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REVIEW

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Recent Advances in Purely Organic Room Temperature Phosphorescence Polymer

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Abstract Room temperature phosphorescence (RTP) has drawn increasing attention for its great potential in practical applications. Polymers with large molecular weights and long chains tend to form coil, which can endow them with a high degree of possible rigidity and result in the much restricted non-radiative transition. Also, the intertwined structure of polymers could isolate the oxygen and humidity effectively, thus reducing the consumption of triplet excitons. In consideration of these points, organic polymers would be another kind of ideal platform to realize RTP effect. This short review summarized the design strategy of the purely organic room temperature phosphorescence polymers, mainly focusing on the building forms of polymers and the corresponding inherent mechanisms, and also gives some outlooks on the further exploration of this field at the end of this paper.

Keywords Room temperature phosphorescence; Polymers; Non-radiative transition

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INTRODUCTION

Room temperature phosphorescence (RTP) has drawn increasing attention for its great potential in the applications of anti-counterfeiting, bioimaging, sensors, organic light-emitting diodes, and so on.[1–17] Generally, most of RTP materials contain noble metals, which would result in the inferior biocompatibility, potential toxicity, and high cost *etc*.[18,19] As for the purely organic luminogens, the phosphorescence mostly occurs in rigid matrix at 77 K, while those at room temperature are really scarce, mainly because of the excessive deactivation of oxygen, humidity, and thermal motion.[20–22] Fortunately, the RTP effect has been successfully achieved in some certain organic small molecules through the rational crystal engineering. For example, Tang *et al*. reported a series of carbonyl derivatives with crystallization-induced phosphorescence effect;[23–25] Kim *et al*. realized a high RTP quantum yield up to 55% through mixed crystals;[26] Chen, Liu, and Huang *et al.* stabilized the triplet excitons through H-aggregation in crystal with RTP lifetime up to 1.35 s.[27] It is a pity that their RTP performance would be much weakened or even disappear after the destruction of crystal, which limited their practical applications to a large degree.

On the other hand, polymers with large molecular weights and long chains tend to form coil, which could endow them with a high degree of possible rigidity and result in the much restricted non-radiative transition (Fig. 1). Also, the intertwined structure of polymers could isolate the oxygen and humidity effectively, thus reducing the consumption of triplet excitons.[28,29] In consideration of these points, organic polymers should be another kind of ideal platform to realize RTP effect in addition to crystal engineering. Furthermore, the polymer-based materials have been found with a series of fantastic properties, such as good flexibility, easy processing, low cost, and high thermal stability. The introduction of RTP polymers would be of great importance for their practical applications. Accordingly, scientists devoted great enthusiasms to developing RTP polymers in recent years. Particularly, some classical phosphor groups were incorporated into polymers, such as difluoroboron dibenzoylmethane, naphthalene imide, and 4-bromobenzaldehyde.[3,28] With these phosphor groups acting as guests, side chains, main chains, or terminal groups of the resultant polymers, their intramolecular motions could be restrained effectively and the RTP effect could be successfully realized. Besides, cross-linked polymers were developed to further increase the rigid degree, thus resulting in the much enhanced RTP performance. More interestingly, even some non-aromatic polymers were found to have RTP effect in recent years, which has greatly expanded people's understanding of luminescence.[30–32] In this short review, we summarized the design strategy of the purely organic room temperature phosphorescence polymers, mainly focusing on the building forms of polymers and the corresponding inherent mechanisms. In the

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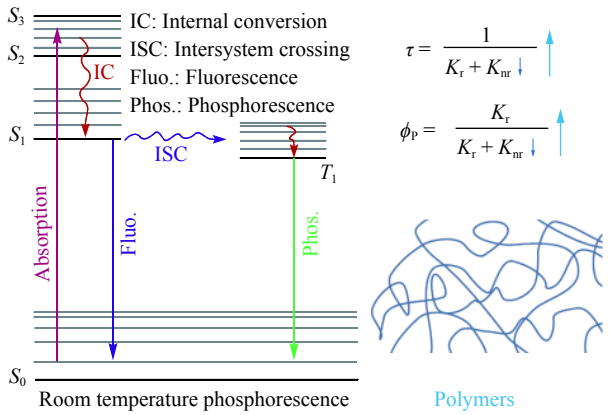


Fig. 1 The general diagram for organic room temperature phosphorescence

end, some in-depth considerations were proposed for open discussions, and some outlooks were presented to possibly guide further development.

RTP POLYMER DESIGN STRATEGY

As stated above, the organic polymers with long chains and intertwined structure could effectively restrict the deactivation of triplet excitons originating from oxygen, humidity, and thermal motion. To achieve this, there are mainly two methods to be utilized: one was non-covalently incorporating phosphor groups into polymer matrixes *via* physical encapsulation; the other was covalently connecting potential phosphor groups into polymers through chemical modification, in which the phosphor groups could act as terminal groups or side chains or main chains.[3,28] Furthermore, the polymer matrixes either in physical encapsulation or with chemical modification could both be further enhanced through crosslinking. Fig. 2 presents the basic models for these strategies, through which some efficient RTP polymers have been obtained.

Aromatic RTP Polymers

Physical encapsulation

Encapsulating small organic molecules in the rigid polymer matrix has been frequently utilized in RTP systems for its effective restriction on non-radiative motion and easy process.[33–37] It was believed that polymers with good transparency and strong hydrogen bonding capability have the potential to act as matrix, such as poly(methyl methacrylate) (PMMA), poly(vinyl alcohol) (PVA), poly-(lactic acid) (PLA), and so on. As shown in Fig. 3, when G1, an organic phosphor, was embedded in PVA to form an amorphous RTP system, multiple intermolecular interactions, including hydrogen bonds (H—O···H) between polymer matrix, and hydrogen bonds (H—O···H) between small phosphor guests and polymer matrix, and halogen bonds (C=O···Br) between small RTP guests, were introduced to restrict the thermal motion.[38] Besides, the C=O···Br halogen bonds could enhance the spin-orbit coupling as well as the intersystem crossing between singlet and triplet states. With these advantages, efficient RTP performance with Φ_P value up to 24% and lifetime of 5.9 ms under ambient conditions could be achieved. If G1 was replaced by another small organic phosphor like (2,5-dihexyloxy-4-bromobenzaldehyde) (Br6A), Φ_P would largely decrease to 12% due to the weakened hydrogen bonds between small phosphor guest and polymer matrix. This control experiment could well certify the significant role of strong intermolecular interactions and rigid environment in RTP systems.

