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Bifunctional Ce$_{1-x}$Eu$_x$O$_2$ (0 ≤ x ≤ 0.3) nanoparticles for photoluminescence and photocatalyst applications: An X-ray absorption spectroscopy study

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Ce$_{1-x}$Eu$_x$O$_2$ (0 ≤ x ≤ 0.3) nanoparticles (NPs) were synthesized by chemical precipitation method. The microstructures and morphology were characterized by the synchrotron X-ray diffraction and high resolution transmission electron microscopy. X-ray absorption near edge structure (XANES) spectra at the Eu M$_{1,3}$-edge and atomic-multiplet calculations revealed that the Eu$^{3+}$ was predominantly present in CeO$_2$ lattice and Eu$^{2+}$ was negligibly present within the entire doping range. The detailed analysis of the Ce M$_{4,5}$-edge and the O K-edge has shown strong dependence of Ce$^{3+}$/Ce$^{4+}$ ratio and oxygen vacancy with Eu content. Extended X-ray absorption fine structure (EXAFS) spectra at the Ce K-edge, along with theoretical fitting, have shown systematic variation in the coordination number, bond length and Debye-Waller factor with Eu doping. A blue shift in the absorption edge was observed which implies a net increase in the charge transfer gap between the O 2p and Ce 4f bands due to the increased number of Ce$^{3+}$ ions in the Eu doped samples. The excitation and emission spectra of pure CeO$_2$ NPs did not show any photoluminescence (PL) characteristic; however, Ce$_{1-x}$Eu$_x$O$_2$ (x = 0.1-0.3) NPs showed significant improvement in the 4f–4f, $^3$D$_0$ – $^7$F$_3$ and $^3$D$_0$ – $^7$F$_1$ transitions induced luminescence properties. Eu doping has two major effects on the electronic structure and optical properties of CeO$_2$ NPs: The first, at an Eu content of 10 mol%, is the formation of Ce$^{3+}$ – O – Eu$^{3+}$ networks, i.e., Eu$^{3+}$ ions substitute the Ce$^{4+}$ ions and introduce oxygen vacancies and Ce$^{3+}$ ions in the host lattice which favors the $^3$D$_0$ – $^7$F$_1$ induced PL properties. The other, at an Eu doping over 10 mol%, is the formation of both Ce$^{4+}$ – O – Eu$^{2+}$ and Ce$^{3+}$ – O – Eu$^{2+}$, i.e., Eu$^{3+}$ ions not only take substitutional sites of Ce$^{4+}$ ions but also replace a fraction of Ce$^{3+}$ ions in the CeO$_2$ lattice which favors $^3$D$_0$ – $^7$F$_1$ induced PL properties. As an application of CeO$_2$ NPs towards the degradation of water pollutants, we demonstrated that the Ce$_{1-x}$Eu$_x$O$_2$ (0 ≤ x ≤ 0.3) NPs can serve as effective photocatalyst materials towards the degradation of methyl-orange aqueous pollutant dye under UV light irradiation.

Introduction

In responding to the needs of modern science/technology and emerging environmental concerns, it is important to investigate those materials which are inexpensive, environment friendly and multifunctional. In this context, metal-oxide nanoparticles (NPs) are promising for their multifunctional behaviour because they often exhibit superior chemical/physical properties and potentially functional in a broad range of applications. However, the performance of such materials is highly sensitive to their size, shape, electronic structure and structural properties. Among the known metal oxide semiconductors, the CeO$_2$, as a rare earth metal oxide, has gained a great attention in a wide range of applications, such as solar-cells, gas-sensing, oxide fuel cells, automotive catalysts, ultraviolet shielding, etc. Efforts also have been made to explore the biomedical applications of CeO$_2$ as a radical scavenging antioxidant. CeO$_2$ can protect the healthy cells from the radiation-induced damage during the radiation therapy and provides neuroprotection to the spinal cord neurons. Thus, the excellent biocompatibility and nontoxic nature of CeO$_2$ can make it a potential candidate in many of the biomedical applications; however, it exhibits weak emission characteristics that limit its applications in the cellular and biological studies. In this regard, various rare earth elements, like Er$^{3+}$, Eu$^{3+}$, Sm$^{3+}$ and Tb$^{3+}$, have been incorporated in the host lattice to improve the photoluminescence (PL) property of weakly emitting CeO$_2$ NPs. However, emission mechanism in these systems is still controversial and is greatly dependent on the synthesis techniques and concentration of lattice defects.

Azo dyes (e.g., Methyl orange (MO)) are widely used in the pharmaceutical, printing, textile and research laboratories. Such dyes can enter into a human body through skin/mouth and can cause vomiting, fast heart rate and death of lung tissues. Therefore, such azo dyes must be degraded into their subdomains, which are less/non-toxic, before they are released into river/sea water. CeO$_2$ exhibits strong light absorption in the UV region, presents high redox potential of Ce$^{4+}$ – Ce$^{3+}$ couples and possesses high resistance to chemical or photo corrosion. Thus, the CeO$_2$ NPs can be utilized in the photocatalytic degradation of various azo dyes. Therefore, in order to explore the pure and doped CeO$_2$ NPs for their improved...
functionality in the technological fields and environmental safety, systematic research efforts are desired with deep understanding of their structural, optical, electronic structure, and catalyst properties.

In most of the previous reports, X-ray photoelectron spectroscopy (XPS) has been employed on the pure and doped CeO$_2$ NPs to determine the concentration and oxidation state of metal ions$^{13-16}$. Although this technique provides information regarding the oxidation state of the probed ion in certain thin samples, (i) it is mainly surface probing technique (ii) and may undergo severe charging effects during the collection of XPS data. Therefore, other element specific techniques which are rather straightforward and modest, like X-ray absorption spectroscopy (XAS), within the low and high energy range may be advantageous to investigate the local atomic structure, coordination number, valence state and hybridization of the probed elements. Here, we take advantage of the synchrotron light source based X-ray absorption near edge structure (XANES) and extended X-ray absorption fine structure (EXAFS) spectroscopy techniques, which can probe the density of states, to reveal the effect of Eu doping on the defect/electronic structure modulated PL and photocatalytic performance of the Ce$_{1-x}$Eu$_x$O$_2$ (0 ≤ x ≤ 0.3) NPs. We demonstrate that the Eu$^{3+}$ takes substitutional sites in the host CeO$_2$ lattice, without formation of trivial oxide phases, and facilitates oxygen ion vacancies and Ce$^{4+}$-O – Eu$^{3+}$ and Ce$^{3+}$ – O – Eu$^{3+}$ networks which favour the photoluminescence properties of the compound. It is also observed that the Eu doping induced modified electron density can improve photocatalytic performance of NPs, leading to degradation of MO aqueous dye under the light irradiation, manifesting the synthesis of bifunctional Ce$_{1-x}$Eu$_x$O$_2$ NPs in the present study.

