

Reproducing simulations in

High efficiency rare-earth emitter for
thermophotovoltaic applications

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High efficiency rare-earth emitter for thermophotovoltaic applications

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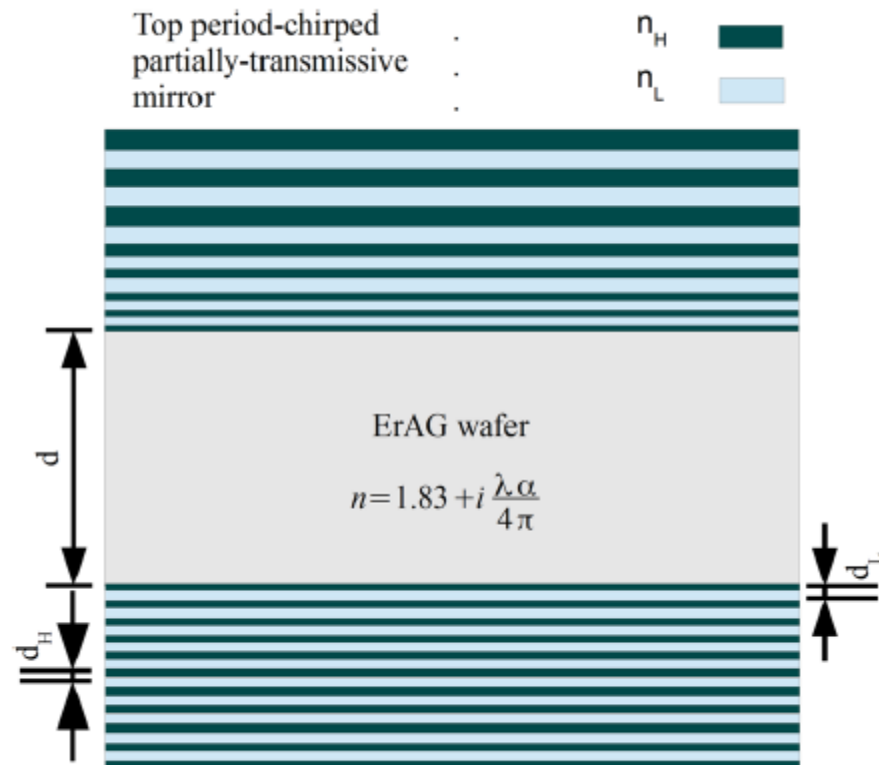
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In this work, we propose a rare-earth-based ceramic thermal emitter design that can boost thermophotovoltaic (TPV) efficiencies significantly without cold-side filters at a temperature of 1573 K (1300 °C). The proposed emitter enhances a naturally occurring rare earth transition using quality-factor matching, with a quarter-wave stack as a highly reflective back mirror, while suppressing parasitic losses via exponential chirping of a multilayer reflector transmitting only at short wavelengths. This allows the emissivity to approach the blackbody limit for wavelengths overlapping with the absorption peak of the rare-earth material, while effectively reducing the losses associated with undesirable long-wavelength emission. We obtain TPV efficiencies of 34% using this layered design, which only requires modest index contrast, making it particularly amenable to fabrication via a wide variety of techniques, including sputtering, spin-coating, and plasma-enhanced chemical vapor deposition. © 2014 AIP Publishing LLC. [<http://dx.doi.org/10.1063/1.4895932>]



Studied spectral emissivity and TPV efficiency for a multi-layer rare-earth doped ceramic emitter, such as Erbium Aluminum Garnet (ErAG):

- Effect of adding dielectric mirror as a back reflector instead of refractory metals to reduce parasitic losses.
- Effect of using integrated chirped filter on top to reduce sub-bandgap parasitic losses



Bottom highly-reflective dielectric mirror

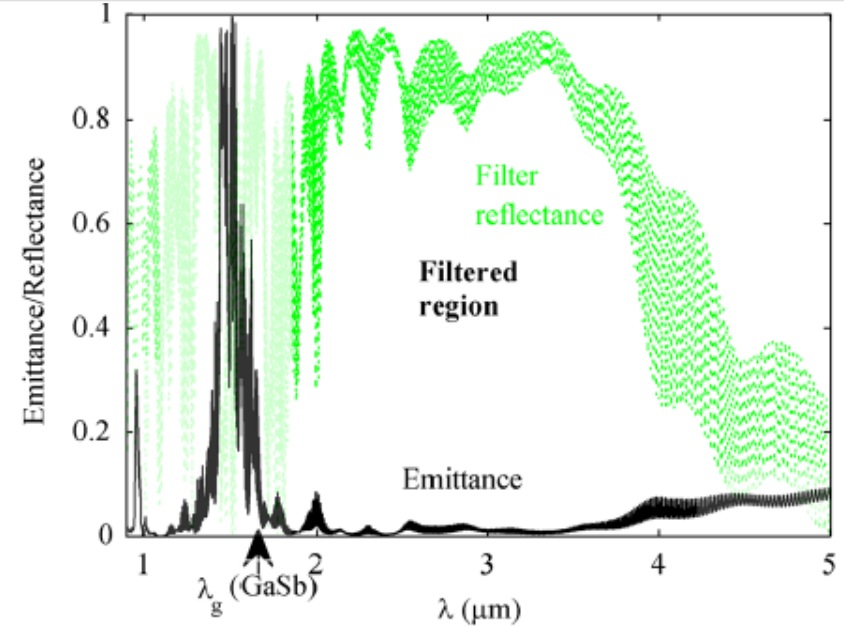
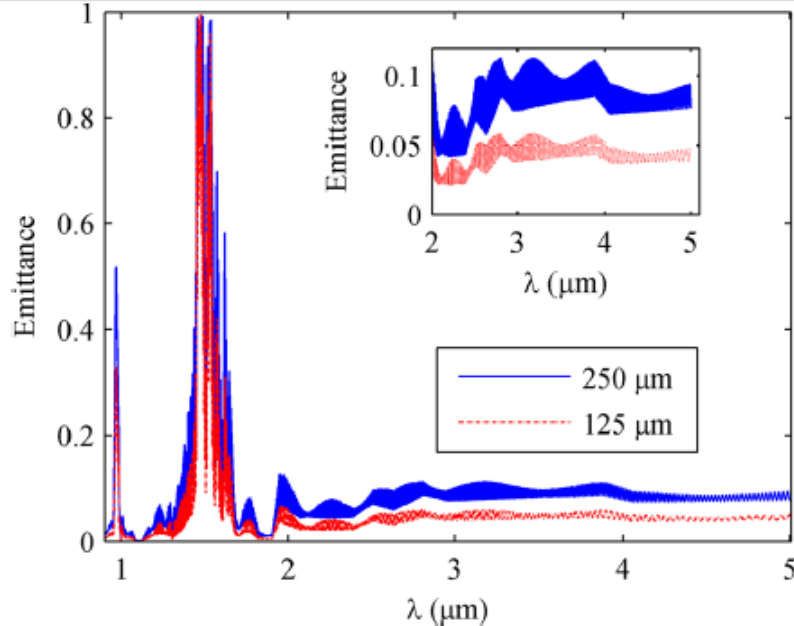
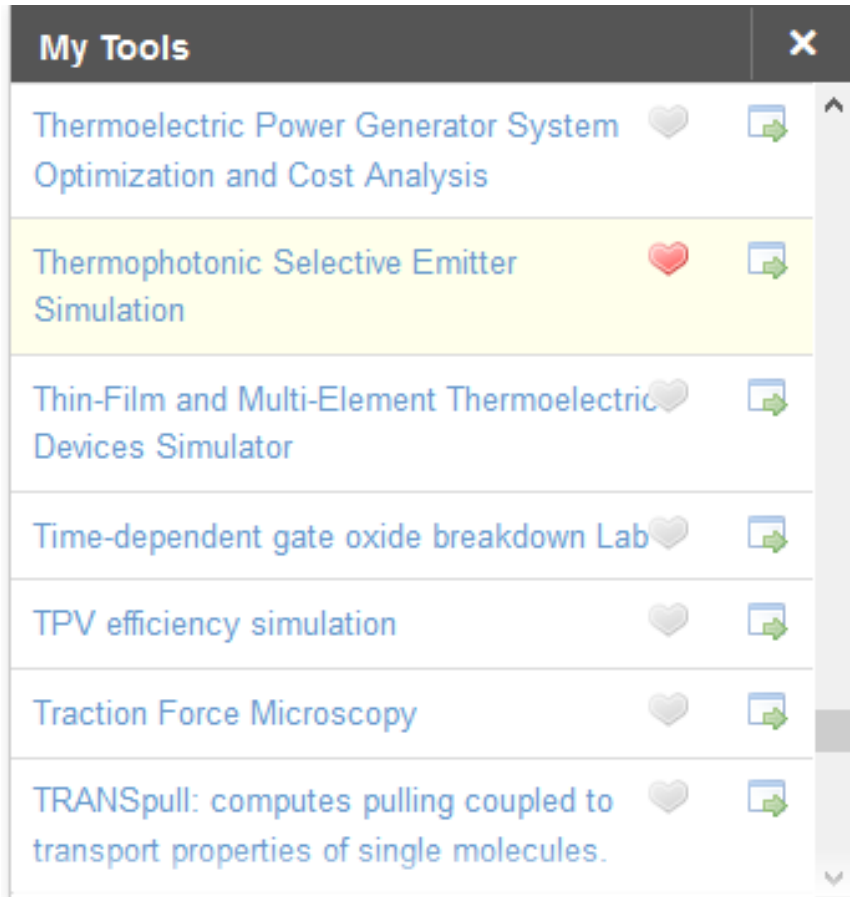


