Red-light-activatable ruthenium phthalocyanine catalysts

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Red-light-activatable ruthenium phthalocyanine catalysts

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Phthalocyanine ruthenium complexes were identified as red-light activatable catalysts for trifluoromethylation reactions. The red-light mediated chlorotrifluoromethylation of alkenes could proceed without any sacrificial reducing reagents. This reaction exhibited good compatibility with a blue-light-absorbing substrate, while under irradiation with blue light, i.e., under traditional photoreaction conditions, this substrate decomposed completely.

In organic reactions, heat is usually used as the energy source. However, light-[1] or electro-mediated[2] reactions can be environmentally more friendly and also achieve transformations that are difficult or impossible to realize via thermal reactions. In the field of light-mediated organic reactions (photoreactions), the wavelength of the incident light is often of critical importance. Visible-light photoredox reactions have attracted significant research interest in modern synthetic organic chemistry. The general mechanism of visible-light-mediated photoreactions is shown in Fig. 1a. After the photocatalyst absorbs the visible light, an electron- or energy-transfer reaction proceeds between the activated photocatalyst and the substrates, and the desired transformations proceed. The catalyst must strongly absorb visible light, and various photocatalysts, including organometallic complexes,[3] organocatalysts,[4] and inorganic compounds[5] have been developed.

Since visible light accounts for the largest proportion of solar energy, materials that absorb visible light, such as fluorescent dyes, organic photovoltaics, and photosensitizers for photodynamic therapy, have also attracted much attention in materials chemistry.[6] The transformation of molecular structures is an effective strategy for modifying and improving the functionality of visible-light-absorbing materials. To develop novel materials, methods to efficiently and conveniently create large numbers of derivatives are required. Molecular transformations provided by visible-light photoredox reactions should also be effective for developing visible-light-absorbing materials. However, this approach is associated with a serious problem (Fig. 1b). When a visible-light-absorbing material is used as a substrate, the substrate and photocatalyst simultaneously absorb the incident irradiation. Therefore, the substrate will prevent the activation of the photocatalyst, or both the catalyst and substrate will be activated in a disorderly manner. This makes it difficult for the desired reaction to proceed selectively.

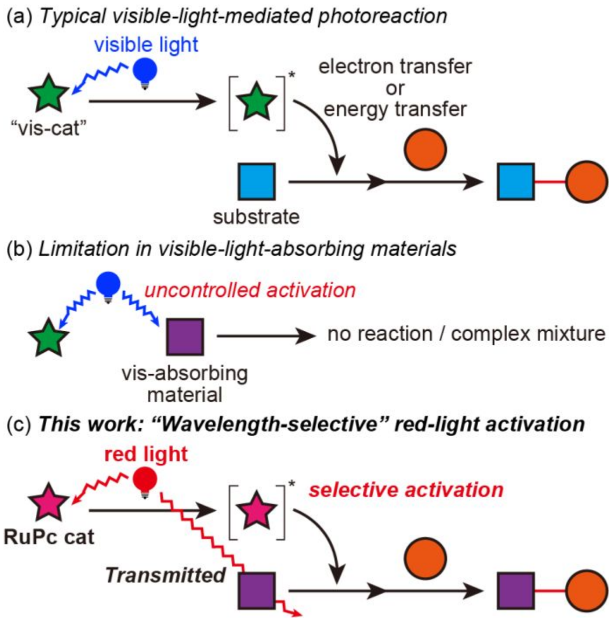

Fig. 1 Concept of red-light-mediated photoreactions.

Herein, we propose using "wavelength-selective" red light as a new transformation method for visible-light-absorbing materials (Fig. 1c). Most visible-light-absorbing materials do not