Experimental details

Ce$_{1-x}$Eu$_x$O$_2$ (x = 0.0 to 0.3) nanoparticles were synthesized by using previously stabilized chemical precipitation method$^{18-19}$. All the reagents used were of analytical grade without further purification. 0.01M solutions of Ce(CH$_3$COO)$_3$·5H$_2$O and Eu(CH$_3$COO)$_2$·H$_2$O were prepared with a molar ratio of x = Eu/(Ce+Eu) by dissolving them into de-ionized (DI) water. Ammonium hydroxide (NH$_4$OH) was added into the solution (drop by drop) under the magnetic stirring to form the white precipitates of Ce$_{1-x}$Eu$_x$O$_2$. The pH value during the reaction was kept constant, pH = 9, for all the compositions. The resultant precipitates were washed several times with DI water to remove organic impurities. The precipitates were heated in air at 80°C for 30 h followed by natural cooling up to room temperature and, finally, the light yellow coloured powders were collected. For identifying the crystal structure of as-synthesized nanoparticles, the synchrotron X-ray diffraction (λ = 1.240 Å) measurements were performed at X-ray scattering beam line [3D beam line of Pohang Accelerator laboratory (PAL), South Korea]. The morphology and size of NPs were studied with JOEL-JEM-2200FS high resolution transmission electron microscope (HR-TEM) accompanied with selected area electron diffraction (SAED). To prepare the samples for the HR-TEM measurements, the powder samples were fairly dispersed in the ethanol solution using sonication for 20 min and then the suspended NPs were drop-wise loaded on carbon film coated Cu grids. XANES spectra at the Eu M$_{4,5}$-edge, O K-edge, and Ce M$_{4,5}$-edge were collected in total electron yield (TEY) mode at the 10D (PAL-KIST) beam line of PAL. The photon energy resolution of this beam line was better than 0.6 eV (at the O K-edge). The XANES measurements at the Ce K-edge and Eu L-edge were collected at the 10C beam line of PAL. This beam line has high flux and wide energy range with a Si (311) double crystal monochromator. Three ionization chambers, filled with Ar gas, were used to record the intensity of the incident (I$_0$) and the transmitted (I$_t$) X-rays (the sample was placed between the first and the second ionization chamber). The PL excitation and emission spectra were recorded by using the Varian-Cary eclipse fluorescence spectrophotometer equipped with a 150 W xenon lamp as excitation source. For the evaluation of photocatalytic activity of the samples, towards the degradation of MO solution, systematic UV-Vis absorption spectra were collected from the samples at different time of light irradiation. To establish the adsorption-desorption reactions of pollutant dye molecules on the catalyst samples surface, 0.2 g of the as-synthesized Ce$_{1-x}$Eu$_x$O$_2$ NPs were fairly dispersed in the 100 ml of previously prepared MO aqueous solution (0.1g/L) in the dark for 45 minutes under the magnetic stirring. A commercial 100 W mercury lamp was used as the light source to irradiate the samples. After regular irradiation intervals (30 min), 20 ml of the suspensions were sampled and then the NPs were separated by centrifugation. The degradation of MO dye was determined by collecting the UV-visible absorption spectra using a Varian Cary-100 UV-visible spectrophotometer.

Results and discussion

XRD and TEM study

Figure 1 shows the XRD patterns of Ce$_{1-x}$Eu$_x$O$_2$ (x = 0.0 to 0.3) samples. All of the XRD spectra were analysed by Powder X software. The diffraction patterns of all the samples were fairly resembled to the cubic fluorite structure of CeO$_2$ with space group - Fm3m (JCPDS# 34-0394). No diffraction peaks from the impurity phases, such as CeO$_2$, Eu$_2$O$_3$, EuO etc., could be detected within the detection limit of used X-ray diffractometer.

Fig.1 (Colour online) XRD patterns of Ce$_{1-x}$Eu$_x$O$_2$ (x=0.0 - 0.3) NPs. Fig. 1(b) shows the closer view of the (311) peak. The spectra are vertically shifted for a clearer view.
This indicates that the Eu dopant does not segregate, in the entire doping range, but occupy the Ce sites in the CeO$_2$ lattice. In the other oxides (e.g., Y$_2$O$_3$ and Gd$_2$O$_3$), the solubility limit of Eu was only up to 3.5 to 5 mol.% leading to the segregation of Eu oxide phases and resulting in the quenching of PL properties. In the present case, both the Ce and Eu belong to the lanthanide series and exhibit higher solubility$^{19,21}$, and, therefore, Eu is expected to be dispersed throughout the CeO$_2$ lattice even at relatively higher Eu (30 mol.%) concentration. Formation of Eu oxide phase was observed in the 40 mol% Eu doped CeO$_2$ NPs (not shown here) owing to the solubility limit of Eu in CeO$_2$ matrix using the present synthesis method and given experimental conditions. The average particle size of CeO$_2$:Eu NPs was calculated using the Scherrer relation; $D = 0.9\lambda / \beta \cos \theta$, where $\lambda$ is the wavelength of used X-rays and $\beta$ is the full width at half maximum of the XRD peaks. Thus estimated particle size is ~ 6.2 nm, ~ 5.4 nm, ~ 4.8 nm and ~ 4.1 nm for CeO$_2$, Ce$_{0.9}$Eu$_{0.1}$O$_2$, Ce$_{0.8}$Eu$_{0.2}$O$_2$ and Ce$_{0.7}$Eu$_{0.3}$O$_2$ samples, respectively. Similar decrease in the particle size has also been reported in the Hf and Zr doped CeO$_2$ NPs and Eu doped TiO$_2$$^{22}$ NPs, because the doping of foreign elements induces local distortion in the crystalline lattice and restricts the long range ordering. Fig. 1 (b) shows that there is peak (e.g., (311) peak) broadening and marginal peak shift towards the lower diffraction angle. Several possibilities can explain the XRD peak shift and peak broadening; like, decrease in the particle size and distortion in the crystal structure, etc. Here, the ionic radii of Ce$^{4+}$ ions is quite smaller (Ce$^{4+}$ = 0.097 nm) than that of Eu$^{3+}$ or Eu$^{2+}$ ions (i.e., Eu$^{3+}$ = 0.106 nm and Eu$^{2+}$ = 0.129 nm). Therefore, any substitution of Ce$^{4+}$ by Eu$^{3+}$ or Eu$^{2+}$ may enlarge the interatomic spacing of the cubic cell of CeO$_2$ which is reflected as the XRD peak shifting in the present case.

