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Review

Transition-Metal-Catalyzed C−C Bond-Forming Reactions via C−H Activation for the Development of Fluorescent Materials with Practical Value

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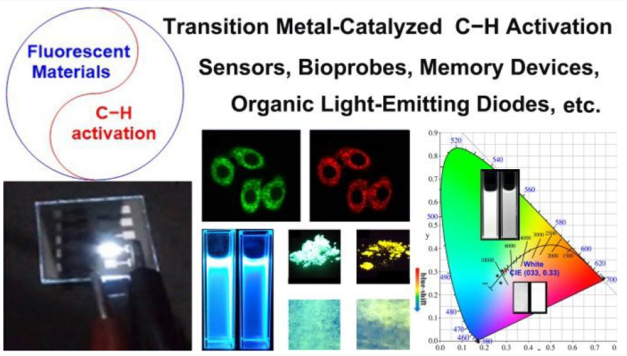

ABSTRACT: Fluorescent materials of practical value have attracted considerable attention because of their important applications in the fields of bioprobes, chemosensors, organic light-emitting diodes, field-effect transistors, memory devices, security systems, etc. As such, these materials have been improving the quality of our daily life. In the past few decades, chemists and materials scientists have constructed various organic fluorescent molecules using transition-metal-catalyzed C−C bond-forming reactions via C−H activation. This approach provides a unique opportunity for efficient and straightforward access to various organic fluorescent frameworks that cannot be easily constructed by traditional synthetic routes. This Review aims to highlight and help better understand the recent development of transition-metal-catalyzed C−C bond-forming reactions via C−H activation for optimized fluorescent materials of practical value. In addition, some perspectives on the challenges and opportunities in this field will be discussed.

KEYWORDS: *transition-metal-catalyzed, C−H activation, C−C bond-forming, cross-coupling, fluorescent materials*

1. INTRODUCTION

Organic fluorescent materials of practical value are of great interest in diverse scientific fields including chemistry, materials science, medicine, and biology due to their excellent photophysical properties, high chemical stability, and synthetic accessibility and the high sensitivity of their photophysical parameters to the microenvironment.[1] As such, organic fluorescent materials of practical value have been widely used in various areas including sensors, bioprobes, memory devices, security systems, organic light-emitting diodes, and field-effect transistors. In the past decade, studies on organic fluorescent materials of practical value have rapidly grown, and transition-metal-catalyzed C−C bond-forming reactions via C−H activation have emerged as a straightforward and effective method to construct various organic fluorescent materials.[1g,2,3]

The transition-metal-catalyzed C−C bond-forming approach via C−H activation has emerged as a powerful synthetic strategy in modern synthetic organic chemistry and has gained widespread attention in recent years because this approach can provide more atom- and step-economic syntheses of complex organic fluorescent materials that cannot be easily prepared by traditional synthetic methods.[1g,2,3] Compared with traditional synthetic methods, this approach can avoid the use of stoichiometric organometallic reagents and prefunctionalized starting materials and is thus environmentally and economically beneficial.[1g,2,3] As a result, a variety of transition-metal-catalyzed C−C bond-forming reactions via C−H activation have been developed in recent years to construct novel organic fluorescent materials of practical value. Clearly, there is an urgent need to summarize this field, analyze the metals used, and discuss the detailed mechanisms of these processes to further accelerate the development of this research.

Although a similar topic was reviewed previously, there is still a lot of space for discussion from different angles and focus points. The previous review summarizes four types of C−H bond functionalization reactions for the preparation of fluorescent materials from April 2007 to January 2020.[1g] In contrast, this new Review will emphasize and discuss C−H arylation, heteroarylation, alkenylations, acyloxylation, and annulation reactions via palladium, rhodium, iridium, copper, cobalt, ruthenium, and bimetal catalysis to construct fluorescent materials of practical value. The emphasis is on the literature

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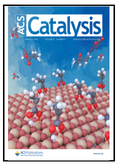
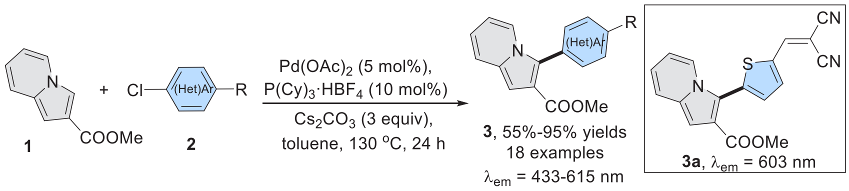
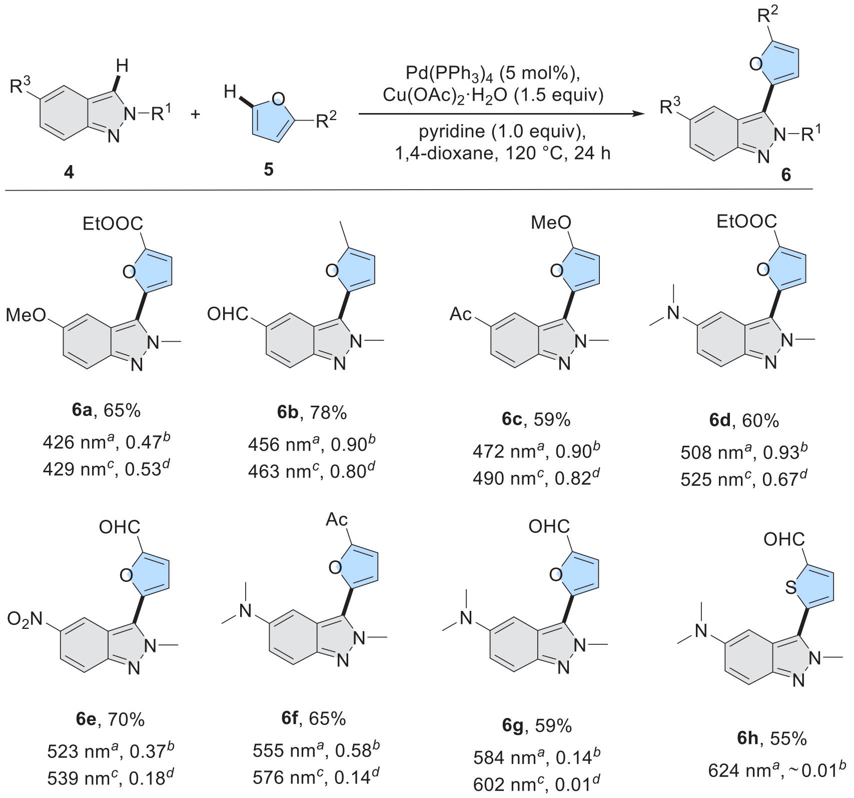


Scheme 1. Palladium-Catalyzed C−H (Hetero)arylation of *N*-Heteroarenes with (Hetero)aryl Chlorides



Scheme 2. Palladium-Catalyzed Oxidative C−H/C−H Cross-Coupling of 2*H*-Indazoles with Various Heteroarenes



^{a,c}Emission maximum in CH_2Cl_2 or CH_3CN at 10.0 μM. ^{b,d}Absolute quantum yield in CH_2Cl_2 or CH_3CN at 10.0 μM.

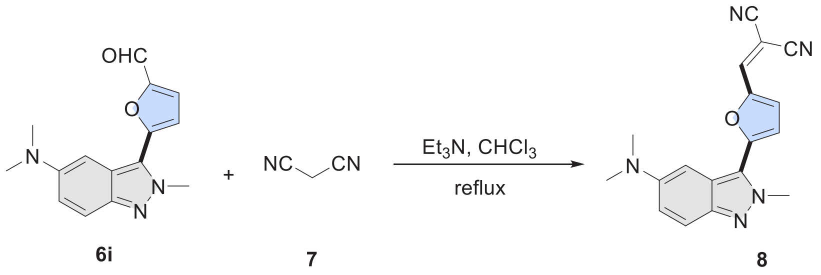
from March 2009 to January 2022. As such, the angle and focus between these two reviews are significantly different. In the past two years, the related fields have developed rapidly, and many novel fluorescent materials have been synthesized via the transition-metal-catalyzed C−C bond-forming reactions via C−H activation. In particular, onium salt fluorescent materials as fluorescent probes and spirocyclic fluorescent materials for thermally delayed fluorescence have been rapidly developed, and these were not included in the previous review article. In addition, while a variety of fluorescent molecules were synthesized through C−H functionalization reactions, only a portion of them can be found useful in bioprobes, chemosensors, organic light-emitting diodes, field-effect transistors, memory devices, and security systems. This new Review focuses on discussing this part of fluorescent materials, and there is no review article specifically reported on this content to date. We will briefly discuss the proposed mechanisms of these reactions and applications of the resulting fluorescent molecules. We hope to offer the readers a good understanding of the state of development in the field. We will also discuss some key ideas and raise awareness for this emerging field to the readers.

2. PALLADIUM-CATALYZED C−C BOND-FORMING REACTIONS VIA C−H ACTIVATION FOR THE DEVELOPMENT OF FLUORESCENT MATERIALS

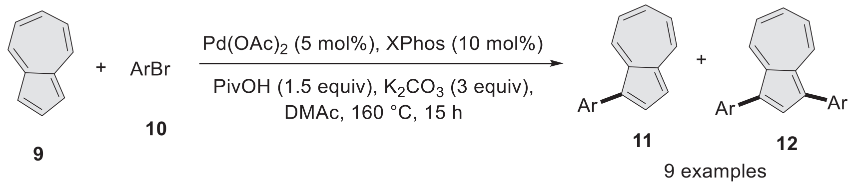
Palladium catalysis is considered one of the most effective organic synthetic approaches and has been extensively investigated in the past few decades.[4,5] Palladium-catalyzed C−C bond-forming reactions are a staple of modern synthetic

Figure 1. Photographic images of Indazo-Fluors **6a**−**6h** in CH_2Cl_2 (excited at 365 nm under a UV lamp). Reproduced from ref 5b. Copyright 2016 American Chemical Society.

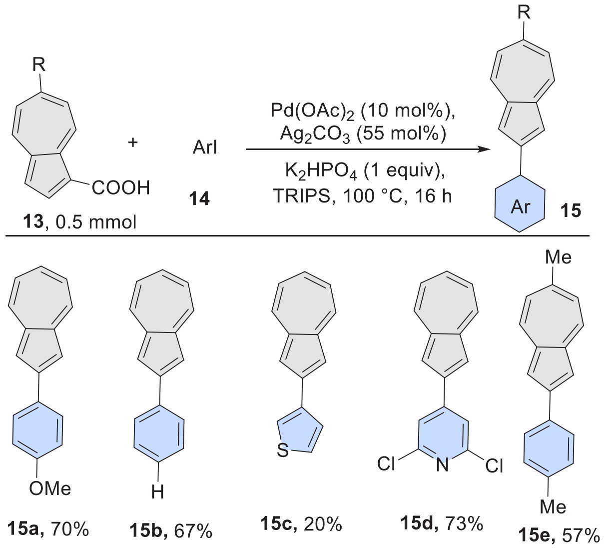
Scheme 3. Synthesis of the Near-Infrared Fluorophore Dye 8



Scheme 4. Pd-Catalyzed Direct C−H Bond Arylation to Synthesize 1-Aryl- and 1,3-Diarylazulenes



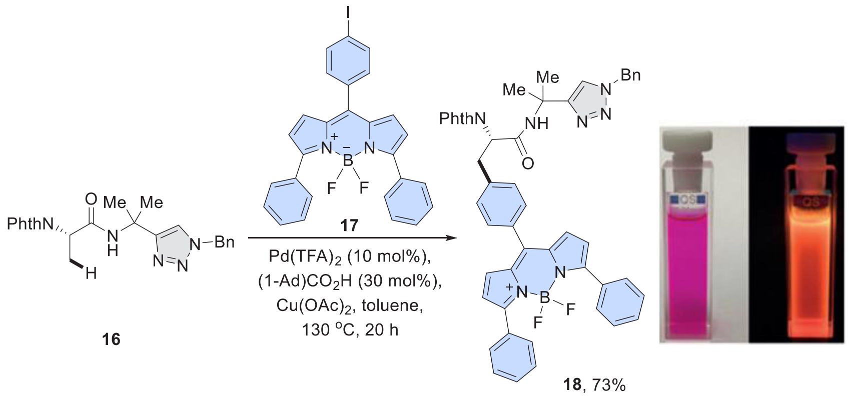
Scheme 5. Carboxylic-Acid-Directed C−H (Hetero)arylation of Azulene



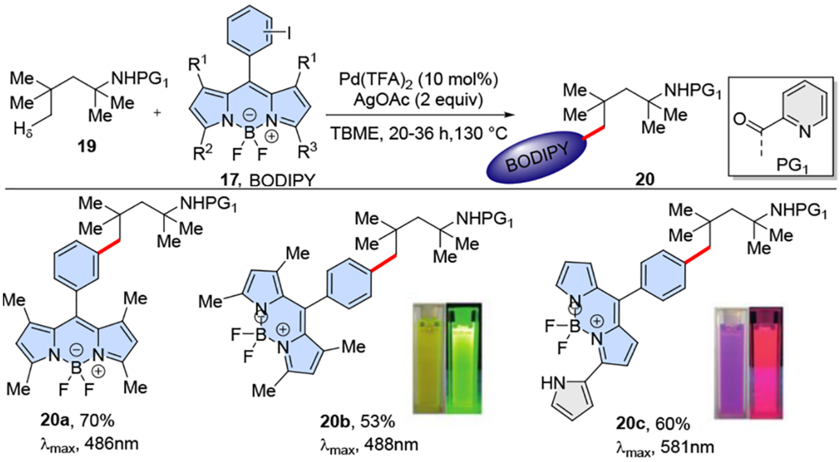
chemistry, allowing for efficient access to diverse products with good functional group compatibility.[5] Palladium-catalyzed C−H (hetero)arylation and annulation reactions have been used extensively to construct organic fluorescent materials of practical value.[5]

2.1. Palladium-Catalyzed C−H (Hetero)arylation. The advantages of palladium-catalyzed C−H (hetero)arylations over traditional cross-coupling methods are significant; they have better synthetic efficiency, can avoid the use of stoichiometric organometallic reagents, and are more conducive to environmental protection. The most widely applied approach for these reactions involves the use of aryl halides, arylboronic acids, aryl acids, and heteroarenes as the (hetero)arene source. The π-conjugated heteroaryl-(hetero)aryl fluorescent core framework has been constructed by palladium-catalyzed C−H (hetero)arylation reactions. In 2012, Lan and You developed a structurally diverse library of organic fluorophores by palladium-catalyzed direct C−H bond (hetero)arylation of *N*-heteroarenes with a wide range of (hetero)aryl chlorides (Scheme 1).[5a] These fluorescent molecules exhibited a full coverage of solid-state emission wavelengths in the range from blue to red (em: 405−616 nm). Furthermore, a novel bioimaging fluorescence probe (**3a**) can be synthesized by this protocol and successfully marked the human malignant melanoma A375 cells.

