CHEMISTRY AND CHEMICAL ENGINEERING

Volume 2026 | Number 1 Article 1

March 2026

STRUCTURE AND MORPHOLOGY OF ULTRADISPERSED ERBIUM YTTERBIUM OXIDE POWDERS OBTAINED BY DEPOSITION METHOD

Eygeniy N. PODDENEZHNY
State Technical University of Gomel, Gomel, Belarus, podd-evgen@yandex.ru

Andrei A. BOIKO
State Technical University of Gomel, Gomel, Belarus, boiko@gstu.by

Natalya E. Drobyshevskaya
State Technical University of Gomel, Gomel, Belarus, podden@gstu.by

Vladimir S. Urbanovich
State association «Scientific and Practical Center for Materials of National Academy of Sciences of Belarus», Minsk, Belarus, urban@physics.by

Ekaterina E. TRUSOVA
Belarusian State Technological University, Minsk, Belarus, trusova@belstu.by

Recommended Citation
PODDENEZHNY, Eygeniy N.; BOIKO, Andrei A.; Drobyshevskaya, Natalya E.; Urbanovich, Vladimir S.; and TRUSOVA, Ekaterina E. (2026) "STRUCTURE AND MORPHOLOGY OF ULTRADISPERSED ERBIUM YTTERBIUM OXIDE POWDERS OBTAINED BY DEPOSITION METHOD," *CHEMISTRY AND CHEMICAL ENGINEERING*: Vol. 2026: No. 1, Article 1.
DOI: https://doi.org/10.70189/1992-9498.1712
Available at: https://cce.researchcommons.org/journal/vol2026/iss1/1

STRUCTURE AND MORPHOLOGY OF ULTRADISPERSED ERBIUM YTTERBIUM OXIDE POWDERS OBTAINED BY DEPOSITION METHOD

Cover Page Footnote

The research was conducted as part of Task 2.8 of the State Program for Scientific Research «Materials Science, New Materials Technologies2 for 2021–2025 in the Republic of Belarus

STRUCTURE AND MORPHOLOGY OF ULTRADISPERSED ERBIUM YTTERBIUM OXIDE POWDERS OBTAINED BY DEPOSITION METHOD

Evgeniy N. PODDENEZHNY[1] (podd-evgen@yandex.ru
Andrej A.BOIKO[1] (boiko@gstu.by)
Natalya E. DROBYSHEVSKAYA[1] (podden@gstu.by)
Vladimir S. URBANOVICH[2] (urban@physics.by)
Ekaterina E. TRUSOVA[3] (trusova@belstu.by)
[1]State Technical University of Gomel, Gomel, Belarus
[2]State association «Scientific and Practical Center for Materials of National Academy of Sciences of Belarus», Minsk, Belarus
[3]Belarusian State Technological University, Minsk, Belarus

The aim of research is to develop a new method for synthesis of ultra-dispersed crystalline powders of lanthanide oxides, in particular, erbium oxide doped with ytterbium oxide, intended for making transparent ceramics. The formation of nanostructured powders of the erbium oxide – ytterbium oxide system using deposition and heat treatment processes by co-deposition of salt solutions mixed with ammonium carbonate and hydrogen peroxide complex solution at temperature of 10 °C followed annealing at 100, 650, 900 and 1200 °C was studied. Studies of the morphological and structural characteristics of the powders using scanning electron microscopy and X-ray phase analysis showed that the Er_2O_5–Yb_2O_3 particles are great extent agglomerated, they have a laminar, plate-like morphology with the laminate thickness of about 50 nm, length of 10–15 μm (650 °C), when sediment is annealed at 900 °C, laminar particles split into 30–60 nm diameter fibers, and during subsequent heating the fibers in agglomerates fuse together forming a mesh structure, the size of the annealed particles being 150–200 nm.

Keywords: rare earth elements oxides, erbium oxide, ytterbium oxide, ultrafine powders, deposition method

СТРУКТУРА И МОРФОЛОГИЯ УЛЬТРАДИСПЕРСНЫХ ПОРОШКОВ ОКСИДА ЭРБИЯ – ИТТЕРБИЯ, ПОЛУЧАЕМЫХ МЕТОДОМ ОСАЖДЕНИЯ

Евгений Н. ПОДДЕНЕЖНЫЙ[1] (podd-evgen@yandex.ru)
Андрей А. БОЙКО[1] (boiko@gstu.by)
Наталья Е. ДРОБЫШЕВСКАЯ[1] (podden@gstu.by)
Владимир С. УРБАНОВИЧ[2] (urban@physics.by)
Екатерина Е. ТРУСОВА[3] (trusova@belstu.by)
[1]Гомельский государственный технический университет, Гомель, Беларусь
[2]Государственное научно-производственное объединение «Научно-практический центр Национальной академии наук Беларуси по материаловедению», Минск, Беларусь
[3]Белорусский государственный технологический университет, Минск, Беларусь

