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 Pulsed Amplification

Thulium-ion-doped materials can be used to amplify light at wavelengths near 1900 nm (1.9 μm). In order to achieve amplification, 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 1 ms long in order to achieve amplification of a 1900 nm seed pulse. A time of 1 ms is long enough to achieve significant amplification in the material, but not long enough for the Tm3+ ion energy level populations to come to steady-state equilibrium with the 790 nm pump. (Note: In another application note that describes approximately continuous wave (CW) amplification, the 790 nm pump pulse is 100 ms long. A pulse length of 100 ms is longer than any of the Tm^{3+} ion relaxation times and allows the Tm^{3+} ion energy level populations to come to approximately steady-state equilibrium with the 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 beam and amplified seed beam confined to the fiber core of radius 10 μm.

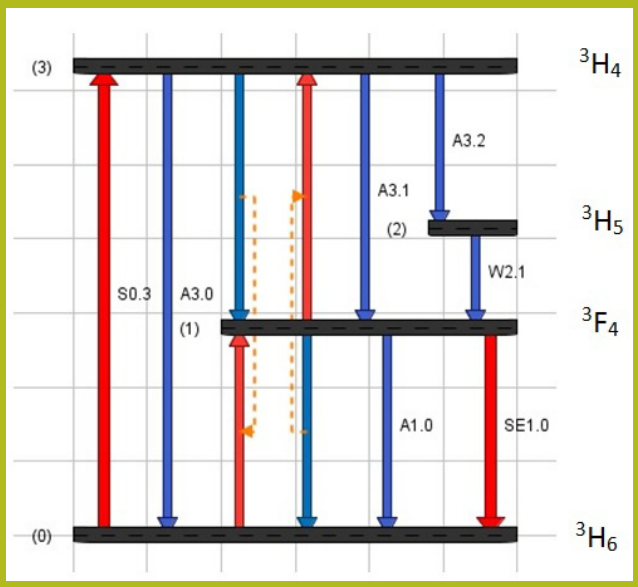
[1] SimphoSOFT requirements: SimphoSOFT v 3.1 with add-ons ET and Multi-Beam (more details on Release 3.1).
SimphoSOFT template project: "Tm pulse amplification".

In this application note, we show that the resulting amplification occurs mainly in the first 250 mm of the 500 mm long sample. We show the electronic populations of the ground state and the emitting excited state and show how these populations effect the amplification. The population of the excited state from which amplification occurs is not uniform along the sample length and the population is high only in the first portion of the sample.

At high doping concentrations, Tm^{3+} ions undergo significant cross-relaxation when pumped at 790 nm. Cross-relaxation (self-quenching) occurs when a donor molecule or ion in an upper excited state exchanges energy with an identical nearby acceptor molecule or 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 molecule or ion will be illustrated for cross-relaxation since donor and acceptor molecules or ions are identical.

Tm^{3+} ions can also undergo upconversion. We define upconversion as occurring between molecules or ions that are chemically identical. Upconversion can occur, for example, if molecules or ions of one type have electrons in their first excited states. Upconversion occurs with the de-excitation of a molecule or ion from the first excited state to the ground state and the simultaneous excitation (via energy transfer) of an identical molecule or 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.

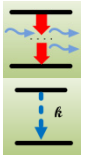


We will now show examples of SimphoSOFT simulations for amplification in a thulium (Tm^{3+})-doped material. The sample is composed of 6% Tm^{3+} ions dispersed in a glass host material. The ions have four important energy states for optical transitions, $^3H_6$ (ground State 0 in the diagram below), $^3F_4$ (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 500 mm or 250 mm.