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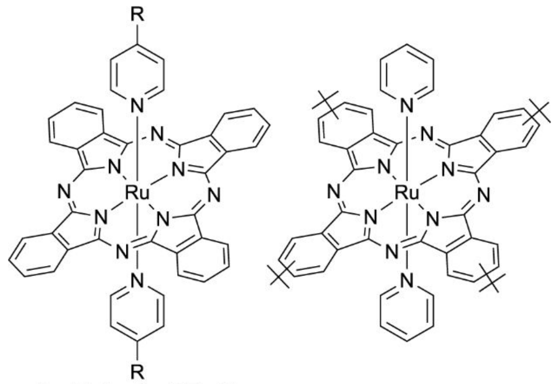
absorb light >600 nm. Therefore, it is possible to use such substrates if the photocatalysts are activated by red-to-near-infrared (NIR) light. To efficiently use longer-wavelength (lower-energy) light, an appropriate chromophore must be chosen. We focused on phthalocyanine ruthenium complexes (RuPcs). Phthalocyanine has a rigid structure, and various elements can be easily introduced into the central core.[7] These features allow precise control of the optical and redox properties involved in the catalytic activity. Several pioneering studies on the use of phthalocyanine derivatives as photocatalysts have been reported, albeit that these photoreactions usually require the addition of sacrificial reagents, such as ascorbic acid.[8] On the other hand, the introduction of ruthenium, which is often found in visible-light photocatalysts, can be expected to efficiently generate an excited triplet state due to the heavy-atom effect. As a model reaction, we chose the chlorotrifluoromethylation of alkenes using $[Ru(phen)_3]Cl_2$ as a visible-light catalyst, which has been reported by Han *et al*.[9] Since the trifluoromethyl group is a strongly electron-withdrawing group, we expected that it would significantly change the functionality of the visible-light-absorbing material. Such photoreactions, which use light that does not interact with the visible-light-absorbing material, should enable "late-stage" transformations of optical functional materials.



R = H: **1a**, R = CF_3: **1b**
R = NMe_2: **1c**

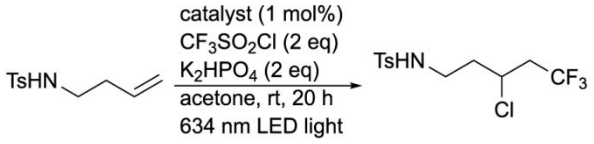
1d

Fig. 2 Structures of the RuPc photocatalysts **1a-d**.

Fig. 2 shows the representative structures of RuPcs, which were prepared by the condensation of phthalonitrile and pyridine derivatives in the presence of ruthenium trichloride as a template ion. **1a–d** were characterized by NMR spectroscopy and HR-MALDI-FT-ICR mass spectrometry. Single crystals of **1b** suitable for X-ray diffraction analysis were obtained by the diffusion of ethanol into a CH_2Cl_2 solution of **1b**. A thermal-ellipsoid plot of **1b** is shown in Fig. S1, ESI†. Two molecules of *p*-trifluoromethyl pyridine are coordinated at the vertical positions of the ruthenium center, suggesting weak π-orbital interactions between the phthalocyanine macrocycle and the axial pyridine substituents. Since the two axial pyridyl ligands also act as bulky substituents, Pc–Pc packing interactions were not observed. The UV-vis absorption spectra of **1a–d** are shown in Fig. S2, ESI†. All RuPcs exhibit an intense absorption band in the red-to-far-red regions. Although typical metallated Pcs have sharp Q-bands, the Q-bands of the RuPcs show broad tails in the longer-wavelength region. The reported calculated electronic structure of **1a** indicated an MLCT contribution to the broad Q-band.[10] The substituents on the axial pyridyl ligands have only a slight effect on the position of the Q-band.

With a series of RuPcs in hand, we investigated the red-light-mediated chlorotrifluoromethylation of alkenes (Table 1). We used a red (peak wavelength: 634 nm) LED light as the light source and **2a** as a model substrate. When the unsubstituted RuPc **1a** was used (1 mol%), the desired difunctionalized product **3a** was obtained in high yield by light irradiation for 20 h (entry 1) without any sacrificial reducing reagents. The catalytic activity of RuPcs depends on the substituents on the axial pyridyl ligand. Catalyst **1b** with electron-deficient substituents realized a catalytic activity similar to that of **1a** (entry 2), while electron-donating substituents (**1c**) decreased the activity (entry 3). Peripheral substituents also suppress the activity (entry 4). Both the central ruthenium ion and the phthalocyanine macrocycle are necessary for the reaction to proceed. Free-base and zinc complexes of Pcs as well as a tetraazaporphyrin ruthenium complex are poor photocatalysts for this reaction (entries 5–7; the detailed structures of the catalysts are summarized in Fig. S3, ESI†). Reactions in the absence of the catalyst, K_2HPO_4, or light, showed no product formation at all (entries 8–10); thus, it is feasible to conclude that the excited state of RuPc mediates this chlorotrifluoromethylation reaction. After the reaction without K_2HPO_4, the solution was highly acidic (pH < 1). Thus, the role of K_2HPO_4 is to neutralize the photodegradation product of CF_3SO_2Cl and to keep the appropriate pH of the reaction mixture. When 1 eq of 2,2,6,6-tetramethylpiperidine 1-oxyl (TEMPO) was added, no product was obtained at all, resulting in a complex mixture. This result supports that the photoreaction is a radical-mediated reaction.

