Advanced temperature sensing with Er$^{3+}$/Yb$^{3+}$ co-doped Ba$_2$GdV$_3$O$_{11}$ phosphors through upconversion luminescence

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Optical thermometry is a non-contact temperature sensing technique with widespread applications. It offers precise measurements without physical contact, making it ideal for situations where contact-based methods are impractical. However, improving the accuracy of optical thermometry remains an ongoing challenge. Herein, enhancing the thermometric properties of luminescent thermometers through novel materials or strategies is crucial for developing more precise sensors. Hence, the present study focuses on the application of four-mode luminescence thermometric techniques in sol–gel synthesized Er$^{3+}$/Yb$^{3+}$ co-doped Ba$_2$GdV$_3$O$_{11}$ phosphors for optical temperature sensing in the temperature range of 298–573 K. The upconversion (UC) luminescence is achieved under excitations of 980 nm or 1550 nm, resulting in bright yellow-green emission in the visible spectral range. Temperature sensing is realized by exploiting the UC emissions of $^{4}S_{3/2}$, $^{2}H_{11/2}$ and $^{4}F_{7/2}$ bands, which represent intensity ratios of thermally coupled levels (TCELs) and non-thermally coupled levels (NTCELs) of Er$^{3+}$/Yb$^{3+}$, along with the emission lifetimes at $^{4}S_{3/2}$. The relative sensitivity ($S_r$) values for TCELs exhibit a gradual decrease with rising temperature, reaching a maximum of 1.1% K$^{-1}$ for 980 nm excitation and 0.86% K$^{-1}$ for 1550 nm excitation at 298 K. Conversely, for NTCELs, the highest $S_r$ value observed is 0.9% K$^{-1}$ at 298 K for 1550 nm excitation. Moreover, the emission lifetimes at $^{4}S_{3/2}$ yield notably high $S_r$ values of up to 5.0% μs K$^{-1}$ (at 425 K).

Furthermore, the studied phosphors have a sub-degree thermal resolution, making them excellent materials for accurate temperature sensing. Overall, this study provides a promising new direction for the development of more precise and reliable optical thermometry techniques, which could have important implications for a range of scientific and industrial optical temperature sensing applications.

1. Introduction

Nanoscale temperature measurement is crucial for applications where precise detection of the local temperature changes is required especially related to biochemical processes like living cells and nanomedicine, microelectronics, optics, microfluidics, and chemical reactions.$^{1-6}$ Herein, optical thermometry has emerged as a promising approach due to its exclusive advantages such as contactless operation, rapid response time, excellent spatial resolution, and wide detection range. Optical temperature sensing is a technique that utilizes temperature-responsive optical parameters such as emission intensity, luminescence peak position, spectral bandwidth, fluorescence decay lifetime (FL), and fluorescence intensity ratio (FIR) for the non-invasive and rapid detection of local temperature values in inspected systems. The fluorescence intensity ratio (FIR) technique, which relies on the temperature-dependent alteration of luminescence intensities of two closely spaced thermally coupled levels (TCELs) or non-thermally coupled levels (NTCELs) of activators, along with fluorescence lifetime (FL) technology, which is based on the temperature-dependent lifetimes, have been recognized as the most viable methods for temperature sensing due to their insensitivity to external interference and measurement conditions.$^7$ Therefore, the technique which exploits the change of the spectroscopic properties of the phosphor materials for remote temperature determination, called luminescent thermometry, is a subject of intensive studies in recent years.$^8-11$

In order to enhance the luminescence properties of phosphors, they are usually coupled with lanthanide ions since lanthanide ions are known to exhibit efficient and superior
spectroscopic properties due to their diverse energy transfer mechanisms, higher luminescence intensities and efficiencies. Therefore, lanthanide-doped phosphor nanoparticles seem to be the best candidates as luminescence nanothermometers, because they can benefit from temperature-dependent emission lifetimes, as well as band ratios of alike TCELs and NTCELs.12–23

Single-mode detection is the foundation of many modern luminescent thermometers. However, they are always susceptible to the error caused by the temperature’s insensitivity in a certain range. To overcome this limitation, dual- or three-mode optical thermometers have been developed continuously in recent years since the combination of multiple optical thermometer modes can leverage their individual advantages to attain greater accuracy and expanded temperature measurement capabilities.24–34 There are four main categories for dual- or three-mode optical thermometers. The first category is the combination of TCELs and NTCELs, known as the FIR technique.27,29–31 Another category involves the integration of FL with FIR, specifically from TCELs.26 A third category involves coupling FL with FIR from NTCELs,27,35,36 while the last category combines FL with FIR from both TCELs and NTCELs.32,34

The ability to convert light from the near-infrared (NIR) to the visible spectral region, resulting from the upconversion (UC) energy transfer mechanism, opens new possibilities to overcome current limitations in solar energy.37,38 autofluorescence-free biosensing and -imaging,39–41 nanoscale electric field sensing,42 and temperature sensing.43 It is quite common to use a 980 nm laser diode as the excitation source and, the UC luminescence usually takes place in different lanthanide ions co-doped systems, including Yb³⁺/Er³⁺, Yb³⁺/Ho³⁺, or Yb³⁺/Tm³⁺, where Yb³⁺ acts as a sensitizer and transfers the absorbed excitation energy to emitting ions, i.e. Er³⁺, Ho³⁺, or Tm³⁺.12,43–48 However, excitation by 980 nm laser source is not suitable for biological applications. It tends to arouse overheating and lower the penetration depth due to the strong absorption of water molecules in human tissue.49 Therefore, excitation and/or emission wavelengths falling in the so-called biological windows (1st 650–950 nm, 2nd 1000–1400 nm, 3rd 1500–1800 nm) have been developed.50–53 Herein, 1550 nm laser excitation has obtained considerable attention due to its wide applications in optical communication and solar cells; meanwhile, it is also an effective excitation source to investigate the UC luminescence properties of some lanthanide-doped materials.54–56 Er³⁺ ions are in particular the material of choice for UC energy transfer mechanism with 1550 nm excitation; however, one limitation of Er³⁺ ions is their relatively low absorption cross-section and brightness.57–60