![Fig.2 (Colour online)](image)

Fig.2 (Colour online) TEM images of (a) CeO$_2$ NPs, (b) Ce$_{0.9}$Eu$_{0.1}$O$_2$ NPs, (c) Ce$_{0.8}$Eu$_{0.2}$O$_2$ NPs and (d) Ce$_{0.7}$Eu$_{0.3}$O$_2$ NPs, respectively. Insets in each figure show the SAED patterns of respective sample.

To further confirm the size and morphology of the NPs, systematic, HR-TEM measurement was performed on the samples. Fig. 2 (a-d) shows the TEM images of pure CeO$_2$, Ce$_{0.9}$Eu$_{0.1}$O$_2$, Ce$_{0.8}$Eu$_{0.2}$O$_2$ and Ce$_{0.7}$Eu$_{0.3}$O$_2$ samples, respectively. The SAED pattern of each sample is also provided in the inset of each TEM image. It is clear from the Fig.2 that all the samples show the spherical kind of morphology with the average diameter of ~ 5±0.5 nm. The encircled area in the TEM images shows the view of the particles and crystallographic planes. The ring patterns in the SAED images are conveying the polycrystalline nature of all the samples, and they support the findings of XRD measurements. Though marginal agglomeration of NPs is present in all of the samples, such agglomeration is anticipated in the chemical precipitation method grown NPs due to the presence of hydroxyl ions on the surface of NPs$^{19,22}$. Our structural investigations ruled out the formation of secondary phases, convincing the substitutional doping of Eu ions at the Ce sites in CeO$_2$ lattice up to x = 0.3, however, the local atomic disorder/structural perturbations were also observed (XRD peak broadening and decrease in the peak intensity). Such structural perturbations are expected to facilitate the interesting variations in electronic structure properties of CeO$_2$:Eu NPs and shall be discussed in the following sections.

**XANES study at the Eu M$_{4,5}\text{-edge, O K-edge, Ce M}_{5,4}\text{-edge, Ce K-edge and Eu L-edge**}

To verify the valence state of Eu in CeO$_2$ lattice, the Eu M$_{4,5}\text{-edge}$ spectra were studied. Fig. 3 (a) shows the Eu M$_{4,5}\text{-edge}$ spectra of Ce$_{1-x}$Eu$_x$O$_2$ (x = 0.1 to 0.3) samples. The favourable valence state of Eu ions is +3, however, +2 valence state of Eu has also been reported when the Eu doping concentrations were large$^{23}$. Therefore, to clear these doubt, we have employed atomic-multiplet calculations to
generate theoretical Eu M\(_{5,4}\) edge spectra from the Eu\(^{2+}\) and Eu\(^{3+}\) ions and presented in the Fig. 3 (b). To compare the discrete lines of the atomic-multiplets with the experiment and to simulate the resolution, they have been broadened with the Lorentzian width of 0.08 eV and Gaussian width of 0.2 eV. Various combinations, with different weight percentage of spectra, of the theoretical Eu\(^{2+}\) and Eu\(^{3+}\) M\(_{5,4}\)-edge were generated. The atomic-multiplet calculations show that the experimental Eu M\(_{5,4}\) edges spectra, from all of the samples, were fairly resembled to those of theoretical Eu\(^{2+}\) M\(_{5,4}\)-edge and, hence, they suggest the presence of +3 valence state of Eu ions in the doped CeO\(_2\) NPs. It is noticeable from the Fig. 3 (a) that the intensity of experimental XANES data at Eu M\(_5\) and M\(_4\) edges is enhanced with increasing the Eu concentration. This indicates the improvement in the hybridization strength of Eu \(d\) and \(f\) orbitals with the doping concentration.

Fig. 4 (a) shows the normalized XANES spectra at the O K-edge of Ce\(_1-x\)Eu\(_x\)O\(_2\) (\(x = 0.0\) to 0.3) NPs along with the bulk CeO\(_2\) and EuO\(_3\) samples. It can be seen from the Fig. 4 (a) that O K-edge spectra of bulk CeO\(_2\) and Ce\(_1-x\)Eu\(_x\)O\(_2\) (\(x = 0.0\) to 0.3) NPs show three intense peaks (A, B and C) at 530.0 eV, 532.5 eV and 536.9 eV. These features can be assigned to the hybridization of the empty O 2p states with the Ce 4f, 5d\(-e\_g\) and 5d\(-t\_g\) states, respectively. The spectral profile of Ce\(_1-x\)Eu\(_x\)O\(_2\) (\(x = 0.0\) to 0.3) nanoparticle samples are closely resembled to those of bulk CeO\(_2\) except the peak broadening and intensity variation. The spectral features and peak positions in the O K-edge spectra of Ce\(_1-x\)Eu\(_x\)O\(_2\) (\(x = 0.0\) to 0.3) nanoparticle samples are different from spectral features of europium oxide, which indicates negligible presence of europium oxide phases. The crystal-field splitting energy (i.e., separation of \(e\_g\) and \(t\_g\) features) is known to exceed, a bit, in the smaller sized NPs \(^{24}\) (because of the association of larger surface with the smaller sized particles) and also varies with the hybridization strength of the \(d\) or \(f\) orbitals, with the O 2p orbitals, of the additive atoms. \(^{19}\) Therefore, it gives information of the particle size and doping effects on the electronic structure properties of the host material. In the present case the crystal field effects are less discriminable in the pure and doped NPs because of the broadening of peak C.