As the covalent bonds were much stronger than the non-covalent ones, including hydrogen and halogen bonds, the cross-linked polymer matrix could be developed to further enhance the rigid degree of the resultant systems, thus greatly promoting the RTP properties of small phosphor guests. As shown in Fig. 4, Su *et al.* have successfully enhanced the RTP effect by utilizing the easy crosslinking character of PVA.[39] A new organic guest molecule, hexa-(4-carboxyl-phenoxy)-cyclotriphosphazene (donated as G), containing six extended benzoic acid arms was introduced, in which the six extended aromatic carbonyl units could provide enough *n* orbitals to trigger the ISC from S_1 to T_n, and the —COOH groups could form hydrogen bonds with the PVA matrix. As a small proportion of G was encapsu-

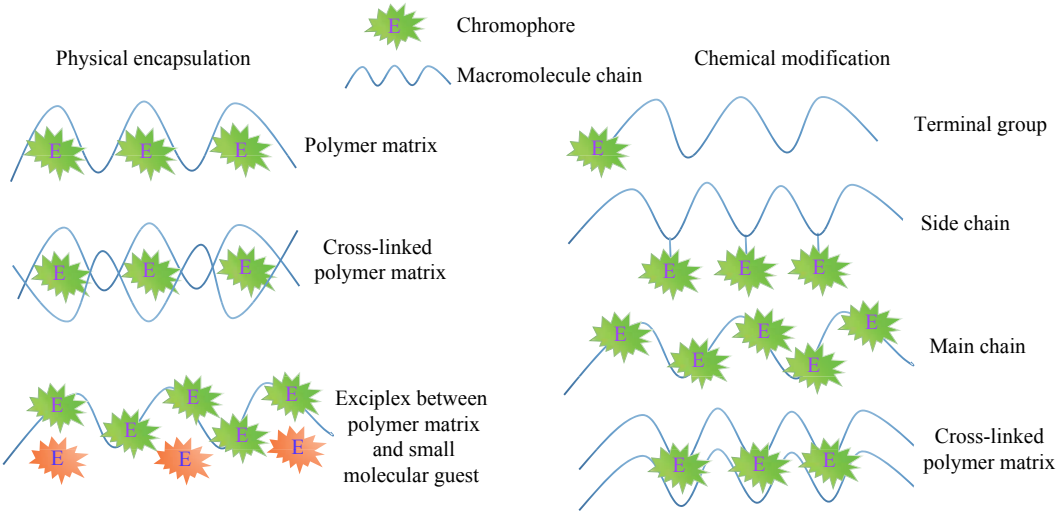


Fig. 2 The basic models for the design strategies of RTP polymers

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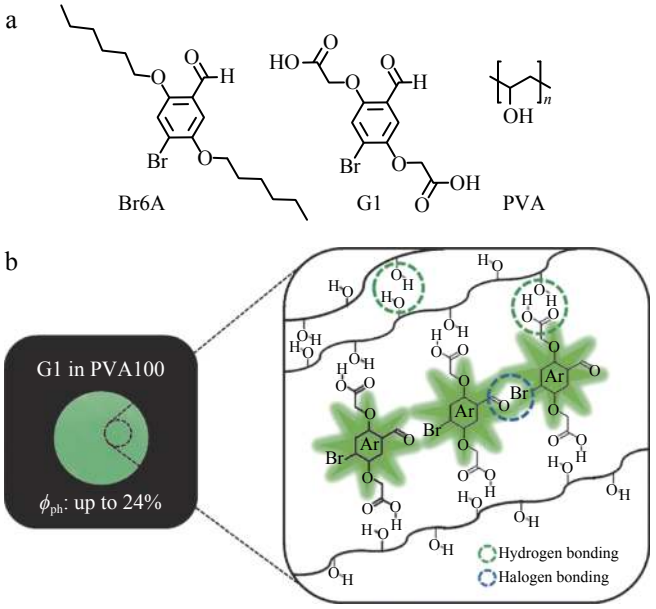


Fig. 3 (a) Chemical structures of Br6A, G1, and PVA; (b) Phosphorescence image of G1 embedded in PVA100 under UV light irradiation (λ = 365 nm) (Reprinted with permission from Ref. [38]; Copyright (2014) John Wiley and Sons)

lated by PVA, just inefficient RTP could be observed with phosphorescence lifetime (τ_P) and quantum efficiency (Φ_P) of 0.28 s and 2.85%, respectively. Interestingly, after 254 nm light irradiation for 65 min, its τ_P and Φ_P could largely increase to 0.71 s and 11.23%, respectively, for the cross-linked PVA and the accompanying further suppression of vibrational dissipation. Thus, it was believed that the introduction of easy cross-linked polymer matrix under external stimulus should be an efficient way to promote the RTP effect of the small phosphor guests in physically encapsulated systems.

Apart from the rigid matrix, the polymer-based host materials could also interact with small phosphor guests to form exciplex, thus could largely prolong the RTP lifetime.[40,41] Pioneering works have been done by Adachi *et al*. As shown in Fig. 5, a blend of TMB (1%), as electron donor, and poly(arylene ether phosphine oxide), namely PBPO (99%), as electron acceptor, could emit long-persistent luminescence lasting more than 7 min after low-power excitation at room temperature.[42] This ultralong luminescence should be mainly attributed to the formation of local exciplex between polymer matrix and small molecular guest with low doping ratio. Thus, the long-lived charge-separated states could be formed, largely increasing the lifetime of excitons. This is the first example of purely organic long-persistent luminescence system with polymer matrix acting as electron acceptor to form exciplex with small molecular guest, which opened up a new avenue to develop ultralong RTP systems.