The development of a multimode temperature sensor relies heavily on the use of an appropriate host material, as the host has a significant impact on the UC emission efficiency. Particularly, a host with lower phonon energy can improve the UC efficiency by inhibiting the multi-phonon relaxation. In order to limit the undesired multi-phonon relaxation processes, the UC materials are usually doped in inorganic matrices having low phonon energy, such as fluorides, oxides, vanadates, phosphates, and borates.10,43,44,61–64 These matrices can be utilized to make extremely effective phosphors that have a strong photoluminescence signal because they are thermally stable and have low phonon energies.65 Herein, Er³⁺ and Yb³⁺ co-doped Ba₂GdV₃O₁₁ holds significant importance for thermometry applications. Ba₂GdV₃O₁₁ is widely acknowledged as a favorable host material due to its capacity for enduring high-temperature processing, versatility for co-doping with various lanthanide ions, facile synthesis under elevated temperatures, and its characteristic self-activated luminescence. This luminescence stems from a broad visible emission band resulting from electronic charge transfer from the oxygen (2p orbital) to the V⁵⁺ ion. Notably, Ba₂GdV₃O₁₁ has been extensively investigated for its doping versatility with several lanthanide ions, including Er³⁺ and Yb³⁺.66–70 In particular, Er³⁺ and Yb³⁺ ions are strategically employed as the activator and sensitizer, respectively, in UC materials due to their abundant ladder-like energy levels and robust absorption cross-section in the near-infrared (NIR) range. This co-doped system presents a promising avenue for precise and efficient thermometry applications, leveraging the unique properties of Er³⁺ and Yb³⁺ ions in the Ba₂GdV₃O₁₁ host matrix. However, to the best of our knowledge, no prior work has been reported on the thermometric properties and UC luminescence characteristics of Er³⁺/Yb³⁺ co-doped Ba₂GdV₃O₁₁ phosphors.

The development of a novel four-mode thermometer with reliable and outstanding modes has been a significant challenge in the field. To address this need, in this work, we present a pioneering investigation of four-mode UC luminescence for high precision optical temperature sensing in Er³⁺/Yb³⁺ co-doped Ba₂GdV₃O₁₁ phosphors. The characteristic luminescence properties, chromaticity diagrams and thermometric parameters are investigated under 980 nm and 1550 nm excitations. The analysis of UC mechanism processes is followed by an investigation of optical temperature sensing characteristics based on TCEL and NTCELs, as well as kinetic-based luminescence. A bright yellow-green UC luminescence is used for multimode optical temperature sensing in the temperature range of 298–573 K in the visible spectral range and ultimately advanced luminescence thermometric techniques are constructed.

2. Experimental studies

2.1 Synthesis of Er³⁺/Yb³⁺ co-doped Ba₂GdV₃O₁₁ phosphors

Er³⁺/Yb³⁺ co-doped Ba₂GdV₃O₁₁ phosphors are synthesized using the sol–gel method with citric acid as the complexing agent. All chemicals employed in the synthesis, including barium nitrate [Ba(NO₃)₂ (99.0%), gadolinium nitrate hexahydrate [Gd(NO₃)₃·6H₂O (99.9%)], ammonium metavanadate [NH₄VO₃ (99.96%)], erbium nitrate pentahydrate [Er(NO₃)₃·5H₂O (99.9%)], ytterbium nitrate pentahydrate [Yb(NO₃)₃·5H₂O (99.9%)], and other reagents, were purchased from Sigma-Aldrich.

The preparation procedur...
(99.9%), and citric acid \([C_6H_8O_7\text{ (99.0%)}]\), are purchased from Sigma-Aldrich and utilized without further purification.

The synthesis procedure initiates with the magnetic stirring of all precursors in an Erlenmeyer flask at 70 °C. Subsequently, citric acid is added, inducing a color change in the solution from green to blue. The solution is subjected to swirling and heating at 80 °C until it undergoes hydrolysis, transitioning into a sol and then a gel. The resulting xerogel is annealed at 400 °C for 3 hours, yielding black-colored flakes. Finally, the gel undergoes calcination at 700 °C for approximately 4 hours to achieve pure-phase crystals. Using this method, Ba\(_2\)GdV\(_3\)O\(_{11}\) phosphors are doped with Yb\(^{3+}\) (10 mol%) and Er\(^{3+}\) (2 mol%). These specific concentrations are strategically chosen to prevent UC luminescence extinction, informed by our previous experience, and supported by both theoretical knowledge and empirical evidence. Notably, the literature commonly adopts a higher quantity of sensitizer (Yb\(^{3+}\)) along with lower concentrations of emitters (Er\(^{3+}\)) in UC systems, as it has proven effective in generating a robust emission. The synthesis details of Er\(^{3+}\)/Yb\(^{3+}\) co-doped Ba\(_2\)GdV\(_3\)O\(_{11}\) phosphors are illustrated in Fig. 1.

### 2.2 Experimental methods for the characterization of Er\(^{3+}\)/Yb\(^{3+}\) co-doped Ba\(_2\)GdV\(_3\)O\(_{11}\) phosphors

The X-ray diffraction (XRD) measurements are performed with a Bruker AXS D8 Advance diffractometer in a scanning mode with Cu K\(\alpha\) radiation (\(\lambda = 1.5406 \text{ Å}\)) at a step size of 0.015° from 20° to 80°. The XRD peak positions and intensities of crystallized phases are compared with the JCPDS card files. The morphology of the materials is examined using a Thermo Scientific Apreo 2 S LoVac field emission scanning electron microscopy (FE-SEM). A Horiba Labram HR 800 monochromator is employed to conduct Raman spectroscopy studies. The spectrometer features a wave number resolution exceeding 3 cm\(^{-1}\) and is outfitted with an Olympus BX41 microscope, a 633 nm He–Ne laser emitting with a power output of less than 5 mW, and a CDD detector. The laser beam is precisely focused on the sample through a 50× microscope objective. Diffuse reflectance spectrum is collected by the use of a PerkinElmer Lambda 365 UV–Vis spectrometer.

The steady-state and time-resolved photoluminescence (PL) properties of the samples are investigated using an Edinburgh Instruments FS5 spectrofluorometer. PL spectra are recorded using laser diodes emitting at 980 and 1550 nm with a signal to noise ratio of water Raman signal greater than 6000 : 1 and 0.5 nm spectral resolution using an excitation power of 0.5 W. The temperature dependence of the PL properties is studied using a Pike Technologies heated solid transmission attachment fitted in the spectrofluorometer to perform measurements over a temperature range of 298–573 K. To avoid biased temperature readings and ensure accurate measurements, a calibration curve relating the optical signal (e.g., fluorescence intensity or lifetime) to temperature is initially established, with the lowest laser power permitting reliable signal detection being employed. A stable and controlled measurement environment is maintained, and baseline measurements are taken without laser excitation to determine the intrinsic temperature of the sample under experimental conditions. During temperature measurements, the laser power and sample temperature are continuously monitored, and the calibration curve is periodically verified by measuring known temperatures using an independent reference thermometer to ensure measurement accuracy and reliability. In the data analysis, the laser heating effect is considered and corrected, if necessary, by subtracting the baseline temperature from the measured temperature to obtain the true temperature change induced by the laser. Subsequently, the temperature measurement protocol is validated under various conditions and sample types to ensure its applicability and accuracy across different scenarios. To obtain time-resolved PL spectra, a 980 nm pulsed laser

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![Fig. 1](https://example.com/fig1.png)

**Fig. 1** Schematic illustration of applied synthesis procedure of 2 mol% Er\(^{3+}\)/10 mol% Yb\(^{3+}\) co-doped Ba\(_2\)GdV\(_3\)O\(_{11}\) phosphors.
operating at a frequency of 1 kHz is used to monitor the characteristic wavelength of Er\(^{3+}\) at 555 nm over time.