Цель исследования состоит в разработке нового метода синтеза ультрадисперсных кристаллических порошков оксидов лантаноидов, в частности оксида эрбия Er_2O_3, легированного оксидом иттербия Yb_2O_3, предназначенных для формования прозрачной керамики. Изучены особенности формирования наноструктурированных порошков системы «оксид эрбия – оксид иттербия» из смешанных карбонатов лантаноидов путем осаждения карбонатом аммония с добавкой перекиси водорода из соответствующих азотнокислых солей при температуре 10 °С с последующим прокаливанием осадков при 100, 650, 900, 1200 °С. Исследования морфологических и структурных характеристик порошков с применением методов сканирующей электронной микроскопии и рентгенофазового анализа показали, что частицы Er_2O_5–Yb_2O_3 в значительной степени агломерированы, имеют пластинчатую морфологию с толщиной ламинатов около 50 нм и длиной 10–15 мкм (650 °С), а при прокаливании осадка при 900 °С пластины расщепляются на волокна диаметром 30–60 нм; при нагревании до 1200 °С волокна в агломератах образуют сетчатую структуру с размерами спекшихся частиц 150–200 нм.

Ключевые слова: оксиды редкоземельных элементов, оксид эрбия, оксид иттербия, ультрадисперсные порошки, метод соосаждения

ULTRADISPERSLANGAN ERBIY-YTERBIY OKSIDI KUKUNLARINING TUZILISHI VA MORFOLOGIYASI

Evgeniy N. PODDENZHNY[1] (podd-evgen@yandex.ru)
Andrey A. BOYKO[1] (boiko@gstu.by)
Natalya E. DROBYSHEVSKAYA[1] (podden@gstu.by)
Vladimir S. URBANOVICH[2] (urban@physics.by)
Ekaterina E. TRUSOVA[3] (trusova@belstu.by)
[1]Gomel davlat texnika universiteti, Gomel, Belarus
[2]"Belarus Milliy fanlar akademiyasining materialshunoslik ilmiy-amaliy markazi" davlat ilmiy-ishlab chiqarish birlashmasi, Minsk, Belarus
[3]Belarus davlat texnologiya universiteti, Minsk, Belarus

Tadqiqotning maqsadi shaffof keramikaga shakl berishga mo'ljallangan lantanoidlar oksidlari, xususan, ytterbiy oksidi Yb_2O_3 bilan legirlangan erbiy oksidi Er_2O_3 ning ultradispers kristall kukunlarini sintez qilishning yangi usulini ishlab chiqishdan iborat. Lantanoidlarning aralash karbonatlaridan 10 °C haroratda tegishli nitrat kislota tuzlaridan vodorod peroksid qo'shib ammoniy karbonat bilan cho'ktirish va cho'kmalarni 100, 650, 900, 1200 °C da qizdirish orqali "erbiy oksidi - ytterbiy oksidi" tizimining nanotuzilishli kukunlarini shakllantirish xususiyatlari o'rganildi. Kukunlarning morfologik va strukturaviy xususiyatlarini skanerlovchi elektron mikroskopiya va rentgen fazali tahlil usullari yordamida o'rganish shuni ko'rsatdiki, Er_2O_5-Yb_2O_3 zarralari sezilarli darajada aglomeratsiyalangan, laminatlarning qalinligi taxminan 50 nm va uzunligi 10-15 mkm (650 °C) bo'lgan plastinka morfologiyasiga ega, cho'kma 900 °C da qizdirilganda plastinkalar diametri 30-60 nm bo'lgan tolalarga bo'linadi; 1200 °C gacha qizdirilganda, aglomeratlardagi tolalar 150-200 nm o'lchamdagi yopishgan zarrachalar bilan to'rli tuzilishni hosil qiladi.

Kalit so'zlar: noyob yer oksidlari, erbiy oksidi, ytterbiy oksidi, ultra mayda kukunlar, qo'shma cho'ktirish usuli

Introduction

Lanthanide oxide-based optically transparent ceramics doped with rare earth element ions is promising for use as active media for solid-state lasers, luminescent converters, scintillators thanks to high optical and thermomechanical characteristics [1–5].

Erbium oxide is a promising matrix for creating lasers and fiber optic amplifiers by doping active lanthanide ions due to excellent physical properties, such as optical transparency over a wide spectrum, high melting temperature (2380 ºC), wide band gap, high thermal conductivity [6–11].

To activate the sintering of rare earth oxide particles in the production of ceramics with high optical transparency, sintering additives in the form of yttrium, lanthanum, and zirconium oxides are used, introduced into the system during the formation of nanostructured powders [12–15]. In this way, transparent ceramics from erbium oxide Er_2O_3 with the addition of La_2O_3 were successfully produced [13]. Er_2O_3 ceramics with the addition of zirconium dioxide (4 at.% ZrO_2), sintered at a temperature of 1850°C for 8 hours in a vacuum [14], demonstrated an optical transmittance of 77% in the visible range and 78% at a wavelength of 1100 nm.

