Rare-earth ions can undergo fluorescence, cross-relaxation (or self-quenching), upconversion, and other non-radiative relaxations. For rare-earth ions, these processes are important for lasers, optical amplifiers and other applications.

SimphoSOFT® is ideally suited to look at complex interactions such as amplification, cross-relaxation, upconversion and stimulated emission in rare-earth materials that have many energy levels and many optical transitions. SimphoSOFT simultaneously calculates the rate equations for the material and light propagation through the material. In particular, SimphoSOFT:

- Can determine the sensitivity of amplification to various material and pump parameters.
- Can be used to optimize amplification in a material.
- Saves time and money by letting the user do virtual experiments on the computer rather than in the lab.
- Provides complete numerical solutions, more accurate than the ones based on the conventional analytical approximations.
- Provides an easy-to-use graphical user interface for changing the number of energy levels, adding and updating optical transitions (including energy transfer, upconversion, and cross-relaxation) in the material, and adding new types of ions/molecules.

In this application note we show how to model amplification in the media similar to single-mode fiber made of Thuliam-ion-doped material. Two critical variables for optimization – pump input energy and the sample length – are analyzed to choose a better regime for amplification by running SimphoSOFT Multi-Beam modeling software.[1]

Example SimphoSOFT simulation of Thulium-Ion-Doped CW Amplification

Thulium-ion-doped materials can be used to amplify light at wavelengths near 1900 nm (1.9 μm). In order to achieve amplification near 1900 nm, thulium ions (Tm^{3+}) can be pumped at approximately 790 nm or at approximately 1550 nm. In this application note, we use a box-shaped 790 nm pump pulse that is 100 ms long in order to achieve amplification of a 1900 nm seed pulse. A time of 100 ms is long enough for the Tm^{3+} ion energy level populations to come to steady-state equilibrium with the 790 nm pump before the seed pulse is introduced. (Note: In another application note that describes pulsed amplification, the 790 nm pump pulse is only 1 ms long. A pulse length of 1 ms is long enough to achieve significant amplification in the material, but not long enough for the Tm^{3+} ion energy level populations to come to approximately steady-state equilibrium with the 790 nm pump beam.)

For this example, the radius of both the pump and seed beams is 10 μm (diameter 20 μm). A radius of 10 μm is similar to the core radius of a single-mode fiber for wavelengths near 1900 μm. With the diffraction feature of SimphoSOFT set to 'off' in Numerical Setup, the pump and seed beams do not expand with distance and the resulting calculation is approximately equivalent to a single-mode fiber solution having both the pump and amplified seed confined to the fiber core of radius 10 μm.

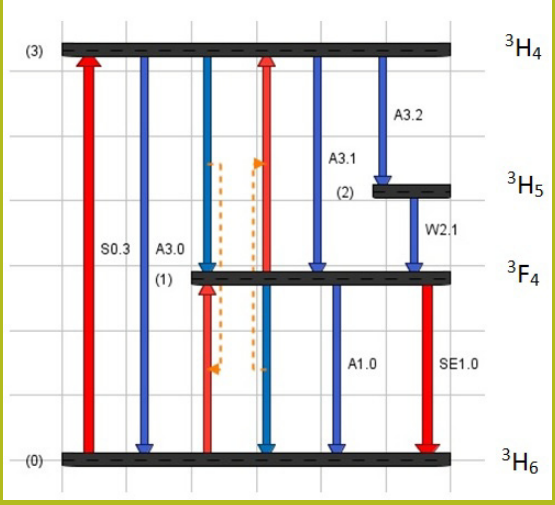
[1] SimphoSOFT requirements: SimphoSOFT v 3.1 with add-ons ET and Multi-Beam (more details on Release 3.1).
SimphoSOFT template project: "Tm pulse amplification".

In this application note, we show that the resulting amplification is very sensitive to the pump energy or power. We show amplifications results for pump energies of 25 mJ (25 mJ/100 ms = 0.25 Watt) and 100 mJ (100 mJ/100ms = 1 Watt) in samples that are 125 mm or 250 mm long. We also show the electronic populations for both the ground state and the emitting excited state and show how these populations effect the amplification. We show that for 25 mJ pump energy, the populations of the ground state and the emitting state are not uniform along a 250 mm long sample resulting in amplification that is not uniform along the sample length. In comparison the populations of the ground state and emitting state for 100 mJ pump energy are nearly uniform along a 250 mm long sample and result in amplification that is also nearly uniform along the total 250 mm sample length.

