanism

Saturation current due to recombination in space charge region

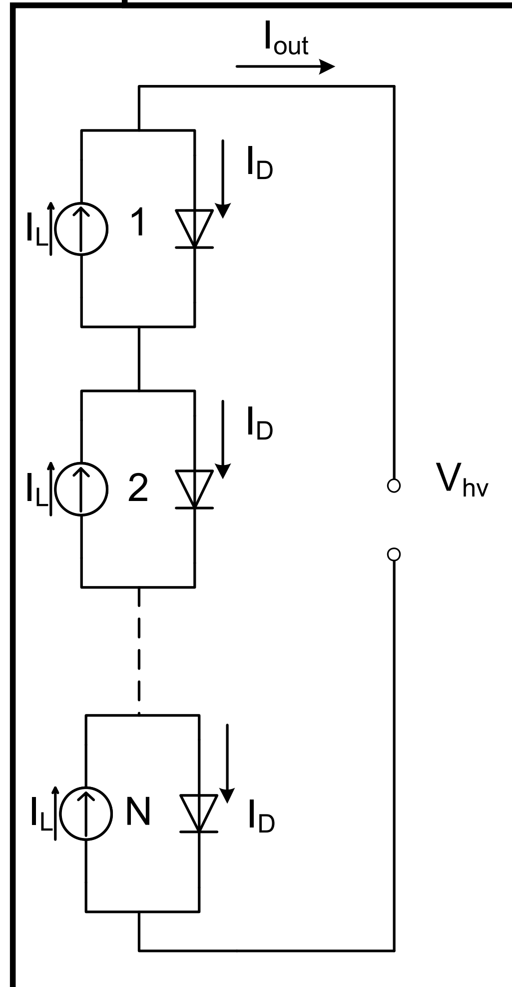


Double Exponential Model

Electrical Modeling – MPA Characteristic Equation



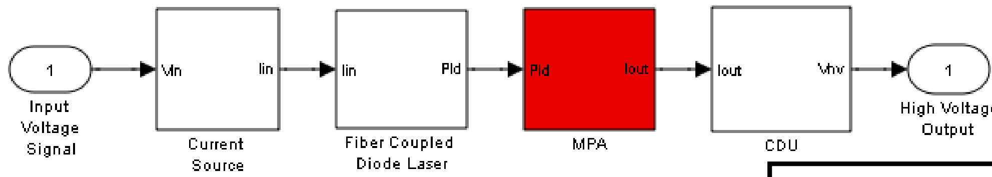
Series Connected Circuit



- **Series Connection of multiple cells**
  - **2400 individual cells on 5 mm device**
  - **All connected in series**
  - **Assumptions**
    - **Identical diode junctions**
    - **All cells are uniformly illuminated**
    - **Single exponential model**
  - **Output Equation**

$$I_{OUT} = I_L - I_O\left(e^{\frac{eV_{hv}}{NnkT_{pv}}} - 1\right) - \frac{V_{hv}}{R_p}$$

Electrical Modeling – MPA
Characteristic Equation & Temperature Effects



Increasing T_{pv} :

$$I_{OUT} = I_L - I_O\left(e^{\frac{eV_{hv}}{NnkT_{pv}}} - 1\right) - \frac{V_{hv}}{R_p}$$

From p-n junction physics

$$I_0 = K_1 T^3 e^{\frac{-qV_g}{kT}}$$

$$I_0 = K_1 T^3 e^{\frac{K_2}{T}}$$

$$I_{OUT} = I_L - K_1 T_{pv}{}^3 e^{\frac{K_2}{T_{pv}}}\left(e^{\frac{eV_{hv}}{NnkT_{pv}}} - 1\right) - \frac{V_{hv}}{R_p}$$

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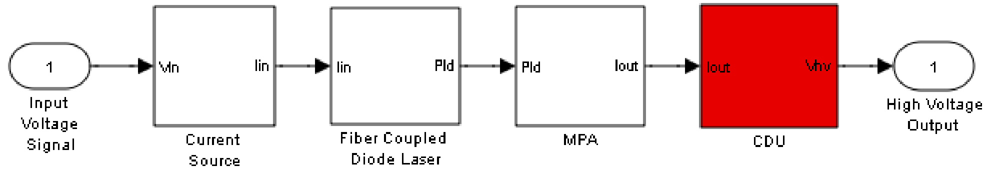
Electrical Modeling – HV CDU General Info

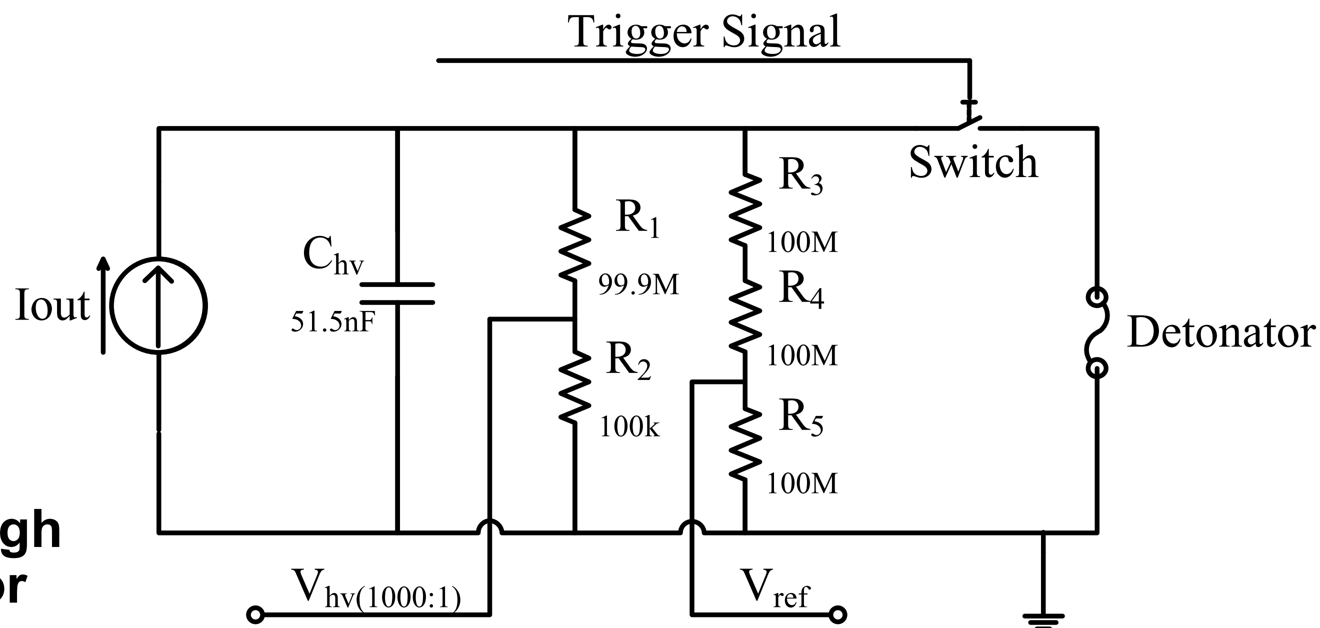


- **MPA provides I_{out}**

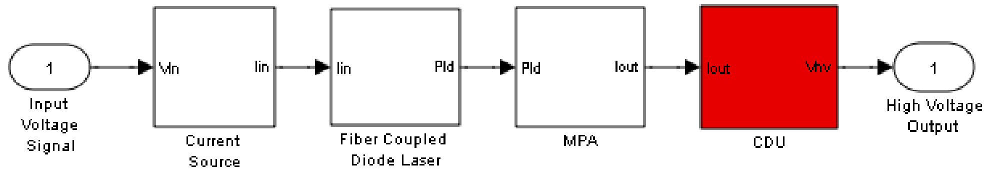
- **Capacitor stores energy**

- **Resistors are for monitoring and bleeding**

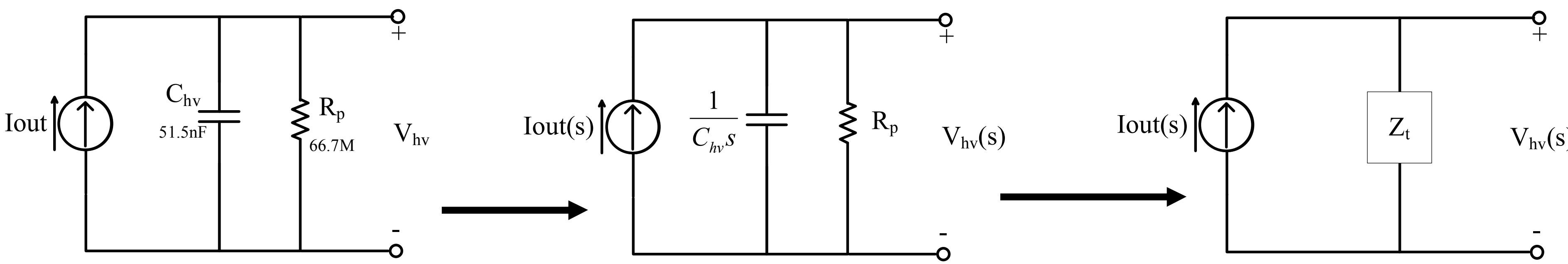
- **Switch used to high energy to detonator**



Electrical Modeling – HV CDU Transfer Function



- HV switch and detonator are not modeled
- Frequency domain – Laplace Transform



$$Z_t = \frac{Z_1 Z_2}{Z_1 + Z_2} \rightarrow Z_t = \frac{R_p \dfrac{1}{C_{HV} s}}{R_p + \dfrac{1}{C_{HV} s}}$$

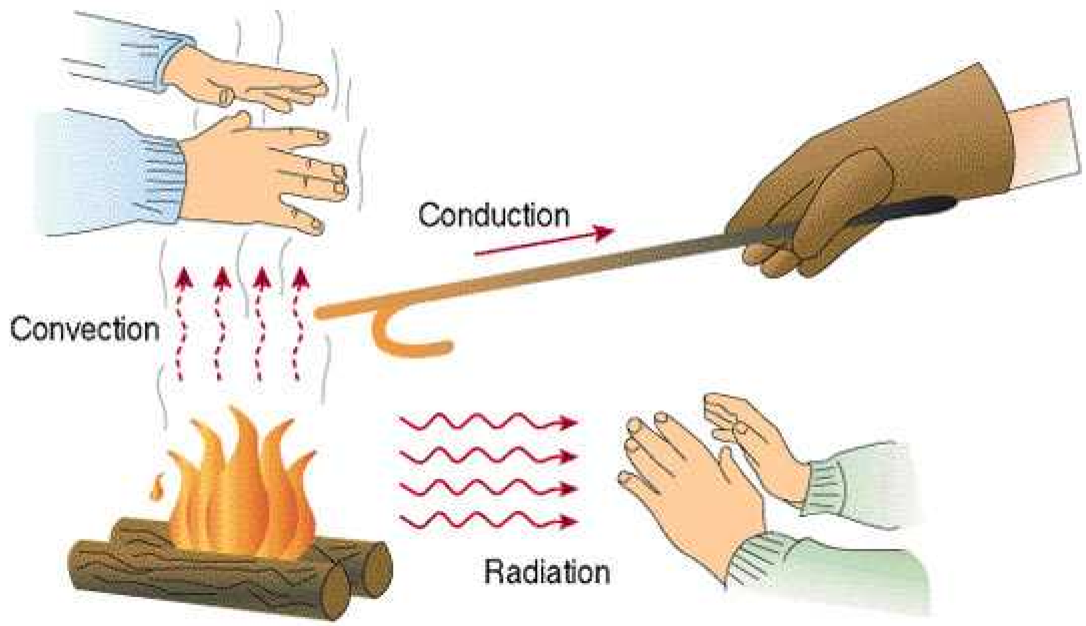
$$V_c(s) = I_{sp}(s) Z_t$$

$$\boxed{G(s) = \frac{V_c(s)}{I_{sp}(s)} = \frac{\dfrac{1}{C_{HV}}}{\left(s + \dfrac{1}{R_p C_{HV}}\right)}}$$

Thermal Modeling
Heat Rate Equations

1. Heat transfer is flow of thermal energy (q) in a medium or between media when thermal difference is present

2. Three Modes
   1. Conduction
   2. Convection
   3. Radiation



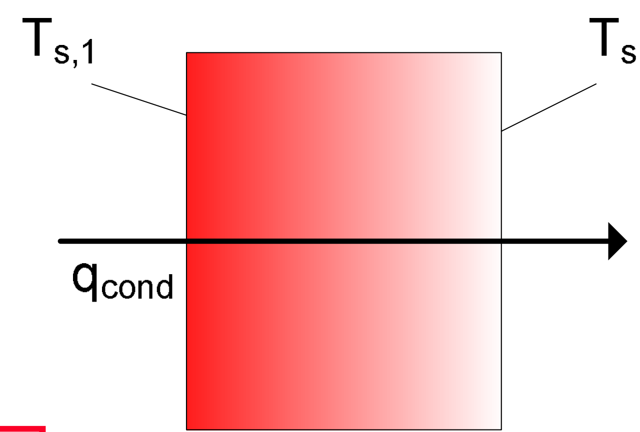
Thermal Modeling
Heat Rate Equations - Conduction

- **Fourier's Law for heat flux**

$$q''_x = -k\frac{dT}{dx}$$

Thermal conductivity (W/m*K)

$$\frac{T_{s,2} - T_{s,1}}{L}$$



- **Heat rate (W)**

$$q''_x = \frac{q_x}{A} \longrightarrow \boxed{q_{cond} = -kA\frac{dT}{dx} = \frac{kA}{L}(\Delta T)}$$

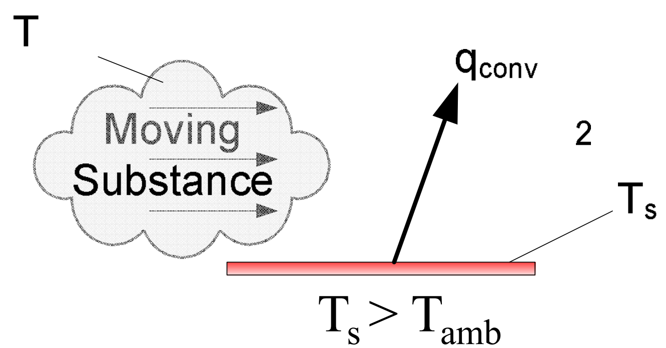
$$\Delta T = T_{s,1} - T_{s,2}$$

Thermal Modeling
Heat Rate Equations - Convection

- **Newton's law of cooling for heat flux**

$$q'' = h(T_s - T_{amb})$$

Convection heat
transfer coefficient
(W/m^2*K)



- **Heat rate (W)**

$$\boxed{q_{conv} = hA(T_s - T_{amb})}$$

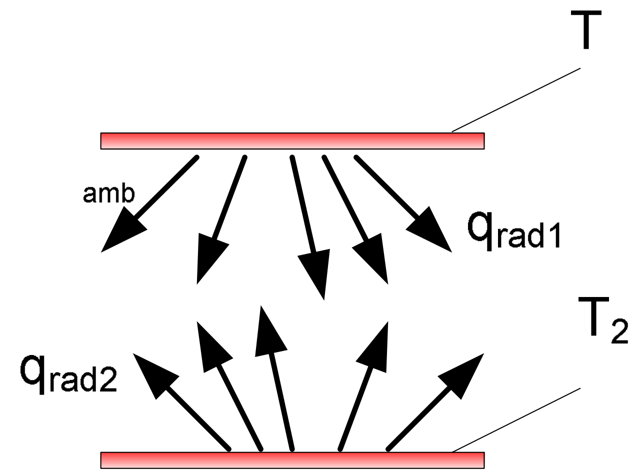
h - coefficient

- surface geometry
- Fluid thermodynamic & transport properties
- Fluid motion

Thermal Modeling
Heat Rate Equations - Radiation

- **All objects radiate energy in the form of electromagnetic waves**
- **0.1 to 100 um wavelength (Thermal radiation) relevant**
- **Emitted or incident radiation**

$$q'' = \varepsilon \sigma T_2^4$$



- **Net rate**

$$q'' = \varepsilon \sigma T_2^4 - \varepsilon \sigma T_1^4 = \varepsilon \sigma (T_2^4 - T_1^4)$$

emitted energy absorbed energy

- **Linearize**

$$\boxed{q_{rad} = h_r A (T_2 - T_1)}$$

$$h_r \equiv \varepsilon \sigma (T_2 + T_1)(T_2^2 + T_1^2)$$

Thermal Modeling
Heat Rate Equations - Simplification

- **Lump thermal properties together as thermal resistance/conductance**

$$R_{elec} = \frac{V_{s,1} - V_{s,2}}{I} = \frac{L}{\sigma A}$$

Ohm's Law

$$R_{thermal} = \frac{T_{s,1} - T_{s,2}}{q} = \frac{L}{kA} \longrightarrow \lambda_{thermal} = \frac{1}{R_{thermal}} = \frac{kA}{L} \longrightarrow \boxed{q_{cond} = \frac{kA}{L}(\Delta T) = \lambda_{cond}(\Delta T)}$$

conduction

$$R_{conv} = \frac{1}{hA} \longrightarrow \lambda_{thermal} = \frac{1}{R_{thermal}} = hA \longrightarrow \boxed{q_{conv} = hA(T_s - T_{amb}) = \lambda_{conv}(T_s - T_{amb})}$$

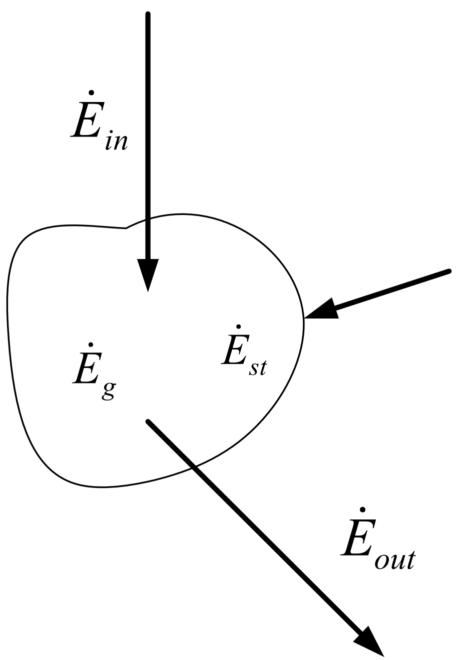
convection

Thermal Modeling
Heat Rate Equations – Nodal Analysis

1

- **First Law of Thermodynamics (Law of Conservation of Energy)**

$$\boxed{\dot{E}_{st} = \dot{E}_{in} - \dot{E}_{out} + \dot{E}_{g}}$$

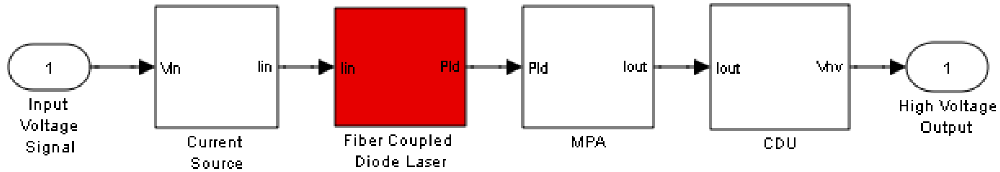


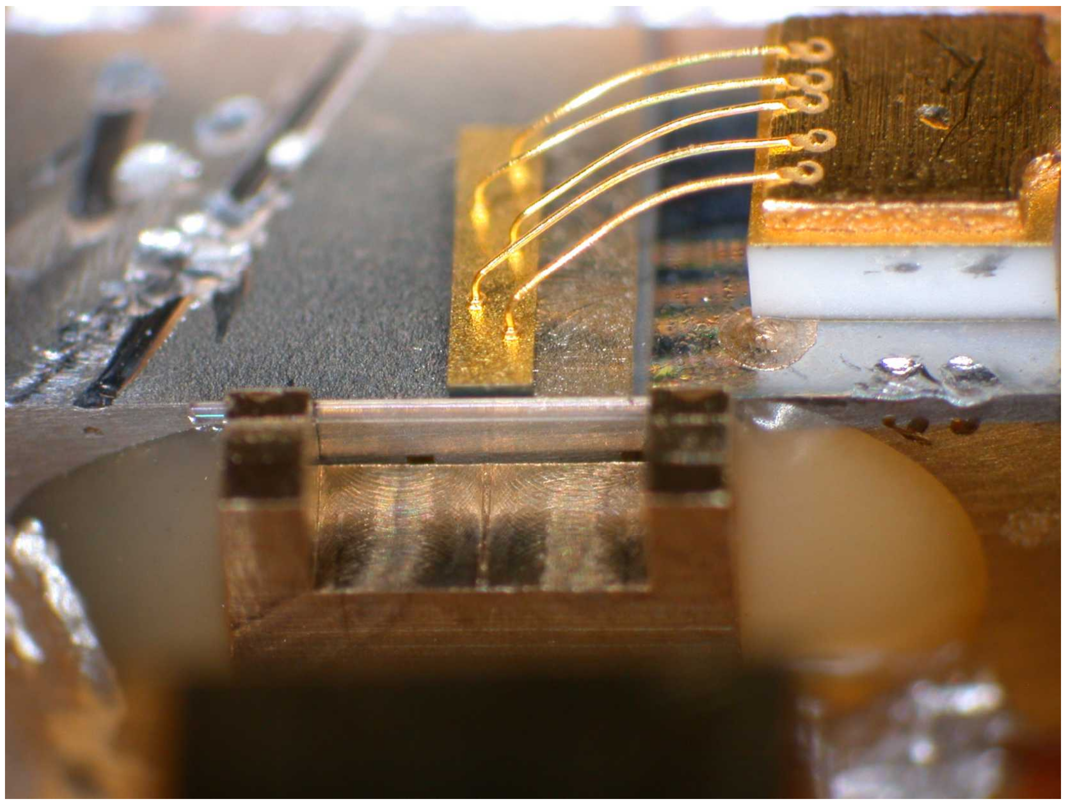
- Energy storage rate due to temperature change $\left(\dot{E}_{st}\right)$

$$\dot{E}_{st} = \frac{dU^{t}}{dt} = \frac{d}{dt}\left(\rho c V_{ld} T_{ld}\right) = \frac{dT_{ld}}{dt} C_{ld}$$

