**ORIGINAL ARTICLE** 



# NIR Luminescence Enhancement of YVO<sub>4</sub>:Nd Phosphor for Biological Application

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#### Abstract

This work reports two systematic studies related to yttrium vanadate (YVO<sub>4</sub>) phosphors. The first evaluates how the annealing temperature and  $V^{5+}/Y^{3+}$  molar ratio determine the emergence of a single YVO<sub>4</sub> tetragonal phase, whereas the second concerns the optimal Nd<sup>3+</sup> concentration to improve the infrared emission properties for bio-labelling applications. The YVO<sub>4</sub>:Nd phosphors were synthesized by adapting the non-hydrolytic sol–gel route. For the first study, samples containing different  $V^{5+}/Y^{3+}$  molar ratios (1.02, 1.48, 1.71, or 3.13) were obtained. For the second study, YVO<sub>4</sub>:Nd phosphors containing different Nd<sup>3+</sup> concentrations (1.0, 3.0, 5.0, or 10.0% in mol) were prepared. X-ray diffractometry and RAMAN spectroscopy results revealed that, regardless of the heat-treatment temperature, the  $V^{5+}/Y^{3+}$  molar ratio of 1.48 was the best composition to avoid undesired phases like Y<sub>2</sub>O<sub>3</sub> and V<sub>2</sub>O<sub>5</sub>. Photoluminescence results indicated that the sample containing 3.0% in mol of Nd<sup>3+</sup> and annealed at 1000 °C presented the best infrared emission properties. This sample displayed an intense broad band in the ultraviolet region, which was ascribed to the VO<sub>4</sub><sup>3-</sup> charge transfer band, as well as several bands in the visible and infrared regions, which were attributed to the Nd<sup>3+</sup> intraconfigurational *f-f* transitions. Regardless of the excitation wavelength (ultraviolet, visible, or near-infrared), the mean radiative lifetime was about 12.00 µs. The prepared phosphors presented absorption and emission bands in the biological window (BW) regions, which are located between 750 and 900 nm and between 1000 and 1300 nm, so they are candidates for applications in medical imaging and diagnoses.

Keywords Infrared emission; photoluminescence; sol-gel · Phosphors · YVO<sub>4</sub> · Nd<sup>3+</sup>

## Introduction

The YVO<sub>4</sub> matrix, which was first introduced by Levine and Palila in 1964 [1], has been extensively studied due to its properties, such as low-energy phonon (around 890 cm<sup>-1</sup>) [2]. In addition, its optical, mechanical, and thermal characteristics are fundamental for light emitters [3, 4] and laser hosts [5, 6]. Moreover, when this matrix is doped with lanthanide ions, it presents highly efficient luminescence to excitation by an electron beam, leading to applications in lamps, displays, scintillation detectors, TVs, and cathode ray [7, 8]. Different lanthanide ions have been used to achieve emission in regions of interest for use in red (YVO<sub>4</sub>:Eu) [7–12], blue (YVO<sub>4</sub>:Tm) [13], or orange (YVO<sub>4</sub>:Sm) [14, 15] emitting devices, for example. Besides emitting in the visible region, some lanthanide ions display excitation and emission in the infrared region, which is very attractive for medical imaging applications. Nd<sup>3+</sup> perfectly fits these requirements: Nd<sup>3+</sup>-doped matrixes can be effectively excited in the near infrared region (at about 800 nm, which corresponds to the first biological window, designated I-BW), and they exhibit intense emission lines around 1060 nm (which matches the second biological window, designated II-BW), which paves the way for applications in living tissue imaging and nanothermometry [16–25].

