Narrowband Clusteroluminescence with 100% Quantum Yield Enabled by Through-Space Conjugation of Asymmetric Conformation

Yipu Wang,[1,2,#] Jianyu Zhang,[3,#] Weihao Tu,[1,2,4] Lei Wang,[1,2] Yuan Xie,[1,2] Jing Zhi Sun,[1,4] Feihe Huang,[2,5] Haoke Zhang,[1,2,7,*] and Ben Zhong Tang[1,3,6,*]

[1] MOE Key Laboratory of Macromolecular Synthesis and Functionalization, Department of Polymer Science and Engineering, Zhejiang University, Hangzhou, 310058, China

[2] Zhejiang-Israel Joint Laboratory of Self-Assembling Functional Materials, ZJU-Hangzhou Global Scientific and Technological Innovation Center, Zhejiang University, Hangzhou 311215, China

[3]Department of Chemistry, Hong Kong Branch of Chinese National Engineering Research Center for Tissue Restoration and Reconstruction, The Hong Kong University of Science and Technology, Hong Kong, 999077, China

[4]Centre of Healthcare Materials, Shaoxing Institute, Zhejiang University, Shaoxing 312000, China

[5]Stoddart Institute of Molecular Science, Department of Chemistry, Zhejiang University, Hangzhou, 310058, China

[6]School of Science and Engineering, Shenzhen Institute of Aggregate Science and Technology, The Chinese University of Hong Kong, Shenzhen (CUHK-SZ), Guangzhou 518172, China

[#]These authors contributed equally: Yipu Wang, Jianyu Zhang.

[*]Corresponding emails: zhanghaoke@zju.edu.cn (Haoke Zhang); tangbenz@cuhk.edu.cn (Ben Zhong Tang)

Abstract: Different from traditional organic luminescent materials based on covalent delocalization, clusteroluminescence (CL) from nonconjugated luminogens relies on noncovalent through-space conjugation (TSC) of electrons. However, such spatial electron delocalization is usually weak, resulting in low luminescent efficiency and board emission peak due to multiple vibrational energy levels. Herein, several nonconjugated luminogens are constructed by employing biphenyl as the building unit to reveal the structure-property relationship and solve current challenges. The intramolecular TSC could be gradually strengthened by introducing building units and stabilized by rigid molecular skeleton and multiple intermolecular interactions. Surprisingly, narrowband CL with full width at half-maximum of 40 nm and 100% efficiency is successfully achieved via an asymmetric conformation, exhibiting comparable performance to the traditional conjugated luminogens. This work realizes highly efficient and narrowband CL from nonconjugated luminogens and highlights the essential role of structural conformation in manipulating the photophysical properties of unconventional luminescent materials.

Introduction

The natural world follows a basic principle of modular assembly, where amino acids are assembled into peptides and proteins and eventually into organisms.[1-3] Similarly, benzene rings can be constructed into graphene and carbon nanotubes with unique functional properties.[4-7] The modular assembly usually endows materials with different properties and behaviors compared to individual building units.[8-10] Currently, the construction of organic luminescent materials is typically achieved by covalently linking building units or incorporating donor-acceptor units, where changes in their properties are primarily induced by electron delocalization or charge-transfer effect.[11-17] However, in recent years, researchers have observed that specific nonconjugated small molecules and polymers do not exhibit luminescence in solution but emit intense light after forming clusters, known as clusteroluminescence (CL).[18-20] The working mechanism of CL has been revealed to be through-space conjugation (TSC) of electrons between isolated building units.[21,22] Using common polyesters as an example, their building units (carbonyl or ester) are connected through spatial *n*-*n* interactions, allowing the formation of TSC and the generation of extrinsic long-wavelength fluorescence.[23-25] Due to the poorly conjugated and flexible structure, these materials possess excellent structural flexibility, processability, biocompatibility, and degradability.[26-29] These advantages show significant implications for developing novel luminescent materials and hold particular value for practical applications.[30,31]

Currently, the development of TSC-based emitters has gained considerable attention from researchers.[32,33] However, creating CL materials with exceptional performance that meet application requirements remains a significant challenge.[34,35] The production of CL relies on noncovalent electron overlap and coupling of each unit, which requires the structural flexibility of molecules to form close interactions of electrons in the excited state.[36,37] Therefore, many reported nonconjugated luminogens, such as triphenylmethane and tetraphenylethane, are constructed by rigid building units, which rely on the flexibility of the molecular skeleton to form suitable conformation for TSC.[38,39] However, these luminescent materials based on TSC encounter several issues, including unclear manipulation strategies due to vague structure-property relationship, low luminescent efficiency due to structural flexibility and excited-state molecular motions, as well as broad emission peaks with large full-width at half-maximum (FWHM) values due to numerous vibrational energy levels.[40-43] These challenges present significant obstacles to developing efficient CL materials with high purity of emissive color.[44-46] To address these challenges, one approach is to transfer the flexibility from the molecular skeleton to the building units, forming TSC via the flexibility of building units while maintaining the structural rigidity of the molecular skeleton.[47-49] By achieving strong TSC while minimizing vibrational motions upon photoexcitation, it is possible to achieve narrowband CL with high luminescent efficiency.[50-52]

In this work, the simplest biphenyl (BP) is employed as the flexible building unit to construct a series of nonconjugated luminogens, and the structure-property relationship of TSC and CL is

systematically studied via two molecule-engineering methods: gradually introducing building units and constitutionally adjusting the connecting positions of building units (**Fig. 1**). The former suggests the feasibility of using biphenyl as the building unit to enhance the strength of TSC, and the latter indicates the role of structural conformation in intra- and intermolecular interactions, which manipulate the stability of intramolecular TSC for CL. Interestingly, the first example of narrowband CL with an FWHM of 40 nm and 100% efficiency is successfully achieved via an asymmetric triarylmethane, which is comparable to the traditional conjugated narrowband luminogens. This work realizes the narrowband CL from nonconjugated luminogens with isolated biphenyls and provides a novel perspective to manipulate TSC for unconventional luminescent materials with high efficiency.

