Temperature Dependence for Cross-Relaxation Rate of Thulium Doped Fiber Amplifiers in Different Glass Hosts

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Abstract
We present two methods to specify the effect of temperature on cross relaxation rate and parameters for three glass hosts doped with Tm^{+3} ions. A comparison is done and an optimal glass host is selected.

1. Introduction
Cross-relaxation is considered as one of the major factors that limit thulium doped fiber amplifiers (TDFAs) operation [1-3]. During the cross-relaxation process, an ion exited to $^3H_4$ level transfers a part of its energy to a nearby ion in the ground state $^3H_6$. Consequently, both ions end up residing at $^3F_4$ level ($^3H_4$, $^3H_6 \longrightarrow$ $^3F_4$, $^3F_4$). This results in an increase of the $^3F_4$ level population and therefore, hampers the population inversion between the $^3H_4$ and $^3F_4$ levels [4-8]. This leads to conclude that cross-relaxation depends on the energy between peaks of the basic absorption and emission bands ($^3H_4 \longrightarrow ^3F_4$ emission and $^3H_6 \longrightarrow ^3F_4$ absorption). This gap cannot be passed without assistance from phonons in the crystal structure which is controlled by lattice vibration [8]. It was reported in [4, 7 and 8] that the amount of energy released by emission is larger than that necessary for absorption. This additional energy will convert to lattice vibration controlled by temperature. Also, since a phonon is defined as an energy quanta of crystalline vibration modes, so phonons that control the cross-relaxation are controlled by lattice vibration and so the temperature [4, 7 and 8]. Therefore, cross-relaxation is described as a phonon assisted energy transfer controlled by temperature.

In this paper, we are going to present two methods for specifying the effect of temperature on cross-relaxation rate (and hence amplifier performance) for different glass hosts doped with Tm^{+3} ions. Our investigation includes chalcohalide, sulfide and heavy metal oxide glass hosts. A comparison is done between these hosts and an optimal one is indicated.

2. Methods to Evaluate Temperature Dependence for Cross-Relaxation Rate and Cross-Relaxation Parameters
The first method to find temperature dependence for cross-relaxation rate is based on knowing the temperature dependence of the measured life time of the upper lazing levels available by published literatures [4-8] and specifying the radiative life time of such levels obtained by Judd-Oflet for the given glass host [4-8]. The second method tries to find the nearest phonon-assisted energy transfer operation that fits carefully results obtained by the first method. The importance of the second method is not only in providing the temperature dependence for cross-relaxation rate at any temperature (since the first method is limited by the corresponding measured temperatures) but also finding the exact effective number of phonons with their total energy that can control the cross-relaxation mechanism effectively [4-8]. The last two specifications are called cross-relaxation parameters. We take into consideration that multiphonon relaxation rate effect is omitted since our glass hosts have a very low phonon energy about 400 cm^{-1} [4, 7 and 8].

3. Mathematical Model
To evaluate the cross-relaxation rate under the effect of changing temperature as described in Sec.2, the following mathematical model is presented. The average number of phonons, n_m, in mode m at temperature T is given by the Bose–Einstein factor:

$$n_m = \frac{1}{\exp(hw_m / kT) - 1}, \quad (1)$$

where hw_m is the energy of a phonon in mode m, k is the Boltzmann's constant. Equation (1) indicates that the number of phonons should decrease with a decrease in temperature. Therefore, the cross- relaxation in rare earth ions, if it is an energy transfer process assisted by phonons, is expected to decrease at low temperatures.

Rates of the cross-relaxation can be calculated from the measured and radiative lifetimes of the $^3H_4$ level. When the concentration of a dopant ion is high, the transition probability from a certain energy level other than the ground state can be expressed as follows:

$$\frac{1}{\tau_{meas}} = \frac{1}{\tau_{rad}} + W_{MPR} + W_{ET}, \quad (2)$$

where τ_{meas} is the measured life time, τ_{rad} is the radiative life time calculated from Judd-Ofelt analysis. W_{MPR} and W_{ET} represent multiphonon relaxation and energy transfer (i.e cross-relaxation).

