ECE 695
Numerical Simulations
Lecture 24: Preparing Your Final Presentation

Prof. Peter Bermel

March 10, 2017

Outline

- Slide 1: Title Slide
- Slides 2-3: Problem Description
- Slides 4-5: Mathematical Model Formulation
- Slides 6-7: Proposed Problem Solution
- Slides 8-10: Problem Solution Implementation
- Slides 11-12: Results and Conclusions

Slide 1: Title Slide

- Class Name: ECE 695
- Instructor: Peter Bermel
- Your Name
- Presentation Date

Slides 2-3: Problem Description

- Describe the problem that is being solved
- Provide a justification for your investigation, citing relevant scientific literature.

Slides 2-3: Grading

	Unsatisfactory (0-3)	Needs Improvement (3-5)	Meets Expectation (5-8)	Exceeds Expectation (9-10)
Problem Description and Abstract (20%) **Describe the problem that is proposed to be solved and provide a justification using literature from relevant research papers.**	An unclear description of the problem statement and no relevant research backing provided.	Description of the problem statement needs refinement. Inadequate research relevance.	The problem is defined appropriately, but will need a little more refinement in terms of relevant literature.	The problem is very well defined, and the literature from relevant research work builds a persuasive case for the problem.

Slides 4-5: Mathematical Model Formulation

Present a physically realistic model related to the class that will help you solve the problem, which may include other relevant information from the scientific literature and/or generally accepted scientific or engineering principles. Identify key assumptions or limitations.

Slides 4-5: Grading

	Unsatisfactory(0-3)	Needs Improvement (3-5)	Meets Expectation (5-8)	Exceeds Expectation (9-10)
Problem Framing **Analytical (10%)** **Numerical (10%)** **Build both analytical and numerical models to help solve the problem.** **Interpret the problem (goals, information, limitations, and assumptions) in terms of relevant models, concepts or theories.**	-No analytical or mathematical model included in the report.	- An analytical and mathematical model is provided, but it is incorrect.	- An analytical model is provided, but needs minor improvisation. - A mathematical model is provided, but needs minor improvisation.	-Both the analytical and mathematical models provided accurately frame the problem.

Slides 6-7: Proposed Problem Solution

Define the approach

- Predictively compare and contrast alternate simulation techniques that will help you solve the problem. State boundary conditions, assumptions and limitations. Describe how this simulation or code implements the model. Provide an explanation of why you chose this particular computational tool.

Validate the solution

- The approach needs to be validated thoroughly. You can validate it by means of experimental data, a theoretical model, or previously documented test cases.

Slides 6-7: Grading

1. Student ID:	Unsatisfactory(0-3)	Needs Improvement (3-5)	Meets Expectation (5-8)	Exceeds Expectation (9-10)
Problem Synthesis **Define and Build (15%)** **Validate (10%)** **Evaluates the quality of the solution approach built to solve the problem. The simulation needs to be validated thoroughly with either experimental data or test cases. Predictively compare and contrast alternate solution processes in terms of relevant metrics (e.g., accuracy, computational time, etc.). Develop a simulation (potentially built on an existing platform like MEEP) to solve the problem.**	-The implementation of the solution approach is incorrect. -The solution approach is not validated	-The implementation of the solution approach serves the purpose, but needs refinement. -The validation process for the solution approach needs to be improved.	-The implementation of the solution approach provides the approach to solve the problem, but needs minor improvements. -The validation process for the solution approach needs minor improvements,	-The implementation of the solution approach is accurate. - The solution approach is validated appropriately.

Slides 8-10: Problem Solution Implementation

- Use your simulation to solve the problem to the extent possible.
- Explain your solution, noting any limitations or inaccuracies in the results, and discuss how these might be fixed.
- Briefly discuss how your approach can be applied to solve important research problems in the current scientific literature.

Slides 8-10: Grading

1. Student ID:	Unsatisfactory(0-3)	Needs Improvement (3-5)	Meets Expectation (5-8)	Exceeds Expectation (9-10)
Problem Implementation and Solution (30%) **Evaluates whether the student can use the model they build to solve the problem in a satisfactory and convincing fashion.** **Can this code help solve significant research problems of current interest?**	-No solution provided to the problem. -Does not discuss the application of solution for a related problem.	- A solution is provided, but it is incorrect or does not adequately address the issue or problem. -Not a clear description of how the solution can be used to resolve a related problem.	-A solution is provided that would adequately address the issue or problem, but it is presented in a way that is unclear, or improperly documented. -A discussion is included which describes the use of the current approach to solve related problems.	- A solution is provided that is correct, clear and well documented. -A very clear explanation is provided of how the current approach can help solve related problems of interest.

Slides 11-12: Results and Conclusions

- Summarize the modeling approach and results
- Show how the proposed solution addresses the problem/project.