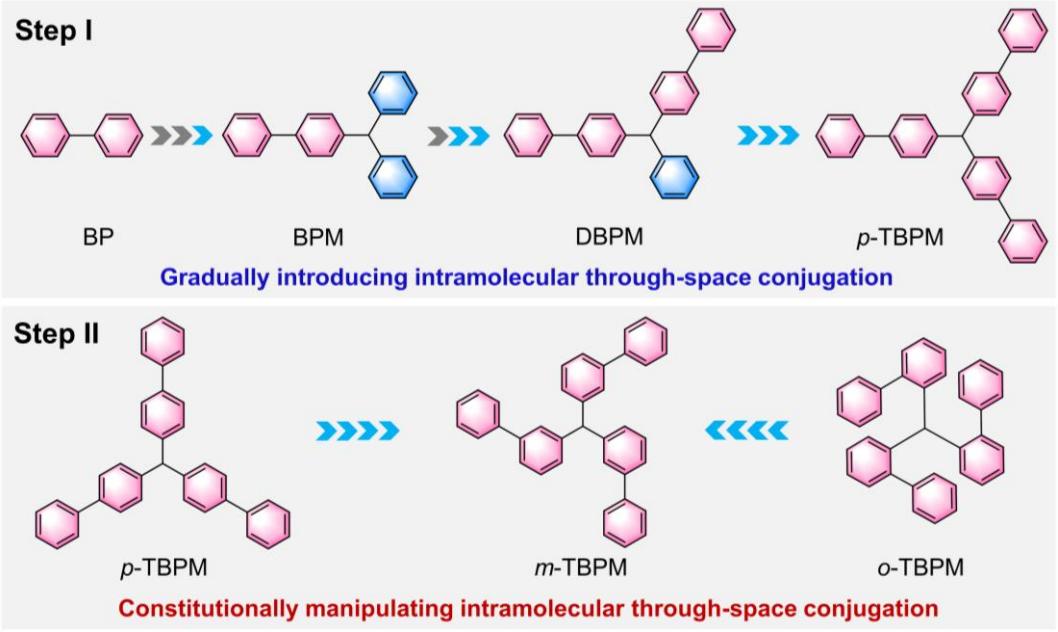


Fig. 1. The design strategy of nonconjugated molecules with narrowband clusteroluminescence using biphenyl as the building unit.

Results

According to the above strategy, five compounds, 4-benzhydryl-1,1'-biphenyl (BPM), 4,4"-(phenylmethylene)di-1,1'-biphenyl (DBPM), tri([1,1'-biphenyl]-4-yl)methane (*p*-TBPM), tri([1,1'-biphenyl]-3-yl)methane (*m*-TBPM), tri([1,1'-biphenyl]-2-yl)methane (*o*-TBPM) have been synthesized and fully characterized by using nuclear magnetic resonance spectra, high-resolution mass spectra, and high-performance liquid chromatography techniques (Supplementary **Figs. 1**-**32**). UV-visible absorption spectra of the building unit (e.g., BP) and the synthesized BPM, DBPM, and *p*-TBPM were performed in tetrahydrofuran (THF) solutions with different concentrations. The maximum absorption wavelength (λ_{abs}) of biphenyl is located at 249 nm (Supplementary **Fig. 33**), suggesting its intrinsic through-bond conjugation. However, the λ_{abs} of BPM, DBPM, and *p*-TBPM are quite close to that of biphenyl (259 nm, 260 nm, and 263 nm,

respectively), indicating their nonconjugated structures. Meanwhile, the slight redshift is caused by the hyperconjugation between the π units and the middle saturated carbon.

Then, the photoluminescence (PL) properties of these compounds were examined in THF solution with different concentrations. **Fig. 2a** and Supplementary **Fig. 34a** demonstrate that BP exhibits only one emission peak at 310 nm, and the position of the peak remains unchanged with varying concentrations. Similar to BP, BPM displays only one intrinsic emission peak at 316 nm in different concentrations, which is also attributed to the biphenyl unit (**Fig. 2b** and Supplementary **Fig. 34b**). In contrast, DBPM exhibits a different behavior compared to the previous two compounds. It shows only one intrinsic emission peak from the biphenyl unit with a low concentration of 10^{-5} M, but a long-wavelength emission peak at 338 nm appears with a high concentration of 10^{-3} M (**Fig. 2c** and **Supplementary Fig. 34c**). According to previous reports, it should arise from the intramolecular TSC between two isolated biphenyl units of DBPM. Compared to DBPM, *p*-TBPM already exhibits a distinct long-wavelength emission peak at 348 nm in THF solution with a concentration of 10^{-4} M, which also excludes the possibility of intermolecular interactions (Supplementary **Fig. 34d**). Moreover, the emission peak becomes dominant when the concentration is increased to 10^{-3} M, indicating that *p*-TBPM has the strongest intramolecular TSC among these four compounds (**Fig. 2d**).