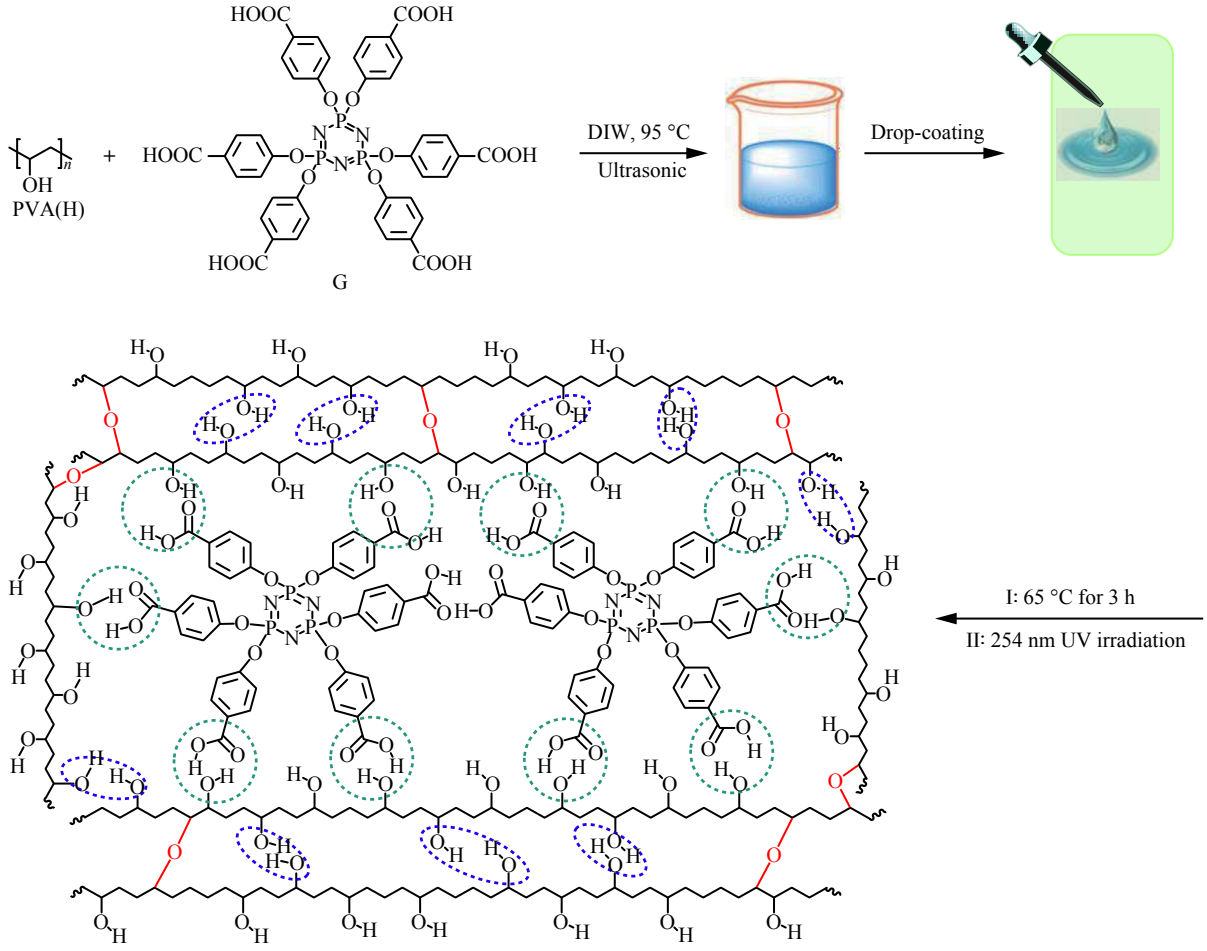


Fig. 4 Chemical structures of G and PVA and the fabrication of G-doped PVA films for RTP

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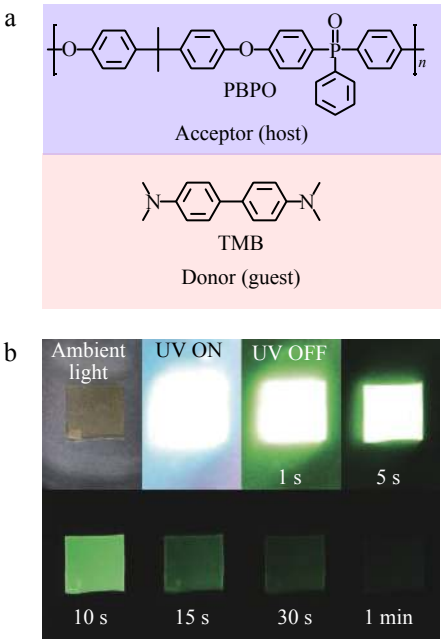


Fig. 5 (a) Chemical structures of PBPO and TMB; (b) Photographs of a 1 wt% TMB/PBPO thick film at 298 K (Reprinted with permission from Ref. [42]; Copyright (2018), John Wiley and Sons)

Chemical modification

In addition to the physical encapsulation, the chemical modification by covalently connecting potential phosphor groups into polymers is another efficient approach to restrict thermal motions as well as non-radiative transitions.[43–47] In 2007, pioneering work was reported by Fraser and co-workers. As shown in Fig. 6, when boron difluoride dibenzoylmethane (BF_2dbm) acted as a terminal group to couple with PLA, the fluorescence quantum yield was enhanced and oxygen-sensitive RTP effect could be observed for the resultant polymer BF_2dbmPLA.[48] In ambient atmosphere, BF_2dbmPLA only showed green fluorescence with a short lifetime of a few nanoseconds. Once upon deoxygenation, the green RTP, lasting for 5−10 s, could be observed for solid BF_2dbmPLA, either as suspensions in aqueous solution or film. This indicated that the intertwined structure of polymer could effectively lock the non-radiative motion of the phosphor terminal groups, thus contributing much to the realization of RTP effect.

It has been widely known that halide substituents could modulate structural and optical properties of materials, especially for those related to the excited triplet state. Later in 2015, Fraser *et al.* synthesized a series of halide-substituted BF_2dbm(X)PLA (Fig. 7, X = H, F, Cl, Br, and I), to effectively tune the triplet emission of polymers *via* the heavy atom effect.[49] Under an atmosphere of nitrogen, the polymers with lighter halide substituents (H, F, and Cl) had weak phosphorescence shoulders in their emission spectra but long green RTP lifetimes of more than 100 ms. As for those with heavier halide substituents (Br and I), phosphorescence dominated the whole emission, while the corresponding lifetimes decreased to < 50 ms. This clearly demonstrated the heavy atom effect in the polymer-based RTP materials,

