Nd$^{3+}$-Sensitized Upconversion Nanostructure as a Dual-Channel Emitting Optical Probe for Near Infrared-to-Near Infrared Fingerprint Imaging

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ABSTRACT: Lanthanide upconversion nanophosphors (Ln-UCNPs) have attracted great attention in a variety of fields, benefiting from low background fluorescence interference and a high signal-to-noise ratio of upconversion luminescence. However, the establishment of Ln-UCNPs with dual near-infrared (NIR) emission channels still remains challenging. Herein, we report the design and synthesis of Nd$^{3+}$-sensitized NaYbF$_4$:Tm@NaYF$_4$:Yb@NaNdF$_4$:Yb hierarchical-structured nanoparticles that emit NIR luminescence at 696 and 980 nm under excitation at 808 nm. The sensitizer-rich NaYbF$_4$ core promotes efficient energy transfer to Tm$^{3+}$. The interlayer of NaYF$_4$:Yb effectively prevents the cross-relaxation process from Tm$^{3+}$ to Nd$^{3+}$ and thus enhances the luminescence emission. The introduction of Nd$^{3+}$ ion as the sensitizer transforms the excitation wavelength from 980 to 808 nm, which subtly averts the laser-induced thermal effect and offers a new pathway for the NIR emission channel at 980 nm. The as-prepared nanoparticles were further applied in developing latent and blood fingerprint images, which exhibited high signal-to-noise ratio and distinguishable details under 808 nm excitation with negligible thermal damage to the sample. Our work provides a promising strategy to realize NIR-to-NIR dual-channel emissions in Ln-UCNPs. With further functionalization, such nanoparticles are expected to have great potential in forensic and biological sciences.

INTRODUCTION

Lanthanide upconversion nanophosphors (Ln-UCNPs) possess the optical property of converting low-energy light in the near-infrared (NIR) region into higher-energy luminescence. This unique photoluminescence mechanism endows Ln-UCNPs with special advantages, such as superior photostability, nonblinking, absence of autofluorescence, and low-energy NIR radiation, which make them suitable for use in bioimaging and biosensing. In a conventional lanthanide upconversion system, Yb$^{3+}$ ion is used to absorb the NIR excitation photon (usually at 980 nm) and to transfer the energy to the emitter ion. However, the application of Yb$^{3+}$-sensitizedLn-UCNPs has been limited to low conversion efficiency due to the low absorption cross-section of the Yb$^{3+}$ ion and the thermal effect induced by a 980 nm laser. Recently, Nd$^{3+}$ ion has been reported as a suitable sensitizer to increase the upconversion emission owing to its large absorption cross-section at $\sim$800 nm and efficient energy transfer from Nd$^{3+}$ to Yb$^{3+}$ ions. Moreover, the excitation wavelength of Nd$^{3+}$-sensitized Ln-UCNPs is 808 nm rather than 980 nm, which subtly circumvents the laser-induced thermal effect. For example, Yang et al. demonstrated NaGdF$_4$:Yb,Er@NaGdF$_4$:Nd,Yb core–shell nanoparticles with a Nd$^{3+}$-enriched shell layer to achieve upconversion luminescence (UCL) under 808 nm excitation.

Liu et al. further improved the doping ratio of Nd$^{3+}$ by an active-shell strategy. Subsequently, Zhao et al. introduced a transition layer to construct quenching-shield sandwich-structured lanthanide nanocrystals that eliminated the deleterious cross-relaxation pathways between the activator and sensitizer. However, the upconversion emission wavelengths used in the reported studies have been mainly limited to the visible region and have seldom been in the NIR region. Herein, we describe the development of hierarchical-structured Nd$^{3+}$-sensitized nanoparticles, NaYbF$_4$:Tm@NaYF$_4$:Yb@NaNdF$_4$:Yb (CSS), with intense dual modes of NIR emission under 808 nm excitation. Our design strategy is shown in Scheme 1. A sensitizer-rich NaYbF$_4$ host is employed as a core to promote efficient energy transfer to Tm$^{3+}$. A Yb$^{3+}$-doped NaYF$_4$ interlayer is then applied to efficiently block the energy relaxation process from Tm$^{3+}$ to Nd$^{3+}$. Nd$^{3+}$ ions, possessing absorption capacity to harvest 808 nm photon energy, are then incorporated into the second shell layer, which facilitates energy transfer from Nd$^{3+}$ to Yb$^{3+}$. Under 808 nm excitation, one NIR emission band at 696 nm is generated from the NaYbF$_4$:Tm upconversion core, and another NIR emission...
Scheme 1. Schematic Design (top) and Energy-Level Diagram (bottom) of NaYbF₄:Tm@NaYF₄:Yb@NaNdF₄:Yb (CSS) Nanoparticle for Dual Modes of NIR Emission under 808 nm Excitation