3. Results and discussion

3.1 Physical, thermal, and structural properties

Powder XRD technique is used to determine the crystal structure of synthesized 2 mol% Er\(^{3+}\)/10 mol% Yb\(^{3+}\) co-doped Ba\(_2\)GdV\(_3\)O\(_{11}\) phosphors. The diffraction peak patterns correspond to the JCPDS card number 45-0097 (see Fig. 2), indicating that the insertion of Er\(^{3+}/\)Yb\(^{3+}\) does not affect the phase pattern.\(^6\) The Rietveld refinement procedure, performed using the FullProf_Suite program, shows that the synthesized phosphors crystallized into a monoclinic crystal structure with \(P2_1/c\) space group symmetry (14).\(^7\) The unit cell parameters are calculated to be \(a = 12.374692\) Å, \(b = 7.731662\) Å, \(c = 11.178051\) Å, \(\beta = 103.56582^\circ\), and \(V = 1029.88\) Å\(^3\).

Fig. 3 shows the representative FE-SEM images revealing surface morphologies, and grain size distribution of Er\(^{3+}/\)Yb\(^{3+}\) co-doped Ba\(_2\)GdV\(_3\)O\(_{11}\) phosphors. The images clearly demonstrate the successful synthesis of Er\(^{3+}/\)Yb\(^{3+}\) co-doped Ba\(_2\)GdV\(_3\)O\(_{11}\) particles at the micro scale. However, the synthesis process employing the sol–gel method leads to particle agglomeration, resulting in tightly packed, irregularly shaped particles due to their high surface energy. Usually, the tightly packed particles contribute to a decrease in scattering of light, producing excellent luminous intensity.\(^7\) As a result, the resulting 2 mol% Er\(^{3+}/10\) mol% Yb\(^{3+}\) co-doped Ba\(_2\)GdV\(_3\)O\(_{11}\) phosphors is a well-crystallized, micro-sized material with strong and vibrant luminescence properties.

The room temperature Raman spectrum of the Er\(^{3+}/\)Yb\(^{3+}\) co-doped Ba\(_2\)GdV\(_3\)O\(_{11}\) phosphor is displayed in Fig. 4. The observed Raman bands can be attributed to various vibrational modes, including asymmetric stretching (\(\nu_{as}\)) and symmetric stretching (\(\nu_s\)) modes of O–V–O, \(\nu_s\) and \(\nu_{as}\) modes of V–O–V vibrations, as well as lattice (\(L'\)) vibrations.\(^7\) The Raman

![Fig. 2 Rietveld refinement of XRD data for 2 mol% Er\(^{3+}/10\) mol% Yb\(^{3+}\) co-doped Ba\(_2\)GdV\(_3\)O\(_{11}\) phosphors.](image1)

![Fig. 4 Raman spectra of 2 mol% Er\(^{3+}/10\) mol% Yb\(^{3+}\) co-doped Ba\(_2\)GdV\(_3\)O\(_{11}\) phosphors.](image2)

![Fig. 3 FE-SEM images of 2 mol% Er\(^{3+}/10\) mol% Yb\(^{3+}\) co-doped Ba\(_2\)GdV\(_3\)O\(_{11}\) phosphors with different magnifications, (a) 50kx, and (b) 100kx.](image3)
bands observed between 880 to 953 cm\(^{-1}\) are linked to the \(\nu_s\) vibrations of vanadium groups, while the vibrations associated with the \(\nu_{as}\) modes of vanadium groups are found in the region of 800 to 878 cm\(^{-1}\). In the range of 410 to 520 cm\(^{-1}\), the observed Raman modes are attributed to both symmetric stretching and asymmetric stretching vibrations of the V–O–V bridge. Terminal bending vibrations are discerned within the region of 318 to 400 cm\(^{-1}\), while the bending vibrations of V–O–V bridges are noted in the range of 206 to 265 cm\(^{-1}\).

Fig. 5(a) depicts the diffuse reflectance spectrum of Er\(^{3+}/\)Yb\(^{3+}\) co-doped Ba\(_2\)GdV\(_3\)O\(_{11}\) phosphors in the UV-Vis-NIR spectral range (200–1100 nm). The O\(^2–\)–V\(^{5+}\) entity is responsible for the high broad bands peaking at 280 and 315 nm. The absorption peaks at 480, 525, and 655 nm are related to Er\(^{3+}\) transitions from \(^{4}I_{15/2} \rightarrow {^{4}F_{7/2}}, {^{2}H_{11/2}}\) and \(^{4}F_{9/2}\), respectively. Additional absorption peaks appear in the 900 nm–1050 nm range which correspond to \(^{4}I_{15/2} \rightarrow {^{4}I_{11/2}}, {^{2}F_{7/2}} \rightarrow {^{2}F_{5/2}}\) transitions of Er\(^{3+}\) and Yb\(^{3+}\) ions, respectively. Employing diffuse reflectance spectrum, the band gap \((E_g)\) of Ba\(_2\)GdV\(_3\)O\(_{11}\) phosphors is measured according to the Kubelka–Munk (KM) theory.\(^{75–77}\) The relation between the diffuse reflectance of the sample \(R\), absorption coefficient \((k)\), scattering coefficient \((S)\), and absorption coefficient of the material \((\alpha)\) are related by the KM remission function \(F(R)\):\(^{67}\)

\[
F(R) = \alpha = \frac{k}{S} = \frac{(1 - R)^2}{2R}
\]

(1)

The well-known Tauc equation relates the \(E_g\) and absorption coefficient \(\alpha\) of a direct band gap semiconductor in the parabolic band structure:

\[
(F(R)h\nu)^n = B(h\nu - E_g)
\]

(2)

In this equation, \(h\nu\) represents the photon energy, \(B\) is a proportional constant, and \(E_g\) is the band gap energy. The nature of optical transitions in a material is determined by a constant \((n)\), which varies depending on the type of transition. For instance, an indirect allowed transition corresponds to \(n = 2\), an indirect forbidden transition corresponds to \(n = 3\), a direct allowed transition corresponds to \(n = 1/2\), and a direct forbidden transition corresponds to \(n = 3/2\). Direct allowed transition is characterized by nonlinear and linear parts in the plot of \([F(R_{\infty})h\nu]^2\) versus \(h\nu\). The fundamental absorption is characterized by the linear portion, whereas the residual absorption involving impurity states is represented by the nonlinear portion. Furthermore, the band gap of 3.06 eV for Er\(^{3+}/\)Yb\(^{3+}\) co-doped Ba\(_2\)GdV\(_3\)O\(_{11}\) phosphors is determined by extrapolating the line for \([F(R_{\infty})h\nu]^2 = 0\), as shown in Fig. 5(b).

