

Minireview Article

Application Progress of Upconversion Luminescent Materials in Fluorescent Anti-counterfeiting Technology

Abstract:

Rare-earth-doped upconversion luminescent materials possess advantages such as high luminescent efficiency, excellent spectral characteristics, ability to emit multiple colors, strong interference resistance, and accurate information response. These advantages make them suitable for various anti-counterfeiting needs, thus making them a key focus of research in the field of fluorescent anti-counterfeiting. This article provides a systematic review and summary of the luminescent principles, preparation conditions, substrate effects, applications in fluorescent anti-counterfeiting, and existing issues of upconversion luminescent materials. Finally, potential research and development directions for the future application of upconversion luminescent materials in the field of fluorescent anti-counterfeiting are proposed.

Keywords: Upconversion luminescent materials, preparation methods, fluorescent anti-counterfeiting applications.

INTRODUCTION:

In modern society, the issue of information security has become increasingly serious and has had a significant impact on various fields. In order to protect information security, anti-counterfeiting and encryption technologies have become common security measures. Among them, luminescent technology is widely applied in anti-counterfeiting and encryption design because of its high visibility, flexibility in design, and portability. Nowadays, people use various luminescent materials such as metal-organic frameworks, organic dye fluorescent powders, semiconductors, and carbon quantum dots to create luminescent anti-counterfeiting and encryption patterns, achieving good results. Rare-earth-doped upconversion luminescent materials, with characteristics such as long lifespan, low toxicity, high fluorescence quantum yield, and chemical stability, have attracted considerable attention. These materials have potential applications in areas such as bioimaging, food detection, and luminescent textiles, and have therefore received attention from research teams both domestically and internationally[1]. In summary, luminescent technology plays a crucial role in the anti-counterfeiting and encryption of information, and rare-earth-doped upconversion luminescent materials have broad development prospects in relevant applications due to their unique characteristics.

1. UPCONVERSION LUMINESCENT MATERIALS

1.1 UPCONVERSION LUMINESCENT MECHANISM

The upconversion luminescence of rare-earth-doped materials is a type of anti-Stokes

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The review article provides contribution to this field.

References to be formatted as per the journal guidelines. Recommended to include more references as the latest reference given below.

Zongzhuo Xie, Zhan Shu, Nengrong Tu, Pengcheng Li, Weiyou Yang, Zhentao Du, Yang Yang, Rationally-designed core-shell structure with double-plasmon effect for efficient and tunable upconversion luminescence emission, *Applied Surface Science*, Volume 643, 2024, 158726, ISSN 0169-4332, <https://doi.org/10.1016/j.apsusc.2023.158726>.

Hao Suo, Qi Zhu, Xin Zhang, Bing Chen, Jiangkun Chen, Feng Wang, High-security anti-counterfeiting through upconversion luminescence, *Materials Today Physics*, Volume 21, 2021, 100520, ISSN 2542-5293, <https://doi.org/10.1016/j.mtphys.2021.100520>.

Chen, Z.; Zhu, H.; Qian, J.; Li, Z.; Hu, X.; Guo, Y.; Fu, Y.; Zhu, H.; Nai, W.; Yang, Z.; et al. Rare Earth Ion Doped Luminescent Materials: A Review of Up/Down Conversion Luminescent Mechanism, Synthesis, and Anti-Counterfeiting Application. *Photonics* **2023**, *10*, 1014. <https://doi.org/10.3390/photonics10091014>.

Bibliography does not cover the recent articles on the literature. Recommended to include.

luminescence process, where shorter wavelength light is emitted through the excitation of longer wavelength light. Currently, the upconversion luminescence efficiency of rare-earth-doped luminescent materials is still relatively low, with a maximum efficiency of only 3%. To achieve upconversion luminescence, appropriate excitation power and excitation power density are required, with the excitation power density playing a more critical role. If the excitation power density is insufficient, upconversion luminescence cannot occur even with sufficient excitation power[2].

The upconversion luminescence process covers a wide range of wavelengths, spanning from visible light to near-ultraviolet. Although they are all forms of upconversion luminescence, the specific luminescent mechanisms vary due to various factors. Differences in rare-earth ions or different doping ratios can lead to variations in the luminescence process. While the f-f transitions of rare-earth ions are generally unaffected by the matrix, the doping concentration of rare-earth ions in the material can also influence the upconversion luminescence process. In general, the upconversion luminescence process can be categorized into the following five situations:

- a) Excited state absorption is the basic form of upconversion luminescence, where ions are excited to higher energy levels by absorbing photons and subsequently emit photons by radiative decay back to lower energy levels or the ground state.
- b) Energy transfer refers to the situation where an ion in an excited state transfers its energy to another ion in the ground state, allowing the receiving ion to transition to an excited energy level. The excited-state ions can also undergo further energy transfer to higher excited energy levels.
- c) Continuous energy upconversion involves the continuous transfer of energy between sensitizer and activator ions, enabling photon level transitions.
- d) Cross relaxation refers to the situation where two ions simultaneously occupy adjacent excited energy levels, and one ion transfers its energy to the other, causing the receiving ion to transition to a higher energy level while the donating ion returns to a lower energy level or ground state. In simple terms, cross relaxation involves the mutual transfer of energy between two ions, leading to one ion being upgraded and the other being downgraded.
- e) Photon avalanche, first observed in LaCl materials by Chivia et al. in 1979, refers to the upconversion luminescence phenomenon in which the P-doped rare-earth ions in LaCl materials are excited. The characteristic of photon avalanche is that it does not require absorption of the ground state light and is the result of the superposition of the processes of excited-state absorption and cross relaxation[3,4].

