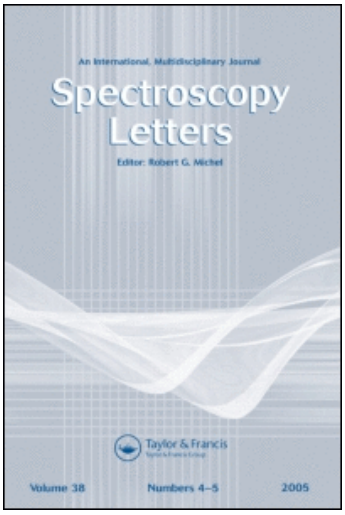

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A Condition in Ln-Doped Materials for Flat Optical Gain

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A Condition in Ln-Doped Materials for Flat Optical Gain

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Abstract: Fundamental conditions that rule gain flatness in Er-doped glass optical amplifiers are investigated using few parameters obtained by drastic simplifications for level positions and widths. The obtained general gain flatness condition for rare-earth–doped glasses contains two parts: a general one valid in any material and a slight modulation of it valid only for glasses when "0–0" transitions are involved. Essentially, the electron–phonon coupling for the considered materials has to be larger than $2/3$. In order to exemplify these conditions, they are calculated for fluoride and silicate glasses, which are known to display respectively flat and non-flat gain behavior.

Keywords: EDFA, gain flatness condition, homogeneous width, inhomogeneous width

INTRODUCTION

In the following, we shall investigate fundamental conditions in order to obtain flat gain optical amplification with a lanthanide-doped material. A flat and wide gain is a prerequisite for high-capacity networks as well as for long-range information transportation. The current generalization of optical information systems is due to the fact that the use of multiple optical carriers allows multiplication of the highest available electronic bandwidth

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by the number of optical carriers. So the use of so-called WDM (wavelength domain multiplex) has been generalized. Yet the number of channels is limited by the gain flatness in silica glass amplifiers, and losses at given wavelength have been deliberately introduced in order to flatten the gain. However, in order to reach HDWDM (high density wavelength domain multiplexing), much wider flat gain than nowadays obtained in Er-doped silica fiber amplifiers (EDFA) are still necessary. It is well-known that fluoride glass fibers have demonstrated a flatter gain allowing WDM without wavelength-dependent corrections.[1]

On the other hand, we experimentally know that fluoride glasses present a much weaker crystal field than silica glasses,[2] and this was an incentive to look for an eventual role of crystal field strength in gain flatness. Besides this, we have recently found some indications that the very nature of the gain structure may be different along the Er^{3+} gain bandwidths. From the conclusions reached for Yb^{3+},[3] we can guess that it would be mainly inhomogeneous for the so-called C-band (1530–1565 nm) and homogeneous for the L-band (1565–1625 nm) even at low temperature. This could lead to some different behavior for channels saturation and the cross talk between adjacent channels in a HDWDM along the whole bandwidth. However, the precise study of the spectroscopic behavior of Er^{3+} in glasses for the $^4I_{13/2}$–$^4I_{15/2}$ transition is a tremendous task because of the 56 transitions between the 7 Stark states of the excited $^4I_{13/2}$ multiplet down to the 8 Stark states of $^4I_{15/2}$, the ground multiplet, each transition being widened *a priori* by both inhomogeneous and homogeneous broadening. The recent detailed studies,[4–8] though having tried to clarify the problem, have shown their limitations.

We believe that more stringent simplifications, based on a critical ordering of the relative importance of the various physical aspects, are necessary in order to clearly approach the gain flatness problem.

In a previous study, we have shown that the local Er^{3+} ion symmetry in a silicate glass could be described in a simplified way by ascending the ion symmetry up to a quasi-spherical icosahedral one.[9] This drastic simplification reduces the 56 transitions down to 12 transitions. Then using our scalar crystal field parameter Nv,[10–12] we could show that each crystal field level position of Er^{3+} in the icosahedral symmetry could be described by Nv alone. Here we shall apply the same approach to an Er-doped fluoride glass and compare with the Er-doped silicate glass we had studied in Ref. 9.