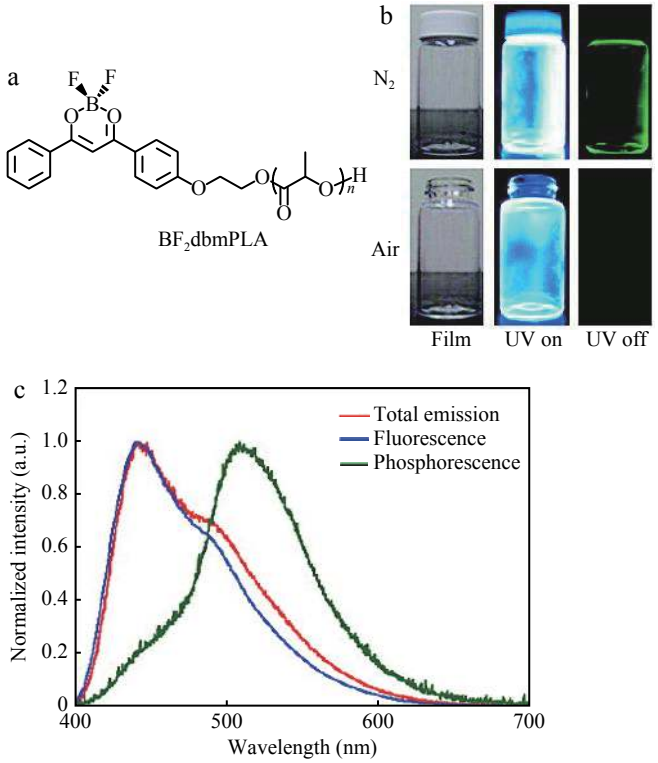


Fig. 6 (a) Chemical structure of BF_2dbmPLA; (b) Photographs of BF_2dbmPLA thin films under air and vacuum; (c) Normalized emission spectra for a BF_2dbmPLA thin film, including the room temperature emission under vacuum (442 nm), fluorescence under air (442 nm), and phosphorescence (509 nm) with delayed fluorescence (~450 nm) under vacuum after the excitation is turned off (Reprinted with permission from Ref. [48]; Copyright (2007) American Chemical Society)

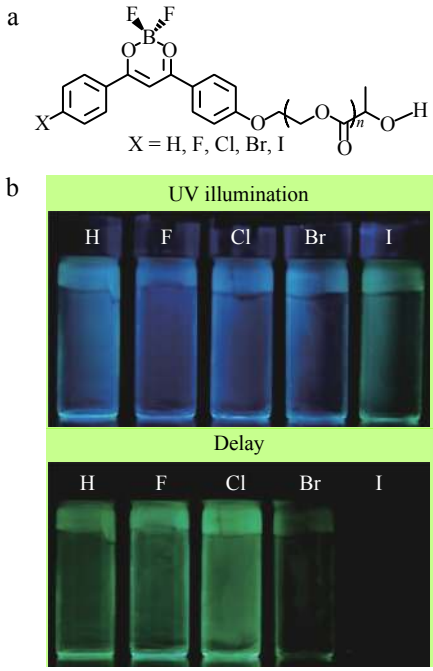


Fig. 7 (a) Chemical structures of BF_2dbm(X)PLA; (b) Images of BF_2dbm(X)PLA films under N_2 with UV illumination and after the lamp is turned off (delay) (Reprinted with permission from Ref. [49]; Copyright (2015) American Chemical Society)

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which could promote ISC transition, thus resulting in the increased RTP intensity but decreased lifetime.

Similarly, the phosphor groups could be covalently linked to the side chain of the polymer matrix to restrict the thermal motion as well as the non-radiative relaxation process of triplet excitons.[50,51] Accordingly, Tian and Ma *et al.* developed a general strategy through the simple radical binary copolymerization of acrylamide and different potential phosphor groups.[52] As shown in Fig. 8, to confirm the universality of this copolymerization method, three RTP polymers with phosphor groups, acting as side chain, were prepared by radical binary copolymerization, in which the phosphors were 2-bromo-5-hydroxybenzaldehyde derivative, *α*-bromonaphthalene derivative, and 4-bromo-1,8-naphthalic anhydride derivative, respectively. As expected, all of them showed efficient RTP properties with phosphorescence efficiencies of 11.4%, 8.4%, and 7.4% under ambient atmosphere. Furthermore, it was found that their RTP performances were all sensitive to water for its destructive effect on the hydrogen bonds between polymeric chains. With this unique property, these polymers could be applied as printer ink, in encryption, and so forth. Taking poly-BrNpA as an example, the five red letters "ECUST" could appear or disappear before and after wetting. This research provided a facile way to construct the purely organic RTP polymer with high phosphorescence efficiency.

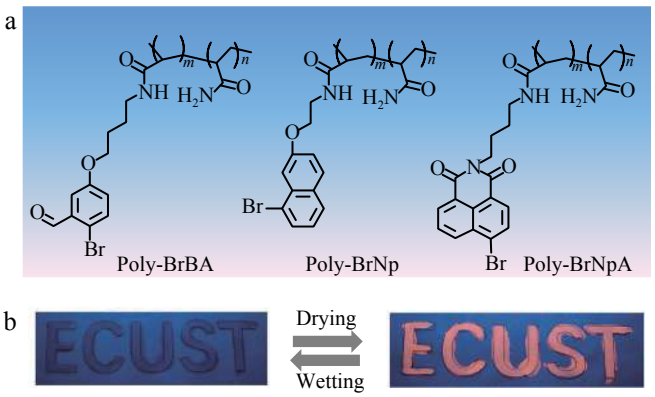


Fig. 8 (a) Structures of poly-BrBA, poly-BrNp, and poly-BrNpA; (b) Photographs of letters written using aqueous poly-BrNpA solution before and after drying, upon light irradiation at 365 nm (Reprinted with permission from Ref. [52]; Copyright (2016) John Wiley and Sons)

Besides the emissive efficiency, RTP lifetime was also an important parameter. Interestingly, ultralong RTP effect was observed in poly(styrene sulfonic acid) (PSS), a sort of commercial polymer material, in which the phenylsulfonic acid group acted as side chain.[53] As shown in Fig. 9, the green afterglow could last for more than 2.2 s in air after turning off the 365 nm UV irradiation, which was longer than most of the RTP materials, including polymers and small mo-