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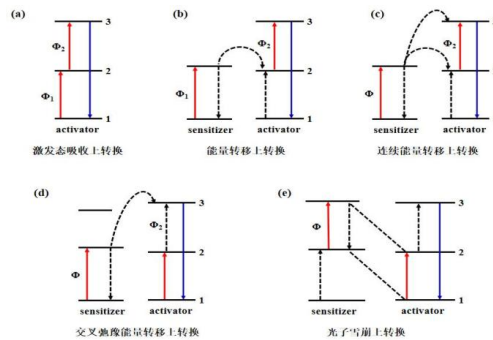


Figure 1 Upconversion Luminescence Processes (a-e)[4]

1.2 CARRIER MATRIX OF UPCONVERSION LUMINESCENT MATERIALS

The choice of carrier matrix can influence the interaction between ions and the matrix, thus affecting the upconversion luminescence process. The matrix material plays a crucial role in upconversion luminescence, requiring both good optical properties and a certain level of chemical stability and mechanical strength. Common matrix materials include glass, ceramics, etc. which serve as platforms for upconversion luminescent materials. Currently, upconversion luminescent matrix materials can be classified into five major categories: fluorides, oxides, phosphates, silicates, and sulfides.

1.2.1 Fluorides

Fluorides are commonly used carrier matrix materials for upconversion luminescence. They possess a characteristic of low phonon energy, which promotes upconversion luminescence and enhances the luminescence efficiency. This low phonon energy property makes fluoride materials ideal for upconversion matrix, enabling effective energy transfer from low energy levels to high energy levels and producing visible light emission. The design and application of such materials play an important role in the fields of optics and optoelectronics, providing strong support for achieving efficient and stable upconversion luminescence[5]. The major drawback of fluoride matrix materials is their weak mechanical strength and chemical stability, which pose challenges during the preparation process and limit their application prospects.

1.2.2 Oxides

Compared to other materials, oxide materials have lower upconversion luminescence efficiency. However, they possess excellent mechanical strength and chemical stability, which make them perform well in various environments. Additionally, rare earth ions can be easily doped into oxide matrix materials, and the preparation process is relatively simple. Some common oxide matrix materials include Y_2O_3 , YVO_4 , $CaWO_4$, and $Nd_2(WO_4)_3$ [6]. By co-doping Tm^{3+} , Ho^{3+} , and Yb^{3+} ions into $CaWO_4$ oxide matrix material, upconversion luminescent materials exhibiting white light emission can be prepared. Likewise, when Er^{3+} is doped into Y_2O_3 oxide material and excited by lasers at 816nm and 486nm, red and green fluorescence emission can be observed [6].

1.2.3 Fluorooxides

Fluorooxides are a hot research topic that combines the advantages of oxide and fluoride matrix materials for upconversion luminescence. They are capable of exhibiting

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upconversion luminescence phenomena. Initially, a fluorooxide glass ceramic material was discovered by French scientist Auzel. Subsequently, more fluorooxides capable of producing upconversion luminescence were reported. However, fluorooxides also have some disadvantages, such as low heat resistance, tendency to deform, and higher cost.

1.2.4 Halides

Researchers have started to explore other matrix materials to address the drawbacks of fluorides, oxides, and halides. Among them, rare earth-doped heavy metal halides are a widely studied new material. This material has lower vibrational energy levels, reducing the possibility of nonradiative relaxation and thus improving upconversion luminescence efficiency. However, the major drawback of halide materials is their instability and susceptibility to hydrolysis. Therefore, stricter requirements are imposed on the preparation and performance testing processes. In terms of stability and processability, the order is oxide > fluoride > halide, while in terms of upconversion luminescence efficiency, the order is halide > fluoride > oxide. However, this order is exactly opposite to their stability and processability. Therefore, it is necessary to find matrix materials that exhibit both efficient luminescence and excellent chemical stability [6].

1.2.5 Sulfides

Sulfide matrix materials have lower phonon energy, which gives them unique physical properties within specific frequency ranges. However, the preparation process for sulfide materials is very stringent and requires operations in a completely sealed environment to ensure that the materials are not exposed to water molecules and oxygen. This is because sulfide materials are highly sensitive to water molecules and oxygen, which may cause the materials to lose certain properties or undergo irreversible chemical reactions. Therefore, to ensure the quality and performance of sulfide matrix materials, researchers must conduct experiments under highly controlled conditions, often using closed reaction chambers or inert gas atmospheres to prevent impurities from entering. These strict operational requirements increase the complexity and difficulty of experiments, limiting large-scale production and application. Despite these challenges, scientists are continuously working on improving preparation techniques to address this issue and promote the application of sulfide matrix materials in various fields [6].

In addition to fluoride, oxide, and halide matrix materials, researchers have explored other types of materials. One example is rare earth amorphous phosphate glass materials. Rare earth phosphates are crystalline materials, but they can be transformed into amorphous states through specific treatments. In addition, crystalline materials are prone to cracking and deformation, with poor processability, while rare earth amorphous phosphate glass materials can overcome these drawbacks. Through this approach, rare earth amorphous phosphate glass materials provide a new option to obtain efficient upconversion luminescence while overcoming the processing challenges associated with crystalline materials. This has made it a highly regarded matrix material. Further research can improve the performance of this material and expand its applications in optics, fluorescence detection, and other fields.