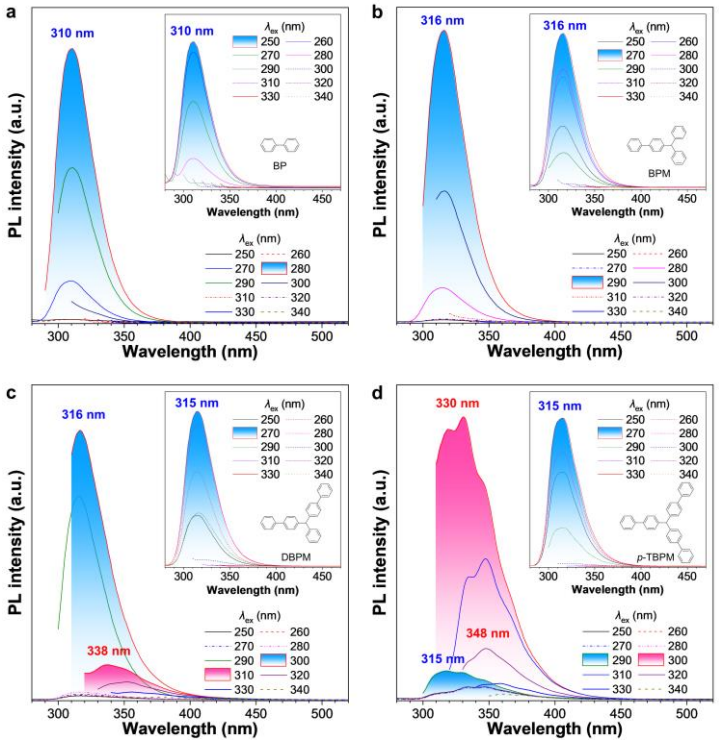
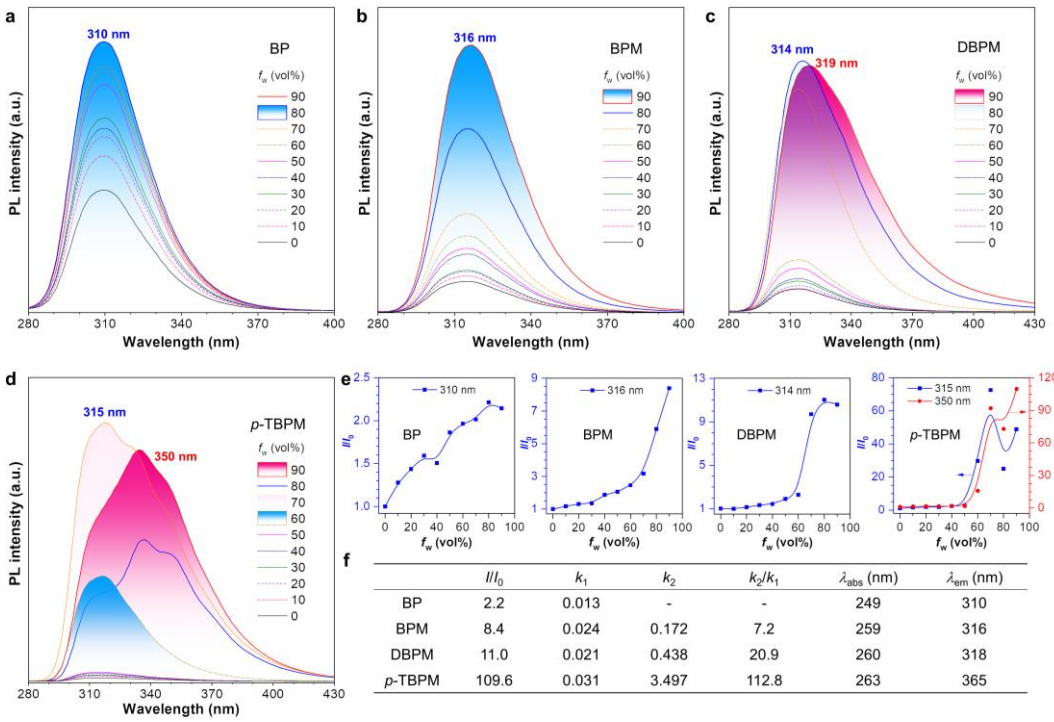


Fig. 2. Photophysical properties of BP, BPM, DBPM, and *p*-TBPM under different excitation wavelengths. a Photoluminescence (PL) spectra of BP, in THF solution (concentration = 10^{-3} M) under different excitation wavelengths. **b** Photoluminescence (PL) spectra of BPM in THF solution (concentration = 10^{-3} M) under different excitation wavelengths. **c** Photoluminescence (PL) spectra of DBPM in THF solution (concentration = 10^{-3} M) under different excitation wavelengths. **d** Photoluminescence (PL) spectra of *p*-TBPM in THF solution (concentration = 10^{-3} M) under different

excitation wavelengths. Inset: PL spectra of the corresponding compound in THF solution with a concentration of 10^{-5} M.

To investigate changes in CL behaviors of these compounds before and after aggregate formation, their PL spectra were further measured in THF/water mixtures with different water fractions (f_w) and the same concentration of 10^{-4} M. As expected, both BP and BPM only exhibit enhanced emission intensity with the increased f_w (**Fig. 3a** and **3b**). Besides, the PL spectra of solid-state BP and BPM also show the intrinsic emission at 310 nm and 316 nm, respectively, indicating no formation of intramolecular TSC (Supplementary **Fig. 35a** and **35b**). However, the photophysical behavior of DBPM in THF/water mixtures is different. When increasing f_w, its PL intensity continuously increased. When f_w reaches 90%, the emission peak redshifts from 315 nm to 319 nm with a vague shoulder peak (**Fig. 3c**). However, the solid-state PL spectra of DBPM do not exhibit a prominent long-wavelength emission peak (Supplementary **Fig. 35c**). These results indicate that the intramolecular TSC in DBPM is slightly enhanced but still weak. Significantly, the emission intensity of *p*-TBPM at 315 nm gradually increases when f_w increases from 0% to 70%, but the shape of the emission peak changes, and a long-wavelength emission at 350 nm becomes distinct when f_w further increases to more than 80% (**Fig. 3d**). As a result, the PL intensity at f_w = 90% is 110 times higher than that in pure THF solution (**Fig. 3e**). The solid-state PL spectra of *p*-TBPM only shows the long-wavelength emission peak at 365 nm, suggesting the presence of the strongest intramolecular TSC among these four compounds (Supplementary **Fig. 35d**).



	I/I_0	k_1	k_2	k_2/k_1	λ_{abs} (nm)	λ_{em} (nm)
BP	2.2	0.013	-	-	249	310
BPM	8.4	0.024	0.172	7.2	259	316
DBPM	11.0	0.021	0.438	20.9	260	318
p-TBPM	109.6	0.031	3.497	112.8	263	365

Fig. 3. Photophysical properties of BP, BPM, DBPM, and *p*-TBPM before and after aggregate formation. a Photoluminescence (PL) spectra of BP in THF/water mixtures with different water

fractions (f_w), concentration (c) = 10^{-4} M. **b** Photoluminescence (PL) spectra of BPM in THF/water mixtures with different water fractions (f_w), concentration (c) = 10^{-4} M. **c** Photoluminescence (PL) spectra of DBPM in THF/water mixtures with different water fractions (f_w), concentration (c) = 10^{-4} M. **d** Photoluminescence (PL) spectra of *p*-TBPM in THF/water mixtures with different water fractions (f_w), concentration (c) = 10^{-4} M. **e** Plots of relative PL intensity (I/I_0) versus f_w of four compounds. I_0 = intensity at f_w = 0%. **f** Summary of photophysical properties of four compounds. k_1 is the slope of I/I_0 with f_w from 0% to 60%; k_2 is the slope of I/I_0 with f_w from 60% to 90%; λ_{abs} is the maximum absorption wavelength in THF solution; λ_{em} is the maximum emission wavelength in the solid state.