Slides 11-12: Grading

	Unsatisfactory(0-3)	Needs Improvement (3-5)	Meets Expectation (5-8)	Exceeds Expectation (9-10)
Problem Description and Abstract (20%) **Describe the problem that is proposed to be solved and provide a justification using literature from relevant research papers.**	An unclear description of the problem statement and no relevant research backing provided.	Description of the problem statement needs refinement. Inadequate research relevance.	The problem is defined appropriately, but will need a little more refinement in terms of relevant literature.	The problem is very well defined, and the literature from relevant research work builds a persuasive case for the problem.
Problem Framing **Analytical (10%)** **Numerical (10%)** **Build both analytical and numerical models to help solve the problem.** **Interpret the problem (goals, information, limitations, and assumptions) in terms of relevant models, concepts or theories.**	-No analytical or mathematical model included in the report.	- An analytical and mathematical model is provided, but it is incorrect.	- An analytical model is provided, but needs minor improvisation. - A mathematical model is provided, but needs minor improvisation.	-Both the analytical and mathematical models provided accurately frame the problem.
Problem Synthesis **Define and Build (15%)** **Validate (10%)** **Evaluates the quality of the solution approach built to solve the problem. The simulation needs to be validated thoroughly with either experimental data or test cases. Predictively compare and contrast alternate solution processes in terms of relevant metrics (e.g., accuracy, computational time, etc.). Develop a simulation (potentially built on an existing platform like MEEP) to solve the problem.**	-The implementation of the solution approach is incorrect. -The solution approach is not validated	-The implementation of the solution approach serves the purpose, but needs refinement. -The validation process for the solution approach needs to be improved.	-The implementation of the solution approach provides the approach to solve the problem, but needs minor improvements. -The validation process for the solution approach needs minor improvements,	-The implementation of the solution approach is accurate. - The solution approach is validated appropriately.
Problem Implementation and Solution (30%) **Evaluates whether the student can use the model they build to solve the problem in a satisfactory and convincing fashion. Can this code help solve significant research problems of current interest?**	-No solution provided to the problem. -Does not discuss the application of solution for a related problem.	- A solution is provided, but it is incorrect or does not adequately address the issue or problem. -Not a clear description of how the solution can be used to resolve a related problem.	-A solution is provided that would adequately address the issue or problem, but it is presented in a way that is unclear, or improperly documented. -A discussion is included which describes the use of the current approach to solve related problems.	- A solution is provided that is correct, clear and well documented. -A very clear explanation is provided of how the current approach can help solve related problems of interest.
Organization of the Presentation (5%) **An important aspect of a project report is its clarity to the audience, as well as the professional nature of its presentation.**	Presentation is highly unclear and unprofessional.	Presentation has a number of unclear or unprofessional problems.	The presentation is mostly clear, but has 5 or fewer minor points of confusion.	The presentation is highly clear, and has

Spring 2015 Final Project Abstracts

- **Presenter**: Haejun Chung
- **Title**: Understanding light trapping in nano-textured silicon thin-film solar cells by a novel simulation approach
- **Abstract**: A significant barrier to highly efficient thin-film crystalline silicon photovoltaics is incomplete light trapping, driven by the indirect bandgap of silicon. Recent efforts to address this gap through plasmonics do not always clearly demonstrate how much useful absorption is enhanced, as opposed to parasitic absorption that cannot improve efficiencies. In this work, we have developed a new method suitable for capturing these parasitic losses within finite-difference time-domain simulations, and we have investigated parasitic losses in three classical types of light trapping cells (e.g., periodic, random and plasmonic). For experimental parameters previously employed, we found that we could reproduce the overall absorption curves in each case, and that combining random front texturing with plasmonic nanoparticles (NPs) in back generally displays the highest useful integrated absorption. Therefore, in order to approach the performance limits, we proceeded to optimize a 2 mm-thick c-Si cell with a correlated random front texturing and a plasmonic back reflector. It is shown that 600 nm diameter NP strongly enhances light absorption for wavelengths ranging from 700 nm to 1100 nm, while a correlated random surface also provides much broader absorption enhancement. As an optimized result, 36.60 mA/cm^2 Jsc is achieved after subtracting 3.74 mA/cm^2 of parasitic loss in the 2 mm-thick c-Si cell. This result is slightly above Lambertian limit (35 mA/cm^2), although there still may be challenges in realizing this value experimentally.

Spring 2015 Final Project Abstracts

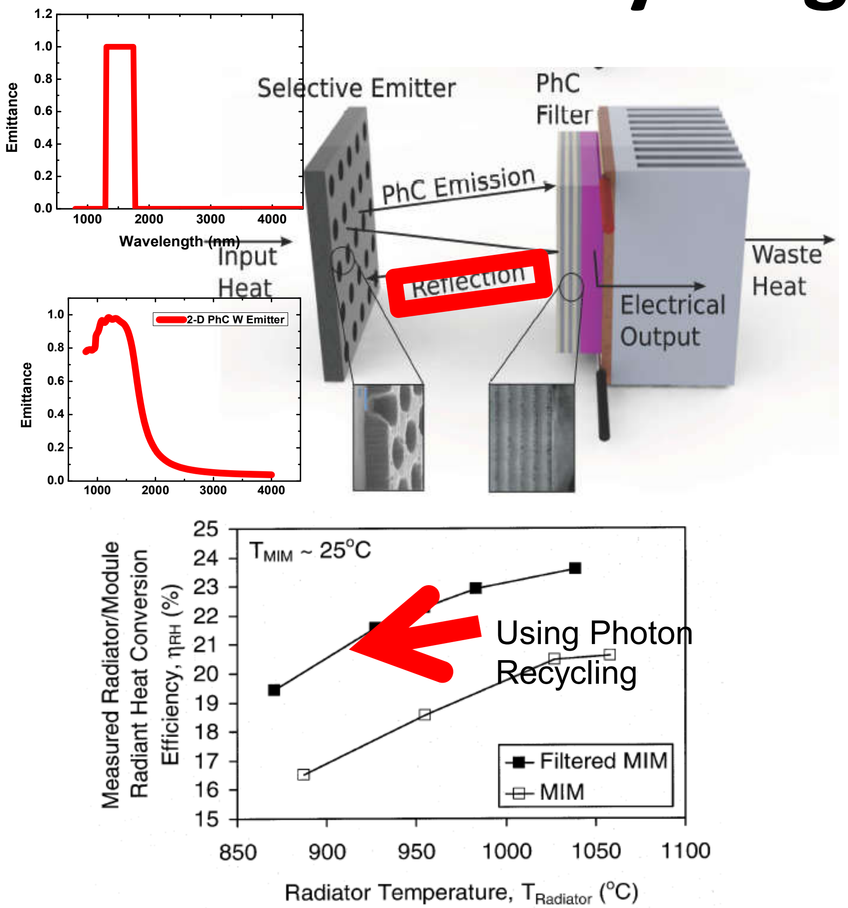
- **Presenter**: Zhiguang Zhou
- **Title**: Integrated Photonic Crystal Selective Emitter Design for High-Performance Thermophotovoltaics
- **Abstract**: Conventional thermophotovoltaic (TPV) systems convert heat to electricity via thermal radiation on photovoltaic (PV) diodes; however, they suffer from low efficiency due to broadband blackbody radiation. Photon recycling offer potentially improved performance, but require extremely close spacing between the emitter and receiver. In this project, we consider the impact of using an alternative approach, the integrated photonic crystal selective emitter (IPSE). Emittance spectra of different IPSE designs are examined using S-matrix algorithm and finite difference time-domain (FDTD). Current transport simulations show that IPSEs can significantly suppress parasitic losses and increase the conversion efficiencies for realistic materials from 35.2% up to a value of 41.9% at 1573 K. The physics of photon recycling and the impact of IPSEs on the TPV system are discussed from the aspect of thermal radiation.

