OL Organic Letters

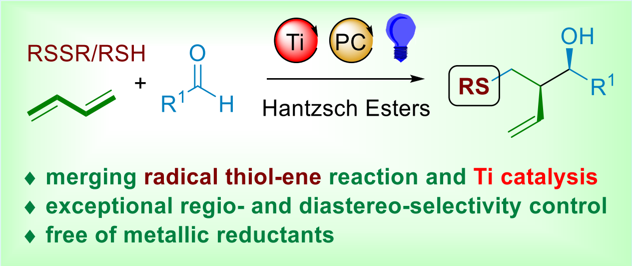
pubs.acs.org/OrgLett Letter

Difunctionalization of 1,3-Butadiene via Sequential Radical Thiol-ene Reaction and Allylation by Dual Photoredox and Titanium Catalysis

Erjun Hao,* Binghui Lu,§ Yonghong Liu,§ Tianxiao Yang, Huaipu Yan, Xiaobo Ding, Yunhe Jin, and Lei Shi*

Cite This: *Org. Lett.* 2023, 25, 5094−5099 Read Online

ABSTRACT: Recently, radical difunctionalization of the feedstock 1,3-butadiene has become an attractive strategy for increasing molecular complexity. Herein, we present a novel approach that effectively combines radical thiol-ene chemistry with Ti^{III} catalysis to enable a three-component aldehyde allylation using 1,3-butadiene as an allyl group source under visible light conditions. This sustainable and straightforward method has facilitated the rapid production of diverse allylic 1,3-thioalcohols with exceptional regio- and diastereoselectivity.



- merging radical thiol-ene reaction and Ti catalysis
- exceptional regio- and diastereo-selectivity control
- free of metallic reductants

The direct difunctionalization of the cheap and abundant feedstock 1,3-butadiene is considered as one of the most appealing approaches for enhancing molecular complexity in synthetic organic chemistry.[1,2] Sulfur-containing compounds are known to exhibit unique biological activities and are of significant value in the pharmaceutical industry.[3−5] Many bioactive compounds, for example, Viracept,[6] Cleocin, and glycosidase inhibitor,[7] contain a similar 1,3-thioalcohol skeleton (Figure 1a). Thus, thiolation chemistry has attracted more interest, leading to the development of novel, cost-effective, and efficient methods for the synthesis of molecules with thiol moieties.[8,9] One of the effective strategies for introducing thiol motifs is the thiol-ene reaction between a thiol and an alkene to form a thioether (Figure 1b).[10,11] In the late 1990s, this reaction gained prominence in click chemistry and is used in sugar modification, complex molecules, material polymer synthesis, biomedical sciences, and other fields due to its mild reaction conditions, high yield, and thermodynamic driving force. Although significant progress has been made in thiol chemistry, difunctionalization of 1,3-butadiene with sulfur remains unexplored.[12]

Recently, there has been more interest in synthesizing high-value allyl compounds using the feedstock 1,3-butadiene as an inexpensive and easily accessible allyl source facilitated by transition-metal catalysis.[13−23] Although the addition of free carbon radicals to 1,3-diene has been extensively studied, to the best of our knowledge, the use of thiyl radicals as triggers for this reaction is unprecedented. This may be due to the strong nucleophilicity of thiols, which can sometimes hinder the reaction by coordinating with transition metals.[24−26] To overcome this limitation, herein, we report a radical-type three-component allylation of aldehydes with 1,3-butadiene and

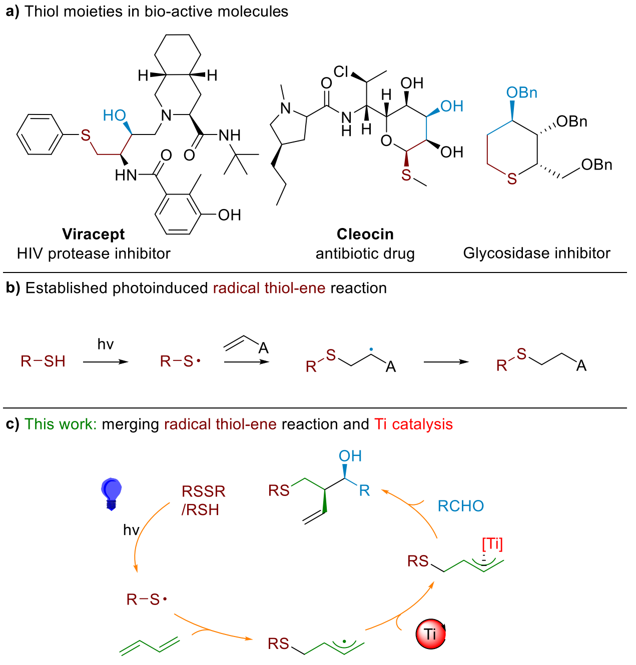
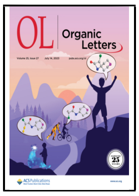