Subsequently, a semi-quantitative analysis was conducted to evaluate the influence of aggregate formation by comparing the slopes of their relative PL intensity (I/I_0) in mixtures (**Fig. 3f**). k_1 and k_2 are defined as the slopes of PL intensity enhancement before and after the formation of aggregates, respectively, and the ratio of k_2/k_1 represents the enhancement solely induced by aggregation without the influence of the mixture polarity. It is found that the k_2/k_1 value gradually increases along with the increased numbers of biphenyl units, from BPM of 7.2 to DBPM of 20.9 and *p*-TBPM of 112.8. This result further confirms that the intramolecular TSC could be stepwise enhanced by introducing the flexible building unit of biphenyl, and *p*-TBPM shows the strongest intramolecular TSC among these four compounds.

By gradually introducing biphenyl moieties, we have successfully constructed *p*-TBPM, which exhibits highly efficient CL with an absolute quantum yield (Φ) of 55% (**Table 1**). However, excitation-dependent emission in the solid state also indicates its flexible molecular skeleton and formed TSC upon photoexcitation. Therefore, *m*-TBPM and *o*-TBPM were designed and synthesized by changing the connecting position of three isolated biphenyl units to study the constitutional manipulation of TSC and structural rigidity (**Fig. 1**). It was expected that altering the position would adjust the distance and dihedral angle between every biphenyl, thereby manipulating the intramolecular interaction of π electrons and TSC among biphenyl units.

The maximum absorption wavelengths of *m*-TBPM and *o*-TBPM in THF solution are located at 255 nm and 230 nm, respectively, also indicating the nonconjugated nature of three biphenyl moieties as *p*-TBPM. The PL properties of these two compounds were measured and compared (Supplementary **Fig. 33**). In pure THF solution with a low concentration of 10^{-5} M, the long-wavelength emission from TSC at 370 nm is already observable for *m*-TBPM, supporting its intramolecular behaviors (**Fig. 4a** and **Supplementary Fig. 36a**). Besides, it completely dominates when the concentration reaches 10^{-3} M and becomes excitation-independent, indicating its strong and stable TSC. In THF/water mixtures, the emission originating from TBC displays negligible change when f_w is less than 60%. As the $f_w \geq 70\%$, the long-wavelength emission from TSC becomes detectable and gradually enhances, reaching an astonishing 136.5 times higher when f_w = 90% than that in pure THF solution (**Fig. 4b**). Moreover, the solid-state PL spectra of *m*-TBPM reveal an almost dominant and excitation-independent emission at 374 nm. Surprisingly, the absolute Φ of solid *m*-TBPM reaches 100%, accompanied by a quite narrow peak with the

FWHM value of 40 nm, which is attributed to its stable and strengthened TSC with few vibrational energy levels (**Fig. 4c** and **Table 1**). To our knowledge, it is the first time for nonconjugated compounds to produce CL with such a high Φ, and the FWHM is comparable to the conventionally conjugated luminescent materials with narrowband emission.[53-55] Therefore, *m*-TBPM should be a novel narrowband luminescent material based on the emerging TSC and CL.

Based on the aforementioned design, it was expected that *o*-TBPM would exhibit the strongest intramolecular TSC due to the crowded molecular configuration that may help result in spatial electron delocalization. However, PL results show that only the intrinsic emission from TBC-based biphenyl units is detected at 318 nm in the dilute THF solution of 10^{-5} M, even in the THF/water mixtures with a f_w of 90% (**Fig. 4d** and **4e**). With the concentration of 10^{-3} M or in the solid state, a weak long-wavelength emission from TSC at 390 nm is observed, while the emission from TBC remains dominant throughout (**Fig. 4f**). In addition, the quantum yield of solid *o*-TBPM is only 4%, and the FWHM of the long-wavelength emission peak is extremely wide, exceeding 70 nm (**Table 1**). It could be seen that adjusting the substituents to the *ortho*-position can indeed increase the overlap of delocalized electrons between the isolated units, as evidenced by the extended emission wavelength compared to the other two isomers. However, the crowded conformation also induces steric hindrance between biphenyls, resulting in dynamic molecular motions and an unstable TSC in the excited state. As a result, *o*-TBPM exhibits the longest emission wavelength of TSC at 390 nm but quite low emission efficiency compared to the other two isomers.

Table 1. Photophysical properties of *p*-TBPM, *m*-TBPM, and *o*-TBPM[a]

	λ_{abs} (nm)	TBC emission		TSC emission			Φ (%)
		λ_{TBC} (nm)	τ (ns)	λ_{TSC} (nm)	FWHM (nm)	τ (ns)	
p-TBPM	263	-	-	365	53	2.76	55
m-TBPM	255	317	4.57	374	40	3.36	100
o-TBPM	230	308	1.49	390	>70	4.43	4

[a]Abbreviation: λ_{abs} = maximum absorption wavelength in the THF solution, TBC = through-bond conjugation, TSC = through-space conjugation, λ_{TBC} = maximum emission wavelength of TBC in the solid state, λ_{TSC} = maximum emission wavelength of TSC in the solid state, FWHM = full-width at half-maximum, τ = fluorescence lifetime, Φ = absolute quantum yield in the solid state.