### 3.2 Power-dependent luminescence properties, and UC mechanism

To gain a better understanding of the UC process, laser pump power-dependent UC spectra of Er\(^{3+}/\)Yb\(^{3+}\) co-doped Ba\(_2\)GdV\(_3\)O\(_{11}\) phosphors are recorded. As shown in Fig. 6(a) and (b), the emission intensity of Er\(^{3+}\) increases with increasing pump power. The relationship between laser pump power \((P)\) and UC emission intensity \((I)\) is commonly expressed using the following formula:\(^{65,78}\)

\[
I = K \times P^n
\]

(3)

where \(K\) is a constant and \(n\) represents the number of infrared photons required to fill the upper emitting state of the lanthanide ions. We illustrate the dependency of the emission intensity on excitation power density for Er\(^{3+}/\)Yb\(^{3+}\) co-doped Ba\(_2\)GdV\(_3\)O\(_{11}\) phosphors in Fig. 6(c) and (d) to obtain the slope and estimate the value of \(n\) more explicitly. The excitation power density refers to the amount of power that reaches the surface of the phosphor, divided by the area of the phosphor that is exposed to the excitation.

To calculate the quantity of infrared photons, the peaks at 555 nm and 665 nm are selected due to their high intensity and variation with laser pump power. It can be observed that the plots of log intensity versus log laser power show a clear linear relationship in the experimental data. The slopes of the 555 nm and 665 nm emission peaks are found to be 2.03 and 1.91, respectively under 980 nm excitation, indicating that the UC processes involve in the phosphors are two-photon processes.\(^{79,80}\)

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**Fig. 5** (a) Diffuse reflectance spectra for Er\(^{3+}/\)Yb\(^{3+}\) co-doped Ba\(_2\)GdV\(_3\)O\(_{11}\) phosphors, (b) the plot of \([F(R_{\infty})h\nu]^2\) versus \(h\nu\).
Furthermore, under 1550 nm excitation, the green and red emissions can be a three-photon process \((n = 3.03 \text{ and } n = 3.05, \text{ respectively})\) as determined by the double-logarithmic fitting of UC luminescence intensity to excitation power. The slight differences in the \(n\) values may be attributed to the calculation error of the integrated intensity and the fitting process.

Fig. 7 shows the energy levels and UC mechanism of Yb\(^{3+}\) and Er\(^{3+}\) in the Ba\(_2\)GdV\(_3\)O\(_{11}\) phosphors under 980 nm and 1550 nm excitation. Upon excitation by a 980 nm laser, Yb\(^{3+}\) ions are excited from the \(2F_{7/2}\) state to the \(2F_{5/2}\) state and serve as sensitizers, transferring the absorbed excitation energy to nearby Er\(^{3+}\) ions. The Er\(^{3+}\) ions are then excited from their initial \(4I_{15/2}\) state to the \(4I_{11/2}\) and \(4F_{7/2}\) states, followed by non-radiative relaxation to the \(2H_{11/2}, 4S_{3/2}\) and \(4F_{9/2}\) states. The excess energy is released through the emission of green light at 525 nm and 555 nm wavelengths. As, Er\(^{3+}\) ions undergo non-radiative de-excitation from the \(4I_{11/2}\) to \(4I_{13/2}\) state, an excitation photon from Yb\(^{3+}\) ion transfers its energy, elevating the population from the \(4I_{13/2}\) to the \(4F_{9/2}\) level. Subsequently, a radiative transition from the \(4F_{9/2}\) to the \(4I_{15/2}\) state results in the emission of a 665 nm photon, as illustrated in Fig. 7(a).\(^{81}\)

Fig. 7(b) and (c) present the UC luminescence of Er\(^{3+}\) ions in Er\(^{3+}\)/Yb\(^{3+}\) co-doped Ba\(_2\)GdV\(_3\)O\(_{11}\) phosphors upon 1550 nm excitation obtained via energy transfer processes. Four possible basic population mechanisms are involved in these UC luminescence processes, including energy transfer UC (ETU or ET), ground state absorption (GSA), excited state absorption (ESA) and back energy transfer (BET) mechanisms.\(^{82}\)

The UC luminescence of Er\(^{3+}\) under 1550 nm excitation shown in Fig. 7(b and c) can be obtained by both direct light absorption of Er\(^{3+}\) ions or energy transfer (ET) from Er\(^{3+}\) ions to Yb\(^{3+}\) ions. By considering only Er\(^{3+}\) ions, the population of \(2H_{11/2}\) and \(4S_{3/2}\) levels upon excitation can be achieved by successive absorbing three 1550 nm photons via one GSA and two ESA or ET processes, and then yielding the green UC emissions.\(^{47,83}\)

The proposed UC mechanisms for the absorption of 1550 nm photons exclusively involve Er\(^{3+}\) ions, as depicted in Fig. 7(b). Initially, Er\(^{3+}\) ions absorb the first 1550 nm photons, raising them to the \(4I_{13/2}\) level through ground-state absorption (GSA). Subsequently, the absorption of a second photon propels the excited ions to the higher \(4F_{9/2}\) energy level.
Additionally, the $^4I_{9/2}$ excited level can be populated through a cross-relaxation (CR) process. The third photon is absorbed from the $^4I_{9/2}$ energy level, promoting the $^4F_{9/2}$ excited level, which then undergoes non-radiative decay to the lower $^2H_{11/2}$ and $^4S_{3/2}$ levels. These latter excited levels contribute to the green emissions from Er$^{3+}$. Another UC mechanism associated with the absorption of 1550 nm photons involves non-radiative depopulation from the $^4I_{9/2}$ excited level to the $^4I_{11/2}$ level, followed by the absorption of a third photon to the $^4F_{9/2}$ level. From this level, Er$^{3+}$ ions radiatively decay to the $^4I_{15/2}$ ground level, emitting red radiation.$^{83-87}$