On the other hand, we had shown that for Yb^{3+} in glasses at low temperature (T), the width of the transitions between Stark levels, except for the "0–0" one, are essentially homogeneously broadened with width related to their positions[3] as given by the crystal field strength. Understanding from Refs. 3 and 13 that for Yb^{3+} and in our simplified approach for Er^{3+}, only the 0–0 can be considered as inhomogeneously broadened at low T but with a width constant with T, all other transitions being essentially homogeneously broadened, we are in a position to define a fundamental general condition for gain flatness. This is the root of the current investigation.

THE ICOSAHEDRAL DESCRIPTION FOR Er–ZBLAN AND COMPARISON WITH Er-DOPED SILICATE GLASS

As in Ref. 9, we consider an average icosahedral site for Er in the ZBLAN (ZrF_4-BaF_2-LaF_3-AlF_3-NaF) glass of Ref. 4. In order to further simplify the problem, we consider the low temperature case and the four absorption transitions to $^4I_{13/2}$ observed at 12 K. As shown in Figure 1, the experimental absorption spectrum can be well deconvoluted by four pseudo-Voigt profiles because the range of values for Gaussian and Lorentzian relative contributions (μ) in Eq. (1) are somewhat known from the same considerations as in Ref. 3: $\mu \cong 0$ for the 0–0 transition, $\mu \cong 1$ for the 0–1,2,3 ones

$$y = y_0 + A\left[\frac{2\mu}{\pi}\frac{\omega_G}{4(x-x_c)^2+\omega_L^2} + (1-\mu)\frac{\sqrt{4\ln 2}}{\omega_G\sqrt{\pi}}e^{4\ln 2/\omega_G^2(x-x_c)^2}\right], \quad (1)$$

where x_c is the center frequency of each of the bands, ω_L the Lorentzian width, and ω_G the Gaussian width of each of them.

The energy scheme of Figure 2 is obtained for the $^4I_{13/2}$ multiplet with for each of them the homogeneous width given in Figure 3 for the four absorption transitions.

A linear behavior is obtained with an electron–phonon coupling parameter defined in Refs. 3 and 14 at low T by:

$$K = \frac{\pi}{Mv^2}\rho(\omega_{ij})|\langle C_{ij}\rangle|^2 \quad (2)$$

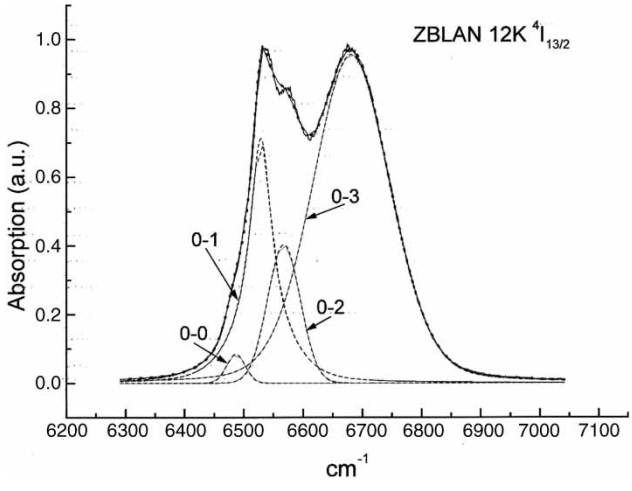

Figure 1. Experimental absorption spectra at 12 K for $^4I_{15/2}$ to $^4I_{13/2}$ transition in Er^{3+}-ZBLAN and its reconstruction by Voigt profiles in the icosahedral site symmetry approximation.

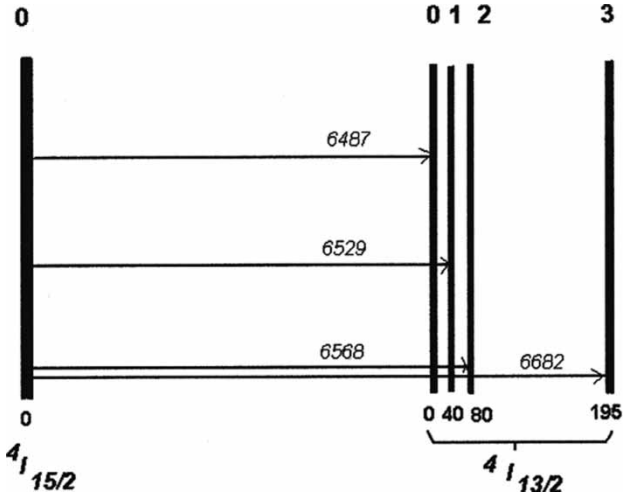

Figure 2. Energy scheme for the $^4I_{13/2}$ multiplet of Er^{3+}-ZBLAN in the icosahedral site hypothesis, derived from Figure 1 for low T absorption. Energies units are cm^{-1}.