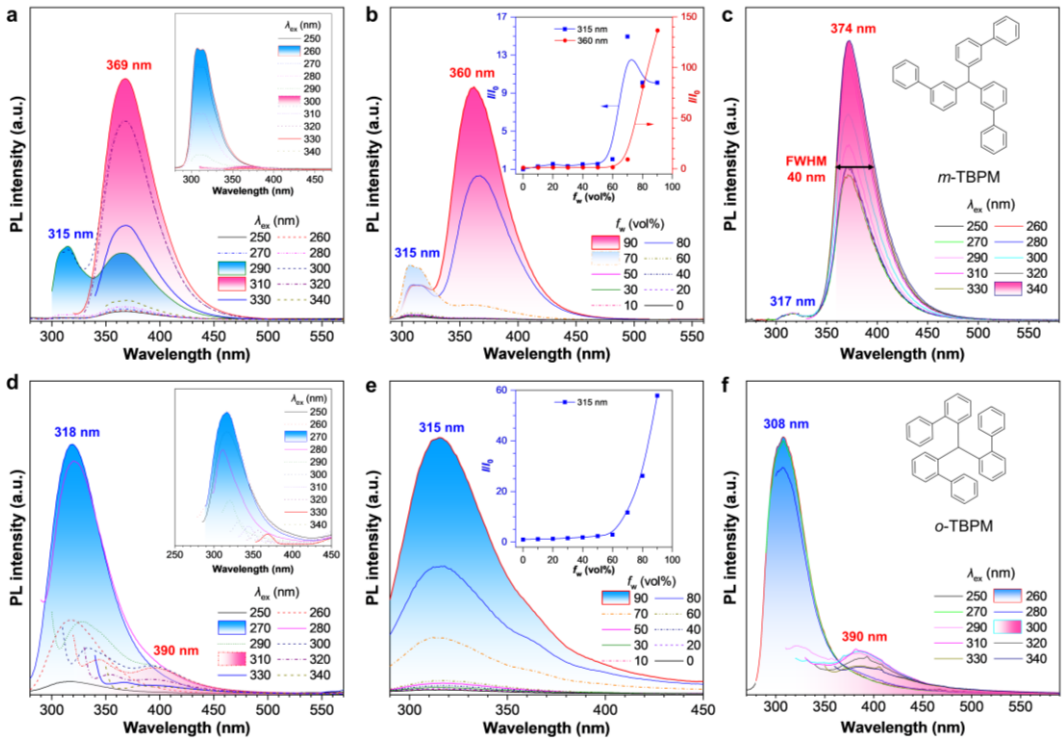


Fig. 4. Photophysical properties of *m*-TBPM and *o*-TBPM. a Photoluminescence (PL) spectra of *m*-TBPM in THF solution under different excitation wavelengths, concentration (*c*) = 10^{-3} M. Inset: PL spectra of the corresponding compound in THF solution with a *c* of 10^{-5} M. **b** PL spectra of *m*-TBPM in THF/water mixtures with different water fractions (f_w), *c* = 10^{-4} M. Inset: Plots of relative PL intensity (I/I_0) versus f_w. I_0 = intensity at f_w = 0%. k_1 is the slope of I/I_0 with f_w from 0% to 60%; k_2 is the slope of I/I_0 with f_w from 60% to 90%. **c** PL spectra of solid-state *m*-TBPM under different excitation wavelengths. **d** Photoluminescence (PL) spectra of *o*-TBPM in THF solution under different excitation wavelengths, concentration (*c*) = 10^{-3} M. Inset: PL spectra of the corresponding compound in THF solution with a *c* of 10^{-5} M. **e** PL spectra of *o*-TBPM in THF/water mixtures with different water fractions (f_w), *c* = 10^{-4} M. Inset: Plots of relative PL intensity (I/I_0) versus f_w. I_0 = intensity at f_w = 0%. k_1 is the slope of I/I_0 with f_w from 0% to 60%; k_2 is the slope of I/I_0 with f_w from 60% to 90%. **f** PL spectra of solid-state *o*-TBPM under different excitation wavelengths.

To explore the working mechanism and the difference in the photophysical properties among the three isomers of TBPM, Hirshfeld surface analysis, which is a quantitative analysis of intermolecular interactions based on single-crystal structures, was utilized.[56] As shown in **Fig. 5a-c**, intermolecular C-C interactions (blue shadows underneath the decomposed plot), which usually result in intermolecular interactions (e.g., π-π stacking) and long-wavelength emission from dimers, account for a negligible proportion of all intermolecular interactions (0.7%, 0.5%, and 0.1% for *p*-TBPM, *m*-TBPM, and *o*-TBPM, respectively). Thus, the results indicate that there is no obvious strong intermolecular interaction and clearly support the idea that the TSC and CL from these isomers are intramolecular behaviors. In addition, the proportions of weak C-H interactions of *p*-TBPM and *m*-TBPM are 48.6% and 46.5%, respectively, while the proportion of

o-TBPM is only 27.0% (Supplementary **Figs. 54-56**), which suggests that *o*-TBPM processes the weakest intermolecular interactions to stabilize its geometry, which is consistent with its dynamic rotations of biphenyl units.

Reorganization energy (λ) was analyzed to quantitatively evaluate their intrinsic geometric changes under photoexcitation and the contributions of different intramolecular motions to nonradiative decay (**Fig. 5d-f**).[57,58] Among the three isomers, the total λ of *p*-TBPM is the largest (13268 cm^{-1}), of which 71.60% is contributed by torsional motions of dihedral angles. Therefore, *p*-TBPM processes significant geometric changes that dissipate energy through nonradiative decay in the excited state. Similarly, the total λ of *o*-TBPM is 8322 cm^{-1}, and the contribution from torsional motions of dihedral angles accounts for 55.03%. This result indicates its weak intramolecular interactions due to the twisted structural conformation and steric hindrance of biphenyl units. Thereby, both the weak intermolecular and intramolecular interactions destroy the formed TSC and endow *o*-TBPM with the smallest Φ of CL in the solid state. Unexpectedly, the total λ of *m*-TBPM is only 1752 cm^{-1}, and the contribution from motions of dihedral angles declines to 30.83%, suggesting its rigid structural conformation and minimized vibrational energy levels. Accordingly, it is believed that the TSC of *m*-TBPM could be stabilized by the stable conformation in both solution and solid states, which endows it to emit strong CL in low-concentration solutions as an isolated luminogen and narrowband CL in the solid state with high purity of color and excitation-independent features (**Fig. 4a-f**).