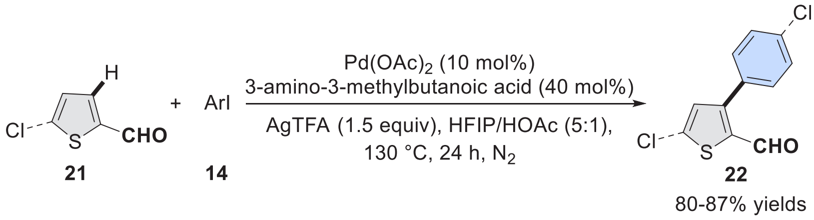
Scheme 6. Palladium-Catalyzed C(sp^3)−H Arylation to Build Novel Peptidomimetic BODIPY Sensors; Reproduced with Permission from ref 5d, Copyright 2018 Wiley-VCH



Scheme 7. BODIPY Labeling of δ-C(sp^3)−H Bonds of Amines; Reproduced with Permission from Ref 5h, Copyright 2019 Wiley-VCH



Scheme 8. Synthesis of 3-Aryl-(2-aldehyde)thiophenes 22



In analogy with the C−H (hetero)arylations employing (hetero)aryl halides, transition-metal-catalyzed oxidative C−H/C−H cross-coupling of (hetero)arenes represents an atom-economic approach for the synthesis of bi(hetero)aryl dyes. In 2016, the You group reported a palladium-catalyzed oxidative C−H/C−H cross-coupling of electron-deficient 2*H*-indazoles with electron-rich heteroarenes to build up a large library of donor−acceptor-type biheteroaryl fluorophores (Scheme 2).[5b] These biheteroaryl dyes exhibit continuously tunable full-color emissions with high quantum yields and large Stokes shifts in solution (Figure 1). Novel near-infrared-emitting dyes (emission wavelengths over 700 nm) were successfully obtained by fine-tuning the donor−acceptor skeleton. Furthermore, the near-infrared-emitting dye **8** has been proven to be a very effective mitochondria-targeted fluorescent probe (Scheme 3).

The development of efficient methods to obtain novel azulene-based functional material molecules is of great research interest in academia and industry.[6] In 2016, Murai and Takai reported a direct palladium(II)-catalyzed arylation of C−H bonds in azulene to produce mono- and diarylazulenes (Scheme 4).[5c] In this protocol, Pd(OAc)$_2$/XPhos were combined as cocatalysts, and pivalic acid was used as a key additive. The resulting 1,3-diarylazulenes have considerable potential as functional materials for optoelectronic devices.

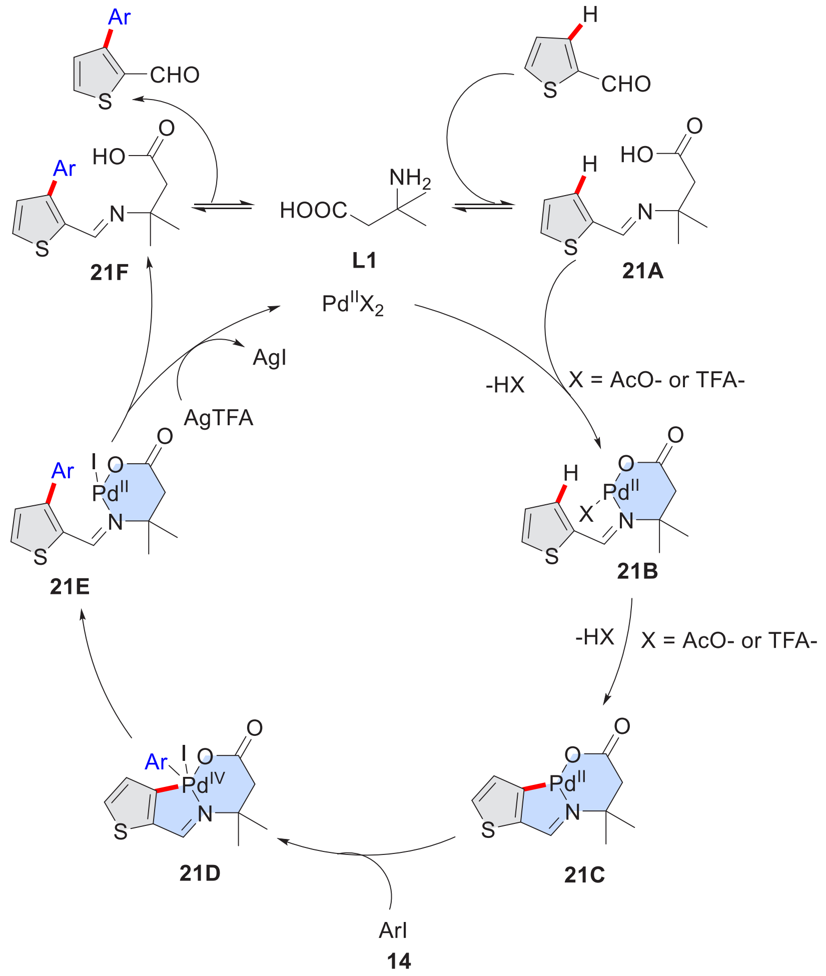
In 2020, Xu and co-workers developed an arylation reaction using 1-azulene carboxylic acids as substrates and Pd(OAc)$_2$ as a catalyst (Scheme 5).[5i] In this study, the phosphate base and bulky carboxylic acid were considered key additives. This reaction showed a broad substrate scope for various heteroarenes and aryl iodides. A variety of 2-arylazulenes were obtained in moderate to good yields under heated reaction conditions.

A notable report by Ackermann showed that a palladium-catalyzed C−H arylation strategy offers a great opportunity for the late-stage functionalization of BODIPY compounds incorporating structurally complex amino acids and peptides (Scheme 6).[5d] A series of novel peptidomimetic BODIPY sensors have been designed and synthesized.

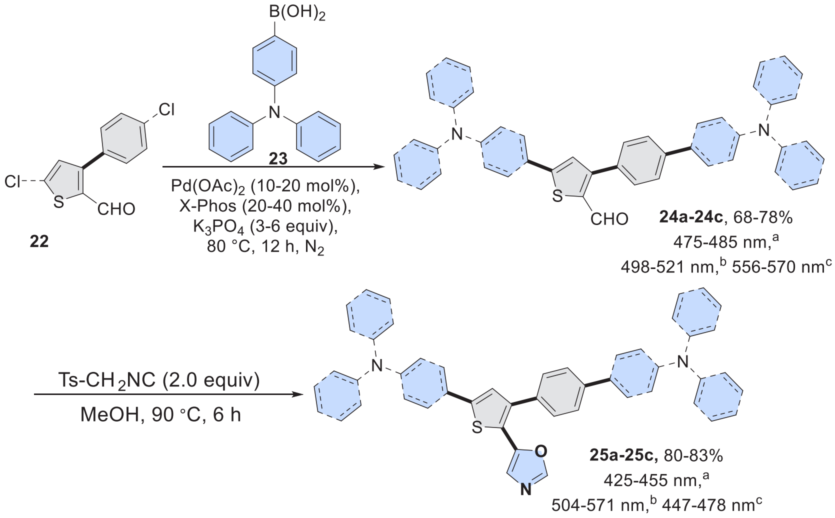
In 2019, Maiti and Paton developed a palladium-catalyzed δ-C(sp^3)−H arylation of aliphatic amines to synthesize BODIPY-based fluorescent molecules. In this study, Pd(TFA)$_2$ was used as a catalyst, and picolinamide was employed as a directing group. A series of BODIPY labelings of bioactive amines were obtained under ligand-free reaction conditions in moderate to good yields (Scheme 7).[5h]

Mechanochromic fluorescent materials are considered to be "smart" stimuli-responsive materials and have attracted extensive interest from both industry and academia due to their promising applications in mechanical sensors, security systems, deformation detectors, memory devices, etc.[7] In 2018, Ge and co-workers developed a palladium-catalyzed C−H arylation and subsequent Suzuki cross-coupling strategy to construct a series of blue- and red-shifted mechanochromic materials (Schemes 8−10; Figure 2).[5e] In this C−H arylation reaction, a condensation of thiophene-2-carbaldehyde and the transient ligand **L1** produces the imine intermediate **21A** (Scheme 9). Coordination of **21A** to the palladium species forms cyclic palladium complex **21B**. Next, **21B** typically undergoes a C−H bond activation step to generate [5,6]-bicyclic palladium intermediate **21C**. Subsequently, oxidative addition of iodobenzene to **21C** gives the palladium(IV) species **21D**. Subsequently, reductive elimination from **21D** followed by ligand dissociation releases the β-arylated product **22** and transient ligand **L1**.

Scheme 9. Proposed Mechanistic Pathway for the Formation of 22



Scheme 10. Suzuki Cross-Coupling Reaction to Construct TPA-Bearing 3-Phenyl-(2-carbaldehyde)thiophenes



[a]Emission maximum in toluene (5×10^{-5} M). [b]Emission maximum in pristine powder. [c]Emission maximum in ground powder.

Furthermore, triphenylamine (TPA) was used as the donor (D) unit and aldehyde or oxazole moiety as the acceptor (A) to construct D−A-type dyes and to further discover mechanochromic regularity. Subsequently, the palladium-catalyzed C−H heteroarylation of TPA-bearing oxazoles (**26**) with (*Z*)-1-chloro-4-styrylbenzene or (*Z*)-1,2-bis(4-chlorophenyl)ethane (**27**) was used to obtain *cis*-olefin-based mechanochromic fluorescent materials (Scheme 11).[5g] In 2020, the same group designed and synthesized two novel mechanochromic fluorescent molecules, TPA-bearing 2-(4-(oxazol-2-yl)phenyl)-

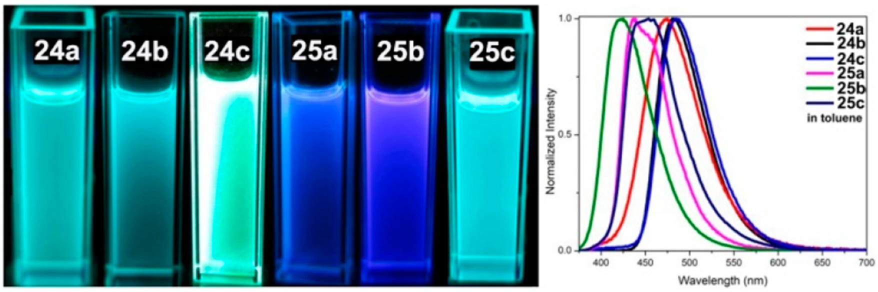
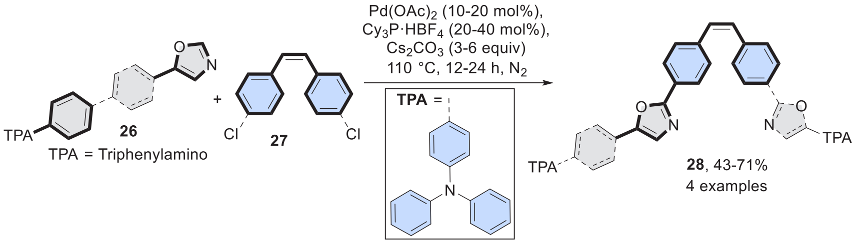
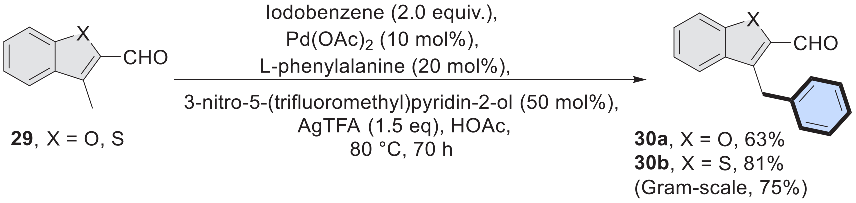


Figure 2. Photographic images and normalized emission spectra of **24a**−**24c** and **25a**−**25c** in toluene (5.0×10^{-5} M). Reproduced with permission from ref 5e. Copyright 2018 Wiley-VCH.