The energy gap between the $^3H_4$ and $^3H_5$ levels is approximately 4300 cm^{-1} and the energy of the highest phonon in sulfide glass is around 400 cm^{-1} while less than that value for chalcohalide and about 550 cm^{-1} for heavy metal oxide glass host. Therefore, multiphonon relaxation rates should be small and can be ignored in the present case. Then, energy transfer rates (i.e. cross-relaxation rates) can be calculated from the following relationship:

$$W_{ET} = \frac{1}{\tau_{meas}} - \frac{1}{\tau_{rad}}, \quad (3)$$

The above equations are the key for the first method discussed in Sec.2.

When phonons of only one vibrational mode are involved in the phonon-assisted process, the temperature dependence of the energy transfer rate is expressed by:

$$W(T) = W(0)(1 - \exp(-hw / kT))^{-N}, \quad (4)$$

where W(0) is the initial cross-relaxation rate at zero K and N represents the number of phonons participating in the energy transfer process and is expressed as:

$$N = \Delta E / hw, \quad (5)$$

where ΔE is the difference between the energies of the donor and acceptor levels. Equations (4) and (5) represent the second method discussed in sec.2 and tries to fit carefully results obtained by method 1.

4. Temperature Dependence of Cross-Relaxation Rate in Chalcohalide Glass Doped with Tm^{+3}

Based on the first method described in sec.2, the temperature dependence of the measured life time of the upper lazing levels is obtained from [7] while the upper lasing level radiative life time is obtained from Judd-Oflet analysis to be 1.499 ms. These are then substituted (2) and (3).

Figure 1 shows the exact cross-relaxation temperature dependence based on the temperature dependence of the measured life time of the upper lazing level ($^3H_4$) for chalcohalide fiber glass doped with 0.2 mole% of Tm^{+3}. It is clear that cross-relaxation increases with temperature (specially after 110 K), while the drop in cross-relaxation rate at 75 K and around it is not clear to us until now. Other literatures [7, 8] concluded that this is may be due to changes in the cross sections of GSA and ESA. The maximum cross section rate calculated at 300 K was 871.35 Hz while the starting and minimum value at 25 K was 358.5 Hz.

For the second method described in Sec.2, Fig.2 shows temperature dependence of cross-relaxation rates for chalcohalide glass doped with 0.2 mole% of Tm^{+3} ions by assuming different number of phonons with different energies that control the phonon- assisted energy transfer and hence cross-relaxation. We use (1), (2) and (5) to get our results.

The best fit was obtained when assuming three phonons with total energy of 250 cm^{-1} controlling the phonon assisted energy transfer Fig.2 (dashed lines spectrum). The above phonon numbers and energy are chosen carefully from a range developed by [7, 8] to address the phonon assisted energy transfer phenomena.

5. Temperature Dependence for Cross-Relaxation Rate in Sulfide Glass Doped with Tm^{+3}.

Based on the first method described in sec.2, the temperature dependence of the measured life time of the upper lazing levels is obtained from [8] while the upper lasing level radiative life time is obtained from Judd-Oflet analysis to be 230 μs. Again, these are then used in (2) and (3).

Figure 3 shows the exact cross-relaxation dependence on temperature based on temperature dependence of the measured life time of the upper lazing level ($^3H_4$) for sulfide fiber glass doped with 0.2 mole% of Tm^{+3} ions. It is shown in Fig.3 that cross relaxation increases with temperature. The maximum cross-relaxation rate calculated at 300 ^{0}K is 5652 Hz while the starting and minimum value at 25 K is 3782 Hz. Comparing results of sulfide with that observed for chalcohalide glass host, a great difference between the two spectrums is observed. For sulfide, the rate of increase is smoother than that observed for chalcohalide and no nonlinear area (around 75 K in chalcohalide) is found for sulfide. On the other hand, cross-relaxation rate obtained for sulfide is much grater than that of chalcohalide glass host (by about 4781 Hz at 300 K) which is a major drawback for amplifier performance using sulfide as a glass host. This is mainly due to the very small value of the measured life time of the upper lazing level obtained for sulfide glass (a maximum value of 125 μs at 75 K) when compared with that for chalcohalide glass host (a max. 1000 μs at 75 K). Also, the radiative life time obtained by judd- oflt is determined as 230 μs for sulfide and 1.499 ms for chalcohalide [7, 8].