By considering Yb$^{3+}$ as a sensitizer ion (see Fig. 7(c)), the UC luminescence process of Er$^{3+}$ can occur through an energy transfer (ET) process, since Yb$^{3+}$ cannot directly absorb the energy of 1550 nm photons. The ET process from Er$^{3+}$ to Yb$^{3+}$ ions is an important mechanism for the UC luminescence of Er$^{3+}$ under 1550 nm excitation.$^{47,88,89}$ Er$^{3+}$ initially absorbs two 1550 nm photons, populating the $^4I_{9/2}$ level, and achieves the population of $^4I_{13/2}$ level via a subsequent non-radiative relaxation process. The energy is then transferred from Er$^{3+}$ to an adjacent Yb$^{3+}$ ion through the BET (back energy transfer) process, exciting Yb$^{3+}$ to the $^2F_{5/2}$ level. The excited Yb$^{3+}$ ion transfers energy to a neighboring Er$^{3+}$ ion, achieving population of $^2H_{11/2}$ and $^4S_{3/2}$ levels of Er$^{3+}$ via ET2 process, and population of the $^2F_{5/2}$ level via the ET3 process. Finally, green and the red UC emissions can be achieved. The green UC emissions involve the absorption of a 1550 nm photon by an Er$^{3+}$ ion, which excites it to the $^4I_{11/2}$ level from the ground state with GSA. Then, the BET process occurs and transfers the excess energy to the $^2F_{5/2}$ level of a neighboring Yb$^{3+}$ ion through ET1. From there, the energy is again transferred to the $^2H_{11/2}$ and $^4S_{3/2}$ states of an adjacent Er$^{3+}$ ion through ET3, and the excited ions relax to ground state by emitting green light at 525 and 555 nm wavelengths, respectively. The green UC emission requires four 1550 nm photons when Yb$^{3+}$ acts as the sensitizer for Er$^{3+}$. On the other hand, the red UC emission involves a similar GSA and BET process, followed by the transfer of excess energy to an Er$^{3+}$ ion through only one ET step from $^2F_{5/2}$ to the ground state.$^{86}$

3.3 Temperature-dependent UC emission, and optical temperature-sensing behavior

Temperature-responsive UC spectra are recorded upon excitation by a 980 nm and 1550 nm laser to assess the suitability of Er$^{3+}$/Yb$^{3+}$ co-doped Ba$_2$GdV$_3$O$_{11}$ phosphors for temperature sensing applications, and the excitation power is held at 0.5 W through the measurements in order to avoid the compound heating under the effect of excitation. As shown in Fig. 8(a), two different green emissions peaks are investigated to illustrate the variation tendency of the intensity ratio as the temperature rises from 298 to 573 K under 980 nm excitation. Temperature-dependent PL intensity of the $^4S_{3/2} \rightarrow ^4I_{15/2}$ (555 nm) transition decreases gradually with increasing temperature. However, the intensity of the $^2H_{11/2} \rightarrow ^4I_{15/2}$ (525 nm) transition also decreases with temperature, but to a lesser extent than the 555 nm transition. Therefore, the 555 nm transition is more affected by temperature compared to the 525 nm transition. The red emission obtained upon 980 nm excitation exhibits very low intensity. Notably, the intensity of the red emission at 665 nm shows no significant correlation with temperature (refer to the inset of Fig. 8(a)), which makes it a suitable reference for optical temperature measurement. Fig. 8(b) shows the CIE chromaticity diagram of Er$^{3+}$/Yb$^{3+}$ co-doped Ba$_2$GdV$_3$O$_{11}$ phosphors upon 980 nm laser excitation, indicating a shift in PL emission color from green to yellow/orange region with increasing temperature. Except for one instance where the color coordinates of the 573 K PL emission are detected beyond those of the 523 K PL emission, PL results show a consistent decrease in the color coordinate values of the emissions with increasing temperature. However, the rates of decrease are different for the two emissions, i.e., 525 nm and 555 nm, which may contribute to the observed exception. Notably, the combined output of the two emissions could influence this result, particularly in the case of the 573 K PL emission, where the difference is more pronounced. Fig. 8(c) shows the temperature-dependent UC luminescence spectra from 298 to 573 K under 1550 nm excitation. The green emission intensities of the $^4S_{3/2} \rightarrow ^4I_{15/2}$ (555 nm) and $^2H_{11/2} \rightarrow ^4I_{15/2}$ (525 nm) transitions decrease with increasing tempera-
Similar to 980 nm excitation, the intensity of the 555 nm emission decreases more significantly than the 525 nm transition. Moreover, the red emission at the transition of $^4F_{9/2} \rightarrow ^4I_{15/2}$ (665 nm) is discernable, and it displays a decrease in intensity as the temperature rises. The corresponding CIE chromaticity diagram of the Er$^{3+}$/Yb$^{3+}$ co-doped Ba$_2$GdV$_3$O$_{11}$ phosphors under 1550 nm laser excitation is presented in Fig. 8(d). As shown in the CIE chromaticity diagram, PL emission color shifts from greenish to the pure green region as the temperature increases.

To evaluate the thermochromic performance of Er$^{3+}$/Yb$^{3+}$ co-doped Ba$_2$GdV$_3$O$_{11}$ phosphors under both 980 nm and 1550 nm excitations, thermo-induced chromaticity shift ($\Delta E$) values are computed as previously reported elsewhere. The resulting $\Delta E$ value is 0.052 for 980 nm excitation and 0.42 for 1550 nm excitation. Despite the seemingly proximity of these chromaticity shift values, the shift in PL emission color from green to yellow/orange under 980 nm excitation, in contrast to the shift from greenish to pure green under 1550 nm excitation, renders the former much more discernible to the naked eye or through digital imaging. This heightened visibility under 980 nm excitation underscores the potential of Er$^{3+}$/Yb$^{3+}$ co-doped Ba$_2$GdV$_3$O$_{11}$ phosphors, not only in luminescent thermometry, but also as effective safety indicators in high-temperature environments.

Er$^{3+} (2H_{11/2}, 4S_{3/2})$ TCELS can be used for optical thermometry. According to previous reports, the FIR for the thermally...
coupled $^2\text{H}_{11/2}$ and $^4\text{S}_{3/2}$ levels follow the Boltzmann distribution and is defined as follows:

$$\text{FIR} = \frac{I_H}{I_S} = A + B \exp\left(-\Delta E \frac{K_B T}{C_0} \right)$$  \hspace{1cm} (4)

where the $I_H$ and $I_S$ refer to the integrated intensities of the transitions from $^2\text{H}_{11/2}$ to $^4\text{I}_{15/2}$ (524–537 nm) and $^4\text{S}_{3/2}$ to $^4\text{I}_{15/2}$ (537–564 nm), respectively. The energy gap between the levels of $^2\text{H}_{11/2}$ and $^4\text{S}_{3/2}$ is represented by $\Delta E$, while $K_B$, which has a value of 0.695 cm$^{-1}$ K$^{-1}$, is the Boltzmann constant. $T$ is the absolute temperature, $A$ is a constant that relies on the degeneracy, spontaneous emission rate, and photon energies of the emitting states in the host material, and $B$ is a parameter associated with the curve of FIR versus $1/T$.

Temperature dependence of the FIR is calculated by PL with variations in temperature for the 525/555 nm bands of the Er$^{3+}$/Yb$^{3+}$ co-doped Ba$_2$GdV$_3$O$_{11}$ phosphors under 980 nm and 1550 nm excitation. The fitting results of temperature dependence of the FIR are depicted in Fig. 9(a) and 10(a), revealing correlation $R^2$ values greater than 99%. The experimental data can be well fitting of FIR = 0.05 + 15.93 exp ($-1150.52/T$) for 980 nm excitation and FIR = 17.99 exp ($-1154.11.05/T$) for 1550 nm excitation. The corresponding energy gap $\Delta E$ of the thermally coupled energy levels ($^2\text{H}_{11/2}$ and $^4\text{S}_{3/2}$) are calculated to be 799.61 cm$^{-1}$ and 802.03 cm$^{-1}$ for 980 nm and 1550 nm excitation, respectively. The results show that, the excitation almost has no impact on thermally coupled energy levels.