Luminescent bio-imaging is widely employed in biomedical sciences. Its applications range from morphological analysis of the anatomical structure to sensitive measurements of intracellular molecular events, and it has several advantages like improved selectivity and sensitivity as compared to conventional imaging methods [26, 27]. Among the various processes that can be used to obtain inorganic matrixes, the non-hydrolytic sol–gel route

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stands out because it provides strict control of stoichiometry, powder morphology, and phase purity; the cations are distributed all over the structure; and the oxo bonds originate from oxygen atoms of donors other than water [28–31]. Furthermore, this route dismisses the need for solvents and may reduce or eliminate the formation of residual metal-OH groups. The mechanisms of the non-hydrolytic sol–gel route have been extensively discussed in the literature [28, 32, 33]. Here, aiming at medical imaging applications, we report the optimal conditions to obtain a single YVO<sub>4</sub> tetragonal phase doped with different Nd<sup>3+</sup> concentrations by adapting the non-hydrolytic sol–gel route.

### **Experimental**

#### **Preparation of the Precursor Chloride Solutions**

The matrixes were synthesized from yttrium oxide ( $Y_2O_3$ , Aldrich, 99.99%), vanadium oxide ( $V_2O_5$ , Aldrich, 99.6%), and neodymium oxide ( $Nd_2O_3$ , Aldrich, 99.9%). Absolute ethanol (99.5%) was used as oxygen donor. By using  $Y_2O_3$ ,  $V_2O_5$ , and  $Nd_2O_3$ , the respective chlorides were obtained by dissolution of these oxides in concentrated hydrochloric acid at a temperature of approximately 70 °C for 3 h, under stirring. Absolute ethanol was added until a pH of 5.5 was achieved. After cooling, more ethanol was added, until a final volume of 25 mL was obtained. The final concentration of the YCl<sub>3</sub>, VCl<sub>3</sub>, and NdCl<sub>3</sub> solutions was 0.1 mol.L<sup>-1</sup>.

#### Non-hydrolytic Sol-gel Synthesis of the YVO<sub>4</sub>:Nd Phosphor

The matrixes were synthesized by the non-hydrolytic sol–gel method described by Acosta et al. [32] and modified by us [12]. In a two-neck round-bottom flask, the precursor solution was prepared by homogenizing a mixture of ethanolic solutions containing YCl<sub>3</sub>, VCl<sub>3</sub>, and EuCl<sub>3</sub> and 0.7 mol of absolute ethanol at the desired proportion (Table 1). The solution was left under reflux and argon atmosphere at 110 °C for 4 h. The condenser was adapted to a thermostatic bath and maintained at -2 °C. After reflux, the mixture was cooled and aged at room temperature for 24 h. The solvent was removed in a rotary evaporator, under vacuum, and the material was thermally treated at 600, 800, or 1000 °C for 4 h.

#### Characterization

X-ray diffraction was performed at room temperature on a Rigaku Geigerflex D/max-c diffractometer operating with monochromated CuK  $\alpha$  radiation ( $\lambda = 1.54$ Å). The diffractograms were recorded in the 2 $\theta$  range from 10–80° at a resolution of 0.05°. Raman spectroscopy was conducted on a micro-Raman Jobin Yvon Horiba Spex spectrometer. The spectra were recorded from 100 to 1,200 cm<sup>-1</sup>, in two cycles. The samples were excited with a He-Ne laser at 632.8 nm. The

Table 1	Nominal	composition	of the	prepared	samples
				P	

Sample	VCl <sub>3</sub> (mol%)	YCl <sub>3</sub> (mol%)	NdCl <sub>3</sub> (mol%)	Y/V (molar ratio)	Re*/V (molar ratio)
YVO-a-1	50.0	49.0	1.0	0.980	1.00
YVO-b-1	59.0	40.0	1.0	0.678	0.695
YVO-c-1	62.5	36.5	1.0	0.584	0.600
YVO-d-1	75.0	24.0	1.0	0.320	0.333
YVO-b-3	59.0	38.0	3.0	0.644	0.695
YVO-b-5	59.0	36.0	5.0	0.610	0.695
YVO-b-10	59.0	31.0	10.0	0.525	0.695

\*Re = Rare-earth elements

photoluminescence data were obtained at room temperature, under continuous Xe lamp (450W) excitation in a Horiba Jobin Yvon Fluorolog-3 spectrofluorimeter equipped with an excitation and emission double monochromator and an R 928 Hammatsu photomultiplier. Emission was collected at 90° from the excitation beam. The slits were placed at 2.0 and 0.5 nm for excitation and emission, respectively; the bandpass was 0.2 nm, and the integration time was 0.5 ms. An emission filter was employed (transmittance 100% for  $\lambda > 830$  nm). All the analyses were carried out at room temperature.