Other sample properties of Tm^{3+} sample	
Tm ion dopant density (concentration) in the 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	500 mm or 250 mm

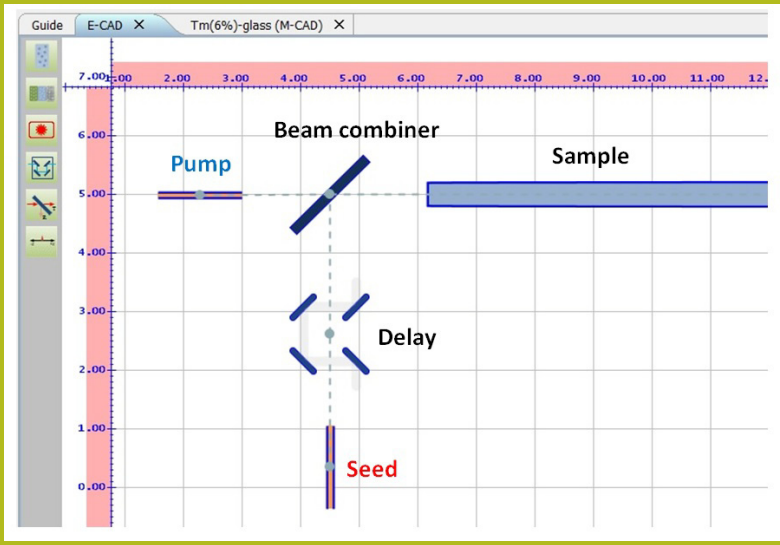
The pump pulse is a box-shaped (flat-topped) pulse of length 1 ms (t_0 = 0.5 ms). The seed pulse is Gaussian in shape with full-width-half-maximum (FWHM) value of 100 ns. In Numerical Setup, the total time domain for the pump beam is set at $4*t_0$ or 2 ms (twice the length of the 1 ms pump pulse). Since the length of the pump pulse (1 ms or 1,000,000 ns) is 10,000 times longer than the value of 100 ns for the seed pulse, the number of time samples used in Numerical Setup for the total time domain of the simulation should be significantly greater than 10,000 in order to fully resolve the seed pulse in the resulting output plots. We choose 100,000 time samples in this example (Reference 1).

Pump Laser properties	
Pulse energy	4 mJ or 6mJ
Pulse radius (HW1/e^2M)	10 µm
Pulse FWHM (box)	1 ms
Wavelength	790 nm

Seed Laser properties	
Pulse energy	0.01nJ
Pulse radius (HW1/e^2M)	10 µm
Pulse FWHM (Gaussian)	100 ns
Wavelength	1900 nm

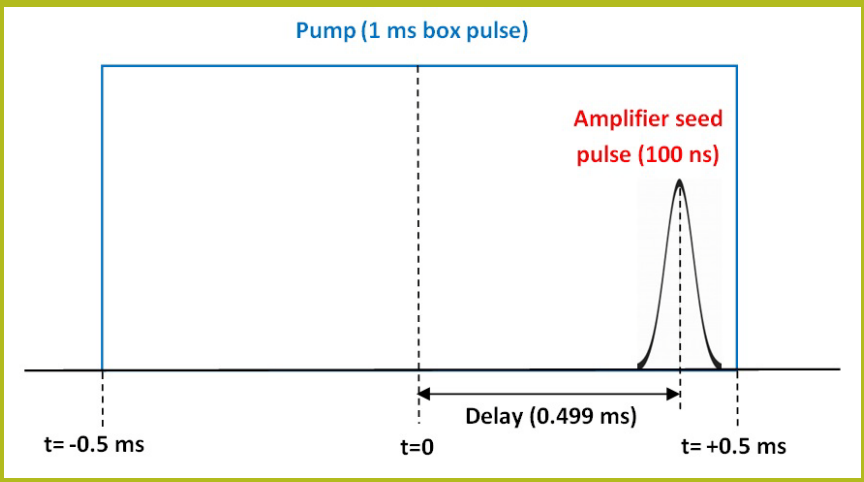
Simulations are run and compared for pump pulse energies of 4 mJ and 6 mJ. The seed pulse energy is much smaller at 0.01 nJ. The sample length is either 500 mm or 250 mm. The radius of each beam is 10 µm (diameter 20 µm).

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



The 100 ns Gaussian-shaped seed pulse at 1900 nm is delayed 0.499 ms relative to the center of the 1 ms box-shaped pump pulse but still overlaps in time with the end of the pump pulse. The timing sequence shown in the plot below for the pump and seed pulses is not to scale.