TABLE I. TPV efficiency for different ErAG emitter designs. Although all designs display overall efficiencies higher than seen for metal substrates, the best overall performance comes from the chirped filter + shifted rugate filter at 33.89%.

ErAG emitter	d (μm)	η (%) at 1323 K	η (%) at 1573 K	η_{rad} (%) at 1573 K	$\bar{\epsilon}$ (%) at 1573 K	Top/bottom layers
AR + rugate filter	125	12.6	19.18	41.4	5.09	1/1
AR + rugate filter	250	12.05	18.63	37	9.26	1/1
Q-matched + rugate filter	125	17	24.32	51.4	6.12	3/21
Q-matched + rugate filter	250	15.34	22.58	44.53	10.44	3/21
Chirped filter + shifted rugate filter	250	25.55	33.89	70.85	6.11	Chirped 26/21
Chirped filter only	250	25.46	32.94	70.85	6.11	Chirped 26/21



From the tools menu launch
“Thermophotonics Selective Emitter
Simulation”, or simply click
<https://nanohub.org/tools/tpxsim>

About the tool:

TPXsim is a GUI-based tool to calculate the emittance spectrum using the S-matrix approach and TPV system efficiency for a rare earth-based multi-layer structure emitter.

Learn more:

- Bermel, Peter, et al. "Design and global optimization of high-efficiency thermophotovoltaic systems." *Optics express* 18.103 (2010): A314-A334.
- S4: Stanford Stratified Structure Solver
- <https://nanohub.org/tools/s4sim>

Objective

We will compute the emittance spectrum, the radiation efficiency and the TPV efficiency for the different structures mentioned in the paper.

Approach

- We will describe the selected structure using the GUI.
- Perform an optical simulation to obtain the absorption spectrum which is the same as the emittance spectrum according to Kirchhoff's law of thermal radiation.
- Perform electrical simulation to obtain a theoretical estimation of the TPV system efficiency.

Thermophotonic Selective Emitter Simulation

⚙️ Terminate

1 Input → 2 Simulate ? About this tool
Questions?

Select Parameters

Selective Emitter | **Filter** | System Parameters

Upload an emittance file?: no

Input Emittance file:

The file format should have 2 columns: Wavelengths in nanometers and Emittance Values

Emitter Parameters

I. Parts Of The Selective Emitter | II. S4 Simulation Parameters

Top | **Cavity** | **Bottom**

Coating: Dielectric Mirror

Add a chirping function?: yes

Chirping Function: Exponential

Enter Chirping Range: 1900-4500
This is the range of wavelengths over which chirping function is to be applied.

Constant Value: 0.5
Enter a constant value you need as the power of the exponent / the number of which you want the logarithm / the

Total Number of Layers: 26

Choose the even function: (LH)ⁿ

Choose the odd function: L(HL)ⁿ

Quarterwave Layer 1

Refractive Index of material with Higher Refractive Index (H): 2

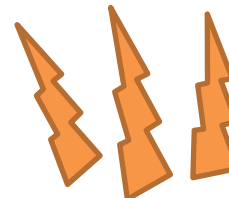
Thickness of the material in nanometers: 183.75

Deposition Rate in Area/sec: 0.580722222

Storage (manage) 22% of 10GB ⚡ ↻ ↶ 757 x 749



Filter



ErAG cavity

Heater



Emitter Parameters

I. Parts Of The Selective Emitter | II. S4 Simulation Parameters

Top | Cavity | Bottom

Coating: Anti-reflection coating

Anti-Reflection Coating Parameters

Thickness of Top Anti-Reflection Layer in nanometers: **271.68**

Refractive Index of the material: **1.35268**

AR

ErAG

AR

Specify the refractive index and thickness of the top and bottom AR coatings to be 1.35268 and 259.9 nm, respectively. The thickness is $\lambda/4$ at 1470 nm.