2.METHODS FOR PREPARATION OF UPCONVERSION LUMINESCENT MATERIALS

To synthesize materials with excellent upconversion luminescence performance, researchers have explored various preparation methods. Below are some commonly used methods.

High-temperature solid-state reaction is a mature synthesis method. It involves simple operations, where high-purity reactants are mixed together, heated at high temperature for reaction, and then undergo grinding treatment to obtain the final product. The advantages of this method are high luminescence intensity, convenience in operation, low equipment requirements, and suitability for industrial production. However, it also has some drawbacks. Due to uneven temperature distribution, the particle size of samples tends to be large and unevenly distributed, making it difficult to control the morphology of the materials [7]. This method primarily involves mixing high-purity reactants according to specific stoichiometric ratios and conducting the reaction under appropriate high-temperature, atmospheric, and time conditions. Finally, upconversion luminescent materials are obtained through grinding treatment. For example, Lin et al. used this preparation method to mix Dy_2O_3 , SrCO_3 , Eu_2O_3 , Al_2O_3 , and a solvent in a specific stoichiometric ratio, sintered in a reducing atmosphere, and obtained yellow-green SrAl_2O_4 phosphor after grinding [8].

The sol-gel method is a common chemical synthesis method used to prepare nanoscale luminescent materials. This method typically uses oil-soluble alcohol salts or water-soluble salts as precursors. Through a reaction, a stable and transparent sol is formed, and organic substances are removed to ultimately prepare nano-sized particles [9]. The sol-gel method has several advantages. Firstly, the reaction temperature is relatively low, which helps in the preparation of materials with uniform distribution and smaller particle sizes. Additionally, this method can be used to synthesize various materials, such as $\text{Y}_2\text{SiO}_5:\text{Eu}^{3+}$, $\text{Y}_2\text{SiO}_5:\text{Eu}^{3+}$, $\text{SrAl}_2\text{O}_4:\text{Eu}^{3+}, \text{Dy}^{3+}, \text{Y}_2\text{SiO}_5:\text{Eu}^{3+}$, $\text{Y}_2\text{Al}_5\text{O}_{12}:\text{Ce}^{3+}, \text{Tb}^{3+}, \text{SrAl}_2\text{O}_4:\text{Eu}^{3+}$, etc. However, the drawback of the sol-gel method is that the luminescence intensity of the obtained materials is not high. Currently, many teams have successfully synthesized various materials using the sol-gel method, such as $\text{Ca}_{0.8}\text{Zn}_{0.2}\text{TiO}_3:\text{Pr}^{3+}, \text{Na}^+$ nano-emitting particles (below 100nm) [10].

The precipitation method involves a chemical reaction between a precipitant and a specified metal salt solution, resulting in the formation of a precipitate. Then, through steps like separation, washing, drying, and finally heat treatment, the final product is obtained [11]. The precipitation method is particularly suitable for synthesizing luminescent materials, especially nanoscale luminescent materials. It has several advantages: Firstly, it has a simple process that is conducive to industrial production. Secondly, it can uniformly mix substances with different compositions. Lastly, the resulting samples have high purity and stable performance. However, samples prepared by the precipitation method may be affected by agglomeration, which affects their morphology. Researchers, such as Chow et al., successfully used the co-precipitation method to prepare $\text{LaF}_3:\text{Ln}^{3+}(\text{Yb}^{3+}, \text{Er}^{3+}, \text{Tm}^{3+}, \text{Ho}^{3+})$ nanocrystals [12]. Compared to $\text{NaYF}_4: 20\% \text{Yb}^{3+}, 2\% \text{Er}^{3+}$ crystals, the yield of LaF_3 increased by 5-6 times. The particle size of the prepared LaF_3 upconversion nanomaterials is approximately 5 nanometers.

The hydrothermal method is a synthesis method that significantly reduces the reaction temperature (typically within the range of 100-200°C), but requires high-temperature and high-pressure reaction conditions to be provided. It allows for good control of the shape and size of the samples and can synthesize materials with high luminescence efficiency and good

dispersibility without the need for subsequent heat treatment [13]. However, the hydrothermal method has higher requirements for the reaction environment, making it relatively more expensive compared to conventional methods. The hydrothermal method can be used to prepare upconversion materials doped with rare earth ions, especially fluoride materials. Zhao's research group synthesized ordered arrays of NaYF₄ nanocrystals using the hydrothermal method, and controlled their shape, crystal structure, and nanosize by adjusting reaction conditions such as reactant concentrations[14].

The precursor thermal decomposition method is a method of heating and decomposing to prepare monodisperse nanoparticles at high temperatures (usually around 250°C). This method effectively controls the reaction rate, thereby improving the dispersion and crystallinity of the material particles. However, this method must be operated in a water-free, oxygen-free, and closed environment, resulting in higher energy consumption and expensive starting materials. This method was first proposed by Yan Chunhua's research group in 2006. By co-thermally decomposing Na(CF₃COO) and RE(CF₃COO)₃, rare earth fluoride nanorods, polyhedra, nanoparticles, and nanosheets were synthesized in a single step[15]. In 2012, Liu Xiaogang's research group utilized this method to synthesize NaYF₄ upconversion nanomaterials by doping Gd ions, while simultaneously controlling and adjusting their crystal structure, nanosize, and optical properties[16].