In general, monitoring the temperature-dependent sensitivities of resulting compounds is critical for determining their suitability for noninvasive thermometry. Therefore, absolute sensitivity ($S_a$) and relative sensitivity ($S_r$) parameters are interesting in order to compare with other sensors. The absolute sensitivity ($S_a$) and relative sensitivity ($S_r$) values are given by:

$$S_a = \frac{d\text{FIR}}{dT}$$

$$S_r = \frac{1}{\text{FIR}} \frac{\delta\text{FIR}}{\delta T}$$  \hspace{1cm} (6)

As depicted in Fig. 9(b), and 10(b) the trends observed in the calculated $S_r$ values show a gradual decrease with increasing temperature, with a maximum of 1.1% K$^{-1}$ at 298 K for 980 nm excitation and 0.86% K$^{-1}$ at 298 K for 1550 nm excitation. On the other hand, the $S_a$ values exhibit an increase for 980 nm and 1550 nm excitation with temperature. The

Fig. 9  (a) Temperature dependence of the FIR for the 525/555 nm bands of the Er$^{3+}$/Yb$^{3+}$ co-doped Ba$_2$GdV$_3$O$_{11}$ phosphors under 980 nm excitation, (b) absolute and relative sensitivities calculated by FIR, (c) thermometric parameter’s resolution limit, and (d) variations in temperature uncertainty with temperature.
maximum value of $S_a$ is $75 \times 10^{-4}$ K$^{-1}$ at 573 K for 980 nm excitation and $84 \times 10^{-4}$ K$^{-1}$ at 573 K for 1550 nm excitation.

Furthermore, the temperature uncertainty (temperature resolution) ($\delta T$), a crucial indicator of the effectiveness of a thermometer, describes the smallest change in temperature that corresponds to a significant variation in the parameter under consideration. The formula below is used to estimate $\delta T$ using the following equation:

$$\delta T = \frac{\delta\text{FIR}}{\text{FIR}} \times \frac{1}{S_r} \quad (7)$$

where $\delta\text{FIR}/\text{FIR}$ is the thermometric parameter’s resolution limit or relative uncertainty, which represents the smallest change in ratio that can be noticed experimentally. The resolution limit is related to thermometer performance, but it is also influenced by the experimental setup.87,90

As a result, implementing enhanced acquisition methods as well as increasing measurement performance, which includes improving integration time and using the average of subsequent measurements to decrease experimental noise, can represent one option for increasing the resolution limit. To evaluate the limit of detection, 20 measurements are conducted at room temperature under comparable conditions for Er$^{3+}$/Yb$^{3+}$ co-doped Ba$_2$GdV$_3$O$_{11}$.

Thermometric parameter’s resolution limit or relative uncertainty ($\delta\text{FIR}/\text{FIR}$) is calculated as the standard deviation of each method’s statistical distribution, with values of 0.014, and 0.015 upon 980 nm and 1550 nm excitations, respectively (see Fig. 9(c) and 10(c)). The minimum temperature uncertainties are calculated to be 0.013 K (at 298 K) and 0.017 K (at 298 K) upon 980 nm and 1550 nm excitations, respectively (see Fig. 9(d) and 10(d)). Using eqn (7), the obtained results are less than 0.5 K, suggesting that FIR methods offer great accuracy throughout this whole temperature range.

Since the red emission is prominent even at low power excitation under 1550 nm, it can be utilized for thermometry applications in the case of NTCELS. Additionally, the intensity of the red emission makes it a suitable reference for optical temperature measurement. Therefore, optical thermometric characteristics of Er$^{3+}$ ions at $^2H_{11/2}$ and $^4F_{9/2}$ levels are investigated under 1550 nm excitation (see Fig. 11), where $I_r$ and $I_H$ refer to the integrated intensities of the transitions from $^4F_{9/2}$ to $^4I_{15/2}$ (650–680 nm) and $^2H_{11/2}$ to $^4I_{15/2}$ (524–537 nm), respectively. The large energy gaps of NTCELS make it challenging to populate them via thermal excitation. Therefore, traditional FIR is not suitable for NTCELS. In the absence of a well-defined physical model that accurately describes the temperature dependencies of FIR values for NTCELS of Ln$^{3+}$,
an empirical approach becomes crucial for capturing the intricate variations observed in experimental data. The choice of a polynomial function over commonly used physical models, such as exponentials, is grounded in its inherent flexibility and general applicability. Polynomial functions provide a versatile framework capable of accommodating diverse trends and behaviors exhibited by the NTCEL under varying temperatures. This empirical approach prioritizes the accurate representation of experimental data, acknowledging the dynamic and complex nature of the observed phenomena. Moreover, the acceptance of empirical functions in similar fields underscores the appropriateness of this approach in the absence of a precise theoretical framework. The experimental FIR can be well fitted by a polynomial function.91,92

\[ \text{FIR} = A + BT + CT^2 + DT^3 \]  

(8)

The sensitivity of a sensor is a crucial parameter to verify its ability to detect temperature changes. The sensitivity of the temperature sensing performance of the synthesized phosphors is evaluated by calculating the absolute sensitivity \( S_a \) and relative sensitivity \( S_r \) using the following equations:

\[ S_a = \frac{\partial \text{FIR}}{\partial T} = 3DT^2 + 2CT + B \]  

(9)

\[ S_r = \frac{1}{\frac{\partial \text{FIR}}{\partial T}} = \frac{1}{\text{FIR}} \left(3DT^2 + 2CT + B\right) \]  

(10)

where \( \frac{\partial \text{FIR}}{\partial T} \) is the slope of the FIR emission intensity as a function of temperature, \( C \) is the temperature-independent part of the equation, \( B \) is the temperature-independent background, and \( D \) is a constant related to the temperature-dependent change of the intrinsic efficiency of the UC process.

The \( S_a \) and \( S_r \) values obtained using eqn (9) and (10) are presented in Fig. 10(b). The maximum \( S_r \) value is 0.9% K\(^{-1}\) at 298 K, while the maximum \( S_a \) value is \( 143 \times 10^{-4} \) K\(^{-1}\) at 298 K. Thermometric parameter’s resolution limit or relative uncertainty (\( \delta \text{FIR}/\text{FIR} \)), is calculated as the standard deviation of each method’s statistical distribution, with a value of 0.017 (see Fig. 11(c)). Additionally, the minimum temperature uncertainties are calculated to be 0.019 K at 298 K (see Fig. 11(d)). In conclusion, the thermometric sensors perform better in the NTCEL case compared to the TCEL case when excited at 1550 nm.