Similarly, highly transparent ytterbium oxide (Yb_2O_3) ceramics were obtained by vacuum sintering using ZrO_2 as a sintering additive [15]. Transparent ceramics doped with 3% ZrO_2 were found to have the best optical properties, with a transmittance of 75% at 1100 nm and about 81% in the mid-infrared region.

Recently, a new, rapidly developing field has emerged: the study and application of transparent, high-entropy optical media based on rare-earth oxides. Such materials are classified as ceramics, consisting of five or more components in equiatomic proportions [16, 17].

A new highly transparent ceramic based on rare earth oxides with the composition $(Lu_{0.2}Y_{0.2}Gd_{0.2}Yb_{0.2}Er_{0.2})_2O_3$ was successfully fabricated by vacuum sintering with the addition of 3 at.% ZrO_2 and 10 at.% La_2O_3 as sintering additives [18]. A single-phase cubic structure of the ceramics from a solid solution with a relative density of 99.95% and an average grain size of 6.91±3.28 μm was obtained. The grain boundary of the ceramics had a thickness of 1.3 nm. The linear transmittance of such ceramics reached 80% at a wavelength of 1100 nm, which was 98.7% of the theoretical value for an Er_2O_3 single crystal. In addition, fluorescence emission was observed in the ultraviolet (311 nm), visible (563, 622 nm), and near-infrared (1032, 1535 nm) spectral regions. The new high-entropy ceramics may have broad potential for use in optical applications, such as scintillators, high-conversion luminescent materials, and infrared lasers.

Nanocrystalline luminescent powders of rare earth oxides can be obtained by thermal decomposition of the corresponding salts [19, 20]. Er_2O_3 powders with crystal sizes of 9.7–27.2 nm were obtained in this way [19].

Nanosized Er^{3+}:Y_2O_3 powders with varying erbium impurity concentrations were synthesized by decomposing a mixture of erbium and yttrium nitrate salts in the presence of a surfactant that ensures particle deagglomeration, followed by calcination at 800 ° C [20]. The calculated particle sizes according to the Scherrer equation range from 20 ±3 to 32 ±3 nm.

There are also methods for obtaining REE oxide powders through thermochemical reactions (combustion method) [21, 22], however, the particles of such oxides are often highly agglomerated and contaminated with combustion reaction products.

Most of the known methods for producing nanosized powders co-doped REE are based on the processes of precipitation of carbonate or oxalate precursors from aqueous solutions of salts, separation of the precipitate from the mother liquor, washing, drying in air, and calcination at high temperatures [23, 24]. For the precipitation of hydrated REE compounds, including erbium oxide, salts, most often nitrates, are used as sources, and solutions of ammonia, oxalic acid, ammonium carbonate or ammonium bicarbonate are used as precipitants. Despite the obvious disadvantages of precipitation methods - labor intensity, large volumes of solvents used, this synthesis option ensures the production of low-agglomerated powders with a narrow size distribution of nanoparticles, as well as a high degree of purity [25].

The aim of the present research is to develop a new method for synthesis of ultra-dispersed crystalline powders of lanthanide oxides, in particular, Erbium oxide Er_2O_3 doped with Ytterbium oxide Yb_2O_3 - additive intended for making transparent ceramics with upconversion effect.

Research methods

Microcrystalline oxide powders Er_2O_3 and Yb_2O_3 a purity of 99.5% and 99.92% respectively; ammonium carbonate $(NH_4)_2CO_3$ and hydrogen peroxide (35% H_2O_2) were used as starting components.

Heated up to 90 ºC and mixed with a magnetic stirrer, the initial microcrystalline Er_2O_3 and Yb_2O_3 powders are dissolved in the concentrated nitric acid till complete dissolution. Then the sediment is dried in a loss-on-drying oven at 90 °C to remove free water and nitric acid. The initial nitrate salts are weighed out: $Er(NO_3)_3 \cdot 6H_2O$ – 8,0 g., $Yb(NO_3)_3 \cdot 6H_2O$ – 0,8 g. and $(NH_4)_2CO_3$ – 5,0 g.

Hydrated carbonate sediments are produced as follows.

Nitric acid salts are dissolved in the distilled water, then ammonium carbonate is dissolved in the distilled water, both solutions are simultaneously poured, H_2O_2 hydrogen peroxide 35 % is added till the pH of 10–12, the mixture being stirred with a magnetic mixer. In the glass sediment is formed, it is placed in the centrifuge, deposited at a speed of about 3000 r/min, then sediment is removed, washed 3 times with distilled water and recentrifuged, then placed in a 150 mL 107 mm-diameter porcelain evaporation bowl No.4 and evaporated in the loss-on-drying oven at the temperature of 100 °C for 7 hours.

The kinetics of the deposition reactions and crystallization conditions of mixed lanthanide carbonates in Er_2O_3–Yb_2O_3 dual system was examined by such methods as XRF, DTA, IR spectroscopy, SEM and energy dispersive X-ray analysis during the sedimentation and subsequent annealing at the temperature of 100, 650, 900, 1200°C.