For nonconjugated luminogens with CL properties, spatial electron overlap is a typical characteristic. Therefore, hole-electron analysis was applied to study their electronic structure and behaviors in the excited state (**Fig. 5g-i**). For these three compounds, the hole distribution is located at three isolated biphenyl units. However, electron distribution forms noncovalent delocalization around the central methyl group, forming the typical TSC of electrons that promotes the long-wavelength CL. To provide a quantitative perspective, electron transitions and redistributions from three nonconjugated biphenyl fragments were segmented and compared. Interestingly, *p*-TBPM and *o*-TBPM exhibit electronic behaviors that are different from *m*-TBPM. Three fragments of *p*-TBPM and *o*-TBPM contribute equally to the hole and electron. In contrast, fragment 2 of *m*-TBPM dominates the hole and electron parts with contributions of 46.90% and 46.82%, respectively, while fragments 1 and 3 show smaller and relatively equal contributions (Supplementary **Fig. S57a-c**). Similarly, the analysis of transferred electrons reveals that the charge delocalization capability among the three fragments of *p*-TBPM and *o*-TBPM is equal, while fragment 2 of *m*-TBPM exhibits a higher charge delocalization capability (**Fig. 5g-i and Supplementary Fig. 57d-f**). These results indicate that the structural conformation and formed TSC of *m*-TBPM are asymmetric, which should be also responsible for its highly efficient and narrowband CL.

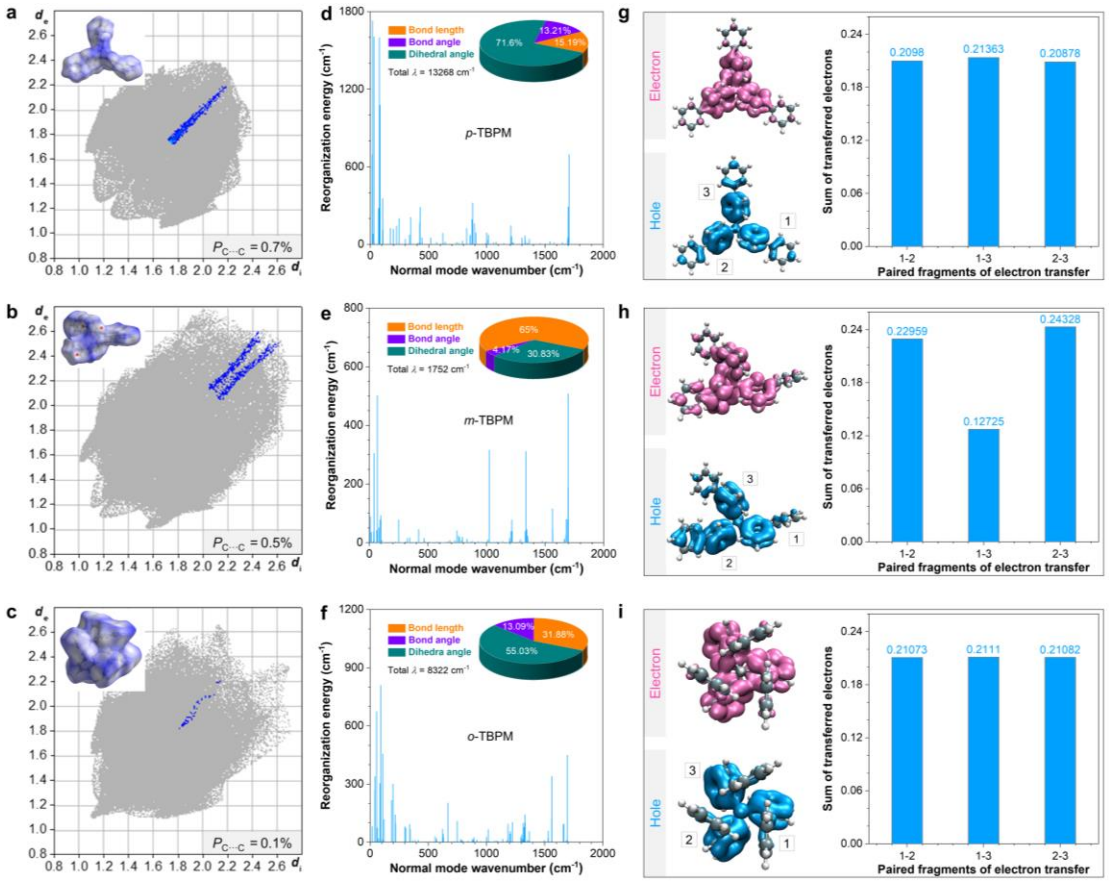


Fig. 5. Theoretical calculations of *p*-TBPM, *m*-TBPM, and *o*-TBPM. a-c Hirshfeld surfaces (mapped over d_{norm}) and decomposed fingerprint plots of intermolecular C-C interaction of (a) *p*-TBPM, (b) *m*-TBPM, and (c) *o*-TBPM. The full fingerprints appeared as grey shadows underneath decomposed plots, and intermolecular C···C interaction was shown as the blue shadow. $P_{C\cdots C}$ = proportion of intermolecular C···C interactions to total intermolecular interactions. **d-e** Plots of reorganization energy *vs* normal mode wavenumber of (d) *p*-TBPM, (e) *m*-TBPM, and (f) *o*-TBPM. **g-i** Hole–electron analysis and transferred electrons of paired fragments of (g) *p*-TBPM, (h) *m*-TBPM, and (i) *o*-TBPM.