Figure 1. (a) Representative drugs and natural products containing thiol moieties. (b) Radical thiol-ene reaction. (c) Three-component allylation of carbonyls with 1,3-butadiene and sulfur.

Received: June 4, 2023
Published: June 30, 2023

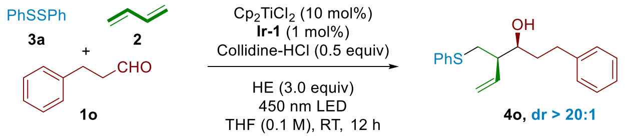


https://doi.org/10.1021/acs.orglett.3c01822
Org. Lett. 2023, 25, 5094−5099

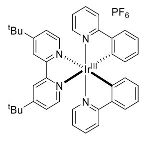
thiols by dual titanium and photoredox catalysis (Figure 1c). In this photocatalysis system, addition of the thiol radical to 1,3-butadiene generates allyl group radicals, which are then selectively trapped by Cp_2TiCl to form active allyl-Ti^{IV} species for aldehyde allylation.[27−31] This approach offers several advantages, including the use of the readily available raw materials of butadiene, simple post-treatment, mild reaction conditions, a wide range of substrates, high functional group tolerance, and excellent yields of the valuable allylic 1,3-thioalcohols with exceptional regio- and diastereoselectivity.

We commenced our work by employing 3-phenylpropanal (**1a**), 1,2-diphenyldisulfane (**3a**) as a template substrate, and a butadiene solution in THF (0.1 M). After considering different factors, fortunately, we discovered that using 0.5 equiv of collidine-HCl, 10.0 mol % Cp_2TiCl_2, 3 equiv of Hantzsch ester (HE) as an electron sacrificial agent, and Ir-**1** as a photosensitizer, followed by exposure to a 450 nm LED lamp for 12 h, could produce **4o** in 47% yield [dr > 20:1 (Table 1, entry 1)]. Then, we screened the conditions to optimize the yield. The exclusion of the photosensitizer prevented product formation, indicating its significance (entry 2). Moreover, the yield decreased upon utilizing different photosensitizers such as Ir-**2**, 4CzIPN, and Ru-**1** instead of Ir-**1** (entries 3−5, respectively). The optimal solvent for producing the desired product was found to be toluene with a yield of 62%, whereas using different solvents, including DMF, dichloromethane, etc., led to decreased yields (entries 6−8). Decreasing the level of Cp_2TiCl_2 to 5.0 mol % could suppress pinacol coupling, which is a major side reaction, and further increased the yield of **4o** to 87% (entry 9). The optimal amount of the electronic sacrificial agent was determined to be 1 equiv, which produced **4o** in 94% yield (entries 10 and 11). The optimal reaction concentration was determined to be 0.1 M (entries 11−13), and adding more additives would slightly decrease the level of product formation (entry 14). Notably, using different electron sacrificial agents did not result in product formation (entries 15 and 16). Finally, it was acknowledged that light, Ti, and electron sacrificial agents were vital for product formation (entry 17), Finally, the optimal conditions for synthesizing the product were determined as 1.0 equiv of disulfide, 1.0 equiv of aldehyde, 1.0 mol % photosensitizer Ir-**1**, 5.0 mol % Cp_2TiCl_2, 50 mol % collidine-HCl, and 1.0 equiv of HE. The catalytic amount of collidine-HCl is important for hydrolysis of the strong Ti−O bond and the release free Ti^{IV} species and alcohol products during the catalytic cycle. The reaction was performed in a 0.1 M toluene solution of 1,3-butadiene exposed to a 450 nm light source.