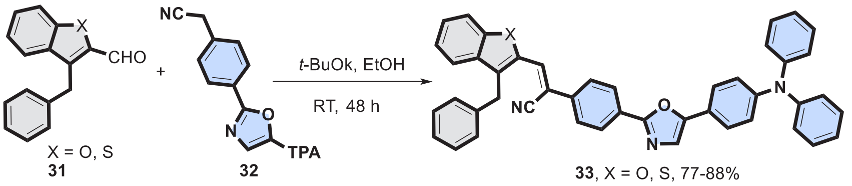
Scheme 11. Synthesis of TPA-Containing (*Z*)-2-(4-Styrylphenyl)oxazoles



Scheme 12. Synthesis of 3-Benzylbenzothiophene-2-carbaldehyde and 3-Benzylbenzofuran-2-carbaldehyde



Scheme 13. Synthesis of TPA-Containing 2-(4-(Oxazol-2-yl)phenyl)acetonitrile-3 Benzylbenzothio/Furanphens



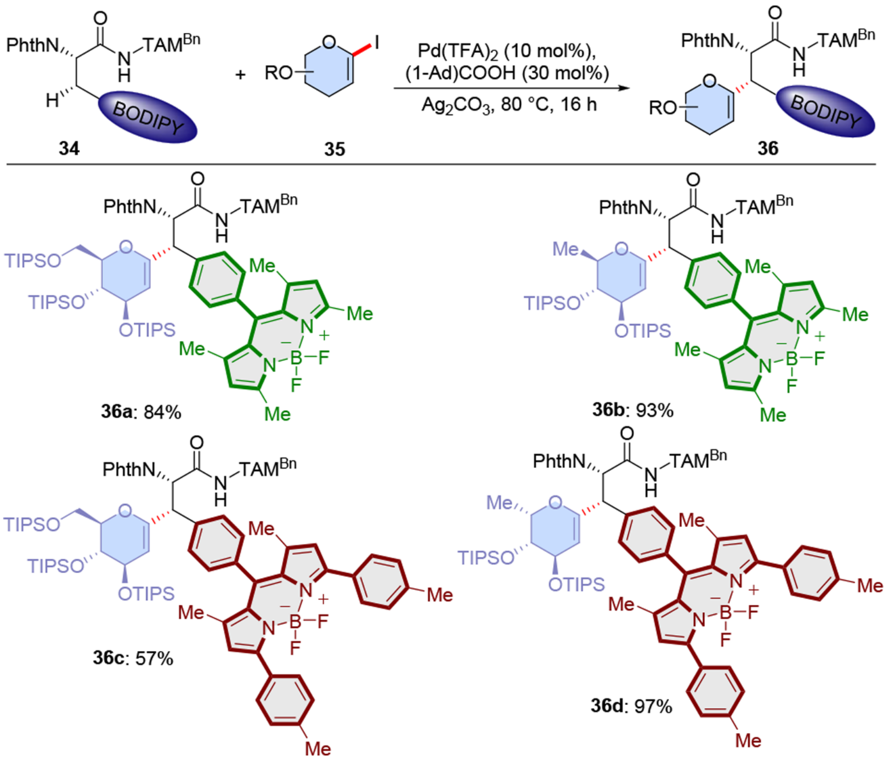
acetonitrile-3-benzylbenzothio/furanphen (**33**), using a palladium-catalyzed C−H arylation and subsequent Knoevenagel condensation strategy (Schemes 12 and 13).[5k]

2.2. Palladium-Catalyzed C−H Glycosylation. As one of the most powerful tools for the late-stage functionalization of natural products and biologically active molecules, the transition-metal-catalyzed C−H bond functionalization reaction has been rapidly developed in the past few decades. In 2020, Ackermann and co-workers achieved palladium-catalyzed late-stage γ-C(sp^3)−H glycosylation of different BODIPY-labeled amino acids (Scheme 14).[5j] In this process, the triazolyldimethylmethyl was used as a directing group, and $Pd(TFA)_2$ was employed as the catalyst. The resulting fluorescent-labeled glycoamino acids have potential applications in biocompatible fluorescent probes.

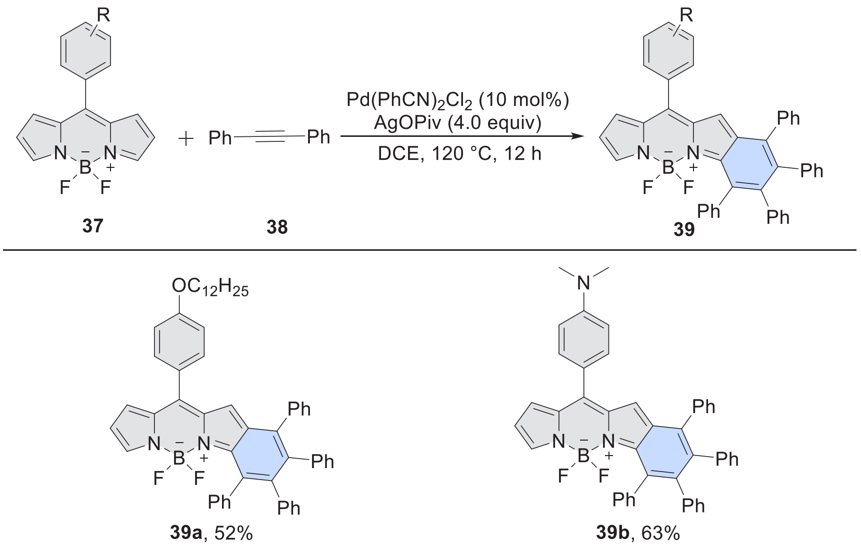
2.3. Palladium-Catalyzed C−H Activation for Annulation. The palladium-catalyzed C−H annulation process has been proven effective for the synthesis of the π-extended conjugated molecules, which represent a particularly valuable framework in organic fluorescent materials. BODIPY-based fluorescent materials usually show high molar absorption coefficients, high fluorescence quantum yields, narrow emission bandwidths, good solubility, and chemical and photochemical stability. In this context, direct C−H functionalization reactions of BODIPY have the promise to greatly expedite the synthesis of fluorescent materials, and they have gained great interest within the synthetic chemistry community. In 2018, Lan and co-workers reported an efficient palladium-catalyzed direct C−H annulation of BODIPYs with alkynes to prepare a series of unsymmetrical benzo[b]-fused BODIPYs from readily available starting materials (Scheme 15).[5f] These new fluorescent probes exhibited strong fluorescence emissions and large Stokes shifts. Fluorescent probes **39a** and **39b** would be potential lysosome-targeted reagents that show low cytotoxicity, specific lysosome-labeling capacities, and turn-on fluorescence emissions in cells.

Spirocyclic aromatic compounds have attracted great research interest in recent years because of their potential applications in organic light-emitting diodes (OLEDs) and organic solar cells.[8] Very recently, a direct synthesis of spirofluorenyl naphthalenones by the palladium-catalyzed C−H spiroannulation of

Scheme 14. BODIPY-Labeled Glycoamino Acids



Scheme 15. Palladium-Catalyzed C−H Annulation of BODIPYs to Prepare Benzo[b]-Fused BODIPYs

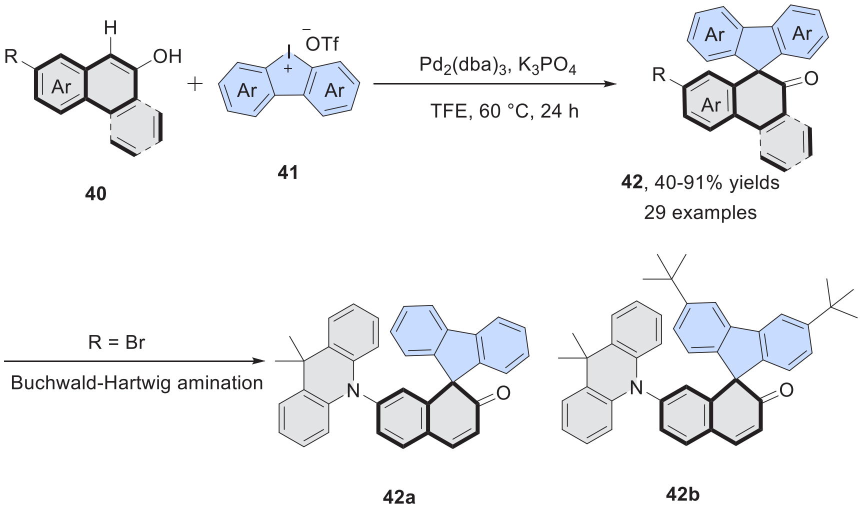


naphthols with cyclic diaryliodonium salts was developed by You and co-workers (Scheme 16).[51] To highlight the efficiency of this reaction, a 1.0 mmol scale reaction was successfully conducted, giving a good yield. The spirofluorenyl naphthalenone unit is further used as the acceptor to construct D−A-type thermally activated delayed fluorescent (TADF) materials. The TADF materials have attracted considerable attention in the field of OLEDs because they can theoretically realize 100% internal quantum efficiency. Based on this strategy, the authors synthesized new TADF host materials **42a** and **42b**. Furthermore, the device based on **42a** as the host material and (Ir(mphmq)$_2$-(tmd)) as the emitter exhibited a maximum external quantum efficiency (EQE$_{max}$) as high as 32.2%, indicating a breakthrough in exciton utilization efficiency (Figure 3).

3. RHODIUM-CATALYZED C−C BOND-FORMING REACTIONS VIA C−H ACTIVATION FOR THE DEVELOPMENT OF FLUORESCENT MATERIALS

Rhodium catalysis is an important organic synthetic approach with numerous applications. Rhodium catalysts often exhibit high reactivity, atom-economy, broad substrate scope, and good functional group compatibility. Rhodium-catalyzed C−C bond-forming reactions via C−H activation have been identified as a useful tool in synthesizing novel fluorescent materials and have witnessed rapid development in the past few decades.[9,10] A

Scheme 16. Palladium-Catalyzed C−H Spiroannulation of Naphthols with Cyclic Diaryliodonium Salts



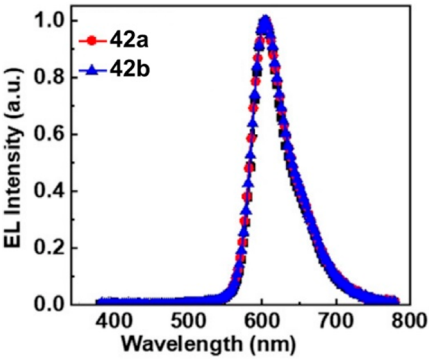


Figure 3. Electroluminescence spectra of the **42a**- and **42b**-based devices at the luminance of 1000 cd m^{-2}; (Ir(mphmq)$_2$-(tmd)) as the emitter, tmd = 2,2,6,6-tetrametylheptane-3,5-dionate, mphmq = 2-(3,5-dimethylphenyl)-4-methylquinoline. (inset) Electroluminescence image of the **42a**-based device. Reproduced with permission from ref 5l. Copyright 2021 Wiley-VCH.

variety of organic fluorescent molecules of practical value have been discovered via C−H heteroarylation and annulation reactions using rhodium complexes as catalysts.[10]

3.1. Rhodium-Catalyzed C−H Heteroarylation.

Bi(hetero)aryl frameworks are widely present in organic fluorescent molecules. The development of efficient and concise approaches to construct bi(hetero)aryls is of great research interest to materials chemistry research scientists. The rhodium-catalyzed C−H/C−H cross-coupling between two (hetero)-arenes is one of the most attractive strategies to obtain bi(hetero)aryls as it avoids the tiresome multistep synthesis and prefunctionalization of both starting materials.

In order to avoid the use of stoichiometric amounts of an external oxidant and extra steps to remove a directing group, scientists have developed the use of a traceless oxidizing directing group as both the directing group and the internal oxidant in the field of oxidative C−H activation. In 2015, Lan and You developed the first example of a rhodium-catalyzed C−H/C−H *ortho*-heteroarylation of phenols with various azoles via a traceless oxidation directing strategy.[10a] A series of highly functionalized 2-(2-hydroxyphenyl)azoles were obtained. 2-(2-Hydroxyphenyl)azoles are a typical class of excited-state intramolecular proton-transfer (ESIPT) molecules, which enable a dual-emission behavior involving the normal enol-form emission with a relatively short wavelength and the proton-transfer keto-form emission with a relatively long wavelength. The authors obtained a white-light-emitting single organic molecule by the incorporation of TPA into 2-(2-hydroxyphenyl)azole skeletons (Scheme 17). These novel white-light-emitting dyes exhibited strong fluorescent emission, high quantum yields, and high thermal stabilities (Figure 4).

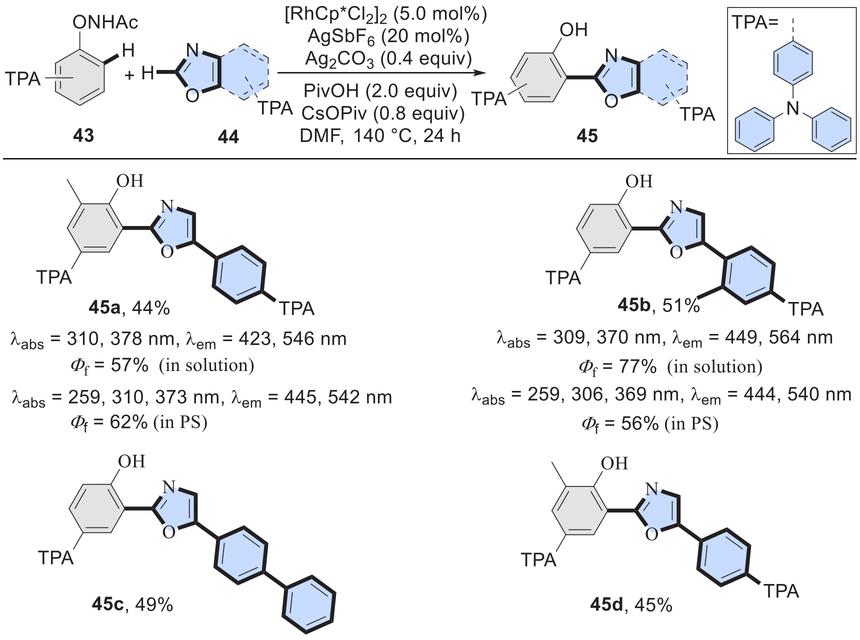
A plausible reaction mechanism is depicted in Scheme 18. Initially, *N*-aryloxy acetamide **43a** reacts with Cp*Rh^{III} to generate the six-membered rhodacycle intermediate **43A** by chelation with the amide nitrogen atom and subsequent C−H bond activation of the arene. Next, intermediate **43A** reacts with **44** to form the key oxazolyl-Rh^{III}-phenyl intermediate **43B**. Reductive elimination of intermediate **43B** affords intermediate **43C**. Finally, the oxidative addition of the N−O bond to intermediate **43C** generates intermediate **43D**, which upon protonation by PivOH produces product **45b**.

In subsequent research, this group constructed new white-light-emitting single organic molecules **45c** and **45d** using the same synthetic strategy and further prepared OLEDs.[10b] The **45c**-based doped device displayed green-white emission with CIE$_{1931}$ (0.25, 0.41) and a high external quantum efficiency (EQE) up to 5.3%, which was the highest EQE in single molecular organic white-light-emitting materials. The singlet exciton yield is up to 63%, which exceeds the theoretical limit of 25% in conventional fluorescent OLEDs. Experimental data and a theoretical analysis demonstrated that **45c** possesses a highly hybridized local and charge-transfer (HLCT) excited state character.

In addition, the **45d**-based doped device (2 wt % in CBZ$_2$-F$_1$) showed sky-blue emission with CIE$_{1931}$ (0.18, 0.16) and an EQE of 8.0%, which indicated that **45d** underwent a hot exciton reverse intersystem crossing (RISC) process.