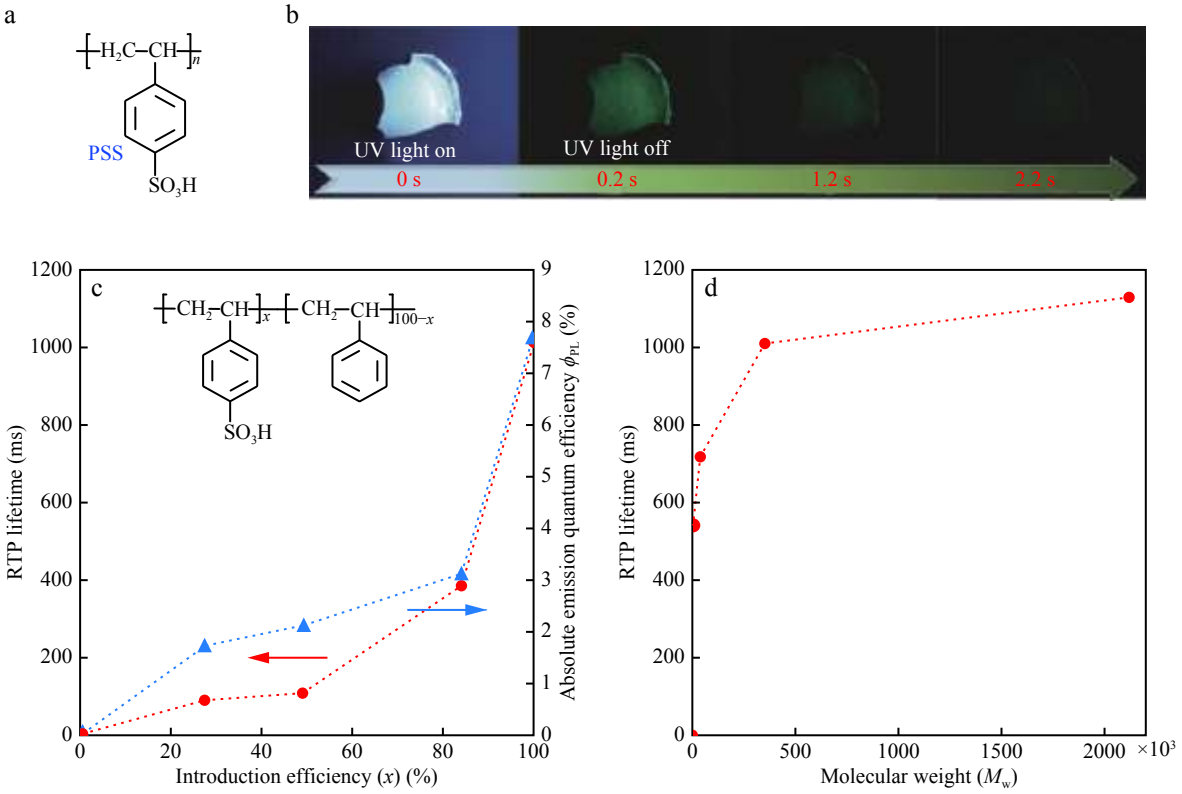


Fig. 9 (a) Chemical structures of poly(styrene sulfonic acid); (b) Luminescence photographs of the self-standing PSS film under 365 nm UV irradiation and at different time after UV irradiation; (c) Effect of introduction ratio of sulfonic acid groups on RTP lifetime (red circles) and absolute emission quantum efficiency (blue triangles). PSS with various introduction efficiencies of sulfonic acid groups were prepared by aromatic sulfonation of PS (M_w 3.50 × 10^5); (d) Effect of PSS polymer weight on RTP lifetime (red circles). PSS (100% introduction ratio of sulfonic acid groups) with various molecular weights were produced by aromatic PS sulfonation (Reprinted with permission from Ref. [53]; Copyright (2018) John Wiley and Sons)

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lecules. Furthermore, the RTP lifetime was found dependent on the ratio of phenylsulfonic acid groups: as the ratio increased, the lifetime of phosphorescence became longer with 1.01 s achieved at PSS carrying a quantitative introduction ratio of phenylsulfonic acid groups. These results further certified that the potential phosphor groups covalently linking to the side chain of the polymer matrix was an effective way to develop efficient persistent RTP materials.

Further on, the potential phosphor groups could be covalently bonded in the main chain of polymer matrix.[54–56] Two main strategies were often utilized: one was to covalently introduce the potential phosphor groups in the non-conjugated polymer chain, while another was the direct polymerization of potential phosphor groups. In 2015, Zhang *et al.* covalently incorporated amino-substituted benzophenone (a phosphor group, R_3) into the waterborne polyurethanes (WPU) with small proportions, and achieved the dual fluorescence and phosphorescence at room temperature in the resultant polymer SDM successfully (Fig. 10).[57] Interestingly, the increasing concentrations of R_3 group could lead to progressively narrowed singlet-triplet energy gaps, resulting in the tunable PL behaviors. As shown in Fig. 10(c), when R_3 was incorporated into the polymer at the weight ratio of 1%, the resultant polymer SDM1 gave dual emissions with fluorescence peaked at 445 nm and phosphorescence of 505 nm. Besides, the RTP lifetime was as long as 53.5 ms under vacuum. Accompanying with the increasing concentrations of R_3 group, the singlet-triplet energy gaps would become narrower for the polymerization-enhanced intersystem crossing (PEX). The similar singlet and triplet levels could be achieved at the R_3 concentrations of about 20%. At this time, the phosphorescence would be replaced by delayed fluorescence completely, with the PL spectrum peaked at 460 nm and corresponding lifetime of 4.0 ms, respectively.

Terephthalic acid and its derivatives have been found showing crystallization-induced dual emission (CIDE) effect for the effective restriction of non-radiative motion and external quenching of triplet excitons from oxygen, humidity, *etc*. Inspired by it, Yuan and co-workers revisited the emission of poly(ethylene terephthalate) (PET), which could be regarded as the direct polymerization of potential phosphor groups (Fig. 11). Similar to its small molecular analogues, PET showed interesting characteristics of concentration-enhanced emission and aggregation-induced emission (AIE).[58] Furthermore, the emissive efficiencies of its films were enhanced with the increased crystallinity besides the appearent RTP, thanks to the conformation rigidification and restricted thermal motion in the crystal state. These experimental results could well certify that the addition of the potential phosphor groups, which acted as the main chain, was also an efficient way to develop RTP polymers.

Similar to that in physical encapsulation, the cross-linking strategy could also be utilized in the chemical modification to further enhance the RTP efficiency.[59] In 2015, Fraser and co-workers reported that through Diels-Alder click chemistry, the phosphor, DA1, and polymer matrix, PFMA, could covalently cross-link together, and the resultant cross-linked DA1 showed a much enhanced Φ_P of 13%, about 2.5 times higher than that of Br6A-doped polymer without such covalent linkage (Fig. 12).[60] Thus, the restricted molecular motions in the vicinity of phosphors by cross-linking between