The microwave method is a relatively new preparation method that utilizes microwave energy to induce reactions under certain conditions for the synthesis of upconversion luminescent materials. By controlling the pressure, temperature, and time of the reaction, nanoparticles with high crystallinity, small particle size, high dispersibility, and high luminescence efficiency can be efficiently and environmentally friendly prepared. Compared to traditional methods, the microwave method offers advantages such as fast reaction rates, high efficiency, and shorter reaction times. Upconversion fluorescence materials prepared using microwave-assisted methods include Y₂O₃: Eu³⁺, CaWO₄, CaMoO₄, (Y,Cd)BO₃: Eu³⁺, (Ce_{0.67}Tb_{0.33})MgAl₁₁O₁₉, etc[17/18]. Yang et al. synthesized (Ce_{0.67}Tb_{0.33})MgAl₁₁O₁₉ using the microwave method, and the resulting product exhibited good crystallinity, small particle size, and uniform distribution. Zhang et al. reported the synthesis of rare earth-doped NaLa(MoO₄)₂ crystals using microwave-assisted hydrothermal method. The synthesis process is simple, involving the mixing of aqueous solutions of La(NO₃)₃ and Na₂(MoO₄)₂, followed by heating in a microwave reactor and subsequent washing and drying to obtain the final product [19].

3.CURRENT STATUS OF UPCONVERSION LUMINESCENT MATERIALS

The emission of upconversion luminescent materials doped with ions is mainly achieved through the cross-relaxation of energy between rare earth ions and the introduction of transition ions for quenching luminescence. The energy transfer between rare earth ions is achieved by doping with appropriate energy levels, which alters or enhances the process of energy transfer between different ions to achieve emission of a single color. This cross-relaxation can result in non-radiative transitions of electrons at intermediate energy levels, thereby achieving emission in a single wavelength band .

3.1 CHANGING ENERGY TRANSFER MECHANISM.

Rare earth ions possess diverse and complex energy level structures, allowing for energy transfer to the excited states of Er^{3+} and the observation of green and red emissions in nanocrystals. Researchers can further explore and control the energy interactions between rare earth ions to achieve singular green or red emission, thereby enhancing the quality and efficiency of luminescence. For example, in nanocrystals doped with Sm^{3+} as an activator, Sm^{3+} undergoes energy transfer with specific energy levels of Er^{3+} by suppressing further electronic transfer to those levels, resulting in preferential emission of green light and quenching of red light emission [20](Figure 2a). Researchers also discovered that by doping Tm^{3+} into nanocrystals containing Er^{3+} , pure red emission can be successfully achieved. The electronic structure of Tm^{3+} enables efficient energy transfer from specific energy levels of Er^{3+} to specific lower levels of Tm^{3+} . Furthermore, the energy gap between Tm^{3+} 's specific levels and the ground state is large, almost prohibiting non-radiative multi-phonon relaxation processes. Therefore, the transferred energy can be effectively stored in Tm^{3+} 's level and promote the population of specific energy levels of Er^{3+} for red emission through figure 2b In 2014, Wei et al. proposed a research outcome that utilizes cross-relaxation (CR) between rare earth ions to regulate monochromatic emission. They conducted experiments using hexagonal-phase rare earth nanocrystals with NaYbF_4 as the host and Tm^{3+} as the luminescent center. It was found that as the concentration of Tm^{3+} increased, pure red emission was achieved, which was due to the strengthening of cross-relaxation between ions and the suppression of non-red emission. In $\text{NaYbF}_4:\text{Tm}^{3+}$ crystals, the energy transfer mechanism for upconversion luminescence is as follows: at low Tm^{3+} concentrations, the influence of ion interactions on the upconversion emission process is minimal, allowing efficient filling of the $^1\text{G}_4$ and $^1\text{D}_2$ energy levels Figure 2c. However, with the increase of Tm^{3+} concentration, the upconversion luminescence process from non-red light to monochromatic red light can be realized. The reason is that when the content of Tm^{3+} is high, the luminescence at 475nm is suppressed due to the small energy mismatch, and at the same time, the two kinds of cross relaxation jointly improve the electron population to $^3\text{F}_{2,3}$ energy level, thus enhancing the red light emission at 698nm, as shown in Figure 2d. Besides Tm^{3+} , Ho^{3+} and Ce^{3+} plasmas can also be used as energy capture centers to confine the excitation energy to the Er^{3+} level. This doping can simultaneously inhibit the luminescence quenching caused by cross relaxation and the energy migration to internal lattice defects, thus enhancing the red upconversion emission effect of Er^{3+} [21].

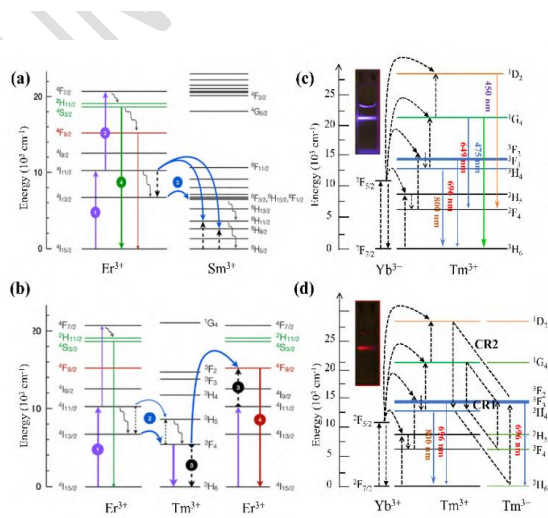


Figure 2(a) illustrates the upconversion luminescence mechanism of $\text{Er}^{3+}/\text{Sm}^{3+}$.

Figure 2(b) illustrates the upconversion luminescence mechanism of $\text{Er}^{3+}/\text{Tm}^{3+}$.