“The 696 nm emission of Tm³⁺ and 980 nm emission of Yb³⁺ are achieved via the Nd³⁺→Yb³⁺→Tm³⁺ energy-transfer process under NIR excitation. The NaYF₄:Yb interlayer is designed to prevent energy back-transfer from activator to sensitizer.”

Experimental Section

Materials. Rare-earth oxides Y₂O₃ (99.999%), Yb₂O₃ (99.999%), Tm₂O₃ (99.999%), and Nd₂O₃ (99.999%) were purchased from Beijing Lansu Co, Ltd. Oleic acid (90%), oleylamine (70%), and 1-octadecene (90%) were purchased from Sigma-Aldrich. Na-(CF₃COO)₃ (98%) was purchased from Alfa Aesar. Ethanol, cyclohexane, acetic acid, and trifluoroacetate acid (99%) were purchased from Sinopharm Chemical Reagent Co, Ltd. NOBF₄ (96%) and 5-sulfosalicylic acid were purchased from J&K Scientific, Ltd. Bovine hemoglobin was purchased from Shanghai Zurui Biotechnology Co, Ltd. RE(CF₃COO)₃ were prepared according to the literature method. Acid yellow 7 was purchased from Dr. Ehrenstorfer GmbH. All other chemical reagents were of analytical grade and were used directly without further purification. Deionized water was used throughout the experiments.

Characterization. Powder X-ray diffraction (XRD) measurements were performed on a Bruker D4 diffractometer (Cu Kα radiation, λ = 1.540 56 Å) at a scanning rate of 1°/min in the 2θ range from 10 to 90°. The size and morphology of nanoparticles were determined at 200 kV using a Tecnai G2 20 TWIN low to high resolution transmission electron microscope (TEM). The standard TEM samples were prepared by dropping a diluted cyclohexane solution of nanoparticles onto the surface of a copper grid. Fourier transform infrared (FTIR) spectra were obtained from samples in KBr pellets using an IRPRESTIGE-21 spectrometer (Shimadzu). Ultraviolet–visible (UV–vis) absorption spectra were recorded on a Lambda 750 UV–vis spectro-photometer. Upconversion luminescence (UCL) and Stokes emission spectra were recorded on Edinburgh FLS-920 instrument using an excitation source of external 0–3 W adjustable 980 nm semiconductor laser and 808 nm pump laser (Connet Fiber Optics, China), instead of the xenon source in the spectro-photometer. All the photoluminescence studies were performed at room temperature. The power of 808 nm and 980 nm continuous wave laser were measured by a PM200 hand-held optical power and energy meter (Thorlabs, Inc). The heat effects of different laser sources were recorded on a professional infrared thermal imaging camera (FLIR E40).

Synthesis of NaYbF₄:Tm (Core) Nanoparticles. In a typical procedure, Na(CF₃COO) (1 mmol) and Ln(CF₃COO)₃ (1 mmol; Ln = Yb, Tm) with a ratio of 99:1 were added to a 100 mL three-necked ask containing oleic acid (10 mmol), 1-octadecene (20 mmol), and oleylamine (10 mmol) at room temperature. Then the slurry was heated to 100 °C to remove water and oxygen with vigorous magnetic stirring under vacuum for 30 min, and a transparent solution was formed. The solution was then heated to 290 °C and maintained for 30 min under an argon atmosphere. When the solution cooled to room temperature, the nanoparticles were precipitated by adding excess amounts of absolute ethanol into the reacted solution and then collected by centrifugation. The as-precipitated nanocrystals were washed several times with ethanol and cyclohexane and redispersed in 10 mL of cyclohexane for the next step.