Differential Thermal Analysis have been performed by NETZSCH STA 449F3 derivatograph (Germany). The heating range was up to 800°C.

SEM measurements have been performed by S-4800 «Hitachi» (Japan).

IR spectra were recorded using IR spectrometer Nexus Nicolet 5700 «Thermo Electron Corporation» (USA).

Results and Discussion

Based on the analysis of derivatograms of the dried sediment (Fig. 1) we conclude that the decomposition of hydrated sediment of Erbium and Ytterbium hydroxides mixture follows a probable pattern $Er–Yb(OH)\cdot yH_2O \rightarrow Er–Yb(OH)_3 \rightarrow (Er–Yb)_2O_3$. At 60 °C the hydrated oxides mixture recrystallizes, at 90 ºC free water is removed, then hydroxyl groups are removed, and at about 600 ºC mixed oxides are formed (exothermic effect), it being followed by slow removal of residual hydroxyl groups to the constant mass (loss of mass of 45%).

Based on the analysis of XRD data on the obtained powders [26] (Fig. 2) it can be concluded that the samples obtained at 650 °C show main diffraction peaks broadening effect, from which it follows that at this temperature the crystalline phase of cubic Erbium oxide has already been formed, the precursor particles are 18±2 nm in size, at annealing temperature of 900 °C the particle size increases to

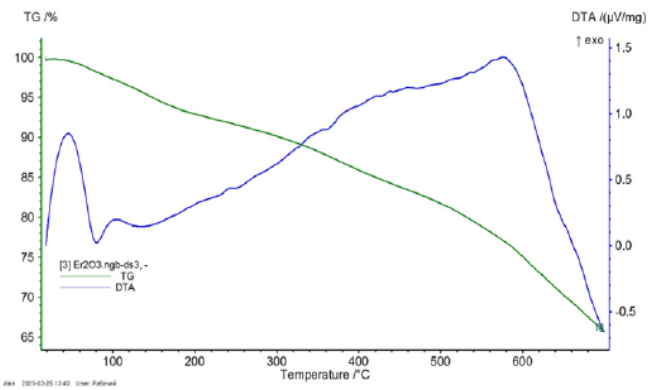

Figure 1. Derivatograms of the dried sediment.

27±2 nm, and at 1200 °C the particle size is within range of 30±2 nm. In all the cases, at the temperatures ranging from 650 to 1200 °C the powders have a cubic crystalline structure of Er_2O_3 chemical composition (JCPDF 77-0777).

Yb_2O_3 peaks in Er_2O_3 mixture in radiographs are almost indiscernible because these oxides have the same single-phase cubic structure, the difference in the peaks being only about 0.08 degrees (they almost coincide, the images must have very high resolution), Ia-3, Z=16 space group is also the same. Grid parameter a a=1,0435 (Yb_2O_3); a=1,0563 (Er_2O_3). The mixtures form solid solution, so elemental composition can be determined by EDX analysis.

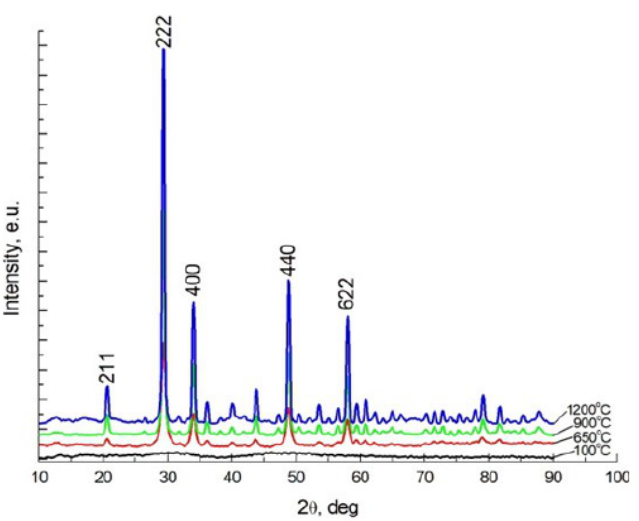

Figure 2. XRD data on the obtained powders Er_2O_3:Yb.

Table 1

Elemental composition of the obtained powders at 650 °C

Element	Atomic number	wt. %	wt. % (standardized)	Atomic %
Oxygen, O	8	14,13	15,88	55,77
Erbium, Er	68	65,91	74,09	24,89
Ytterbium, Yb	70	5,63	6,33	2,06
Carbon, C	6	3,29	3,70	17,29
Total content, %		88,96	100	100

Examination of the elemental composition of the obtained powders by energy dispersion microanalysis (EDX) that is used to determine local chemical composition of phases, showed presence of erbium, ytterbium and oxygen atoms in composition in the following ratio (Table 1).

Presence of carbon impurities in the powder annealed at 650 ºC is related to residual compounds formed during decomposition of Er/Yb $(OH)CO_3 \cdot yH_2O$ hydrated Erbium Ytterbium oxide compound, which is confirmed by IR spectroscopy and IR analysis; it significantly decreases during subsequent annealing: 3.29 (650 °C); 2.52 (900 ºC); 2.16 (1200 ºC) wt.%.