### 3.4 Temperature dependent lifetime analysis

In addition to FIR techniques from TCEL and NTCEL, the FL technique is a crucial optical thermometry method. FL-based sensitivity presents advantages over FIR methods, offering a

![Fig. 11](image-url)
broader temperature range, heightened sensitivity to subtle changes, and greater resilience to experimental variations and quenching effects. The suitability of FL-based techniques for complex, multicomponent systems further enhance their appeal. The time-resolved nature of decay measurements allows for precise temporal analysis, providing valuable insights into dynamic processes and lifetimes.

The FL of Er\(^{3+}/Yb^{3+}\) co-doped Ba\(_2\)Gd\(_3\)V\(_3\)O\(_{11}\) phosphors is highly sensitive to changes in temperature. The average lifetime of Er\(^{3+}\) ions in the \(4S_{3/2}\) state is calculated according to the following equation:\(^{93}\)

\[
\tau = \int \frac{t I(t)dt}{\int I(t)dt}
\]  

(11)

where \(t\) is the time and \(I(t)\) is the intensity of the emission and \(\tau\) is the average lifetime.

The variation of the average lifetime with temperature is fitted according to the following equation:\(^{7}\)

\[
\frac{1}{\tau} = \frac{1}{\tau_0} \times \left[1 + C e^{-\frac{\Delta E}{kT}}\right]
\]  

(12)

where \(\tau(T)\) and \(\tau_0\) represent the FL at various temperatures and at 0 K, respectively. \(C\) is a constant and \(\Delta E\) signifies the energy gap between \(4F_{7/2}\) and \(4S_{3/2}\) states.

Absolute \((S_a)\) and relative sensitivity \((S_r)\) values of an optical temperature sensor is determined using FL according to the following equations:

\[
S_a = \frac{|d\tau|}{dT}
\]  

(13)

\[
S_r = \left|\frac{1}{\tau} \frac{\delta\tau}{\delta T}\right|
\]  

(14)

As illustrated in Fig. 12, an increase in temperature leads to a noticeable decrease in the Er\(^{3+}\) UC lifetime of the 555 nm green emission, likely due to the increased non-radiative transitions and phonon energies. Consequently, the average lifetime Er\(^{3+}\) ions in the \(4S_{3/2}\) state experiences a decline from

Fig. 12  Decay curves of 555 nm \(4S_{3/2}\) level emissions of Er\(^{3+}/Yb^{3+}\) co-doped Ba\(_2\)Gd\(_3\)V\(_3\)O\(_{11}\) phosphors at different temperatures \((\lambda_{exc} = 980\ nm)\).

Fig. 13  (a) Temperature dependency of the PL of \(4S_{3/2}\) level of Er\(^{3+}\) average lifetime under 980 nm excitation, (b) absolute and relative sensitivities calculated by FIR, and (c) variations in temperature uncertainty with temperature.
Table 1  Comparative analysis of the calculated $S_r$ and $S_a$ thermometric parameters for Er$^{3+}$/Yb$^{3+}$ or Er$^{3+}$/Yb$^{3+}$/Er$^{3+}$ doped in various hosts, and employing different strategies

<table>
<thead>
<tr>
<th>Material</th>
<th>Temperature range</th>
<th>$S_{r_{\max}}$</th>
<th>$S_{a_{\max}}$</th>
<th>Method used</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Na$_3$Gd(VO$_4$)$_3$:Er$^{3+}$/Yb$^{3+}$</td>
<td>300–600 K</td>
<td>0.83% K$^{-1}$</td>
<td>$48 \times 10^{-4}$ K$^{-1}$</td>
<td>FIR = $I_H/I_L$</td>
<td>65</td>
</tr>
<tr>
<td>YP$_2$O$_3$:Er$^{3+}$/Yb$^{3+}$</td>
<td>20–440 K</td>
<td>6.58% K$^{-1}$</td>
<td>$40 \times 10^{-4}$ K$^{-1}$</td>
<td>FIR = $I_H/I_L$</td>
<td>93</td>
</tr>
<tr>
<td>Na$_3$GdMg$_2$(VO$_4$)$_3$:Yb$^{3+}$/Er$^{3+}$</td>
<td>303–573 K</td>
<td>9.76% K$^{-1}$</td>
<td>$74.9 \times 10^{-4}$ K$^{-1}$</td>
<td>FIR = $I_H/I_L$</td>
<td>94</td>
</tr>
<tr>
<td>La$_2$O$_3$:Er$^{3+}$/Yb$^{3+}$/Bi$^{3+}$</td>
<td>300–625 K</td>
<td>—</td>
<td>$71 \times 10^{-4}$ K$^{-1}$</td>
<td>FIR = $I_H/I_L$</td>
<td>95</td>
</tr>
<tr>
<td>Y$_2$Ti$_2$:Er$^{3+}$/Yb$^{3+}$/Li$^+$</td>
<td>298–673 K</td>
<td>—</td>
<td>$67 \times 10^{-4}$ K$^{-1}$</td>
<td>FIR = $I_H/I_L$</td>
<td>96</td>
</tr>
<tr>
<td>Na$_3$(WO$_4$)$_2$:Yb$^{3+}$/Er$^{3+}$</td>
<td>293–503 K</td>
<td>1.2% K$^{-1}$</td>
<td>$80 \times 10^{-4}$ K$^{-1}$</td>
<td>FIR = $I_H/I_L$</td>
<td>97</td>
</tr>
<tr>
<td>BaMoO$_4$:Yb$^{3+}$/Er$^{3+}$</td>
<td>293–573 K</td>
<td>0.47% K$^{-1}$</td>
<td>$8.3 \times 10^{-4}$ K$^{-1}$</td>
<td>FIR = $I_H/I_L$</td>
<td>98</td>
</tr>
<tr>
<td>Na$_3$Gd(PO$_4$)$_2$:Er$^{3+}$/Yb$^{3+}$</td>
<td>300–440 K</td>
<td>1.45% K$^{-1}$</td>
<td>$14 \times 10^{-4}$ K$^{-1}$</td>
<td>PL lifetime $S_{a/2}$</td>
<td>7</td>
</tr>
<tr>
<td>Cs$_3$GeO$_3$:Er$^{3+}$/Yb$^{3+}$</td>
<td>300–550 K</td>
<td>0.49% K$^{-1}$</td>
<td>$16.34% \mu$s K$^{-1}$</td>
<td>PL lifetime $S_{a/2}$</td>
<td>91</td>
</tr>
<tr>
<td>Ca$_3$MgWO$_6$:Er$^{3+}$/Yb$^{3+}$</td>
<td>300–573 K</td>
<td>0.11% K$^{-1}$</td>
<td>$12.6% \mu$s K$^{-1}$</td>
<td>PL lifetime $S_{a/2}$</td>
<td>92</td>
</tr>
<tr>
<td>Ba$_2$Gd$_2$V$<em>3$O$</em>{11}$:Er$^{3+}$/Yb$^{3+}$</td>
<td>298–573 K</td>
<td>1.1% K$^{-1}$</td>
<td>$75 \times 10^{-4}$ K$^{-1}$</td>
<td>FIR = $I_H/I_L$ (980 nm)</td>
<td>This work</td>
</tr>
<tr>
<td></td>
<td>298–573 K</td>
<td>0.86% K$^{-1}$</td>
<td>$84 \times 10^{-4}$ K$^{-1}$</td>
<td>FIR = $I_H/I_L$ (1550 nm)</td>
<td>97</td>
</tr>
<tr>
<td></td>
<td>298–573 K</td>
<td>0.9% K$^{-1}$</td>
<td>$143 \times 10^{-4}$ K$^{-1}$</td>
<td>FIR = $I_H/I_L$ (1550 nm)</td>
<td>97</td>
</tr>
</tbody>
</table>