## **Results and Discussion**

First, we evaluated how the annealing temperature and the  $Y^{3+}$  and  $V^{5+}$  concentrations affected the structural properties and determined the emergence of a pure  $YVO_4$  tetragonal phase. For this study, the Nd<sup>3+</sup> concentration was 1.0% in mol.

Figure 1 shows the X-ray diffractogram patterns of the samples annealed at 600, 800, or 1000 °C. All of them presented the characteristic peaks of the YVO<sub>4</sub> tetragonal phase (JCPDS 16–250) with spatial group I41 / a m d (D4h) and crystal lattice parameters a = b = 7.123 and c = 6.291. The three main peaks at  $2\theta = 25.0$ , 33.5, and  $49.7^{\circ}$  corresponded to the Miller indices (200), (112), and (312), respectively. The sample containing the highest Y<sup>3+</sup> concentration (YVO-a-1) displayed not only the peaks attributed to the YVO<sub>4</sub> phase, but also peaks related to the undesired Y2O5 cubic phase (JCPDS 41-1105). As for the samples prepared with smaller  $Y^{3+}$ amounts (YVO-c-1 and YVO-d-1), the extra peaks were ascribed to the V<sub>2</sub>O<sub>5</sub> orthorhombic phase (JCPDS 41-1426). YVO-b-1 was the only sample that showed peaks that were exclusively related to the YVO<sub>4</sub> tetragonal phase, indicating that the Y/V molar ratio of 0.678 was the optimal ratio to obtain the pure YVO<sub>4</sub> tetragonal phase.

For all the samples, we estimated the average crystallite size from the X-ray peak width by using Scherrer's formula (Dsc =  $0.9 \lambda / \beta \cos\theta$ , where  $\lambda$  is the wavelength of the Cu K<sub> $\alpha$ </sub> radiation (1.5406 Å),  $\theta$  is the diffraction angle of the most



Fig. 1 X-ray diffractogram patterns of the prepared samples: a IVO-a-1, b YVO-b-1, c YVO-c-1, and d YVO-d-1. The markers represent the crystalline phases of  $Y_2O_5$  (star) and  $V_2O_5$  (circle)

intense peak, and  $\beta$  is the full width at half maximum of the Bragg peaks) [10, 34]. Table 2 lists the corresponding values. In the case of sample YVO-a-1, the mean crystallite size was 23 nm regardless of the annealing temperature. However, this sample presented the smallest crystallite size when compared to the samples containing higher Y<sup>3+</sup> concentrations. This fact can be ascribed to the difference in the ionic radii of V<sup>5+</sup> (0.335 Å) and Y<sup>3+</sup> (0.892 Å) and to the limiting Y<sup>3+</sup> concentration, which indicated that the low Y<sup>3+</sup> amount inhibited crystallite growth along the process [35, 36].

As for the other samples (YVO-b-1, YVO-c-1, and YVO-d-1), the crystallite size values increased for the samples annealed above 800 °C. Nevertheless, the  $Y^{3+}$  concentration did not affect the crystallite size values of these samples significantly. Other works have reported similar results. For instance, Matos et al. [37] reported

crystal size of 50 nm for YVO<sub>4</sub>:Eu<sup>3+</sup> phosphors annealed a 1000 °C. Another work showed that crystallite size depended on the doping ion (Eu<sup>3+</sup> or Bi<sup>3+</sup>) concentration [2]. In our previous works, we reported that annealing temperature, precursors, and catalysts influenced the structural and luminescent properties of YVO<sub>4</sub>:Eu<sup>3+</sup> prepared by the conventional sol–gel route. The crystallite sizes were estimated to range from 6 to 55 nm, with particle sizes ranging from 25 up to 50 nm depending on the parameters that were used in the synthesis [10, 12].