Figure 2(c) illustrates the upconversion luminescence mechanism of $\text{NaYbF}_4:\text{Tm}^{3+}$ at low dopant concentration.

Figure 2(d) illustrates the upconversion luminescence mechanism of $\text{NaYbF}_4:\text{Tm}^{3+}$ at high dopant concentration.

at high dopant concentration[22].

3.2 INTRODUCING TRANSIENT ION QUENCHING LUMINESCENCE.

In addition to rare earth ions, transition metal elements are often used as co-dopants to modulate the upconversion luminescence process of rare earth ions. These transition elements have energy levels that match those of the luminescent ions and can serve as intermediate levels, facilitating electron transitions from the impurity levels to the desired emissive levels. In other words, transition elements act as bridging energy levels, enabling efficient upconversion luminescence of rare earth ions. In a study by [23], the doping of Mn^{2+} ions into $NaYF_4:Yb/Er$ was found to alter the electron transitions within the Er^{3+} energy levels, promoting red light emission and allowing for color tuning from green to red. This is because the 4T_1 level provided by Mn^{2+} acts as an intermediate transition level within the Yb/Er system. When the electrons of Yb/Er are at the ${}^2H_{9/1}$ and ${}^4S_{3/2}$ levels, they first undergo nonradiative energy transfer to the 4T_1 level of Mn^{2+} , followed by reverse energy transfer to the ${}^4F_{9/2}$ level of Er^{3+} , thereby transferring the energy originally intended for green light emission to the red light emission process, enhancing red light emission. By controlling the doping concentration of Mn^{2+} , the R/G ratio can be adjusted from 0.83 to 163.78, achieving color tuning from green to red, as shown in Fig.3(a-b). Wang et al[24] synthesized lanthanide-doped $KMnF_3$ nanocrystals using a novel oil-phase synthesis method, which exhibited single-band upconversion luminescence attributed to Er^{3+} , Ho^{3+} , or Tm^{3+} ions. The principle of this single-band upconversion luminescence is similar to the energy transfer process mentioned earlier between Mn^{2+} and Er^{3+} ions. Additionally, there are other materials containing Mn^{2+} in the host matrix, such as $NaMn_3F_{10}:Er^{3+}/Yb^{3+}$ [25][26], Tm^{3+}/Yb^{3+} [27][28], and $NaMnF_3:Er^{3+}/Yb^{3+}$ [29], which exhibit strong pure red upconversion emission in the presence of Mn^{2+} . In other words, these nanocrystals achieve single-color upconversion luminescence by utilizing Mn^{2+} as an intermediate energy transfer mediator, wherein the presence of Mn^{2+} induces intense red light emission. Liu et al[28] successfully obtained UCNPs with a hollow cubic morphology by doping Mn^{2+} ions into $NaErF_4$. The unique structure of these UCNPs allows for high-concentration doping of Yb^{3+} and uniform distribution within the UCNPs. Under 980nm NIR excitation, single red upconversion luminescence is observed. Additionally, besides Mn^{2+} , transition metal ions such as Fe^{3+} [30], Cr^{3+} [31], and Mo^{3+} [32] can also match the energy levels of Er^{3+} and participate in energy transfer processes. This energy transfer can enhance the color purity and intensity of the nanocrystal's luminescence. Therefore, by controlling the doping of different transition metal ions, we can further modulate the optical properties of

UCNPs and achieve improved luminescence efficiency.

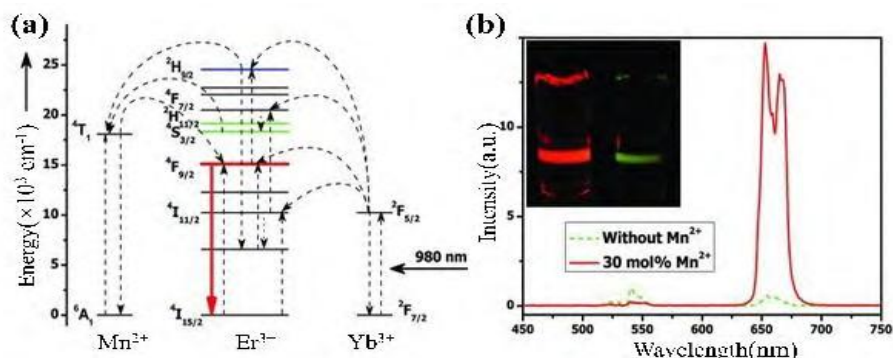


Figure 3-(a) Mn^{2+} doped NaYF_4 : Y/Er upconversion luminescence mechanism (b) upconversion emission spectrum comparison [22]

4. ANTI-COUNTERFEITING APPLICATIONS OF UPCONVERSION LUMINESCENT MATERIALS.

4.1 MONOMODAL ANTI-COUNTERFEITING APPLICATION

In the past few years, researchers have prepared luminescent materials in a Y_2O_3 matrix by doping with elements such as Eu^{3+} , Tb^{3+} , and Ce^{3+} , which emit red, green, and blue light under ultraviolet illumination, achieving tricolor luminescence. These luminescent materials have been synthesized with polyvinyl chloride (PVC) ink and used in the production of

anti-counterfeiting two-dimensional (2D) QR code patterns using simple printing techniques.