Emitter Parameters

I. Parts Of The Selective Emitter | II. S4 Simulation Parameters

Top | Cavity | Bottom

Selective Emitter Cavity material: Erbium Aluminium Garnet

Text File: Enter the text file here

Choose "Upload" to upload your script from local disk

Thickness Of The Cavity (micrometers): **250**

Specify the ErAG cavity thickness in micrometers (125 and 250 for cases 1 & 2 respectively).



Select a dielectric mirror top coating, disable chirping and change the circled parameters. Click simulate.

Emitter Parameters

I. Parts Of The Selective Emitter | II. S4 Simulation Parameters

Top | Cavity | Bottom

Coating: **Dielectric Mirror**

Add a chirping function?: no

Chirping Function: Exponential

Enter Chirping Range: 1900-4500
This is the range of wavelengths over which chirping function is to be applied.

Constant Value: 0.5
Enter a constant value you need as the power of the exponent / the number of which you want the logarithm / the slope of the linear function

Total Number of Layers: **3**

Choose the even function: (HL)ⁿ

Choose the odd function: **L(HL)ⁿ**

Quarterwave Layer 1

Refractive Index of material with Higher Refractive Index (H): **2**

Thickness of the material in nanometers: **183.75**

Deposition Rate in Area/sec: **0.580722222**

Quarterwave Layer 2

Refractive Index of material with Lower Refractive Index (L): **1.4141**

Thickness of the material in nanometers: **259.86**

Deposition Rate in Area/sec: **0.249777778**

Simulate >

Select a dielectric mirror bottom coating, disable chirping and change the circled parameters.

I. Parts Of The Selective Emitter | II. S4 Simulation Parameters

Top | Cavity | Bottom

Coating: **Dielectric Mirror**

Add a chirping function?: no

Chirping Function: Exponential

Enter Chirping Range: 1900-4500
This is the range of wavelengths over which chirping function is to be applied.

Constant Value: 0.5
Enter a constant value you need as the power of the exponent / the number of which you want the logarithm / the slope of the linear function

Total Number of Layers: **21**

Choose the even function: $(HL)^n$

Choose the odd function: $L(HL)^n$

Quarterwave Layer 1

Refractive Index of material with Higher Refractive Index (H): **2**

Thickness of the material (nanometers): **183.75**

Deposition Rate in Area/sec: **0.580722222**

Quarterwave Layer 2

Refractive Index of material with Lower Refractive Index (L): **1.4141**

Thickness of the material (nanometers): **259.86**

Deposition Rate in Area/sec: **0.249777776**

Simulate >

I. Parts Of the Selective Emitter | II. 34 Simulation Parameters

Top | Cavity | Bottom

Coating: Dielectric Mirror

Add a chirping function?: yes

Chirping Function: Exponential

Enter Chirping Range: 1900-4500

This is the range of wavelengths over which chirping function is to be applied.

Constant Value: 0.5

Enter a constant value you need as the power of the exponent / the number of which you want the logarithm / the slope of the linear function

Total Number of Layers: 26

+ -

Choose the even function: (HL)ⁿ

Choose the odd function: L(HL)ⁿ

Quarterwave Layer 1

Refractive Index of material with Higher Refractive Index (H): 2

Thickness of the material in nanometers: 183.75

Deposition Rate in Area/sec: 0.580722222

Quarterwave Layer 2

Refractive Index of material with Lower Refractive Index (L): 1.4141

Thickness of the material in nanometers: 259.86

Deposition Rate in Area/sec: 0.249777778

Select a dielectric mirror top coating with enabled chirping and change the circled parameters.

Simulate >

Try different emitter temperatures e.g. 1573 K and 1323 K

1 Input → 2 Simulate ? About this tool
Questions?

Select Parameters

Selective Emitter | Filter | System Parameters

Upload an emittance file?: no

Input Emittance file:

The file format should have 2 columns: Wavelengths in nanometers and Emittance Values

Emitter Parameters

I. Parts Of The Selective Emitter | II. S4 Simulation Parameters

Emitter Temperature:

