Down conversion of Er^{3+} - Yb^{3+} couple in Y_2BaZnO_5

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Abstract

Er^{3+} - Yb^{3+} co-doped Y_2BaZnO_5 phosphors were synthesized via high temperature solid-state reaction method. The quantum cutting properties for Er^{3+} - Yb^{3+} co-doped Y_2BaZnO_5 phosphors have been detailedly exploited under different wavelength excitation. Unlike in fluoride host, only the $\text{Er}(^4\text{S}_{3/2})+\text{Yb}(^2\text{F}_{7/2})\rightarrow\text{Er}(^4\text{I}_{13/2})+\text{Yb}(^2\text{F}_{5/2})$ energy transfer process in Y_2BaZnO_5 effectively performs the down-conversion, which can split an absorbed high-energy photon into two photons of 1000nm and 1550nm radiations. The quantum cutting properties of Er^{3+} - Yb^{3+} couple in Y_2BaZnO_5 provides meaningful reference in search of new efficient Er^{3+} - Yb^{3+} co-doped quantum cutting phosphors.

1. Introduction

Quantum cutting (QC), which can cut one high energy photon absorbed into two or more low-energy photon, provides a solution for phosphors realizing over 100% quantum efficiency. It was firstly

predicted by Dexter as early as in 1957[1]. Seventeen years later, the QC phenomenon was firstly observed from Pr^{3+} ions doped YF_3 phosphors under excitation of 185nm wavelength [2-4]. After then, QC has attracted much attention and widely investigated due to its possible application in plasma display panels (PDPs) and mercury-free fluorescent lamps (MFFLs). Owing to the special energy-level structures, the near-infrared (NIR) QC phosphors based on $\text{Yb}^{3+}\text{--RE}^{3+}$ ($\text{RE} = \text{Tb}, \text{Pr}, \text{Tm}, \text{Ho}$ and Ce) [5-9] couple has become a focus in recent years. In these phosphors, RE^{3+} ion acts as the sensitizer to absorb UV–Visible photons and Yb^{3+} acts as acceptors. Since the emission of Yb^{3+} ions is around 1000 nm and matches well with the band gap of crystalline Si, QC phosphors based on $\text{Yb}^{3+}\text{--RE}^{3+}$ is believed to be possibly applied in Si-based solar cells and NUV detectors.

Among the $\text{Yb}^{3+}\text{--RE}^{3+}$ co-doped phosphors for QC, $\text{Er}^{3+}\text{--Yb}^{3+}$ co-doped phosphors such as $\text{NaYF}_4: \text{Er}^{3+}\text{--Yb}^{3+}$ and $\text{YF}_3: \text{Er}^{3+}\text{--Yb}^{3+}$ are latest to be discovered. Unlike traditional second-order cooperative QC phosphors, some intermediate levels of Er^{3+} directly participates in the energy transfer (ET) process during the QC process in the $\text{Er}^{3+}\text{--Yb}^{3+}$ co-doped system. Thus a higher QC efficiency is possible and correspondingly the utilization of solar energy for cells might be more efficient too. QC process of $\text{Er}^{3+}\text{--Yb}^{3+}$ couple doped in bromide, fluoride

or oxy-fluorides ceramics has been widely investigated [7, 10-16] and the QC mechanism of Er^{3+} - Yb^{3+} is also proposed based on experiment results. However, QC of Er^{3+} - Yb^{3+} couple in oxide host is rarely reported. As the oxides have better thermal and chemical stability, simple production process and environmental friendliness, oxide-based phosphors are believed to be more applicable in many fields.

The ternary oxide BaY_2ZnO_5 is a kind of luminescence host with a stable crystal structure and an excellent physical and chemical stability. BaY_2ZnO_5 has an orthorhombic structure with a space group of Pbnm [17], and the basic structure contains of YO_7 , BaO_{11} , ZnO_5 polyhedra. Y is sevenfold coordinated inside a mono capped trigonal prism. These prisms share edges to form wavelike chains parallel to the long b axis; two such units join to form the structure motif of Y_2O_{11} . The chains are cross-linked by BaO_{11} and ZnO_5 polyhedra.[18] The dense packing of ions (i.e. distorted chains formed by the two YO_7 trigonal prisms in orthorhombic Y_2BaZnO_5 oxide system results in the strong polarizability of the crystal. This increases the local field of the doped rare earth ions and correspondingly enhances the oscillator strength of rare-earth optical transitions. Therefore, Y_2BaZnO_5 is an excellent host for various activator ions-doped phosphors [19-22], and has gained much attention. In this work, Er^{3+} - Yb^{3+} co-doped Y_2BaZnO_5 phosphors have been prepared by

solid-state reactions and the QC mechanism of Er^{3+} - Yb^{3+} couple in Y_2BaZnO_5 oxide host is discussed in detail.