This has enabled the recognition of anti-counterfeiting QR codes. However, due to their monomodal nature, the anti-counterfeiting capability of these materials is relatively low, limiting their application scenarios [33]. Furthermore, other researchers have obtained $\text{NaYGeO}_4:\text{Pr}^{3+}$ and $\text{Y}_2\text{GeO}_5:\text{Pr}^{3+}$ samples through high-temperature solid-state methods. They have achieved tunable luminescent colors by adjusting the dopant concentration of Pr^{3+} and applied them in the field of anti-counterfeiting (Figure (4)). However, the anti-counterfeiting level of these

materials is relatively low, thereby not achieving better applications. In summary, current

luminescent materials have some limitations in the field of anti-counterfeiting, such as

monomodal luminescence and lower anti-counterfeiting capability. To develop better applications, further research and improvement of the characteristics of luminescent materials

are needed to enhance their anti-counterfeiting level and expand their scope of application [34][35].

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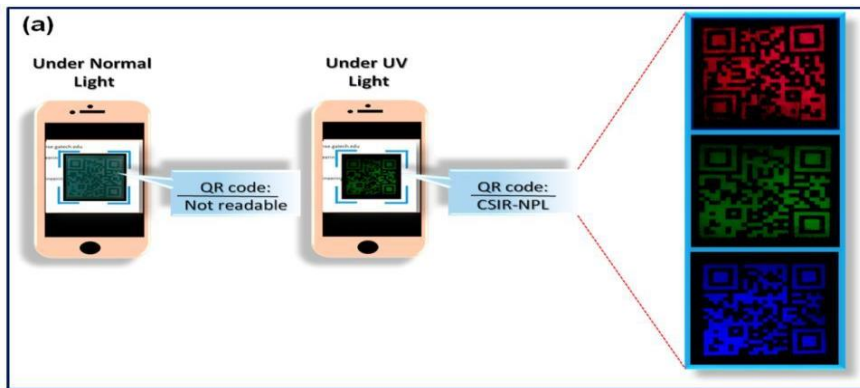


Figure 4: Monomodal luminescent anti-counterfeiting QR code.

The research group led by Xu[36] successfully synthesized $\beta\text{-NaYF}_4\text{:Yb}^{3+},\text{Er}^{3+}/\text{Tm}^{3+}$ nanomaterials using a hydrothermal method. These materials emit green or blue light when excited by 980nm near-infrared light. By adjusting the ratio of anti-counterfeiting ink and fluorescent powder, and utilizing an inkjet printer, they successfully created anti-counterfeiting patterns with high resolution and high intensity luminescent effects(Figure 5)This work provides a new approach to achieve high brightness and colorful anti-counterfeiting patterns.

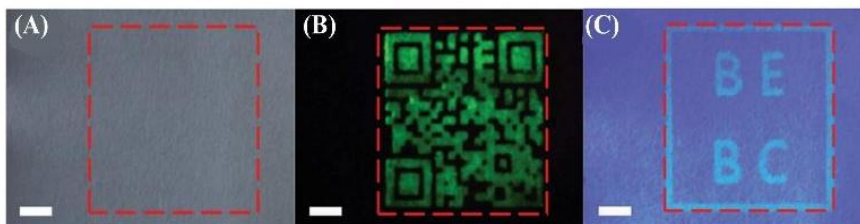


Figure 5 Monomodal luminescent anti-counterfeiting pattern using $\beta\text{-NaYF}_4\text{:Yb}^{3+},\text{Er}^{3+}/\text{Tm}^{3+}$ fluorescent powder.

4.2 ADVANCED ANTI-COUNTERFEITING APPLICATION WITH BIMODAL FUNCTIONALITY.

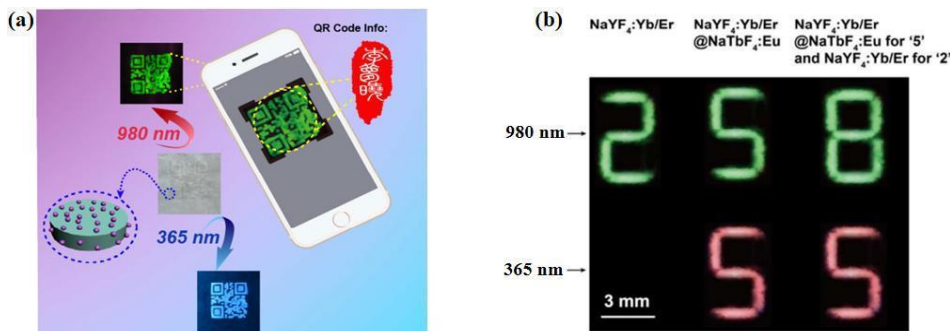


Figure 6 Application effect of $\text{NaYF}_4:\text{Yb/Er}$, $\text{NaYF}_4:\text{Yb/Er}@\text{NaTbF}_4:\text{Eu}$ material dual-mode luminescence anti-counterfeiting

Li et al. made an anti-counterfeiting label by combining the two luminous modes of up and down conversion, as shown in Figure. The pattern shows blue under a 365 nm laser and green under a 980 nm laser [37]. Han et al [38]. successfully prepared $\text{NaYF}_4:\text{Yb/Er} @ \text{NaTbF}_4:\text{Eu}$ luminescent material. They used this material to achieve two luminescent modes and applied it

in the anti-counterfeiting field. As shown in Figure three numbers "8" are used to design anti-counterfeiting patterns. $\text{NaYF}_4:\text{Yb/Er}$ material, it will emit green light under 980 nm laser. Using this feature, they filled in the first number as a "2." For $\text{NaYF}_4:\text{Yb/Er} @ \text{NaTbF}_4:\text{Eu}$, it emits both green and red light under a 980 nm laser. They took advantage of this by coloring in the second number as a "5." In the third numeric area, they filled the "5" with $\text{NaYF}_4:\text{Yb/Er} @ \text{NaTbF}_4:\text{Eu}$ sample and the remaining blank area with $\text{NaYF}_4:\text{Yb/Er}$ sample. In the end, when irradiated with 980 nm laser, the anti-counterfeiting pattern will display a green "258", while under 365 nm it will display a red "55". The unique combination of this material enables it to achieve two different luminescent modes, thus enhancing its level of security in the anti-counterfeiting field. This will provide greater security and reliability to anti-counterfeiting labels.