Table 1 Catalyst screening for the red-light-mediated chlorotrifluoromethylation of **2a** [a]



2a

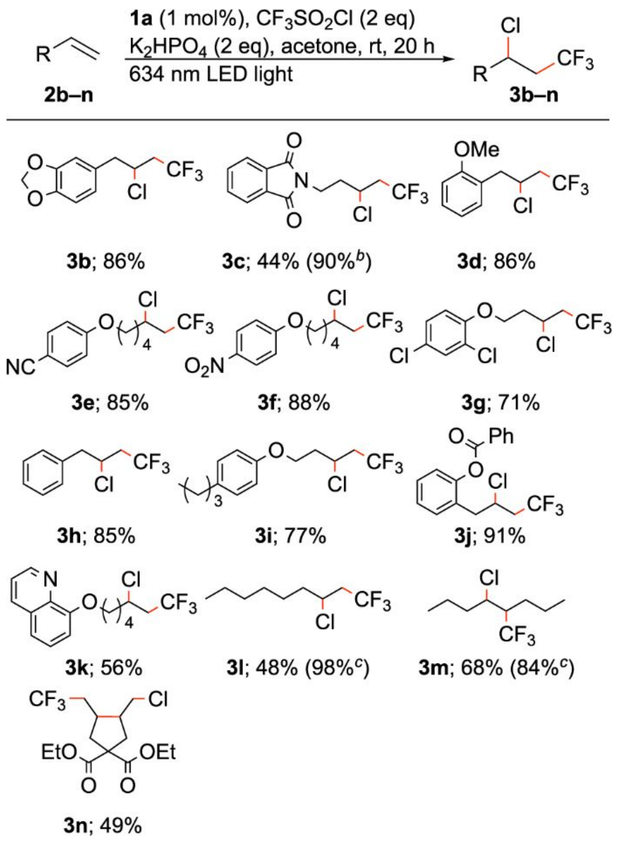
3a

Entry	catalyst	Yield /%[b]	Entry	catalyst	Yield /%[b]
1	**1a**	94	6	**ZnPc**	22
2	**1b**	81	7	**$Ru(py)_2TAP$**	0
3	**1c**	31	8	none	0
4	**1d**	59	9	**1a**[c]	0
5	**H_2Pc**	0	10	**1a**[d]	0

[a] **2a** (0.5 mmol), catalyst (1 mol%), CF_3SO_2Cl (1.0 mmol), and K_2HPO_4 (1.0 mmol) in acetone (3 mL) under an Ar atmosphere were irradiated using a red LED (λ_{ex} = 634 nm) at room temperature for 20 h. [b] ^{19}F NMR yield; $PhCF_3$ was used as an internal standard. [c] In the absence of K_2HPO_4. [d] In the dark.