The phase purity, morphology, and luminescence characteristics are thoroughly evaluated using X-ray diffraction (XRD), scanning electron microscopy (FE-SEM), and photoluminescence spectroscopy (PL) analysis, respectively. Er$^{3+}$/Yb$^{3+}$ co-doped Ba$_2$Gd$_2$V$_3$O$_{11}$ phosphors exhibit remarkable thermochromic behavior, with the emission color changing from green to yellow/orange (980 nm excitation) and greenish to pure green (1550 nm excitation) with an increase in temperature. This change is due to the distinct temperature-dependent effects of Er$^{3+}$'s green and red luminescence and is easily discernible to the naked eye. By utilizing the distinct thermoresponse of luminescence at 523, 555 and 665 nm, the fluorescence intensity ratio ($S_{t/2}$) and fluorescence decay lifetime ($S_{t_{\max}}$) of Er$^{3+}$/Yb$^{3+}$ co-doped Ba$_2$Gd$_2$V$_3$O$_{11}$ phosphors under 980 nm and 1550 nm excitation are exploited to achieve excellent sensitivities. This enables the realization of a four-mode temperature sensor in a single luminous center (Er$^{3+}$) within Er$^{3+}$/Yb$^{3+}$ co-doped Ba$_2$Gd$_2$V$_3$O$_{11}$ phosphors, which is temperature dependent on FIR from $^4$I$_{11/2}/^2$H$_{15/2}$ TCEL, FIR from $^4$I$_{11/2}/^2$H$_{13/2}$ NTCEL from the 980 nm and 1550 nm excitations, as well as the fluorescence decay lifetime ($S_{t_{\max}}$) based on FIR ($^2$H$_{11/2}/^4$F$_{9/2}$). The maximal relative sensitivities achieved are 1.1% K$^{-1}$, 0.86% K$^{-1}$ for the TCEL upon 980 nm and 1550 nm respectively, and 0.9% K$^{-1}$ for the NTCEL upon 1550 nm. Additionally, the fluorescence decay lifetime ($S_{t_{\max}}$) of Er$^{3+}$/Yb$^{3+}$ co-doped Ba$_2$Gd$_2$V$_3$O$_{11}$ under 980 nm excitation gives a high relative sensitivity with 5.0% µs K$^{-1}$ (at 425 K). The obtained results highlight the potential of Er$^{3+}$/Yb$^{3+}$ co-doped Ba$_2$Gd$_2$V$_3$O$_{11}$ phosphors for applications such as temperature visualization and smart high-temperature alarms. Furthermore, this work serves as a platform for the design and exploration of multi-mode self-reference optical temperature sensors, opening new avenues for future research in this field.

4. Conclusions

In conclusion, investigation of Er$^{3+}$/Yb$^{3+}$ co-doped Ba$_2$Gd$_2$V$_3$O$_{11}$ phosphors synthesized through a sol-gel method has revealed promising results for optical temperature sensing applications. The phase purity, morphology, and luminescence characteristics are thoroughly evaluated using X-ray diffraction (XRD), scanning electron microscopy (FE-SEM), and photoluminescence spectroscopy (PL) analysis, respectively. Er$^{3+}$/Yb$^{3+}$ co-doped Ba$_2$Gd$_2$V$_3$O$_{11}$ phosphors exhibit remarkable thermochromic behavior, with the emission color changing from green to yellow/orange (980 nm excitation) and greenish to pure green (1550 nm excitation) with an increase in temperature. This change is due to the distinct temperature-dependent effects of Er$^{3+}$'s green and red luminescence and is easily discernible to the naked eye. By utilizing the distinct thermoresponse of luminescence at 523, 555 and 665 nm, the fluorescence intensity ratio ($S_{t/2}$) and fluorescence decay lifetime ($S_{t_{\max}}$) of Er$^{3+}$/Yb$^{3+}$ co-doped Ba$_2$Gd$_2$V$_3$O$_{11}$ phosphors under 980 nm and 1550 nm excitation are exploited to achieve excellent sensitivities. This enables the realization of a four-mode temperature sensor in a single luminous center (Er$^{3+}$) within Er$^{3+}$/Yb$^{3+}$ co-doped Ba$_2$Gd$_2$V$_3$O$_{11}$ phosphors, which is temperature dependent on FIR from $^4$I$_{11/2}/^2$H$_{15/2}$ TCEL, FIR from $^4$I$_{11/2}/^2$H$_{13/2}$ NTCEL from the 980 nm and 1550 nm excitations, as well as the fluorescence decay lifetime ($S_{t_{\max}}$) based on FIR ($^2$H$_{11/2}/^4$F$_{9/2}$). The maximal relative sensitivities achieved are 1.1% K$^{-1}$, 0.86% K$^{-1}$ for the TCEL upon 980 nm and 1550 nm respectively, and 0.9% K$^{-1}$ for the NTCEL upon 1550 nm. Additionally, the fluorescence decay lifetime ($S_{t_{\max}}$) of Er$^{3+}$/Yb$^{3+}$ co-doped Ba$_2$Gd$_2$V$_3$O$_{11}$ under 980 nm excitation gives a high relative sensitivity with 5.0% µs K$^{-1}$ (at 425 K). The obtained results highlight the potential of Er$^{3+}$/Yb$^{3+}$ co-doped Ba$_2$Gd$_2$V$_3$O$_{11}$ phosphors for applications such as temperature visualization and smart high-temperature alarms. Furthermore, this work serves as a platform for the design and exploration of multi-mode self-reference optical temperature sensors, opening new avenues for future research in this field.

Author contributions

&editing, visualization, validation, supervision, project administration, funding acquisition. Ali Erçin Ersundu: writing – original draft, writing – review & editing, validation, supervision, project administration, funding acquisition.

Conflicts of interest
The authors declare no competing financial interest.

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