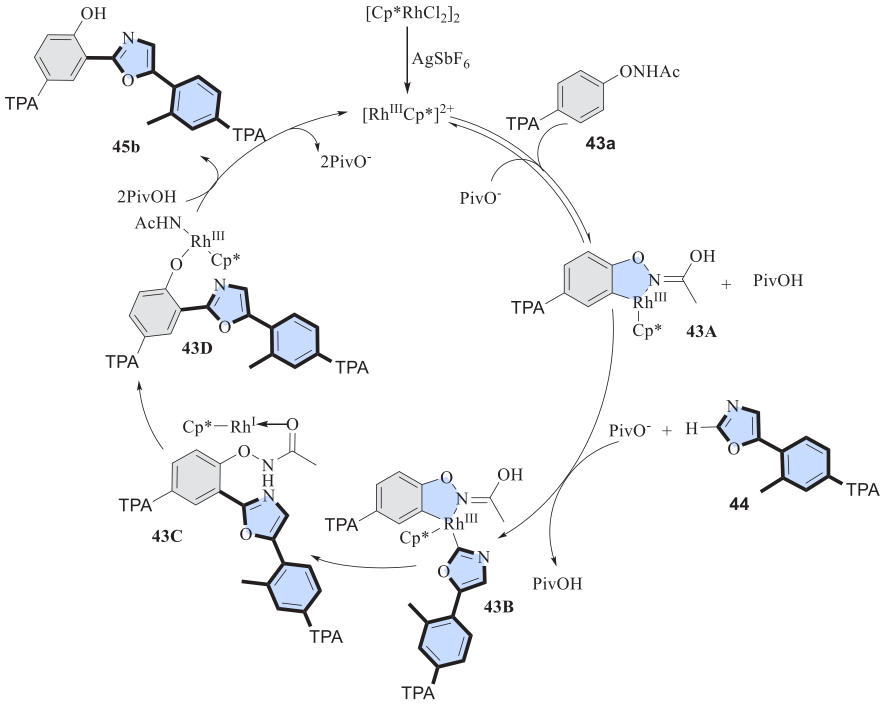
Based on the rhodium-catalyzed internally oxidative C−H heteroarylation strategy, You and Lan synthesized the deep-blue fluorescent molecule 2-(2′-hydroxyphenyl)azole **48** (Scheme 19), which showed the sole enol-form emission.[10c] In the deep-blue hot exciton molecule **48**, TPA was used as a moderate donor, and oxazole was used as a weak acceptor. The **48**-based doped device exhibits a highly efficient deep-blue emission with the CIE$_{1931}$ (0.15, 0.08) and an EQE up to 7.1%.

Scheme 17. Synthesis of TPA-Bearing 2-(2-Hydroxyphenyl)oxazoles[a]



[a]Absolute quantum yields, absorption, and emission maxima were measured in toluene (5.0×10^{-5} M), in toluene (1.0×10^{-6} M), and in the PS films (0.2 wt %), respectively.

Scheme 18. Plausible Mechanism for the Cross-Coupling of *N*-Aryloxyacetamide with Azoles

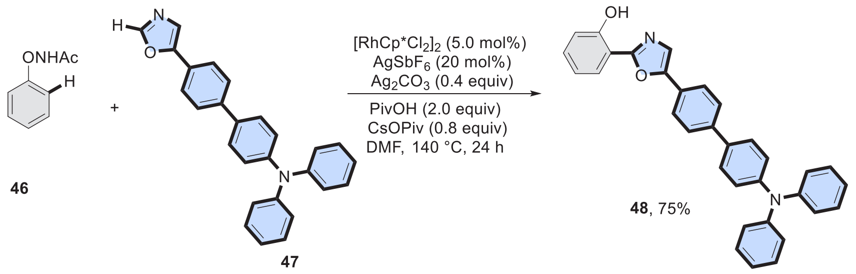


In addition, this group further prepared novel ESIPT fluorescent molecules in moderate yields using the rhodium-catalyzed C−H/C−H cross-coupling of *N*-(4-bromophenoxy)-acetamide with azoles and a subsequent Suzuki coupling reaction strategy (Scheme 20).[10e,f] The new fluorescent molecules still possess hybridized local and charge-transfer excited-state characters. The doped devices of **52a** and **52b** exhibit high external quantum efficiencies of 5.6% and 4.9%, respectively. The organic functional molecule **52c** clearly exhibited mechanochromic luminescent properties. The mechanochromic behaviors of **52c** were further applied (Figure 5). The pristine powder of **52c** exhibited a yellowish-green emission upon excitation with a UV lamp (λ_{ex} = 365 nm). Then, the letters "ESIPT" were engraved on the thin film with a spatula. Due to the pressure-induced mechanochromism, these letters emitted white fluorescence (Figure 5a). The letters "ESIPT" could be easily erased by using CH_2Cl_2 vapor as an "eraser" (Figure 5b).[10e]

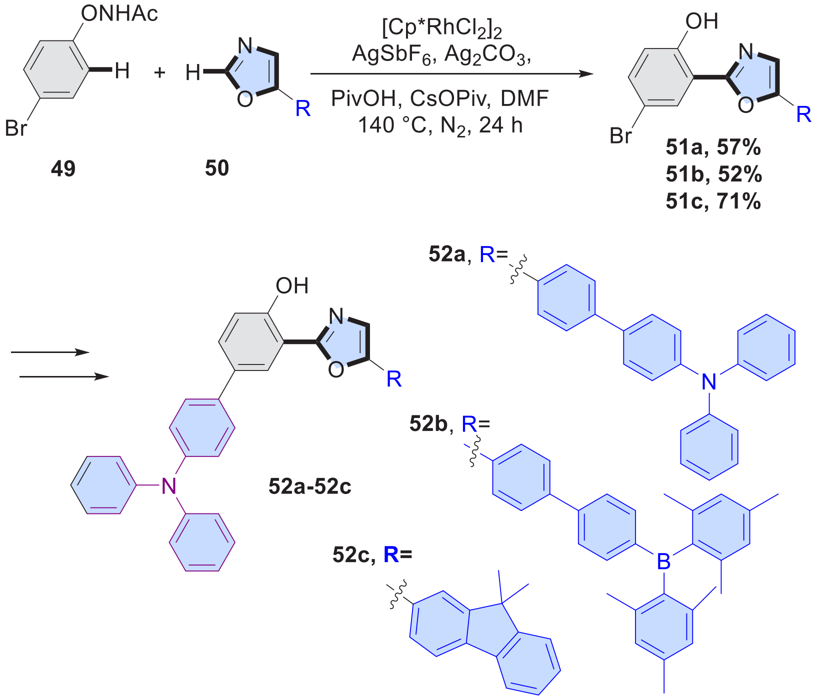
3.2. Rhodium-Catalyzed C−H Activation for Annulation.

The C−H activation/annulation reaction is considered to

Scheme 19. Synthesis of the Deep-Blue Fluorescent Molecule 48



Scheme 20. Synthesis of the ESIPT Fluorescent Molecules 52a−52c



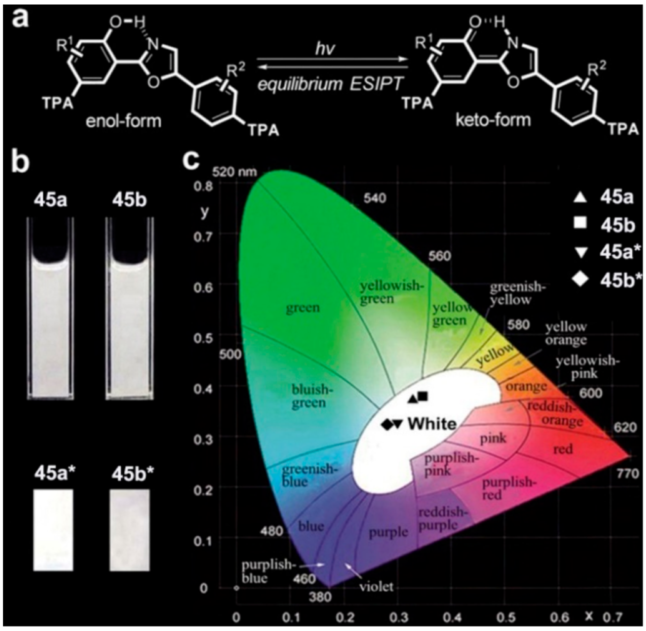


Figure 4. Photographic images and emission color coordinates of **45a** and **45b** in toluene and PS films. Reproduced with permission from ref 10a. Copyright 2015 Wiley-VCH.

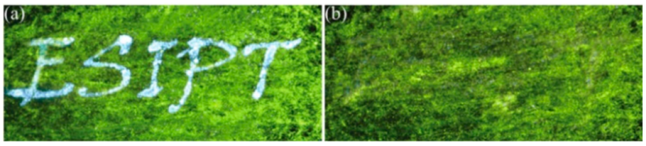


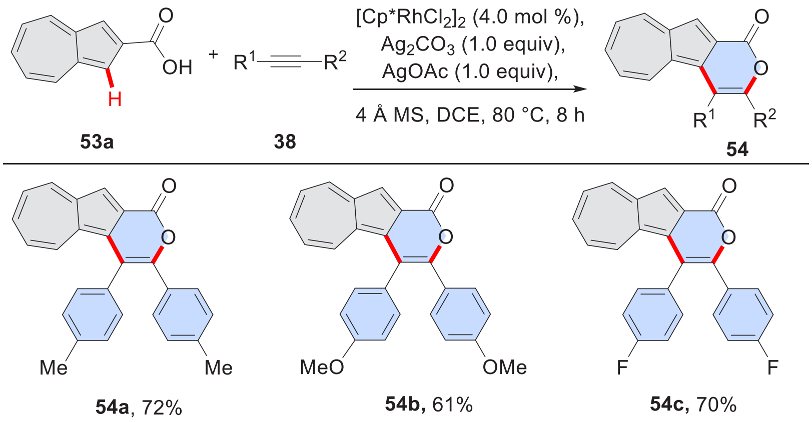
Figure 5. Photographs are shown under UV light (365 nm). (a) "ESIPT" was written on a **52c**-coated paper under mechanical pressure. (b) "ESIPT" was erased after treating the coated paper with CH_2Cl_2 vapor. Reproduced with permission from ref 10e. Copyright 2021 Royal Society of Chemistry.

be an ideal tool that can quickly build extended π-systems and consequently has aroused great interest among scientists in chemical and materials research. In recent years, a large library of novel fluorescent molecules was rapidly constructed via rhodium-catalyzed C−H activation/annulation with potential applications in fluorescence bioimaging, chemosensors, and OLEDs.

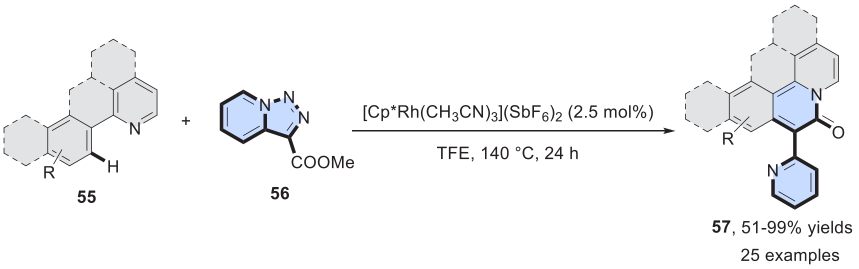
In 2020, the Lee group reported rhodium-catalyzed oxidative [4 + 2] cyclization reactions of azulene carboxylic acids with alkynes (Scheme 21).[10d] A series of azulenolactone derivatives were obtained in good to excellent yields under aerobic conditions. The resulting azulenolactone derivatives have potential applications in biocompatible fluorescent probes.

https://doi.org/10.1021/acscatal.1c05722
ACS Catal. 2022, 12, 2796−2820

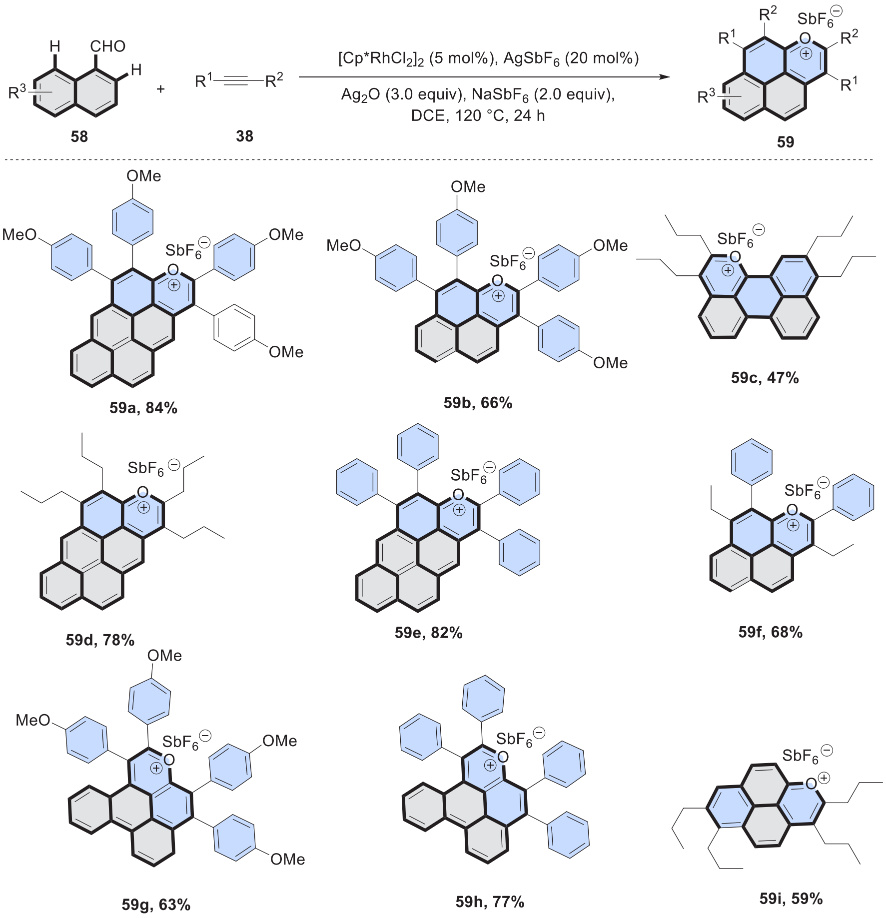
Scheme 21. Rh-Catalyzed [4 + 2] Cyclization Reactions of Azulene-2-carboxylic Acids with Alkynes



Scheme 22. Rh^{III}-Catalyzed C−H Bond Activation and Subsequent Carbene Insertion with Pyridotriazoles



Scheme 23. Rhodium-Catalyzed C−H Activation/Annulations of Naphthalene-Type Aldehydes with Internal Alkynes



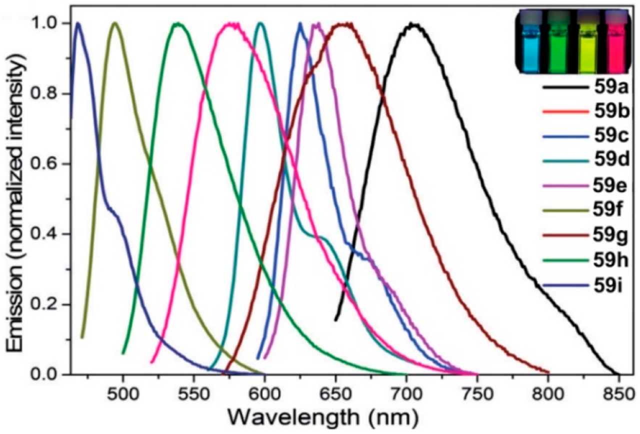


Figure 6. Emission spectra of **59a**–**59i** in DCM. (inset) Fluorescence images of **59i**, **59f**, **59h**, and **59e** (from left to right) in DCM under a UV lamp. Reproduced with permission from ref 12a. Copyright 2017 Wiley-VCH.