At high doping concentrations, Tm^{3+} ions undergo significant cross-relaxation when pumped at 790 nm. Cross-relaxation occurs when a donor ion in an upper excited state exchanges energy with an identical nearby acceptor ion that is in the ground state, resulting in each molecule or ion simultaneously undergoing energy transfer to either: (1) an intermediate excited state on both the donor and acceptor that is energetically halfway between the upper excited state and the ground state or (2) two energetically different intermediate excited states (one on the donor and one on the acceptor) that are between the upper excited state and the ground state. In either case, energy is conserved in the cross-relaxation transition and the decrease in energy on the donor equals the increase in energy on the acceptor. In the SimphoSOFT M-CAD dialog, the energy level diagram of only one type of ion will be illustrated for cross-relaxation since donor and acceptor ions are identical.

Tm^{3+} ions can also undergo upconversion. Upconversion can occur between ions that are chemically identical. Upconversion can occur, for example, if ions of one type have electrons in their first excited states. Upconversion occurs with the de-excitation of an ion from the first excited state to the ground state and the simultaneous excitation (via energy transfer) of an identical ion from the first excited state to a higher excited state. In the example described below, upconversion has a much smaller rate than cross-relaxation and is therefore not as significant as cross-relaxation in the simulation results.

Screenshot of SimphoSOFT® M-CAD with energy level diagram for Tm^{3+}.
It will be pumped at 790 nm and undergoes stimulated emission at 1900nm.

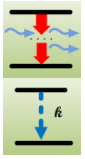


We will now show examples of SimphoSOFT simulations for amplification in a thulium (Tm^{3+})-doped material. The sample is composed of 6% Tm^{3+} ions dispersed in a glass host material. The ions have four important energy states for optical transitions, $^3H_6$ (ground State 0 in the diagram above), $^3F_4$ (excited State 1), $^3H_5$ (excited State 2) and $^3H_4$ (excited State 3). For simplicity, other energy levels will not be shown but can be added if needed. Note that under some conditions, the illustrated energy levels may each be split into several additional levels. This more complicated situation will not be considered in this example. The pump laser wavelength is 790 nm and pumps electrons from ground State 0 to excited State 3. Several relaxation processes can occur from State 3, but the most important relaxation process in this example is cross-relaxation from States 3 and 0 to State 1. Amplification at 1900 nm is due to stimulated emission (SE) from State 1 to State 0.

The values listed below are representative values for cross-sections, relaxation times and rates for 6% doping and will need to be modified for other sample compositions. Actual values can depend on the host material, the level of doping and the sample temperature (References 1 and 2). Relaxation rates are from Walsh et al (Reference 1). Cross-relaxation and up-conversion rates are from Dinndorf (Reference 2). Cross-sections for absorption and stimulated emission are estimates.

Cross-section, relaxation times and rates for Tm^{3+}:

Energy levels are labeled from 0 to 3

From level(s):	To level(s):	Cross-section:	Relaxation time (ms):	Upconversion rate:	Cross-relaxation rate:	SimphoSOFT icons
0	3	2.5×10^{-22} cm^2 (absorption)				
3	0		2.9 (radiative)			
3	2		12.4 (non-rad.)			
2	1		0.067 (non-rad.)			
3	1		30 (radiative)			
1	0	1.0×10^{-21} cm^2 (stimulated emission)	13.5 (radiative)			
1	0 and 3			3.0×10^{-19} cm^3 s^{-1}		
3 and 0	1				3.2×10^{-17} cm^3 s^{-1}	

The Tm^{3+} doping level of 6% corresponds to a dopant concentration of 8.39×10^{20} ions/cm^3 as listed in the table below. The host glass material is assumed to have a refractive index $n_0 = 1.45$ (790 nm and 1900 nm). Simulations are run and compared for sample lengths of 250 mm or 125 mm.