Once the X-ray diffraction results of sample YVO-b-1 demonstrated that the pure YVO<sub>4</sub> tetragonal phase was formed, we investigated the effects of the Nd<sup>3+</sup> concentration and annealing temperature, aiming to obtain better luminescence properties such as higher infrared emission intensity, longer lifetime, and wide excitation spectrum range, without

Table 2	Average	crystallite	size	of the	samples

YVO-a-1		YVO-b-1		YVO-c-1		YVO-d-1						
	600 °C	800 °C	1000 °C	600 °C	800 °C	1000 °C	600 °C	800 °C	1000 °C	600 °C	800 °C	1000 °C
Dsc (nm)	23	20	23	23	46	46	23	46	46	27	46	46

structural changes. Figure 2 depicts the X-ray diffractograms patterns of sample YVO-b-1 annealed at 600, 800, or 1000 °C and containing 1.0, 3.0, 5.0, or 10.0% in mol of Nd<sup>3+</sup>. As observed in Fig. 1, all the samples presented the characteristic peaks of the YVO<sub>4</sub> tetragonal phase (JCPDS 16-250). Concerning the samples YVO-b-3, YVO-b-5, and YVO-b-10 calcined at 600 °C, we detected peaks ascribed to the V<sub>2</sub>O<sub>5</sub> orthorhombic phase (JCPDS 41-1426). However, this undesired phase did not emerge in the samples calcined at higher temperatures. In addition, the samples containing 3.0, 5.0, and 10.0% in mol of  $Nd^{3+}$  had the main peaks displaced probably because of the difference between the ionic radii of  $Nd^{3+}$  (0.995 Å) and  $Y^{3+}$  (0.892 Å), which distorted the unit cell of the YVO<sub>4</sub> tetragonal phase. [36, 38]. We did not verify these displacements for YVO-b-1 because it contained a low Nd<sup>3+</sup> concentration.

Raman spectroscopy measurements helped to confirm changes in the  $YVO_4$  structure as a function of  $Nd^{3+}$  concentration. All the samples presented intense bands, which implied strong interactions between the ions that arose mainly from the stretching and bending of the shorter metal–oxygen bonds within the anionic groups [39]. Table 1, in supplementary information, lists the Raman vibrational mode values for the samples YVO-b-1, YVO-b-3, YVO-b-5, and YVO-b-10, calcined at different temperatures.

For the samples calcined at 600 °C, the bands at 280, 402, and 690 cm<sup>-1</sup> referred to the formation of the yttrium oxide and oxychloride phases. These bands disappeared, giving rise to the simple YVO<sub>4</sub> phase, as proven by X-ray diffraction [40]. Thus, YVO<sub>4</sub> possibly originated above 600 °C via solid-state reaction between yttrium oxychloride and V<sub>2</sub>O<sub>5</sub>. The band around 994 cm<sup>-1</sup> is associated with V<sub>2</sub>O<sub>5</sub> vibrations [41] and was observed for samples containing 5 and 10% in mol of Nd<sup>3+</sup> and calcined at 600 °C. This fact indicated that YVO<sub>4</sub> formation involved V<sub>2</sub>O<sub>5</sub> formation, which was also observed in the X-ray diffractograms.

Depending on the difference between the ionic radii of the replacing and the replaced ions, doping ions may cause crystal lattice expansion or contraction, which is reflected in the Raman band displacements [40, 42, 43]. In this work,  $Y^{3+}$  replacement with Nd<sup>3+</sup> increased the crystal lattice, as proven by the broadening and shifting of the Raman bands [44]. The



Fig. 2 X-ray diffractograms patterns of the prepared samples: a IVO-b-1, b YVO-b-3, c YVO-b-5, and d YVO-b-10. The crystalline phase of  $V_2O_5$  is represented by the circle symbols

literature has attributed these facts to defects caused by the larger ionic radius of the doping  $Nd^{3+}$  as a function of concentration [45–47].