Based on analysis of SEM data for the obtained samples, it can be concluded that the powders produced after the heat treatment at 650 °C are to a great extent agglomerated, have a laminar, plate-like morphology with the laminate thickness of about 50 nm and its length of 10–15 μm (Fig 3). When the sediment is annealed at 900 °C, laminar particles split into fibres of 30–60 nm in diameter, and when fibres making up agglomerates are further annealed, they fuse forming a mesh structure, the size of the annealed particles being 150–200 nm (Fig. 4 and 5).

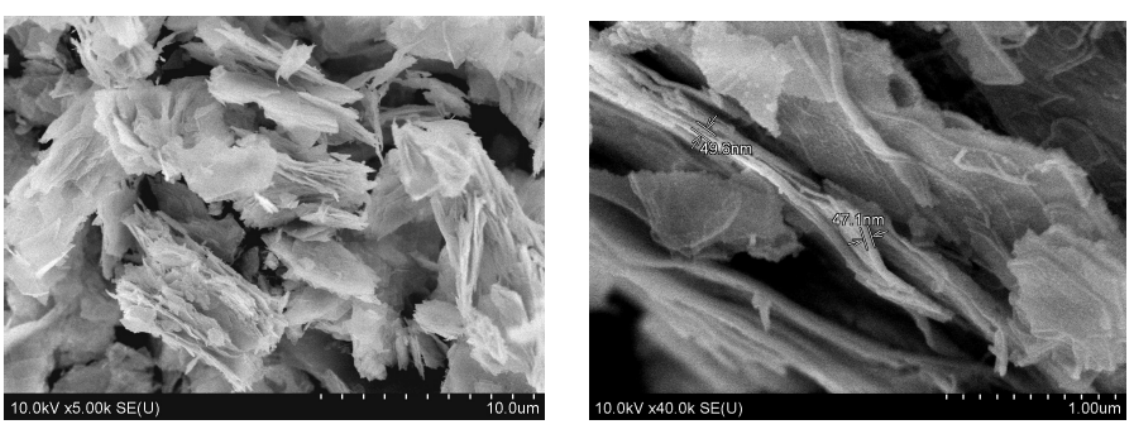

Figure 3. Morphology of Er_2O_3–Yb_2O_3 powders after the heat treatment at 650 ºC.

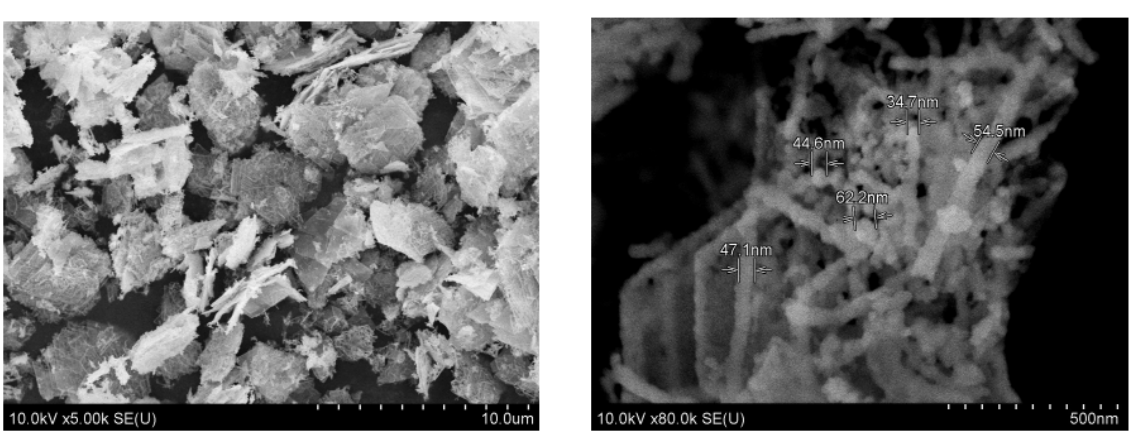

Figure 4. Morphology of Er_2O_3–Yb_2O_3 powders after the heat treatment at 900 °C.