While comparing the spectral features of Eu doped NPs samples relative to the undoped CeO\(_2\) NPs, it seems that intensity of A peak is decreased and the intensity of B peak is increased. To understand this intensity variation, the difference spectra were obtained by subtracting the O K-edge spectra of Eu doped nanoparticle samples from the spectrum of undoped CeO\(_2\) nanoparticle sample. It is visible from Fig. 4 (b) that the difference of peak \(\sim 530\) eV (pre-edge peak) is increased in upward direction and the difference of peak \(\sim 532.5\) (5d\(-e\_g\) peak) eV is enhanced in downward direction with the variation of Eu content. This indicates that the Eu doping has caused a net reduction in the Ce 4f unoccupied states and enhanced the density of empty \(d\) (\(e\_g\)) states. It is also noticeable from the Fig 4 (b) that the peak at \(\sim 530\) eV is splitted/broadened and the weight changes with Eu concentration. This may be because of the distortion in oxygen octahedra by Eu doping induced structural disorders via formation of Ce\(^{4+}\) = O – Eu\(^{3+}\) and Ce\(^{3+}\) = O – Eu\(^{3+}\) networks. The increase in the weight of spectral feature at \(\sim 530\) eV (main notice in the spectral change) could be due to the net reduction of Ce 4f unoccupied states, hybridized with the O 2p states, with increasing the Eu contents. The enhancement in the available \(d\) states may be due to the mix-up of Eu related empty \(d\) states with the Ce \(d\) states in the Ce\(_1-x\)Eu\(_x\)O\(_2\) (\(x = 0.0\) to 0.3) compounds. The variation in the intensity of peak A implies a change in the hybridization of O 2p and Ce 4f states and reflects the change in the 4f occupancy number and the valence of Ce\(^{2+}\). To quantify the variation in the intensity of peak A, area under the curves was inspected by Gaussian peak fitting and presented in the inset of Fig. 4 (a). It is clearly visible that the area under the peak A is significantly decreased with Eu doping. The net decrease in the area under the peak A indicates that the Ce 4f orbitals are partially filled by the electrons or Ce\(^{3+}\) ions are formed via formation of oxygen ion vacancies in the Eu doped NPs. It is noticeable from the inset that

![Fig. 4. (Colour online) (a) O K-edge spectra of Ce\(_1-x\)Eu\(_x\)O\(_2\) (\(x = 0.0\) to 0.3) NPs along with the spectra of bulk CeO\(_2\) and EuO\(_3\). (b) Difference spectra, obtained by subtracting the O K-edge spectra of Eu doped nanoparticle samples from the spectrum of undoped CeO\(_2\) nanoparticle sample. Inset shows the variation in the area under the pre-edge peak (A) as a function of Eu concentrations. The spectra are vertically shifted for the clarity of data.](image-url)
the decrease in the area under the peak A is substantial in case of Ce0.8Eu0.2O2 NPs samples and then marginally decreased for the Ce0.6Eu0.4O2 and Ce0.4Eu0.6O2 NPs samples. Formation of Eu+3 – O – Ce+4 and Eu+3 – O – Ce+3 networks and decrease in the area under the pre-edge peak will be discussed in the following sections.

The Ce M5,4-edge is attributed to the Ce 3d5/2 and 3d3/2 core level transitions into 4f unoccupied electronic state, and thus, directly reflects the occupancy of the 4f orbitals. To probe the variation in the valence state of Ce with Eu doping, systematic, XANES spectra at the Ce M5,4-edge were collected and are shown in the Fig. 5(a). To distinct the Ce valence state (+3 or +4), Ce M5,4-edge XANES spectrum of CeAl2 was also collected (Ce is regarded as trivalent and tetravalent in CeAl2 and CeO2, respectively) and presented along with the spectra of Ce3.5Eu0.5O3 (x = 0.0 to 0.3) NPs. It is visible from Fig. 5(a) that all Ce3.5Eu0.5O3 (x = 0.0 to 0.3) NPs show two major peaks at ~887 eV and at ~905 eV, representing the Ce M5,4-edge and Ce M5,3-edge, respectively. Besides, of these two major peaks, all of the as-synthesized samples show two post edge peaks at ~892 eV and at ~909.8 eV. The post-edge peaks are known to represent the contribution of 4f states because they originate from the transitions to the 4f states in the conduction band. At the first sight, the as-synthesized NPs are seemed to enclose both Ce+4 and Ce+3 ions, because the spectral features of Ce3.5Eu0.5O3 (x = 0.0 to 0.3) NPs partially matches with spectral features of bulk CeAl2. The Ce M5,4-edge is known as the replica of Ce M3,1-edge. In order to understand the 3d transitions into 4f states and to reveal the variation in the valence state of Ce with Eu doping, the Ce M5,4-edge was deconvoluted with its post edge peak P (using the Gaussian peak fittings) and the result is presented in Fig. 5(b). It is noticeable from the Fig. 5(b) that the peak R evolves in the Eu doped CeO2 NPs and its intensity increases with increasing the Eu concentration, implying an increase in the Ce+3 contribution in Eu doped NPs. Ce+3/Ce+4 ratio was calculated by examining the area under the R, S and P peaks, as a function of Eu concentration, and presented in the Fig. 6. The ratio of R to (S+P) is low, but non-zero, in the pure CeO2 NPs implying that the Ce+4 is dominating in this sample with marginal presence of Ce+3. R to (S+P) ratio is increased with increasing the Eu concentration, indicating that the Ce+4 is reduced to Ce+3 in the Eu doped samples. This variation in the Ce+3/Ce+4+Ce+4 ratio tallies with the findings of the O K-edge results, where a net reduction in the unoccupied Ce 4f states was observed when Eu concentration was increased. It is noticeable that net decrease in the intensity of peak A in the O K-edge spectra and the increase in the Ce+3/Ce+4+Ce+4 ratio are significant for the first 10 mol% Eu doping, indicating an efficient substitution of Ce+4 ions by the Eu+3 ions in the CeO2 lattice and formation of favourable Ce+4 – O – Eu+3 networks. At higher doping level, although Ce+3/Ce+4+Ce+4 ratio increases and the area under the peak A of O K-edge decreases, some of the existing Ce+3 ions are expected to be substituted by the Eu+3 ions and form Ce+3 – O – Eu+3 networks along with the Ce+4 – O – Eu+3 networks. As a consequence of this, the increase in Ce+3/Ce+4+Ce+4 ratio and decrease in the area under peak A of O K-edge spectra are complementary.
substitution of a large number of Ce⁴⁺ ions by the Eu³⁺ ions in the CeO₂ lattice at the low Eu doping level; however, the replacement of Ce⁵⁺ ions by the Eu³⁺ is also likely at higher Eu doping. Therefore, low energy shift in the Ce K-edge spectra and calculated Ce⁴⁺/Ce⁵⁺ ratio are in accordance with each other. Fig. 7 (b) shows the Eu L-edge XANES spectra of Eu doped CeO₂ samples. The spectral features from all of the samples are very similar to each other and resemble to the previously reported XANES spectra for Eu³⁺. In the spectra, we could not find any low energy peak related to the Eu⁴⁺ as observed by Rakovan et al. Thus the present Eu L-edge XANES tally our findings of the Eu Mn₄⁺-edge XANES that Eu³⁺ ions are present throughout the doping range. Increase in the intensity of Eu L-edge white line peak, which originates from the transitions from 2p to 5d states, indicates the net increase in the unoccupied states with Eu doping concentration. This behaviour could be attributed to the fair localization of Eu³⁺ ions within the CeO₂ lattice via formation of either Ce⁴⁺ – O – Eu³⁺ or Ce⁵⁺ – O – Eu³⁺ networks.

