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Abstract: We report on the temperature dependent spectroscopic properties of Yb^{3+} and Er^{3+} co-doped glass gain media in the eye-safe spectral region. Measurements suggest that judicious selection of the operating wavelength can lead to a laser output with minimal dependence on the temperature of the gain medium.

OCIS codes: (140.0140) Lasers and laser optics; (140.3500) Lasers, erbium; (140.3580) Lasers, solid-state

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1. Introduction

Efficient laser systems are desirable for applications requiring performance over a broad range of operating temperatures. This is specifically important for systems that operate with limited input power where thermal management systems can require a significant portion of the input power budget. By appropriately minimizing thermal management requirements, battery powered operational life can be greatly extended.

Previous work studied the temperature dependence of basic four-level Nd^{3+} lasers [Ref. 1]. Here we report on the temperature dependence of the emission properties of the Yb,Er:glass gain medium in the "eye-safe" region from 1500-1600 nm, important for remote sensing applications. Yb^{3+} co-doping of the gain medium has long been known to provide an efficient means to absorb pump light in the 900 nm band and transfer the energy to Er^{3+} [Ref. 2].

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Pumping in this band is also thermally advantageous due to the rapid increase in laser diode efficiencies [Ref. 3], and the broad absorption feature requiring no control of the diode pump wavelength [Ref. 4]. Gain saturation has been suggested as a means of stabilizing the output energy of the material system [Ref. 5], however this is difficult to achieve in a diode pumped system. This work presents an alternative approach through a systematic study of the spectroscopic properties of Yb,Er:phosphate glasses, indicating that proper selection of the emission wavelength can be exploited to maintain the laser gain independent of the operational temperature of the gain medium for a given inversion level.

2. Spectroscopy

Thin Yb,Er:glass samples were acquired from Schott Glass (IOG-1 phosphate, IOG-2 phosphate, and IOG-10 silicate) and Kigre, Inc. (MM-2 phosphate) for spectroscopic testing. Measurements were made of the absorption and emission spectra as well as the fluorescent lifetime of the Er^{3+} $^4I_{13/2}$ state.

The absorption spectra were measured at room temperature (RT) for each material and due to the amorphous nature of glass, only unpolarized data was recorded. The absorbance data was corrected for Fresnel reflections and the absorption coefficient $\alpha(\lambda)$ calculated according to the relation:

$$\alpha(\lambda) = \frac{\ln 10 \cdot ABS(\lambda)}{l} \tag{1}$$

where l is the thickness of the sample, and ABS(λ) is the absorbance of the sample at wavelength λ. We then used the calculated oscillator strength for all the observed transitions from the ground state in order to apply the Judd-Ofelt (JO) theory [Refs. 6, 7]. Because extensive literature exists that details JO theory, we report only the main expressions used for the numerical application of JO.

The electric-dipole line strengths can be calculated using the experimentally determined absorption coefficient for all the observed transitions from the ground state and

$$S_{DE}^{\exp}(J \to J') = \frac{3hc(2J+1)\cdot 9n(\bar{\lambda})\cdot \int \alpha(\lambda) d\lambda}{N \cdot 8\pi^3 \bar{\lambda} \cdot (n(\bar{\lambda})^2 + 2)^2} \tag{2}$$

where N is the Er^{3+} concentration, h is Planck's constant, c is the speed of light, J is the angular momentum of the ground state (15/2 in our case), and n($\bar{\lambda}$) is the refractive index at $\bar{\lambda}$.

JO theory provides another formula which gives the line strength theoretically as:

$$S_{DE}^{calc}(J \to J') = e^2 \sum_{t=2,4,6} \Omega_t \left| \left\langle J \left\| U^{(t)} \right\| J' \right\rangle \right|^2 \tag{3}$$

where Ω_2, Ω_4 and Ω_6 are the JO parameters and are characteristic of the host material. The values of Ω_t are calculated by a least-squares fitting of the experimental to theoretical line strengths. We use those values to estimate the emission parameters with the following expressions:

$$\tau_{rad,J'}(J' \to J) = \frac{1}{\sum_{J'} A_{DE}(J' \to J)} \tag{4}$$

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$$A_{DE}(J' \to J) = \frac{64\pi^4}{3h(2J'+1)} \frac{n(n^2+2)^2}{9\bar{\lambda}^3} S_{DE}^{calc}(J' \to J). \quad (5)$$

A summary of the calculated values of Ω_t and the emission parameters for the four glasses is given in Table 1.