The strategy showed a simple and efficient method for constructing novel azulenolactone-based functional materials.

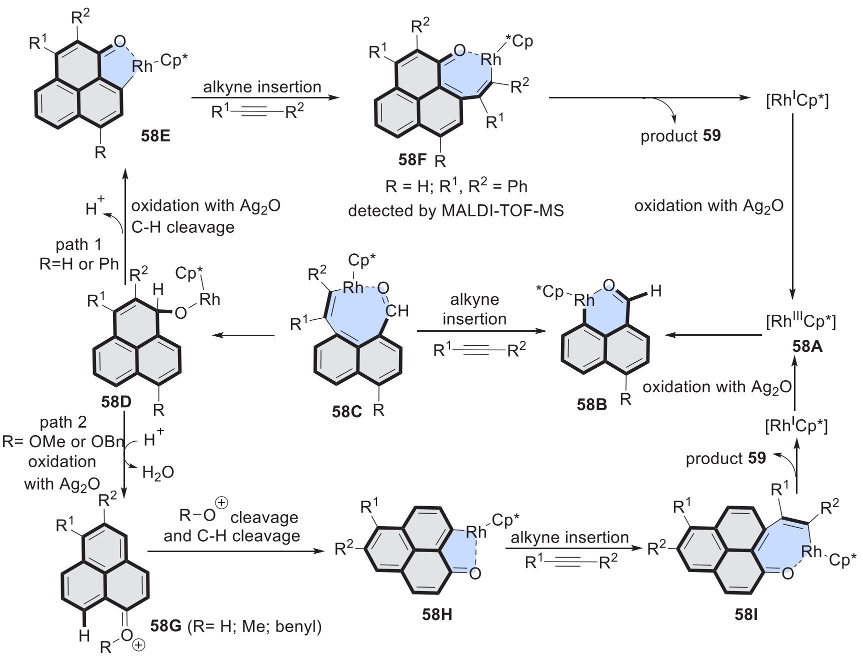
In 2015, Glorius and co-workers developed rhodium-catalyzed C–H activation and subsequent carbene insertion with pyridotriazoles to access a new family of fluorescent extended π-systems (Scheme 22).[11] In this transformation, the $[Cp^*Rh(CH_3CN)_3]$-$(SbF_6)_2$ was used as the catalyst, and the pyridotriazoles served as carbene precursors. These new fluorophores can be applied for the detection of Cu^{2+} and Zn^{2+} ions.

Stable polycyclic aromatic hydrocarbon (PAH) cations are important fluorescent molecules with potential applications in the fields of photochemistry, materials science, and biology. In 2017, the You group developed a novel class of stable oxonium-doped polycyclic aromatic hydrocarbons through the rhodium-catalyzed C–H activation/annulations of naphthalene-type aldehydes with internal alkynes (Scheme 23).[12a] The reaction shows exquisite regioselectivity, broad substrate scope, and a high tolerance of sensitive functional groups. A diverse library of novel oxonium-PAH cations was obtained and exhibited full-color tunable fluorescence emission and high quantum yields (Figure 6).

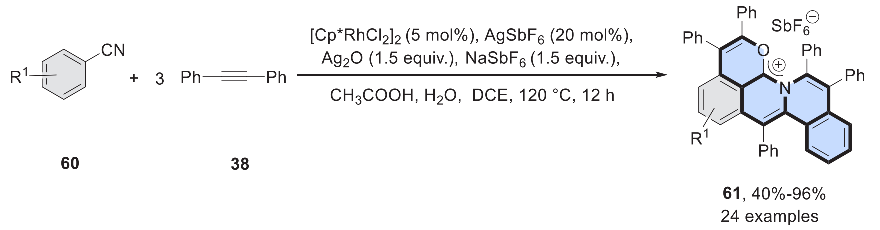
A plausible reaction mechanism was proposed for the C–H activation/annulations of naphthalene-type aldehydes with internal alkynes (Scheme 24). First, the six-membered rhodacycle intermediate **58B** was formed through the reaction of aryl aldehydes with the $[Rh^{III}Cp^*]$ species generated from $[\{RhCp^*Cl_2\}_2]$ and $AgSbF_6$ and a subsequent aldehyde-assisted C8–H bond activation process. Next, an internal alkyne was inserted into the C8–rhodium bond to give an eight-membered intermediate **58C**, which then undergoes an electrophilic cyclization step to yield intermediate **58D**. In path 1, **58D** underwent oxidation with Ag_2O and subsequent C2–H cleavage to produce the five-membered intermediate **58E**. Subsequently, the seven-membered intermediate **58F** was generated via insertion of the second equivalent of alkyne into the C2–rhodium bond. Finally, reductive elimination of **58F** affords the desired product **59**. In path 2, **58D** was protonated to provide an alcohol intermediate that then underwent aromatization by dehydration/oxidation to give the intermediate **58G**. After cleavage of the $R–O^+$ bond, a second rhodium-catalyzed carbonyl-directed C–H annulation reaction with alkyne yielded product **59** (Scheme 24).

Subsequently, the reaction scope was successfully extended to aryl nitriles under slightly modified reaction conditions. A structurally diverse family of delocalized PAH carbocations was synthesized by rhodium(III)-catalyzed hydration and C–H annulation of aryl nitriles with alkynes (Scheme 25).[12b] To demonstrate the practicality and efficiency of this method, the reaction was successfully conducted on a 2.0 mmol scale. These PAH carbocations exhibit tunable emission wavelengths via an adjustment of the electron-withdrawing ability of substituents on the aryl nitriles. Further biological studies demonstrated that

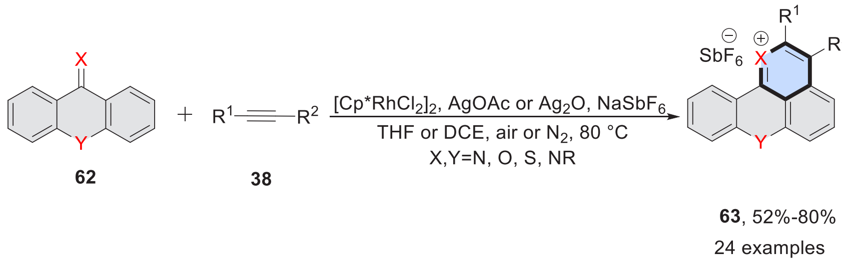
Scheme 24. Proposed Mechanism for the Formation of 59



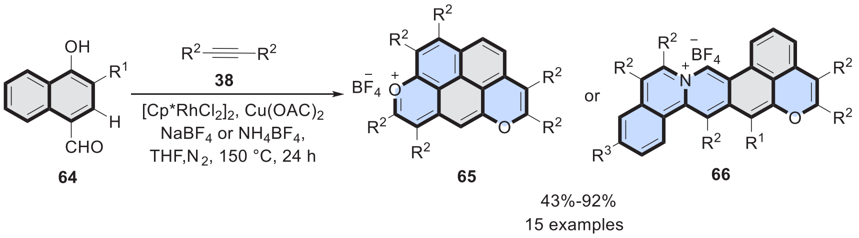
Scheme 25. Rhodium(III)-Catalyzed Hydration and C−H Activation/Annulation Cascade of Arylnitriles with Alkynes



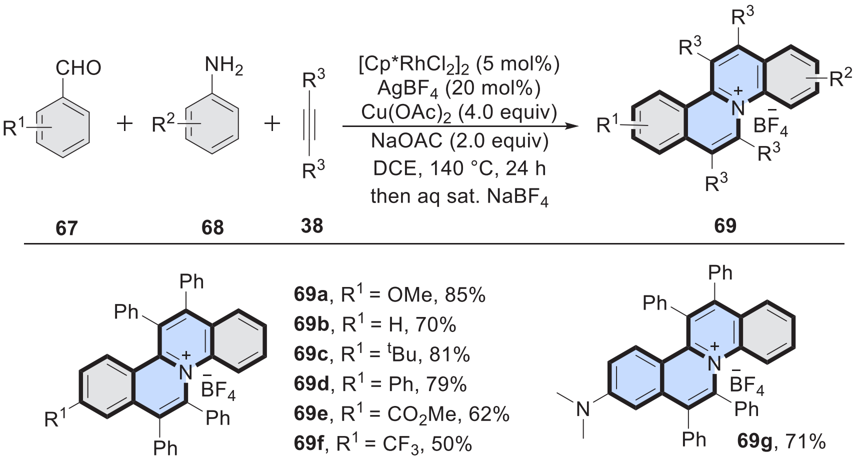
Scheme 26. Oxidative [4 + 2] Annulation of Acridin-9(10*H*)-one and Analogues with Alkynes



Scheme 27. Rhodium-Catalyzed Cascade Triple C−H Annulation of 4-Hydroxy-1-naphthaldehydes with Alkynes



Scheme 28. Synthesis of the Fluorescent Molecules 69a−69g



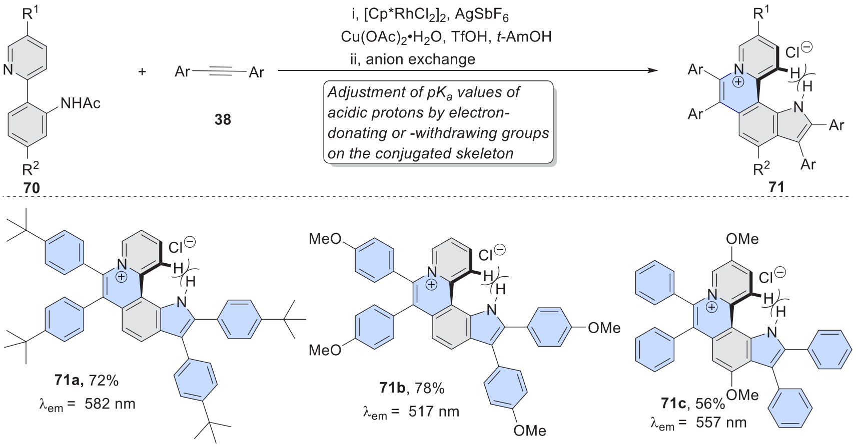
these cations have low cytotoxicity and the ability to specifically target lysosomes.

As a further extension, the same group expanded the substrate scope to acridin-9(10*H*)-one and analogues. A series of structurally diversified heteroatom-doped polycyclic aromatic hydrocarbons were obtained in good yields via the rhodium-catalyzed oxidative [4 + 2] cyclization of C═X (X = N, O, S) bonds with alkynes (Scheme 26).[12e] These novel tetracyclic acridine-type luminogens are potential fluorescent organelle trackers and possess unique features as the nitrogen atom could modulate the targeting regions. Multiple organelles including the lysosome, endoplasmic reticulum, mitochondrion, and mitochondrion-nucleus can be targeted by these novel dyes.

Later, the same group obtained diverse polycyclic pyrylium and pyridinium fluorophores through rhodium-catalyzed cascade triple C−H annulation of 4-hydroxy-1-naphthaldehydes with alkynes (Scheme 27).[12f] These polycyclic pyrylium and pyridinium fluorophores displayed strong emission and quantum yields up to 69%. Further costaining experiments disclose that these dyes may be potential mitochondrial-targeted fluorescent probes with low cytotoxicity.

Utilizing similar catalytic synthesis strategies, fluorescent mitochondrial trackers with the dibenzo[a,f]-quinolizinium core

Scheme 29. Synthesis of Aza[4]helicenes



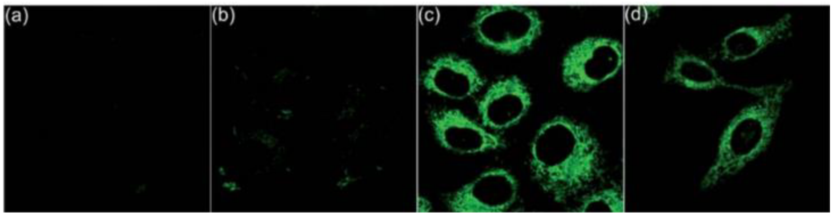
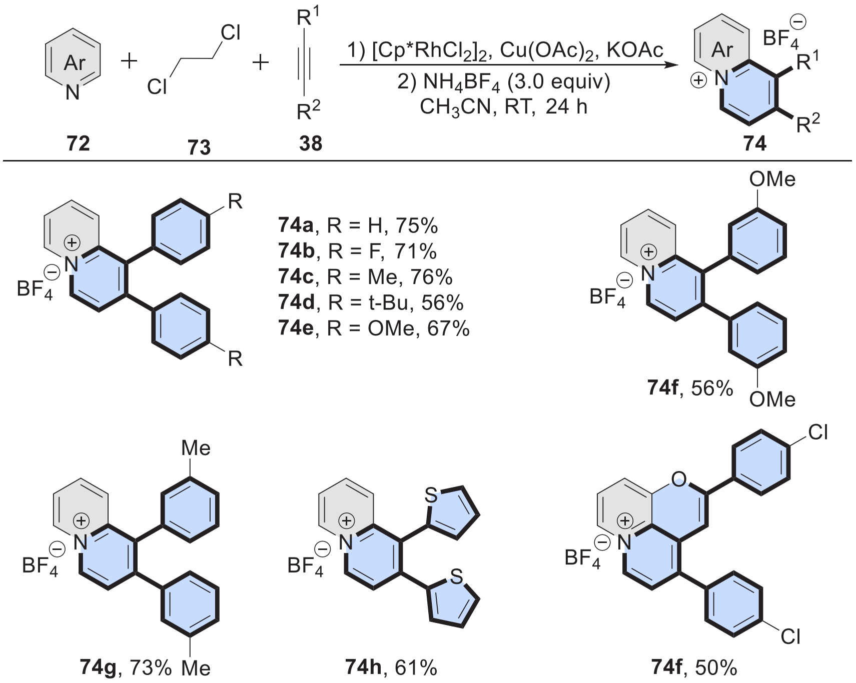


Figure 7. Fluorescence images of HepG2 cells. (a) Incubated with **71a** for 20 min and (b) followed by treatment with acetic acid for another 30 min. (c) Incubated with **71b** for 20 min. (d) Incubated with **71c** for 20 min. Reproduced with permission from ref 12g. Copyright 2020 Royal Society of Chemistry.