- Energy rate into control volume $\left(\dot{E}_{in}\right)$
- Energy rate out control volume $\left(\dot{E}_{out}\right)$
- Energy generation rate in control volume $\left(\dot{E}_{g}\right)$

Thermal Modeling – Diode Laser





I_{in}

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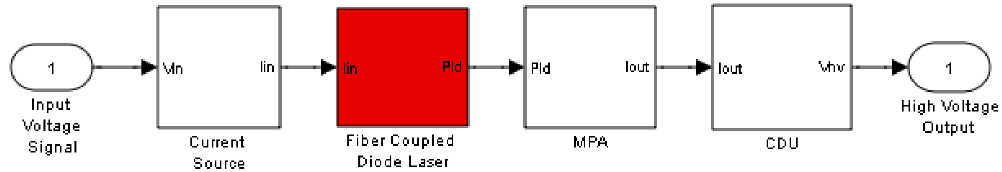
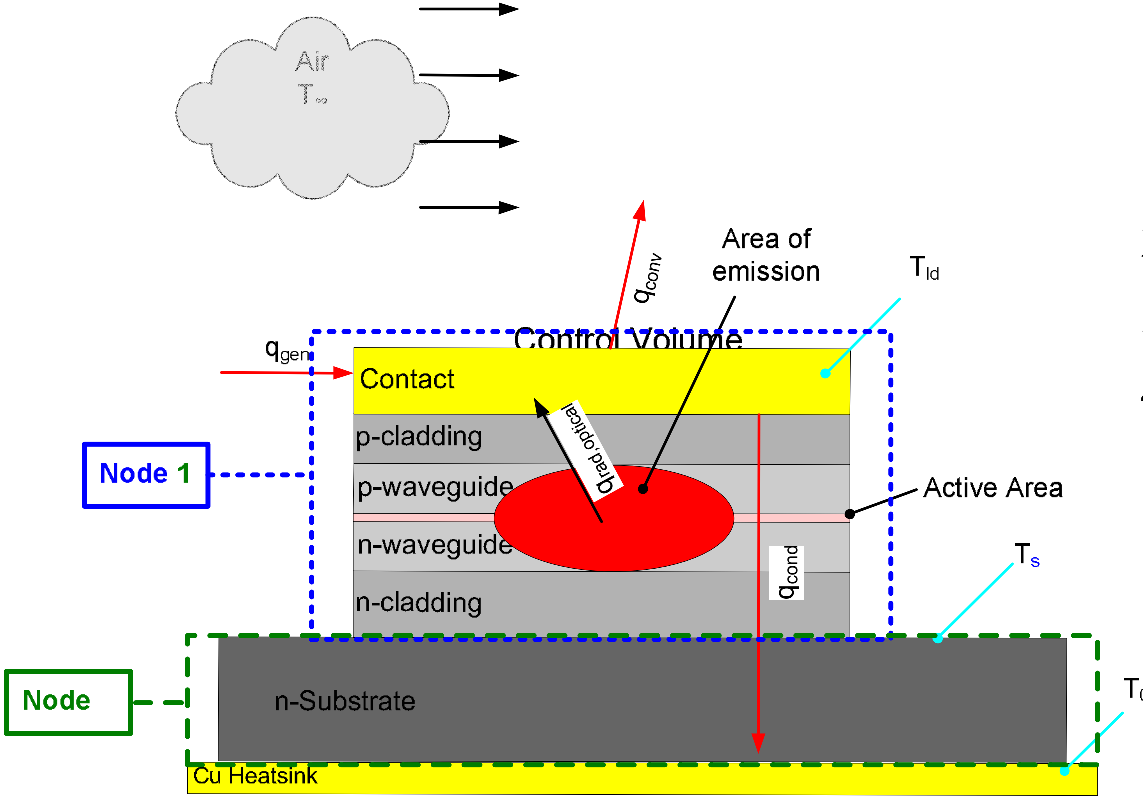
Thermal Modeling – Diode Laser



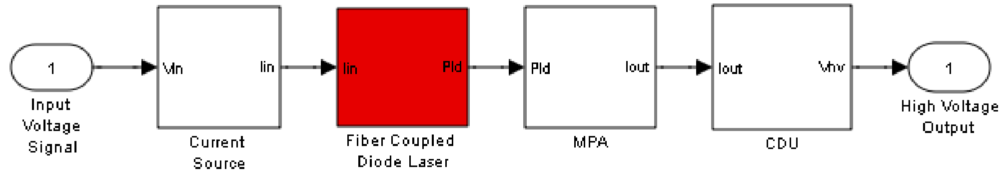
Nodal Analysis:



Assumptions:

1. Temperature at (t) in material is uniform
2. 1-D heat transfer
3. Constant material properties
4. $T_0 = T_\infty$

Thermal Modeling – Diode Laser: Node 1



$$\dot{E}_{st} = \dot{E}_{in} - \dot{E}_{out} + \dot{E}_g$$

$$\dot{E}_{st} = \dot{E}_g - \dot{E}_{out}$$

$$\left(\dot{E}_{out}\right)$$

$$\dot{E}_{out} = q_{conv} + q_{cond} + q_{rad} + q_{rad,optical}$$

$$\dot{E}_{out} = \lambda_{1,conv}(T_{ld} - T_\infty) + \lambda_{1,cond}(\Delta T_1) + h_r A(T_{abs} - T_{sur}) + P_{ld}$$

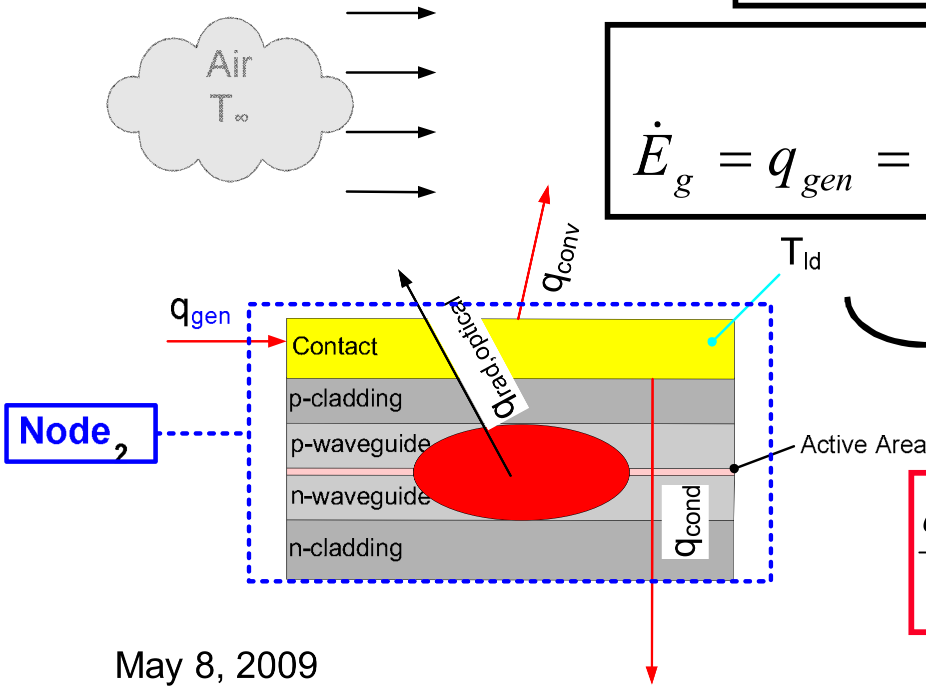
$$\dot{E}_{out} = \lambda_{1,cond}(\Delta T_1) + P_{ld}$$

$$\left(\dot{E}_g\right)$$

$$\dot{E}_g = q_{gen} = P_{in} = I_{in}V_{ld} - I_{in}^{\ 2}R_{cable}$$

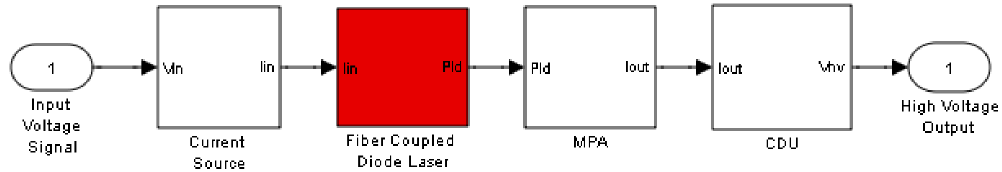
$$\left(\dot{E}_{st}\right)$$

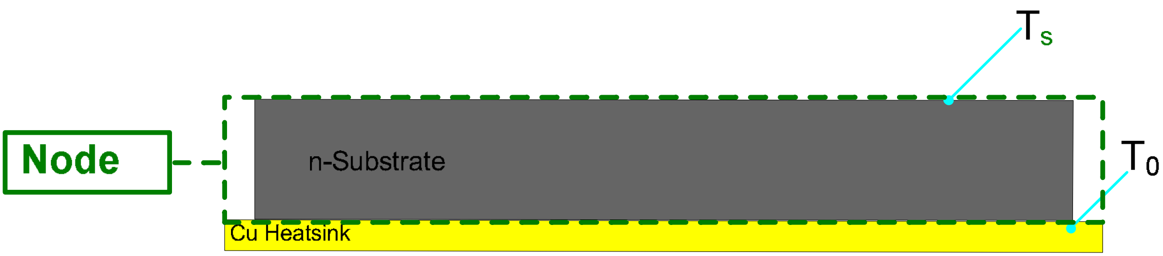
$$\dot{E}_{st} = \frac{dU^t}{dt} = \frac{dT_{ld}}{dt}C_{ld}$$



$$\frac{dT_{ld}}{dt} = \left[\frac{-\lambda_{1,cond}}{C_{ld}}\right]T_{ld} + \left[\frac{\lambda_{1,cond}}{C_{ld}}\right]T_s + \left[\frac{1}{C_{ld}}\right]P_{total}$$

Thermal Modeling – Diode Laser: Node 2





$$\dot{E}_{st} = \dot{E}_{in} - \dot{E}_{out} + \dot{E}_{g}$$

$$\dot{E}_{st} = \dot{E}_{in} - \dot{E}_{out}$$

$$\left(\dot{E}_{st}\right)$$

$$\dot{E}_{st} = \frac{dU^t}{dt} = \frac{dT_{ld}}{dt} C_{ld}$$

$$\left(\dot{E}_{out}\right)$$

$$\dot{E}_{out} = q_{conv} + q_{cond} + q_{rad}$$

$$\dot{E}_{out} = \lambda_{2,conv}(T_s - T_\infty) + \lambda_{2,cond}(\Delta T_2) + h_r A(T_{abs} - T_{sur})$$

$$\dot{E}_{out} = \lambda_{2,cond}(\Delta T_2) = \lambda_{2,cond}(T_s - T_0)$$

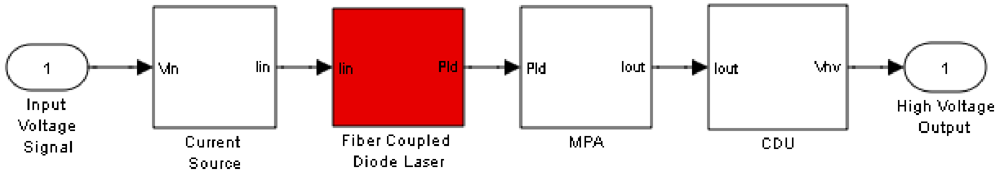
1

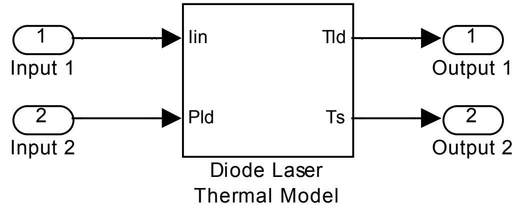
$$\left(\dot{E}_{in}\right)$$

$$\dot{E}_{in} = \lambda_{1,cond}(\Delta T_1) = \dot{E}_{out(Node-1)}$$

$$\frac{dT_s}{dt} = \left[\frac{\lambda_{1,cond}}{C_s}\right] T_{ld} + \left[\frac{(-\lambda_{1,cond} - \lambda_{2,cond})}{C_s}\right] T_s + \frac{\lambda_{2,cond} T_0}{C_s}$$

Thermal Modeling – Diode Laser: Final Equation



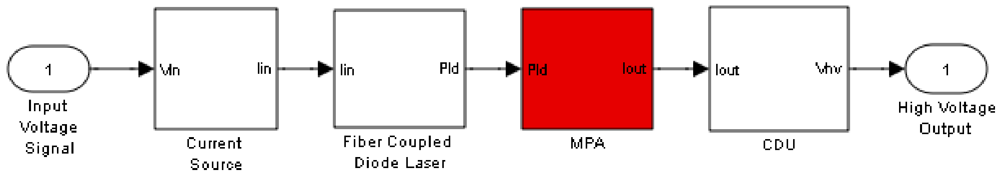


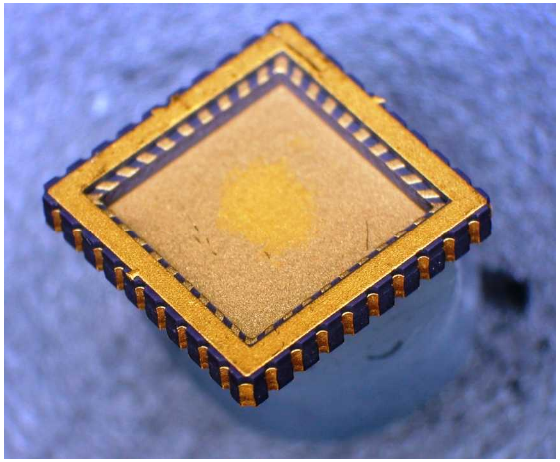
$$\frac{dT_{ld}}{dt} = \left[\frac{-\lambda_{1,cond}}{C_{ld}}\right] T_{ld} + \left[\frac{\lambda_{1,cond}}{C_{ld}}\right] T_s + \left[\frac{1}{C_{ld}}\right] P_{total}$$

$$\frac{dT_s}{dt} = \left[\frac{\lambda_{1,cond}}{C_s}\right] T_{ld} + \left[\frac{(-\lambda_{1,cond} - \lambda_{2,cond})}{C_s}\right] T_s + \frac{\lambda_{2,cond} T_0}{C_s}$$

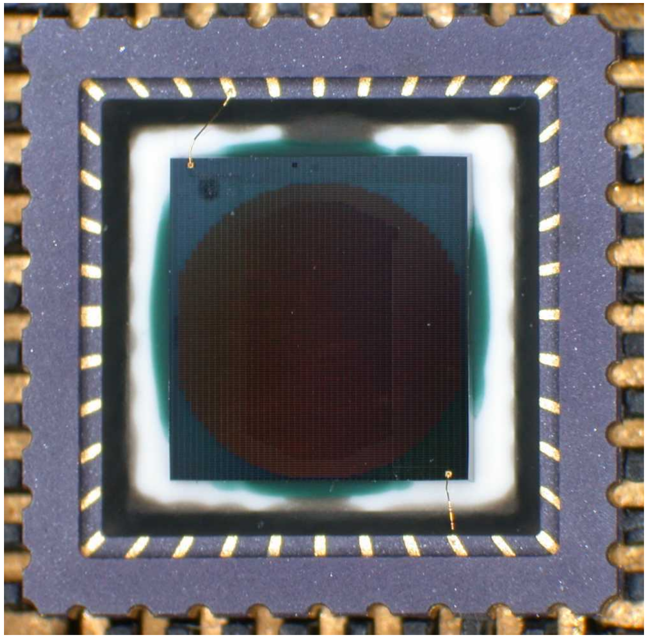
$$\mathrm{Output} = \mathrm{T_{ld}}$$

Thermal Modeling – MPA

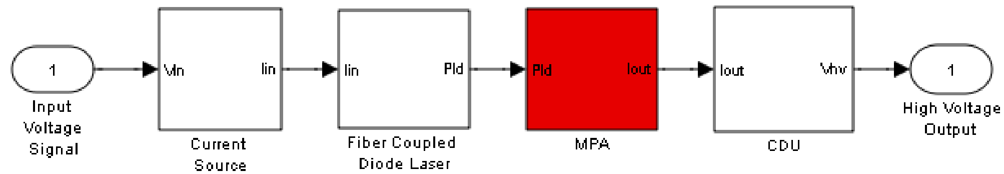


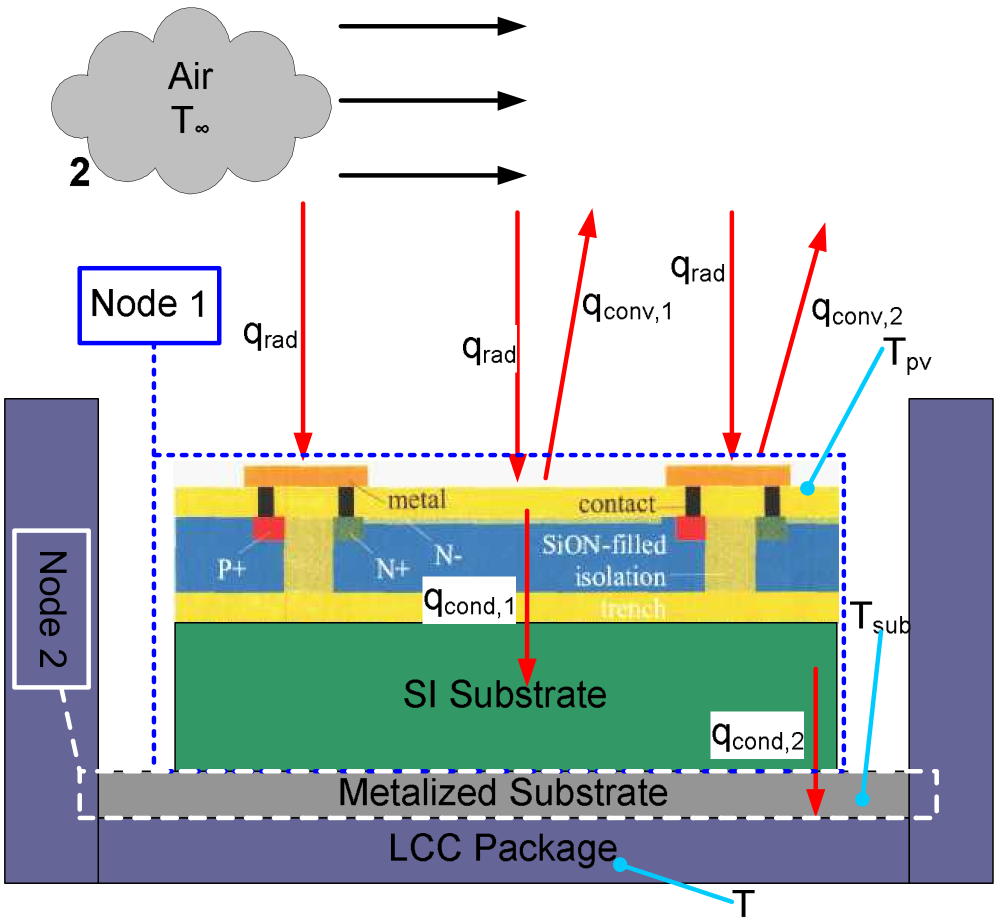


0.400” square



Thermal Modeling – MPA



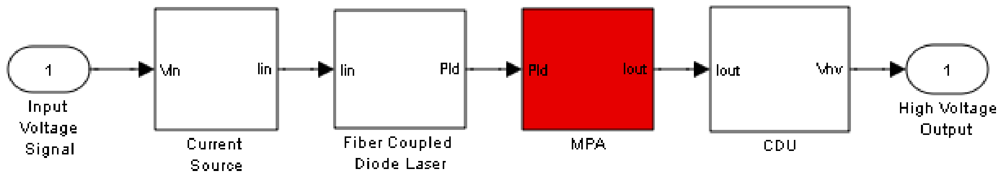


Assumptions:

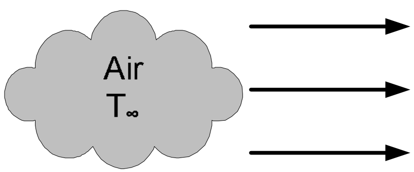
1. Temperature at (t) in material is uniform
2. 1-D heat transfer
3. Constant material properties
4. T0 = T∞

* Process is similar to diode laser thermal model

Thermal Modeling – MPA: Node-1



$$\dot{E}_{st} = \dot{E}_{in} - \dot{E}_{out} + \dot{E}_{g} \longrightarrow \dot{E}_{st} = \dot{E}_{in} - \dot{E}_{out} \longrightarrow$$



$$\left(\dot{E}_{in}\right)$$

$$\dot{E}_{in} = \left(1 - R_{mat}(\lambda)\right)P_{ld}$$

$$\left(\dot{E}_{st}\right)$$

$$\dot{E}_{st} = \frac{dU^{t}}{dt} = \frac{dT_{pv}}{dt}C_{pv}$$

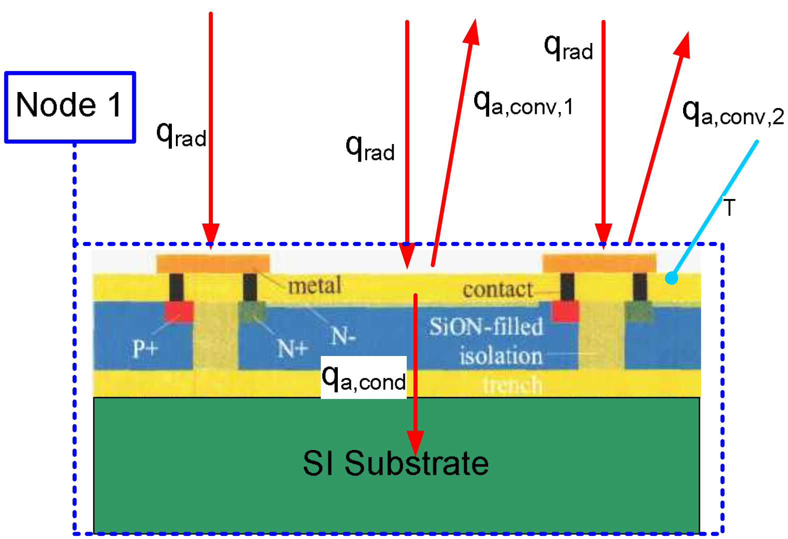
$$\left(\dot{E}_{out}\right)$$

$$\dot{E}_{out} = q_{conv} + q_{cond} + q_{rad}$$

$$\dot{E}_{out} = \lambda_{a,conv}(T_{pv} - T_{\infty}) + \lambda_{a,cond}(\Delta T_{a}) + h_{r}A(T_{abs} - T_{sur})$$

$$\dot{E}_{out} = \lambda_{a,cond}(\Delta T_{a})$$

$$\boxed{\frac{dT_{pv}}{dt} = \left[\frac{-\lambda_{a,cond}}{C_{pv}}\right]T_{pv} + \left[\frac{\lambda_{a,cond}}{C_{pv}}\right]T_{sub} + \left[\frac{(1 - R_{mat}(\lambda))}{C_{pv}}\right]P_{ld}}$$



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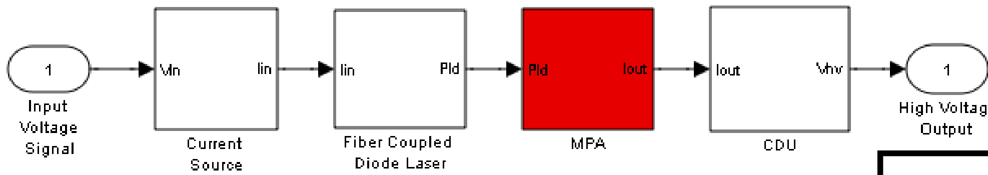
Thermal Modeling – MPA: Node-2



$$\dot{E}_{st} = \dot{E}_{in} - \dot{E}_{out} + \dot{E}_g$$

$$\dot{E}_{st} = \dot{E}_{in} - \dot{E}_{out}$$

$$\left(\dot{E}_{st}\right)$$

$$\dot{E}_{st} = \frac{dU^t}{dt} = \frac{dT_{sub}}{dt} C_{sub}$$

$$\left(\dot{E}_{in}\right)$$

$$\dot{E}_{in} = \lambda_{a,cond}(\Delta T_a) = \dot{E}_{out}$$

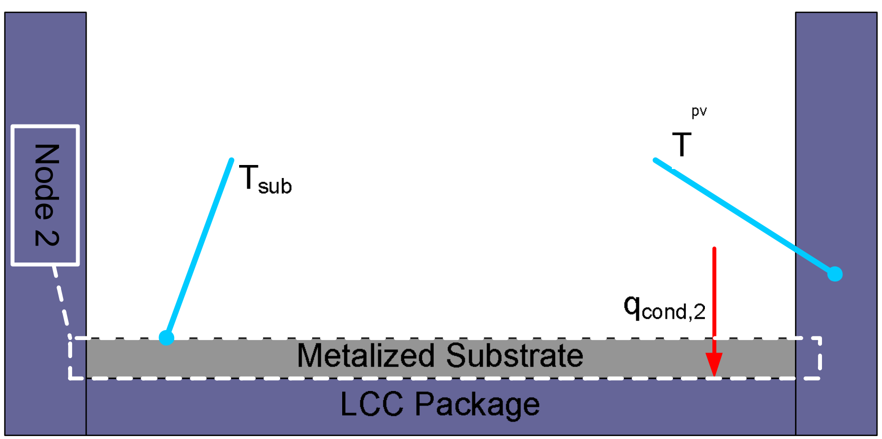
$$\left(\dot{E}_{out}\right)$$

$$\dot{E}_{out} = q_{conv} + q_{cond} + q_{rad}$$

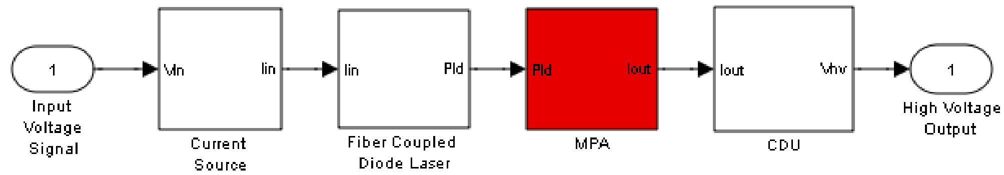
$$\dot{E}_{out} = \lambda_{b,conv}(T_{sub} - T_\infty) + \lambda_{b,cond}(\Delta T_b) + h_r A(T_{abs} - T_{sur})$$

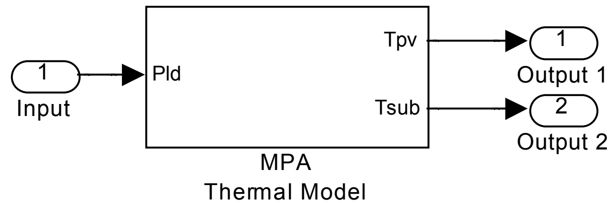
$$\dot{E}_{out} = \lambda_{b,cond}(\Delta T_b) = \lambda_{b,cond}(T_{sub} - T_0)$$

$$\frac{dT_{sub}}{dt} = \left[\frac{\lambda_{a,cond}}{C_{sub}}\right] T_{pv} + \left[\frac{(-\lambda_{a,cond} - \lambda_{b,cond})}{C_{sub}}\right] T_{sub} + \frac{\lambda_{b,cond} T_0}{C_{sub}}$$



Thermal Modeling – MPA: Final Equation





2-Node Equation

$$\frac{dT_{pv}}{dt} = \left[\frac{-\lambda_{a,cond}}{C_{pv}}\right] T_{pv} + \left[\frac{\lambda_{a,cond}}{C_{pv}}\right] T_{sub} + \left[\frac{(1 - R_{mat}(\lambda))}{C_{pv}}\right] P_{pv}$$

$$\frac{dT_{sub}}{dt} = \left[\frac{\lambda_{a,cond}}{C_{sub}}\right] T_{pv} + \left[\frac{(-\lambda_{a,cond} - \lambda_{b,cond})}{C_{sub}}\right] T_{sub} + \frac{\lambda_{b,cond} T_0}{C_{sub}}$$

$$\text{Output} = \mathrm{T_{pv}}$$

3-Node Equation

$$\frac{dT_{pv}}{dt} = \left[\frac{-\lambda_{a,cond}}{C_{pv}}\right] T_{pv} + \left[\frac{\lambda_{a,cond}}{C_{pv}}\right] T_{sub} + \left[\frac{(1 - R_{mat}(\lambda))}{C_{pv}}\right] P_{pv}$$

$$\frac{dT_{sub}}{dt} = \left[\frac{\lambda_{a,cond}}{C_{sub}}\right] T_{pv} + \left[\frac{(-\lambda_{a,cond} - \lambda_{b,cond})}{C_{sub}}\right] T_{sub} + \frac{\lambda_{b,cond} T_{pack}}{C_{sub}}$$

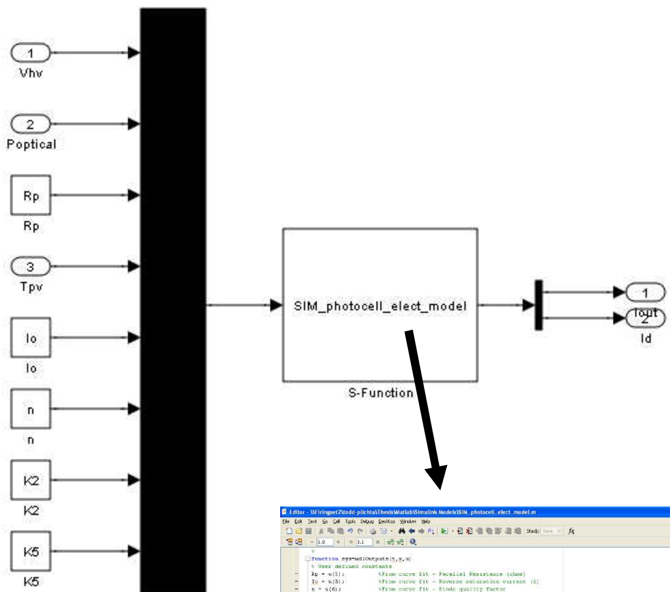
$$\frac{dT_{pack}}{dt} = \left[\frac{\lambda_{b,cond}}{C_{pack}}\right] T_{sub} + \left[\frac{(-\lambda_{b,cond} - \lambda_{c,conv})}{C_{pack}}\right] T_{pack} + \frac{\lambda_{c,conv} T_{\infty}}{C_{pack}}$$

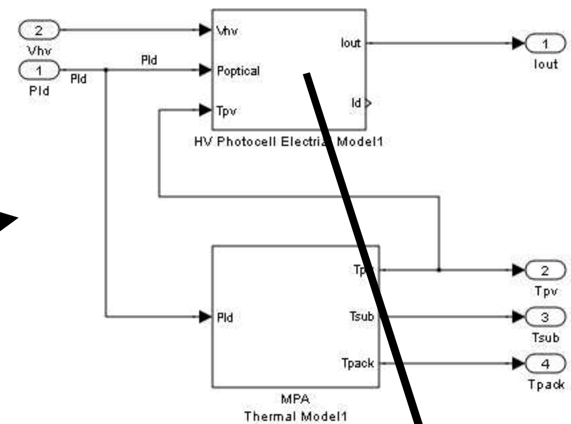
$$\text{Output} = \mathrm{T_{pv}}$$

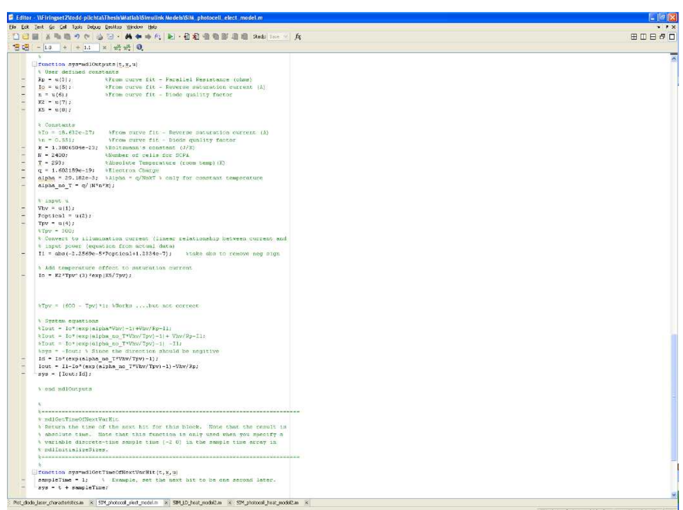
Model Verification Process

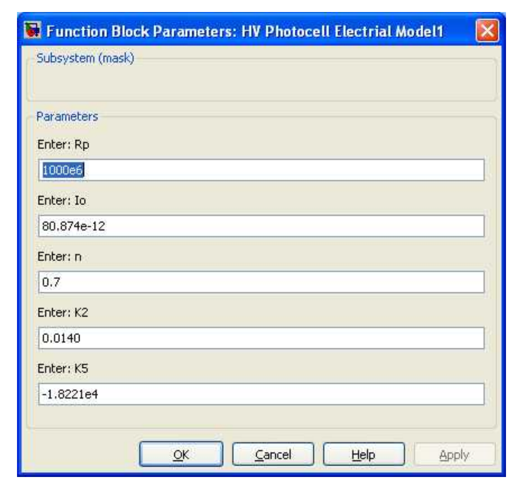
1. Calculate/estimate equation parameters
   - based on previous work, educated guesses, calculations from experimental data
2. Solve ODE's with MATLAB
   - m-files were created for each component
   - Check for basic output response characteristics
3. Create a block for each component in Simulink
   - s-functions used
   - Created subsystem for each component
   - Created menu for component parameters
4. Simulate blocks and compare to experimental data
   - Adjust unknown parameters to fit experimental data

Model Verification Process – Creating Blocks in Simulink



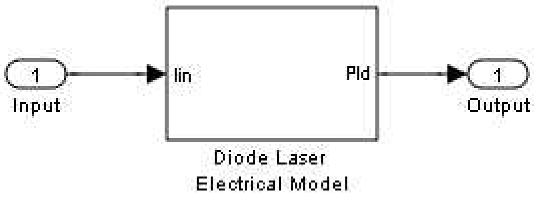


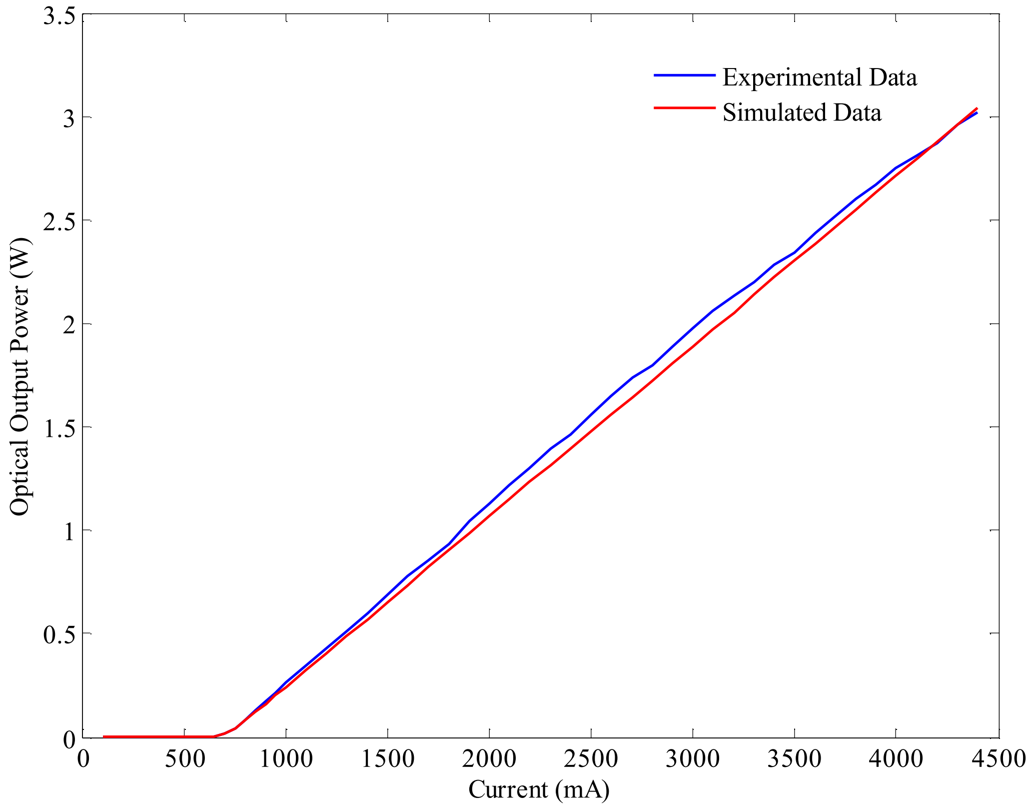




Electrical Model Verification – Diode Laser Fundamental PI response

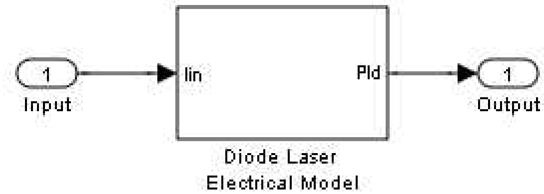
- Experimental Data
  - JOLD-3-BAFC-11 S/N#: EK-08211
  - 53 input current levels
  - Scientech AC 2501H Power Head
- Simulated Data
  - 53 input current levels
  - Solver: Ode23s
  - 1 second for each simulation
- Results
  - 97 mW at 2700 mA (5.6% error)

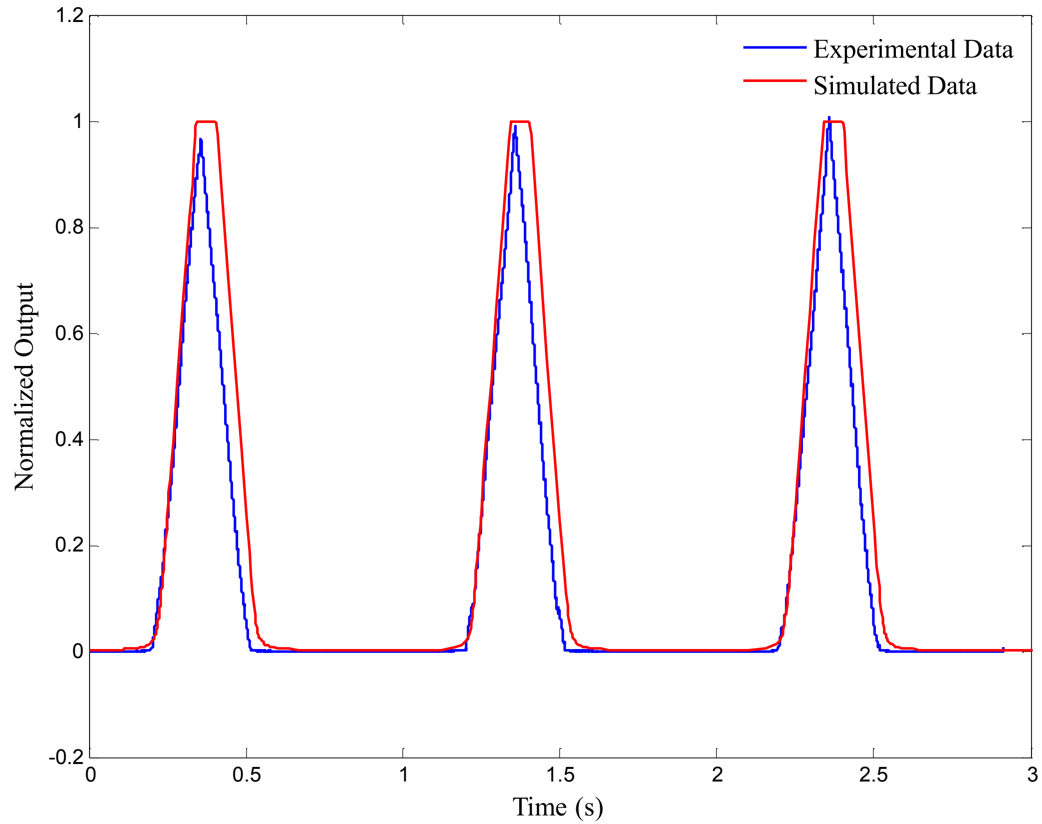




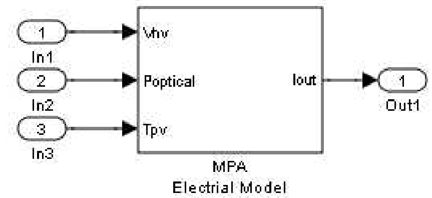
Electrical Model Verification – Diode Laser Ramp Input response