Table 1. Calculated values of Ω_t and the emission parameters for the four glasses

Host	Yb [10^{20} ions/cm^3]	Er [10^{20} ions/cm^3]	Ω_2 [10^{-20} cm^2]	Ω_4 [10^{-20} cm^2]	Ω_6 [10^{-20} cm^2]	A_{DE} [s^{-1}]	τ_{rad} Judd-Ofelt [msec]	τ_{rad} Exp. [msec]
MM2	3.2	0.99	6.038	1.189	1.401	107.521	9.301	10.5
IOG1	4.0	1.00	6.616	1.342	1.552	119.206	8.389	9.85
IOG2	4.2	0.90	6.619	1.549	1.666	128.133	7.804	10.35
IOG10	4.2	0.90	4.662	0.508	0.839	64.213	16	13 - 17

When the signal strength permitted it, direct pumping of the Er^{3+} $^4I_{13/2}$ state was used; otherwise the samples were pumped at the strong Yb^{3+} absorption feature at 975 nm. The fluorescence decay observed in the case of energy transfer is still characteristic of the Er^{3+} $^4I_{13/2}$ decay time due to the comparatively long state lifetime. This was verified for samples in which the 1530 nm signal was strong enough following both types of excitation.

For levels having strong coupling to the ground state, self-absorption and radiation trapping is of concern and can hide the dynamics of the level. We therefore paid attention to studying optically thin samples and having the excitation beam close to the detection face in order to minimize the path of the emitted light inside the sample.

In all four glasses studied, the decay times were exponential and increased with decreasing temperature. When heating the samples, the signal strength dropped, requiring higher pumping intensities in order to increase the signal-to-noise ratio. This increased up-conversion effects and lead to less reliable values of the fluorescence lifetime.

The absolute emission cross-sections for the glasses can be obtained from the Fuchtbauer-Ladenburg (F-L) equation:

$$\sigma_{em}(I \to K, \lambda) = \frac{1}{8\pi} \cdot \frac{\lambda^5 \cdot \beta(I \to K)}{n^2 \cdot c} \cdot \frac{1}{\tau_{rad}} \cdot \frac{I_{em}(\lambda)}{\int_{I \to K} I_{em}(\lambda) \cdot \lambda \cdot d\lambda}, \quad (6)$$

where $\beta(I \to K)$ is the branching ratio (1 in the case of the $^4I_{13/2}$ of Er^{3+}), τ_{rad} is the radiative lifetime (lifetime at T=33K in our case), and $I_{em}(\lambda)$ is the emission intensity. Shown in Fig.1 are the emission cross-sections for the Kigre MM2 Yb,Er:phosphate glass at various temperatures.

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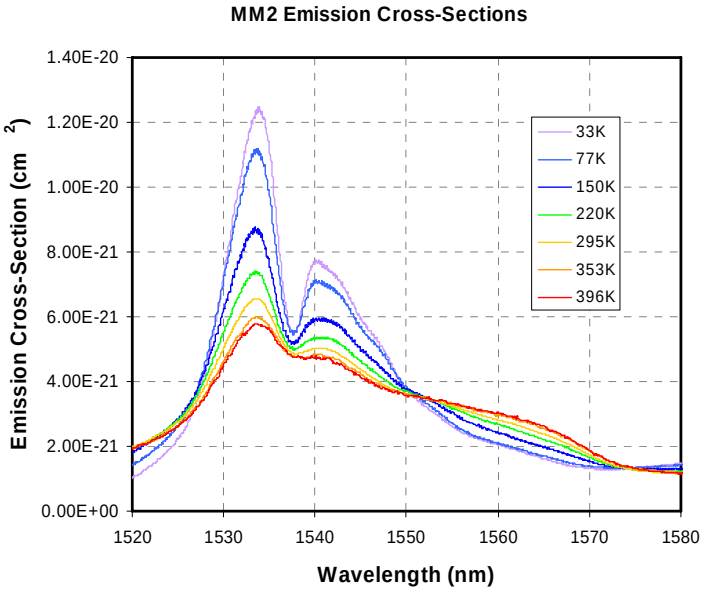

Fig. 1. Emission cross-sections for the Kigre MM2 Yb,Er:phosphate glass at various temperatures.