Synthesis of Core/Shell NaYbF₄:Tm@NaYF₄:Yb (CS) Nanoparticles. To a 100 mL three-necked flask containing oleic acid (10 mmol) and 1-octadecene (20 mmol) was added not only NaYbF₄:Tm core (1 mmol) but also Na(CF₃COO) (1 mmol) and RE(CF₃COO)₃ (1 mmol, RE = Y, Yb) with a ratio of 9:1. Then the slurry was heated to 100 °C to remove water and oxygen with vigorous magnetic stirring under vacuum for 30 min and formed a transparent solution. The solution was then heated to 290 °C and maintained 30 min under an argon atmosphere. When the solution cooled to room temperature, the nanoparticles were precipitated by adding excess amounts of absolute ethanol into the reacted solution and then collected by centrifugation. The as-precipitated nanocrystals were washed several times with ethanol and cyclohexane and dispersed in 10 mL of cyclohexane for the next step.

Synthesis of Core/Shell/Shell Nanoparticles NaYbF₄:Tm@NaYF₄:Yb@NaNdF₄:Yb (CSS). The procedure is identical to the synthesis of core/shell nanoparticles, except the NaYbF₄:Tm@NaYF₄:Yb (1 mmol) was used as the seeds and Ln(CF₃COO)₃ (1 mmol, Ln = Nd, Yb) with a ratio of 19:1 as the precursor.

Preparation of Citrate-Coated CSS Nanoparticles. First, a ligand exchange strategy was used to acquire ligand-free nanoparticles in aqueous solution. In a typical process, 10 mL of oley acid-capped nanoparticles dispersion in hexane (∼5 mg/mL) was combined with 6 mL of dichloromethane solution of NOBF₄ (0.01 M) at room temperature. The resulting mixture was shaken gently until the...
precipitation of nanoparticles was observed, typically within 5 min. After centrifugation to remove the supernatant, absolute ethanol was added to wash the nanoparticles. Then, the ligand-free nanoparticles were redispersed in trisodium citrate solution (10 mg/mL); after they are washed with deionized water, the citrate-coated nanoparticles (cit-CSS) can be achieved.

Preparation of cit-CSS Staining Solution. The cit-CSS staining solution was prepared before use. Tween 20 is added to cit-CSS, and the pH is lowered to 2.6 by citric acid 0.1 M to obtain the working solution.

Fingerprints Collection. The fingerprints were deposited on semiporous substrate (soft-drink labels) and nonporous substrate (polyethylene bags). For the latent fingerprint, volunteers were asked to touch their foreheads and then rub their hands together before pressing their fingers on the chosen surfaces. For the bloody fingerprint, 20 μL of bovine hemoglobin solution (150 g/L, dissolved in deionized water) was pipetted onto the fingerprint and immediately spread as uniformly as possible with the pipet tip across the surface of the finger. Then the bovine hemoglobin was transferred onto each different surface by applying some pressure. The substrates were cleaned with deionized water and dried in air before use. After 12 h, the fingerprints were used for incubation procedure.

Protocol of Fingerprints Incubation. For latent fingerprints, the incubation procedure was as follows: (1) the samples were rinsed with deionized water for 1 min; (2) immersed in cit-CSS staining solution for 15 min under rotating; (3) finally rinsed with deionized water for 30 s. For bloody fingerprints, the incubation procedure was as follows: (1) the prints were immersed in 5-sulfosalicylic acid solution (2%, dissolved in deionized water) for 10 min to complete fixation process; (2) they were rinsed in water for 30 s; (3) immersed in CSS staining solution for 10 min under rotating; (4) the prints were finally rinsed with water for 30 s. The samples were dried in air before imaging.

Acid yellow 7 (AY7), which is considered as an effective commercial reagent to detect blood fingerprint, was used to make comparison with the strengths of CSS in the bloody fingerprints imaging. Briefly, 0.2 g of AY7 was mixed with 10 mL of acetic acid, 50 mL of ethanol, and 140 mL of distilled water to form working solution. Blood fingerprint sample preliminarily fixed by 5-sulfosalicylic acid solution was incubated in the working solution for 6 min to be labeled with AY7.