- **Experimental Data**
  - **JOLD-3-BAFC-11 S/N#: EK-08211**
  - **800mA injected current**
  - **det210 photodiode**
- **Simulated Data**
  - **Estimated input current from measured output current**
- **Results**
  - **Rise time match**



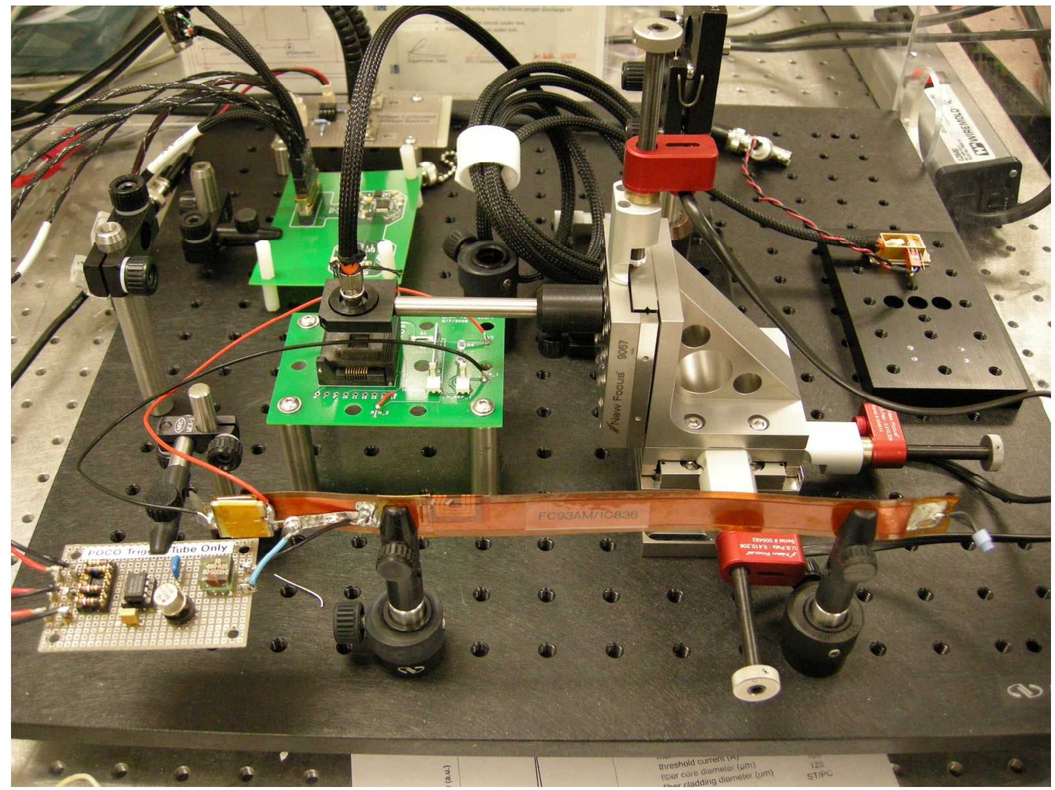


Electrical Model Verification – MPA Experimental Data



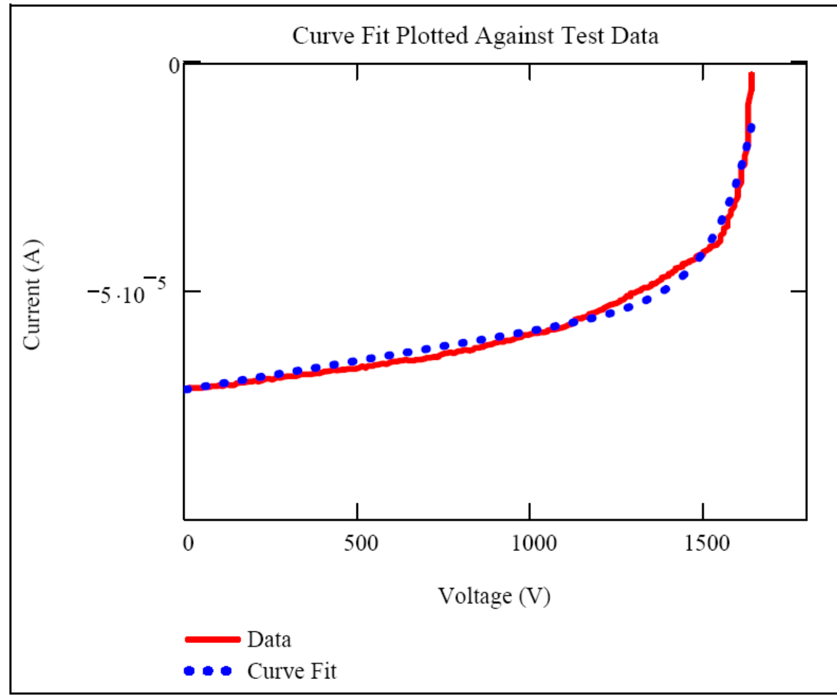
1. **Active optical alignment**
   - **Entire semi-circular area of active cells need illumination**
   - **Provide maximum illumination current**

2. **Non-illuminated curve**
   - **Check for correct operation**
   - **Illuminated curve is just shifted**



Electrical Model Verification – MPA Calculation and Estimation of Parameters

- Could develop equations from p-n junction physics for each parameter that is a function of semiconductor material constants and manufacturing variables
- Most semiconductor constants vary with production spread
- Curve fitting is therefore used to determine these parameters

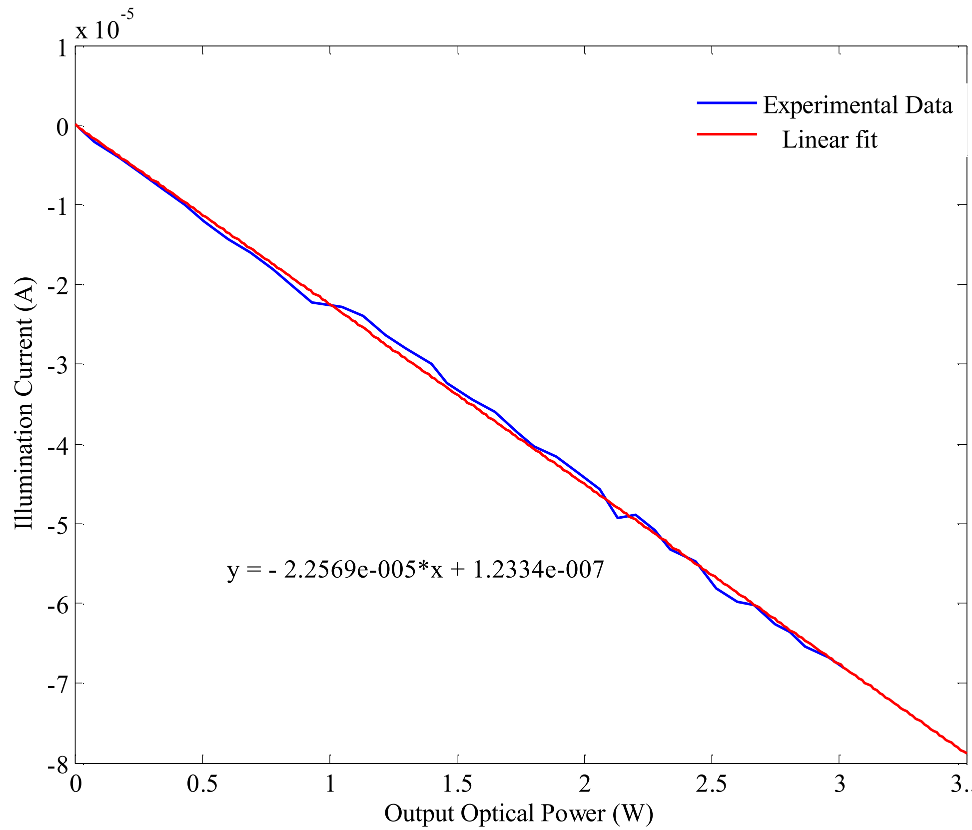


Parameter	Description	Initial value	Final Tuned Value	Final Tuned Value with Temperature included in model	Units
Io	Reverse Saturation Current	2.57E-11	1.59E-11	NA	A
n	Diode Quality Factor	1.864	1.94	0.7	none
Rp	Parallel Resistance	7.85E+07	1.00E+09	1.00E+09	Ω

Electrical Model Verification – MPA Calculation and Estimation of Parameters

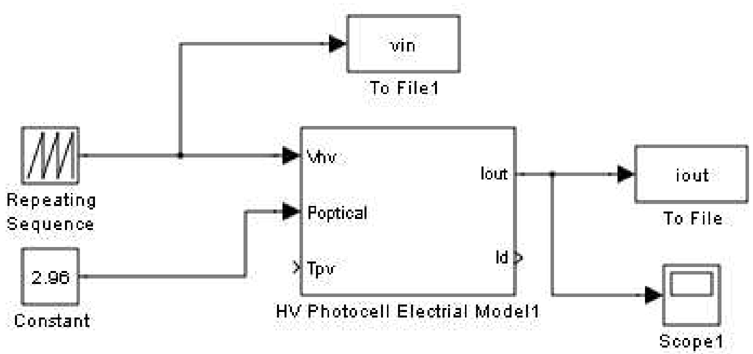
Illumination current

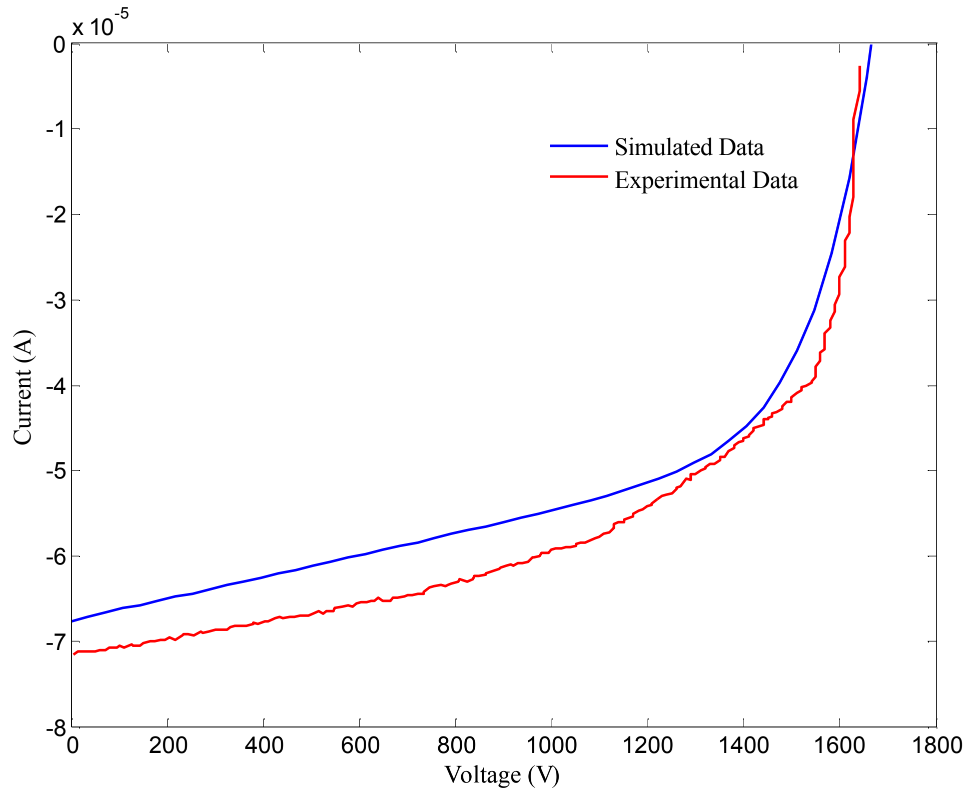
- **function of input optical power**
- **experimental data was taken at different illumination powers**
- **$R^2 = 0.9985$**
- **It is dependant on uniformity of illumination**
- **Variation of temperature not conducted**



Electrical Model Verification – MPA Simulated vs. Experimental Data

- **Experimental Data**
  - **Tektronix 370B curve tracer**
  - **AC sweeping used**
- **Simulated Data**
  - **Input ramp signal 0 to 1800 V**
  - **Model followed trend of experimental data**



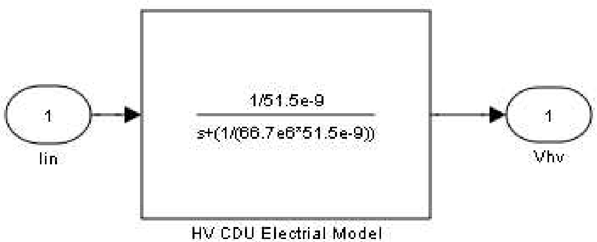


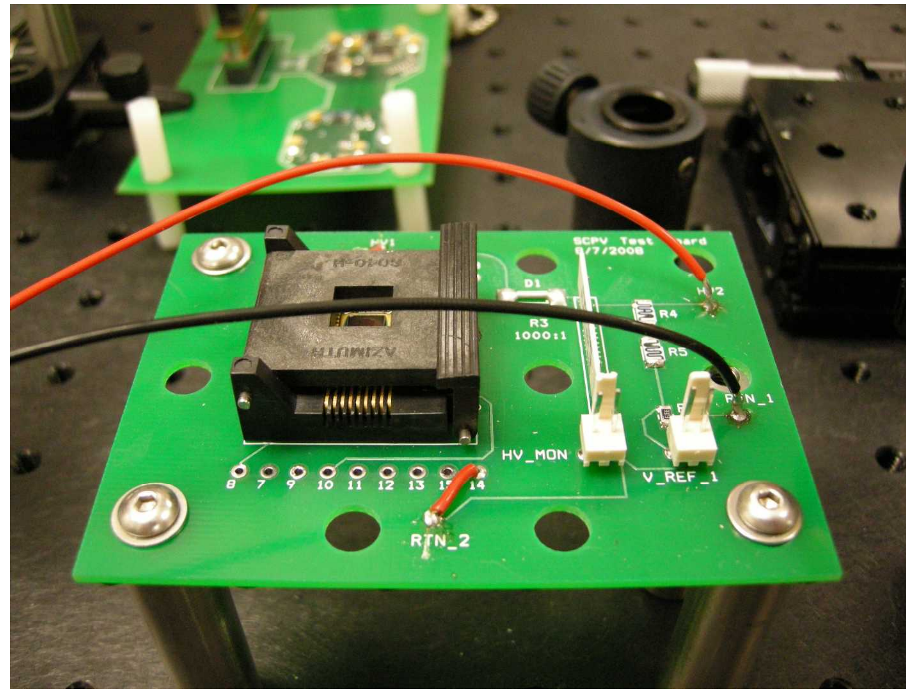
* Further verification was conducted when connected to CDU

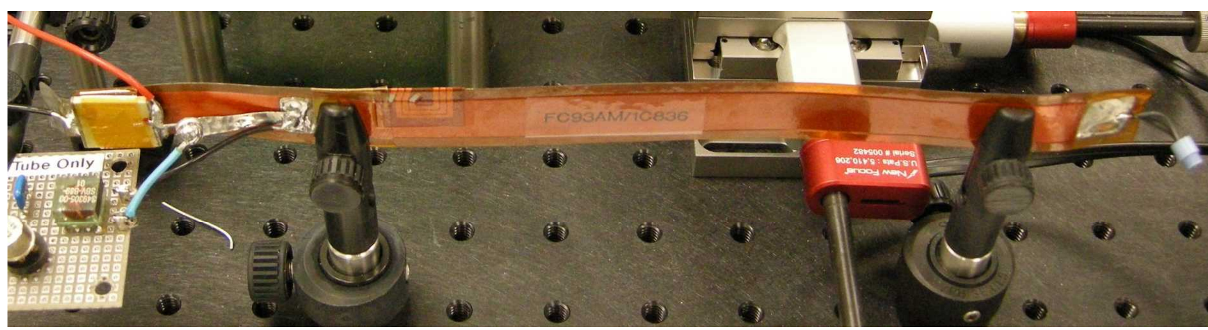
Electrical Model Verification – CDU Experimental Setup

- **PWB was designed to hold MPA and bleeder resistors**

- **HV capacitor, HV switch, and detonator mounted on a strip line cable**







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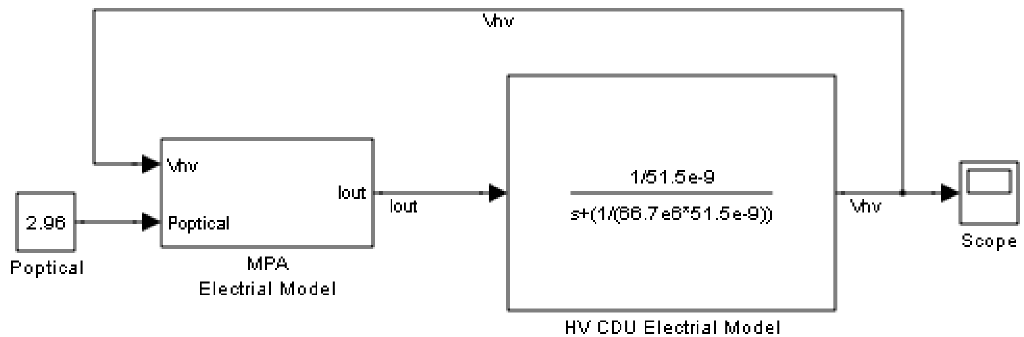
Electrical Model Verification – CDU Experimental Data

- Experimental Data of the HV CDU subsystem could not be obtained

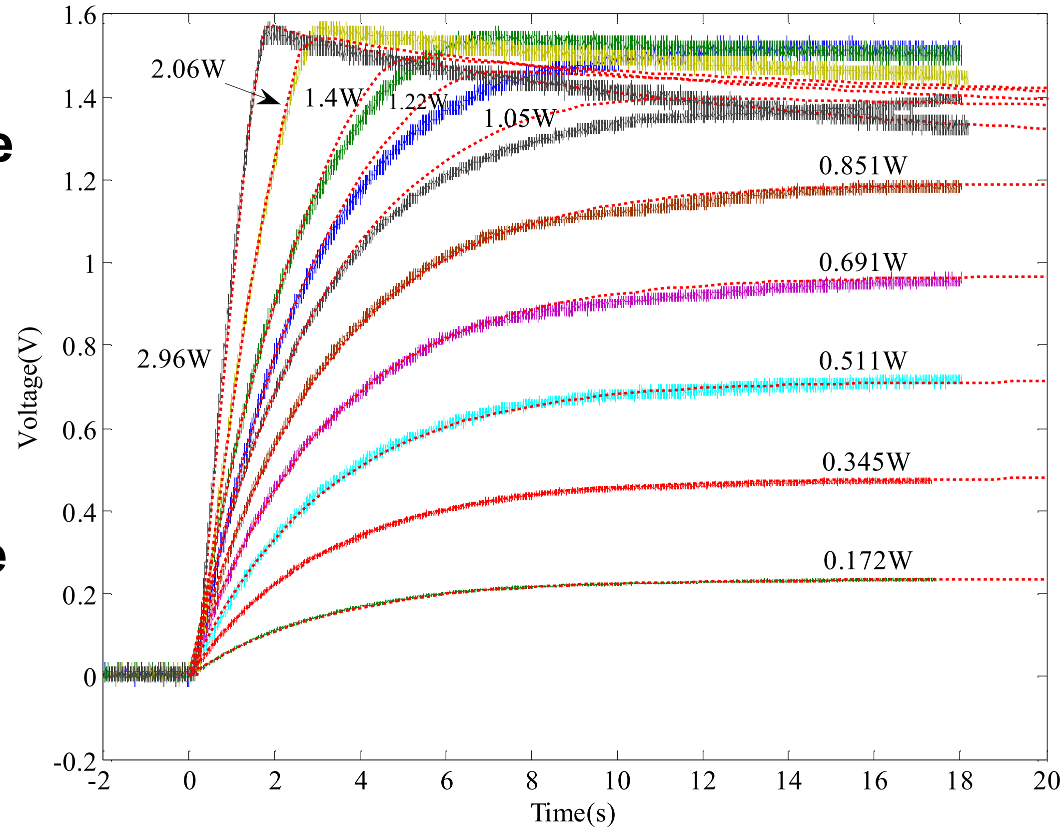
- MPA was added as the current source

- 38 different levels of optical illumination were injected

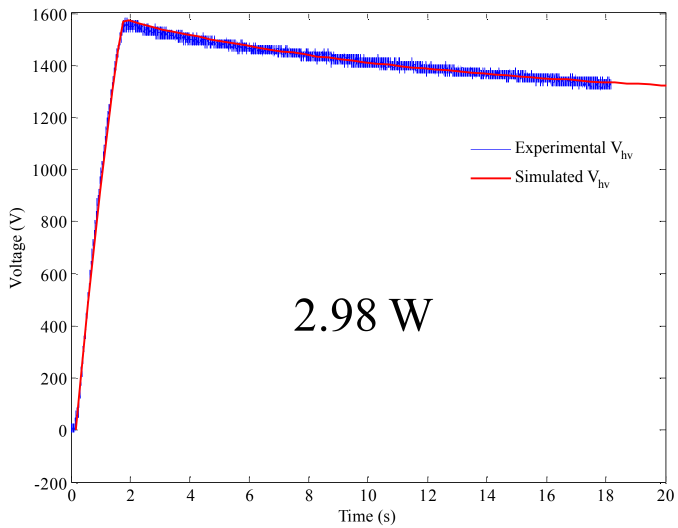


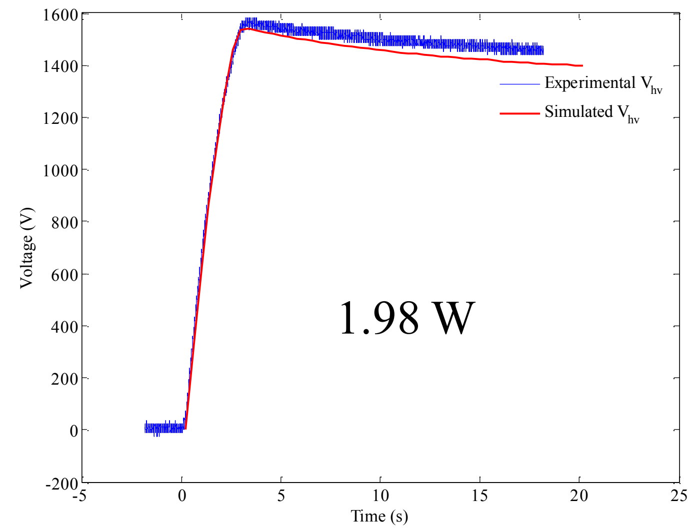
Electrical Model Verification – CDU Experimental vs. Simulated Data