Liu et al [39]. developed a method for preparing stable lanthanide-doped fluoride nanoparticles and mixed them with ink for dual-mode anti-counterfeiting applications. They demonstrated a transparent film that appeared patternless under natural sunlight, but when exposed to 980 nm laser and 365 nm ultraviolet light, the applied fingerprints and engraved characters became

clearly visible (see Figure 6). The fingerprints were observed and analyzed using scanning electron microscopy to study their shape and patterns. This technology enables dual-mode anti-counterfeiting with high visibility and anti-counterfeiting capabilities (see Figure 6). This study provides new ideas and approaches for dual-mode anti-counterfeiting applications.

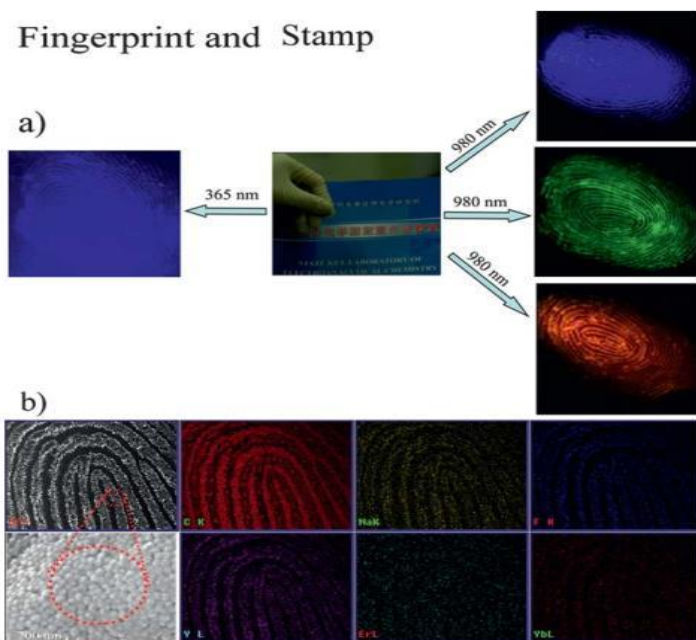


Figure 7: Novel fingerprint anti-counterfeiting technology using lanthanide-doped fluoride nanoparticles.

In 2022, a research team led by Wei et al [40]. designed and synthesized a novel dual-mode luminescent nanocomposite material named $\text{NaYF}_4:\text{Yb,Er}@\text{CDs}$. They prepared two anti-counterfeiting patterns, denoted as "Sc" and "Au", using $\text{NaYF}_4:\text{Yb,Er}@\text{CDs}$ and $\text{NaYF}_4:\text{Yb,Er}$, as shown in Figure(7). These anti-counterfeiting patterns exhibited various colors under irradiation of 365nm ultraviolet light, 980nm near-infrared light, as well as 365nm and 980nm mixed light. This indicates the multi-modal luminescent properties of $\text{NaYF}_4:\text{Yb,Er}@\text{CDs}$. Furthermore, by using a 550nm filter, additional colors can be read, enhancing the level of anti-counterfeiting. The utilization of dual-mode excitation to obtain composite materials with different color characteristics is of great significance for advanced anti-counterfeiting. Although $\text{NaYF}_4:\text{Yb,Er}@\text{CDs}$ possesses favorable optical properties, its preparation conditions are stringent, reaction steps are complex, and it is costly with certain toxicity. Therefore, these drawbacks limit the widespread application of fluorescent carbon dots in the field of anti-counterfeiting.



Figure 8(a,b) shows the luminescent anti-counterfeiting application patterns of NaYF₄:Yb,Er@CDs nanocomposite material and NaYF₄:Yb,Er phosphor.

In 2020, Wang et al[41].successfully prepared a multi-modal anti-counterfeiting material, CaTiO₃:Pr³⁺,Er³⁺,with both upconversion and downconversion functions. This material exhibits color persistence.Moreover,under the irradiation of 980nm near-infrared light, this material also generates green upconversionluminescence.To utilize this phenomenon for anti-counterfeiting applications,the researchers blended this material with PDMS and used screen printing technology to create 2D barcode anti-counterfeiting patterns, as shown in Figure(8).This material not only enhances the difficulty of counterfeiting but also demonstrates high-level anti-counterfeiting effects.Subsequently, many scientists have further introduced other functionalities such as mechanoluminescence and thermoluminescence based on this foundation, bringing more possibilities for the development of anti-counterfeiting technology.