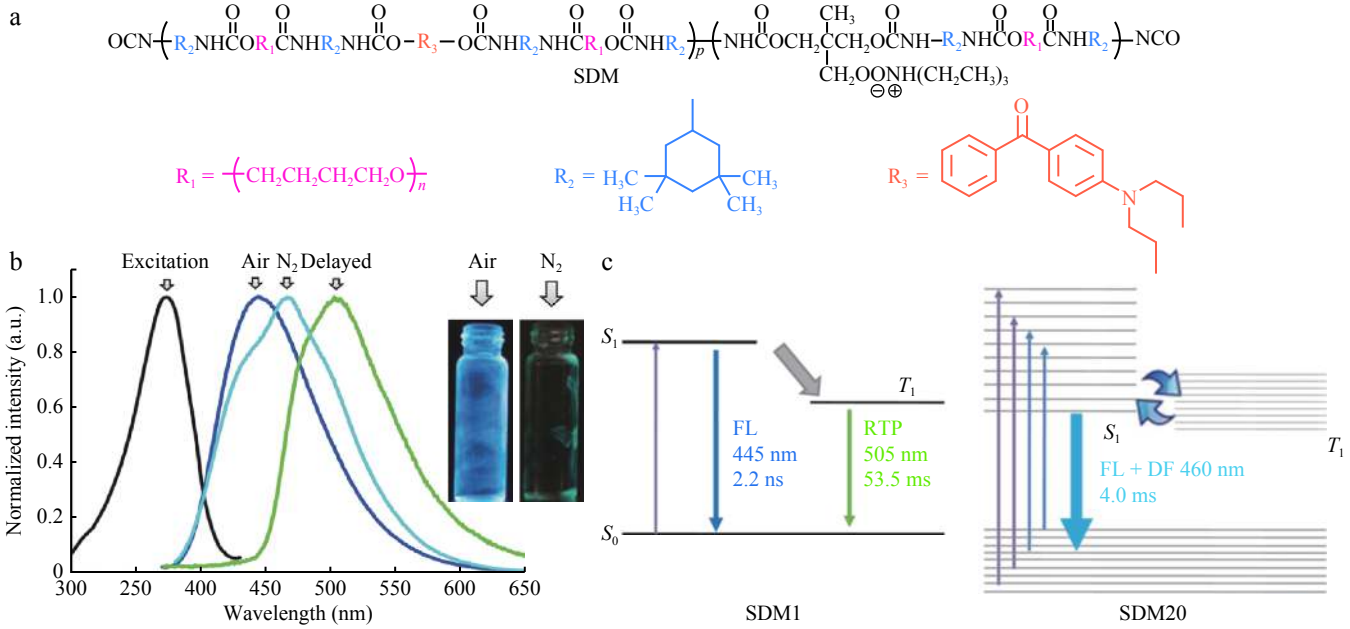


Fig. 10 (a) Chemical structures of SDM; (b) Steady-state excitation (black line) and emission spectra of SDM1 thin film in air (blue line) and in N_2 (cyan line), and delayed emission of SDM1 thin film under vacuum (Δt = 50 ms, λ_{ex} = 389 nm). Images showing that, when the SDM1 thin film on the inner wall of a vial is exposed to air, only blue fluorescence is observed under UV excitation from a hand-held lamp (λ_{ex} = 365 nm); when a stream of N_2 is blown into the vial, a "afterglow" can be captured after the excitation has ceased; (c) Illustration of polymerization-enhanced intersystem crossing (PEX) with simplified Jablonski diagrams (Reprinted with permission from Ref. [57]; Copyright (2015) American Chemical Society)

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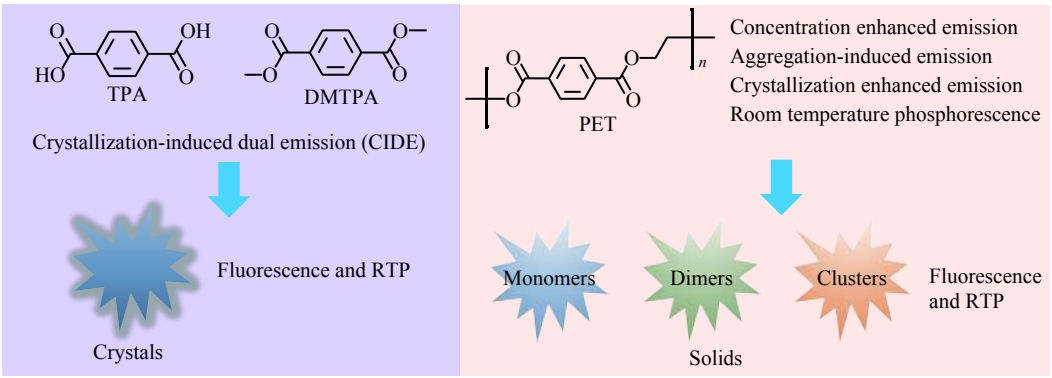


Fig. 11 Chemical structures of TPA, DMTPA, and PET and the schematic illustration of their emission properties at various states

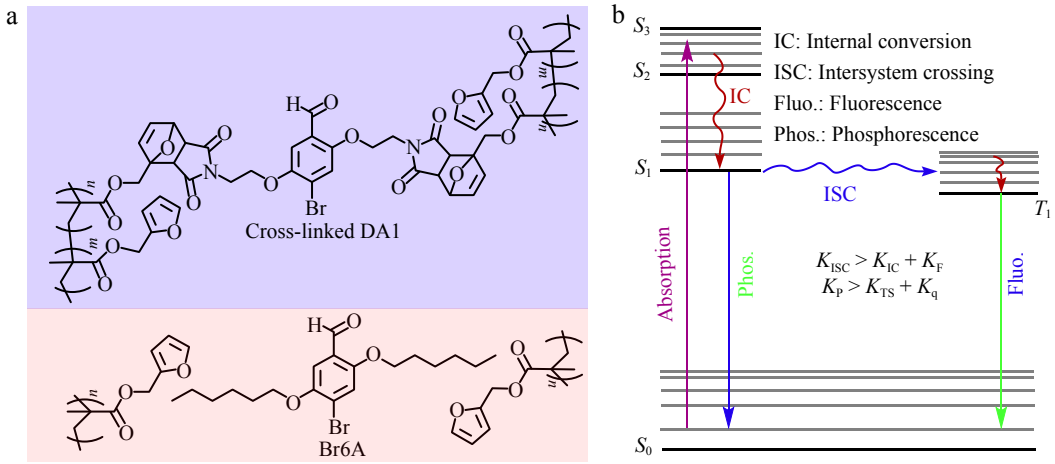


Fig. 12 (a) Chemical structures of designed phosphor; (b) A general Jablonski diagram of organic emitters

phosphors and polymer matrix were the most important factor to suppress the non-radiative decay, leading to a much enhanced phosphorescence efficiency.

Later on, Kim *et al.* designed a new RTP-based oxygen detection system by adopting the same strategy with nanoparticles. In this RTP system, the core-shell structure was realized with water-soluble polymethyloxazoline shells and oxygen-permeable polystyrene cores crosslinked with purely organic phosphors (Fig. 13).[61] With this unique structure, the intramolecular thermal motion was effectively restricted, while oxygen could pass through the oxygen-permeable cores and quench the triplet excitons. Thus, it exhibited bright green RTP when it was dispersed in argon saturated water, but the phosphorescence much decreased with the addition of oxygen, indicating the high sensitivity to oxygen with the limit of detection (LOD) of 60 nmol/L. Thus, this new detection platform might be widely utilized for the convenient and easy monitoring of dissolved oxygen.