Based on the above analysis, we have gained insights into the molecular interactions, excited-state molecular motions, and electronic structure that influence the CL of these three isomers. To support the relationship between structural conformation and CL of these nonconjugated compounds, we further revisited their single-crystal structures and packing modes (Supplementary **Figs. 58-60**). Although the three compounds exhibit symmetric chemical structures with a C3 symmetry axis (**Fig. 6a**), their structural conformations of single molecules in the crystalline state differ significantly. Similar to their chemical structures, the structural conformations of *p*-TBPM and *o*-TBPM are close to symmetric. In contrast, the structural conformation of crystalline *m*-TBPM is asymmetric (**Fig. 6b**). Within the packing mode of *p*-TBPM, although there are many intermolecular interactions that could restrict intramolecular motions (Supplementary **Fig. 58**), its flexible skeleton cannot sufficiently stabilize the formed

TSC, endowing it with moderate Φ and FWHM of CL in the crystalline state. For *o*-TBPM, accompanied by the flexible biphenyl groups with steric hindrance, the limited number of intermolecular interactions cause dynamic molecular motions and energy dissipation, resulting in its lowest Φ of CL (Supplementary **Fig. 59**). On the other hand, the rigid molecular skeleton and numerous intermolecular interactions of *m*-TBPM block active intramolecular motions and facilitate the formation of stable TSC for highly efficient CL (Supplementary **Fig. 60**). Notably, no strong intermolecular interactions of π-π stacking for these three compounds are observed, further verifying their intramolecular behaviors for the long-wavelength emission.

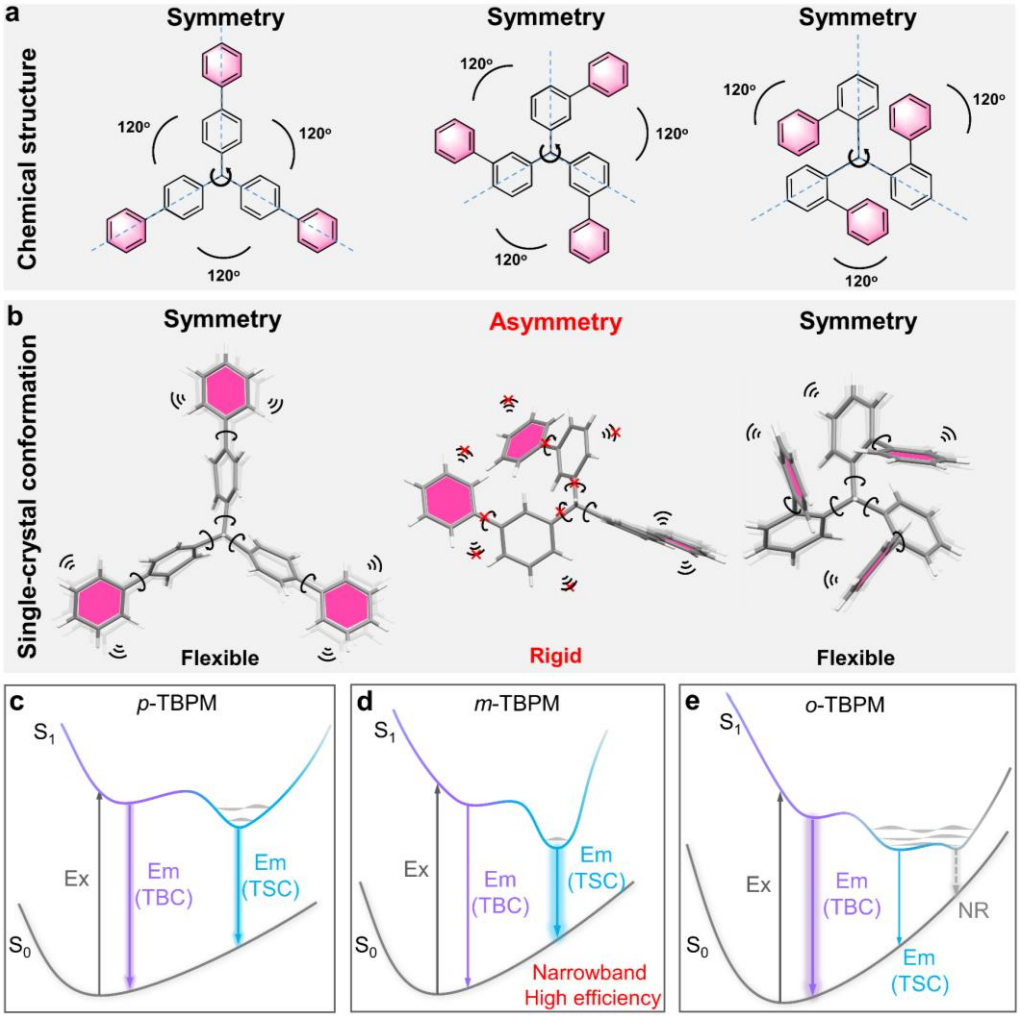


Fig. 6. Structural analysis of *p*-TBPM, *m*-TBPM, and *o*-TBPM and and photoluminescence working mechanism. a Chemical structures of *p*-TBPM, *m*-TBPM, and *o*-TBPM. **b** Structural conformation of *p*-TBPM, *m*-TBPM, and *o*-TBPM in the crystalline state. **c-e** Schematic diagram of potential energy surface and electronic behaviors of (c) *p*-TBPM, (d) *m*-TBPM, and (e) *o*-TBPM.

Accordingly, a complete picture of the working mechanism and different CL properties from these isomers was summarized (**Fig. 6c-e**). When compounds are excited from the ground state (S_0) to the excited state (S_1), some excitons release energy through the TBC-based radiative channel with short-wavelength emission from biphenyl units. Meanwhile, some excitons could