The full width at half maximum (FWHM) band of the samples YVO-b-1 and YVO-b-3, containing 1 and 3% in mol of Nd<sup>3+</sup>, respectively, decreased as a function of the heat-treatment temperature, which was ascribed to the increase in YVO<sub>4</sub> matrix crystallinity. For these samples, we did not verify any influence of the doping ion concentration due to its small amount. As for the samples containing 5 and 10% mol of Nd<sup>3+</sup>, the bands at 808, 822, and 882 cm<sup>-1</sup>, corresponding to VO<sub>4</sub> deformation, asymmetric mode, and symmetric stretching, respectively, were approximately 30% broader than the samples containing 1 and 3% mol of Nd<sup>3+</sup>, which attested to the distortion in the YVO<sub>4</sub> matrix reticulum [43].

We accomplished photoluminescence measurements only for the samples calcined at 1000 °C because they presented more interesting properties, as observed by the X-ray diffraction and RAMAN spectroscopy results. Figure 3 illustrates the excitation spectra of the Nd<sup>3+</sup> ion doped into the YVO<sub>4</sub> matrix, at different concentrations. Table 3 summarizes the maximum values of the observed bands and their transitions.

The excitation spectra presented a broad band around 320 nm, which was assigned to the V<sup>5+</sup>– O<sup>2-</sup> charge transfer band (CTB) of VO<sub>4</sub><sup>3-</sup>. According to the molecular orbital theory, this band is associated with transitions from the <sup>1</sup>A<sub>2</sub> (<sup>1</sup>T<sub>1</sub>) ground state to the <sup>1</sup>A<sub>1</sub> (<sup>1</sup>D) and <sup>1</sup>B<sub>1</sub> (<sup>1</sup>D) excited states of the VO<sub>4</sub><sup>3-</sup> [48]. Energy transfer occurred more easily between the VO<sub>4</sub><sup>3-</sup> group and Nd<sup>3+</sup> due to the different ionic radii of V<sup>5+</sup> (0.355 Å) and Nd<sup>3+</sup> (0.995 Å) [11]. The CTB can be used to measure the covalent character of the Ln<sup>3+</sup>-ligand bond [12, 49]. The higher the energy of the CTB, the higher the Ln<sup>3+</sup>-ligand interaction. The CTB shifts to higher

wavelength due to lattice distortion. Increasing concentration of  $Nd^{3+}$  distorted the  $D_{2d}$  symmetry caused by the larger ionic radius of  $Nd^{3+}$  as compared to  $Y^{3+}$  [50].

The maximums values were 325 nm for the samples containing 1 and 3% mol of Nd<sup>3+</sup> and 317 nm for the samples containing 5 and 10% mol of Nd<sup>3+</sup>. This shift indicated a distorted site symmetry for Nd<sup>3+</sup>, as previously reported [10–12]. Furthermore, the Nd<sup>3+</sup> concentration impacted the CTB intensity. Therefore, the decreasing ratios between CTB and the hypersensitive bands at 520 nm ( ${}^{4}I_{9/2} \rightarrow {}^{2}K_{13/}$ 2;  ${}^{4}G_{9/2}$ ) and 590 nm ( ${}^{4}I_{9/2} \rightarrow {}^{2}G_{7/2}$ ;  ${}^{4}G_{5/2}$ ) [51] also suggested distortions in the Nd<sup>3+</sup> symmetry site. The calculated CTB/ 520 nm ratios were 49.7, 20.3, 8.0, and 7.1, whereas the calculated CTB/590 nm ratios were 14.0, 4.1, 3.3, and 1.8 for the samples containing 1, 3, 5, and 10% mol of Nd<sup>3+</sup>, respectively.