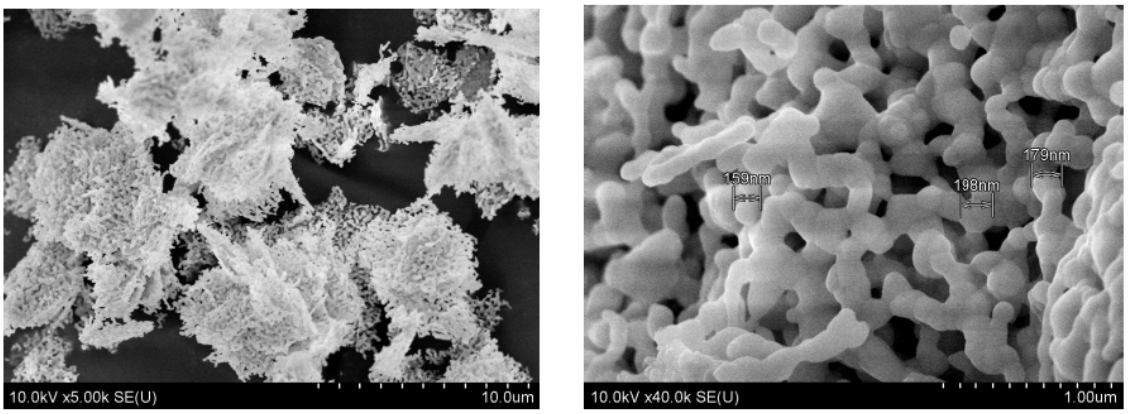

Figure 5. Morphology of Er_2O_3–Yb_2O_3 powders after the heat treatment at 1200 °C.

IR spectra curves for Er_2O_3–Yb_2O_3 powders at the temperatures of 100, 650, 900 and 1200 °C are shown in the Fig. 6. Based on examination of IR reflection curves received from the dried sediment samples annealed in the air atmosphere at 100, 650, 900 and 1200 °C, it can be concluded that CO_3^{2-} stretching vibrations appear as broad bands at 1580 (asymmetrical), 1390 and CO_3^{2-} out-of-plane deformation vibrations – at 848 cm^{-1} (for the annealing temperatures of 100, 650 and 900 °C) [27], their intensity decreasing as the heating temperature increases. Band at 563 cm^{-1} refers to Er–O bond vibrations. Band at 3600 cm^{-1} is most likely related to O-H groups vibrations, absorbed by Er_2O_3-$Yb_2O_3 \cdot x(OH^-)$ porous particles [28], however, it is significantly reduced at the annealing temperature of 1200 °C.

Based on the analysis of the IR spectra of the dried sediment we conclude that erbium-ytterbium carbohydrate decomposes according to the scheme $Er/Yb(OH)CO_3 \cdot yH_2O \rightarrow Er_2O_3$-$Yb_2O_3 \cdot x(OH^-) \rightarrow Er_2O_3$-$Yb_2O_3$, two intermediate compounds being formed [29, 30].

The reduced concentration of hydroxyl groups, adsorbed gaseous impurities and the residual carbon-containing impurities resulting from annealing at T=1200°C confirms the viability of the high temperature treatment at formation of dehydrated Er_2O_3–Yb_2O_3 samples.

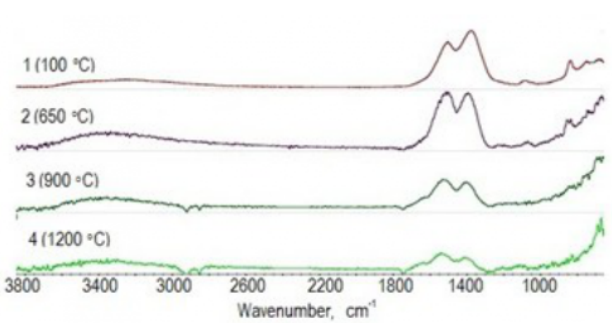

Figure 6. IR spectra curves for Er_2O_3–Yb_2O_3 powders at the temperatures of 100, 650, 900 and 1200 °C.

Conclusion

A new method has been developed to produce the ultra-dispersed powders of Er_2O_3–Yb_2O_3 system using deposition and heat treatment processes by co-deposition of salt solutions mixed with ammonium carbonate and hydrogen peroxide complex solution at low temperature.

It has been established that during drying and annealing at 100, 650, 900 and 1200°C in the air atmosphere, water is removed from sediment, further at the temperature of 650°C volatile organic pollutants that may have been contained in $(NH_4)_2CO_3$ are removed from the carbonates, and at the temperature of 900°C the carbonates decompose to hydrated erbium ytterbium oxide compound.

It is shown that the reduction of concentration of hydroxyl groups, adsorbed gaseous impurities and residual carbon-containing impurities as a result of annealing at T=1200°C confirms viability of high temperature treatment for forming dehydrated Er_2O_3–Yb_2O_3 samples.

The kinetics of the deposition reactions and crystallization conditions of mixed lanthanide carbonates in $Er/Yb(OH)CO_3xH_2O$ was examined by the methods of X-ray diffraction, DTA, IR spectroscopy, SEM and energy dispersive X-ray analysis. It has been established that Erbium-Ytterbium carbonate decomposes according to scheme

$$Er/Yb(OH)\,CO_3 \cdot xH_2O \rightarrow Yb_2O_3–Yb_2O_3 \cdot x(OH\text{-}) \rightarrow Er_2O_3–Yb_2O_3.$$

The powders obtained after the heat treatment at 650 °C have been found to be to a great extent agglomerated, they have a laminar, plate-like morphology with the laminate thickness of about 50 nm, length of 10–15 μm, when sediment

is annealed at 900 °C, laminar particles split into 30–60 nm diameter fibers, and during subsequent heating the fibers in agglomerates fuse together forming a mesh structure, the size of the annealed particles being 150–200 nm.