with $\rho(\omega_{ij})$ the phonon density of states with energies in resonance with Stark energy differences all lower than kT_D the maximum phonon energy of the host; M is the host mass and v is the average sound velocity in the considered glass; $|\langle C_{ij}\rangle|^2$ is the crystal field coupling

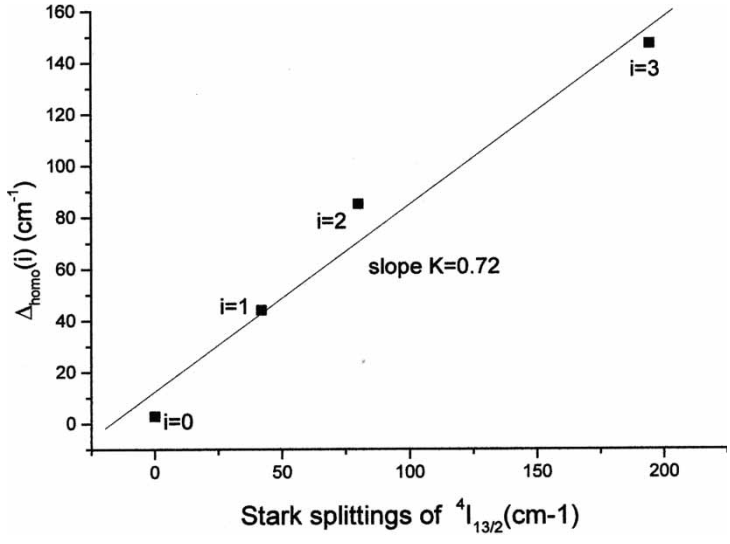

Figure 3. Homogeneous width for absorption transitions $0 \rightarrow 0,1,2,3$ of $^4I_{13/2}$ in ZBLAN glass at 12 K versus energy of Stark splittings.

matrix element between Stark states *ij* providing the electron–phonon coupling.

Here we find $K = 0.72$, not far from the value obtained for Yb^{3+},[3] $K = 0.76$ for the same matrix. It can be noted that for the 0–0 transition, the Voigt deconvolution gives a Gaussian width of 37 cm^{-1} and a Lorentzian one of 3 cm^{-1}; the Gaussian value is not far from the 27 cm^{-1} given by Bigot et al.[6,8] for the inhomogeneous width for the same type of glass.

For a silicate glass (SiO_2–Na_2O), we had found in Ref. 9 that the deconvolution in the icosahedral approximation into four bands for the low T absorption from the ground state to the four Stark states of $^4I_{13/2}$ was obtained only with Lorentzian and not with Gaussian fits. Except for the 0–0 transition known to be inhomogeneous, we shall here consider the obtained Lorentzian width as the corresponding homogeneous width. The results are given in Figure 4. The linear fit gives $K = 0.32$ for the electron–phonon coupling parameter in the Er-doped silicate.

THE INHOMOGENEOUS WIDTH IN VARIOUS GLASSES

As a first approximation, we consider that the inhomogeneous width is related more to the glass nature than to the considered transition of a given RE (Rare Earth) ion. This approximation is used in many papers studying transition width in crystals and glasses.[3,6,14,15] Because the inhomogeneous contribution to the linewidth of a transition is due to random crystal strain