- **Presenter**: Min Teng
- **Title**: BPM simulation on Multi-mode Interference (MMI) device
- **Abstract**: The project mainly covers simulation aspects of Multi-mode Interference (MMI) device using Beam propagation Method (BPM). Other algorithms are also applied to validate the BPM simulation on MMI. In simulation, mode evolution based on self-imaging effect is studied, according to which MMI coupler can be designed as optical switch.

Integrated Photonic Crystal Selective Emitter for High-Performance Thermophotovoltaics(TPV)

Zhiguang Zhou
ECE695 Final Project
Instructor: Peter Bermel
4/23/2015

Photon Recycling in TPV Systems



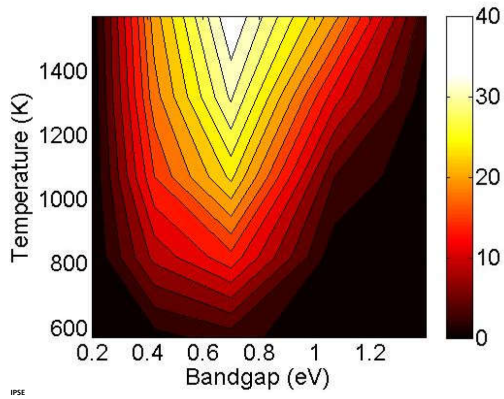
- TPV converts thermal energy into electricity via thermal radiation and photovoltaic effect.
- 2-D photonic Crystals enable selective thermal emission for highly effective TPV energy conversion
- The photonic crystal filter enables multi-reflections between the emitter and the filter.
- Low energy photons are recycled and reabsorbed by the emitter

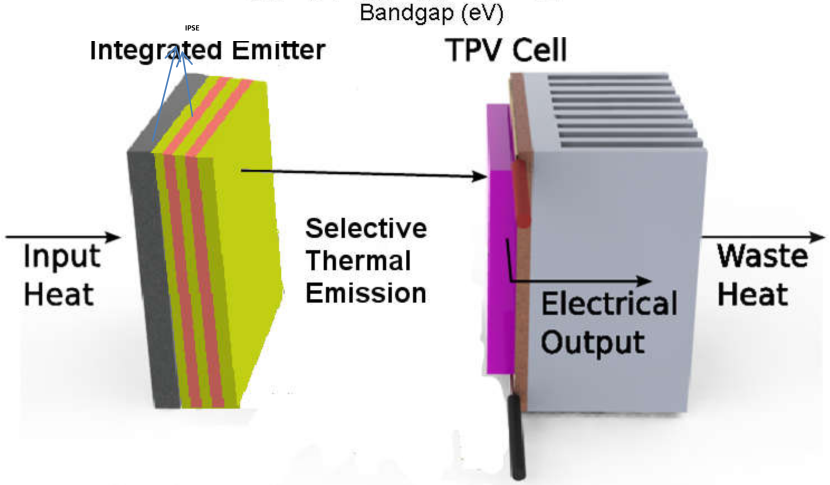
$$\eta = \frac{I_{sc}V_{oc}FF}{P_{em} - P_{re}}$$

- However, sufficient photon recycling requires high view factors between the emitter and the filter.

P. Bermel *et al.*, Opt. Express **18**, A314 (2010).
B. Wernsman *et al.*, *IEEE Trans. Electron Dev.* **51**, 512 (2004)
P. Bermel *et al. in TPV9: Ninth World Conference on Thermophotovoltaic Generation of Electricity.* (2010).

Integrated Emitter instead of Cold-side Filter





Z.Zhou *et al.*, *Energ. Convers. Manage.* **97** (2015)

- W has highest estimated conversion efficiency of 35% at 1573K ,$E_g = 0.7eV$ with photon recycling
- Corresponding geometry is:

$$a_x = a_y = 0.969\mu m;$$
$$d = 3.228\mu m;$$
$$r = 0.397\mu m$$

- Integrated photonic crystal selective emitter (IPSE).
- The view factor from the emitter to the filter approaches unity
- Different IPSE designs are examined in this work.

Mathematical Formulations

3-D FDTD simulation:

$$-\mu\frac{\partial \boldsymbol{H}}{\partial t} = \boldsymbol{\nabla}\times\boldsymbol{E}$$
$$\frac{\partial \boldsymbol{E}}{\partial t} = \frac{1}{\epsilon}\boldsymbol{\nabla}\times\boldsymbol{H} - \frac{1}{\epsilon}\boldsymbol{J}$$

Models for metals:

$$\varepsilon_r(\omega) = \varepsilon_{r,\infty} + \sum_{m=0}^{M}\frac{G_m{\Omega_m}^2}{{\omega_m}^2 - \omega^2 + j\omega\Gamma_m}$$

Where, $\varepsilon_{r,\infty}$ is the dielectric constant at infinite frequency; G_m is the strength of the oscillator; Ω_m is the plasma frequency; ω_m is the resonant frequency; Γ_m is the damping factor

Taflove A, Hagness SC. Computational electrodynamics: the finite-difference time-domain method. Artech House; 2000.
Roberts S., *Phys Rev* 1959;114:104–15.