Acknowledgments

The research was conducted as part of Task 2.8 of the State Program for Scientific Research «Materials Science, New Materials Technologies2 for 2021–2025 in the Republic of Belarus.

REFERENCES

1. Xiao Z., Yu S., Li Y., Ruan S., Kong L. B., Huang Q., Huang Z., Zhou K., Su H., Yao Z., Que W., Liu Y., Zhang T., Wang J., Liu P., Shen D., Allix M., Zhang J., Tang D. Materials development and potential applications of transparent ceramics. *Materials Science & Engineering R.*, 2020, 139, 1–6. DOI: 10.1016/j.mser.2019.100518
2. Kong L. B., Huang Y., Que W., Zhang T., Li S., Zhili D., Tang D. Transparent Ceramics. *Springer International Publishing Switzterland*, 2015. 734. DOI: 10.1007/978-3-319-18956-7
3. Snetkov I.L., Yakovlev A.I., Permin D.A., Balabanov S.S., Palashov O.V., Magneto-optical Faraday effect in dysprosium oxide (Dy_2O_3) based ceramics obtained by vacuum sintering. *Opt. Lett.*, 2018, 43, 4041–4044. DOI: 10.1364/ol.43.004041
4. Yavetskiy R.P., Vovk E.A., Kosmyna M.B., Sergienko Z.P., Tolmachev A.V., Puzikov V.M., Nazarenko B.P., Shekhovtsov A.N. Lu_2O_3:Eu^{3+}. Ultradispersed Powders and Translucent Ceramics. *In book: Ceramic Materials and Components for Energy and Environmental Applications*, 2010, 597–603. DOI: 10.1002/9780470640845.ch855
5. Yin D., Wang J., Wang Y. Fabrication of Er:Y_2O_3 transparent ceramics for 2.7 μm mid-infrared solid-state lasers. *Journal of the European Ceramic Society*, 2020, 40(2), 444–448. DOI: 10.1016/j.jeurceramsoc.2019.09.051
6. Guo Q., Zhao Y., Jiang C., Mao W. L., Wang Z., Zhang J., and Wang Y. Pressure-Induced Cubic to Monoclinic Phase Transformation in Erbium Sesquioxide Er_2O_3. *Inorganic chemistry*, 2007, 46(15), 6164–6169. DOI:10.1021/ic070154g
7. Urbanovich V.S., Leonchik S.V., Jivulko V.D., Shloma E.N., Grigorev S.V., Poddenejnii E.N., Lavish E.O., Niss V.S. Poluchenie keramiki na osnove oksidov erbiya i itterbiya spekaniem pod visokim davleniem [Production of ceramics based on erbium and ytterbium oxides by sintering under high pressure]. *Vestmik GGTU im. P. O. Suhogo*, 2023, 4, 61–69.
8. Abdusalamova M.N., Kabov H.B., Sharapov F.S., Shulga Y.M. Sostav i magnitnie svoistva nanostrukturirovannih oksidov erbiya [Composition and magnetic properties of nanostructured erbium oxides]. *Jurnal po alternativnoy energii i ekologii,* 2012, 112(8), 66–70.
9. Wang L., Lu B., Liu X., Shi Y., Li J., Liu Y. Fabrication and upconversion luminescence of novel transparent Er_2O_3 ceramics. *Journal of the European Ceramic Society*, 2020, 40/4, 1767–1772. DOI: 10.1016/j.jeurceramsoc.2019.11.048
10. Azad F., Maqsood A. Fabrication, Structural Characterization, Dielectric and Electrical Parameters of the Synthesized Nano-Crystalline Erbium Oxide. *Electron. Mater. Lett.,* 2014, 10(3), 557–563. DOI:10.1007/s13391-013-3195-y
11. Ratzker B., Wagner A., Kalabukhov S., Frage N. Transparent Er_2O_3 ceramics fabricated by high-pressure spark plasma sintering. *Journal of the European Ceramic ceramics*, 2020, 40(13), 4700–4703. DOI: 10.1016/j.jeurceramsoc.2020.05.056
12. Balabanov S.S, Bykov Y.V., Egorov S.V., Eremeev A.G., Gavrishchuk E.M, Khazanov E.A., Mukhin I.B., Palashov O.V., Permin D.A., Zelenogorsky V.V. Transparent Yb:$(YLa)_2O_3$ ceramics produced by self-propagating high-temperature synthesis and microwave sintering. *Opt. Mater.,* 2013, 35(4), 727–730. DOI: 10.1016/j.optmat.2012.09.010
13. Balabanov S., Ivanov M., Filofeev S., Kaigorodov A., Krugovykh A., Kuznetsov D., Permin D., Popov P., Rostokina E. Fabrication and Fabrication and characterizations of erbium oxide based optical ceramics. *Optical Materials,* 2020, 101, 109732. DOI: 10.1016/j.optmat.2020.109732