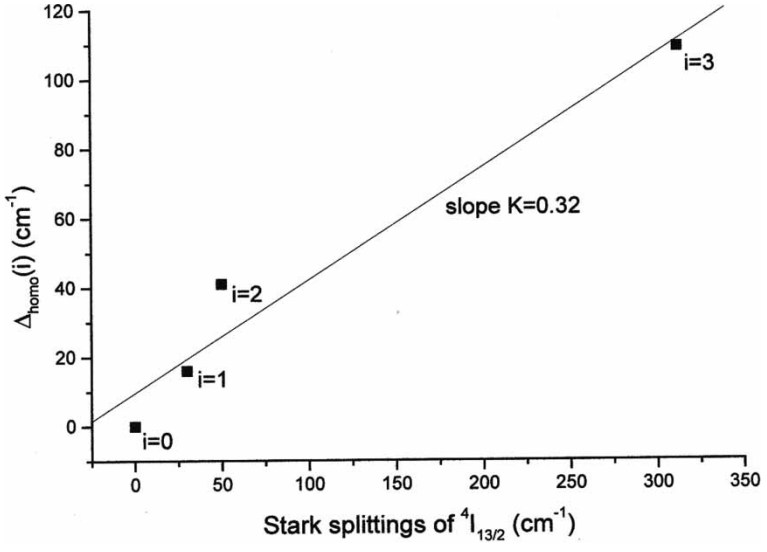

Figure 4. Homogeneous width for absorption transitions $0 \rightarrow 0,1,2,3$ of $^4I_{13/2}$ in the silicate glass of Ref. 9 at 12 K versus energy of Stark splittings.

inhomogeneity, such temperature-independent contribution has a lineshape representing the strain distribution. In glasses, the usual Gaussian distribution of strains provides a Gaussian lineshape that has been studied at least for the so-called 0–0 transition at 1530 nm of Er^{3+} in various glasses by the fluorescence line-narrowing techniques.[6,7] Because the 0–0 transition has an inhomogeneous width at low T larger than its homogeneous contribution,[3,6,13] this technique is probably the best for this type of study. Apart from cases where few definite crystal field sites would exist, we propose that the Gaussian distribution of our N_v crystal field scalar parameter can describe the inhomogeneous linewidth. This approximation shall be so much the better that the local sites for the lanthanides in a glass are the nearest to a random distribution.

Recalling that a normalized Gaussian distribution is completely defined by the ordinate of its maximum that is the average value of its variable, we may assume that the measured N_v parameter[2,9] for a given ion in a given glass is the average value of the distribution of the crystal field strength in the considered glass, and the standard deviation of the distribution is

$$\sigma = \sqrt{N_v}. \tag{3}$$

From it, the Gaussian width at half height is given by

$$\Gamma = \sigma\sqrt{2\mathrm{Ln}2} = 2.354\sigma = 2.354\sqrt{N_v}. \tag{4}$$

From this we may write

$$\Delta_{inhomo} = k\sqrt{\Delta E_{max}}, \tag{5}$$

as we have:[12]

$$\Delta E(J)_{max} = \left[\frac{3g_a^2}{\pi g(g_a+2)(g_a+1)}\right]^{1/2}\left[\prod_{k'}\left|\left\langle J\left\|\sum_i C_{(i)}^{(k')}\right\|J\right\rangle\right|\right]^{1/3} N_v, \tag{6}$$

where g_a is the degeneracy effectively removed by the crystal field and g the total degeneracy of the J multiplet; k contains the above proportionality factor and a normalization factor with dimension $\mathrm{cm}^{-1/2}$.

Interestingly, Eq. (5) may explain an observation by Pellegrino et al.,[18] who noted a kind of correlation between the splitting of $^4F_{3/2}$ and the inhomogeneous width of the low T emission of Nd^{3+} in various glasses. The amount of validity of Eq. (5) is shown in Figure 5 for a large number of various glasses they have studied in Ref. 18. Though the splitting of $^4F_{3/2}$ is not due to all the crystal field parameters, B_k^q, we had shown that the splitting of $^4F_{3/2}$ is somewhat correlated with N_v.[10]

For the Er^{3+} case, we have plotted in Figure 6 the results from Ref. 6 and 8 to which our result obtained here for ZBLAN has been added.

The linear fit to Eq. (5) provides a value $k = 2.4\ \mathrm{cm}^{-1/2}$ for the various types of Er^{3+}-doped glasses.