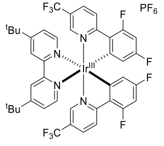
Table 1. Reaction Optimization[a,b]



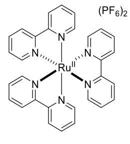
entry	variation from standard conditions	yield (%)
1	none	47
2	no photosensitizer	NR
3	Ir-**2** instead of Ir-**1**	44
4	4CzIPN instead of Ir-**1**	39
5	Ru-**1** instead of Ir-**1**	27
6	PhMe instead of THF	62
7	DMF instead of THF	trace
8	DCM instead of THF	30
9	PhMe (0.1 M) and 5% Cp_2Ticl_2	87
10	PhMe (0.1 M), HE (1 equiv), and 5% Cp_2TiCl_2	94
11	PhMe (0.1 M), HE (0.5 equiv), and 5% Cp_2TiCl_2	64
12	PhMe (0.05 M), HE (1 equiv), and 5% Cp_2TiCl_2	86
13	PhMe (0.2 M), HE (1 equiv), and 5% Cp_2TiCl_2	84
14	PhMe (0.1 M), collidine-HCl (1 equiv), HE (1 equiv), and 5% Cp_2TiCl_2	81
15	DIPEA (1 equiv) instead of HE	NR
16	Et_3N (1 equiv) instead of HE	NR
17	no light, HE, or Cp_2TiCl_2	NR



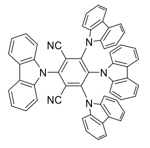
Ir(ppy)2(dtbbpy)PF6 **Ir-1**



Ir[dF(CF3)ppy]2(dtbbpy)PF6 **Ir-2**



Ru(bpy)3(PF6)2 **Ru-1**



4CzIPN

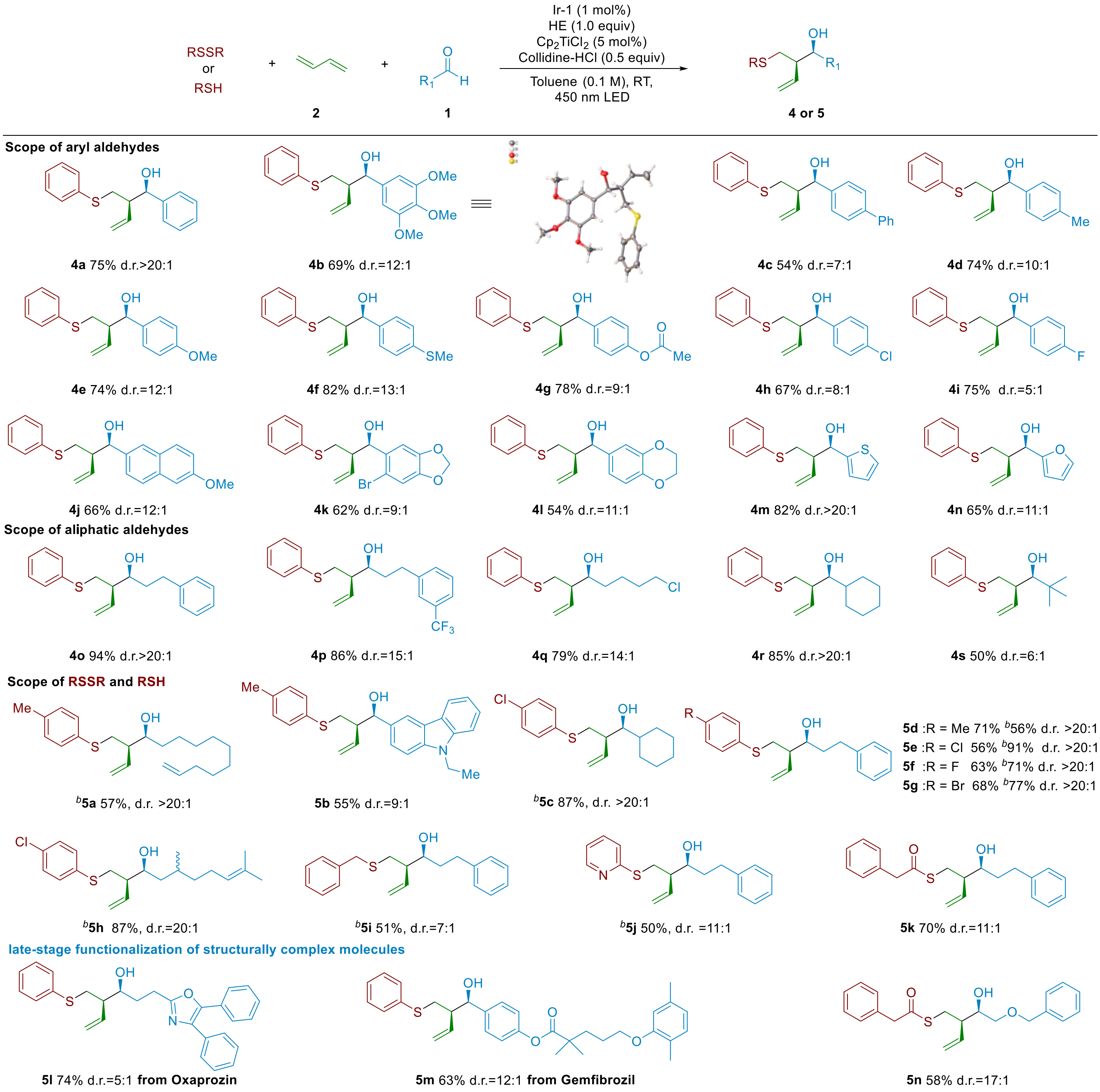
[a]Reaction conditions: **1a** (0.2 mmol), **3a** (0.2 mmol). [b]Yields were determined by ^1H NMR spectroscopy vs an internal standard (1,2,3-trimethoxybenzene).