Fingerprints Detection. UCL and Stokes luminescence imaging were performed with a modified Kodak imaging system consisting of an external 0–5 W adjustable 980 nm semiconductor laser or 808 nm pump laser (Connet Fiber Optics, China) as the excited source and an Andor DU937 EMCCD as the signal collector. UCL and Stokes emission signals were collected at 660–720 nm and >830 nm, respectively. Images of UCL and Stokes emission signals were analyzed with Carestream MI SE and Photoshop using the same parameters. The luminescent fingerprint signals developed by AY7 were collected at 515–575 nm under excitation of ultraviolet lamp (365 nm).

RESULTS AND DISCUSSION

Synthesis and Characterization of NaYbF₄:Tm@NaYF₄:Yb@NaNdF₄:Yb Core/Shell/Shell (CSS) Nanoparticles. The hierarchical-structured nanoparticles NaYbF₄:Tm@NaYF₄:Yb@NaNdF₄:Yb (CSS) were prepared by an epitaxial growth method (Figure 1a). The NaYbF₄:Tm core was synthesized by thermolysis of trifluoroacetate precursors, and this was followed by continuous deposition of NaYF₄:Yb and NaNdF₄:Yb shells. As shown by transmission electron microscopy (TEM), the NaYbF₄:Tm core nanoparticles were monodisperse with diameters of ∼8.6 nm (Figure 1b,e). After the NaYF₄:Yb interlayer was coated, the size of the nanoparticles increased to ∼13 nm (Figure 1c,f). Eventually, with the deposition of the outermost NaNdF₄:Yb shell layer, CSS nanoparticles with diameter of ∼18 nm were successfully synthesized, showing a polygonal morphology and good dispersity (Figure 1d,g). On the basis of high-resolution TEM (HRTEM) images with fast Fourier transform (FFT), the nanoparticles synthesized at each step showed high crystallinity and similar FFT patterns (Figure 1e–g insets). High-angle annular dark field scanning transmission electron microscopy (HAADF-STEM) and energy-dispersive X-ray (EDX) line analysis were used to validate the successful synthesis of CSS structure UCNPs. The HAADF-STEM apparently distinguished the different hosts in CSS structure by image contrast resulting from the different atomic weight (Supporting Information, Figure S1a). The EDX line analysis further disclosed the distribution of Nd³⁺, Yb³⁺, and Tm³⁺ ions in the nanoparticles corresponded with the designed composition of CSS nanostructure (Supporting Information, Figure S1b). XRD analysis showed that the obtained CSS nanoparticles were of cubic crystal structure, which also matched the interplanar spacing of corresponding nanoparticles (Supporting Information, Figure S2).

Near-Infrared-to-Near-Infrared Luminescence Properties of the CSS Nanoparticles. To further investigate the Nd³⁺-sensitized upconversion process, photoluminescence emission spectra of NaYbF₄:Tm (core), NaYbF₄:Tm@NaYF₄:Yb (CS), NaYbF₄:Tm@NaYF₄:Yb@NaNdF₄:Yb (CSS), and NaYbF₄:Tm@NaNdF₄:Yb (without the interlayer NaNdF₄:Yb) were recorded under 808 nm excitation. As shown in Figure 2, no UCL emission of Tm³⁺ was generated in the core or CS, but after adding Nd³⁺ ions as the sensitizer, the emission of Tm³⁺ was generated in CSS. Note that there was no discernible Tm³⁺ emission from NaYbF₄:Tm@NaNdF₄:Yb without the NaYF₄:Yb transition layer. In addition, CSS showed Stokes emission at 980 nm (∆F1/2→∆F1/2) under 808 nm excitation.

On the basis of the above phenomena, a possible energy-transfer mechanism may be summarized as follows. Upon excitation at 808 nm, the 4F5/2 state of Nd³⁺ was populated, and this was followed by nonradiative relaxation to the 4F7/2 state. Subsequently, the energy was transferred to Yb³⁺, which was excited to its 2F5/2 state. The energy in a part of the stimulated Yb³⁺ ions resulted in Stokes emission at 980 nm through a
radiation transition process. The other part of the energy migrated across the inner layer and led to population of Tm\(^{3+}\) energy states such as \(^1G_4\) and \(^3F_4\), thereby giving rise to UCL emissions of Tm\(^{3+}\) at 696 nm (\(^{3}F_4 \rightarrow ^{1}H_6\)) and 475 nm (\(^{1}G_4 \rightarrow ^{3}H_6\)). Note that an increased amount of Yb\(^{3+}\) ions in the core layer can enhance the absorption cross-section per nanoparticle and increase the energy-transfer efficiency between Yb\(^{3+}\) and Tm\(^{3+}\).\(^{28}\)