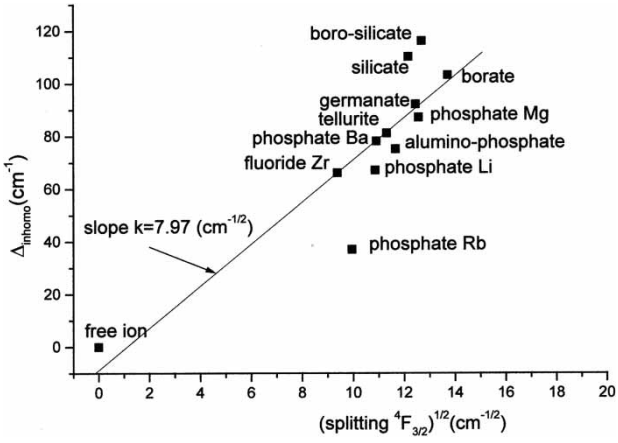

Figure 5. Inhomogeneous width emission from $^4F_{3/2}$ of Nd^{3+}-doped glasses at low T versus $^4F_{3/2}$ Stark splittings. Values taken in Ref. 16.

A GENERAL FUNDAMENTAL CONDITION FOR FLAT GAIN AMPLIFICATION IN LANTHANIDE-DOPED GLASSES

Starting from the Rayleigh criterion for separating two spectral bands, $\Delta \geq 1/2$ $(\Gamma_1 + \Gamma_2)$, with Δ the frequency separation between the two bands and $\Gamma_{1,2}$ their width at half height, we set the inverse of it (the two bands cannot be separated) as the condition for gain flatness for two consecutive transitions from two Stark states 1 and 2 from an upper multiplet. For the sake of simplicity and generality, we use the same approximation as in Ref. 3 for the

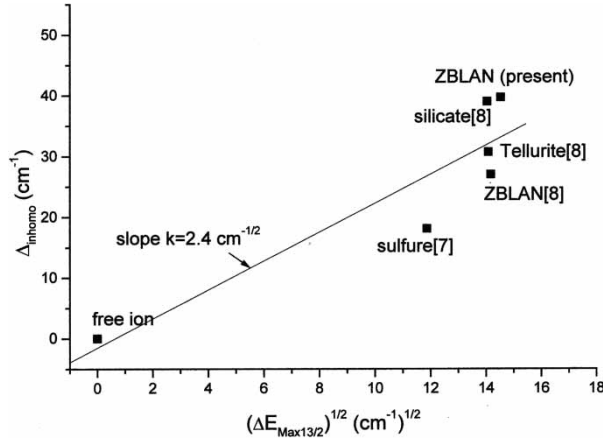

Figure 6. Inhomogeneous width emission from $^4I_{13/2}$ of Er^{3+}-doped glasses at low T versus $^4I_{13/2}$ maximum Stark splitting. Values taken in Refs. 7 and 8.

homogeneous widths at low T, from excited Stark states from the upper multiplet, that is we assume an average equal separation between them; the observed quasi-linear behavior for homogeneous width for them with respect to their position[3] is an argument for such an approximation:

$$\Delta(i)_{homo} = iK\Delta E_{max}/(g-1), \tag{7}$$

where $\Delta\,(i)_{homo}$ is the homogeneous width of level i among the g levels of the considered multiplet of maximum splitting ΔE_{max}; K is the electron–phonon coupling parameter defined in Ref. 3 providing the homogeneous width. The average energy separating the Stark levels in a multiplet is with the same approximation as used for Eq. (7):

$$\Delta = \Delta E_{max}/(g-1). \tag{8}$$

For most of the transition from the upper multiplet, the width of the emission band Γ is $\Delta(i)_{homo}$ except for the so-called 0–0 transition for which at low temperature the width is known to be essentially inhomogeneous[3,6,13] and constant with temperature; it is also assumed as in Refs. 14 and 15 to be the same for each Stark level of a given material, here a given glass type as seen above.

The gain more general flatness condition is then simply:

$$\frac{1}{2}(i+i+1)K\Delta E_{max}/(g-1) \geq \Delta E_{max}/(g-1) \tag{9}$$

or

$$\frac{1}{2}(2i+1)K \geq 1, \tag{10}$$

which shall be *a fortiori* valid for the minimum value of the left member, that is, for $i = 1$:

$$K \geq 2/3 = 0.66. \tag{11}$$

This condition is very general and valid for any transitions in lanthanide-doped materials except when 0–0 transitions are involved.