Maximum Fourier Expansion Orders: + -

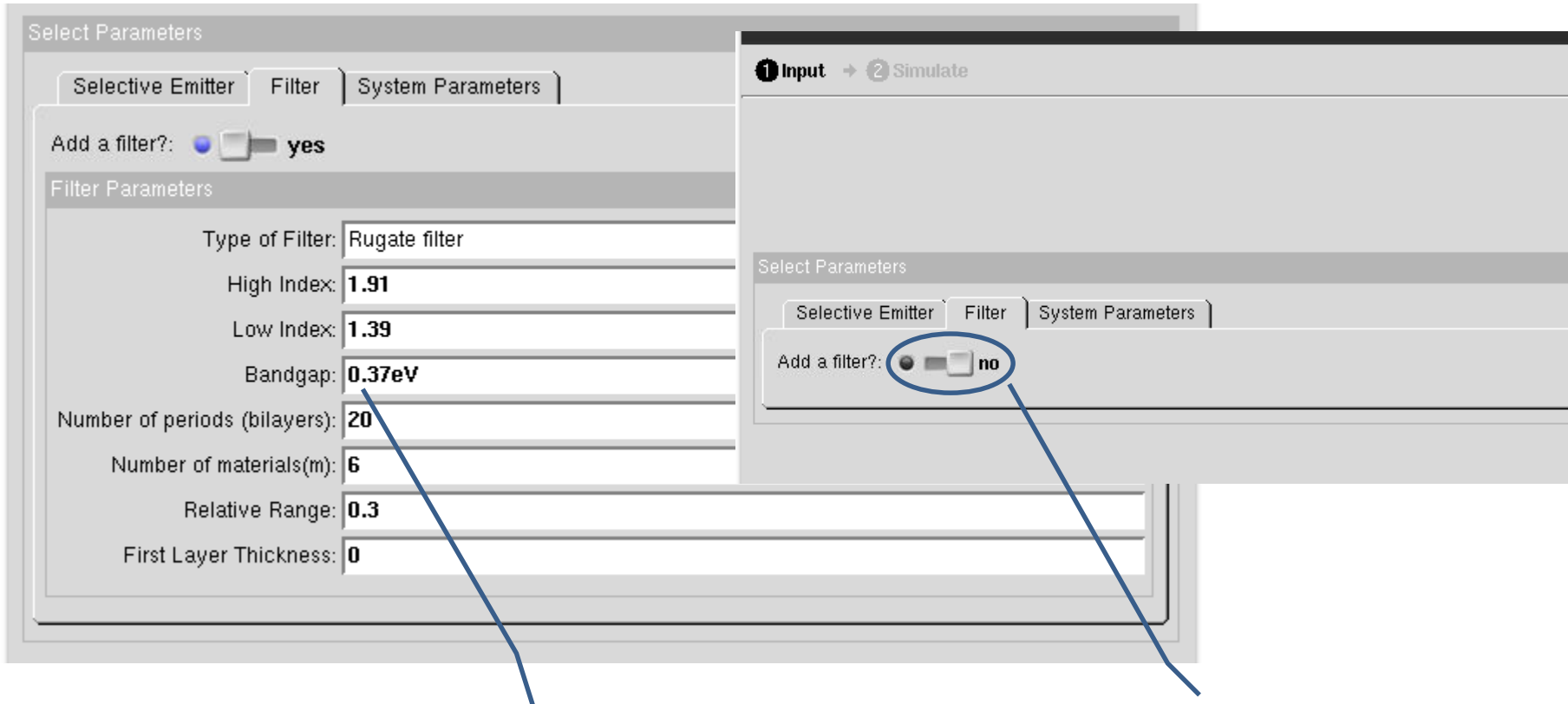
Wavelength Parameters

Reduced units -> Period: Type in a number or the word "default".
Default means to set the period to 0.9 * wavelength_min.
If you set it to 1, the frequency will have a unit of c/nm, where c is the speed of light.

Minimum Wavelength (nm):

Maximum Wavelength (nm):

Simulate >



The image displays two screenshots of the nanoHUB interface. The left screenshot shows the 'Filter' parameters for a rugate filter. The 'Add a filter?' toggle is set to 'yes'. The 'Bandgap' parameter is set to 0.37 eV. The right screenshot shows the same interface with the 'Add a filter?' toggle set to 'no'. Blue arrows point from the 'Bandgap' parameter in the left screenshot to the text box below, and from the 'no' toggle in the right screenshot to the text box below.

Parameter	Value
Type of Filter	Rugate filter
High Index	1.91
Low Index	1.39
Bandgap	0.37 eV
Number of periods (bilayers)	20
Number of materials(m)	6
Relative Range	0.3
First Layer Thickness	0

Shift the rugate filter bandgap to 0.37 eV and keep other parameters to their default values

Enable /disable the rugate filter

Select Parameters

Selective Emitter | Filter | System Parameters

External quantum_efficiency: **0.82**

Band Gap: **0.75**

room_temp:  **300K**

Device Ideality Factor: **1.171**

View Factor: **0.99**

Dark Current Density (microAmperes per cm²): **0.0011**

Add a Contour Plot for variations in Bandgaps?: no

Add a Contour Plot For Different number of Layers?: no

Simulate >

Use the default values of system parameters and click simulate

1 Input → 2 Simulate ? About this tool
Questions?

Result: Efficiency

- Emittance Spectrum
- Reflection Spectrum of the Filter
- Cutoff wavelength (nm)
- Efficiency**
- Average Emissivity
- Radiation Efficiency
- Control File
- Efficiency With Number Of Layers
- Total Time for the Deposition of Top L
- Total Time for the Deposition of Botto Mesh
- Efficiency Contour Plot
-
- Download