Other sample properties of Tm^{3+} sample	
Tm ion dopant density (concentration) in host material	8.39×10^{20} ions/cm^3
The host material linear refractive index	$n_0 = 1.45$ (790 nm and 1900 nm)
Sample length	250 mm or 125 mm

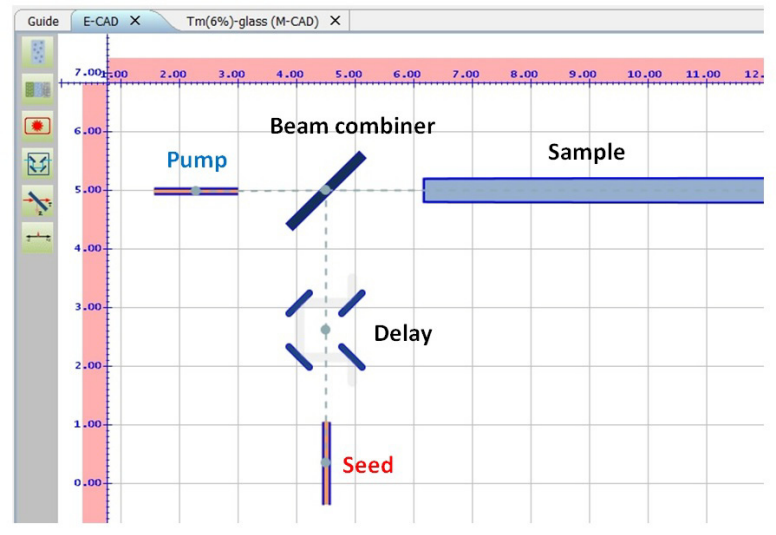
The pump pulse is a box-shaped (flat-topped) pulse of length 100 ms (t_0 = 50 ms). The seed pulse is also box-shaped with a pulse length of 50 ms. The seed pulse length of 50 ms is also longer than the time needed for the Tm^{3+} ion energy level populations to come to steady-state equilibrium with the 790 nm pump.

Pump Laser properties	
Pulse energy	25 mJ or 100 mJ
Pulse radius (HW1/e^2M)	10 µm
Pulse FWHM (box)	100 ms
Wavelength	790 nm

Seed Laser properties	
Pulse energy	0.01nJ
Pulse radius (HW1/e^2M)	10 µm
Pulse FWHM (box)	50 ms
Wavelength	1900 nm

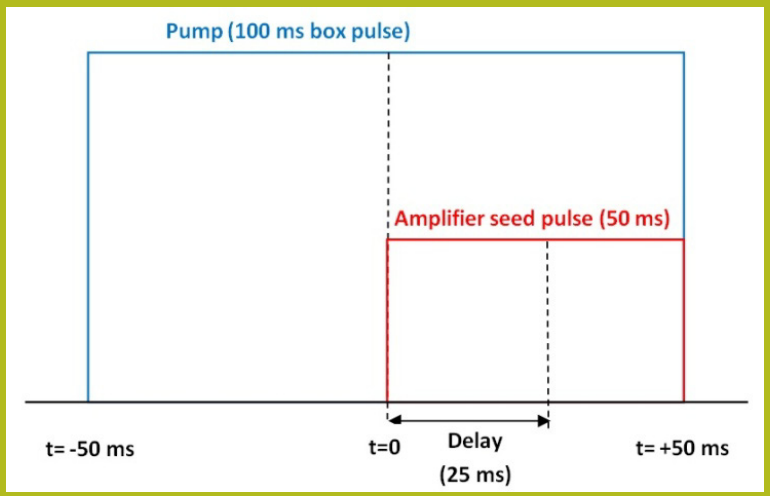
Simulations are run and compared for pump pulse energies of 25 mJ and 100 mJ. The seed pulse energy is much smaller at 0.01 nJ. The sample length is either 250 mm or 125 mm. The radius of each beam is 10 µm (diameter 20 µm).

Screenshot of SimphoSOFT® E-CAD with 790 nm pump beam and the 1900 nm seed beam, co-propagating through the sample.



The 50 ms box-shaped seed pulse at 1900 nm is delayed 25 ms relative to the center of the 100 ms box-shaped pump pulse but still overlaps in time with the last half of the pump pulse. The timing sequence is shown in the plot below for the pump and seed pulses.

Shapes and timing of the pump and see pulses.

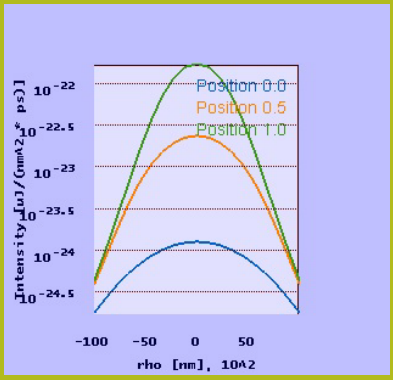


Results of SimphoSOFT simulations for 25 mJ pump box-pulse:

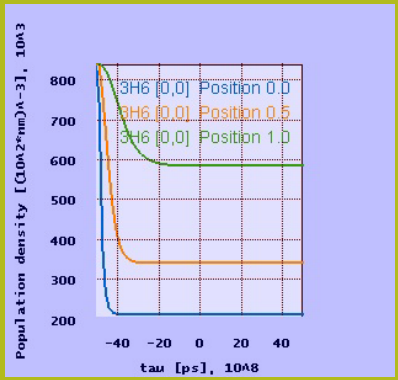
First, we will see whether amplification is equally strong along the entire sample, by analyzing the gain within the first half of the sample and the second half. It turns out that the second half of the sample underperforms and the reason for that is lower population density of Tm^{3+} ions excited to the State 1.

Below we show results for pump energy of 25 mJ and a sample length of 250 mm. The figure on the left shows the increase in the intensity of the seed pulse as it propagates through the 250 mm long sample. Position 0.0 (0 mm, blue) is at the sample input surface, Position 0.5 (125 mm, orange) is half way through the sample and Position 1.0 (250 mm, green) is at the output surface of the sample. The total amplification is higher in the first 125 mm of the sample than in the last 125 mm. The center figure shows the populations of State 0 at positions 0.0, 0.5 and 1.0 during the time that the 100 ms pump pulse is passing through the sample. Time tau=0 is the center of the pump pulse. At the sample input surface (Position 0.0), the population of State 0 is nearly depleted in the first 15 ms of the 100 ms pump beam. Once State 0 is depleted of electrons, the state will no longer absorb the pump light. At the center of the sample (Position 0.5), State 0 is about 75% depleted during the time of the 100 ms pulse. At the output surface (Position 1.0), State 0 is only about 40% depleted.

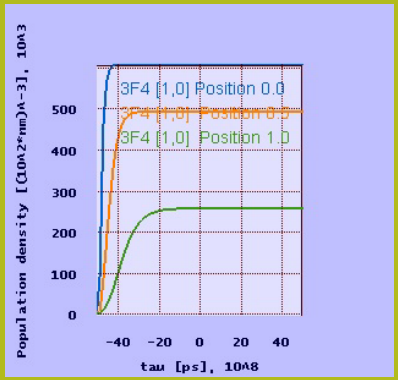
Screenshots of SimphoSOFT® graphical output with calculated intensity profile and population densities.
25 mJ pump pulse and 250 mm sample length



Pulse intensity within seed pulse moving frame at 3 sample locations



Populations of state 0 at 3 sample locations



Populations of state 1 at 3 sample locations

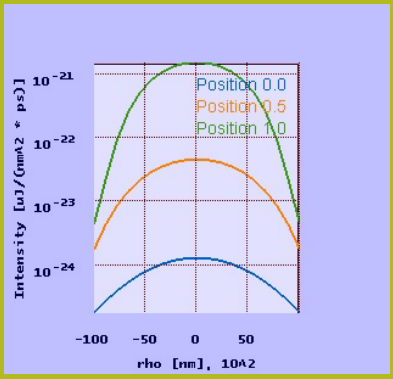
The figure on the right shows the populations of excited State 1 at positions 0.0, 0.5 and 1.0 during the time that the 100 ms pump pulse is passing through the sample. State 1 is the state from which stimulated emission and amplification occurs. At the sample input, the State 1 population rises to a steady-state value during the first 15 ms of the 100 ms pump pulse. At the center of the sample, State 1 pumped to a steady state that is about 85% occupied after the first 20 ms of the pulse. At the sample output surface, State 1 is pumped to a steady state that is only about 40% occupied after the first 30 ms of the pulse. The high population of State 1 at the sample input 0.0 and lower populations of State 1 for positions 0.5 and 1.0 explain why the seed pulse amplification is not uniform along the sample length.

Results of SimphoSOFT simulations for 100 mJ pump box-pulse:

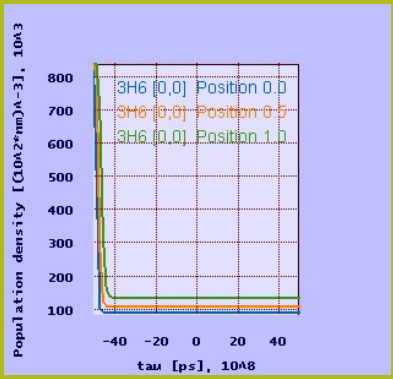
Second, we will investigate if increasing pump energy will increase the gain from the entire sample. It turns out that the gain increases non-linearly versus the pump energy increase, which helps to improve effectiveness of the gain material.