The other glass samples exhibited similar behaviors as the temperature was varied. As a check, we applied the reciprocity method at room temperature in order to validate the results using F-L equation with an ion which could present strong re-absorption such as Er^{3+}. The emission cross-sections σ_e were calculated from the absorption cross-sections σ_a using the relation [Ref. 8]

$$\sigma_e(\lambda) = \sigma_a(\lambda)\frac{Z_l}{Z_u}\exp\left[\frac{\frac{hc}{\lambda_0}-\frac{hc}{\lambda}}{kT}\right] \quad , \qquad (7)$$

where k is the Boltzmann constant, T the temperature, and λ_0 the zero-phonon line (the energy separation between the lowest crystal field components of the upper and lower levels). Z_l / Z_u is the ratio of the partition functions of the upper and lower levels; in this case we assume the ratio to be 1. In glasses, each Er^{3+} ion sees a different surrounding field, so the zero-phonon line is not well defined and only a statistical average makes sense. We take λ_0 = 1533 nm as it is the peak absorption and emission wavelength. At room temperature a discrepancy of approximately 5% exists between the two methods; which may be attributed to the weak re-absorption of the emitted light at shorter wavelengths when measuring the emission spectrum or the assumption of the ratio of the partition functions. This leads to a slight over-estimation of the emission cross-section when using F-L in the less absorbing regions.

3. Athermal Gain Cross-Section

It is immediately evident from the data in Fig. 1 that there is a significant decrease in the peak emission cross-section at approximately 1533 nm as temperature is increased, as expected. The striking feature of the temperature dependence of the emission cross-section is the convergence and actual inversion of the trend at a wavelength of ~ 1552 nm, highlighting the potential for "athermal" emission from the gain medium or even compensation of potential cross-section variation of a passive q-switch material.

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For a three level system such as Er^{3+}, the gain is of interest rather than just the emission cross-section, and this is dependent on the integrated inversion of the medium. Considering the small signal regime, the single pass gain can be calculated from

$$G = \exp[(\sigma_e n_u - \sigma_a n_l) \cdot L], \tag{8}$$

where σ_e and σ_a are the emission and absorption cross-sections respectively, n_u and n_l are the upper and lower population densities, and L is the length of the gain medium. Note that this does not include energy transfer and upconversion which are host glass dependent and will cause deviation from this simple calculated value.

Using the emission and absorption cross-sections as a function of temperature, the change in gain was calculated for the glasses at the concentrations specified for the samples assuming a 1 cm length of gain medium. Fig. 2 shows the calculated variation in small signal gain for the Kigre MM2 glass assuming an 80% inversion level. The other glass hosts showed similar behavior.

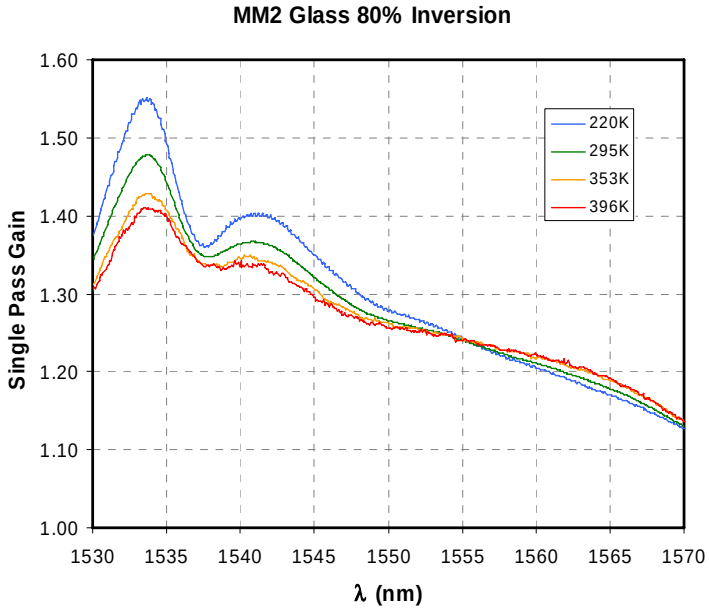

Fig. 2. Single pass gain for the Kigre MM2 Yb,Er:phosphate glass at various temperatures.