14. Linlin Zhu, Hong-lan Liu, Hua-Tay Lin, Xing-hao Tan, Jiahao Chen, Baoyu Gao,uang-Xiang Zhang, Yu-Jian Jian, Min-Min Dai, Cheng-Cai Zhao. Effects of ZrO_2 concentration on the properties of pressureless-sintered highly transparent Er_2O_3 ceramics, *Ceramics International*, 2023, 49(23), 39076–39082. DOI: 10.1016/j.ceramint.2023.09.245
15. Zhou Cong, Xiu Ling Wang, Libo Liang. Vacuum sintering of Yb_2O_3 transparent ceramics: Effect of ZrO_2 concentration on structural and optical properties. *Journal of Alloys and Compounds,* 2022, 907, 164454. DOI: 10.1016/j.jallcom.2022.164454
16. Kuo-Pin Tseng, Qun Yang, Scott James Mccormack. High entropy, phase constrained, lanthanide sesquioxide. *Journal of the American Ceramic Society*, 2019. 103(1). DOI:10.1111/jace.16689
17. Shin Y-B, Ham S B, Kim H-N. Novel transparent high-entropy sesquioxide ceramics with high phisico-chemical plasma eaching resistance. *J. Adv. Ceram.,* 2025, 14(1), 9221013. DOI: 10.26599/JAC.2024.9221013
18. Lin-Lin Zhu, Wei-Ming Guo, Hua-Tay Lin. Fabrication and luminescent properties of highly transparent novel high-entropy $(Lu_{0.2}Y_{0.2}Gd_{0.2}Yb_{0.2}Er_{0.2})_2O_3$ ceramic. *Journal of Materials Science and Technology,* 2025, 223, 123–130. DOI: 10.1016/j.jmst.2024.10.033
19. Tabanli S., Eryurek G., Baldassare Di Bartolo. White light emission from Er_2O_3 nano-powder excited by infrared radiation. *Optical Materials,* 2017, 69, 207–213. DOI: 10.1016/j.optmat.2017.04.007
20. Tabanli S., Bilir G., Eryurek G. Color tunable up-conversion emission from Er^{3+}:Y_2O_3 nanoparticles embedded in PMMA matrix. *Journal of Luminescence*, 2017, 182, 146–153. DOI: 10.1016/j.jlumin.2016.10.009
21. Mukasyan A.S., Epstein P., Dinka P. Solution combustion synthesis of nanomaterials. *Proceedings of the Combustion Institute*, 2007, 31 (2), 1789–1795.
22. Boiko A.A., Poddenezhnyi E.N., Drobyshevskaya N.E. Sposob polucheniya nanorazmernogo poroshka oksida erbiya_ legirovannogo lantanom [A method for producing nanoscale erbium oxide powder doped with lanthanum], *Patent RB*, no. 24201, 2024.
23. Siddaramana Gowd G., Kumar Patra M., Songara S. Effect of doping concentration and annealing temperature on luminescence properties of Y_2O_3:Eu^{3+}nanophosphor prepared by colloidal precipitation method. *Journal of Luminescence,* 2012, 132(8), 2023–2029. DOI: 10.1016/j.jlumin.2012.03.004
24. Bahaa M.A-Z., Asiri A.M., Hussein M.A. Characterization and Electrical Conductivity of Nano-Crystalline Erbium Sesquioxide by the Precipitation Method and Subsequent Calcination. *Int. J. Electrochem. Sci.*, 2016, 11, 7182–7197. DOI:10.20964/2016.08.61
25. Castaneda-Contreras J., Meneses A., Guevara H.P.L., Marañon V. Properties of Er_2O_3 nanoparticles synthesized by a modified co-precipitation method. *Revista Mexicana de Fısica,* 2015, 61(3-4), 127–131.
26. Klug H.P., Alexander L.E. X-ray diffraction procedures for polycrystalline and amorphous materials. *New York., Wiley,* 1973. 687.
27. Nakamoto K. Infrared and Raman. Spectra of Inorganic and. Coordination Compounds IK-spektry` i spektry. A JOHN WILEY & SONS, INC., Publ., 1978. (Russ. ed.: Nakamoto K. IK-spektry` i spektry` KR neorganicheskikh i koordinatsionnykh soedineniy. Moscow, Mir Publ, 1991. 450.).
28. Turcotte R.P., Sawyer J.O., Eiring L.R. On the rare-earth dioxymonocarbonates and their decomposition. *Inorg. Chem.*, 1969, 8, 238–246. DOI: 10.1021/ic50072a012
29. Sharov V.A. Bezdenezhnykh G.V.O termicheskom razlozhenii oksalatov i karbonatov lantanoidov, ittriya i skandiya [Thermal decomposition of oxalates and carbonates of lanthanides, yttrium and scandium]. *Uspekhi khimii*, 1981, 50(7), 1197–1201.
30. Shtutsa, M.G., Kardapolov A.V., Filippov V.B., Sysina N.A. Issledovanie protsessa osazhdeniya karbonatov RZE [Investigation of the process of precipitation of REE carbonates]. *Izv. Tomskogo politekhnicheskogo universiteta*, 2003, 306(5), 71–74.