Figure 4 contains the emission spectra of the Nd<sup>3+</sup>-doped samples excited at different wavelengths (ultraviolet, visible, and infrared regions). Regardless of the excitation wavelength, all the samples presented infrared emission bands at 1064 and 1340 nm, which were ascribed to the  ${}^{4}F_{3/2} \rightarrow {}^{4}I_{11/2}$ and  ${}^{4}F_{3/2} \rightarrow {}^{4}I_{13/2}$  transitions of Nd<sup>3+</sup>, respectively. The Nd<sup>3+</sup> concentration shifted the  ${}^{4}F_{3/2} \rightarrow {}^{4}I_{11/2}$  transition slightly [10–12]. For samples YVO-b-1 and YVO-b-3, the maximum intensity emerged at 1067 nm, whereas for the samples YVOb-5 and YVO-b-10, the maximum intensity appeared at 1065 and 1064 nm, respectively. Lanthanide ions (Ln<sup>3+</sup>) can replace Y<sup>3+</sup> in the YVO<sub>4</sub> structure, to occupy D<sub>2d</sub> symmetry sites. However, the band displacements could also be ascribed to the Nd<sup>3+</sup> symmetry distortion to D<sub>2</sub> and C<sub>2v</sub> due to its larger ionic radius [50].

Sample YVO-b-3 presented the most intense emission bands, which suggested that 3.0% mol of Nd<sup>3+</sup> was the optimal concentration, as confirmed in Fig. 4.



Wavelength (nm)

 Table 3
 Transitions of the bands

 observed in the excitation spectra
 illustrated in Fig. 3 and their

 wavelengths and energy values
 illustrated in Fig. 3

Wavelength (nm)	Energy (cm <sup>-1</sup> )	Transitions
320	31,250	Charge transfer band
354	28,248	${}^{4}I_{9/2} \rightarrow {}^{4}D_{3/2}; {}^{4}D_{5/2}; {}^{4}D_{1/2}$
431	23,200	${}^{4}\mathrm{I}_{9/2} \rightarrow {}^{2}\mathrm{D}_{5/2};  {}^{2}\mathrm{P}_{1/2}$
469	21,321	${}^{4}I_{9/2} \rightarrow {}^{2}K_{15/2};  {}^{4}G_{11/2};  {}^{2}G_{9/2};  {}^{2}(D,P)_{3/2}$
520 and 528	19,342 and 18,939	${}^{4}I_{9/2} \rightarrow {}^{2}K_{13/2};  {}^{4}G_{9/2};  {}^{4}G_{7/2}$
590	16,949	${}^{4}I_{9/2} \rightarrow {}^{2}G_{7/2};  {}^{4}G_{5/2}$
679	14,727	${}^{4}\mathrm{I}_{9/2} \longrightarrow {}^{4}\mathrm{F}_{9/2}$
749	13,351	${}^{4}I_{9/2} \rightarrow {}^{4}S_{3/2};  {}^{4}F_{7/2}$
804 e 831	12,437 and 12,033	${}^{4}I_{9/2} \rightarrow {}^{2}H_{9/2}; {}^{4}F_{5/2}$
875	11,428	${}^{4}I_{9/2} \rightarrow {}^{4}F_{3/2}$

Figure 5 shows the intensity values of the Nd<sup>3+</sup> emission bands related to the  ${}^{4}F_{3/2} \rightarrow {}^{4}I_{11/2}$  and  ${}^{4}F_{3/2} \rightarrow {}^{4}I_{13/2}$  transitions at 1064 and 1344 nm, respectively. Increasing Nd<sup>3+</sup> concentration above 3.0% mol decreased both infrared emission bands. We also observed this behavior when we analyzed the radiative lifetime ( $\tau_{rad}$ ) values regardless of the wavelength excitations, as shown in Table 4. However, sample YVO-b-3 sample presented a very high emission band at 1064 nm (which matches the II-BW) when it was excited at 808 nm (which corresponds to the I-BW). Besides that, the

radiative lifetime was much higher as compared to other excitation wavelengths.