2. Experiments and characterization

A series of $\text{Y}_{1.97-x}\text{Yb}_x\text{Er}_{0.03}\text{BaZnO}_5$ phosphors (with $0 \leq x \leq 0.35$) were synthesized by solid-state reactions. Stoichiometric amounts of Y_2O_3 (Alfa Aesar, 99.99%), Yb_2O_3 (Alfa Aesar, 99.99%), Er_2O_3 (Alfa Aesar, 99.99%), ZnO (Fisher Scientific, 99.5%), and BaCO_3 (Fisher Scientific, 99%) were mixed and ground thoroughly, and then the mixture were filled in corundum crucible and sintered at 1250°C for 12 hours under air atmosphere [21, 23, 24]. Then the samples were cooled to room temperature naturally for further characterization.

The crystalline phases of the phosphors were identified by a D/MAX 2500 X-ray diffract (XRD) meter using Cu tube with $\text{K}\alpha$ radiation of 0.15406nm in the 2θ range of $20^\circ \sim 80^\circ$. The excitation and emission spectra were obtained by a monochromator (Zolix Instrument, Omni- $\lambda 320\text{i}$) coupled with photomultiplier (PMTH-S1-CR131) and NIR sensitive detector (DInGaAs 2600-TE), which is equipped with a 150 W xenon lamp as the excitation source. The luminescence decay curves were measured by PTI QM 40 spectrofluorometer. All the measurements were performed at room temperature.

3. Results and discussion

Fig. 1 shows the XRD patterns of $\text{Y}_2\text{BaZnO}_5: 3\%\text{Er}^{3+}, x\%\text{Yb}^{3+}$, ($x = 0, 5, 10$ and 15). All the peaks of the XRD pattern of $\text{Y}_2\text{BaZnO}_5: 3\%\text{Er}^{3+}, x\%\text{Yb}^{3+}$ are in a good agreement with the JCPDS card #49-0516 for Y_2BaZnO_5 and no obviously peaks of impurity phase have been observed, indicating that the doped Er^{3+} and Yb^{3+} ions have embedded into the crystal lattice and replaced sites of Y^{3+} ions successfully and the doped ions should be homogeneously distributed in the host from a statistical point of view. The cell volumes of the $\text{Er}^{3+}\text{-Yb}^{3+}$ co-doped Y_2BaZnO_5 were calculated with the XRD data. The inset in **Fig.1** gives the tendency of unit cell volumes as function of Yb^{3+} concentration. It is found that the unit cell volume slightly decreases with Yb^{3+} concentration increasing, in that the ionic radius of the doped Yb^{3+} is smaller than that of Y^{3+} .

Fig.1. XRD patterns of Y_2BaZnO_5 : 3% Er^{3+} , $x\%$ Yb^{3+} ($x = 0, 5, 10, 15$) and the JCPDS card #49-0516 for Y_2BaZnO_5 . The inset shows the Yb^{3+} concentration dependence of unit cell volume of the Y_2BaZnO_5 : Er^{3+} , Yb^{3+} samples.

The visible and near infrared (NIR) emission spectra for $\text{Y}_{1.97}\text{BaZnO}_5$: 3% Er and $\text{Y}_{1.82}\text{BaZnO}_5$: 3% Er , 15% Yb under excitation of 455nm are shown in **Fig.2**. The emissions around 525nm, 550nm and 675nm in the visible region are originated from the $^2\text{H}_{11/2}/^4\text{S}_{3/2} \rightarrow ^4\text{I}_{15/2}$ and $^4\text{F}_{9/2} \rightarrow ^4\text{I}_{15/2}$ transition of Er^{3+} , and the NIR emissions around 870nm and 1550nm are originated from the $^4\text{S}_{3/2} \rightarrow ^4\text{I}_{13/2}$ and $^4\text{I}_{13/2} \rightarrow ^4\text{I}_{15/2}$ transitions of Er^{3+} ions, respectively. In the Er^{3+} single doped sample, the near infrared emission band centered on around 1000nm is assigned to the transition $^4\text{I}_{11/2} \rightarrow ^4\text{I}_{15/2}$ of Er^{3+} . However, in the Er^{3+} - Yb^{3+} co-doped samples, the emission at