Non-aromatic RTP Polymers

Generally, PL emission mostly occurs in aromatic systems rather than non-aromatic ones, for their flexible structures could easily induce frequent vibrations and rotations. Recently, a series of natural products without aromatic structures were found to show distinct PL emission in solid state, such as rice, starch, cellulose, and BSA, *etc.*[62–65] Their corresponding lifetimes were measured to be as high as microsecond level, indicating the possible RTP effect. These interesting phenomena have greatly expanded the research content of luminescence. It was believed that the existence of electron-rich heteroatoms with lone pair electrons played the significant role for their PL emission. On the one hand, the electron clouds of the heteroatoms would overlap and share in crystalline state, thus generating new clustered electron-rich chromophores with lowered energy gaps and extending the effective conjugation length. On the other hand, effective molecular interactions, including hydrogen bonds, could significantly prevent non-radiative decays. Thus, the synergistic effect of these two factors led to the efficient RTP effect in non-aromatic systems in solid state.

Inspired by it, the PL behaviors of non-aromatic poly(amino acids), like ε-poly-L-lysine (ε-PLL), was explored by Yuan *et al.*, as polymers possessed more rigid conformations with the constraint of polymer chains (Fig. 14).[66] Also, the polymeric structure could facilitate intra- and intermolecular interactions in concentrated solutions and solids. Interestingly, persistent RTP effect could be observed in ε-PLL powder, which presented bright blue-violet emission under 365 nm UV light, while green afterglow could be caught by naked eyes after ceasing the irradiation. Thus, with the rigid environment, such as crystalline state or polymer

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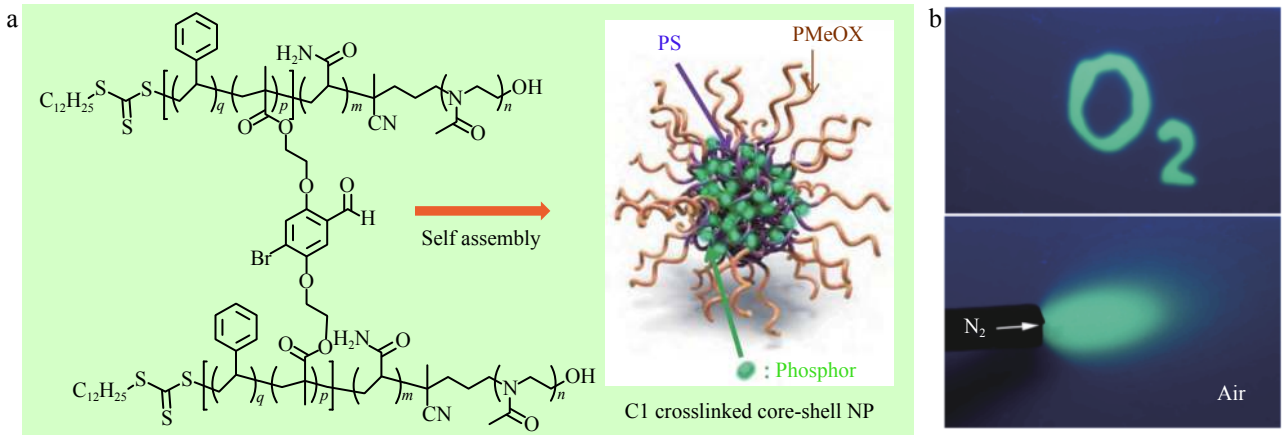


Fig. 13 (a) Synthetic routes to C1-crosslinked NPs; (b) Images obtained with an RGB camera upon illumination of the planar optical sensor with the 366 nm line of a UV-lamp. Bright green phosphorescence indicates the areas of the sensor soaked with an anoxic aqueous solution (containing 5 wt% of glucose and 0.05 wt% of glucose oxidase) (top image) and the area of the sensor deoxygenated with a flow of nitrogen (bottom image) (Reprinted with permission from Ref. [61]; Copyright (2017) John Wiley and Sons)

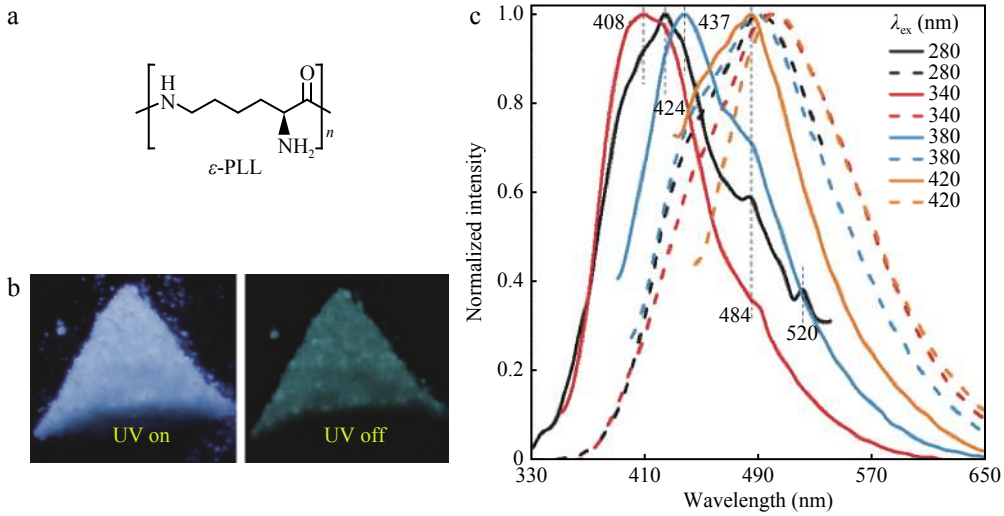


Fig. 14 (a) Chemcial structure of ε-PLL; (b) Solid powders taken under 365 nm UV light or after ceasing the UV irradiation; (c) Normalized emission spectra of ε-PLL solids with t_d of 0 (solid line) and 0.1 ms (dash line) under varying λ_{ex}s (Reprinted with permission from Ref. [66]; Copyright (2017) Science China Press and Springer Verlag GmbH Germany, part of Springer Nature)

chain, distinctly persistent RTP effect could also occur in non-aromatic systems.