Efficiency

0.21

0.2

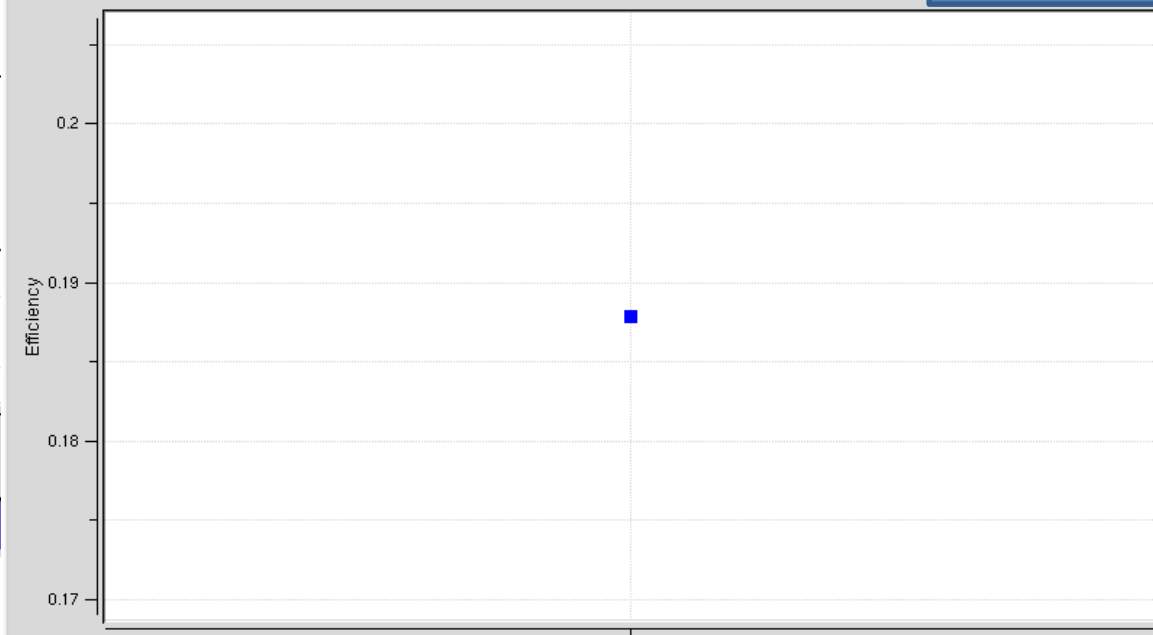
0.19

0.18

1 result

1 Input → 2 Simulate

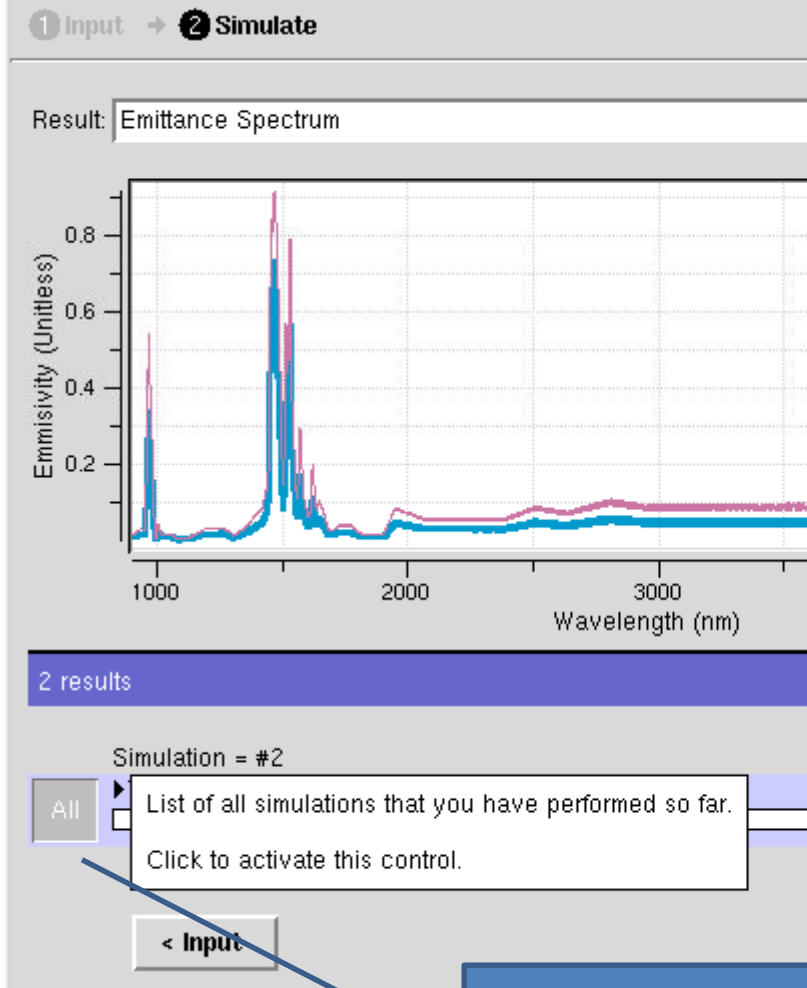
Result: Efficiency



Simulation	Efficiency
#1	0.188

#1 Simulation

Select different output options from the scroll down menu



1 Input → 2 Simulate

About this tool
Questions?

I. Parts Of The Selective Emitter | II. S4 Simulation Parameters

Top Cavity Bottom

Selective Emitter Cavity material: Erbium Aluminium Garnet

Text File: Enter the text file here

Choose "Upload" to upload your script from local c

Thickness Of The Cavity (micrometers): 125

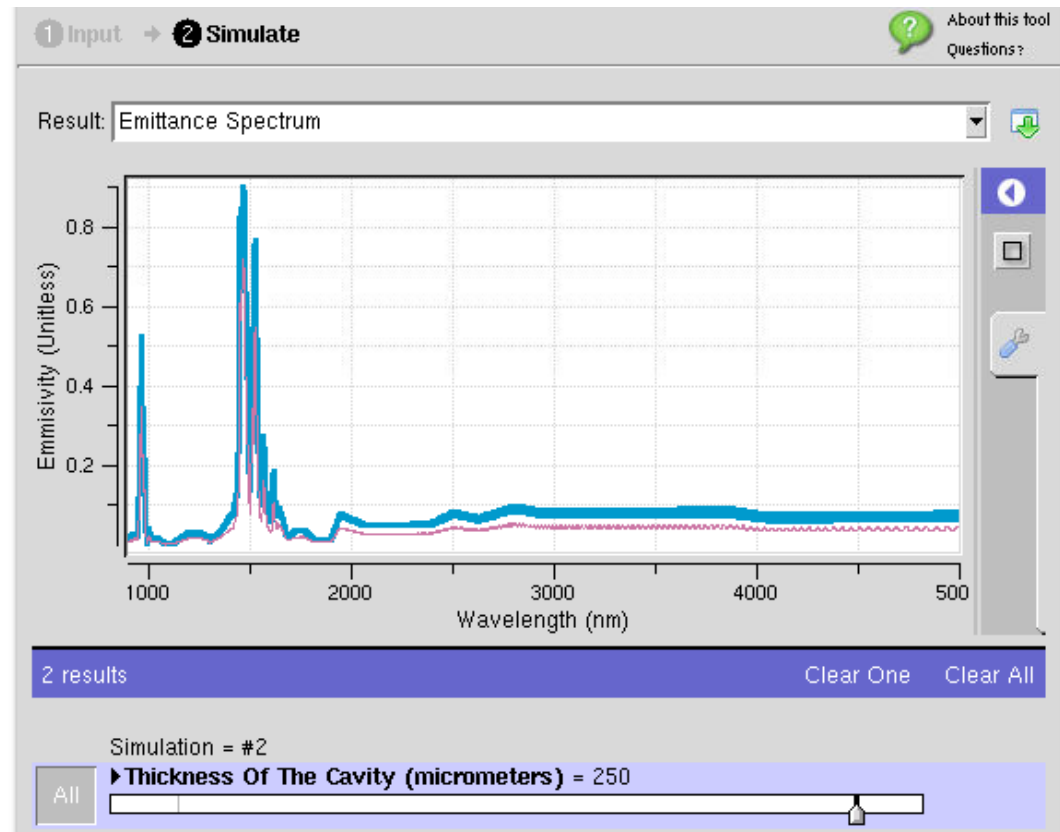
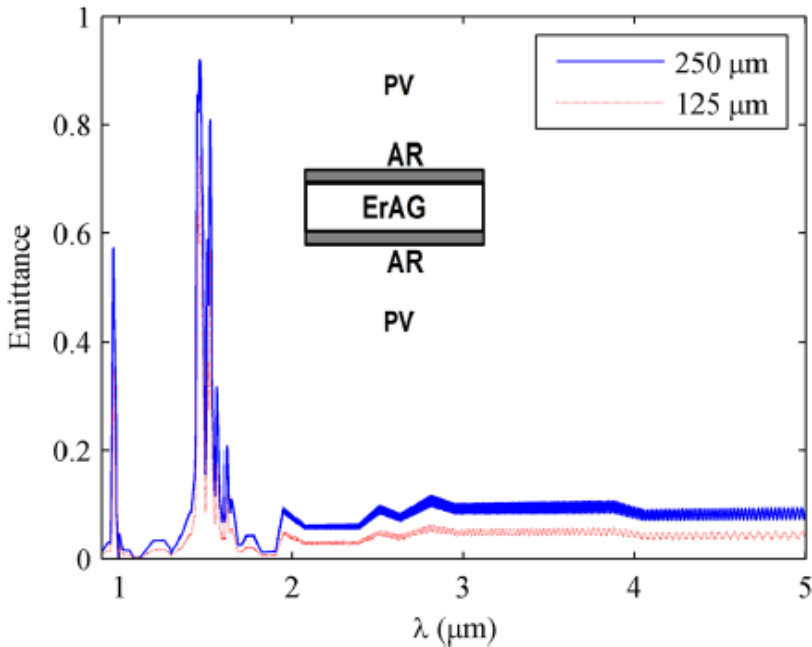
Simulate >