around 1000nm is greatly broadened and intensified, while the 550nm green emission is largely weakened. Obviously, the broadened and intensified emission in range of 920-1100nm should ascribed to the Yb^{3+} : $^2\text{F}_{5/2} \rightarrow ^2\text{F}_{7/2}$ emission, indicating that the $^2\text{F}_{5/2}$ level of Yb^{3+} is populated with energy transfer from Er^{3+} ions when Er^{3+} ions excited at 455nm.

The dependence of the integrated intensities of the near infrared emissions at 1000nm and 1550nm on Yb^{3+} concentration is further given in the insets of **Fig.2**. The near infrared emissions at 1000nm and 1550nm both increase with Yb^{3+} concentration increasing, reaching their maximal values at Yb^{3+} concentration of 15%, and then tend to decreases. Above Yb^{3+} concentration dependent luminescence properties suggest that an energy transfer caused quantum cutting takes place between the Er^{3+} and Yb^{3+} ions.

Fig.2 emission spectra of $\text{Y}_{1.97-x}\text{BaZnO}_5$: 3%Er, x%Yb (x= 0, 15) under excitation of 455nm. The inset shows the emission intensity tendency of 1000nm ($\text{Yb}^{3+}: {}^2\text{F}_{5/2} \rightarrow {}^2\text{F}_{7/2}$ + $\text{Er}^{3+}: {}^4\text{I}_{11/2} \rightarrow {}^4\text{I}_{15/2}$) and 1550nm ($\text{Er}^{3+}: {}^4\text{I}_{13/2} \rightarrow {}^4\text{I}_{15/2}$) when changing Yb^{3+} concentration.

To gain insight on the energy transfer processes between Er^{3+} ions and Yb^{3+} ions, the luminescence decay curves for $\text{Er}^{3+}: {}^4\text{F}_{7/2} \rightarrow {}^4\text{I}_{15/2}$ emission ($\lambda_{\text{em}} = 492\text{nm}$), ${}^4\text{F}_{5/2} \rightarrow {}^4\text{I}_{15/2}$ ($\lambda_{\text{em}} = 455\text{nm}$) and ${}^4\text{S}_{3/2} \rightarrow {}^4\text{I}_{15/2}$ emission ($\lambda_{\text{em}} = 550\text{nm}$) in $\text{Y}_{1.97-x}\text{BaZnO}_5$: 3% Er^{3+} with different Yb^{3+} concentration were measured on the excitation at the $\text{Er}^{3+}: {}^4\text{G}_{11/2}$ level (380nm), shown in **Fig.3** (a), (b), (c). Similar measurements for $\text{Er}^{3+}: {}^4\text{S}_{3/2} \rightarrow {}^4\text{I}_{15/2}$ emission ($\lambda_{\text{em}} = 550\text{nm}$) on excitation at the $\text{Er}^{3+}: {}^4\text{F}_{7/2}$ level (492nm) also performed, and given in **Fig.3** (d).

Fig.3 the Luminescence decay curves of (a) Er³⁺: ⁴F_{5/2}→⁴I_{15/2} emission (455), (b) Er³⁺: ⁴F_{7/2}→⁴I_{15/2} emission (492nm) and (c) Er³⁺: ⁴S_{3/2}→⁴I_{15/2} emission (550nm) in Y₂BaZnO₅ with 3%Er³⁺ and x%Yb³⁺ (0%, 5%, 10%, 15%, 20%, 25% and 35%), after

excitation at the $\text{Er}^{3+} {}^4\text{G}_{11/2}$ level (380nm); (d) the Luminescence decay curves of Er^{3+} : ${}^4\text{S}_{3/2} \rightarrow {}^4\text{I}_{15/2}$ emission (550nm) after excitation at the $\text{Er}^{3+} {}^4\text{F}_{7/2}$ level (492nm).