**Surface Modification and Heating Effect Evaluation of the CSS Nanoparticles.** The as-prepared CSS were transferred to an aqueous phase by a facile ligand-exchange method using NOBF\(_4\).\(^{23}\) For latent fingerprint imaging, CSS should be further modified with trisodium citrate. FTIR indicated that the oleate ligands on CSS were removed after treatment with NOBF\(_4\). Successful modification of CSS with citrate was verified by the appearance of C=O stretching bands at \(\nu = 1589\) and 1396 cm\(^{-1}\) (Supporting Information, Figure S3). The UCL and Stokes emission intensities of CSS were maintained after transfer to an aqueous phase (Supporting Information, Figure S4).

During fingerprint imaging, heating effect will result in irreversible damage to the substrate and affect further study of the fingerprints. In the present work, we investigated the heating effects on fragile substrates (polyethylene bags and soft-drink labels) under 808 or 980 nm laser irradiation at different power densities. The corresponding temperature increase profiles were recorded by an infrared thermal imaging device. For the polyethylene bags, time-dependent temperature distribution images revealed a remarkable temperature increase of ca. 40 °C and preliminary deformation of the substrates after 5 s of irradiation at 980 nm, at a power density of 50 mW/cm\(^2\) (Figure 3a; Supporting Information, Figure S7a). In comparison, a temperature increase of only ca. 3 °C was monitored in the case of the 808 nm laser (80 mW/cm\(^2\)) after the same duration of irradiation (Figure 3b; Supporting Information, Figure S7b). Note that 808 nm laser irradiation at 80 mW/cm\(^2\) was the optimized power density for fingerprint imaging, whereas 980 nm laser irradiation at 50 mW/cm\(^2\) was insufficient for obtaining good image quality (Figure 4; Supporting Information, Figure S11). For the soft-drink labels, as shown in Figure S6a (see Supporting Information), the temperature profile showed an increase of ca. 40 °C for these substrates after 5 s of irradiation with a 980 nm laser at 40 mW/cm\(^2\) (Supporting Information, Figure S5a), as opposed to ca. 7 °C with an 808 nm laser at 80 mW/cm\(^2\) (Supporting Information, Figure S6b). Taken together, the above results confirmed that an 808 nm laser can significantly reduce the heating effect on a fragile substrate compared to that when using a 980 nm laser.

**Latent Fingerprint Imaging.** Since the heating effect evaluation data revealed that 808 nm laser irradiation did not damage fingerprint substrates, the as-prepared cit-CSS nanoparticles were explored for latent fingerprint imaging on the two kinds of fragile substrates, namely, polyethylene bags as a nonporous substrate and soft-drink labels as a semiporous substrate, at this wavelength. The incubation procedures are illustrated in Figure S8 (see Supporting Information), which are similar to the established technique of multimetal deposition.\(^{24}\) The fingerprint imaging on polyethylene bags and soft-drink labels under excitation at 808 nm (80 mW/cm\(^2\)) is depicted in Figure 4 and Supporting Information, Figure S9. Evidently, clear and well-defined images on the chosen surfaces could be
achieved in both NIR emission channels, the Tm$^{3+}$ emission at 696 nm (UCL), and the Yb$^{3+}$ emission at 980 nm (Stokes emission). To identify details in the fingerprint and to match ridge characteristics, the “analysis, comparison, evaluation, and verification” (ACE-V) examination method, which is a well-established process, was used for comparative identification.\textsuperscript{29} ACE-V usually involves the recognition of details, such as the ridge details in fingerprint images. The enlarged view of a fingerprint (Figure 4c) revealed specific ridge details, such as whorl (level 1), termination, bifurcation, hook, opposed bifurcation, enclosure, and crease (level 2), which were sufficient for identity recognition. Scanning electron microscope (SEM) images confirmed the preferential deposition of cit-CSS on the ridges of fingerprints, as shown in Figure S10 (see Supporting Information). The successful fingerprint labeling is attributed to the electrostatic interaction between cit-CSS and fingerprints as well as chemical reaction between the carboxyl functions on cit-CSS and amine groups of latent secretions.\textsuperscript{24,30} At 980 nm, the fingerprints showed ambiguous and lower contrast images, and the irradiation power density started to generate thermal damage (50 mW/cm$^2$ for polyethylene bags and 40 mW/cm$^2$ for soft-drink labels). At a power density of 80 mW/cm$^2$, the substrates were completely damaged, and the whole fingerprint image could not be recognized (Supporting Information, Figure S11). Thus, an 808 nm excitation source, which exhibited excellent imaging quality in the absence of an overheating effect, will supersede 980 nm excitation in latent fingerprint imaging on fragile substrates.