With the optimized reaction conditions in hand, a series of substrates were examined. Initially, we studied the applicability of aromatic aldehydes. To our delight, both electron-rich aryl groups (**4b**, **4e**, and **4f**) and electron-poor aryl groups (**4c** and **4g**−**4i**) exhibited high reactivity under the optimized conditions (Scheme 1). Additionally, heterocyclic aldehydes **4m**, **4n**, and **5b** did not interfere with the reactions and displayed smooth and efficient functionality. Moreover, **4j** containing naphthalene rings was also employed as a substrate. Later, we explored the applicability of the aliphatic aldehydes. Straight chain (**4o** and **4q**) or cyclic (**4r**) aliphatic aldehydes did not affect the acquisition of the desired product. Subsequently, we investigated the scope of thiyl radical precursor. Importantly, under similar reaction conditions, various thiophenols can be used for coupling. For instance, when there were fluorine, chlorine, or bromine atoms or a methyl group in the *para* position of thiophenol, allylic alcohols were obtained with excellent regio- and diastereoselectivity (**5d**−**5g**). Notably, strongly coordinating 2-thiopyridine was also well-tolerated, giving the product in satisfactory yield (**5j**). Furthermore, the reaction of aliphatic phenylmethanethiol proceeded smoothly, yielding the desired product (**5e**). Interestingly, phenylacetyl disulfide was also coupled to give the desired products **5k** and **5n**. The derivatization of bioactive products is crucial in the pharmaceutical industry. The selected optimal conditions were capable of accommodating structurally complex architectures bearing multiple functional groups such as oxaprozin (**5l**) and gemfibrozil (**5m**). The corresponding products were obtained with satisfactory yield and selectivity, highlighting the potential of this reaction in complex product derivatization. Overall, this reaction system displays favorable reactivity toward different types of thiyl radical precursors, yielding structurally diverse allylic alcohols with notable yields and selectivities.

Both sulfone and sulfoxide structures are commonly found in natural products and bioactive drugs. To investigate the usefulness of allylic 1,3-thioalcohols, Oxone was used to oxidize product **4e** (Figure 2). By controlling the amount of Oxone and the duration of the reaction, we were able to

https://doi.org/10.1021/acs.orglett.3c01822
Org. Lett. 2023, 25, 5094−5099

Scheme 1. Scope of Allylation with Butadiene[a−c]



[a]Reactions were performed with a toluene solution of butadiene (0.1 M). Condition A (for RSSR): **1** (0.20 mmol, 1.0 equiv), RSSR (0.20 mmol, 1.0 equiv), Cp_2TiCl_2 (5.0 mol %), Ir-**1** (1.0 mol %), HE (1 equiv), collidine-HCl (0.5 equiv), 450 nm LED, 12 h. [b]With RSH (0.40 mmol, 2.0 equiv). [c]Isolated yields. dr values were determined by ^1H NMR analysis of the crude products.

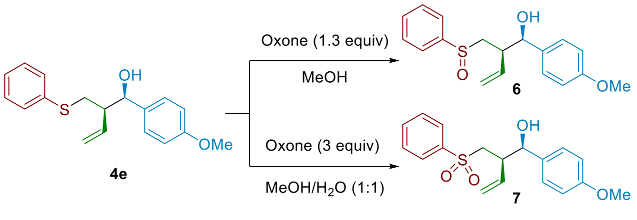


Figure 2. Functional transformation of **4e**.

convert sulfur into sulfone **6** and sulfoxide **7** without affecting the integrity of the allylic alcohol structure.