As shown in **Fig.3**, the luminescence decay curves of the ${}^4\text{F}_{5/2} \rightarrow {}^4\text{I}_{15/2}$ (455nm) and ${}^4\text{F}_{7/2} \rightarrow {}^4\text{I}_{15/2}$ (492nm) emission of Er^{3+} under excitation of 380nm almost have no change at different Yb^{3+} concentration, meaning that the doped Yb^{3+} ions almost had no influence on the lifetime of ${}^4\text{F}_{5/2}$ and ${}^4\text{F}_{7/2}$ states. The result indicates that the resonant energy transfer originating from the ${}^4\text{F}_{5/2}$ or ${}^4\text{G}_{11/2}$ state of Er^{3+} that previously reported [10, 13-15, 25] has not occurred or the probability of which is negligible in the Y_2BaZnO_5 host. This may attributed to the relatively high phonon energy of Y_2BaZnO_5 host. The maximum phonon energy is approximately 590 cm^{-1} for Y_2BaZnO_5 host [18]. The relative high phonon energy results in the rapid multi-phonon relaxation from ${}^4\text{F}_{5/2}$ or ${}^4\text{F}_{7/2}$ state to ${}^4\text{S}_{3/2}$ state[15]. The rapid relaxation makes the effective particle population at ${}^4\text{G}_{11/2}$ and ${}^4\text{F}_{7/2}$ levels difficult, which prohibits the occurrence of the energy transfer between the Er^{3+} ions at ${}^4\text{G}_{11/2}$ / ${}^4\text{F}_{7/2}$ state and Yb^{3+} ions at ${}^2\text{F}_{7/2}$ state.

However, the luminescence decay time of 550nm (${}^4\text{S}_{3/2} \rightarrow {}^4\text{I}_{15/2}$) decreases monotonically with the increasing concentration of the Yb^{3+} ions doped, whether excited by 380nm or 492nm, as shown in **fig.3** (c) and (d). The result indicates that the energy transfer between Er^{3+} and Yb^{3+} originates from the ${}^4\text{S}_{3/2}$ of Er^{3+} . This is a nonresonant energy

transfer which was known as impossible or inefficient in chloride, fluoride hosts [14, 15]. In the Er^{3+} - Yb^{3+} co-doped chloride or fluoride compounds, the energy transfer between the Er^{3+} - Yb^{3+} couples originates from the $^4\text{F}_{7/2}$ level of Er^{3+} on the excitation of 492nm, or from $^4\text{G}_{11/2}$ level on the excitation of 380nm.[10, 13-15, 25] In the Y_2BaZnO_5 host, however, the resonant energy transfer originating from the $^4\text{G}_{11/2}$ or $^4\text{F}_{7/2}$ level of Er^{3+} does not occur even the Er^{3+} ions are excited to an upper level like $^4\text{G}_{11/2}$ (380nm).

What is noteworthy is that an evident rise-up process in the early stage of the curve excited at 380nm can be observed when the Yb^{3+} doping concentration is less than 10mol% and is hardly observed at any Yb^{3+} concentration under 492 nm excitation, as presented in **Fig.3** (c) and (d). This is ascribed to the different relaxation time between the $^4\text{G}_{11/2}$ to $^4\text{S}_{3/2}$ and $^4\text{F}_{7/2}$ to $^4\text{S}_{3/2}$ non-radiative transitions. Obviously the relaxation time of the non-radiative transition from the $^4\text{G}_{11/2}$ to $^4\text{S}_{3/2}$ state of Er^{3+} is longer than that from the $^4\text{F}_{7/2}$ to $^4\text{S}_{3/2}$ state, but still shorter than decay time of the $^4\text{S}_{3/2}$ state at low Yb^{3+} concentration, making the population of Er^{3+} ion on $^4\text{S}_{3/2}$ state sustaining growth for a period of time when the 380nm excitation light is stopped. Once the Yb^{3+} concentration is further increased, the rise-up process is hardly observed because of the rapid depopulation of the Er^{3+} ions on $^4\text{S}_{3/2}$ state performed by the energy

transfer process occurs on $^4S_{3/2}$ state. However, the fast non-radiative transition from the $^4F_{7/2}$ to $^4S_{3/2}$ results in that the rise-up time is too short to be observed when excited at 492 nm. The Yb^{3+} concentration dependent 550 nm emission decaying behavior excited at 380 nm and 492 nm gives obvious and powerful evidence that the energy transfer from the Er^{3+} ions to Yb^{3+} ions is occurs on the $^4S_{3/2}$ state of Er^{3+} ions.