1-D S-Matrices simulation:

$$\begin{pmatrix} u^{p+1} \\ d^0 \end{pmatrix} = \begin{pmatrix} {T_{uu}}^p & {R_{ud}}^p \\ {R_{du}}^p & {T_{dd}}^p \end{pmatrix}\begin{pmatrix} u^0 \\ d^{p+1} \end{pmatrix}$$

Quarter-wave stack(QWS) design:

$$t_i = \frac{\lambda_0}{4n_i}$$

Where t_i is the thickness of the ith material, whose refractive index is n_i; λ_0 is the cutoff wavelength of the stopband; usually $i = 1{,}2$

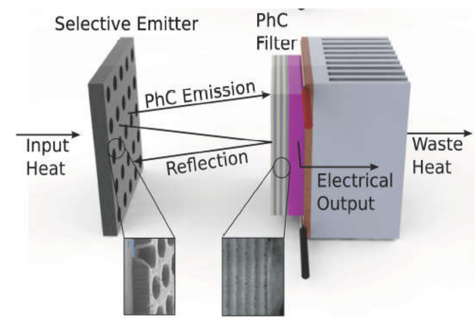
Rugate filter design:

$$\ln(n_i) = \frac{\ln(n_l/n_h)}{2\cos(\pi/2m)}\cos\frac{\pi\,(i-1/2)}{m} + \frac{1}{2}\ln(n_l n_h)$$
$$t_i = \frac{\lambda_0}{4m}$$

Y. Fink *et al, Science* **282**, 1679 (1998).
Carniglia CK. *Appl Opt* 1989;28:2820–3.

Mathematical Formulations

- TPV conversion efficiency calculations



$$\eta = \frac{I_{sc} V_{oc} FF}{P_{em} - P_{re}}$$

Short-circuit current:

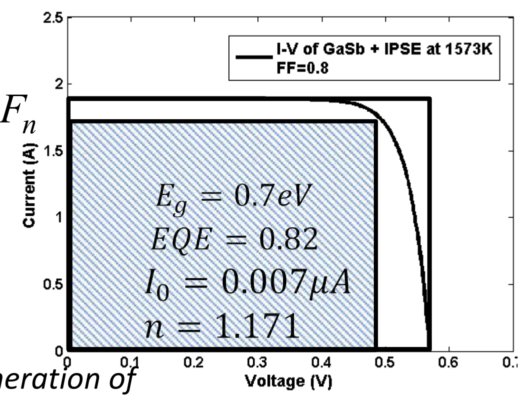
$$I_{sc}(\lambda) = \sum_{n=0,2...}^{\infty} A_1 \frac{2qcEQE(\lambda)(R_1 R_2)^{n/2} \varepsilon(\lambda)}{\lambda^4 \left[\exp\left(\frac{hc}{\lambda kT}\right) - 1\right]} F_n$$

Recycled power:

$$P_{re}(\lambda) = \sum_{n=1,3...}^{\infty} A_1 I_{BB}(\lambda) R_2^{(n+1)/2} R_1^{(n-1)/2} (1 - R_1) \varepsilon(\lambda) F_n$$

I-V calculation:

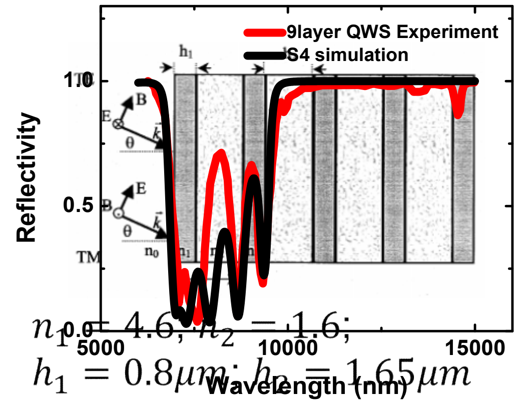
$$I = I_{sc} - I_0 \left[\exp\left(\frac{qV}{nkT}\right) - 1\right]$$



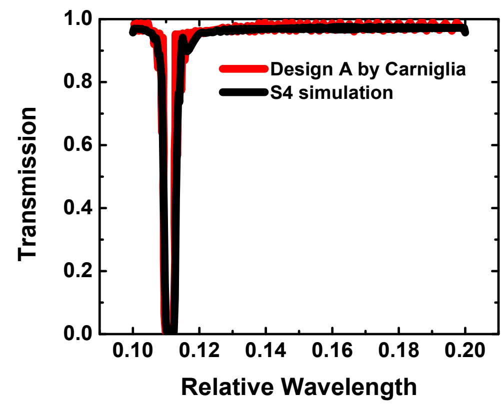
P. Bermel *et al. in TPV9: Ninth World Conference on Thermophotovoltaic Generation of Electricity.* (2010).

Numerical Approach and Validation

- The S4 (S-matrices) simulation first check the performance of the designed filters of IPSE.
  - Quick and accurate for 1-D stratified structure
- Assumptions
  - periodic boundary conditions in the transverse direction;
  - non-dispersive material;
  - the optical properties of the materials at high temperatures are the same as room temperature
- Validation: The reflectivity spectrum of a 9-layer QWS fabricated by Fink et al; Rugate filter proposed by Carniglia



$n_1 = 4.6; n_2 = 1.6;$
$h_1 = 0.8\mu m; h_2 = 1.65\mu m$

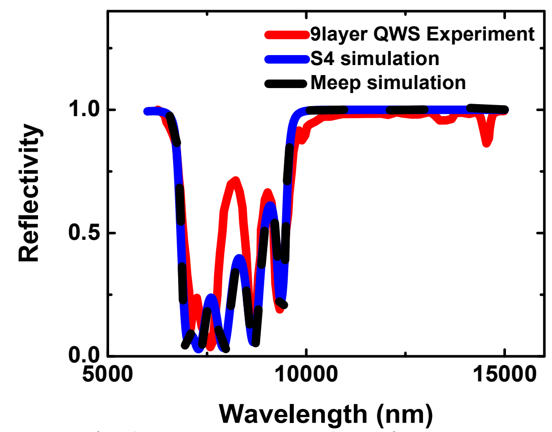


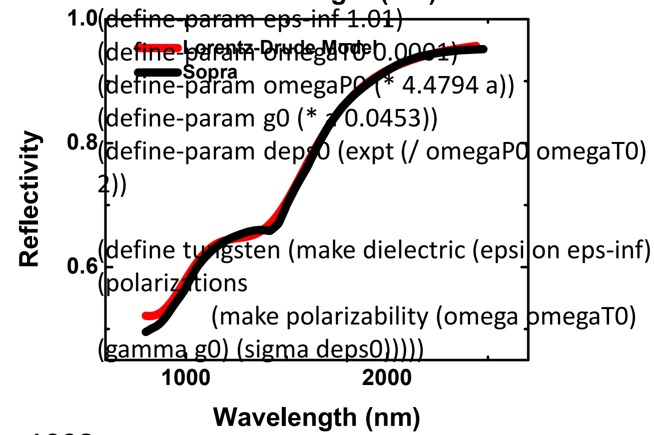
Y. Fink *et. al Science* **282**, 1679 (1998).