At higher temperature, the level positions are not modified and only the left member of Eq. (9) is known to increase with temperature T as $T^{1.4-2}$[6,13,15] through K, so condition (8) is still more easily verified and the stricter condition is still given by (11). In Figures 3 and 4, we have respectively found $K = 0.72$ and $K = 0.32$ for ZBLAN and silicate glasses, showing that condition (11) is fulfilled for ZBLAN but not for the silicate glass.

Now when the 0–0 transition is involved, one of the transitions is inhomogeneous, at low T, the other is the 1–0 ($i = 1$) homogeneous line. This is in fact the case for the C-band in EDFA. Equation (9) has to be

modified and becomes:

$$\frac{1}{2}[k(\Delta E_{max})^{1/2} + K\Delta E_{max}/(g-1)] \geq \Delta E_{max}/(g-1) \tag{12}$$

or

$$\frac{1}{2}\left[\frac{k(g-1)}{(\Delta E_{max})^{1/2}} + K\right] \geq 1 \tag{13}$$

It can be noted that condition (13) is now glass type–dependent both through K and ΔE_{max}, that is electron–phonon coupling and crystal field strength. For the 0–0 transition from $^4I_{13/2}$, we have seen from Figure 6 that $k = 2.4\ \text{cm}^{-1/2}$ for the various types of glasses, and condition (13) may be written:

$$\frac{1}{2}\left[\frac{14.4}{(\Delta E_{max13/2})^{1/2}} + K\right] \geq 1 \tag{14}$$

From the values obtained for K from Figures 3 and 4, we respectively obtain for the left member of (14) the values 0.88 for ZBLAN and 0.56 for our silicate, both smaller than 1. However, it shows that for the ZBLAN glass, condition (14) is indeed better fulfilled than for silicate but is only approached. It is an indication that for C-band, the gain flattness condition is harder to fulfill than for L-band.

CONCLUSIONS

Simplifying drastically the theoretical approaches for crystal field sites, homogeneous and inhomogeneous linewidths, and considering the low-temperature case as the most critical, we reduce the number of involved parameters so obtaining a general simple condition for any transitions from upper Stark states, valid for any lanthanide-doped materials. When 0–0 transitions are involved, the inhomogeneous aspect has to be considered and the generality of the approach is reduced to glasses with a large number of random sites. The gain flatness condition then contains two parts: a general one, for all transitions except the 0–0 one, stating that the electron–phonon coupling as defined above for the considered materials has to be larger than $2/3$. When the considered amplification bandwidth includes the 0–0 transition, a weak modulation of the main condition, inversely proportional to the square root of the crystal field strength, appears and the condition is limited to lanthanide-doped glasses.

Flat gain amplifiers shall be obtained with glasses showing the largest K and the weakest crystal field strength, that is from Eq. (2) with the weakest speed of sound in turn pointing to "soft" glasses with large mass constituents. The correlation between homogeneous width and the speed of sound has been

well verified in Nd-doped glasses.[16] Interestingly, we had shown[11] that weak crystal field strength does correspond also to soft materials with weak "scratch hardness." So the conditions for gain flatness for any type of transitions, 0–0 and 0-*i*, are finally the same at the chemistry level.

Contrary to common beliefs found in the literature, because most of the transitions in glasses are not 0–0, spectra are more reflecting the electron–phonon coupling than the site inhomogeneity and this so much the better that temperature is higher.

The principal characters of the transitions involved in the gain spectra of EDFA have been stressed in their fundamental simple aspects. This approach could be a simple guideline for researches on new glasses with defined amplification properties. Of course, refined studies would modulate our conclusions but at the cost of a lack of generality and of predictive properties.

From the amplification point of view, it explains the differences observed for C- and L-bands for the gain saturation hole burning[17] and confirms the interpretation given in Ref. 6. Further, it shows that fundamentally, conditions for gain flatness for C-band shall be more difficult to obtain than for L-band, which has a more homogenous behavior.

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