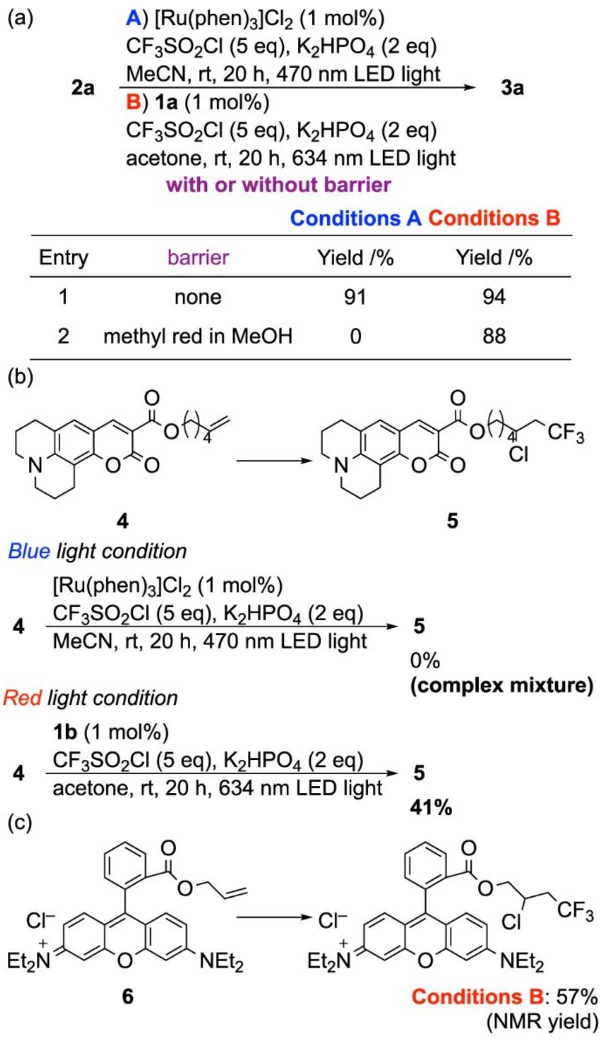
This RuPc-catalyzed red-light-mediated reaction could be applied to various functionalized alkenes (Table 2). The desired difunctionalized products were obtained in high yields for substrates containing acetal (**3b**), imide (**3c**), and ether (**3d**) groups. When **1a** was used as the catalyst, **3c** was obtained in moderate yield; however, the yield was improved when **1b** was used instead of **1a**. The reaction also proceeded with electron-withdrawing cyano (**2e**), nitro (**2f**), and chloro (**2g**) groups. In the case of a sterically demanding substrate with an ester group (**2j**), the desired product (**3j**) was obtained with high yield and high chemoselectivity. A quinoline (π-deficient heterocycle)-substituted compound (**3k**) was obtained in moderate yield. A simple aliphatic alkene (**2l**) and the internal alkene (**2m**) could be applied, and the corresponding difunctionalized alkanes were obtained. Moreover, when diethyl-2,2-diallylmalonate (**2n**) was subjected to the standard conditions described above, the cyclized product (**3n**) was obtained in moderate yield,[11] which indicates a radical-mediated reaction mechanism.

Table 2 Substrate scope for alkenes[a]



[a] Substrate (0.5 mmol), **1a** (5 μmol, 1 mol%), CF_3SO_2Cl (1.0 mmol), and K_2HPO_4 (1.0 mmol) in acetone (3 mL) under an Ar atmosphere was irradiated using a red LED (λ_{ex} = 634 nm) at room temperature for 20 h. Isolated yields. [b] **1b** was used instead of **1a**. [c] ^{19}F NMR yield; $PhCF_3$ was used as an internal standard.

We also conducted the optimized red-light reaction under shielded conditions (Fig. 3a) to demonstrate the high penetration depth of the red light. The reported $[Ru(phen)_3]Cl_2$ catalyst/blue-light system[9] (Conditions A) was compatible with our RuPc-catalyst/red-light system (Conditions B) in the absence of any barriers between the light source and the reaction vessel. Next, the reaction vessel was immersed in a methyl red solution (Fig. S4, ESI†), and the same conditions were applied. Since blue light is strongly absorbed by the methyl red solution, the reaction under Conditions A did not proceed. On the other hand, the reaction under Conditions B proceeded even under shielding.



Entry	barrier	Yield /%	Yield /%
1	none	91	94
2	methyl red in MeOH	0	88

Fig. 3 Penetration experiments. (a) Reactions under shielded conditions. (b) Chlorotrifluoromethylation of visible-light-absorbing substrate **4**. (c) Chlorotrifluoromethylation of rhodamine derivative **6**.