EXAFS study at Ce K-edge

EXAFS provides element specific and local short-range structural information, which is complementary to that provided by the XRD, and also includes information about the identification of the atoms surrounding the absorbing atom, coordination number and bond length etc. In a typical EXAFS spectrum, the plot of absorption (μ(E)) versus photon energy (eV) is obtained by monitoring the intensities I₀ and Iₛ. In determining the Iₛ, thickness (t) and absorption coefficient (μ) of the sample material play crucial role, given by the relation: Δµ = k̅μ(E)ΔE. The absorption function is achieved from the absorption coefficient by using the relation 28:

\[ \chi(E) = \frac{\mu(E) - \mu_0(E)}{\Delta \mu(E)} \]

where, \( \mu_0(E) \) is the bare atom background, Δµ(E₀) is the step in the μ(E) value at the absorption edge and the E₀ is the absorption edge energy. During the analysis of data, the EXAFS function was derived from the raw absorption data through pre-edge and post-edge background subtraction and then normalization with respect to the edge jump by using the ATHENA software package. After being k²-weighted, k is the photo-electron wavenumber given by

\[ k = \sqrt{2m(E - E_0)/h^2} \]

transformed from k-space to r-space to generate the \( \chi(R) \) versus R (or FT-EXAFS) spectra in terms of the real distance from the central absorbing atom. To simulate the FT-EXAFS data, theoretical CeO₂ structure (space group - Fm3m, a = b = c = 5.410 Å, α = β = γ = 90°) was generated using the ARTIMIS (ATOM and FEFF codes) software package. The data range taken for the transformation was 2-10 Å⁻¹ in the k-space. Structural parameters were obtained, without phase corrections, by fitting the data in the r-space within the interval of 1-6 Å. Fig 8 show the \( \chi(R) \) vs. R spectra along with the corresponding best fit theoretical spectra of pure and Eu doped CeO₂ NPs. Structural parameters obtained from the Ce K-edge EXAFS fittings are tabulated in the Table 1. The first and the second shells in the CeO₂ K-edge EXAFS data arise from the single scattering paths of Ce–O and Ce–Ce paths, respectively.

\[ \text{Fig. 7. (Colour online)} \text{ (a) Ce K-edge XANES spectra of Ce}_{1-x}\text{Eu}_x\text{O}_2 \text{ (x=0.0 - 0.3) NPs. (b) Eu L-edge XANES spectra of Ce}_{1-x}\text{Eu}_x\text{O}_2 \text{ (x=0.1 - 0.3) NPs.} \]

\[ \text{Fig. 8. (Colour online)} \text{ Radial distribution function [}\chi(R)\text{] vs. R spectra along with the theoretical fits for Ce}_{1-x}\text{Eu}_x\text{O}_2 \text{ (x=0.0 - 0.3) NPs.} \]
The third and the fourth peaks contain single and multiple scattering contributions from a variety of paths, such as O–Ce–O, Ce–O–O–Ce, etc. Therefore, larger uncertainties in the third/fourth shell fitted parameters have been observed in the derived parameters 31. In the present study, we focussed on the fittings of Ce–O and Ce–Ce paths for undoped CeO$_2$ and Ce–O, Ce–Ce and Ce–Eu paths for Eu doped CeO$_2$ samples. The first peak in the Fig. 8 at ~ 1.65 Å is assigned to the Ce–O shell and the second peak ~ 3.58 Å is assigned to the Ce–Ce shell of CeO$_2$ compound. The third Ce–O shell seems to overlap with the second Ce–Ce or Ce–Eu shell and is consistent to the previous reports because of the closer radial distribution functions of these two shells 24, 31. It is clear from the Fig. 8 that CeO$_2$ theoretical structure was fairly generated for all of the samples and nullify the peaks from the Eu-oxide or metallic Eu/Ce, indicating the single phase formation of Eu-doped CeO$_2$ NPs in the present study and supporting the XRD results. It is noticeable from the table 1 that O coordination number and bond distance are decreased in the whole range of Eu doping. In general, the oxygen coordination is high (8) in the bulk CeO$_2$ 31 because of octahedral environment (O$_h$) of oxygen atoms within the ceria lattice. In the present case, the oxygen coordination number is found to lower, even, in the pure CeO$_2$ NPs. This may be due the fact that larger number of atoms reside on the surface of nano-dimensional samples and $V_{a}^{-}$ are generated in the small and/or doped oxide NPs 13, 25. It is also observed that bond length of Ce–Ce shell is enlarged with 10 mol% Eu doping and then slightly decreased for the higher Eu doping. This indicates that at the lower Eu doping the Eu$^{3+}$ ions are expected to replace the Ce$^{4+}$ ions (ionic radii of Eu$^{3+}$ > Ce$^{4+}$) in the CeO$_2$ lattice resulting an enlargement in Ce–Ce shell via formation of Ce$^{4+}$–O–Eu$^{3+}$ networks. Further increase in the Eu$^{3+}$ doping may lead to formation of Ce$^{3+}$–O–Eu$^{3+}$ networks (ionic radii of Eu$^{3+}$ > Ce$^{3+}$) along with the Ce$^{4+}$–O–Eu$^{3+}$ networks. Thus, the existence of both networks may affect the Ce–Ce shell at the higher Eu doping.