To explore the possible pathways involved in the reaction, several mechanistic experiments were carried out. Fluorescence quenching shows that the photosensitizer $^*Ir^{III}$-**1** in the excited state can effectively undergo an electron transfer process with Cp_2TiCl_2 ($K_q = 2.3 \times 10^9$ L mol^{-1} s^{-1}) and HE ($K_q = 1.6 \times 10^8$ L mol^{-1} s^{-1}) (Figure 3).[32−34] Although the quenching rate of photosensitizer $^*Ir^{III}$-**1** and Cp_2TiCl_2 in the excited state is slightly faster than that of HE, due to its higher concentration, the excited $^*Ir^{III}$-**1** will preferentially undergo an electron transfer process with HE and then be oxidized by Cp_2TiCl_2 to return to the ground state. However, fluorescence quenching was not obviously observed between Ir-**1** and diphenyl

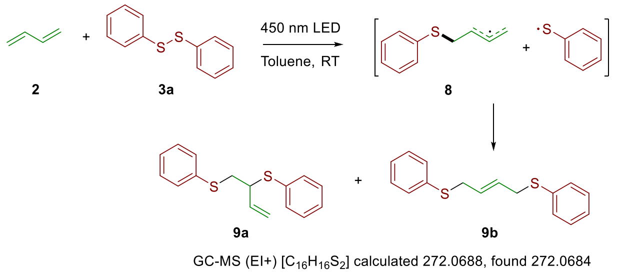


Figure 3. Production of thiyl radicals.

disulfide. To further investigate the mechanism for the production of thiyl radicals, a solution containing diphenyl disulfide and 1,3-butadiene in toluene was subjected to 450 nm light irradiation, as shown in Figure 3. The reaction was analyzed using mass spectrometry, which revealed the formation of two compounds (**9a** and **9b**). These results suggest that the S−S bond in diphenyl disulfide breaks upon irradiation, generating both a thiyl radical and an allyl radical **6** intermediate.[35,36] Additionally, because 1,3-butadiene is a good radical acceptor, it is also possible for the free thiyl radical to add to butadiene and produce allyl radical **6**.

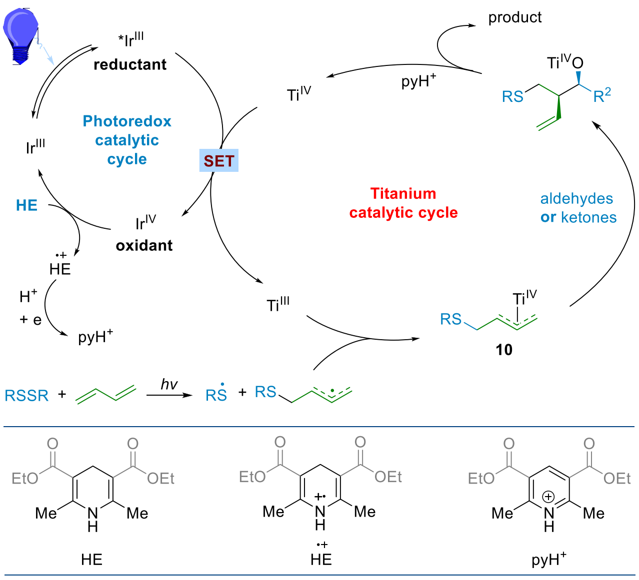


Figure 4. Proposed catalytic mechanism.