Click all to view multiple outputs
on a single graph

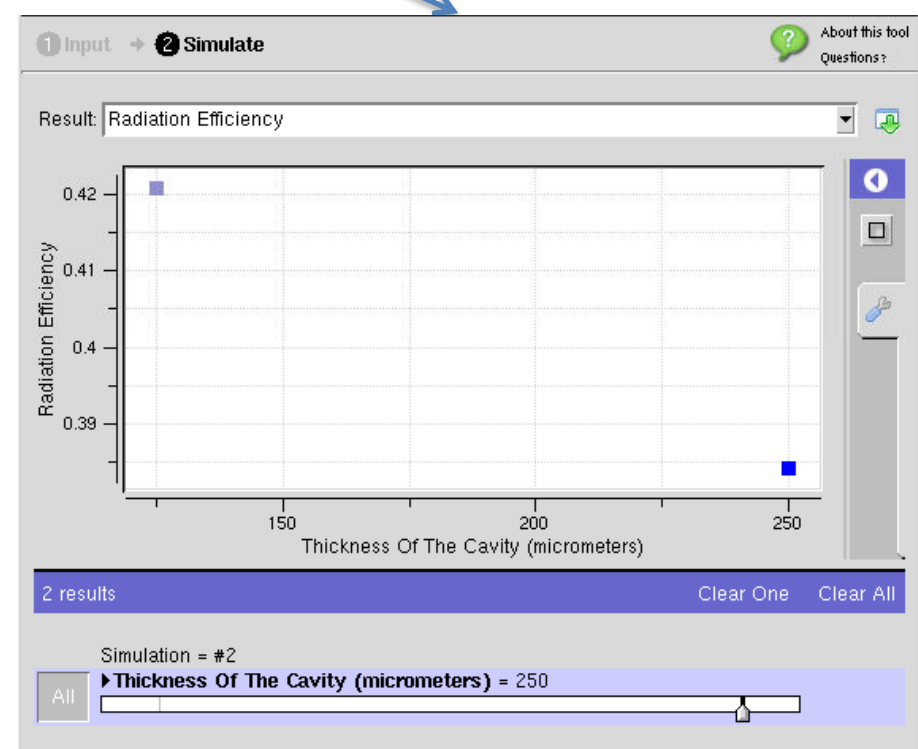
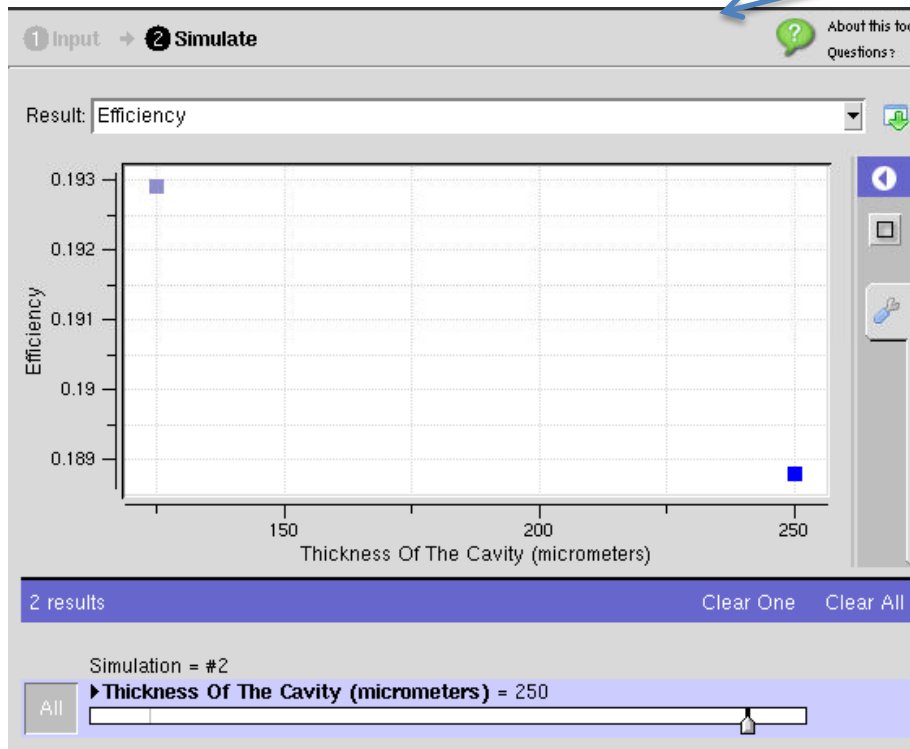
Change
thickness
and click
simulate

ErAG emitter	d (μm)	η (%) at 1323 K	η (%) at 1573 K	η_{rad} (%) at 1573 K	$\bar{\epsilon}$ (%) at 1573 K	Top/bottom layers
AR + rugate filter	125	12.6	19.18	41.4	5.09	1/1
AR + rugate filter	250	12.05	18.63	37	9.26	1/1