<table>
<thead>
<tr>
<th>Sample name</th>
<th>Shell</th>
<th>R</th>
<th>CN</th>
<th>DW factor</th>
<th>$\Delta E$ (eV)</th>
<th>r-factro</th>
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<tr>
<td>CeO$_2$</td>
<td>Ce–O</td>
<td>2.33(77)</td>
<td>7.8</td>
<td>0.008(2)</td>
<td>-4.9</td>
<td>0.075</td>
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<tr>
<td></td>
<td>Ce–Ce</td>
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<td>11.8</td>
<td>0.007(3)</td>
<td>-1.3</td>
<td>0.075</td>
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<td>Ce$<em>{0.9}$Eu$</em>{0.1}$O$_2$</td>
<td>Ce–O</td>
<td>2.29(10)</td>
<td>6.5</td>
<td>0.005(6)</td>
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<td>3.1</td>
<td>0.019(1)</td>
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<td>Ce–Ce</td>
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<td>7.3</td>
<td>0.005(1)</td>
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<td>0.321</td>
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<tr>
<td>Ce$<em>{0.9}$Eu$</em>{0.2}$O$_2$</td>
<td>Ce–O</td>
<td>2.28(38)</td>
<td>6.4</td>
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<td>Ce–Eu</td>
<td>3.81(46)</td>
<td>3.6</td>
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<td>3.84(53)</td>
<td>7.1</td>
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**Table 1.** Structural parameters obtained from the Ce K-edge EXAFS fittings (bond distance (R), coordination number (N), Debye-Waller (DW) factor, edge-energy correlation ($\Delta E$) and r-factor).

**UV-visible absorption spectroscopy study**

UV-visible absorption spectroscopy is known to probe size-confinement effects in the NPs and provides information on defect sites in the materials 13, 16. Therefore, in order to understand the grain-size variation and doping effects on the optical absorption and band gap of the as-synthesized samples, systematic UV-visible absorption spectroscopy measurements were conducted on Ce$_{1-x}$Eu$_x$O$_2$ (x = 0.0 to 0.3) NPs and the results are shown in the Fig. 9. It is noticeable from the spectra that the absorption edge shows variations with the Eu doping. The band gap energy was calculated by plotting the (ahu)$^2$ versus photon energy (hv) for each sample, as shown in the inset of the Fig. 9. The intersection of the extrapolated liner portions gives the direct band gap energy$^{13, 16}$. Thus calculated band gap energy of Ce$_{1-x}$Eu$_x$O$_2$ (x = 0.0 to 0.3) NPs is 2.98 eV, 3.63 eV, 3.52 eV and 3.46 eV, respectively, and presented in the Fig. 6. It is evidenced from the Fig.6 that the 10 mol% Eu doping not only enhanced the band gap energy but also increased Ce$^{3+}$ concentration in the CeO$_2$ host. Particle size reduction was expected to increase the band gap energy. But, in contrary to this, we observed a marginal increase in the Ce$^{3+}$/Ce$^{4+}$/Ce$^{3+}$ ratio and little decrease in the band gap energy in the higher Eu content doped CeO$_2$ NPs samples. The increase in the band gap energy and blue shift in the absorption edge arise not only by the particle size reduction but also due to the reduction of the valence state of Ce$^{4+}$ ions into Ce$^{3+}$ ions 32. The net reduction of Ce$^{4+}$ into Ce$^{3+}$ ions increases the charge transfer gap between the 2P and Ce 4f bands and results in the blue shift in the absorption spectrum of CeO$_2$ NPs 13, 32. At low doping concentration (10 mol%) most of the Eu$^{3+}$ dopant are expected to replace the Ce$^{4+}$ ions in the CeO$_2$ lattice via formation of Ce$^{4+}$–O–Eu$^{3+}$ networks which gives a plenty of O vacancies and thus more Ce$^{3+}$ ions in the CeO$_2$ host. With increasing the Eu contents some of the Ce$^{3+}$ sites can be occupied by Eu$^{3+}$ ions and the formation of, both, Ce$^{4+}$–O–Eu$^{3+}$ and Ce$^{3+}$–O–Eu$^{3+}$ networks may lower the band gap energy, by narrowing the charge-transfer gap between O 2p and Ce 4f bands, and also resulting in marginal increase in Ce$^{3+}$/Ce$^{4+}$/Ce$^{3+}$ ratio. Hence, our UV-visible absorption spectra helps us to understand that the particle size reduction is not only the factor to engineer the optical band gap but the Eu doping induced structural/electronic structure perturbations also play an important role.

**Figure 9.** (Colour online) UV-visible absorption spectra of Ce$_{1-x}$Eu$_x$O$_2$ (x=0.0-0.3) NPs. Inset shows the band gap energy determination by plotting the (ahu)$^2$ versus photon energy (hv) curves for each sample.
Photoluminescence study

To probe the luminescence property of as synthesized samples, excitation and emission spectra of Ce$_{1-x}$Eu$_x$O$_2$ (x = 0.0 to 0.3) NPs were recorded. The excitation spectra are collected by measuring the emission intensity at a fixed wavelength (615 nm). It is visible from the Fig.10 (a) that pure CeO$_2$ does not exhibit any excitation peak throughout the wavelength range escape of one band at 309 nm; whereas, the Ce$_{1-x}$Eu$_x$O$_2$ (x = 0.1 to 0.3) NPs have shown three major spectral features at 393 nm, 414 nm and 463 nm. In the previous reports, the CeO$_2$:Eu NPs have shown a broad band between 300 – 350 nm which originates from the charge transfer (CT) transitions between O$^{2-}$ and Ce$^{4+}$ ions of the CeO$_2$ host. In the present case, the peak at 309 nm is not broaden enough; however, its position lies within the range of CT transitions of CeO$_2$ host. The sharp peaks at 393 nm, 414 nm and 463 nm can be assigned to the intra-configurational 4f-4f transition of Eu$^{3+}$ in the CeO$_2$ lattice: $^7F_0$ to $^5I_{6}$, $^5D_0$ and $^7D_4$, etc. In the excitation spectra, the dominant excitation peak is at 463 nm which is corresponding to $^7F_0$ – $^5D_2$ transition. This peak position fairly matches with the emission of commercial GaN light emitting diodes (440-470 nm) chips. Further, the appearance of 463 nm peak in the present excitation spectra is quite different from the other Eu$^{3+}$ activated molybdates and tungstates samples which exhibit the strongest excitation line at 395 nm in the near-UV-region. It is also noticeable from the Fig. 10 (a) that the intensity of peaks at 393 nm, 414 nm and 463 nm increases with increasing the Eu concentration, while excited with blue light, indicating that the red phosphor materials having similar optical properties to that of commercial GaN light emitting diodes can be synthesized using the chemical precipitation method with varying Eu concentrations.