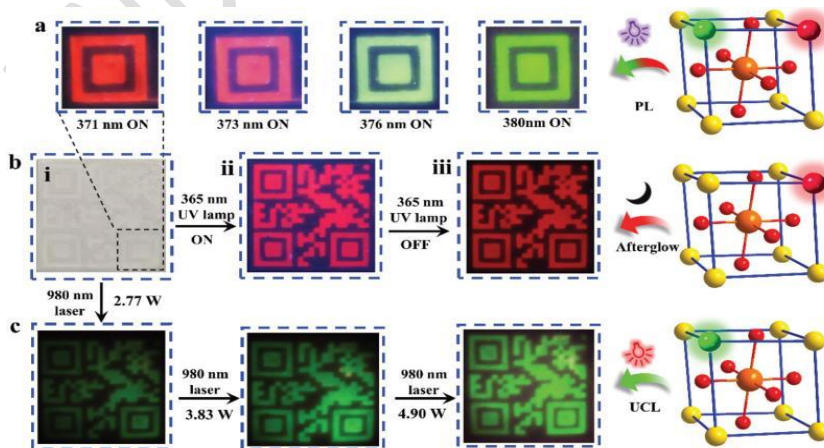


Figure 9(a,b,c): shows the multi-modal luminescent anti-counterfeiting pattern of CaTiO₃:Pr³⁺,Er³⁺.

CaTiO₃:Pr³⁺,Er³⁺ phosphor.

Pei Pengxiang et al[42].utilized the unique multi-modal luminescent properties of La₄GeO₈Eu^{2+/3+},Er³⁺ phosphor and applied it in the field of anti-counterfeiting, as shown in Figure(9).Under portable ultraviolet lamp irradiation, it exhibits red (254 nm) and green (365 nm) emissions. When illuminated with 980 nm or 808 nm near-infrared lasers on a two-dimensional code, it displays green emission. By using a portable ultraviolet lamp and near-infrared laser to irradiate the two-dimensional code, the hidden information embedded in the code can be easily read through the WeChat scan function. This indicates that La₄GeO₈Eu^{2+/3+},Er³⁺ material possesses excellent information encryption and anti-counterfeiting capabilities.The application technology of this anti-counterfeiting material is simple and convenient, requiring only commonly used equipment such as ultraviolet lamps and near-infrared lasers to quickly scan and interpret the information inside the two-dimensional code.Such multi-modal luminescent properties provide an efficient and reliable solution in the field of anti-counterfeiting, effectively preventing information forgery and tampering.

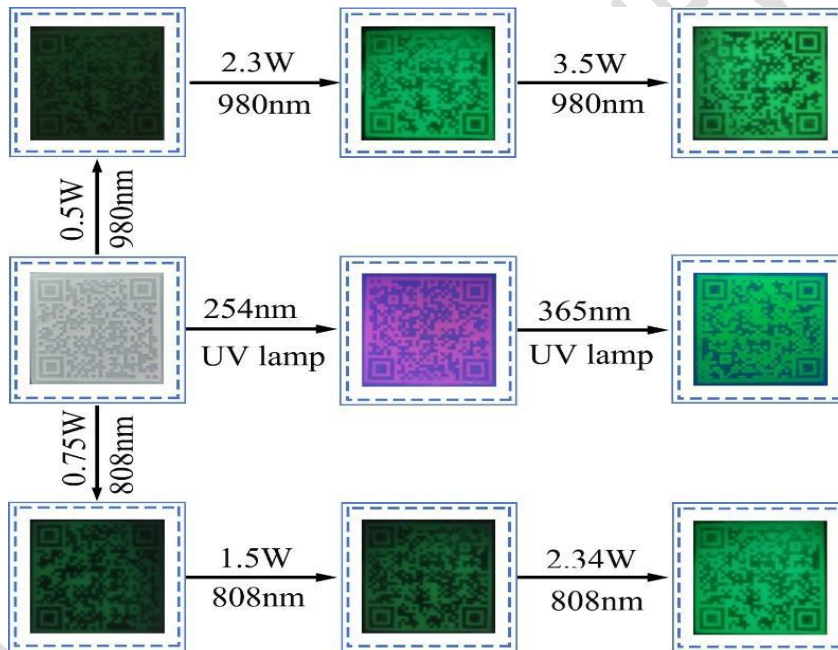


Figure 10: Design of La₄GeO₈Eu^{2+/3+},Er³⁺ multi-modal anti-counterfeiting QR code.

5.SUMMARY AND OUTLOOK

Upconversion luminescent materials, as a new type of functional materials, have made significant progress in the application of fluorescence anti-counterfeiting technology. By rational design and optimization of the material's chemical composition and crystal structure, researchers have successfully improved the luminescence efficiency and stability, achieving high brightness and long lifespan luminescence effects. Additionally, upconversion luminescent materials possess excellent spectral characteristics and multi-color luminescence capability, making them widely applicable in the field of anti-counterfeiting for currencies, documents, and goods. However, upconversion luminescent materials still face some challenges in

fluorescence anti-counterfeiting technology. Firstly, the synthesis methods and preparation processes need further optimization for large-scale production and high efficiency yield. Secondly, luminescence efficiency and stability still need enhancement to meet the requirements of long-term usage and practical applications. Furthermore, the cost of materials is also a factor to consider, as reducing costs would aid in promoting and popularizing this technology.

Looking ahead, the application of upconversion luminescent materials in fluorescence anti-counterfeiting technology has great development potential. Researchers can further optimize the synthesis methods and develop low-cost, large-scale production processes. Simultaneously, by controlling the structural modulation and ligand composition, the luminescence efficiency and stability can be further improved to meet the requirements of practical applications. Additionally, new material combinations and design ideas can be explored to achieve more diverse luminescent colors and multifunctional applications. Overall, although upconversion luminescent materials have made significant progress in fluorescence anti-counterfeiting technology, further research and development are still needed. With the continuous advancement of science and technology, it is believed that upconversion luminescent materials will gradually become an important technological means in the field of anti-counterfeiting, bringing more innovation and application possibilities to the commercial and security sectors.

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