The next set of figures show the results for pump energy of 10 mJ with the same sample length of 250 mm. The figure on the left shows the increase in the intensity of the seed pulse as it propagates through the 250 mm long sample. Amplification is relatively uniform along the 250 mm sample. The center figure shows the populations of State 0 at positions 0.0, 0.5 and 1.0 during the time that the 100 ms pump pulse is passing through the sample. At the sample input surface (Position 0.0, blue), the population of State 0 is nearly depleted after the first 10 ms of the 100 ms pump beam. Once State 0 is depleted of electrons, the state will no longer absorb the pump light. At the center of the sample (Position 0.5, orange), State 0 is about 98% depleted during most of the pump pulse. At the output surface (Position 1.0, green), State 0 is about 94% depleted during most of the pump pulse.

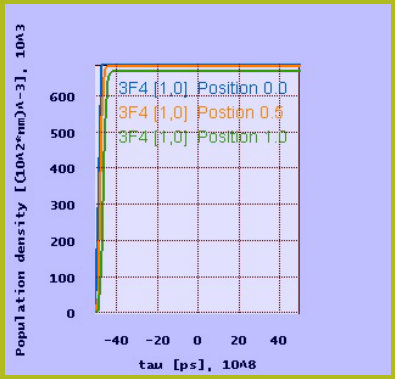
Screenshots of SimphoSOFT® graphical output with calculated intensity profile and population densities.
100 mJ pump pulse and 250 mm sample length



Pulse intensity within seed pulse moving frame at 3 sample locations



Populations of state 0 at 3 sample locations



Populations of state 1 at 3 sample locations

The figure on the right shows the populations of State 1 at positions 0.0, 0.5 and 1.0 during the time that the 100 ms pump pulse is passing through the sample. At both the sample input (Position 0.0) and at the center of the sample (Position 0.5), the State 1 population rises to approximately the same steady-state value after the first 5 ms of the pump pulse. At the sample output surface (Position 1.0), the population of State 1 is nearly 97% as high. The nearly uniform population of State 1 along the sample length results in nearly uniform amplification.

Conclusion 1: more amplification can be achieved (15 times) by increasing the pump energy (4 times).[2]

By varying the sample length and the pump input energy together, one can find an optimal configuration which would deliver the greatest amplification for the amount of gain material used.

[2] See the table on the next page.

In addition to simulations at 25 mJ and 100 mJ pump pulse energies for a sample length of 250 mm, simulations are also done for the same two pulse energies when the sample length is reduced to 125 mm. The combined results are shown below. For pump pulse energy of 25 mJ, the results show that the amplification was 9.5 in the 125 mm sample or in the first 125 mm of the 250 mm sample, but only 4.2 (i.e. 40/9.5) in the last 125 mm of the 250 mm sample. The amplification was not uniform over the entire 250 mm sample length. For pump pulse energy of 100 mJ, the results show that the amplification was 25.6 in the 125 mm sample or in the first 125 mm of the 250 mm sample and was also nearly the same at 24.2 (i.e. 619/25.6) in the last 125 mm of the 250 mm sample. In summary, the results show that amplification for 100 mJ pump pulse was approximately uniform throughout the 250 mm lenght.

Calculated amplification varying pump pulse energy and sample length:

25 mJ – 100 mJ, 125 mm – 250 mm

Pump pulse energy:	Sample length:	Amplification:
25 mJ	0-125 mm	9.5
25 mJ	125-250 mm	4.2
25 mJ	250 mm	40 (total)
100 mJ	0-125 mm	25.6
100 mJ	125-250 mm	24.2
100 mJ	250 mm	619 (total)

Conclusion 2: the sample length is very important parameter during material optimization, which can define effectiveness of target amplifying material.

It is clear from these amplification simulations that photo dynamics of rare-earth materials are very complex. Following the same type of analysis, SimphoSOFT users can get a better understanding and graphical visualization of what happens when rare-earth sample properties or laser properties are changed. This will help the user to design better amplifiers

References:
(1) Walsh, B. M, Barnes, N. P., Di Bartolo, B., J. Appl. Phys. 83(5), 2772 (1998). (for relaxation rates and times)
(2) Dinndorf, K. M., "Energy transfer between thulium and holmium in laser hosts", PhD thesis, Massachusetts Institute of Technology (1993). (for cross relaxation and upconversion rates)