Fig. 10 (b) presents the emission spectra of Ce$_{1-x}$Eu$_x$O$_2$ (x = 0.0 to 0.3) NPs collected under the excitation wavelength of 466 nm. It is visible from the emission spectra that the pure CeO$_2$ does not exhibit any emission peak under the excitation of 466 nm light wavelength; whereas the Ce$_{1-x}$Eu$_x$O$_2$ (x = 0.1 to 0.3) NPs exhibit several emission peaks between orange-to-red region of the solar spectrum (at 593 nm, 617 nm, 628 nm, 654 nm and 702 nm). The multiple emission peaks in the present spectra are due to the splitting of Eu$^{3+}$ 4f shells and mainly originate from the combination of magnetic dipole (MD) and electric dipole (ED) transitions. The MD and ED transitions are very specific to the environment of Eu$^{3+}$ ions in the host material. The MD transition ($^5D_0$ – $^7F_3$, around 590 – 600 nm) usually dominates when the Eu$^{3+}$ ions occupy the lattice sites with inversion centers. However, if the Eu$^{3+}$ ions are located in the sites of without centro-symmetry, the ED transition ($^5D_0$ – $^7F_2$, around the 610-630 nm) plays a crucial role. In the present emission spectra the peak at 593 nm is assigned to MD ($^5D_0$ – $^7F_3$) transition and the peaks at 617 nm, 628 nm are due to ED ($^5D_0$ – $^7F_2$) transitions and rest of the peaks are due to the upper splitting transitions of Eu 4f shells. Our XRD results have confirmed the single phase formation of CeO$_2$ NPs with space group of Fm3m; within the CeO$_2$ lattice the point-group symmetry of Ce sites is ideally O$_h$ i.e., every Ce ion is surrounded by eight equatorial oxygen ions.

When Eu substitutes the Ce in CeO$_2$ lattice the O$_h$ symmetry can be either improved or lowered, depending on the site occupancy of Eu$^{3+}$ ions. Since the Ce can exist in Ce$^{4+}$ and Ce$^{3+}$ ionic states in CeO$_2$ NPs, doping of Eu$^{3+}$ ions may form Ce$^{4+}$ – O – Eu$^{3+}$ or Ce$^{3+}$ – O – Eu$^{3+}$ networks. It is also known that the size of Eu$^{3+}$ ions is larger than that of Ce$^{4+}$ ions and comparable to that of Ce$^{3+}$ ions, which gives lower symmetric Ce$^{4+}$ – O – Eu$^{3+}$ and higher symmetric of Eu$^{3+}$ – O – Ce$^{3+}$ networks in the Eu doped CeO$_2$ NPs.

![Fig. 10. (Colour online) (a) Excitation spectra of Ce$_{1-x}$Eu$_x$O$_2$ (x = 0.0-0.3) NPs for the emission wavelength of 615 nm. (b) Emission spectra of Ce$_{1-x}$Eu$_x$O$_2$ (x = 0.0-0.3) NPs excited with wavelength of 466 nm.](image)

![Fig. 11. Intensity ratio of $^5D_0$ – $^7F_3$ and $^5D_0$ – $^7F_2$ transitions as a function of Eu concentration.](image)
In the present case the MD and ED transitions (peaks at 593 nm and 617 nm, respectively) were appeared within the lowest doping concentration of Eu, indicating the fruition of PL properties in the host CeO$_2$ without losing the FCC lattice. Similar to the previous reports on the PL properties of other trivalent dopants (i.e., Dy$^{3+}$ and Sm$^{3+}$) in CeO$_2$ systems, the intensity of all the emission peaks, in the present study, also improved with increasing the Eu concentration. The apparent changes in the emission spectra are the enhancement in the intensity of MD and ED transitions and evolution of 628 nm peak, after the 20 mol.% Eu doping. It is known that, the intensity ratio of $\Gamma (D_0^- \rightarrow F_2^-)$ and $\Gamma (D_0^- \rightarrow F_1)$ transitions is called asymmetry ratio of the lattice and signifies the degree of distortion from the inversion symmetry of CeO$_2$. Fig. 11 shows that $\Gamma (D_0^- \rightarrow F_2^-)/\Gamma (D_0^- \rightarrow F_1)$ ratio increases for Ce$_{1-x}$Eu$_x$O$_2$ (x = 0.0 to 0.3) NPs, with increasing the Eu concentration, indicating that the Eu$^{3+}$ ions mainly occupy those lattice sites (i.e., Ce$^{3+}$ sites) which can reduce the O$_h$ inversion symmetry of CeO$_2$ cell. Furthermore, noticeable increase in the MD transition has also been observed in the emission spectra with increasing the Eu concentration. This indicates that Eu$^{3+}$ ions not only substitute the Ce$^{4+}$ ions but also occupy the Ce$^{3+}$ sites in the oxygen deficient CeO$_2$ lattice. Our O K-edge, Ce M$_{4,5}$-edge and Ce K-edge XANES spectra have shown a net reduction of Ce$^{4+}$ into Ce$^{3+}$ with increase in the Eu concentration. However, the increase of Ce$^{3+}$ is prominent in the 10 mol% Eu doped CeO$_2$ and then marginally increase for the higher Eu content doped samples. This could be possible if a fraction of Eu$^{3+}$ ions occupy the Ce$^{3+}$ sites (i.e., formation of Ce$^{3+}$ – O – Eu$^{3+}$ networks) in case of the higher Eu concentration doped CeO$_2$ samples which favours MD transition induced PL properties along with ED transitions.