There are two mostly possible energy transfer pathways depopulating the $^4S_{3/2}$ state of Er^{3+} and performing the quantum cutting, As shown in **Fig.4**, the first one is ET1: $Er(^4S_{3/2}) + Yb(^2F_{7/2}) \rightarrow Er(^4I_{11/2}) + Yb(^2F_{5/2})$ and the second one is ET2: $Er(^4S_{3/2}) + Yb(^2F_{7/2}) \rightarrow Er(^4I_{13/2}) + Yb(^2F_{5/2})$. Neither is resonant because of the large energy mismatch. It can be roughly estimated that the mismatched energy is about $1800cm^{-1}$ for ET1 and $1700cm^{-1}$ for ET2. Both the two energy transfer processes need about three phonons to assist, considering that the highest phonon energy in Y_2BaZnO_5 lattice is approximately $590cm^{-1}$. However, ET1 is a phonon-absorption energy transfer which is believed to be difficult to take place at room temperature, while ET2 is a phonon-emission one and should be mainly responsible for the quantum cutting[12, 14, 15, 26].

Fig.4 the energy level schemes of the Er^{3+} and Yb^{3+} couple and possible mechanisms for DC. Energy transfer (ET1) from Er^{3+} to Yb^{3+} (Er^{3+} : ($^4\text{S}_{3/2} \rightarrow ^4\text{I}_{13/2}$), Yb^{3+} : ($^2\text{F}_{7/2} \rightarrow ^2\text{F}_{5/2}$)), energy transfer (ET2) from Er^{3+} to Yb^{3+} (Er^{3+} : ($^4\text{S}_{3/2} \rightarrow ^4\text{I}_{11/2}$), Yb^{3+} : ($^2\text{F}_{7/2} \rightarrow ^2\text{F}_{5/2}$)). And the reverse energy transfer (RET) from the excited Yb^{3+} to Er^{3+} ions (Yb^{3+} : ($^2\text{F}_{5/2} \rightarrow ^2\text{F}_{7/2}$), Er^{3+} : ($^4\text{I}_{13/2} \rightarrow ^4\text{F}_{9/2}$)).

Based on the discussion above, the energy transfer induced quantum cutting between the Er^{3+} and Yb^{3+} ion in the Y_2BaZnO_5 host excited by 455nm as described in **Fig.4**. Firstly the Er^{3+} ions were excited to their $^4\text{F}_{5/2}$ state by 455nm light. Followed fast multi-phonon relaxation from the $^4\text{F}_{5/2}$ state and populates the $^4\text{S}_{3/2}$ state. Then the energy transfer ET2 from Er^{3+} to Yb^{3+} ions occurs and brings about the population of the $^2\text{F}_{5/2}$ state of Yb^{3+} , resulting in its $^2\text{F}_{5/2} \rightarrow ^2\text{F}_{7/2}$ transition. Meanwhile this energy transfer also increases the population the $^4\text{I}_{13/2}$ state of Er^{3+} , enhancing the

$^4I_{13/2} \rightarrow ^4I_{15/2}$ transition. As a result, the emissions at around 1000nm and 1550nm are both intensified. Obviously, the energy transfer intensifies the near infrared emission, but weakens the 550nm emission of Er^{3+} , which is manifested in **Fig.5**.

Fig.5 The 550nm ($^4S_{3/2} \rightarrow ^4I_{15/2}$)(a, c, e) and 675nm ($^4F_{9/2} \rightarrow ^4I_{15/2}$)(b, d, f) emission intensity tendency depended on Yb^{3+} concentration, excited with wavelength of 455nm (a, b), 492nm(c, d) and 525nm(e, f) respectively.

In **Fig.5**, the emission intensities at 550nm and 655nm in visible region are plotted as functions of Yb^{3+} concentration under excitation of 455nm, 492nm and 525nm by which the Er^{3+} ion is excited to its $^4F_{5/2}$, $^4F_{7/2}$ and $^2H_{11/2}$ state, respectively. The structures of emission spectra of Er^{3+} under different excitation are similar. However, the emission intensity

of 550nm decreases monotonously with the Yb^{3+} doping concentration increasing due to the enhanced energy transfer rate of ET2, whether excited at 455nm, 492nm or 525nm.