On the basis of the findings presented in this work and previous research, a plausible mechanism can be proposed and is illustrated in Figure 4. Initially, the excited state $^*\mathrm{Ir^{III}}$ [$E_{1/2}(^*\mathrm{Ir^{III}}/\mathrm{Ir^{IV}}) = -0.96$ V vs SCE] reduces $\mathrm{Cp_2TiCl_2}$ [$E_{1/2}(\mathrm{TiI^{V}}/\mathrm{Ti^{III}}) = -0.76$ V vs SCE] to $\mathrm{Cp_2Ti^{III}Cl}$ while oxidizing the photosensitizer to $\mathrm{Ir^{IV}}$. The highly oxidizing $\mathrm{Ir^{IV}}$ is then reduced by HE [$E_{1/2}(\mathrm{HE^{\bullet+}}/\mathrm{HE}) = 0.97$ V vs SCE], returning to its ground state and completing the photocatalytic cycle.[28,37] Meanwhile, HE is converted into a radical cation ($\mathrm{HE}\bullet^+$) and participates in the photocatalytic process, ultimately leading to the formation of Hantzsch pyridine.[38] Additionally, under light irradiation, the disulfide bonds undergo homolytic cleavage, resulting in the formation of thiyl radicals. These thiyl radicals react with 1,3-butadiene to form allylic radicals, which undergo subsequent reactions with $\mathrm{Cp_2Ti^{III}Cl}$ to form allyl-$\mathrm{Ti^{IV}}$ intermediates **10**. The latter attack aldehydes to produce homoallylic alcohols, which upon proton decomposition by collidine-HCl yield the desired product and release $\mathrm{Ti^{VI}}$, thus completing the catalytic cycle. The excellent regio- and diastereoselectivity provided by Ti catalysis may be due to the two cyclopentadienyl rings around the titanium metal, increasing steric hindrance and thereby enhancing selectivity.

In this study, a successful combination of radical thiol-ene chemistry and $\mathrm{Ti^{III}}$ catalysis facilitated a three-component aldehyde allylation using 1,3-butadiene as an allyl group source under visible light conditions. This sustainable and simple approach enabled the rapid generation of a wide array of valuable and structurally diverse allylic 1,3-thioalcohols with outstanding regio- and diastereoselectivity. With its broad substrate scope, this method presents a promising strategy for converting 1,3-butadiene and other essential raw materials into high-value fine chemicals while also being ecofriendly and operationally easy.

■ ASSOCIATED CONTENT

Data Availability Statement

The data underlying this study are available in the published article and its Supporting Information.

SI Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.orglett.3c01822.

Experimental details, characterization data of compounds, and NMR spectra (PDF)

Accession Codes

CCDC 2268540 contains the supplementary crystallographic data for this paper. These data can be obtained free of charge via www.ccdc.cam.ac.uk/data_request/cif, or by emailing data_request@ccdc.cam.ac.uk, or by contacting The Cambridge Crystallographic Data Centre, 12 Union Road, Cambridge CB2 1EZ, UK; fax: +44 1223 336033.

■ AUTHOR INFORMATION

Corresponding Authors

Erjun Hao − *Collaborative Innovation Center of Henan Province for Green Manufacturing of Fine Chemicals, Key Laboratory of Green Chemical Media and Reactions, Ministry of Education, School of Chemistry and Chemical Engineering, Henan Normal University, Xinxiang 453007, China*; Email: hej@htu.edu.cn

Lei Shi − *Collaborative Innovation Center of Henan Province for Green Manufacturing of Fine Chemicals, Key Laboratory of Green Chemical Media and Reactions, Ministry of Education, School of Chemistry and Chemical Engineering, Henan Normal University, Xinxiang 453007, China; School of Chemistry, Dalian University of Technology, Dalian 116024, China*; orcid.org/0000-0002-2644-1168; Email: shilei17@dlut.edu.cn

Authors

Binghui Lu − *Collaborative Innovation Center of Henan Province for Green Manufacturing of Fine Chemicals, Key Laboratory of Green Chemical Media and Reactions, Ministry of Education, School of Chemistry and Chemical Engineering, Henan Normal University, Xinxiang 453007, China*

Yonghong Liu − *School of Chemistry, Dalian University of Technology, Dalian 116024, China*

Tianxiao Yang − *School of Chemistry, Dalian University of Technology, Dalian 116024, China*
Huaipu Yan − *School of Chemistry, Dalian University of Technology, Dalian 116024, China*
Xiaobo Ding − *Collaborative Innovation Center of Henan Province for Green Manufacturing of Fine Chemicals, Key Laboratory of Green Chemical Media and Reactions, Ministry of Education, School of Chemistry and Chemical Engineering, Henan Normal University, Xinxiang 453007, China*
Yunhe Jin − *School of Chemistry, Dalian University of Technology, Dalian 116024, China;* orcid.org/0000-0003-0626-4587

Complete contact information is available at:
https://pubs.acs.org/10.1021/acs.orglett.3c01822

Author Contributions

§B.L. and Y.L. contributed equally to this work.