As mentioned above, the transparency regions of the biological window (BW) can be divided into three parts: I-BW, from 750 to 950 nm; II-BW, from 1000 to 1350 nm; and III-BW, from 1500 to 1800 nm. On the basis of the images only, I-BW may suffer interference from the autofluorescence of tissues, but, as excitation source, it is better suited for biomedical applications than ultraviolet (UV) light because it penetrates deeper into tissues and causes less photodamage to



Fig. 4 Emission spectra of Nd<sup>3+</sup> doped into the YVO<sub>4</sub> matrix calcined at 1000 °C, at different concentrations, excited at (a) 320 nm, (b) 590 nm, and (c) 808 nm



**Fig. 5** Nd<sup>3+</sup> emission intensity values (a)  ${}^{4}F_{3/2} \rightarrow {}^{4}I_{11/2}$  (1064 nm) and (b)  ${}^{4}F_{3/2} \rightarrow {}^{4}I_{13/2}$  (1340 nm), obtained under different excitation wavelengths

biological systems. On the other hand, II-BW and III-BW are suitable for NIR images in large tissue depths [16–25]. Thus, the ideal luminescent biolabeling should be excited in the I-BW and emit light in the II-BW or III-BW regions [19]. Figure 6 shows the luminescence spectra of the YVO-b-3 sample emphasizing the I-BW and II-BW regions.

The five bands fit the biological windows, with maximum at 804 and 872 nm with FWHM of 12 and 9 nm, respectively, for I-BW. As for II-BW, the maximum bands values were

Table 4 Radiative lifetime ( $\lambda_{em}$ : 1064 nm) under different excitation wavelengths

Samples	$\tau_{rad}$ (µs) ( $\lambda_{exc}$ = 320 nm)	$\tau_{rad} (\mu s)$ ( $\lambda_{exc} = 590 \text{ nm}$ )	$\tau_{rad} (\mu s)$ ( $\lambda_{exc} = 808 \text{ nm}$ )
YVO-b-1	$12.85 \pm 1.29$	$10.64 \pm 1.06$	$3.49 \pm 0.35$
YVO-b-3	$12.26\pm1.23$	$12.69 \pm 1.27$	$11.18\pm1.12$
YVO-b-5	$11.96 \pm 1.20$	$10.31\pm1.03$	$6.84 \pm 0.68$
YVO-b-10	$10.54\pm1.05$	$9.72\pm0.97$	$1.10\pm0.11$



Fig. 6 Excitation (a) and emission (b) spectra of sample YVO-b-3 emphasizing the I-BW and II-BW regions

1067, 1088, and 1344 nm with FWHM of 6, 9, and 6 nm, respectively, confirming the potential application of this phosphor in medical imaging and diagnoses [16–25].

## Conclusion

The non-hydrolytic sol–gel methodology has been used to prepare diverse oxide-based matrixes under mild conditions, doped with dopants at different levels. In this work, the  $Y^{3+}/V^{5+}$  molar ratio and the annealing temperature proved to be important parameters to obtain the  $YVO_4$  tetragonal phase, directly affecting purity and crystallite size.

We also investigated how the Nd<sup>3+</sup> concentration affected the luminescent properties of the prepared phosphor. In addition to excitation bands in the visible region, all the samples presented luminescence bands around 750–950 and 1000– 1350 nm, which fit the first and second biological windows, respectively. According to the results, the  $Y^{3+}/V^{5+}$  molar ratio of 0.678, doping with 3.0% mol of Nd<sup>3+</sup>, and annealing at 1000 °C was the optimal composition to obtain pure  $Y^{3+}/V^{5+}$  tetragonal phase with high luminescence intensity and longer radiative lifetime in the NIR range.

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**Data Availability** The data that support the findings of this study are available from the corresponding author, upon reasonable request.

# **Compliance with Ethical Standards**

Conflict of Interest The authors declare no conflict of interests.

Code Availability Not applicable.

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