Carniglia CK. *Appl Opt* 1989;28:2820–3.

Numerical Approach and Validation

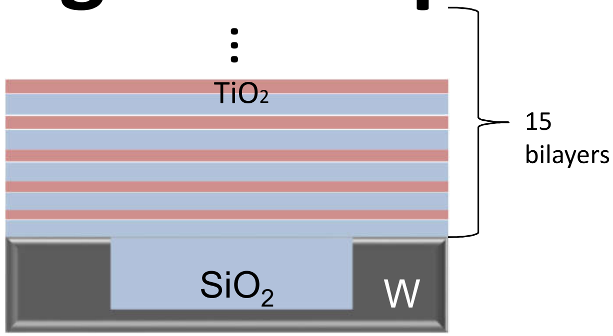
- Designs that can potentially improve the TPV conversion efficiencies are further examined by MEEP simulations:
- Capable of complex 3-D geometries
- Slow for large structure
- Assumptions:
  - •periodic boundary conditions in the transverse direction;
  - •non-dispersive material;
  - •the optical properties of the materials at high temperatures are the same as room temperature
- Validation: The reflectivity spectrum of a 9-layer QWS fabricated by Fink et al; The Lorentz-Drude model of Tungsten(W);





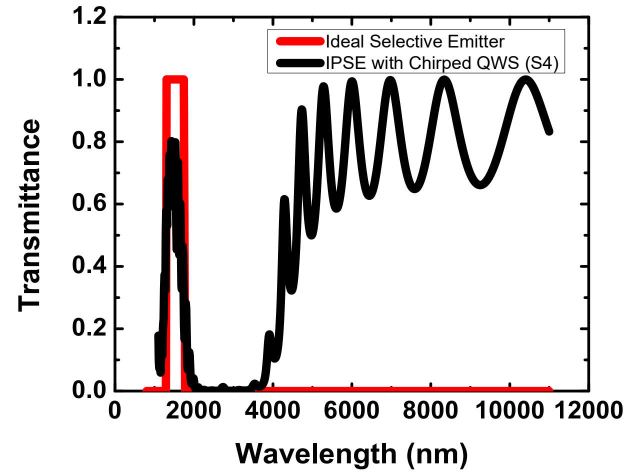
Y. Fink *et. al Science* **282**, 1679 (1998).
Palik ED. Handbook of optical constants of solids, vol. 3 Elsevier; 1998.

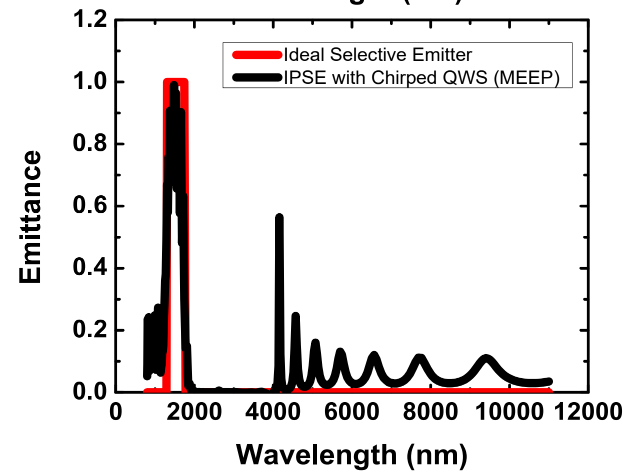
IPSE Design – Chirped QWS



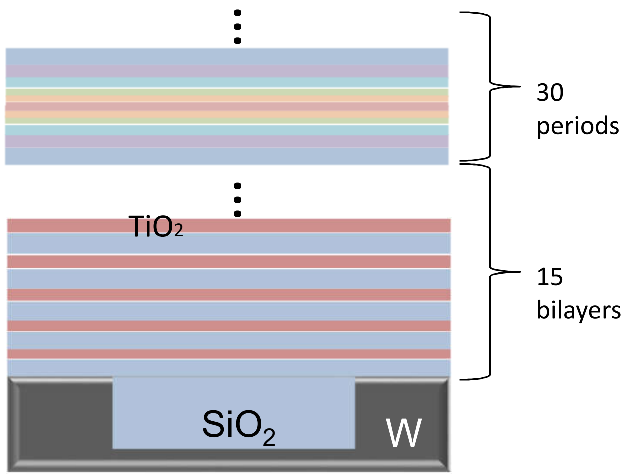
$n_{SiO2} = 1.46$; $n_{TiO2} = 2.5$;
$t_{SiO2} = 314nm$; $t_{TiO2} = 183nm$;
$chirping\ rate = 5.1\%$

- Conversion efficiency @ 1573K: 38.2%
- Loss contribution from the emission between $4\mu m - 11\mu m$: 4%
- Wider stopband is needed to suppress the parasitic emission
- More periods or higher chirping rate will shift the high order reflection and suppress the useful emission