As polymers are mixtures without exactly accurated structures and some impurities can be easily trapped, the internal mechanism of the RTP effects is still unclear. Could the persistent RTP effect also be realized in non-aromatic small molecules? If the persistent RTP effect could also be realized in non-aromatic small molecules, with it, more important informations on the relationship between RTP and molecular structure, as well as the molecular packing, could be revealed. Recently, cyanoacetic acid (CAA), an ultra-simple molecule without any aromatic group, was found to show RTP lifetime as long as 862 ms by Li *et al*., which should be the first example of a non-aromatic purely organic small molecule with persistent RTP property (Fig. 15).[67] Through careful analyses of single crystal, it was found that CAA molecules assembled layer by layer with an interlayer spacing (d) of 3.0225 Å, which would be very beneficial to the extended conjugation of electron cloud, thus resulting in the much narrower energy gap. Furthermore, strong hydrogen bonds ($d_{O–O}$ = 2.6337(16) Å) were observed to extend over the whole CAA crystal. With this, a unique structure, which is similar to polymer, could be formed through non-covalent connections. This would increase the molecular rigidity and help to lock the molecular conformations, thus effectively restricting the non-radiative transition. These two factors both contributed much to the realization of persistent RTP effect of CAA. Therefore, with the exact molecular structure and crystal packing in CAA, the internal mechanism of RTP effect could be well studied and understood.

OUTLOOK

So far, the research of purely organic luminogens with RTP has been attracting more and more interests, and polymers are an important kind of RTP materials. For the further

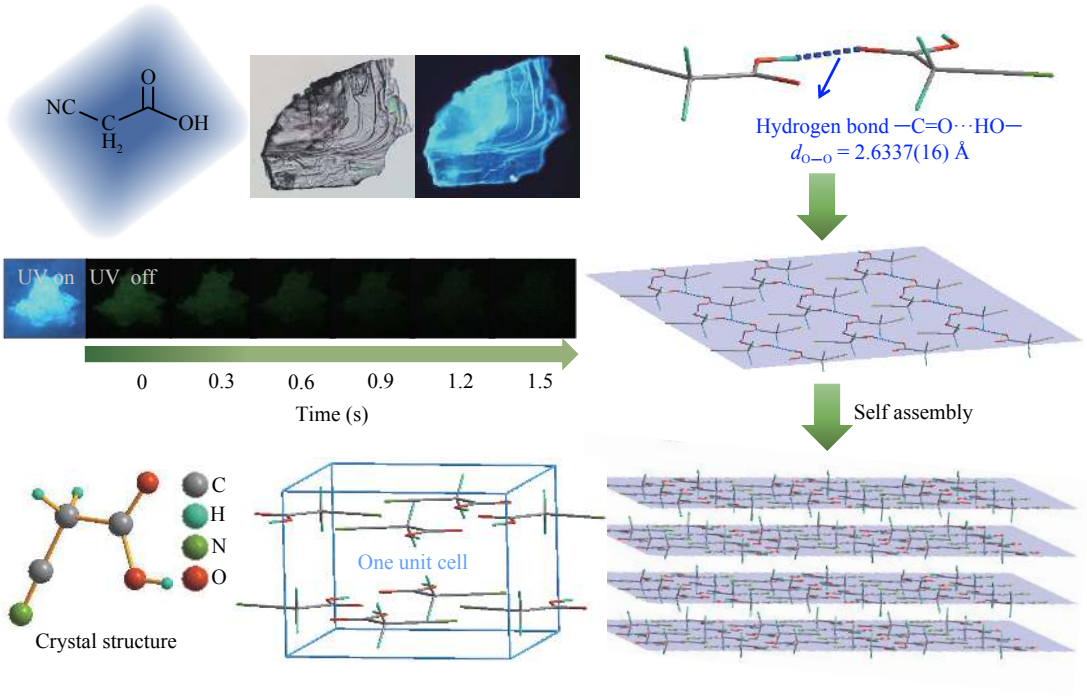


Fig. 15 RTP behaviors and crystal structure of CAA[67]

development of organic RTP polymers, perhaps, at least four issues should be considered seriously: the defined structure, the inherent mechanism, the better performance, the well-established structure-property relationship and the potential application.

As mentioned above, the RTP polymers so far reported are mixtures without defined structure and the possibly trapped impurities make the RTP properties unreliable in some cases. It is well known that different batches of polymers should not be mixed together as small organic molecules do because of their different components. Thus, without defined structure, the same properties might not be retained easily. Fortunately, the CAA example could be considered as an alternative approach to design non-covalent polymers, but with well-defined structure required. Perhaps, the self-assembly effect could be utilized for the design of this kind of RTP polymers. Surely, dendrimers with defect-free structure and accurate molecular weights should be a good approach for the development of RTP polymers, although there have been no related reports so far.

Without the defined structure, it is reasonable that deep understanding has been barely developed on the inherent mechanism of RTP polymers. Actually, the present proposed explanations for the RTP properties of polymers are just some speculations and imagination to a large extent. Thus, more serious work should be conducted to explore the inherent mechanism, while totally getting rid of the possible influence of impurities and double confirming the RTP properties. The involvement of photophysical and theoretical scientists is badly needed, in addition to the polymer physicists.

Although some RTP polymers and small molecules have been reported, the RTP performance still needs improving to meet the practical applications. Actually, with more purely organic RPT systems being developed, more information could be obtained for systematically exploring the mechanism, especially those having good RTP performances. From this point, the enhancement of RTP performance and the understanding of the inherent mechanism could promote each other.

As for the summarization of the structure-property relationship, it is a difficult task even with the defined structure and exact properties, since it is not easy to assign functions to specific moieties. For the RTP property, it is highly related to the molecular/functional group packing and their interactions, but not single moieties. Thus, how to get the accurate information of the packing status in addition to their electronic structure is the key point for deeper understanding. For small organic molecules, analysis of single crystals is the best choice. However, for those without single crystals especially RTP polymers, some modern testing instruments and techniques should be considered and developed.

With the clear structure-property relationship, various RTP materials could be developed to meet the different requirements for practical applications. For example, some organic luminogens with high RTP quantum yields could be developed to be utilized in organic light emitting diode, optical waveguide, and organic laser, *etc*. As for those with ultralong RTP lifetimes, they would show great potential in bioimaging. To increase the imaging depth and promote the imaging effect, RTP luminogens with long wavelength absorption/emission or two/three-photon absorption are badly needed. Besides, information storage and security are also important applications of RTP materials and the stimulus-responsive RTP polymers might be good candidates.

Thus, systematic research should be conducted based on the present results with full consideration of the above is-

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sues. It is not so easy, but the future development in this area will surely broaden our knowledge of light emission, and extend the utilization of organic luminogens.

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