Emittance spectrum



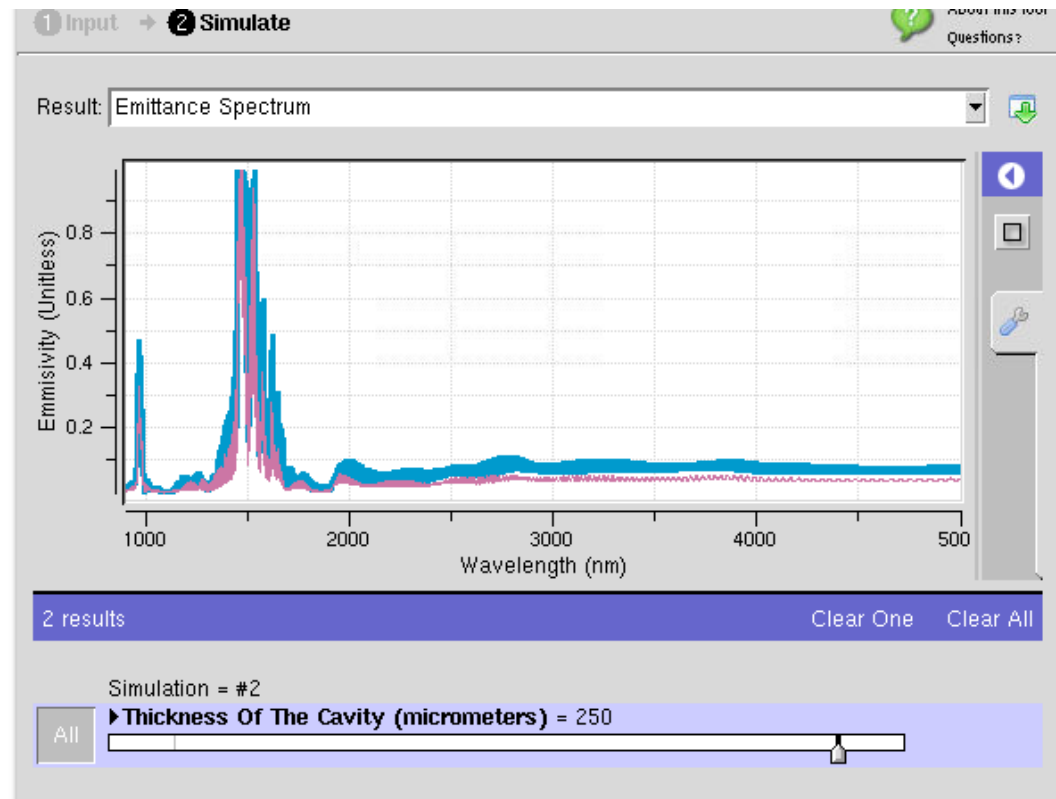
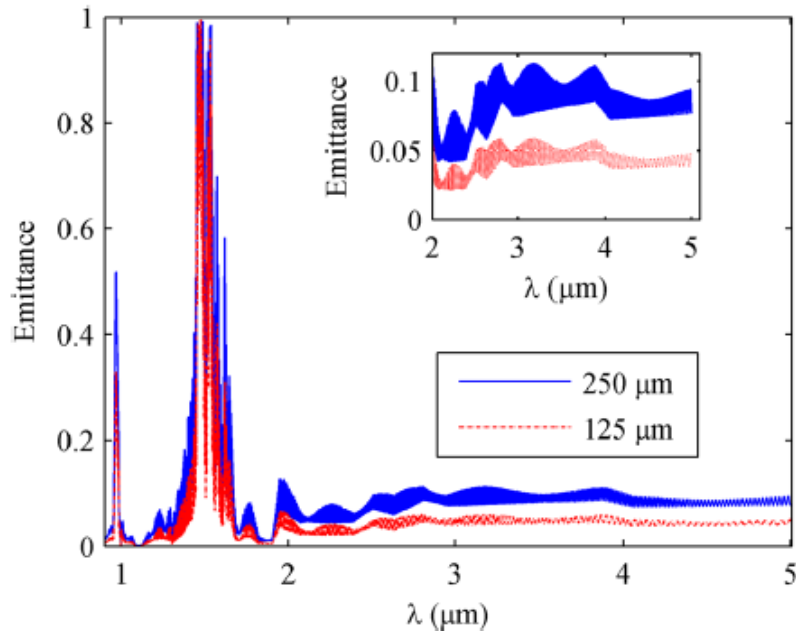
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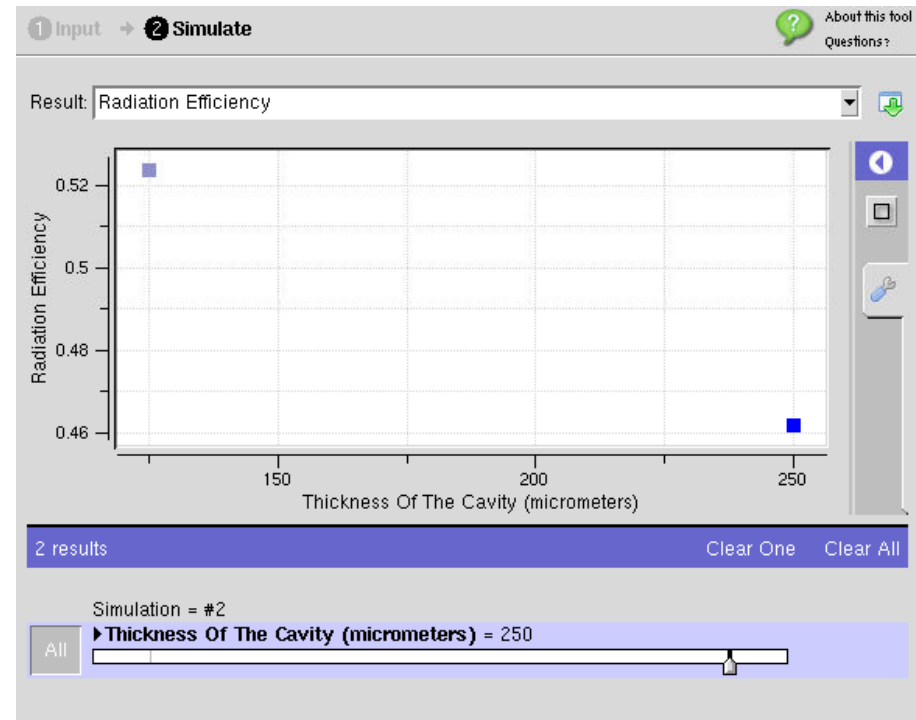
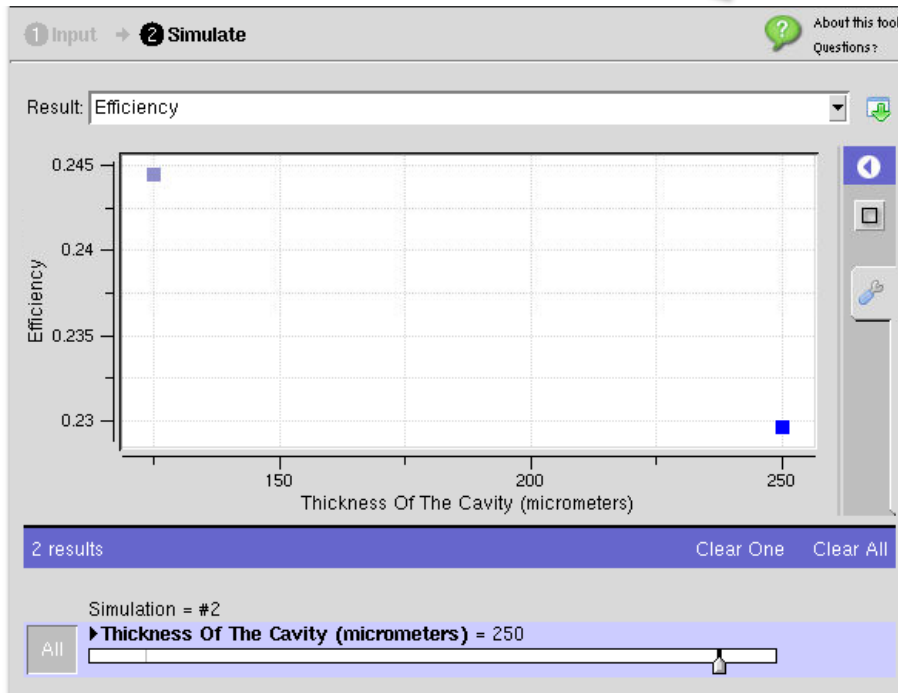
The small discrepancy is because the tool does implement a random change in the layers thicknesses as deduced from experimental evidence

ErAG emitter	d (μm)	η (%) at 1323 K	η (%) at 1573 K	η_{rad} (%) at 1573 K	$\bar{\epsilon}$ (%) at 1573 K	Top/bottom layers
Q-matched + rugate filter	125	17	24.32	51.4	6.12	3/21
Q-matched + rugate filter	250	15.34	22.58	44.53	10.44	3/21