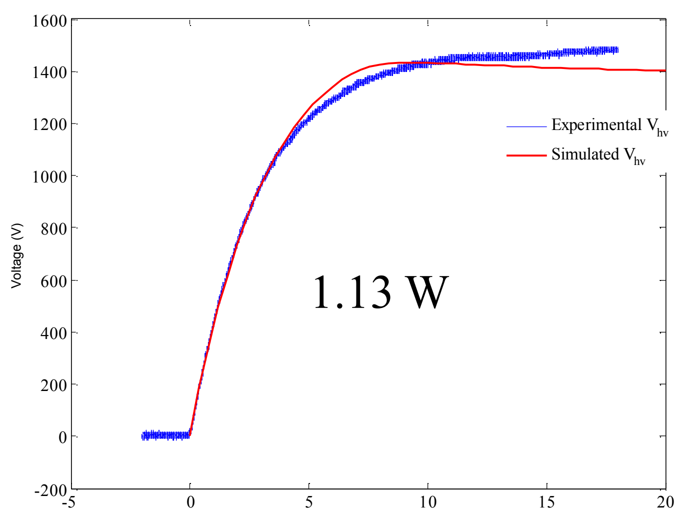
- **Charge time is a function of illuminated input power, capacitance, and resistance**
- **At 2.96 W CDU will charge to 1560 V in 1.7 seconds**
- **At input optical power below 1.22 W will take more than 20 seconds to reach 1500V**

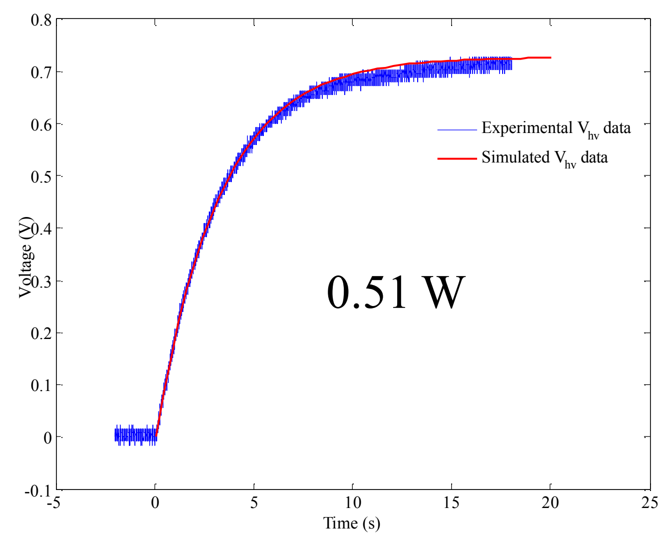


Electrical Model Verification – CDU Experimental vs. Simulated Data

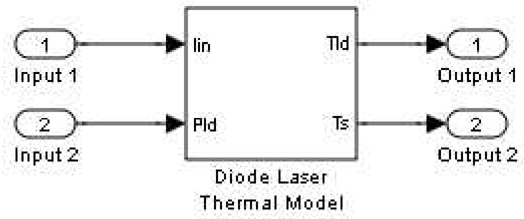


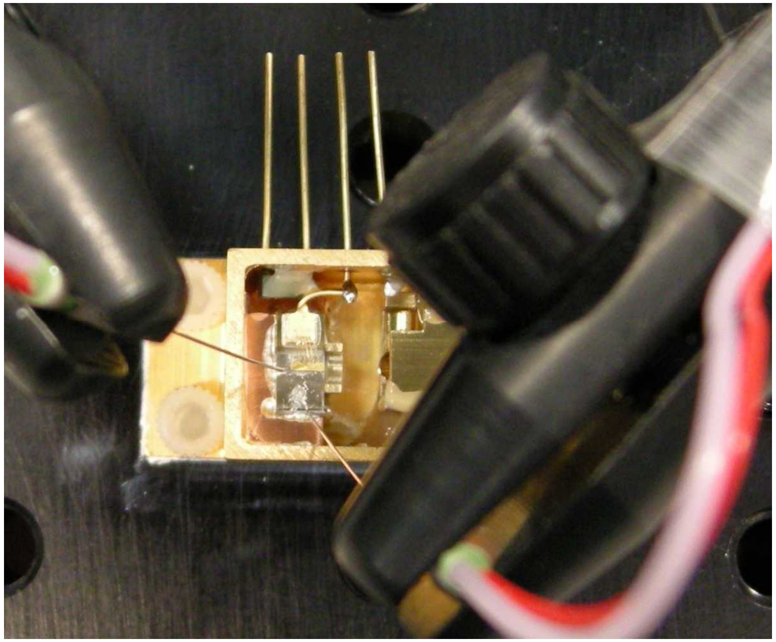


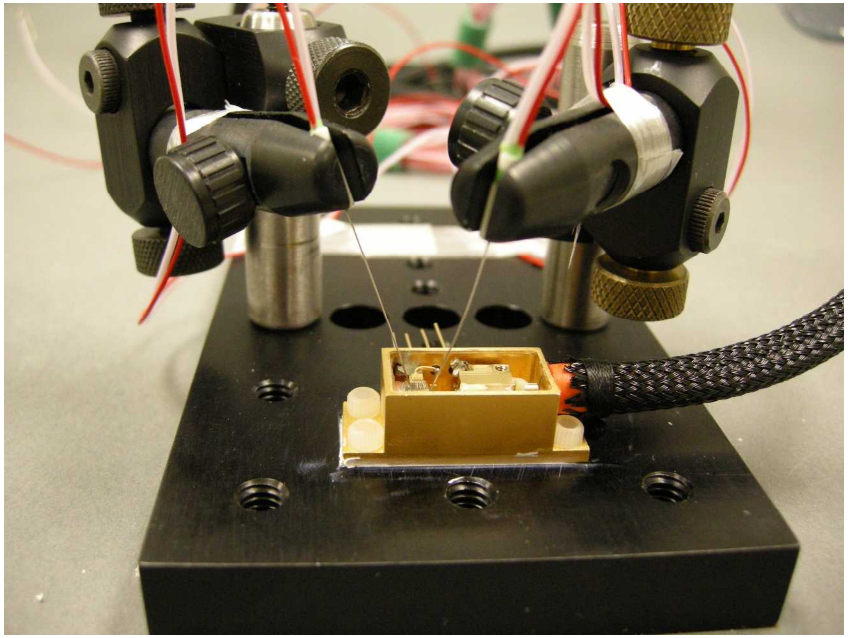




Thermal Model Verification – Diode Laser Experimental Setup

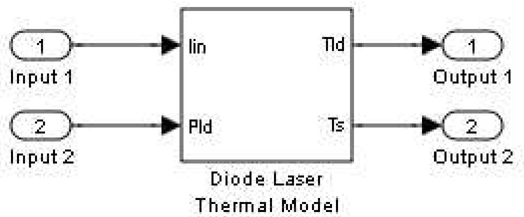


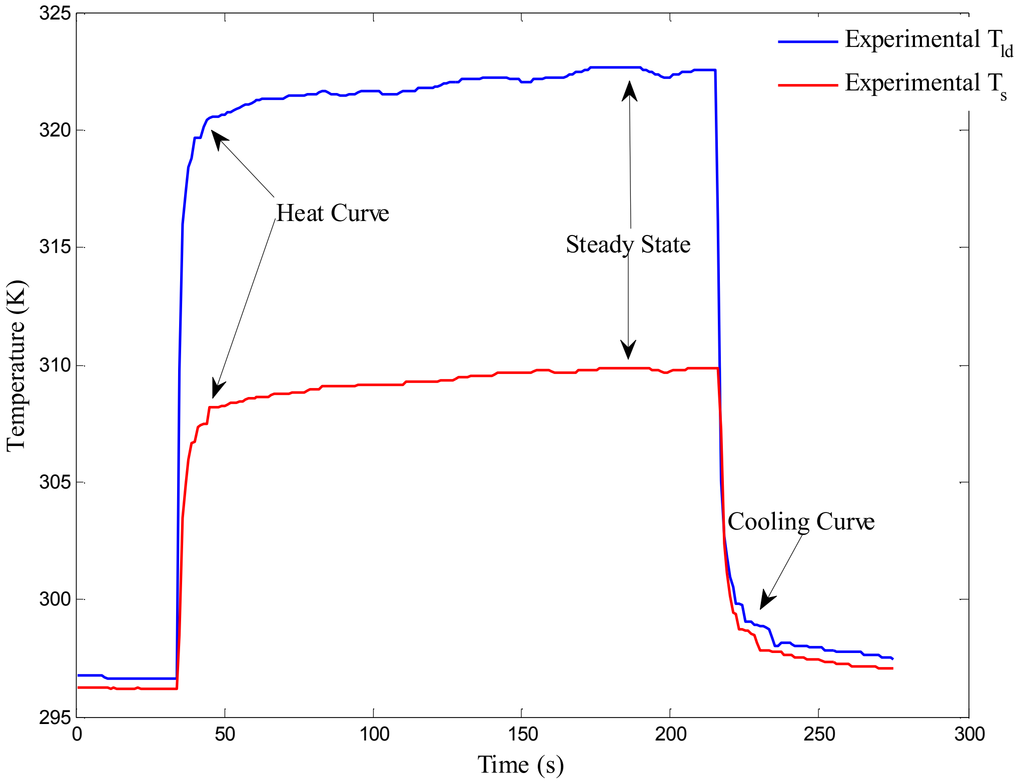




Thermal Model Verification – Diode Laser Experimental Data

- **Experimental Data**
  - **11 input current values for 200 seconds**
  - **Temperature data was gathered at 1 second sampling rate**





Experimental Heating Curve

Thermal Model Verification – Diode Laser Calculation and Estimation of Parameters

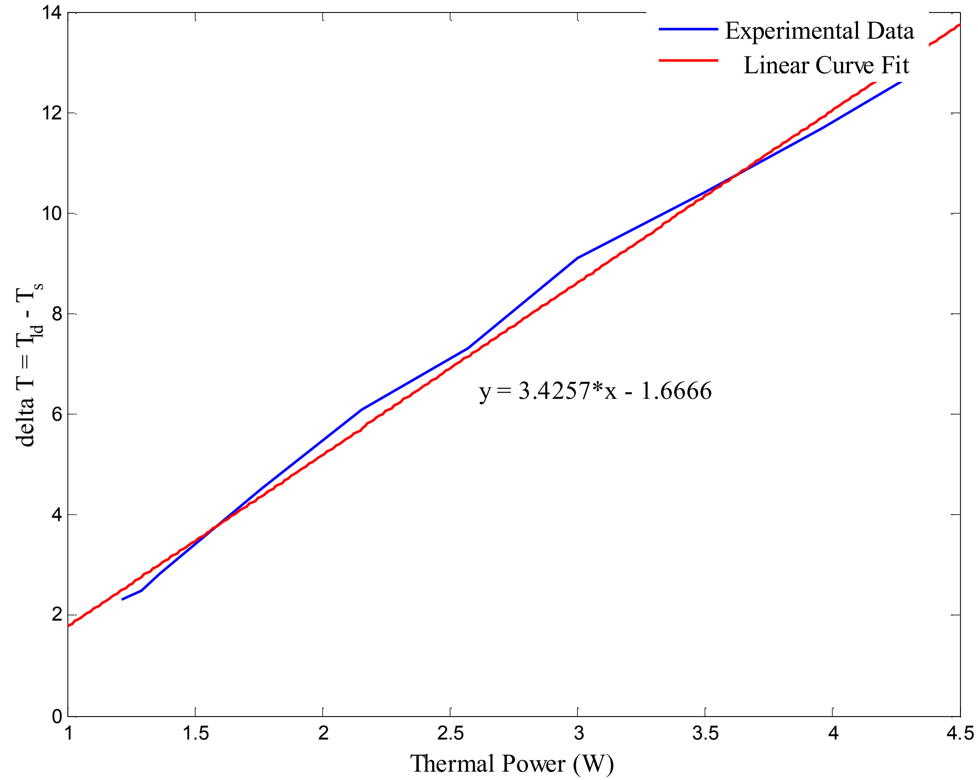
- **Cable resistance**
  - **Measured on calibrated digital ohmmeter**

    0.134 Ω

- **Thermal Conductance for Node 1**

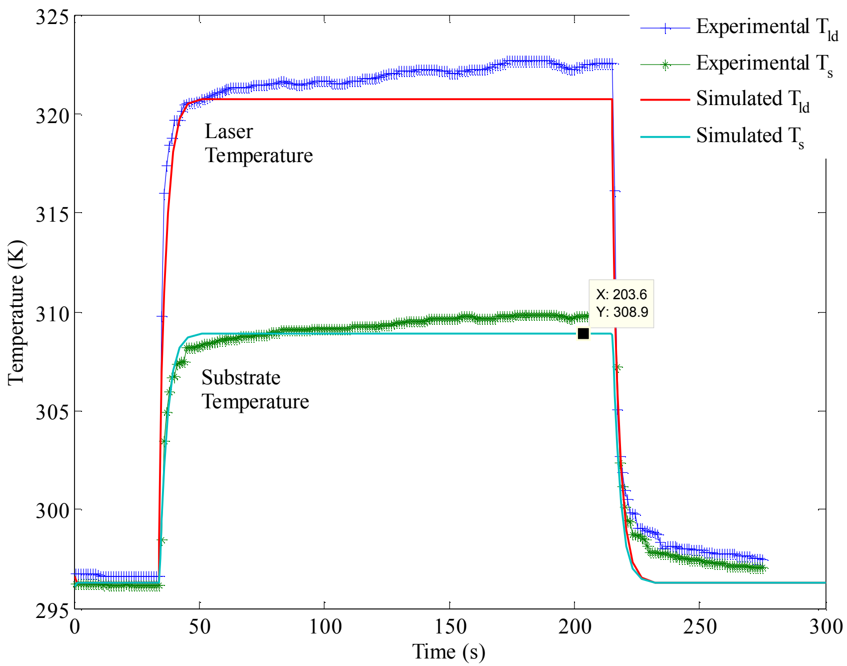
$$\frac{1}{\lambda_{1,cond}} = \frac{\Delta T}{P}$$

- **Three additional parameters cannot be experimentally calculated – used initial values from [2]**

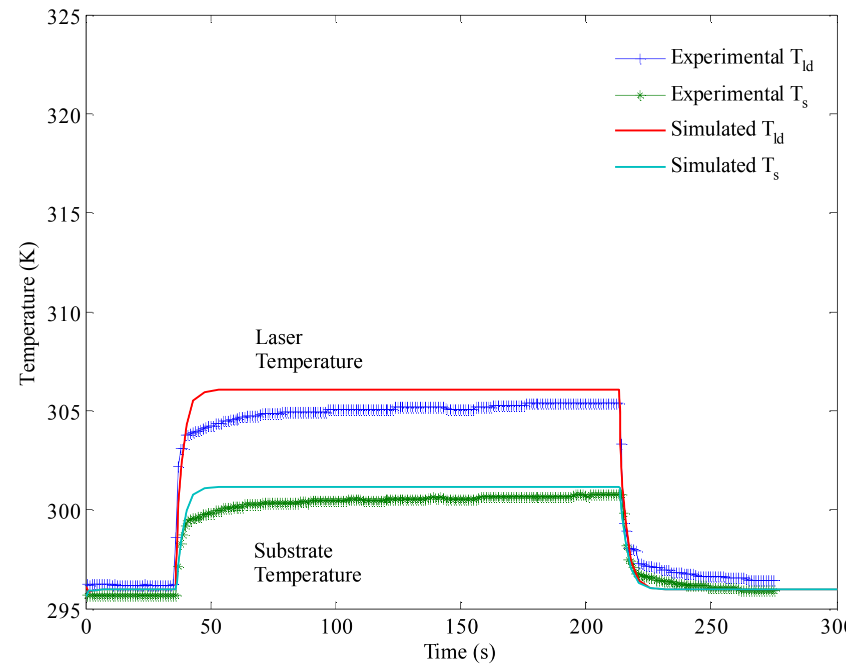


Parameter	Description	Initial value	Final Tuned Value	Units
$\lambda_{1,cond}$	thermal conductance between laser and substrate	0.292	0.36	W/K
$\lambda_{2,cond}$	thermal conductance between substrate and heat sink	0.192	0.34	W/K
C_{ld}	thermal capacitance of laser [C]	0.1396	0.3	J/K
C_s	thermal capacitance of substrate [C]	0.1819	0.5	J/K