Scheme 30. Rhodium(III)-Catalyzed Three-Component Annulation Reaction of Simple Pyridines, Alkynes, and 1,2-Dichloroethane



were prepared using rhodium(III)-catalyzed cascade C−H N- and C-annulation of benzaldehydes and anilines with alkynes (Scheme 28).[12c] The cell-imaging experiments and photophysical data demonstrated that **69g** is a promising fluorescent tracker for mitochondria imaging.

Based on the efficient annulation strategy, this group synthesized novel fluorescent aza[4]helicene molecules by rhodium-catalyzed C−H activation/cyclizations of 2-(pyridin-2-yl)anilines with alkynes (Scheme 29).[12g] A broad substrate scope was achieved, and the system included an electron-rich pyrrole unit as well as an electron-deficient pyridinium unit. The

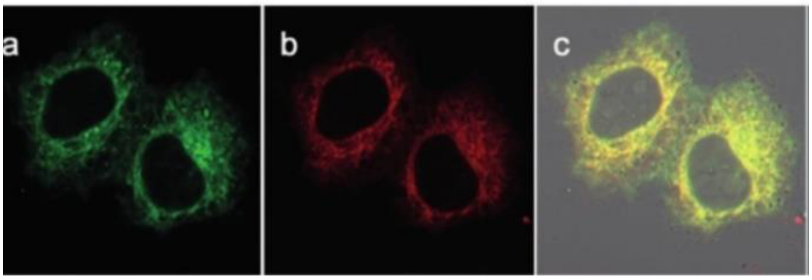
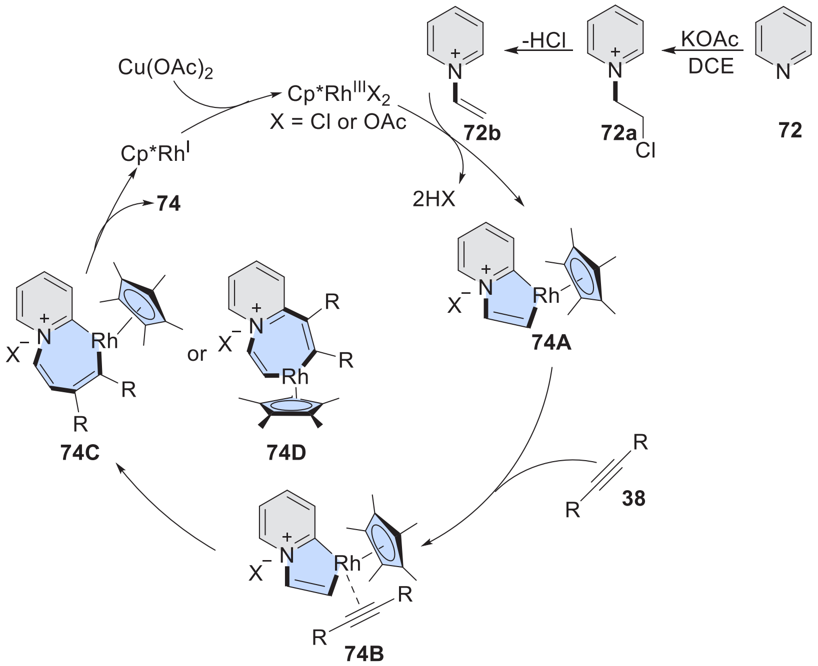


Figure 8. Fluorescence images of HepG2 cells cultured with **74f** (a; 5.0 μM, λ_{ex} = 405 nm, λ_{em} = 450−550 nm) and with mitochondrial-targeted tracker (MTR) (b; 1.0 μM, λ_{ex} = 546 nm, λ_{em} = 550−650 nm). (c) Merged image of panels a and b. Reproduced with permission from ref 12d. Copyright 2019 Wiley-VCH.

Scheme 31. Plausible Mechanistic Pathway for the Formation of 74



aza[4]helicenes-type luminogens can be transformed into planar molecules via cleavage of the acidic pyrrole N−H bond, which leads to turn-off fluorescence. Further research showed that these new fluorescent molecules are a potentially effective reagent for pH-controlled intracellular selective fluorescence imaging (Figure 7).

Ring-fused pyridinium salts have excellent fluorescent properties and have attracted great research interest in recent years. In 2019, the You group disclosed a rhodium(III)-catalyzed three-component annulation reaction to build diverse ring-fused pyridiniums (Scheme 30).[12d] In this reaction, commercially available simple pyridines and alkynes were used as starting materials, while 1,2-dichloroethane was used as a solvent and a vinyl equivalent which can act as an in situ activating agent for pyridine C2−H activation. The tricyclic-fused pyranoquinolizinium salts are potential fluorescence biomarkers that can target mitochondria of living cells (Figure 8).

A possible mechanism is depicted in Scheme 31. First, alkylation of pyridine produces 1-(2-chloroethyl)pyridin-1-ium (**72a**), followed by the formation of *N*-vinylpyridinium (**72b**). Next, the five-membered cyclometalated intermediate **74A** was generated by the double C−H bond activations of alkene and pyridinium. The intermediate **74A** undergoes coordination with **38**, and subsequent alkyne insertion into the Rh−C bond yields the seven-membered rhodacycle **74C** or **74D**. Reductive elimination of **74C** or **74D** then affords the desired product **74** with both Cl$^-$ and OAc$^-$ as the counteranion (Scheme 31). Finally, the Rh^{III} species is regenerated by the oxidation of Cu(OAc)$_2$ to fulfill the catalytic cycle.

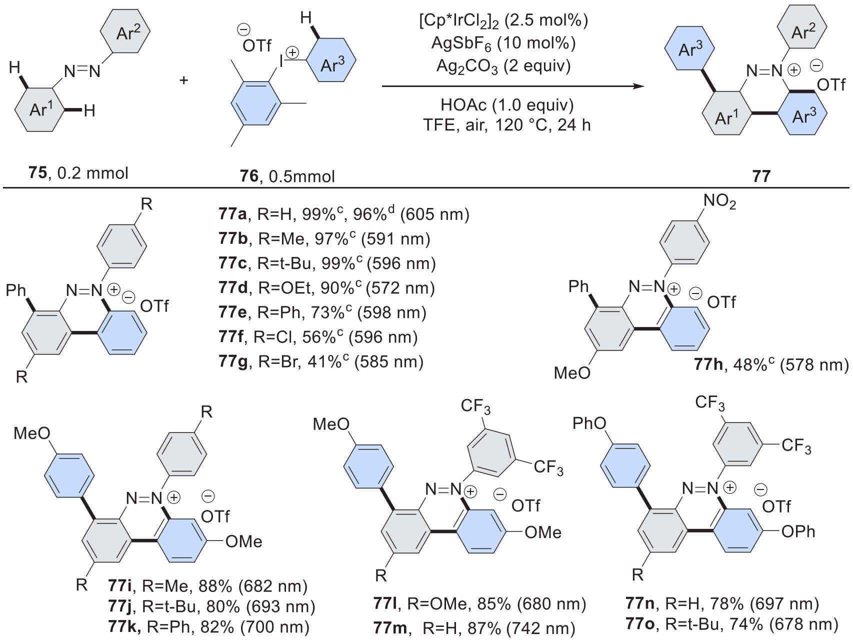
4. IRIDIUM-CATALYZED C−C BOND-FORMING REACTIONS VIA C−H ACTIVATION FOR THE DEVELOPMENT OF FLUORESCENT MATERIALS

The half-sandwich iridium(III) catalyst has received much attention in organic catalytic synthesis owing to its excellent reactivity toward the C−H activation of hydrocarbons.[13,14] Recently, iridium(III)-catalyzed C−H arylation and annulation processes have been used to construct organic fluorescent materials of practical value.[14]

4.1. Iridium-Catalyzed C−H Activation for Annulation.

Far-red and near-infrared (NIR) fluorescent probes have many excellent features, including low autofluorescence interference, minimal photodamage, and deep tissue penetration. Thus, the development of the far-red/NIR imaging agents has attracted ever-growing attention. In 2019, You and Lan exploited an iridium-catalyzed tandem *ortho*-C−H arylation and aryl quaternization of azoarenes to produce 5,6-phenanthrolinium

Scheme 32. Iridium-Catalyzed Tandem *ortho*-C−H Arylation and Aryl Quaternization of Azoarenes



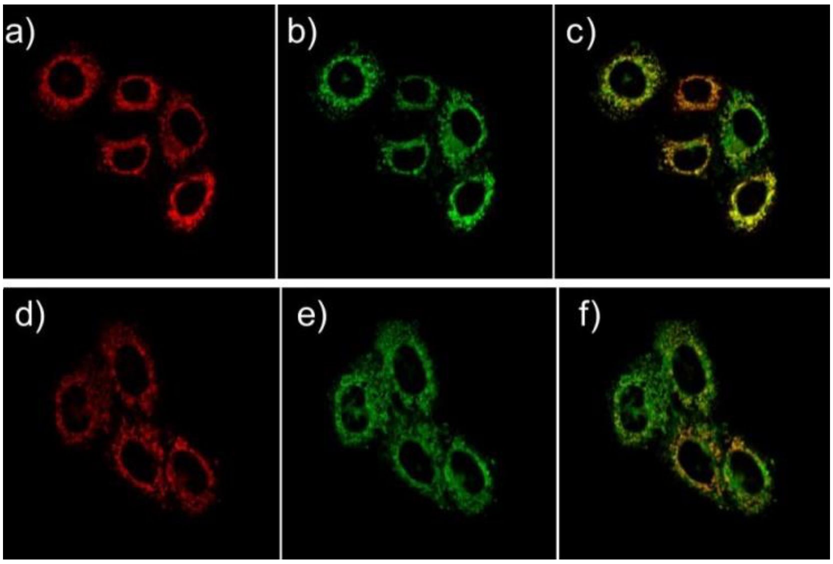


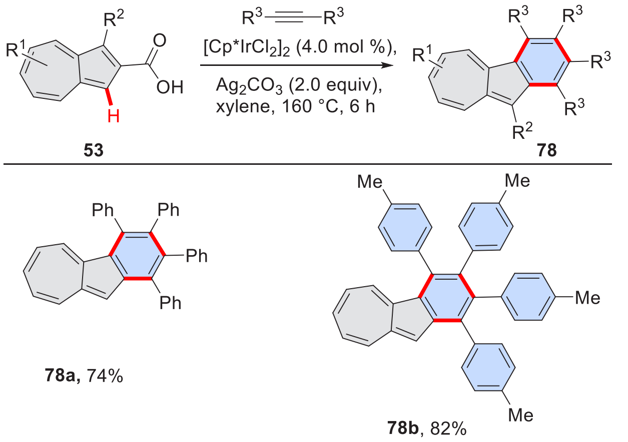
Figure 9. Fluorescence images of HepG2 cells cultured with **77k** (a) and **77m** (d; $\lambda_{ex} = 488$ nm, $\lambda_{em} = 650-750$ nm); with MTG (b, e; $\lambda_{ex} = 488$ nm, $\lambda_{em} = 500-540$ nm); and merged images (c, f). Reproduced from ref 14a. Copyright 2019 American Chemical Society.

skeletons in moderate to excellent yields (Scheme 32).[14a] In addition, fluorescent molecule **77b** was prepared in 96% yield on a gram scale (1.11 g). Based on this synthetic strategy, a series of far-red to NIR fluorescent dyes have been synthesized. These compounds possess excellent photostability and low cytotoxicity, indicating their potential for applications in mitochondria-targeted reagents (Figure 9).

Lee and co-workers developed an iridium-catalyzed [2 + 2+2] cyclization reaction of azulene carboxylic acids with alkynes by decarboxylation to afford tetra-(aryl)-substituted benzoazulene derivatives in 2020 (Scheme 33).[10d] The protocol displayed broad substrate scope and high functional group tolerance under standard reaction conditions. To demonstrate the applicability of the protocol, **78a** was synthesized in 52% yield on a 1.0 mmol scale (0.18 g). This method is an efficient strategy for constructing novel π-conjugated azulene-based functional materials.

In 2021, Lan and You disclosed the first example of iridium-catalyzed C−H diarylation/annulation of benzoic acids and the subsequent nucleophilic addition reaction and intramolecular Friedel−Crafts alkylation to build 1-aryl, 1,3-diaryl, 1,7-diaryl, and 1,3,7-triaryl spirobifluorenes, which are potential host materials for phosphorescent organic light-emitting diodes (PhOLEDs).[14b] In the diarylation/annulation reaction, $[Cp^*IrCl_2]_2/AgSbF_6$ was used as a catalyst system; diphenyliodonium trifluoromethanesulfonate (Ph_2IOTf) was employed as the arylation reagent, and Ag_2O was chosen as an oxidant. This reaction showed a broad substrate scope, good to excellent yields, and excellent site-selectivity, thus providing an opportunity to rapidly assemble a series of aryl-substituted

Scheme 33. Iridium-Catalyzed [2 + 2 + 2] Cyclization Reaction of Azulene Acids with Alkynes



fluorenones (Scheme 34). In addition, multiaryl spirobifluorenes **82a–82f** were synthesized from **80** (Scheme 35), which exhibit strong phosphorescence emission in toluene at 77 K. After the preparation and performance test of the PhOLEDs, 1,3-diaryl, 1,7-diaryl, and 1,3,7-triaryl spirobifluorenes were proven to be good host materials of blue, green, and red PhOLEDs, respectively. This work highlighted the charm of C–H activation in the development of organic optoelectronic materials.