Emittance spectrum



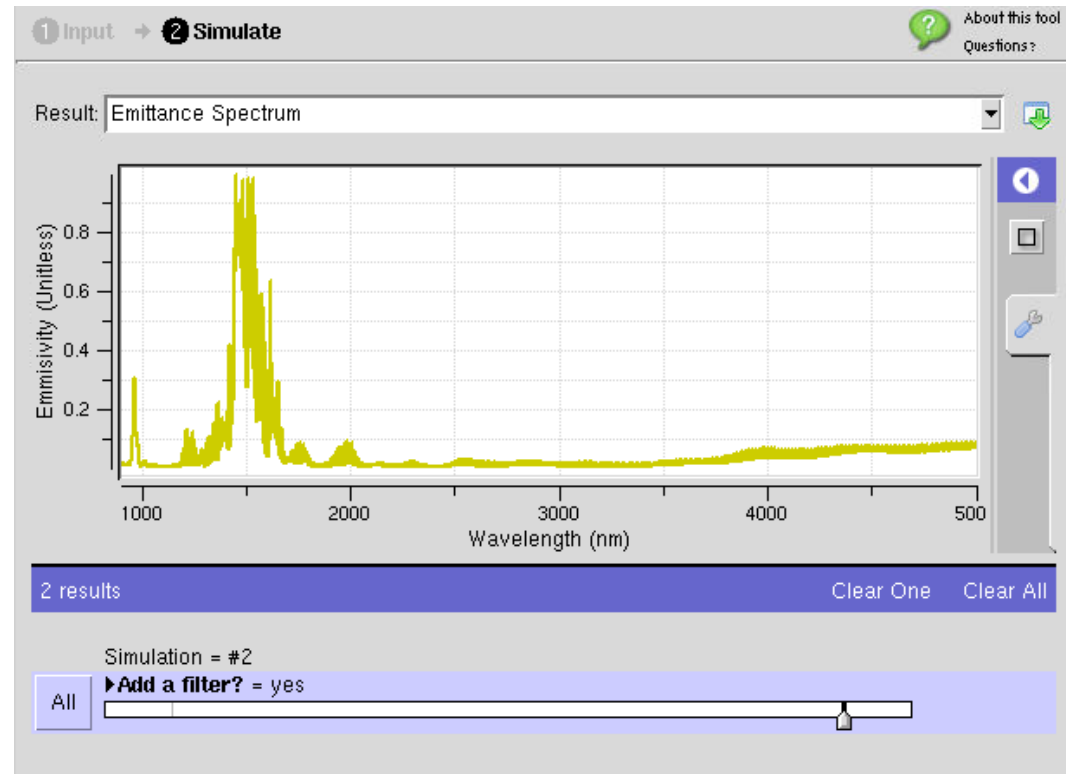
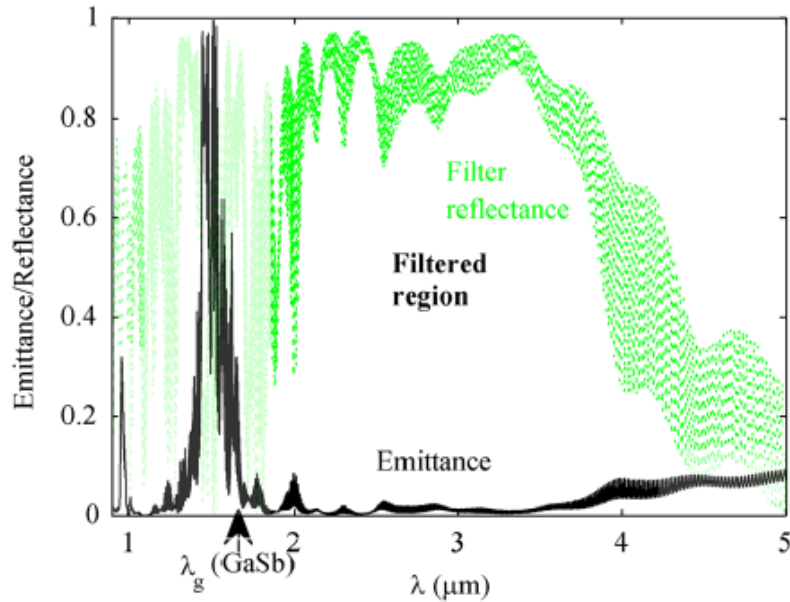
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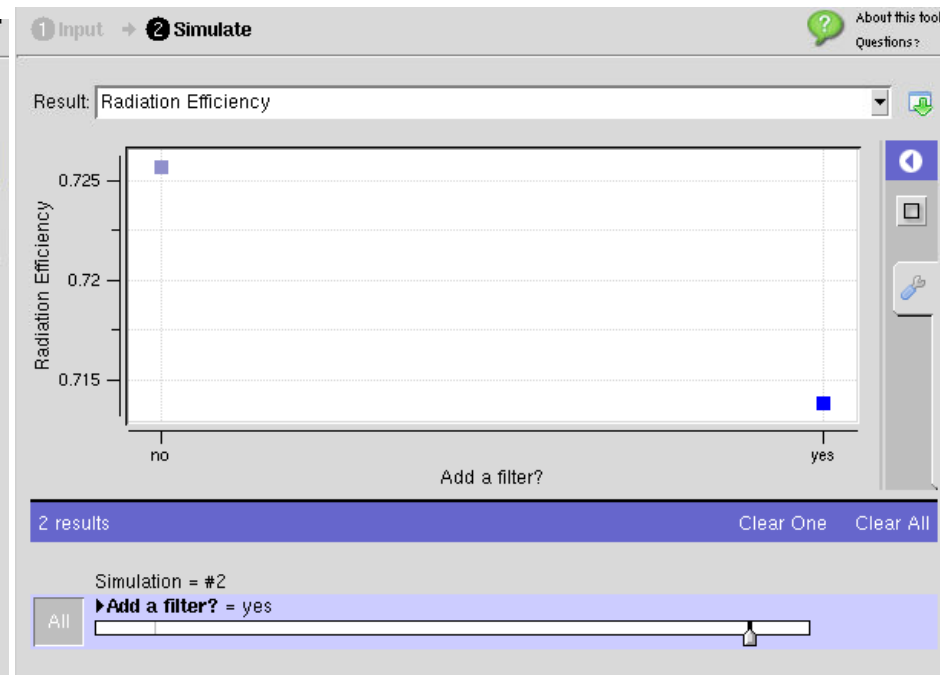
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Emittance spectrum



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Q-matched + rugate filter	250	15.34	22.58	44.53	10.44	3/21



The small discrepancy is because the tool does implement a random change in the layers thicknesses as deduced from experimental evidence

- Simulate other naturally-selective rare earth materials.
- Optimize the number of layers for the maximum TPV efficiency.