Thermal Model Verification – Diode Laser Simulated vs. Experimental Data



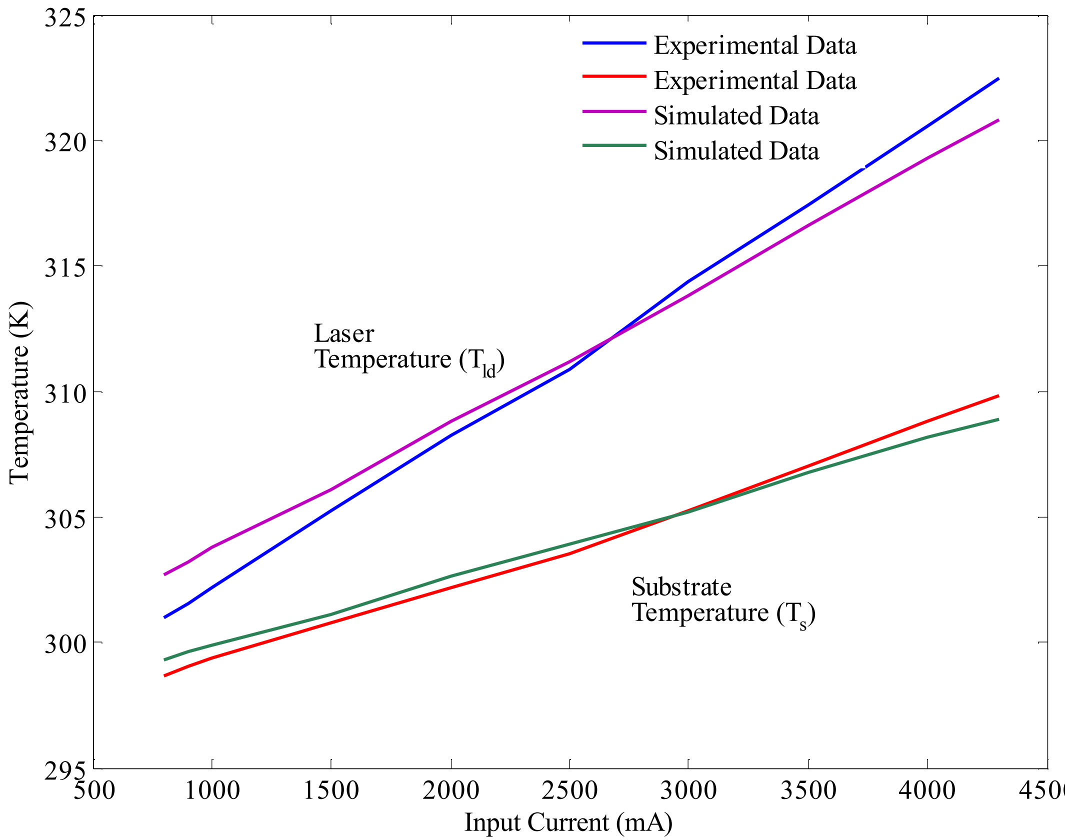
4300 mA input



1500 mA input

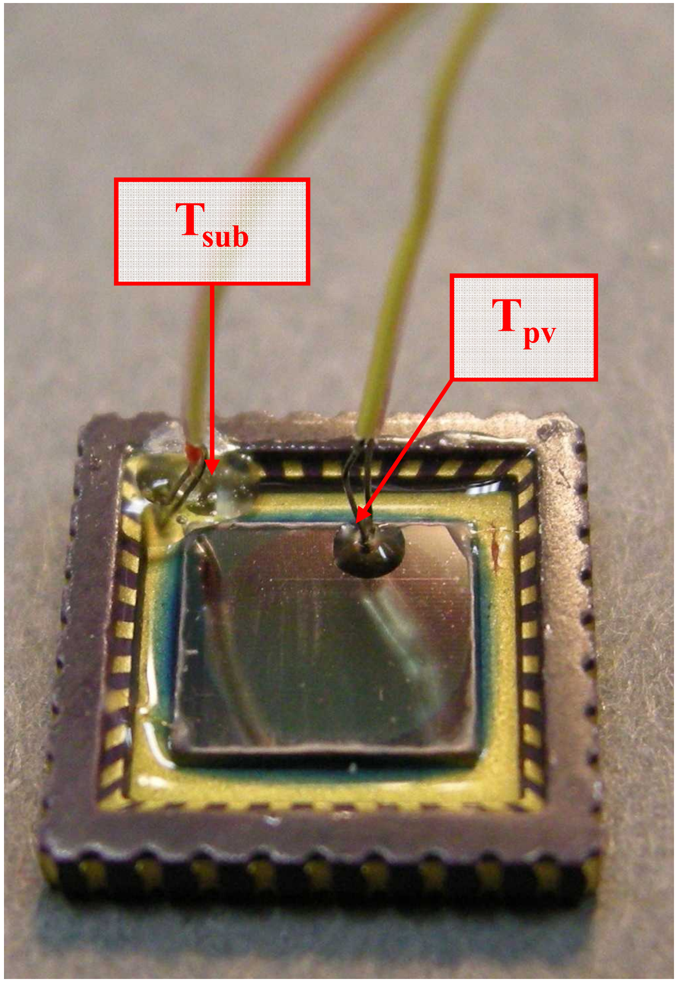
Thermal Model Verification – Diode Laser Simulated vs. Experimental Data

- **Results**
  - **Diode Laser Temperature**
    - **1.8 K at 800 mA**
  - **Substrate Temperature**
    - **0.9 K at 4300 mA**
  - **Heating curve matches well**
  - **Cooling curve**
    - **Possibly due to assumptions in thermal equation**



Thermal Model Verification – MPA Experimental Setup

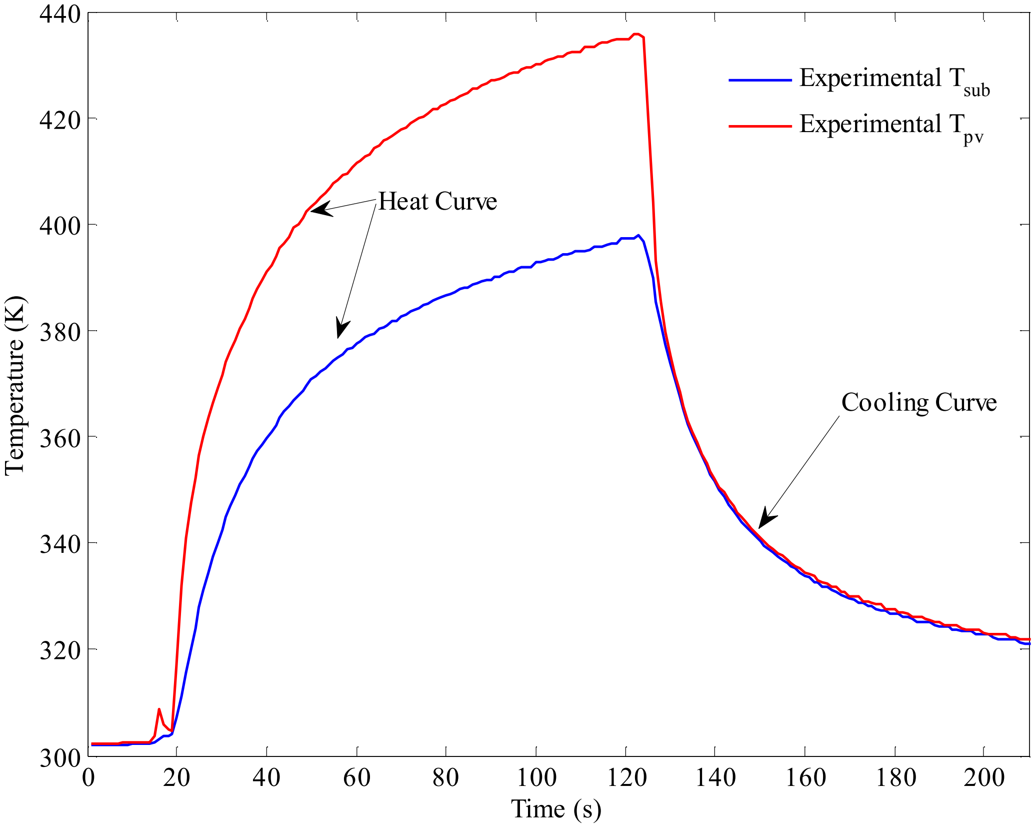
- 11 different optical power levels were used
- Fine wire thermocouples were used
- Input levels above 2.75 W saw excessive heating
- At 2.96 W – MPA reached 435 K (324.41 F) after 100 seconds



Thermal Model Verification – MPA Experimental Data

- MPA was illuminated between 200 and 100 seconds

- No steady state condition due to testing geometry



Input of 2.96 W

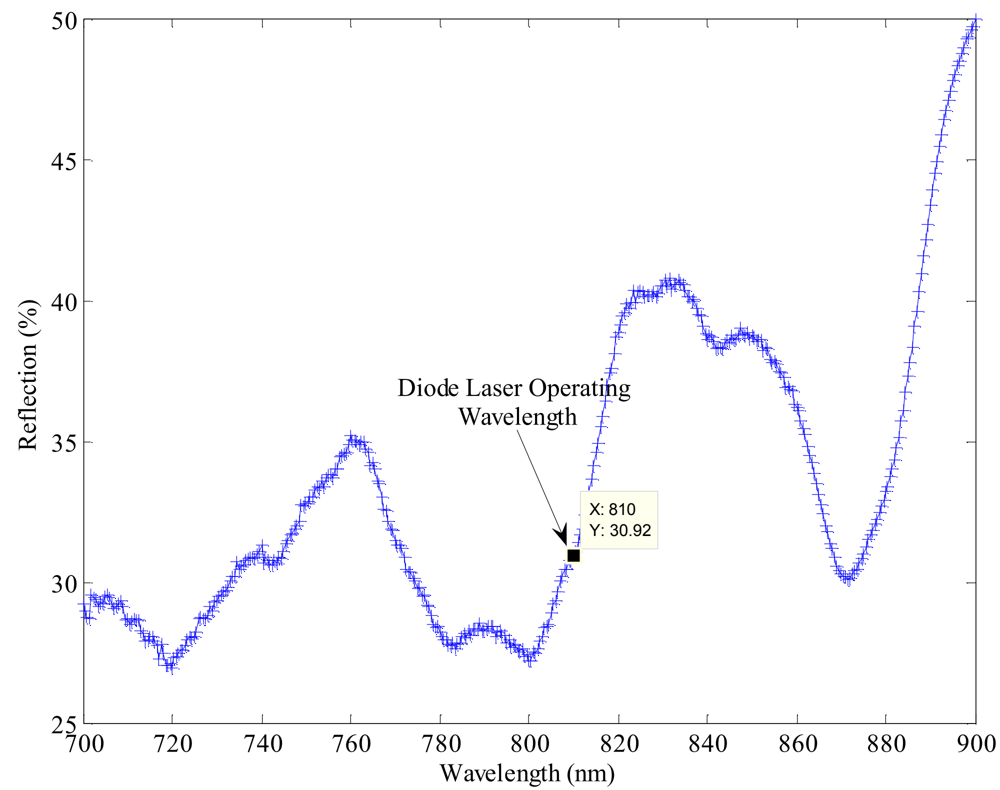
Thermal Model Verification – MPA
Calculation and Estimation of Parameters

Reflectivity $R_{mat}(\lambda)$ of device

- **Dependant on wavelength**
- **Cary spectrophotometer was used to measure reflectance**
- **810 um – 30.92% reflection**
- **Parameter related to efficiency of device**

$$\uparrow R_{mat}(\lambda) \xrightarrow{causes} \downarrow P_{thermal}$$

$$\uparrow R_{mat}(\lambda) \xrightarrow{causes} \downarrow Efficiency$$

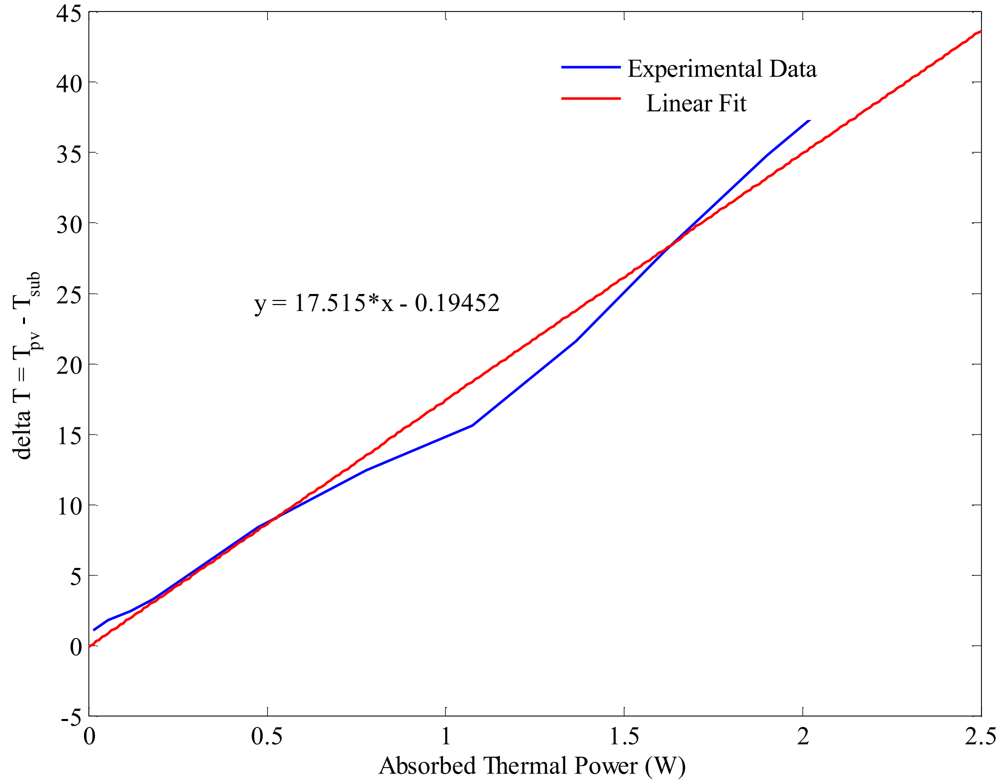


Thermal Model Verification – MPA
Calculation and Estimation of Parameters

- **Thermal Conductance for Node 1**

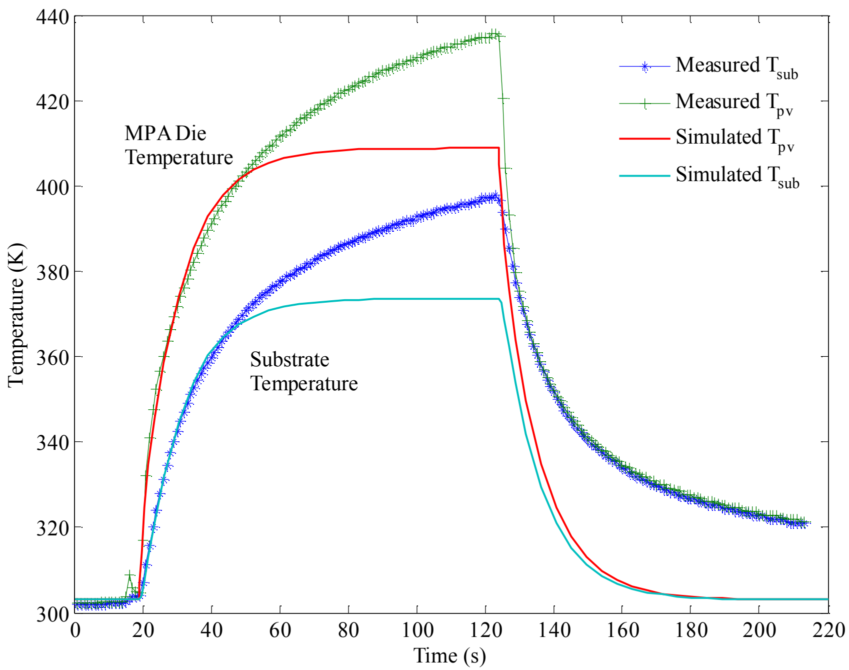
$$\frac{1}{\lambda_{a,cond}} = \frac{\Delta T}{P}$$

- **Three additional parameters cannot be experimentally calculated – used initial values from [2]**

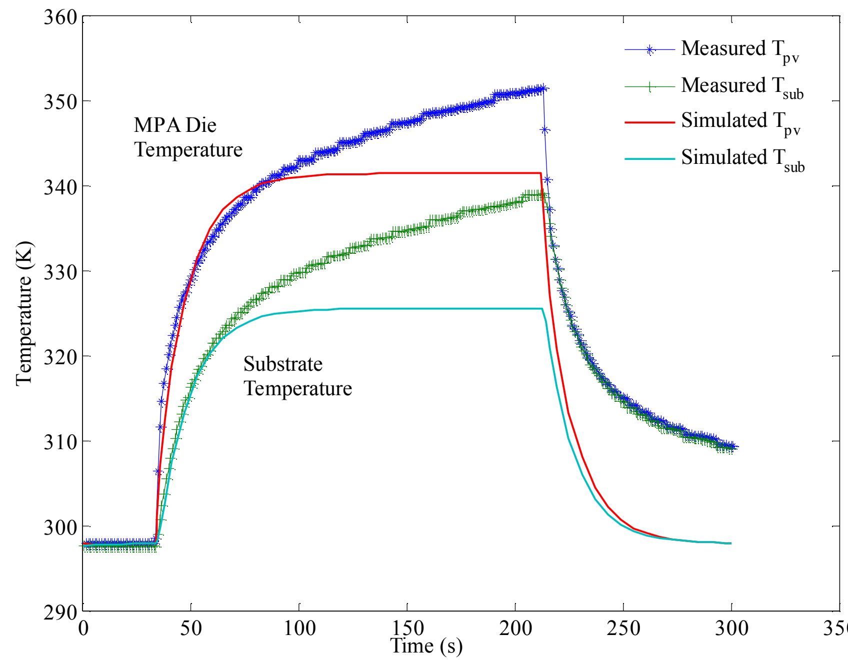


Parameter	Description	Initial value	Final Tuned Value	Units
$\lambda_{a,cond}$	thermal conductance between MPA die and metalized substrate	0.0571	0.058	W/K
$\lambda_{b,cond}$	thermal conductance between metalized substrate and package	0.0471	0.029	W/K
C_{pv}	thermal capacitance of MPA die	0.1396	0.11	J/K
C_{sub}	thermal capacitance of substrate	0.1819	0.2	J/K

Thermal Model Verification – MPA Simulated vs. Experimental Data



2.96 W Input



1.13 W Input

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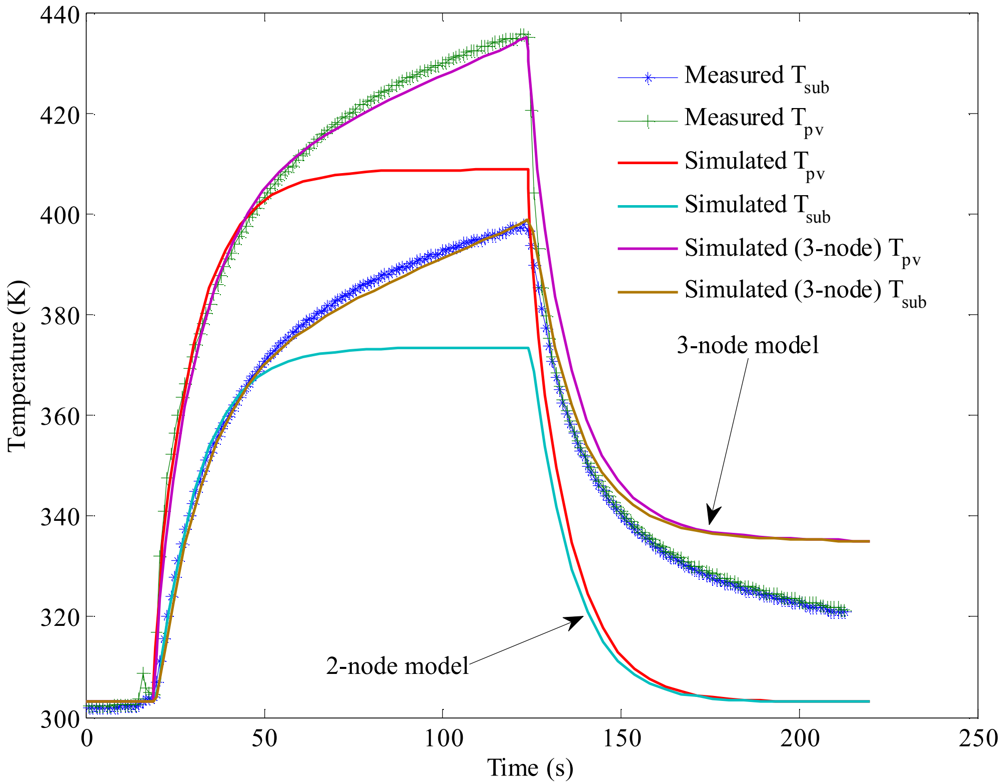
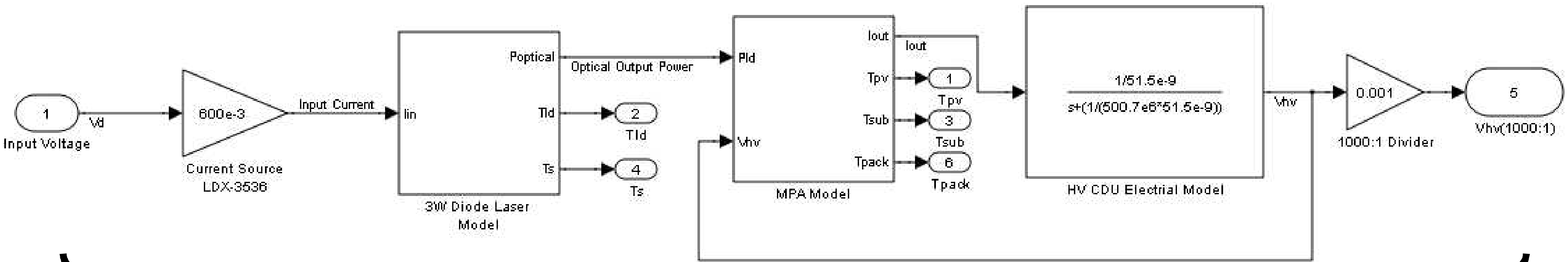
Thermal Model Verification – MPA Simulated vs. Experimental Data