For the second method, Fig.4 shows the temperature dependence of cross-relaxation rates for sulfide glass doped with 0.2 mole% of Tm^{+3} ions by assuming different number of phonons with different energies that control the phonon-assisted energy transfer and hence cross-relaxation. The best fit is obtained when assuming two phonons with total energy with 350 cm^{-1} controlling the phonon assisted energy transfer.

6. Temperature Dependence of Cross- Relaxation Rate in Heavy Metal Oxide Glass Host Doped with Tm^{+3}

Based on the first method described in sec.2, the temperature dependence of the measured life time of the upper lazing levels is obtained from [4-6] while the upper lasing level radiative life time is obtained from Judd-Oflet analysis to be 250 μs. Both are then used in (2) and (3).

Figure 5 shows the exact cross-relaxation dependence on temperature based on temperature dependence of the measured life time of the upper lazing level ($^3H_4$) for the heavy metal oxide fiber glass doped with 0.1 mole% of Tm^{+3} ions. It is seen that the cross-relaxation increases with temperature. The maximum cross-relaxation rate is obtained at 280 K with the value 1355 Hz, while the starting and minimum value at 20 K is 1295 Hz. Comparing with the previous results, one notice that the cross-relaxation rate in heavy metal oxide is larger than that of the chalcohalide glass host at 300 K by about 484 Hz, but sulfide still provides the largest cross relaxation rate with a difference of about 4297 Hz at 300 K greater than that of the heavy metal oxide.

For the heavy metal oxide host , doped with 0.1 mole% of Tm^{+3}, and using the second method, Fig.6 shows the temperature dependence of cross-relaxation rates ions by assuming different number of phonons with different energies that control the phonon assisted energy transfer and hence cross-relaxation. The best fit is obtained when assuming one phonon with total energy with 590 cm^{-1} controlling the phonon assisted energy transfer, Fig.6 (filled squares spectrum).

7. Conclusion

We discussed the effect of temperature on the cross-relaxation rate for different glass hosts. From the obtained results, one can observe that lowest cross- relaxation rate can provided by chalcohalide glass host followed by heavy metal oxide and finally sulfide glass host. As mentioned in previous sections, this is because sulfide glasses have the lowest measured upper level life time compared to other glasses with maximum values: 125 μs at 75 K for sulfide, 1000 μs for chalcohalide and 189 μs for heavy metal oxide, at the same temperature.

8. References

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9. Figures

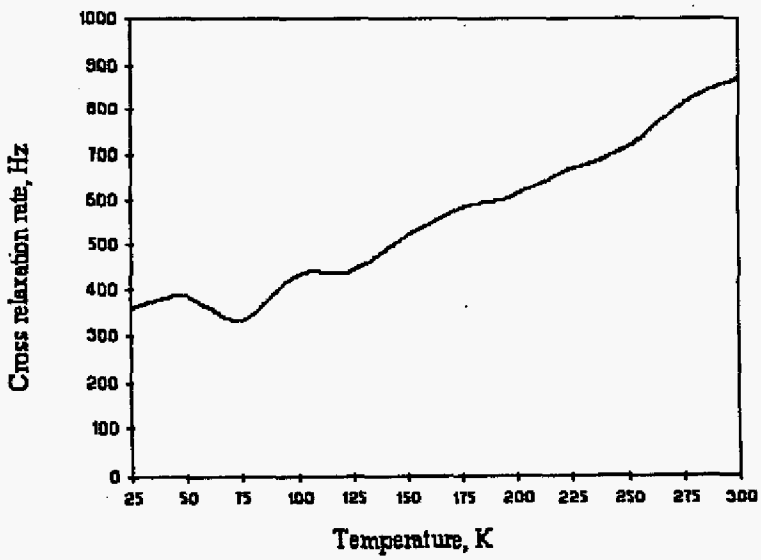

Fig.1 Exact cross-relaxation rate for Chalochalide glass.