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

This project is supported by the National Natural Science Foundation of China (22171036), the Open Research Fund of School of Chemistry and Chemical Engineering, Henan Normal University (2020YB03), and the Natural Science Foundation of Henan Province (232300421126). The authors thank WATTCAS CHEM-TECH Co., Ltd., for kindly providing the photoreactor.

■ DEDICATION

Dedicated to the 100th anniversary of Henan Normal University.

■ REFERENCES

(1) Wang, P.; Xiao, W.; Chen, J. Recent advances in radical-mediated transformations of 1,3-dienes. *Chin. J. Catal.* **2022**, *43*, 548−557.

(2) Xiong, Y.; Sun, Y.; Zhang, G. Recent advances on catalytic asymmetric difunctionalization of 1,3-dienes. *Tetrahedron Lett.* **2018**, *59*, 347−355.

(3) Wang, N.; Saidhareddy, P.; Jiang, X. Construction of sulfur-containing moieties in the total synthesis of natural products. *Nat. Prod. Rep.* **2020**, *37*, 246−275.

(4) Lee, C.; Liu, Y.; Badsara, S. S. Transition-Metal-Catalyzed C-S Bond Coupling Reaction. *Chem- Asian J.* **2014**, *9*, 706−722.

(5) Naowarojna, N.; Cheng, R.; Chen, L.; Quill, M.; Xu, M.; Zhao, C.; Liu, P. Mini-Review: Ergothioneine and Ovothiol Biosyntheses, an Unprecedented Trans-Sulfur Strategy in Natural Product Biosynthesis. *Biochemistry* **2018**, *57*, 3309−3325.

(6) Musarrat, F.; Chouljenko, V.; Dahal, A.; Nabi, R.; Chouljenko, T.; Jois, S. D.; Kousoulas, K. G. The anti-HIV drug nelfinavir mesylate (Viracept) is a potent inhibitor of cell fusion caused by the SARSCoV-2 spike (S) glycoprotein warranting further evaluation as an antiviral against COVID-19 infections. *J. Med. Virol.* **2020**, *92*, 2087−2095.

(7) Malone, A.; Scanlan, E. M. Applications of Thiyl Radical Cyclizations for the Synthesis of Thiosugars. *Org. Lett.* **2013**, *15*, 504−507.

(8) Huang, S.; Wang, M.; Jiang, X. Ni-catalyzed C-S bond construction and cleavage. *Chem. Soc. Rev.* **2022**, *51*, 8351−8377.

(9) Meng, Y.; Wang, M.; Jiang, X. Multicomponent Reductive Cross-Coupling of an Inorganic Sulfur Dioxide Surrogate: Straightforward Construction of Diversely Functionalized Sulfones. *Angew. Chem., Int. Ed.* **2020**, *59*, 1346−1353.

(10) (a) Hoyle, C. E.; Lowe, A. B.; Bowman, C. N. Thiol-click chemistry: a multifaceted toolbox for small molecule and polymer synthesis. *Chem. Soc. Rev.* **2010**, *39*, 1355. (b) Kolb, H. C.; Finn, M. G.; Sharpless, K. B. Click Chemistry: Diverse Chemical Function from a Few Good Reactions. *Angew. Chem., Int. Ed.* **2001**, *40*, 2004−2021.

(11) Zeng, D.; Ma, Y.; Deng, W.; Wang, M.; Jiang, X. Divergent sulfur (VI) fluoride exchange linkage of sulfonimidoyl fluorides and alkynes. *Nat. Synth.* **2022**, *1*, 455−463.

(12) Gullapalli, K.; Vijaykumar, S. Photo-sensitized oxy-thiocyanation of terminal alkynes/1,3-aryldienes and their one-pot conversion to 2-hydroxy 4-substituted aryl thiazoles. *Org. & Biomol. Chem.* **2019**, *17*, 2232−2241.

(13) Huang, H. M.; Bellotti, P.; Glorius, F. Transition metal-catalysed allylic functionalization reactions involving radicals. *Chem. Soc. Rev.* **2020**, *49*, 6186−6197.

(14) Xiong, Y.; Zhang, G. Enantioselective 1,2-Difunctionalization of 1,3-Butadiene by Sequential Alkylation and Carbonyl Allylation. *J. Am. Chem. Soc.* **2018**, *140*, 2735−2738.

(15) Huang, H.; Koy, M.; Serrano, E.; Pflüger, P. M.; Schwarz, J. L.; Glorius, F. Catalytic radical generation of π-allylpalladium complexes. *Nat. Catal.* **2020**, *3*, 393−400.