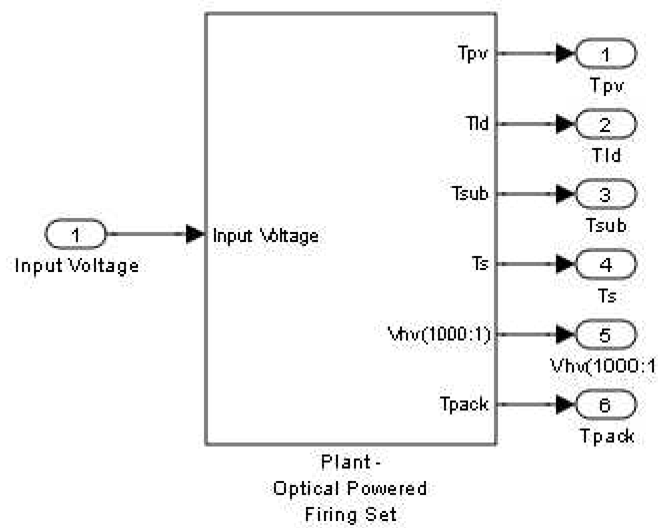


2.96 W Input

Control Solution
Optical Powered Firing Set



• **nonlinear ODE's**
were not linearized



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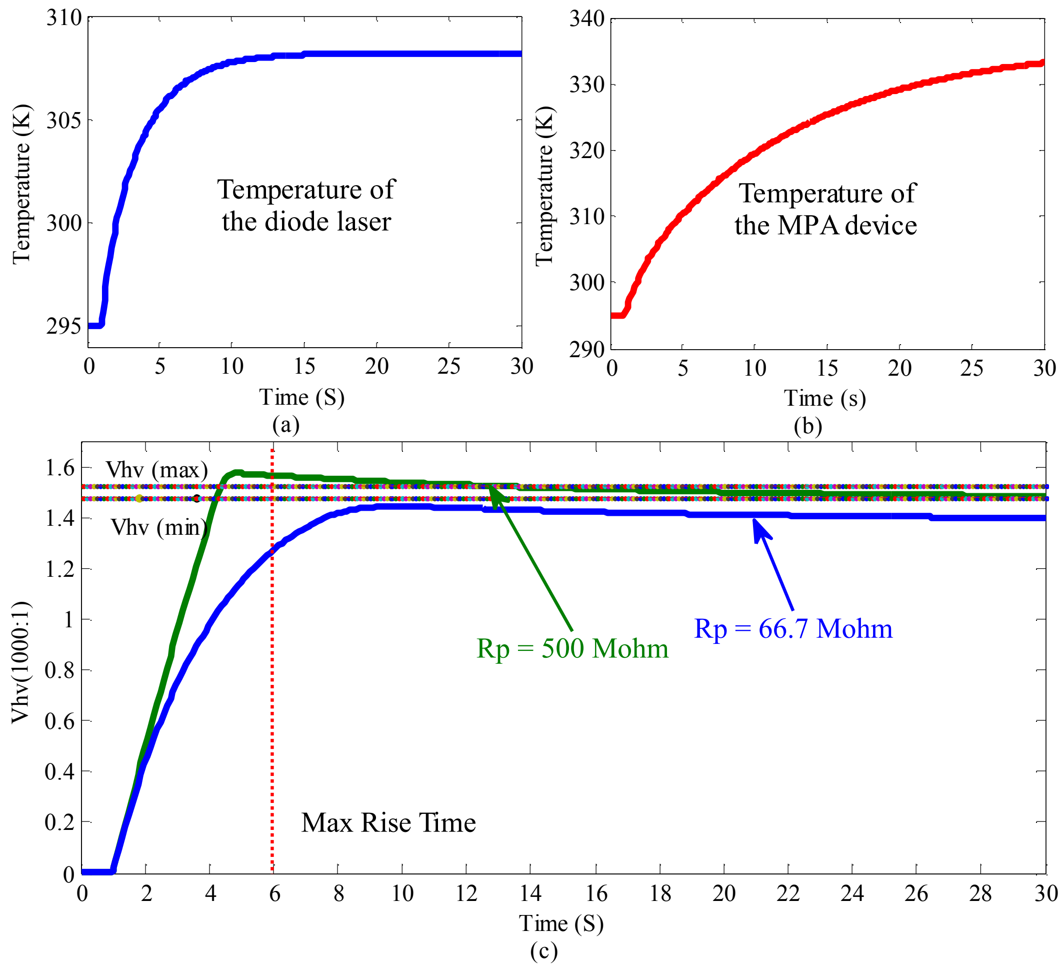
Control Solution - Optical Powered FS Simulated open loop response

- **Experimental data showed that at 2100 mA injected to diode laser would provide an output of about 1510 V**

- **Plant was simulated with 3.5 V (2100 mA)**

- **Varied Rp and input voltage but requirements could not be met**

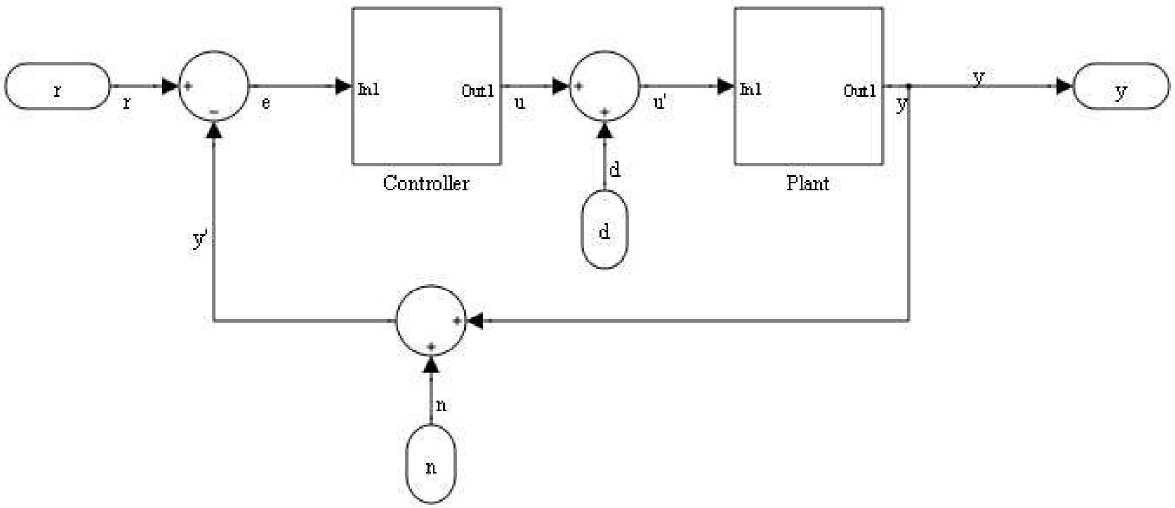


Control Solution
Closed loop feedback

- Keep output state at desired level

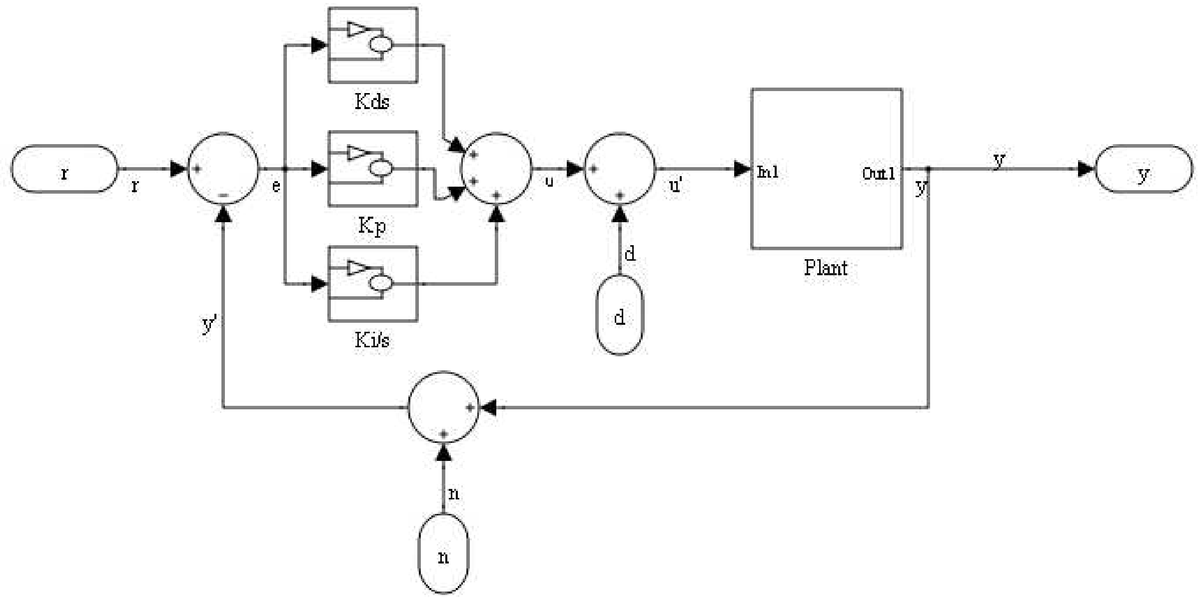
- output voltage will be feedback signal

- PID controller was chosen



Control Solution
Proportional-plus-Integral-plus-Derivative (PID) Controller

- **Chosen for easy implementation on a nonlinear plant**
- **Adjusts both transient and steady-state response**
- **Three tunable parameters – Kp, Kd, Ki**

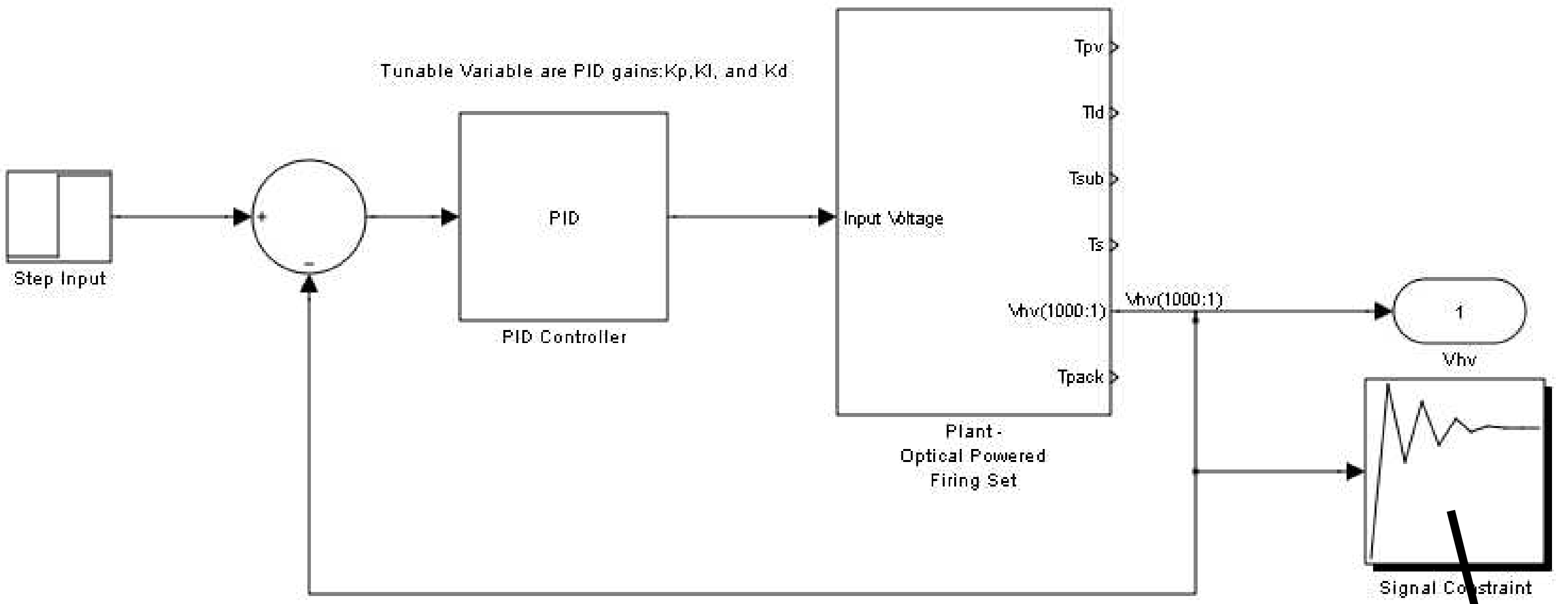


PID Tuning		Transient Response			Steady-State Error	Stability
		Rise time	Settling Time	Overshoot		
Increasing	Kp	Reduces	Slight Increase	Increase	Reduces	Degrade
	Ki	Slight Reduction	Increase	Increase	Large Reduction	Degrade
	Kd	Slight Reduction	Reduces	Reduces	Very slight change	Improve

$$C(s) = K_p + \frac{K_i}{s} + K_d s$$

PID Transfer function

Control Solution
PID Implementation



Optimization Progress

Iter	S-count	f(x)	max constraint	Step-size	Directional derivative	First-order optimality	Procedure
0	1	0	141				
1	10	0	54.05	2.04	0	1	infeasible
2	15	0	6.837	0.3	0	1	infeasible
3	20	0	0.02294	0.422	0	1	Hessian modified; infeasible
4	25	0	0.003286	2.99	0	0.000173	Hessian modified twice
5	30	0	0	0.168	0	0.0101	Hessian modified twice

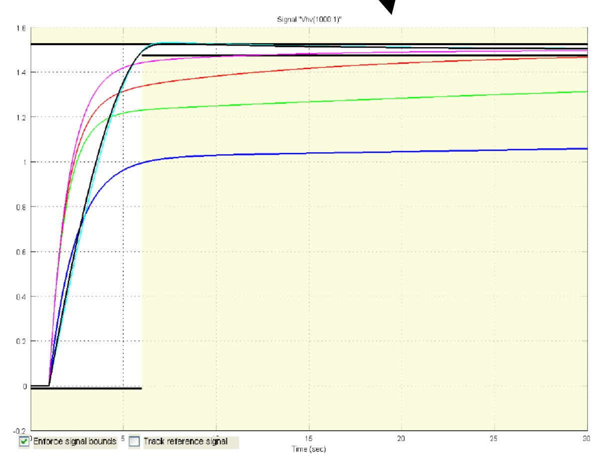
Successful termination.
Found a feasible or optimal solution within the specified tolerances.

Ki =

0.7178

Kp =

2.1887



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Control Solution
PID Implementation – Simulated Data

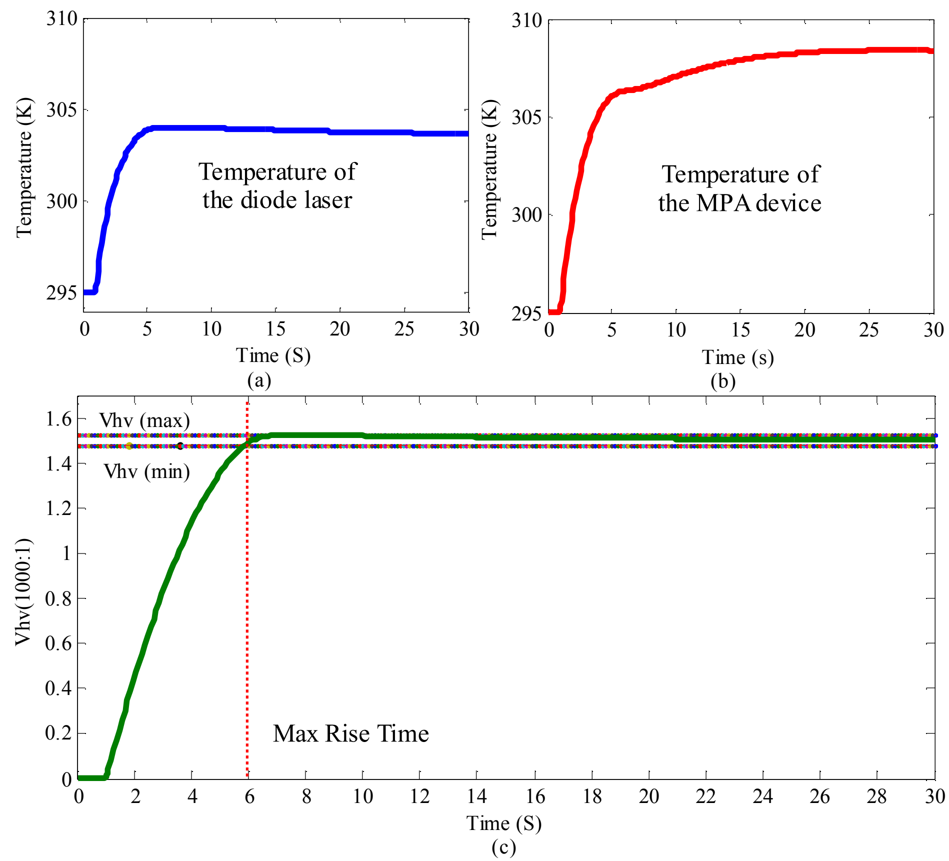
- **PID parameters used to meet requirements**

  Kp = 2.1887

  Ki = 0.7178

  Kd = 0

	Initial Requirements	Open Loop Response	Final System Response
Rise Time	5	2.633	3.7
Settling Time	NA	9.61	4.778
Max Regulation Votlage	1525	1574*	1525
Min Regulation Voltage	1475	1485	1475
Max Diode Laser Temperature	Minimize	308.2	303.7
Max MPA Temperature	Minimize	333.2	304.8
Adjustable Output	Desired	No*	Yes
		* did not meet requirements	



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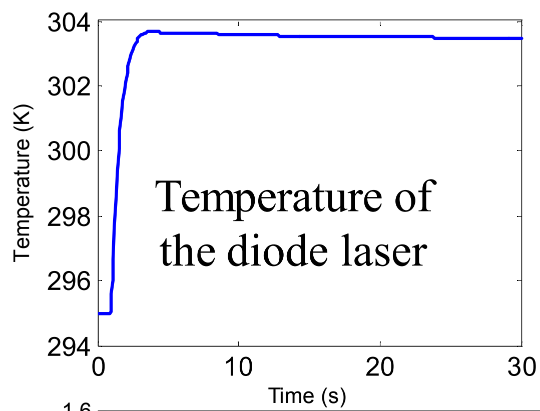
Control Solution
PID Implementation – Simulated Data

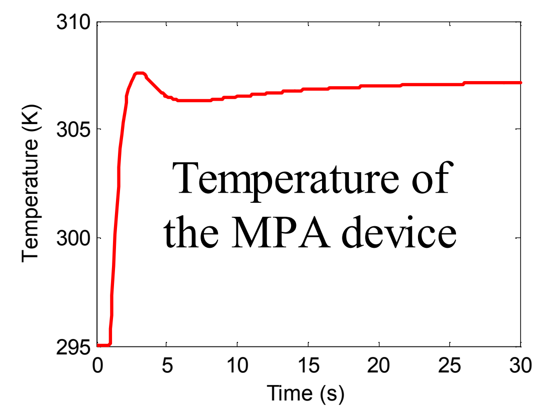
PID parameters when margin is added (Set for fastest rise time)