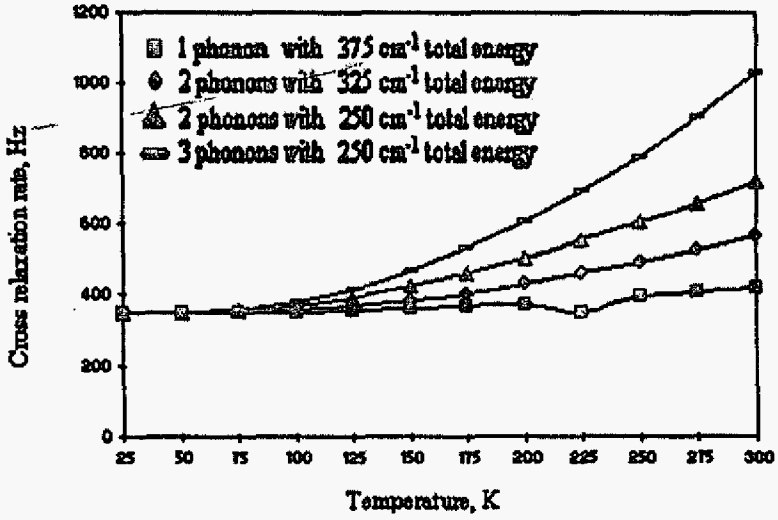

Fig.2 Temperature dependence for cross relaxation rate obtained for different phonon-assisted operations for Chalochalide glass host.

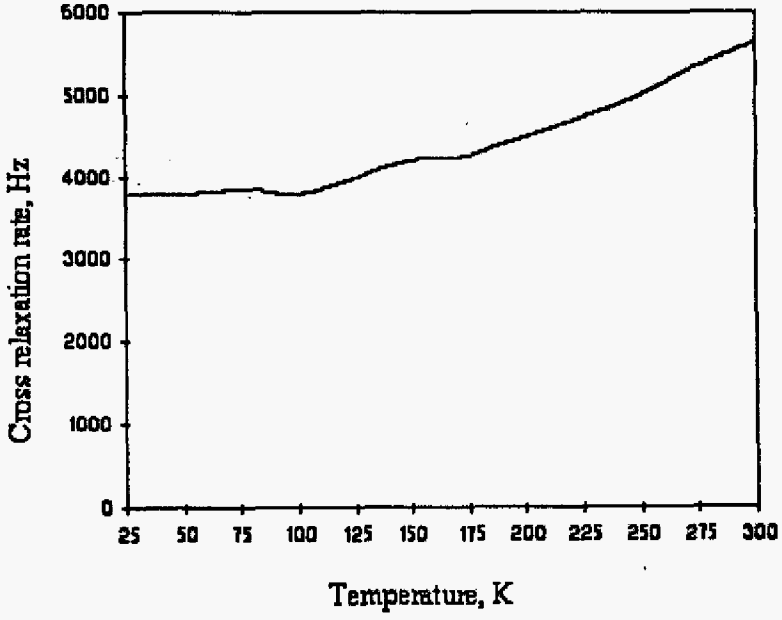

Fig.3 Exact cross-relaxation rate for sulfide glass.