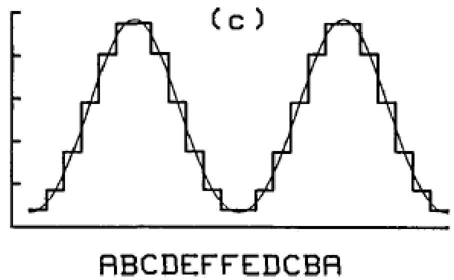
IPSE Design – Chirped Rugate Filter



$n_{SiO2} = 1.46;\ n_{TiO2} = 2.5;$

$t_{SiO2} = 314nm;\ t_{TiO2} = 183nm;$

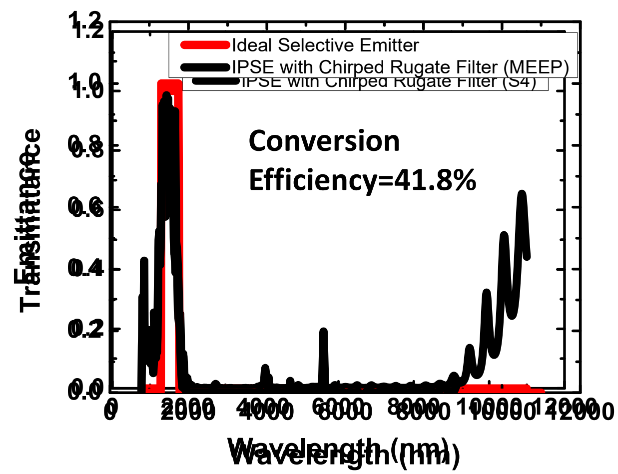
Chirping rate $= 5.1\%$



Chirping rate $= 3.5\%$

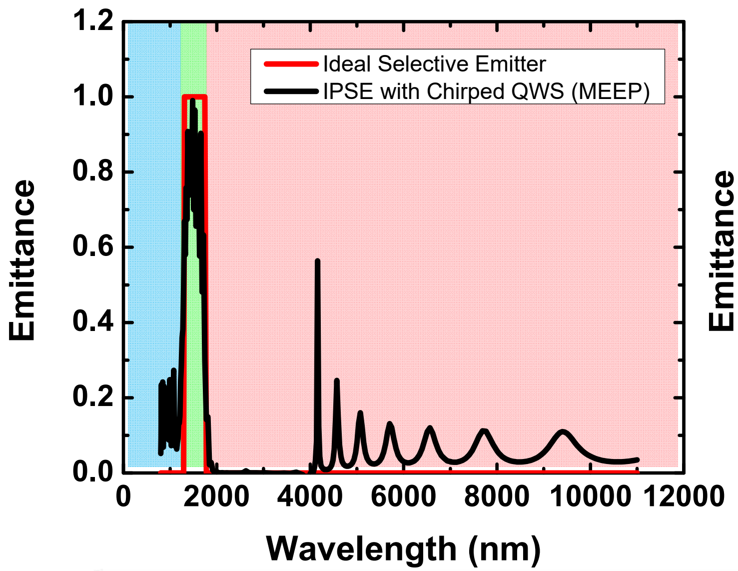
i	n_i	t_i/nm
1	1.460	100
2	1.569	93
3	1.778	82
4	2.053	71
5	2.326	63
6	2.500	58

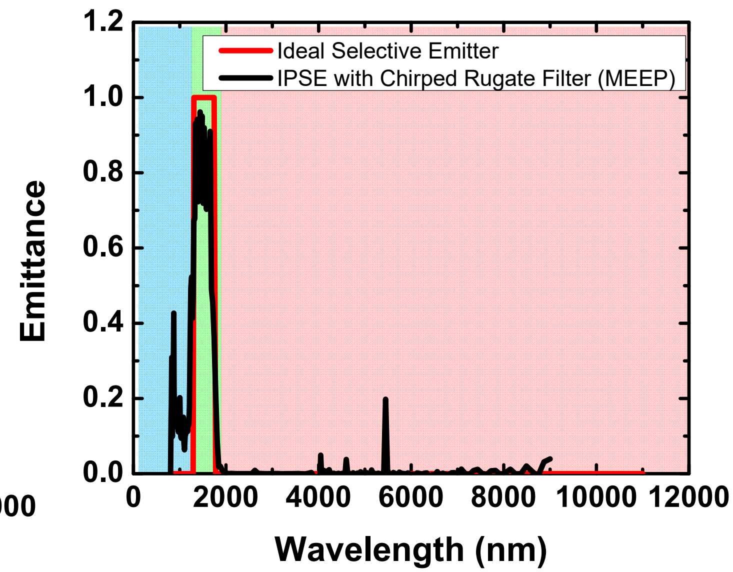
6 material Rugate filter (cut-off wavelength at 3500nm) preserves the band-pass property of the 15-bilayer QWS and increase the width of the stopband



Carniglia CK. *Appl Opt* 1989;28:2820–3.

IPSE Design





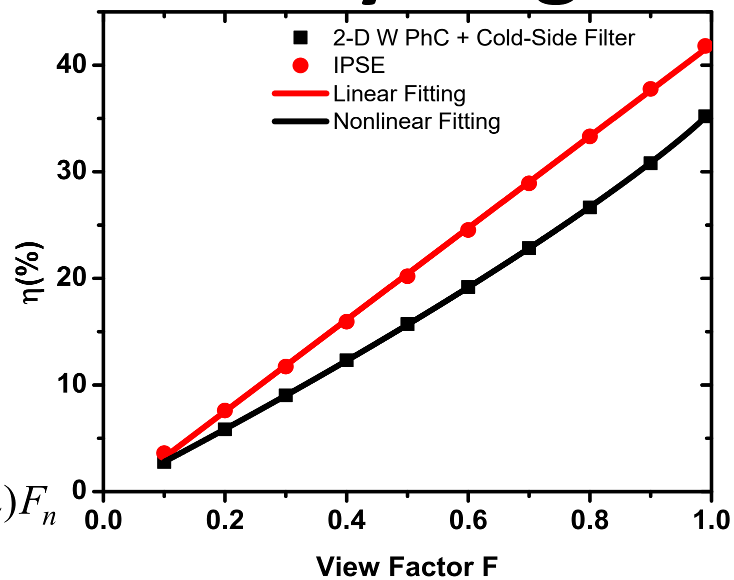
IPSE Structure	Conversion Efficiency η	Total Losses in Efficiency	Parasitic Emission	Insufficient Emission	Short-Wavelength Emission
15-Bilayer QWS	38.2%	7.89%	5.38%	1.71%	0.80%
15-Bilayer QWS+ 30periods Rugate Filter	41.8%	4.29%	1.74%	1.66%	0.89%

The Impact of IPSE on Photon Recycling

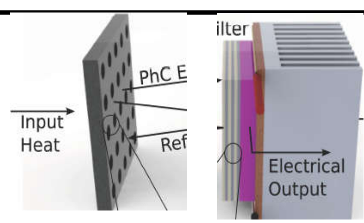
$$\eta = \frac{I_{sc} V_{oc} FF}{P_{em} - P_{re}}$$