Recently, Murai disclosed an iridium-catalyzed intramolecular dehydrogenative silylation of C–H bonds of azulene to afford the benzosilole-fused azulene derivatives (Scheme 36).[14c] 4,4′-Di-*tert*-butyl-2,2′-bipyridyl was found to be the most effective ligand for this transformation, while other ligands such as 1,10-phenanthroline and 3,4,7,8-tetramethyl-1,10-phenanthroline were less reactive. The authors found that the fluorescence of azulene-fused benzosiloles could be turned on and off via a simple acid/base reaction. The resulting azulene derivatives have potential applications in acid–base responsive reagents.

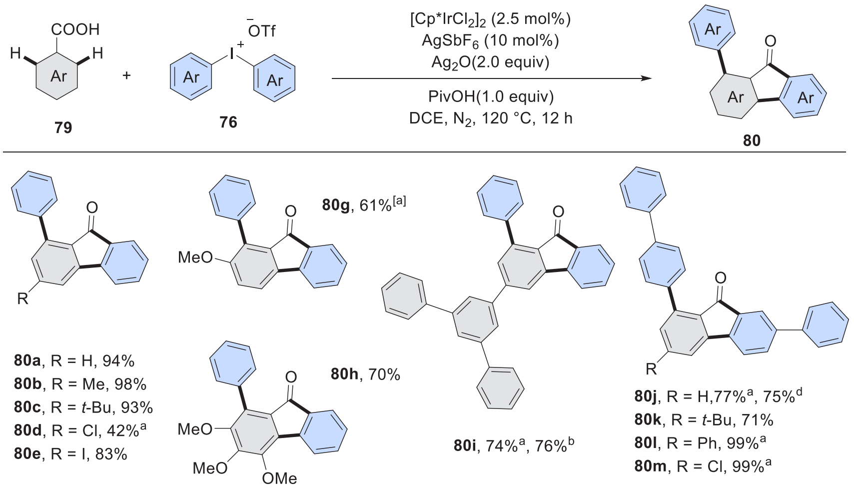
5. COPPER-CATALYZED C–C BOND-FORMING REACTIONS VIA C–H ACTIVATION FOR THE DEVELOPMENT OF FLUORESCENT MATERIALS

Inexpensive 3d metal catalysts for C–H activation have been shown to be significantly environmentally benign and economically attractive in C–H functionalization reactions.[15] Copper complexes are among the most commonly used 3d metal catalysts in organic synthesis owing to their low toxicity, cost-effectiveness, and easily accessible oxidation states. Copper-catalyzed C–H activation reactions have gained significant momentum in the past couple of decades.[15,16] The copper-catalyzed C–C bond-forming reactions via C–H activation provide atom-economic access to structurally complex organic fluorescent materials of practical value.[16]

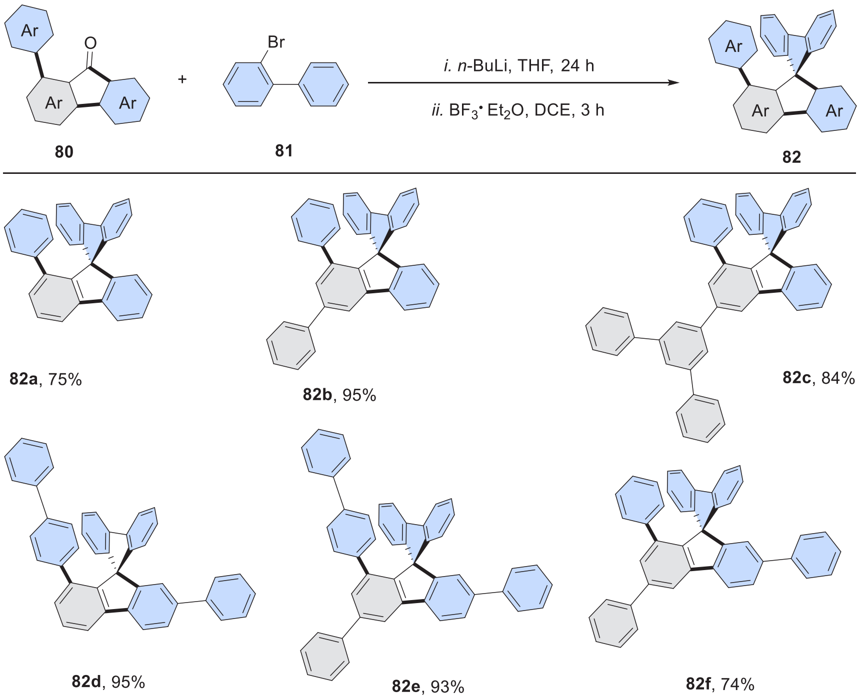
5.1. Copper-Catalyzed C–H Arylation. The direct functionalization of heteroarenes to valuable products is among the most attractive and challenging tasks for chemists and materials scientists. The direct copper-catalyzed C–H arylation of heteroaromatic compounds to forge fluorescent core frameworks was reported by You in 2009. In this transformation, copper(I) iodide was used as the catalyst, and 1,10-phenanthroline served as a ligand. A relatively wide range of heterocycles and aryl bromides were identified as viable substrates (Scheme 37).[16a] The coupling product **86a** can mark Lewis lung cancer cells and human embryo kidney 293 cells, indicating its potential for applications as a useful reagent for biological imaging.

Further progress in the field of copper-catalyzed functionalizations to produce fluorescent materials was achieved by the groups of You and Lan, who reported a programmed C–H arylation to construct 2,7-diaryl-[1,2,4]triazolo[1,5-*a*]-pyrimidines (2,7-diaryl-TAPs) with fluorescent properties (Scheme 38).[16b] A library of donor–acceptor-type fluorophores was rapidly synthesized and used to screen mechanochromic regularity under an external stimulus. After the screening, the 2,7-diaryl-TAPs with electron-withdrawing groups on the 2-aryl and electron-donating groups on the 7-aryl were found to have a relatively large dipole moment and displayed a blue-shifted mechanochromism. When the two aryl groups are interchanged, the resulting luminogens have a relatively small dipole moment and exhibited a red-shifted mechanochromism (Figure 10).

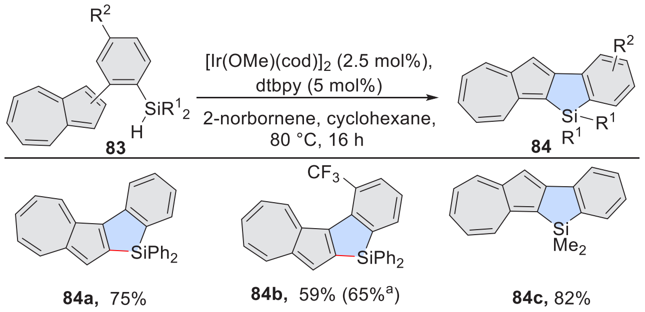
Scheme 34. Synthesis of Fluorenone Intermediates 80 via Iridium-Catalyzed C–H Diarylation/Annulation of Benzoic Acids



Scheme 35. Synthesis of Multiaryl Spirobifluorenes 82 from 80



Scheme 36. Iridium-Catalyzed Intramolecular Dehydrogenative Silylation of Azulene to Synthesize Benzosilole-Fused Azulenes



6. COBALT-CATALYZED C−C BOND-FORMING REACTIONS VIA C−H ACTIVATION FOR THE DEVELOPMENT OF FLUORESCENT MATERIALS

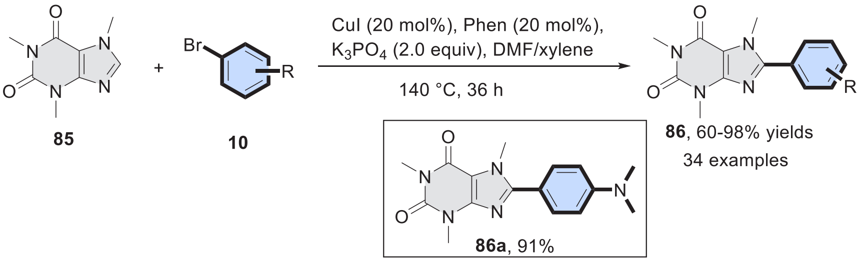
In nature, Cobalt is a relatively abundant and less toxic element. In 1955, Murahashi reported a dicobalt octacarbonyl-catalyzed reaction to synthesize phthalimidine, which is the earliest example of cobalt catalysis in C−H activation.[17a] Cobalt is another typical 3d metal catalyst that has received significant attention in C−H functionalization reactions in the past several decades.[15c] The cobalt catalysts have been proven to be uniquely effective for straightforward access to extended π-systems with luminescent properties.[17b,c]

6.1. Cobalt-Catalyzed C−H Activation for Annulation.

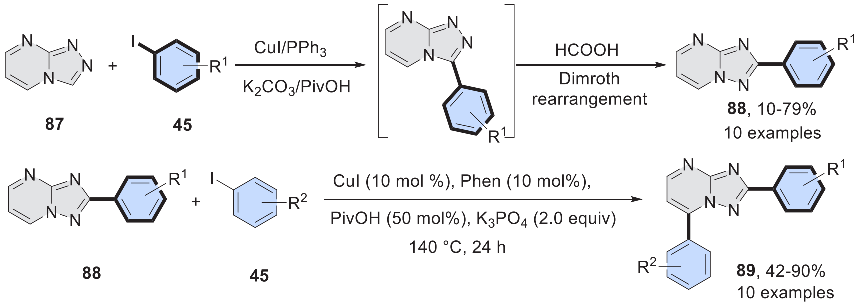
In 2015, Glorius and co-workers utilized a cobalt(III)-catalyzed C−H activation strategy for the coupling of diazo compounds with aromatic and heteroaromatic compounds to obtain a new family of extended π-systems (Scheme 39).[17b] In addition, the reaction can be conducted on a gram scale (1 g). Comparative experiments demonstrated the dual role of the cobalt complexes as a transition metal and a Lewis acid catalyst in the annulation reaction. These conjugated polycyclic hydrocarbons displayed tunable emission wavelengths and high quantum yields and have great potential in the preparation of organic light-emitting diodes.

In 2016, the Cheng group disclosed a cobalt-catalyzed oxidative annulation of 2-arylpyridines, aryl ketimines, and 2-vinylpyridines with alkynes to build quaternary heteroaromatic ammonium salts with luminescent properties (Scheme 40).[17c] The cobalt-catalyzed reaction can be conducted on a 1.95 g scale, clearly highlighting the convenience of its practical use. This reaction showed a broad substrate scope and high yield,

Scheme 37. Synthesis of Fluorescent Molecules 86 by Copper-Catalyzed Direct C−H/C−Br Cross-Coupling of Caffeine with Aryl Bromides



Scheme 38. Synthesis of 2,7-Diaryl-TAPs by a Programmed C−H/C−X Coupling Reaction



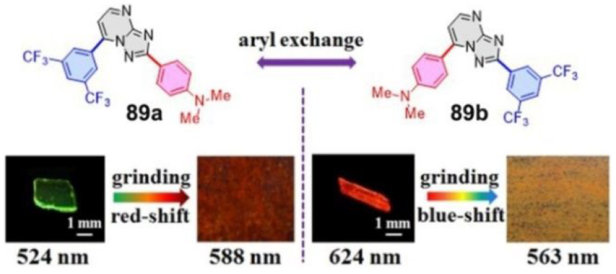


Figure 10. Photographs of single crystals and ground samples of **89a** and **89b** under UV light. Reproduced from ref 16b. Copyright 2016 American Chemical Society.

thus providing an opportunity to rapidly assemble a series of biologically useful quaternary ammonium salts.

7. RUTHENIUM-CATALYZED C−C BOND-FORMING REACTIONS VIA C−H ACTIVATION FOR THE DEVELOPMENT OF FLUORESCENT MATERIALS

Ruthenium catalysis has emerged as a very attractive synthetic approach due to its high efficiency in C−H functionalization reactions.[18,19] These reactions usually show excellent functional group compatibility, a broad substrate scope, and atom-economy, providing an effective method to develop fluorescent materials of practical value.[19]

7.1. Ruthenium-Catalyzed C−H Arylation. In 2020, the You group built an aggregation-induced delayed fluorescence material through a ruthenium-catalyzed oxidative Ar−H/Ar−H homocoupling reaction followed by amination, cyclization, and imidization (Scheme 41).[19b] The operationally simple catalytic system is composed of $RuCl_3$ as the catalyst and O_2 as the oxidant. The luminous **99** (DMAC-BPI) exhibits significant aggregation-induced delayed fluorescence with high quantum yields in neat film. It is noteworthy that the corresponding OLEDs showed an excellent electroluminescence performance with an EQE of up to 24.7% (Figure 11).

7.2. Ruthenium-Catalyzed C−H Activation for Annulation. In 2017, Perumal and co-workers reported an efficient catalytic system consisting of $[RuCl_2(p\text{-cymene})]_2$ as the catalyst and $Cu(OAc)_2{\cdot}H_2O$ as the oxidant in 1,2-DCE to construct a diverse library of isochromeno[8,1-ab]phenazines with moderate to good yields (Scheme 42).[19a] These products exhibit strong fluorescence emissions. Furthermore, this strategy was applied by the authors to construct far-red fluorescent probes for cancer cell imaging.

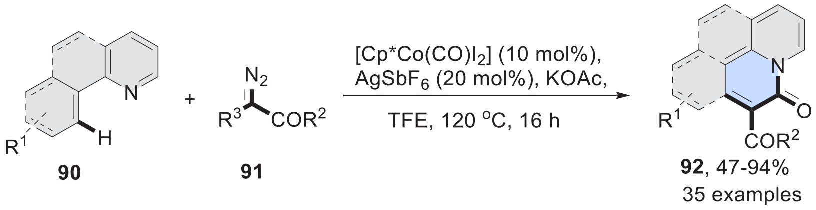
7.3. Ruthenium-Catalyzed C−H Alkylation. In 2020, Ma and Szostak outlined a ruthenium(II)-catalyzed *ortho*-C−H alkylation of naphthylamines with diazo compounds to provide 2,2-disubstituted π-extended 3-oxindoles (Scheme 43).[19c] In the study, $[RuCl_2(p\text{-cym})]_2$ was used as a cost-effective and operationally simple catalyst. This is the first time water was used as a sustainable solvent in C−H alkylation via carbenoid insertion. The resulting 2,2-disubstituted π-extended 3-oxindole products displayed a strong fluorescence emission in aqueous solutions with potential applications in fluorescence bioimaging (Figure 12).