Shapes and timing of the pump and see pulses.

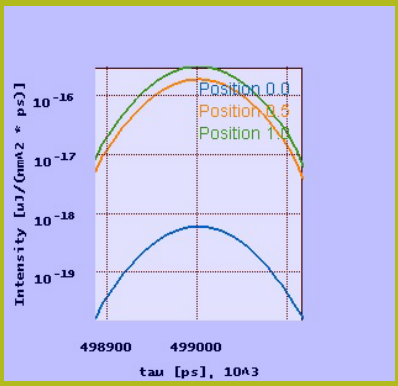


Results of SimphoSOFT simulations for 4 mJ pump pulse:

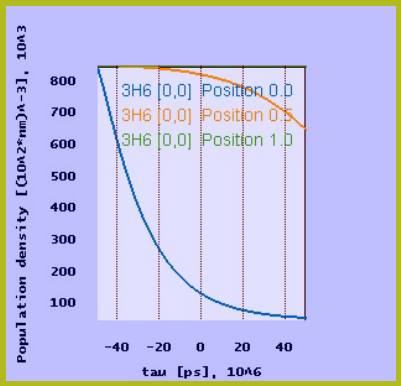
First, we will see whether amplification is equally strong along the entire sample, by analyzing the gain within the first half of the sample and the second half. It turns out that the second half of the sample underperforms and the reason for that is insufficient population density of Tm^{3+} ions excited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

Below we show results for pump energy of 4 mJ and a sample length of 500 mm. The figure on the left shows the increase (amplification) of the intensity of the seed pulse as it propagates through the 500 mm long sample. Position 0.0 (0 mm, blue) is at the sample input surface, Position 0.5 (250 mm, orange) is half way through the sample and Position 1.0 (500 mm, green) is at the output surface of the sample. Most of the amplification occurs in the first 250 mm of the sample. The center figure shows the populations of State 0 at positions 0.0, 0.5 and 1.0 during the time that the 1 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 by the 1 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 only about 25% depleted during the time of the 1ms pulse. At the output surface (Position 1.0), State 0 shows no significant depletion.

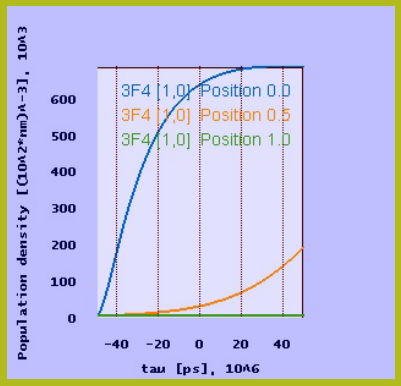
Screenshots of SimphoSOFT® graphical output with calculated intensity profile and population densities.
4 mJ pump pulse and 500 mm sample length



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

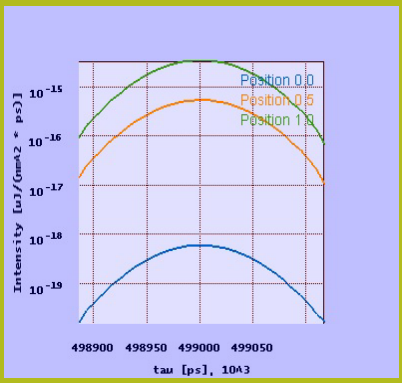
The figure on the right shows the populations of State 1 at positions 0.0, 0.5 and 1.0 during the time that the 1 ms pump pulse is passing through the sample. State 1 is the state from which stimulated emission and amplification occurs. At the sample input, the State 1 population rises to approximately a steady-state value during the time of the pump pulse. At the center of the sample, state 1 is only about 25% occupied. At the sample output surface, there is no significant electron population in State 1. Amplification can only occur when State 1 is occupied. The high population of State 1 at the sample input 0.0 and low populations of State 1 for positions 0.5 and 1.0 determine why most of the seed pulse amplification occurs in the first half of the sample.