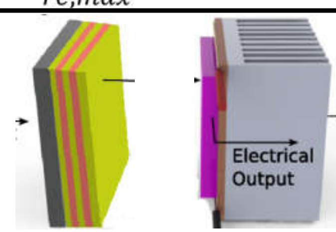
$$I_{sc}(\lambda) = \sum_{n=0,2\ldots}^{\infty} A_1 \frac{2qcEQE(\lambda)(R_1R_2)^{n/2}\varepsilon(\lambda)}{\lambda^4\left[\exp\left(\frac{hc}{\lambda kT}\right)-1\right]} F_n$$

$$P_{re}(\lambda) = \sum_{n=1,3\ldots}^{\infty} A_1 I_{BB}(\lambda) R_2^{(n+1)/2} R_1^{(n-1)/2}(1-R_1)\varepsilon(\lambda) F_n$$



Photon Recycling Strategy	I_{sc}	P_{re}	η
Cold-Side Filter	$I_{sc} \propto F$	$P_{re} \propto F$	a nonlinear function of F
IPSE	$I_{sc} \propto F$	$P_{re,max}$	a linear function of F





Conclusion

- MEEP simulations show that IPSEs can significantly suppress the parasitic loss at long wavelength
- System Conversion Efficiencies above 41% can be reached by appropriate engineering
- IPSE maximizes the photon recycling in TPV
- With IPSE, photon recycling in TPV is independent of the distance between the emitter and the receiver
- Further optimization may lead to higher conversion efficiencies

Modeling Transient Heating and Cooling in High-Power Laser Systems

By
Dan Konopa
ECE 695 – Spring 2015
Instructor: Peter Bermel

Problem Statement

- How can high-power solid state laser diode arrays be modeled so as to design effective highly transient cooling architectures for improved laser performance?

High Energy Lasers

2004

YAL-1 Airborne COIL Laser

As laser technology advances, the size and power of these systems continues to increase, which drives ever more significant thermal management issues

2009

Northrop Grumman demonstrates first 100kW class DEW

2014

DARPA High Energy Laser (HEL) hits a target 7 kilometers away, the first of several tests over the next 3 years

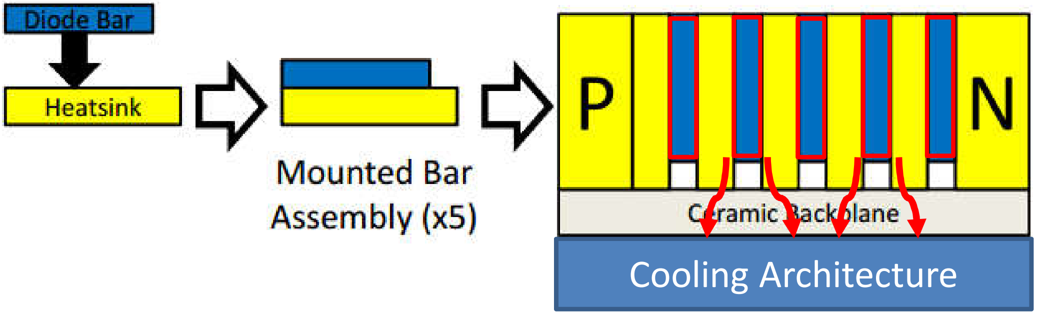
2014

US Navy LaWS deployed on the USS *Ponce*

Images from: http://www.wikipedia.com

Thermal Management of High Power Laser Diode Arrays

Diode bars are arrayed between heatsinks to spread heat down towards the cooling architecture.



- What applied cooling is needed to maintain the laser diodes at an operational temperature for a given duty cycle, specifically for a highly transient cooling architecture?
- Others have researched finite 2D modeling of diode arrays, but focused on optimizing duty cycle and array dimensions given a standard cooling architecture.*
- This research will be applied to innovative new transient cooling techniques being designed here at Purdue.

*Bezotosnyi, V. V., Kumykov, Kh. Kh., 1998, Modelling of the thermal parameters of high-power linear laser-diode arrays. Two-dimensional transient model, *Quantum Electronics*, v. 28(3), p. 217-220.

Image from: http://www.northropgrumman.com/BusinessVentures/CEO/Documents/AppNote15_High_Density_Stacks.pdf

Analytical Model

- Solving for the temperature in a laser diode architecture is essentially an application of the first law of thermodynamics:

$$dU = \partial Q \quad \partial W$$

- Thus follows the so called “balance equation”:

$$c_v \frac{\partial T}{\partial t} \quad \nabla \cdot [\kappa (\nabla T)^T] \quad Q = 0$$

Numerical Model

- Using the Galerkin method of weighted residuals yields the finite element discretization of the balance equation:

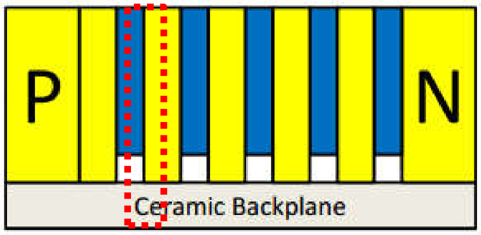
$$\sum_{free\ i}\left[C_{ji}\frac{\delta T_i}{\delta t}+K_{ji}T_i+H_{ji}T_i\right]+\sum_{prescribed\ i}\left[\overline{C}_{ji}\frac{\delta \overline{T}_i(t)}{\delta t}+\overline{K}_{ji}\overline{T}_i\right]-L_{Q,j}-L_{q2,j}-L_{q3,j}=0$$

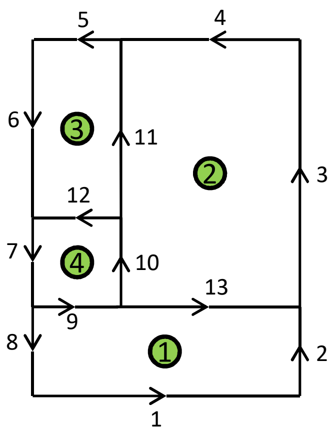
- Finally, applying the generalized trapezoidal method to solve the above equation gives:

$$\left[\frac{1}{t}\tilde{C}+\theta K\right]T_{n+1}$$
$$=\left[\frac{1}{t}C-(1-\theta)K\right]\tilde{T}_n+\theta L_{n+1}+(1-\theta)L_n-\overline{C}\frac{\overline{T}_{n+1}-\overline{T}_n}{\Delta t}-\overline{K}[\theta\overline{T}_{n+1}+(1-\theta)\overline{T}_n]$$