relax to the low-energy state caused by the TSC of three isolated biphenyl groups, emitting long-wavelength CL. It is worth noting that the efficiency of CL is mainly determined by the strength of TSC and the stability of the corresponding conformation. The former mainly focuses on the magnitude of electron communication, and the latter is achieved by the rigid molecular skeleton and surrounding environment (e.g., multiple intermolecular interactions). Therefore, structural conformation plays an essential role in manipulating the CL properties of these isomers. (1) For the structurally symmetric *p*-TBPM, the flexibility of its skeleton allows the formation of TSC upon excitation from the ground state to the excited state. However, its flexible skeleton with active molecular motions cannot be totally restricted via multiple intermolecular interactions, resulting in multiple vibrational energy levels. Therefore, *p*-TBPM produces intrinsic emission from biphenyl units and CL from TSC with a moderate FWHM of 53 nm and comparable Φ of 55% (**Fig. 6c**). (2) For *m*-TBPM with asymmetric conformation and rigid molecular skeleton, numerous intermolecular interactions can largely stabilize the formed TSC, provide a fixed environment to block molecular motions, and minimize vibrational energy levels.[59,60] As a result, most excitons can relax to the TSC-based state to produce excitation-independent and narrowband CL with an FWHM of 40 nm and a quantitative Φ of 100% in the crystalline state (**Fig. 6d**). To the best of our knowledge, it is the first time that nonconjugated luminogens have achieved 100% quantum yield, and the FWHM value is comparable to reported conjugated compounds with narrowband emission. It is worth noting that TSC-based narrowband emission can also avoid the wide shoulder peaks in some traditional conjugated luminogens with multiple resonance effect (e.g., perylene), further improving the color purity of luminescence.[61-63] (3) For symmetric *o*-TBPM, although the crowded subunits endow it with the largest overlap of electrons to form TSC and the longest wavelength of CL at 390 nm, steric hindrance and weak intermolecular interactions cause the flexible skeleton and dynamic molecular motions to deactivate the formed TSC. Thus, a large portion of energy dissipates via nonradiative decay, and a small part of excitons relaxes via the TSC-based channel with a board emission peak (FWHM > 70 nm) and a much low Φ of 4% (**Fig. 6e**).

Discussion

Achieving efficient CL via spatial electron interaction and narrowband emission simultaneously seems contradictory. In this work, biphenyl is utilized as a building block to construct a series of nonconjugated luminogens with CL properties. Two molecule-engineering strategies have been utilized to manipulate TSC and CL: (1) Introducing building blocks of biphenyl units enhances the strength of intramolecular TSC, which promotes the shift of luminescence from the TBC-based channel to the TSC-based CL; (2) Constitutionally adjusting the connection positions of building blocks affects structural conformation and intermolecular interactions, which regulate the stability of TSC and efficiency of CL. Different from the structurally symmetric *p*-TBPM and *o*-TBPM with flexible skeleton, *m*-TBPM with asymmetric

conformation exhibits multiple intermolecular interactions and rigid skeleton to promote the formation and stabilization of TSC, achieving narrowband CL with an FWHM of 40 nm and 100% efficiency. The narrowband emission and luminescent efficiency of this nonconjugated compound are highly competitive to traditional luminogens with extended conjugated and planar structures. This work highlights the critical role of structural conformation in manipulating the photophysical properties of nonconventional luminescent materials and provides a strategy for developing narrowband CL with improved properties.

Methods

Materials. All chemicals and reagents were purchased from commercial sources such as Bide Pharmatech Ltd., Energy Chemical, Thermo Fisher Scientific, J&K Scientific, and TCI. Common reagents and raw materials were purchased from formal channels, analytically pure, and used without further purification. All the final products used in experiments were purified by silica gel column. The purification of all designed samples was carefully checked by HPLC. Tetrahydrofuran (THF), acetonitrile (ACN), and water used for photophysical measurements were all checked by HPLC.

Instrumentation. ^{1}H and ^{13}C nuclear magnetic resonance spectra were recorded on a Bruker AVANCE NEO 600-MHz instrument. UV–vis absorption spectra were recorded by a mid-range UV spectrophotometer (UV-2600i, SHIMADZU). Steady photoluminescence (PL) measurements of all samples were performed on an RF-6000 spectrofluorometer (SHIMADZU) and FLS5 Photoluminescence Spectrometer (Edinburgh Instrument). Fluorescence lifetime was measured by FLS1000 Photoluminescence Spectrometer (Edinburgh Instrument). Absolute fluorescence quantum yields were measured on FLS5 Photoluminescence Spectrometer (Edinburgh Instrument) at least three times. Single-crystal X-ray diffraction (XRD) data were collected on a Rigaku Oxford Diffraction SuperNova with Atlas Diffractometer (RIGAKU), and crystal structures were solved with Olex2 (a software, https://www.olexsys.org/olex2/). HPLC measurements were carried out on Agilent 1260 Infinity II instrument with Agilent 10 (Prep-C18, 250 × 21.2 mm) column, using THF. High-resolution mass spectra of these compounds were all obtained through Fourier transform mass spectrometry (FTMS), and the test instrument is Thermo Scientific Exactive GC Orbitrap (Thermo Scientific).

Computational details. All the compounds were fully optimized with the density functional theory (DFT) method by using M06-2X density functional and 6-31G(d,p) basis set. London-dispersion effects were also taken into consideration using Grimme's DFT-D3 correction. Analytical frequency calculations were also performed at the same level of theory to confirm that the optimized structures were at a minimum point. Time-dependent density functional theory (TD-DFT) was utilized at the same level of theory to calculate optimized excited (S_1) geometries and energy levels. All the above quantum chemical calculations were carried out using Gaussian 16 program.[64] Reorganization energy analysis was performed using the Molecular Materials Property Prediction Package (MOMAP).[65-67] Besides, the Hirshfeld surfaces and decomposed fingerprint plots were calculated and mapped using

CrystalExplorer 17.5 package[68], and the hole-electron analysis were calculated using Multiwfn[69] and displayed using VMD.[70]

Data availability

The authors declare that all the data supporting the findings of this manuscript are available within the manuscript and Supplementary Information files and available from the corresponding authors upon reasonable request. The X-ray crystallographic coordinates for structures reported in this study have been deposited at the Cambridge Crystallographic Data Centre (CCDC) under deposition numbers of *p*-TBPM (2310837), *m*-TBPM (2310838), *o*-TBPM (2310839). These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.

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Author contributions

Y.W. and J.Z. performed research, wrote the original draft of the article and carried out theoretical calculation. W.T., L.W., and Y.X. contributed synthesis. J.Z.S. and F.H. participated in the discussion. H.Z. and B.Z.T. contributed to project administration, funding acquisition, and revision of the article.

Competing interests

The authors declare no competing interests.

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