Substituted coumarins show intense absorption and fluorescence bands in the visible-light region. The coumarin platform has been widely adopted in the design of small-molecule fluorescent chemosensors.[12] Coumarin 343 derivative **4** can also absorb blue light, and the main absorption band of **4** overlaps with that of $[Ru(phen)_3]Cl_2$ (Fig. S5a, ESI†). When Conditions A were applied to **4**, **4** decomposed completely and the desired compound (**5**) was not obtained. On the other hand, we speculated that Conditions B could potentially allow the desired functionalization without photodegradation of **4**, since the absorption band of the RuPc catalyst and red light are exclusive to the absorption of **4**. After tuning the reaction conditions based on the optimized conditions, we succeeded in obtaining difunctionalized **5** with high chemoselectivity using **1b** as the catalyst and increasing the amount of CF_3SO_2Cl (Fig. 3b). Rhodamine derivative **6**, which absorbs longer-wavelength light (Fig. S5b, ESI†), could also be applied (Fig. 3c). Thus, the wavelength-selective reaction using red light directly transforms functional materials that absorb blue-to-green light.

A plausible reaction mechanism for the red-light-mediated reaction is shown in Fig. S6, ESI†. The cyclic voltammograms of RuPcs **1a–c** showed single reversible oxidation waves at 0.18–0.30 V vs Fc$^+$/Fc (Fig. S7, ESI†). The phosphorescence band of **1a** appeared in the NIR region (Fig. S8, ESI†). The ground- and excited-state redox potentials are summarized in Table S2, ESI†. The calculated excited oxidation potential (E_{ox}*) of **1a** is –1.25 V vs Fc$^+$/Fc, which is comparable to that of $[\mathrm{Ru(phen)_3}]\mathrm{Cl_2}$ (–1.25 V vs Fc$^+$/Fc[13]). The reduction potential of CF_3SO_2Cl (E_{red} = –0.56 V vs Fc$^+$/Fc)[14] is suitable for it to be reduced by excited **1a** to generate a trifluoromethyl radical. Furthermore, the Stern-Volmer phosphorescence quenching experiment illustrated that the excited state of **1a** was quenched in the presence of CF_3SO_2Cl (Fig. S9a, ESI†). In contrast, the emission was not quenched by the addition of substrate **2a** or K_2HPO_4. The Stern-Volmer constant of **1a** and CF_3SO_2Cl is 78.3 M^{-1} (Fig. S9b, ESI†), which is consistent with the previous literature for CF_3SO_2Cl-mediated photoredox reaction.[15] These results clearly support the electron-transfer-based oxidative quenching pathway in the catalytic cycle. One-electron-oxidized phthalocyanines and subphthalocyanines are often unstable in solution,[16] while the oxidation wave of **1a** is reversible, and intermolecular single-electron-transfer reactions between **1a**$^{\bullet+}$ and the CF_3-radical-added substrate can proceed without a sacrificial reducing agent. The substituents on the axial pyridyl ligands change the reactivity of the excited state of the RuPcs.[17] The low catalytic activity of **1c** is most likely due to quenching of the triplet excited state of **1c** by the electron-donating groups. Peripheral substituents of RuPcs also suppress their catalytic activity via vibrational quenching.

In summary, we have developed a red-light-mediated chlorotrifluoromethylation reaction of alkenes. The axial and peripheral substituents of RuPcs are essential to their catalytic activity, and **1a** and **1b** serve as efficient catalysts. Various functional groups are compatible with these difunctionalization reactions, and the reaction can be used as an alternative to the higher-energy blue light reaction. The addition of a sacrificial reducing agent was not necessary due to the high stability of the one-electron oxidized catalyst. The reaction also proceeded with high chemoselectivity for blue-light-absorbing fluorophore **4**, to which the traditional blue-light-mediated reaction conditions cannot be applied. This reaction can thus be expected to realize “late-stage” conversions of visible-light-absorbing functional materials. It can provide a new strategy for the synthesis of visible-light-harvesting materials and tuning of their physical properties. The parameters of the phthalocyanines can be adjusted by the choice of central metal and substituents while preserving their intense absorption of red-to-NIR light. In other words, it should be possible to tailor the catalyst for different photoreactions. Further work is currently in progress to prepare a Pc-based red-to-NIR photocatalyst to modify light-harvesting functional materials.

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Conflicts of interest

There are no conflicts to declare.

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