Solving the Problem

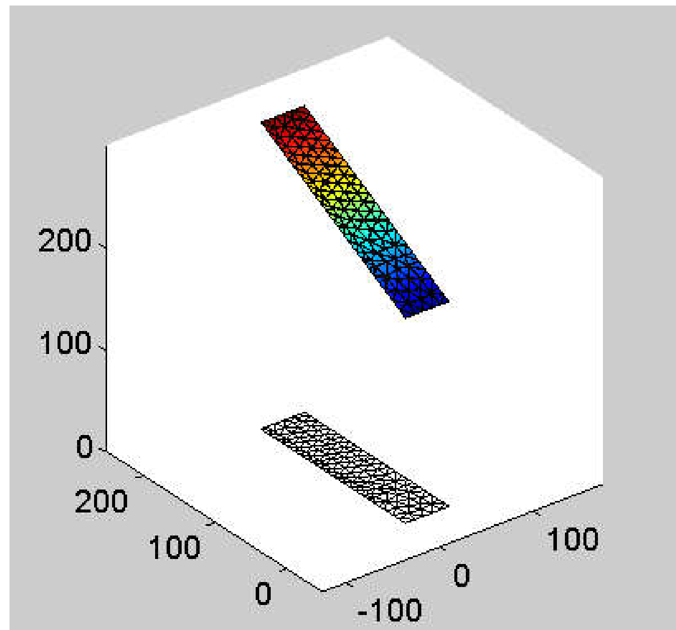
- Symmetry conditions allow us to analyze a single diode bar and apply adiabatic boundary conditions on either side(6-7-8 and 2-3). The top boundary (4-5) is also assumed to be adiabatic.
- The bottom boundary (1) will have a convective heat flux BC. Region 3 is assumed to have a uniform heat generation (Q) throughout; this is the diode bar generating heat through inefficiencies.
- The four regions are modeled in MATLAB using the FAESOR finite element method toolkit to solve for the balance equation throughout.
- This approach neglects effects at the edge of the diode array and uses a simplified, uniform heat generation model (Q) and heat flux boundary condition. Also, radiative heat transfer is ignored.





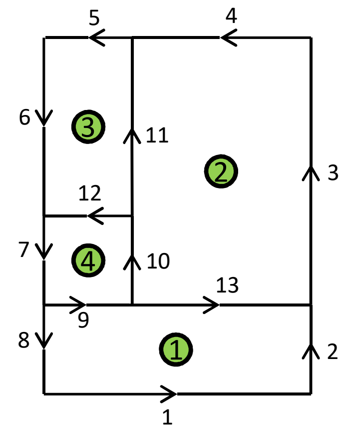
Validating the Solution

- Set top and bottom boundary condition as T=300 and T=200 K
- All meshes and structures the same, but made homogeneous
- Behaves linearly as expected

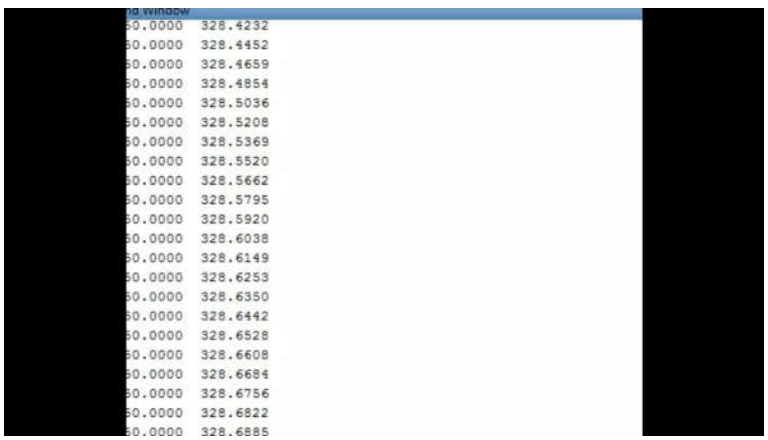


FAESOR Solution Code

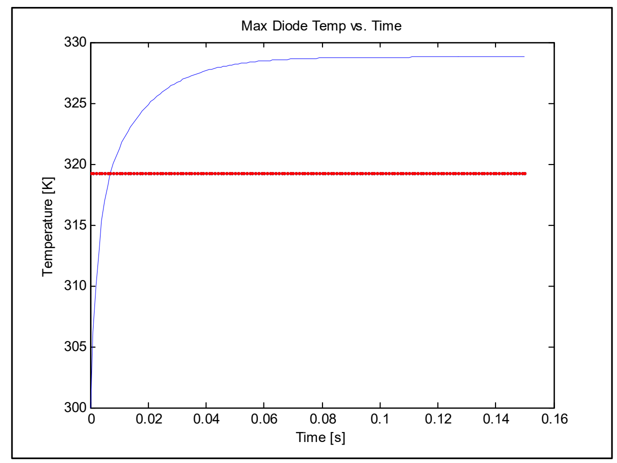
- Step 1: Define material constants and system parameters
- Step 2: Define geometry and initiate targe2_mesher
- Step 3: Create material objects blocks of cells
- Step 4: Apply initial conditions and generate system matrices
- Step 5: Solve for heat field and iterate



FAESOR Solution Results


nd Window

0.0000	328.4232
0.0000	328.4452
0.0000	328.4659
0.0000	328.4854
0.0000	328.5036
0.0000	328.5208
0.0000	328.5369
0.0000	328.5520
0.0000	328.5662
0.0000	328.5795
0.0000	328.5920
0.0000	328.6038
0.0000	328.6149
0.0000	328.6253
0.0000	328.6350
0.0000	328.6442
0.0000	328.6528
0.0000	328.6608
0.0000	328.6684
0.0000	328.6756
0.0000	328.6822
0.0000	328.6885



Summary

- I have demonstrated a FEM model of a high powered laser diode array solving the balance equation under a given set of conditions
- From this model, useful data on the heating of this device can be drawn to inform the design of effective transient cooling architectures

Next Class

- Is on Monday, March 20
- Will discuss coupled mode theory