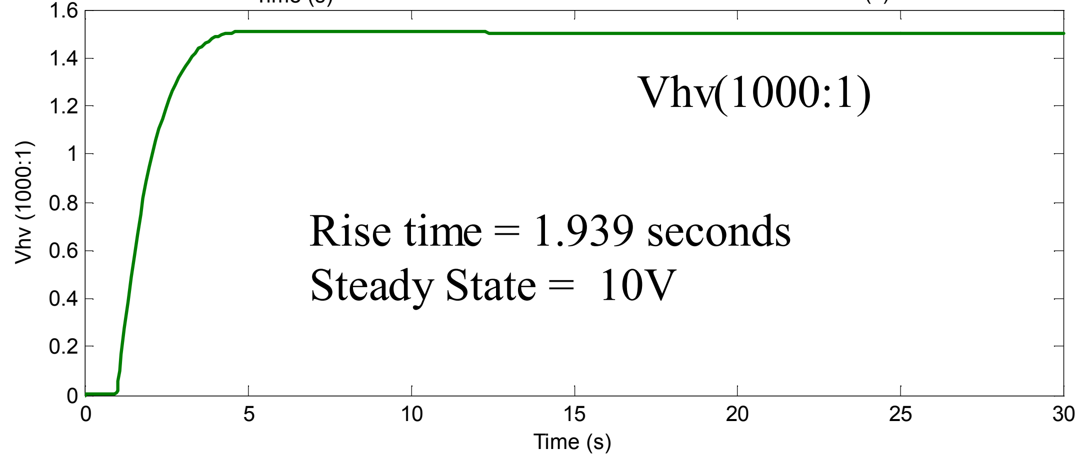
Kp = 5

Ki = 1.445

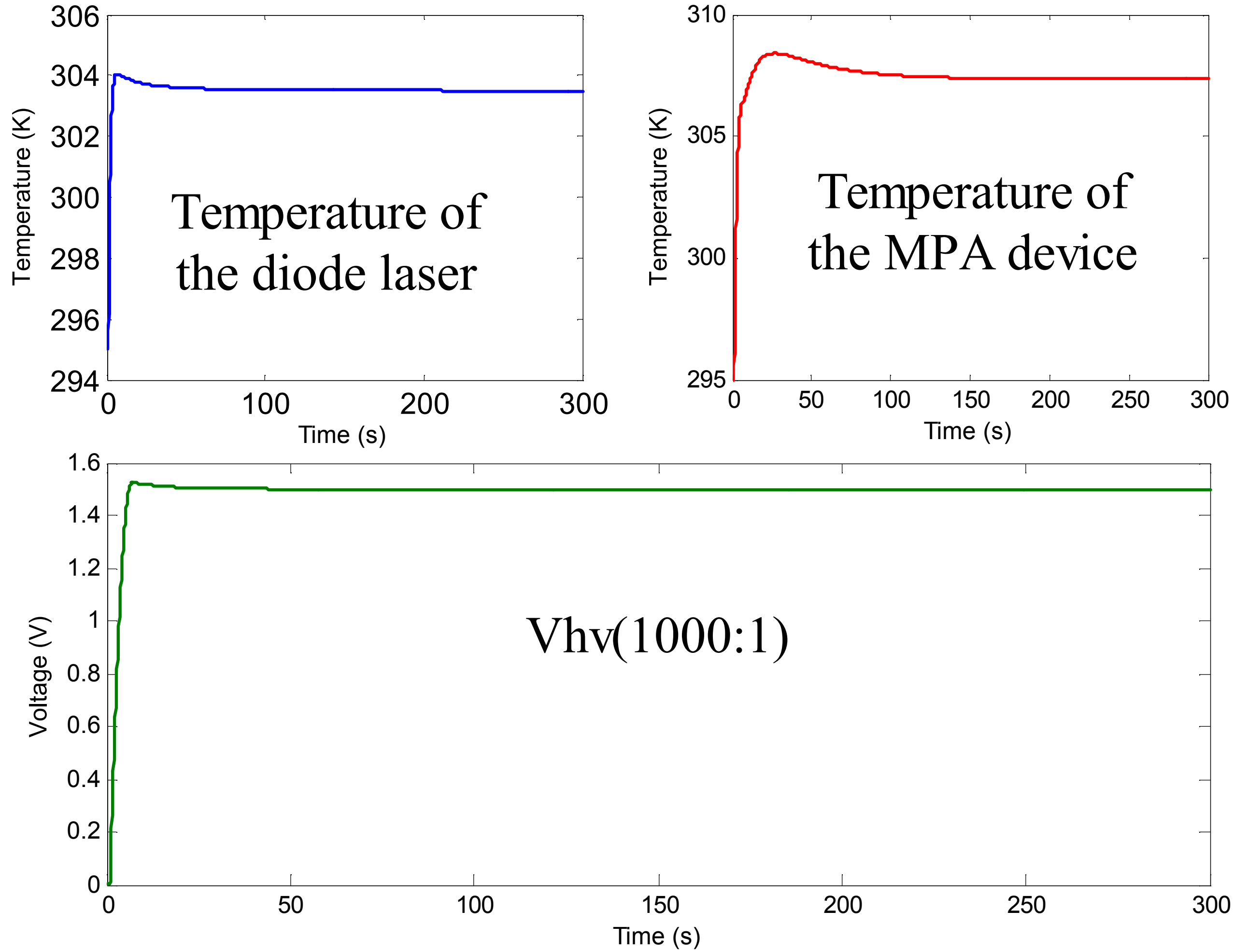
Kd = 0





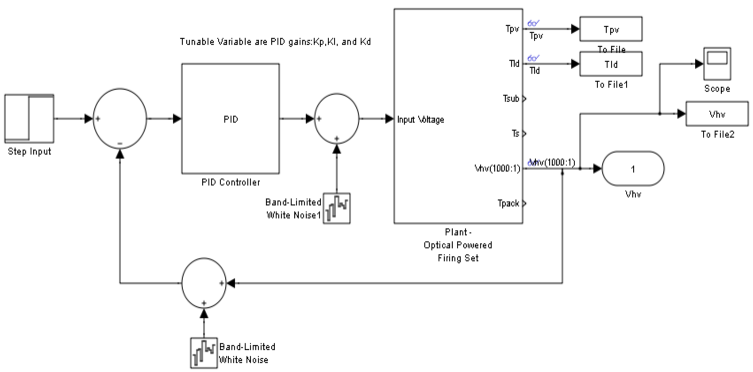


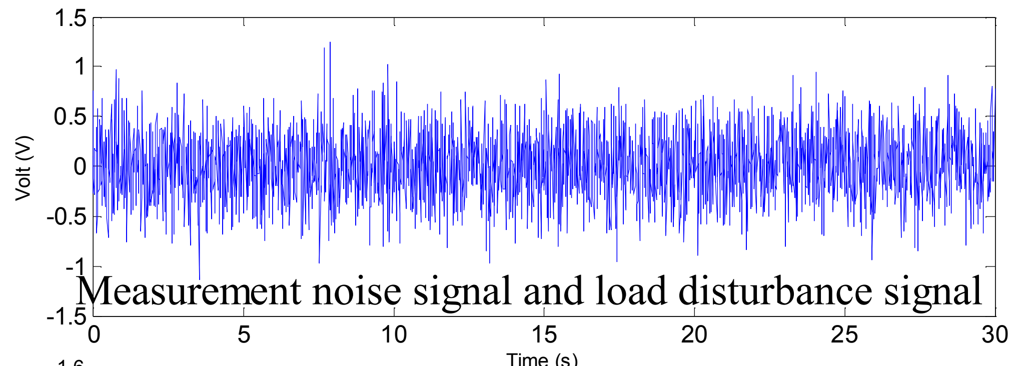
Control Solution
PID Implementation – Simulated Data

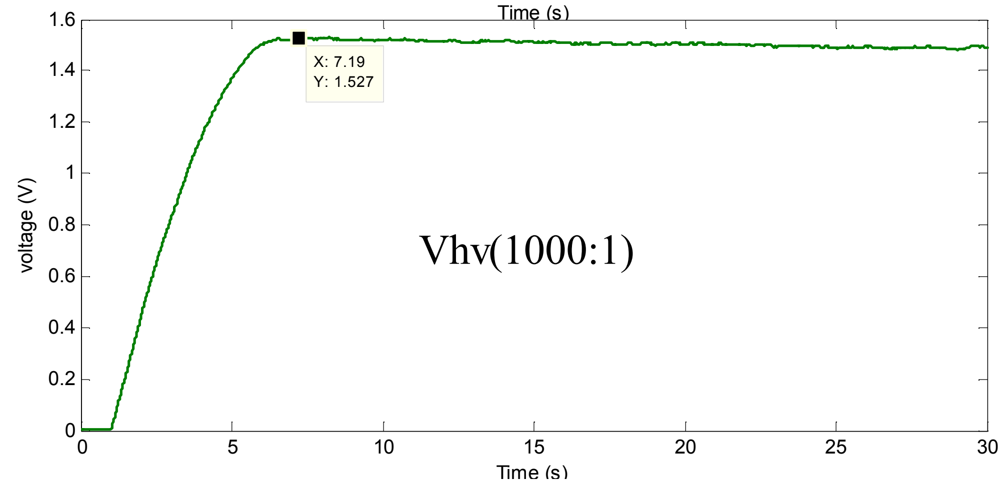


Control Solution
Simulated Data w/ Disturbances

- **Worse case with 0.5 V noise signal**
- **Noise is usually 10's mV**





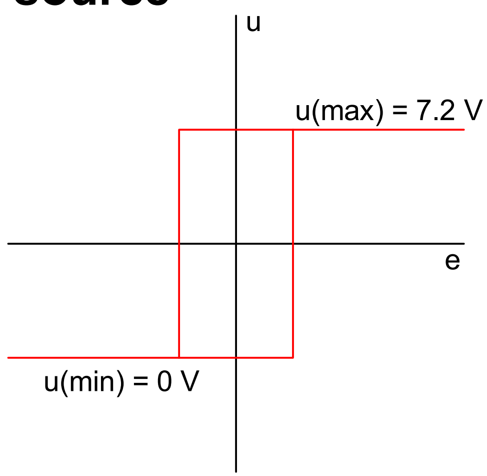


Control Solution
On-Off Control – Experimental Setup

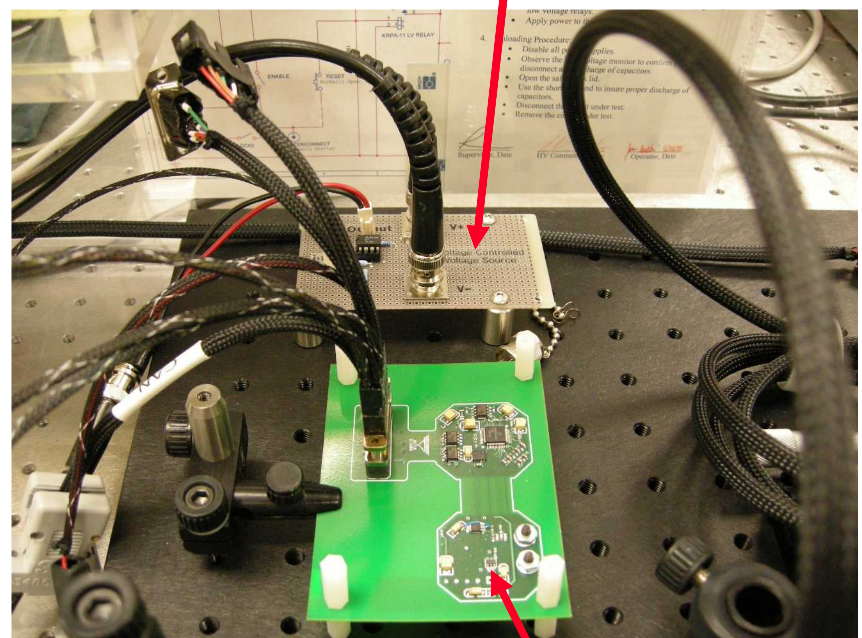
- **one of the simplest controllers**

$$u = \begin{cases} u_{\max} & \text{if } e>0 \\ u_{\min} & \text{if } e<0 \end{cases}$$

- **added hysteresis**
- **embedded code controls GPIO connected to voltage controlled voltage source**



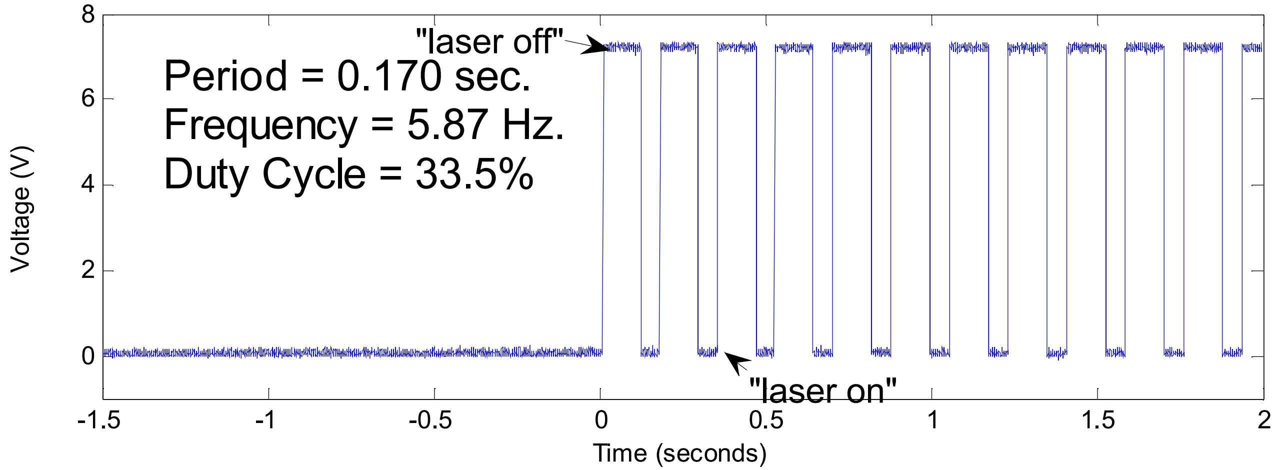
voltage controlled
voltage source

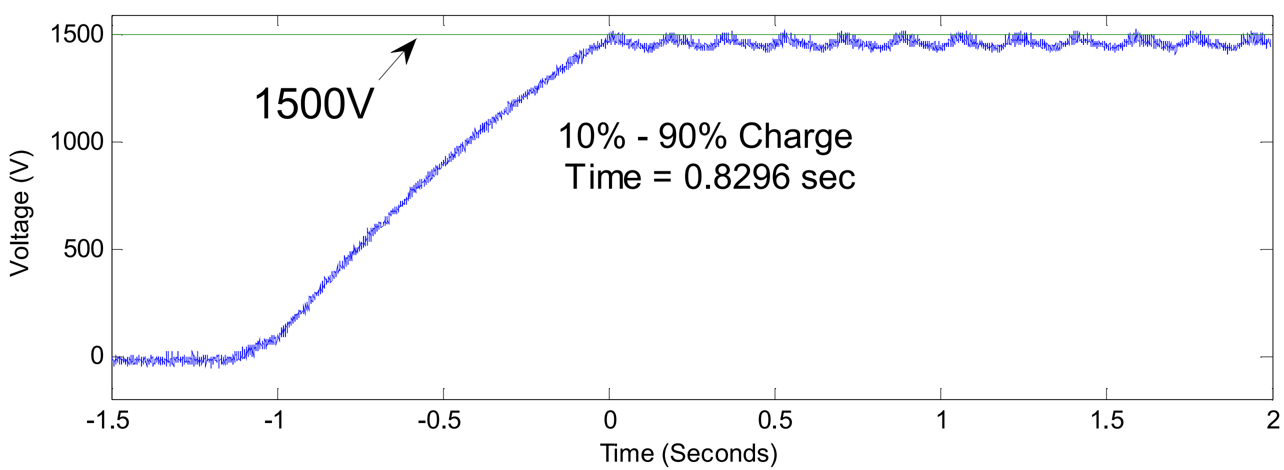


uprocessor board

MC56F8322

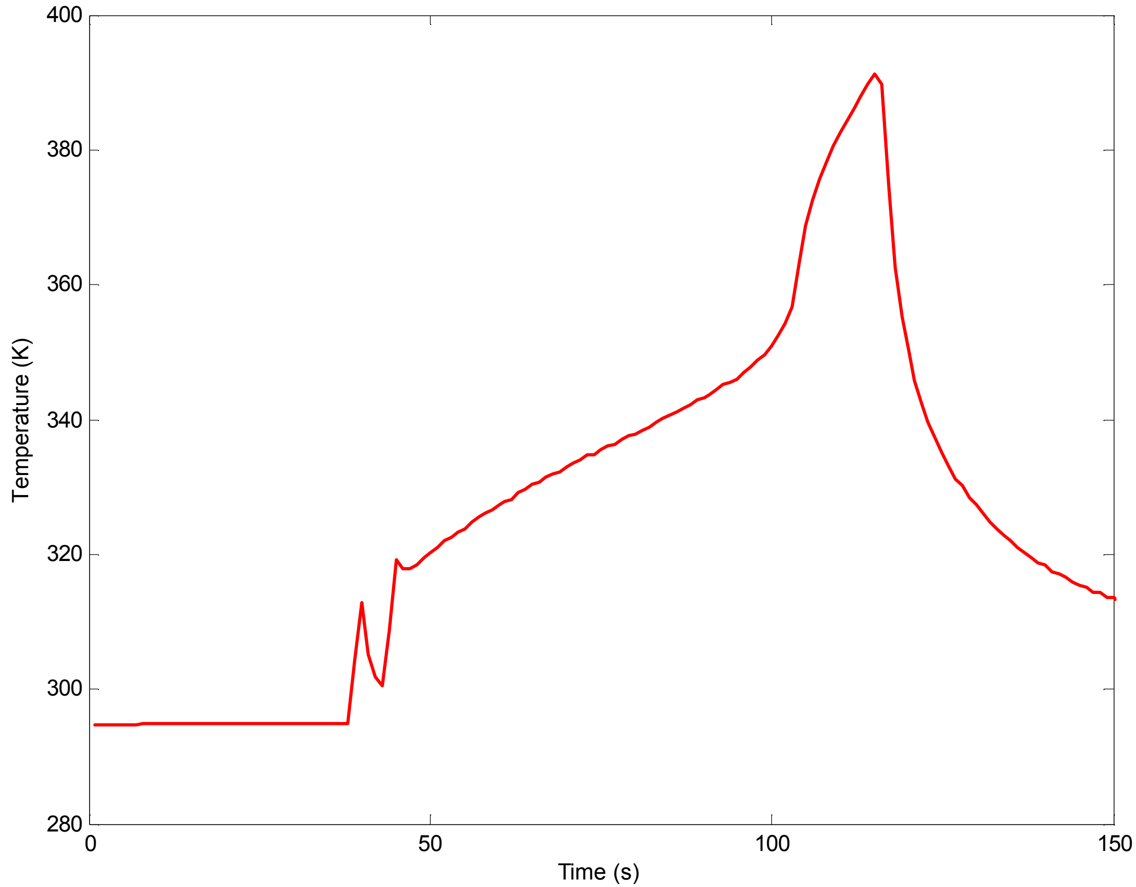
Control Solution
On-Off Control – Experimental Data



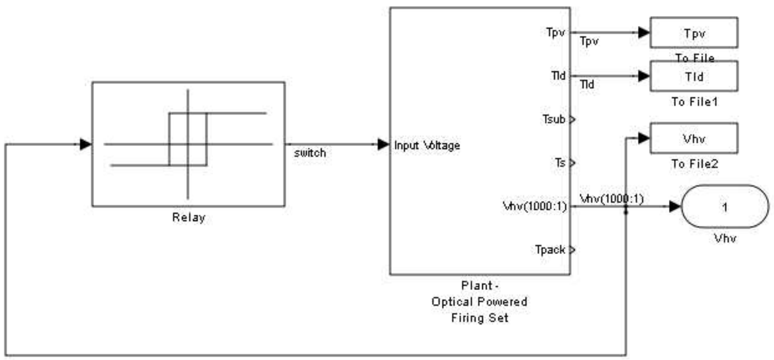


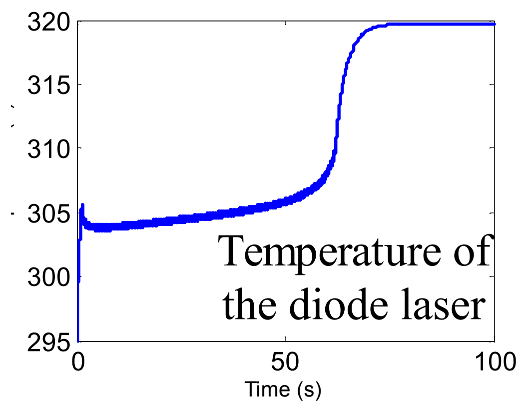
Control Solution
On-Off Control – Experimental Data

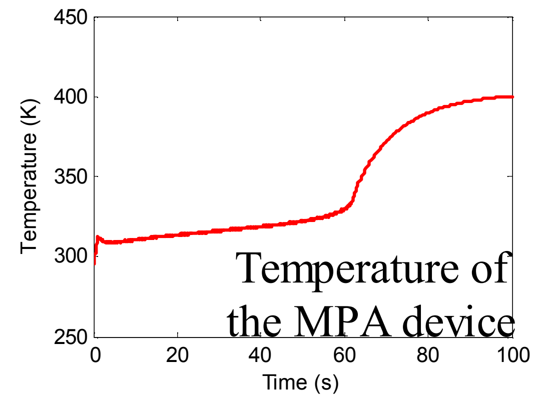
- **Temperature of MPA at 3W running On-Off controller**
- **at 100 seconds, HV output begins to fall off**
- **Initial dip occurs after HV output hits regulation voltage**

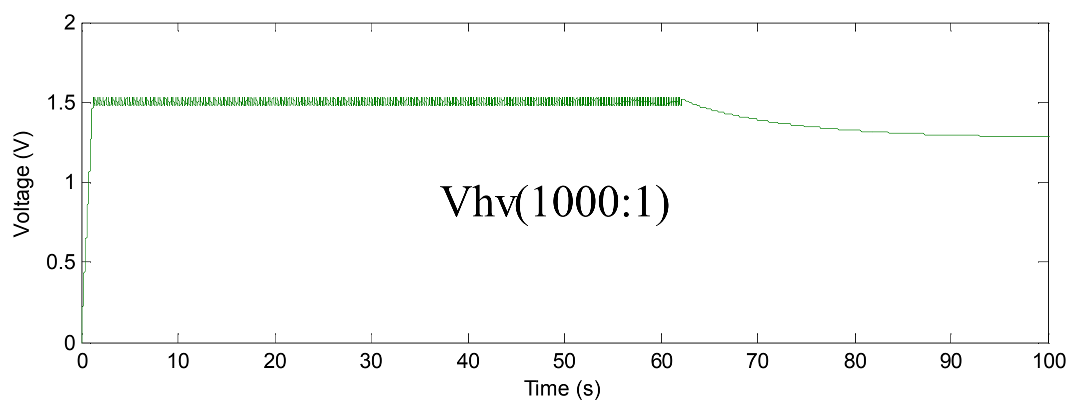


Control Solution
On-Off Control – Simulation Data









Conclusion & Recommendations

1. **Develop accurate models**
2. **Analyze and understand experimental data for model validation**
3. **Create flexible models**
4. **Linearize non-linear systems**
5. **Add temperature effects to diode laser**
6. **Refine MPA model**
7. **Check effect of illumination wavelength and efficiency**

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