Photocatalyst study

Photocatalytic performances of the Ce$_{1-x}$Eu$_x$O$_2$ NPs were investigated by the degradation of MO aqueous solution under the UV light irradiation. Fig. 12 (a–e) show UV-visible spectra of MO aqueous solution, taken at different time intervals, in the absence and presence of catalyst samples. It is visible from the Fig. 12 (a) that the MO aqueous solution was hardly degraded, under the similar experimental conditions, when no catalyst was employed with the dye solution. When MO dye solutions were subjected to the as-synthesized Ce$_{1-x}$Eu$_x$O$_2$ NPs, under the light irradiation, the dye was degraded to different extents by each of the samples indicating specific photocatalytic properties of individual sample. The characteristic absorption peak of MO, at ~464 nm, was monitored to evaluate the photocatalyst performance of the samples. Fig. 13 shows the C$/$C$_0$ ratio of the catalyst samples, where C$_0$ is the initial intensity of absorption peak, recorded in the dark, and C is the intensity of same absorption peak at the different time of light irradiation. It is noticeable from the Fig. 13 that catalyst performance enhances with increasing the Eu concentration. It has been reported that the catalyst properties of the catalyst materials depends on their size, morphology and electronic structure properties. In the present case, we could not observe any special morphology (i.e., rod, wire or other fascinating structures) in the TEM results escape of some spherical NPs in all of the samples. Therefore, the observed variations in the catalyst performance are expected to relate with the structural and electronic structural perturbations caused by the Eu doping in the CeO$_2$ lattice. 

An elemental insertion of Eu in the CeO$_2$ lattice may advance the electron density of the compound by altering the valance state of cations and oxygen concentration and this is evidenced by the O K-edge, Ce M$_{4,5}$-edge and Ce K-edge XANES results in the present study. The large number of photo generated e$^-$ – h$^+$ pairs are also essential to establish the oxidation-reduction reactions for degrading the azo dye. In the present case, although the energy band gap was found to increase in the Eu doped NPs, the energy of photons, provided by the mercury light source, is quite enough to generate large number of e$^-$ – h$^+$ pairs from the electronic density advanced Ce$_{1-x}$Eu$_x$O$_2$ (x = 0.0 – 0.3) NPs. It is also inferred from the PL measurements that the enhanced electronic transition (excitation and de-excitation) takes place in the Eu doped samples which resulted in the excellent PL properties. Therefore, in the present photocatalyst study the Eu doping induced advance electronic density is expected to enhance the photocatalytic performance of higher Eu content doped CeO$_2$ NPs. Further, XRD results have shown a little size reduction for the Eu doped NPs. The smaller size provides larger surface area to the adsorption reactions of MO dye on to the NPs surface, and higher migration rates of photo-generated charge carriers, towards the surface, have also been observed in the case of smaller sized NPs. Photocatalytic activity of the luminescent NPs is presented in the schematic diagram (see Fig. 14). Here we expect that significant adsorption reactions have been taken
place on the small sized NPs (6.25 nm – 4.15 nm) and photo-generated $e^- - h^+$ pairs provide effective pathways for the oxidation (from the holes) and reduction (from the electrons) reactions to degrade the MO dye molecules. The photoelectrons scavenge the molecular oxygen and produce hydrogen-peroxide molecules in the aqueous medium\textsuperscript{18,36} by the following reactions;

\[(hv > E_g) + \text{Catalyst material} \rightarrow e^-_{CB} + h^+_{VB} \quad (1)\]

\[n e^-_{CB} + nO_2 \rightarrow n(O_2^-) \quad (2)\]

\[n e^-_{CB} + nO_2 + nH_2O \rightarrow H_2O_2 \quad (3)\]

On the other hand, the holes generate hydroxyl radicals from the water \textsuperscript{18,34}. The hydroxyl radicals work as a powerful oxidizing agent and degrade most of the pollutant dyes \textsuperscript{18,34,36} by the following reactions;

\[H_2O + (h^+) \rightarrow \cdot OH + H^+ \quad (4)\]

\[MO + OH \rightarrow CO_2 + H_2O \quad (5)\]

\[MO + O_2^- \rightarrow CO_2 + H_2O \quad (6)\]

Therefore, the vigorous adsorption and redox reactions from the electronic structurally advanced Eu doped CeO$_2$ NPs are responsible for high catalyst performance of doped NPs.

\[\text{Fig. 13. (Colour online) Photocatalytic performance of catalyst samples by monitoring the absorbance of the 464 nm peak for degradation of MO at different time intervals of light irradiation.}\]

\[\text{Fig. 14. (Colour online) Schematic of the generation of electron–hole pairs and the degradation of MO pollutant dye, via oxidation and reduction reactions.}\]

\[\text{Conclusions}\]

Pure and Eu doped (up to 30 mol.%) CeO$_2$ NPs were synthesized using the chemical precipitation method. XRD and TEM results have shown formation of small (6.2 nm – 4.1 nm) sized and single phase NPs. Eu M$_{5,4}$-edge and Eu L-edge XANES results have confirmed the existence of Eu$^{3+}$ ions in the CeO$_2$ lattice within the entire doping range. Analysis of the O K-edge spectra, Ce M$_5$-edge spectra and Ce K-edge spectra show that Ce$^{4+}$ ions reduce to Ce$^{3+}$ ions via substitutional doping of Eu$^{3+}$ ions in CeO$_2$ lattice. The substitutional doping of Eu in the CeO$_2$ lattice reduces the local $O_h$ symmetry via creating oxygen vacancies/Ce$^{3+}$ ions and thus favors the ED transitions ($^5D_0 - ^7F_2$) induced optical emission in the CeO$_2$. At higher Eu doping the Ce$^{3+} - O - Eu^{3+}$ networks also form along with Ce$^{4+} - O - Eu^{3+}$ networks and fertilize the MD ($^5D_0 - ^7F_1$) and ED transitions induced PL properties in the samples. Furthermore, enhanced photocatalytic performance of NPs indicates that Eu doping induced modified electronic structure of CeO$_2$ can offer its applicability in the photocatalyst applications.

\[\text{Acknowledgements}\]

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Notes and references