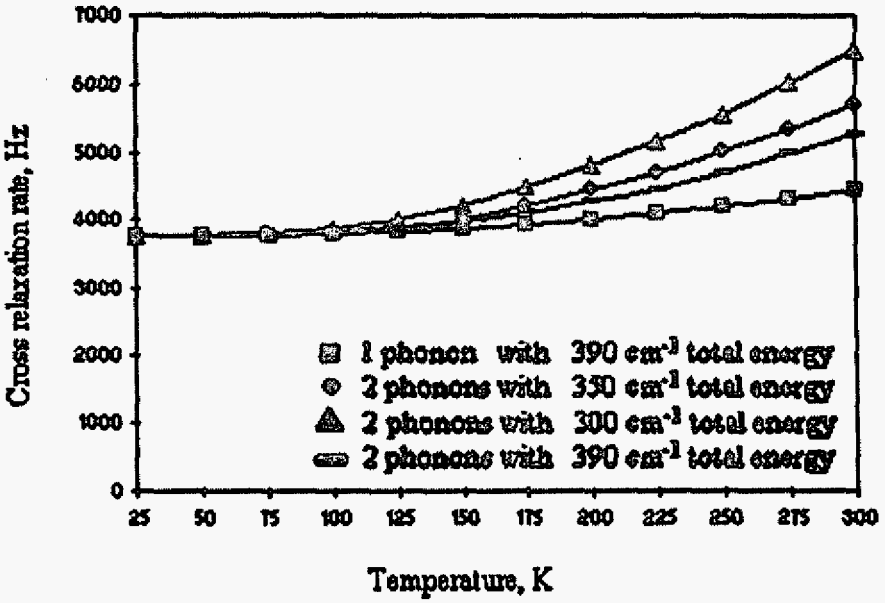

Fig.4 Temperature dependence for cross relaxation rate obtained for different phonon-assisted operation for sulfide glass host.

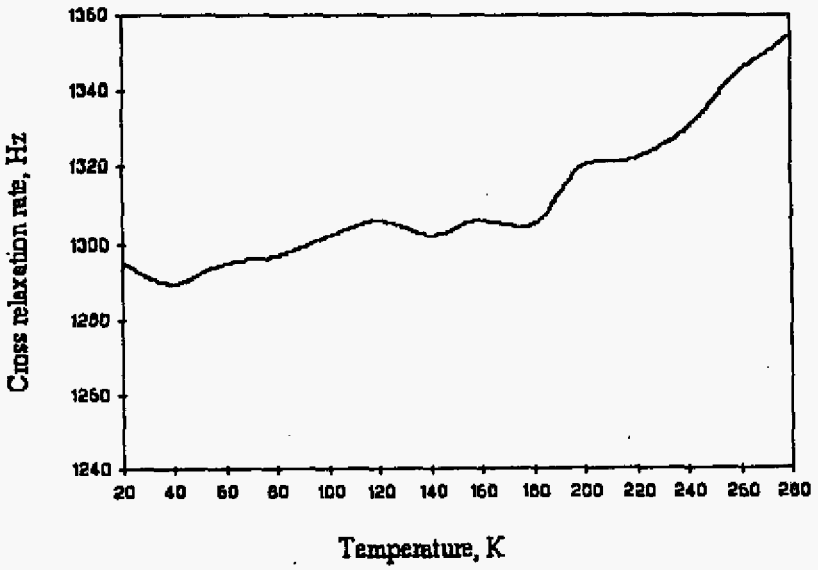

Fig.5 Exact cross-relaxation rate for heavy metal oxide glass.

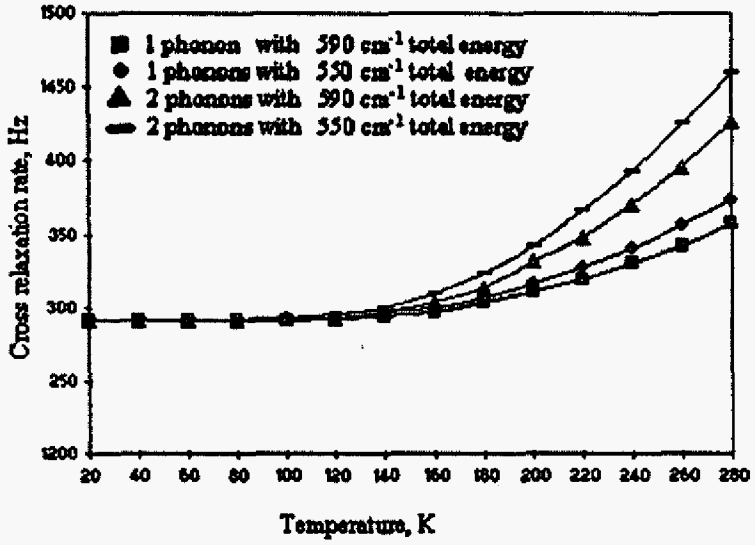

Fig.6 Temperature dependence for cross relaxation rate obtained for different phonon-assisted operation For Heavy metal oxide glass host