Results of SimphoSOFT simulations for 6 mJ pump pulse:

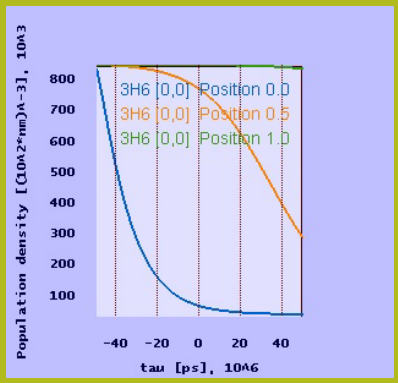
Second, we will investigate if increasing pump energy will increase the gain from the entire sample. It turns out that the gain increases non-linearly versus the pump energy increase, which helps to improve effectiveness of the gain material.

The next set of figures show the results for pump energy of 6 mJ with the same sample length of 500 mm. The figure on the left shows the increase of the intensity of the seed pulse as it propagates through the 500 mm long sample. Although most of the amplification still occurs in the first 250 mm of the sample, more amplification occurs in the last 250 mm of the sample for the 6 mJ pump pulse than for the 4 mJ pump pulse. The center figure shows the populations of State 0 at positions 0.0, 0.5 and 1.0 during the time the 1 ms pump pulse is passing through the sample. At the sample input surface, Position 0.0 (0 mm, blue), the population of State 0 is nearly depleted by the 1 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 (250 mm, orange), State 0 is about 75% depleted during the time of the 1ms pulse. At the output surface, Position 1.0 (500 mm, green), State 0 shows no significant depletion.

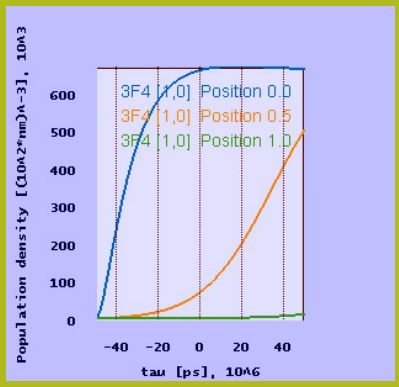
Screenshots of SimphoSOFT® graphical output with calculated intensity profile and population densities.
6 mJ pump pulse and 500 mm sample length



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 the 1 ms pump pulse is passing through the sample. At the sample input, the State 1 population rises to a steady-state value during the time of the pump pulse. At the center of the sample, state 1 is about 75% occupied by the end of the pump pulse. At the sample output surface, there is no significant electron population in State 1. Amplification can only occur when State 1 is occupied. With the high population of State 1 at the sample position 0.5 for the 6 mJ pump pulse, more amplification can now occur near and past the center of the sample and result in more seed pulse amplification in the second half of the sample.

Conclusion 1: more amplification can be achieved (10 times) by increasing the pump energy (1.5 times).

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.

In addition to simulations at 4 mJ and 6 mJ pump pulse energies for a sample length of 500 mm, simulations are also done for the same two pulse energies when the sample length is reduced to 250 mm. The combined results are shown below. For pump pulse energy of 4 mJ, the results show that the amplification was 109 in the 250 mm sample or in the first 250 mm of the 500 mm sample but only 1.52 (i.e. 166/109) in the last 250 mm of the 500 mm sample. For pump pulse energy of 6 mJ, the results show that the amplification was 363 in the 250 mm sample or in the first 250 mm of the 500 mm sample and improved to 4.49 (i.e. 1630/363) in the last 250 mm of the 500 mm sample. In summary, the results show that although the gain was better in the last 250 mm of the 500 mm sample for 6 mJ pump pulse energy than for 4 mJ, most of the gain still occurred in the first 250 mm for both pump energies.

Calculated amplification varying pump pulse energy and sample length:

4 mJ – 6 mJ, 250 mm – 500 mm

Pump pulse energy:	Sample length:	Amplification:
4 mJ	0-250 mm	109
4 mJ	250-500 mm	1.52
4 mJ	500 mm	166 (total)
6 mJ	0-250 mm	363
6 mJ	250-500 mm	4.49
6 mJ	500 mm	1630 (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 visualization of what happens when rare-earth sample properties are changed.

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)

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