A comparison of the variation in gain between temperatures of 220 K and 396 K is shown in Fig. 3. All glasses show a similar behavior, with the silica host (IOG-10) shifted towards longer wavelengths and exhibiting a higher secondary peak variation compared to that seen in the phosphate hosts.

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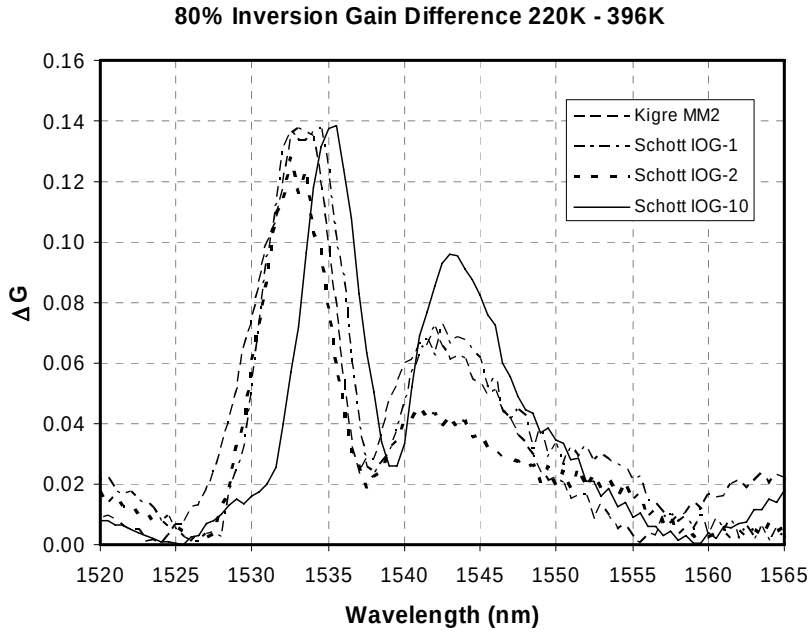

Fig. 3. Comparison of the variation in small single gain between the glass hosts.

A summary of the calculated peak gain and gain at the minimum variation over the temperature range for various inversion levels is given in Table 2.

Table 2. Calculated single pass small signal gain for the various glasses

Host	70% Inversion		80% Inversion		90% Inversion	
	Peak Gain	Gain @ Minimum ΔG	Peak Gain	Gain @ Minimum ΔG	Peak Gain	Gain @ Minimum ΔG
MM2	1.30 (1534 nm)	1.16 (1559 nm)	1.55 (1534 nm)	1.24 (1555 nm)	1.68 (1534 nm)	1.32 (1553.5nm)
IOG1	1.36 (1534 nm)	1.12 (1565 nm)	1.59 (1534 nm)	1.20 (1560 nm)	1.85 (1534 nm)	1.27 (1558 nm)
IOG2	1.30 (1534 nm)	1.12 (1560 nm)	1.48 (1533.5 nm)	1.17 (1560 nm)	1.69 (1533 nm)	1.23 (1558.5 nm)
IOG10	1.32 (1536 nm)	1.10 (1563 nm)	1.53 (1536 nm)	1.13 (1560 nm)	1.76 (1536 nm)	1.18 (1557 nm)

4. Summary

In summary, we have measured the spectroscopic properties of various phosphate and silicate host Yb, Er co-doped glasses. From these measurements, it is evident that the co-doped system has the potential for athermal emission properties in the eye-safe band, of interest to many remote sensing applications. This feature makes possible a transmitter source with complete passive temperature control operating over a wide range of environmental conditions. Further work will investigate actual laser performance and passive wavelength control using volume Bragg gratings [Ref. 9].

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