8. BIMETAL COCATALYZED C−C BOND-FORMING REACTIONS VIA C−H ACTIVATION FOR THE DEVELOPMENT OF FLUORESCENT MATERIALS

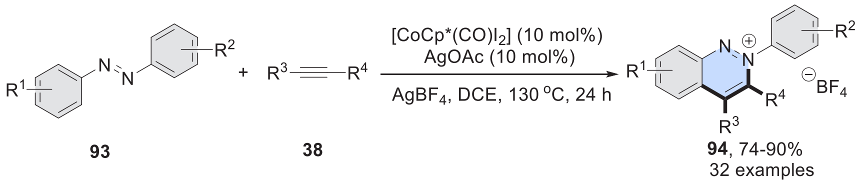
Bimetal cocatalyzed C−C bond-forming reactions via C−H activation have emerged as a powerful synthetic tactic in the past couple of decades and have generated great interest among scientists in materials chemistry research because of the bimetallic catalyst system that combines the characteristics of two metals to provide unique reactivity and achieve reactions that are often difficult to complete with a single metal catalyst.[20,21]

8.1. Palladium/Copper-Cocatalyzed C−H Alkenylations. In 2012, You et al. developed a palladium/copper-catalyzed dehydrogenative Heck coupling between *N*-heteroarenes and alkenes to construct π-extended alkenylated *N*-heteroarenes, which showed interesting fluorescent properties and have proven to be potentially useful biological imaging

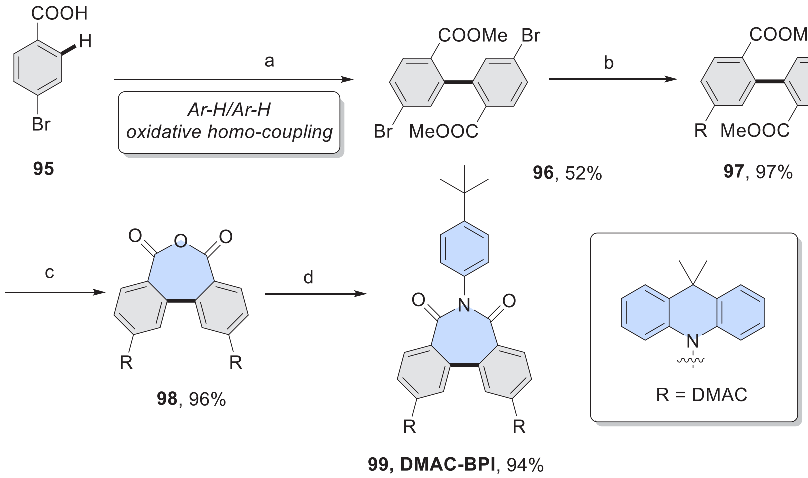
Scheme 39. Synthesis of Extended π-Systems by a Cobalt(III)-Catalyzed Coupling of Diazo Compounds with Heteroaromatic Compounds



Scheme 40. Synthesis of Cinnolinium Salts 94



Scheme 41. Synthesis of Aggregation-Induced Delayed Fluorescence Molecule 99 (DMAC-BPI)



^{a}Reaction conditions: first step, 4-bromobenzoic acid, $RuCl_3$, DBU, O_2, 1,2-dimethoxyethane, 110 °C, 30 h; second step, MeI, K_2CO_3, rt, 6 h. ^{b}Reaction conditions: DMAC, $Pd(OAc)_2$, PPh_3, Cs_2CO_3, toluene, 120 °C, 30 h. ^{c}Reaction conditions: first step, NaOH (aq), MeOH/THF, reflux, 6 h; second step, Ac_2O, reflux, 6 h. ^{d}Reaction conditions: first step, 4-*tert*-butylaniline, Et_3N, 4-dimethylaminopyridine, DCM, rt, 12 h; second step, Ac_2O, reflux, 6 h.

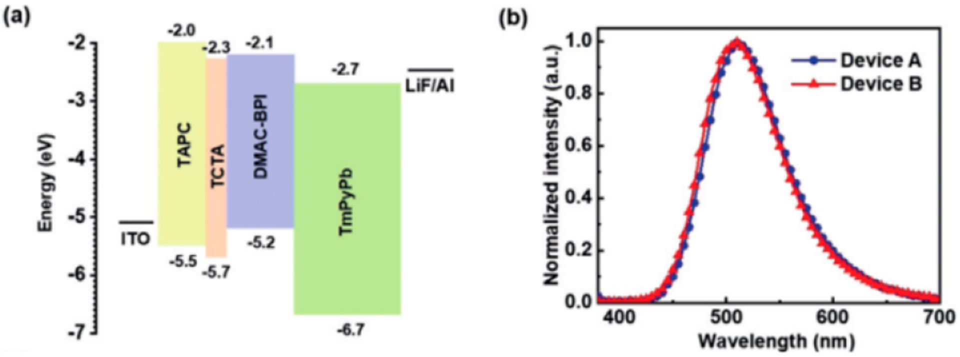
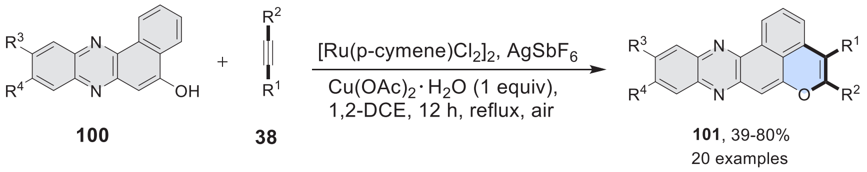


Figure 11. (a) Device structure and energy level diagrams of OLEDs. (b) Electroluminescence spectra at 1000 cd m^{-2}. Reproduced with permission from ref 19b. Copyright 2020 Wiley-VCH.

Scheme 42. Synthesis of Isochromeno[8,1-ab]phenazines via a Ru-Catalyzed Oxidative Annulation Reaction

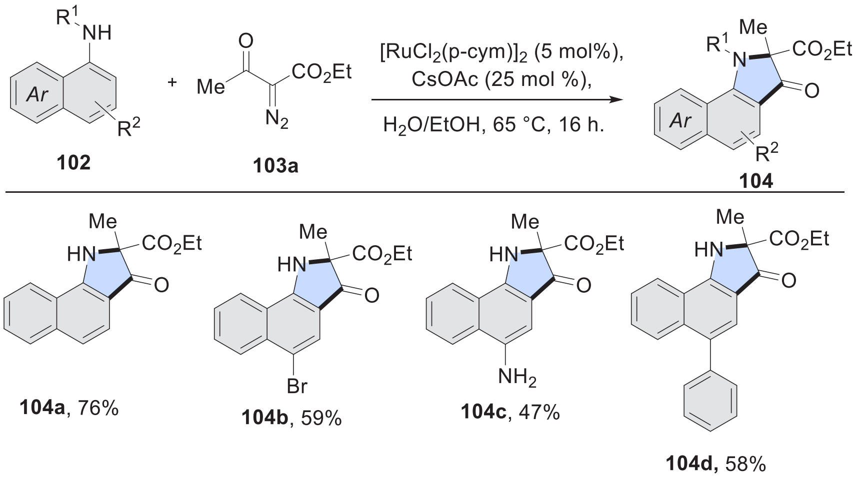


agents (Scheme 44).[21a] Compared with other synthetic methods, the use of this bimetallic catalyst system avoids a tedious multistep synthesis and prefunctionalization of starting materials.

8.2. Rhodium/Copper-Cocatalyzed C−H Addition/Oxidative/Cyclization Cross-Coupling. In 2020, the You group developed rhodium/copper-cocatalyzed C−H activation and radical reactions to construct organic functional skeletons (Scheme 45).[21b] A class of flavylium fluorophores were obtained using a combination of radical chemistry and C−H activation starting from (hetero)aryl ketones and alkynes. Mechanistic experiments demonstrate that the key step is the addition of the acyl radical formed through the copper-catalyzed C−C bond cleavage of aryl ketone to the rhodacycle produced by C−H

https://doi.org/10.1021/acscatal.1c05722
ACS Catal. 2022, 12, 2796−2820

Scheme 43. Ruthenium(II)-Catalyzed *ortho*-C−H Alkylation of Naphthylamines with Diazo Compounds for Synthesis of 2,2-Disubstituted π-Extended 3-Oxindoles



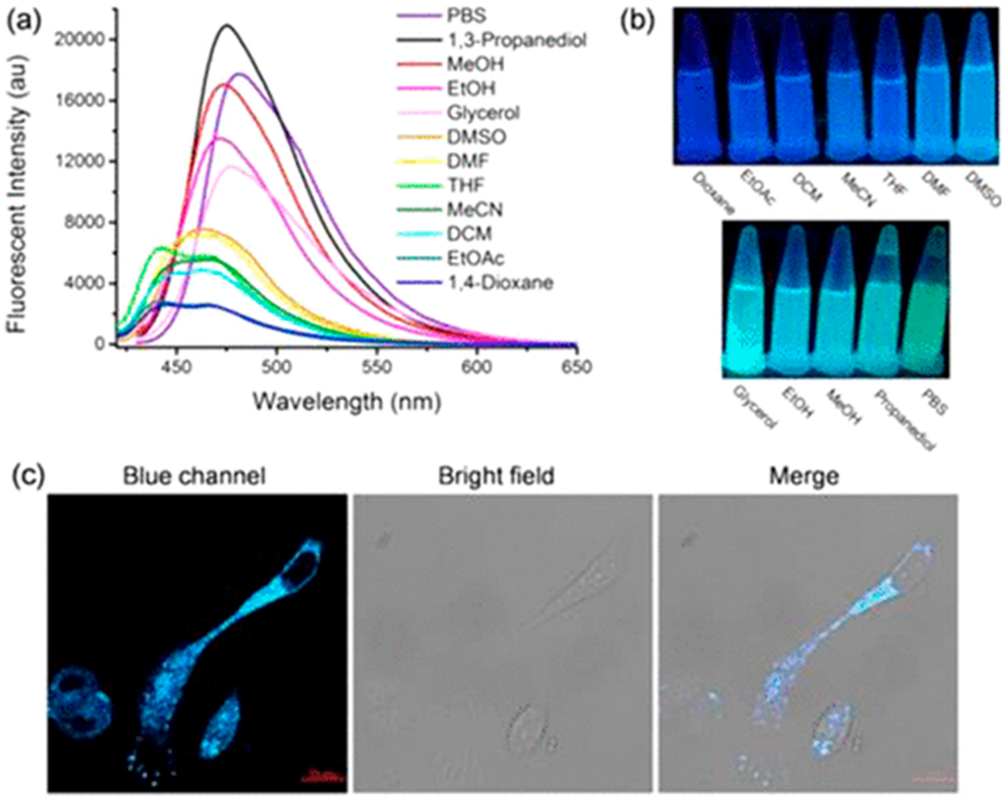


Figure 12. Fluorescent properties and fluorescent imaging of compound **104d** in living cells. Reproduced from ref 19c. Copyright 2020 American Chemical Society.

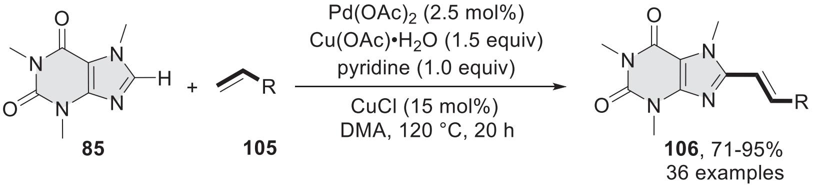
activation of the aryl ketone. These molecules have a nearly planar skeleton, delocalized positive charge, and butterfly symmetrical configuration and displayed tunable fluorescence emission wavelengths and high quantum yields, indicating great potential as new luminescent materials.

9. CONCLUSIONS AND FUTURE DIRECTIONS

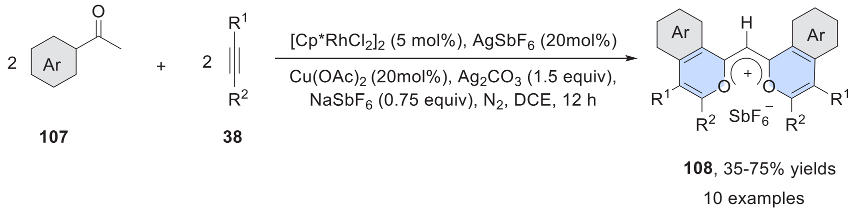
This Review presents an overview of the transition-metal-catalyzed C−C bond-forming reactions via C−H activation for the development of fluorescent materials of practical value along with a brief outlook on the remaining challenges and future directions.

Using the C−H activation strategy for constructing organic fluorescent molecules can not only greatly shorten the synthetic routes required for traditional fluorescent materials but also overcome the challenges brought by traditional methods during the activation process of substrates. This provides opportunities for creating new fluorescent skeletons that cannot be prepared by traditional synthetic methods. The research carried out for C−C bond-forming reactions based on C−H activation will trigger original innovation to discover new fluorescent materials with nontraditional structures. At the same time, developing precision syntheses for the construction of fluorescent molecules

Scheme 44. Synthesis of π-Extended Alkenylated *N*-Heteroarenes via Palladium/Copper-Catalyzed Dehydrogenative Heck Coupling between *N*-Heteroarenes and Alkenes



Scheme 45. Rhodium/Copper-Cocatalyzed C−H Activation and Radical Reactions for the Synthesis of Flavylium Fluorophores 108



will open a door for the discovery of new organic synthetic methods with universal significance.

Although some achievements have been made in the development of transition-metal-catalyzed C−C bond-forming reactions via C−H activation for the construction of fluorescent materials of practical value, there are still many challenges. At present, precious metals (such as rhodium and palladium) are mainly used as catalysts, and future development should perform more C−H functionalization reactions with cheap metals to construct fluorescent materials. Additionally, the developed catalytic strategies often use metal salts as oxidants and require high reaction temperatures. In the future, it will be necessary to develop solutions using oxygen as the oxidant and develop new technologies such as electrocatalytic/photocatalytic C−H activation strategies to construct fluorescent materials. Furthermore, the C−H activation strategy for constructing organic delayed fluorescent molecules is still in its infancy, and more efforts are needed to develop more structural types of delayed fluorescent materials.

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Notes

The authors declare no competing financial interest.

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