Interestingly, it is noted that 675nm emission increases firstly with the increasing of doped Yb^{3+} concentration and then decreases when the Yb^{3+} concentration is higher than 15%. The Yb^{3+} concentration dependent 655 emission is quite similar with that of the near infrared emission and it is complete different from the 550nm emission. The reasonable interpretation for this phenomena should be ascribed to the reverse energy transfer (RET) from Yb^{3+} to Er^{3+} ions: $\text{Yb}(^2\text{F}_{5/2}) + \text{Er}(^4\text{I}_{13/2}) \rightarrow \text{Yb}(^2\text{F}_{7/2}) + \text{Er}(^4\text{F}_{9/2})$, as shown in **Fig.4**. It increases the particle population on $^4\text{F}_{9/2}$ state of Er^{3+} , leading to the increase of Er^{3+} emission at around 675nm ($^4\text{F}_{9/2} \rightarrow ^4\text{I}_{15/2}$)[26, 27].

When the Yb^{3+} concentration is higher than 15%, the emission intensities at 1000nm, 1550nm and 655nm all tend to decrease, just as shown in **Fig.5** and the insets of **Fig.2**. The luminescence quenching phenomenon should be ascribed to the energy transfer to traps with the increased energy transfer probability among the doped ions at high Yb^{3+} concentration.

The average lifetime (τ) of the $^4\text{S}_{3/2}$ state of Er^{3+} and the energy transfer efficiency (η) can be calculated by using the following equations

[28, 29]:

$$\tau = \frac{\int_0^{\infty} t I(t) dt}{\int_0^{\infty} I(t) dt}, \quad (1)$$

$$\eta_T = 1 - \tau_{x\%} / \tau_0. \quad (2)$$

Here $I(t)$ is the time-dependent luminescence intensity. $\tau_{x\%}$ and τ_0 are the average lifetime of the $^4S_{3/2}$ state with $x\%$ Yb^{3+} and without Yb^{3+} doping, respectively. It is found that the values of average lifetime for the $^4S_{3/2}$ state of Er^{3+} excited at 380nm and 492nm are similar at a certain doping Yb^{3+} concentration. For instance, the average lifetimes are 93.89 μs and 92.81 μs for the Yb^{3+} free sample when excited at 380nm and 492nm, respectively, and they are 33.42 μs and 29.11 μs at Yb^{3+} concentration of 35 mol%. The similarity of the lifetime excited at 380nm and 492nm indicates that the probability of the energy transfer occurring on the $^4S_{3/2}$ state of Er^{3+} is independent on the excitation wavelength.

Fig.6 the average lifetime of 550nm under excitation of 492nm wavelength and the efficiency tendency of energy transfer from Er^{3+} to Yb^{3+} ions when changing Yb^{3+} concentration.

The energy transfer efficiencies at different Yb^{3+} doping concentration were calculated using Eq.(2) and shown in **Fig.6**. It is found that the energy transfer efficiency increases monotonically from 23.16% to 68.83%, with the Yb^{3+} concentration increasing from 5 to 35 mol%. However, both the 1500nm and 1000nm emission intensities begin to decrease when the Yb^{3+} concentration is higher than 15%, indicating that the transferred energy has not been entirely converted into light emission at high Yb^{3+} concentration due the concentration quenching.

4. Conclusion

In this work, Er^{3+} - Yb^{3+} co-doped Y_2BaZnO_5 phosphors were synthesized via traditional high temperature solid-state reaction method. The luminescence performance and the energy transfer mechanism for the Er^{3+} - Yb^{3+} couple in Y_2BaZnO_5 host has investigated under different wavelength excitation. It is found that an QC occurs in Er^{3+} - Yb^{3+} co-doped Y_2BaZnO_5 performed by the $\text{Er}(^4\text{S}_{3/2}) + \text{Yb}(^2\text{F}_{7/2}) \rightarrow \text{Er}(^4\text{I}_{13/2}) + \text{Yb}(^2\text{F}_{5/2})$ energy transfer process. With this quantum cutting process, a high-energy photon absorbed can be split into two photons of 1000nm and 1550nm radiations, instead of two photons of 1000nm emission.

Regretfully, the Yb^{3+} ions cannot efficiently convert the received energy from Er^{3+} into near infrared emission due the concentration quenching effect. Therefore, more suitable oxide host that can realize efficient quantum cutting luminescence meeting the practical application for the Er^{3+} - Yb^{3+} couple still needs to be further exploited.

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