**Blood Fingerprint Imaging.** Previous studies have revealed that the absorption behavior of blood is mainly caused by hemoglobin,\textsuperscript{31} which is characterized by remarkable absorbance in the visible light region and low absorbance in the NIR region (Supporting Information, Figure S12).\textsuperscript{32} Hence, the detection of blood fingerprints is quite challenging when using visible-light-emissive luminescent material due to the substantial quenching effect. To address this problem, NIR-emissive CSS was investigated for application to blood-contaminated fingerprints. First, emission spectra of hydrophilic CSS in blood and water were collected to investigate the influence of hemoglobin on luminescence. As shown in Figure 5, the UCL signal in the visible region was dramatically quenched by hemoglobin in blood, whereas the emission intensity located in the NIR window was comparable to that in water. To assess their potential for bloodstain detection, the hydrophilic CSS nanoparticles described herein were incubated with blood fingerprints, as schematically illustrated in Figure S13 (see Supporting Information). Distinct ridge patterns were observed in both the UCL and Stokes emission imaging modes in the NIR regions for the two different substrates, especially for the surfaces of polyethylene bags (Figure 5 insets; Supporting Information, Figure S14). In distinct contrast, the UCL image in the visible region was ambiguous, since the emission was quenched by the blood (Figure 5 insets). Moreover, a commercial dye, AY7, was applied in blood fingerprint imaging to make comparison with the results obtained by CSS nanoparticles. In the experiment, two types of blood fingerprints are tested with AY7 dye. One sample is prepared with normal concentration of blood, and another is prepared with diluted blood. As shown in Figure S15 (see Supporting Information), imaging qualities of both fingerprint samples are poorer than the blood fingerprint stained with CSS nanoparticles. These results proved that our CSS nanoparticle can serve as an ideal alternative for blood fingerprint detection. The interaction between hemoglobin and CSS is possibly based on physicochemical affinity and needs to be further investigated. Overall, the CSS nanoparticles can provide high contrast, low heat effect, and sufficient details for developing both latent and blood fingerprints on fragile substrates.

**CONCLUSION**

In conclusion, we have demonstrated the potential of hierarchical-structured NaYbF$_4$:Tm@NaYF$_4$:Yb@NaNdF$_3$:Yb (CSS) nanoparticles with dual NIR emissions at 696 and 980 nm under excitation at 808 nm for latent and blood fingerprint imaging. The Yb$^{3+}$-rich NaYbF$_4$ core promotes efficient energy transfer to Tm$^{3+}$. The interlayer of NaYF$_4$:Yb in the CSS nanoparticles effectively prevents the cross-relaxation process from Tm$^{3+}$ to Nd$^{3+}$ and thus enhances the luminescence emission. The introduction of Nd$^{3+}$ ion as a sensitizer shifts the excitation wavelength from 980 to 808 nm, which subtly averts laser-induced thermal damage of fingerprint samples and offers a new pathway for the NIR emission channel at 980 nm. The CSS nanoparticles have been successfully applied to latent and blood fingerprint development on nonporous and semiporous substrates, facilitating excellent imaging quality for personal identification. Compared with 980 nm excitation, 808 nm excitation results in a low heat effect and dual imaging of fingerprints on fragile substrates. This work points to a promising strategy for realizing NIR-to-NIR dual-channel emission in lanthanide-based upconversion nanoparticles. Through further modification, it is believed that such nanoparticles may be tailored for more extensive applications in forensic and biological sciences.

**ASSOCIATED CONTENT**

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.inorgchem.6b01536.

XRD patterns, FTIR results, emission spectra of nanoparticles, temperature increase profiles for soft-drink labels, schematic representation of latent fingerprint incubation, and UCL and Stokes emission images of fingerprints on soft-drink labels. (PDF)
REFERENCES

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