(16) Huang, H.; Bellotti, P.; Pflüger, P. M.; Schwarz, J. L.; Heidrich, B.; Glorius, F. Three-Component, Interrupted Radical Heck/Allylic Substitution Cascade Involving Unactivated Alkyl Bromides. *J. Am. Chem. Soc.* **2020**, *142*, 10173−10183.

(17) Huang, H.; Bellotti, P.; Kim, S.; Zhang, X.; Glorius, F. Catalytic multicomponent reaction involving a ketyl-type radical. *Nat. Synth.* **2022**, *1*, 464−474.

(18) Cheung, K. P. S.; Kurandina, D.; Yata, T.; Gevorgyan, V. Photoinduced Palladium-Catalyzed Carbofunctionalization of Conjugated Dienes Proceeding via Radical-Polar Crossover Scenario: 1,2-Aminoalkylation and Beyond. *J. Am. Chem. Soc.* **2020**, *142*, 9932−9937.

(19) Jiang, X.; Jiang, H.; Yang, Q.; Cheng, Y.; Lu, L.; Tunge, J. A.; Xiao, W. Photoassisted Cobalt-Catalyzed Asymmetric Reductive Grignard-Type Addition of Aryl Iodides. *J. Am. Chem. Soc.* **2022**, *144*, 8347−8354.

(20) Wang, P. Z.; Wu, X.; Cheng, Y.; Jiang, M.; Xiao, W. J.; Chen, J. R. Photoinduced Copper-Catalyzed Asymmetric Three-Component Coupling of 1,3-Dienes: An Alternative to Kharasch−Sosnovsky Reaction. *Angew. Chem., Int. Ed.* **2021**, *60*, 22956−22962.

(21) Lu, F.; Lu, L.; He, G.; Bai, J.; Xiao, W. Enantioselective Radical Carbocyanation of 1,3-Dienes via Photocatalytic Generation of Allylcopper Complexes. *J. Am. Chem. Soc.* **2021**, *143*, 4168−4173.

(22) Li, F.; Lin, S.; Chen, Y.; Shi, C.; Yan, H.; Li, C.; Wu, C.; Lin, L.; Duan, C.; Shi, L. Photocatalytic Generation of π-Allyltitanium Complexes via Radical Intermediates. *Angew. Chem., Int. Ed.* **2021**, *60*, 1561−1566.

(23) Li, F.; Lin, S.; Li, X.; Shi, L. Photocatalytic Generation of π-Allyltitanium Complexes from Butadiene via a Radical Strategy. *Synthesis* **2021**, *53*, 1889−1900.

(24) Liu, C.; Fang, Y.; Wang, S.; Ji, S. Highly Regioselective RhIII-Catalyzed Thiolation of N-Tosyl Acrylamides: General Access to (Z)-β-Alkenyl Sulfides. *Org. Lett.* **2018**, *20*, 6112−6116.

(25) Cera, G.; Ackermann, L. Weak O-Assistance Outcompeting Strong N, N-Bidentate Directing Groups in Copper-Catalyzed C−H Chalcogenation. *Chem. - Eur. J.* **2016**, *22*, 8475−8478.

(26) Yang, L.; Wen, Q.; Xiao, F.; Deng, G. Silver-mediated oxidative vinylic C−H bond sulfenylation of enamides with disulfides. *Org. Biomol. Chem.* **2014**, *12*, 9519−9523.

(27) Yan, H.; Liao, Q.; Chen, Y.; Gurzadyan, G. G.; Lu, B.; Wu, C.; Shi, L. Photocatalytic Metal Hydride Hydrogen Atom Transfer Mediated Allene Functionalization by Cobalt and Titanium Dual Catalysis. *Angew. Chem., Int. Ed.* **2023**, *62*, e202302483.

(28) Chen, Y.; Lin, S.; Li, F.; Zhang, X.; Lin, L.; Shi, L. $Cp_2Ti^{III}Cl$ Catalysis in a New Light. *ChemPhotoChem* **2020**, 659−663.

(29) Gualandi, A.; Calogero, F.; Mazzarini, M.; Guazzi, S.; Fermi, A.; Bergamini, G.; Cozzi, P. G. Cp_2TiCl_2-Catalyzed Photoredox Allylation of Aldehydes with Visible Light. *ACS Catal.* **2020**, *10*, 3857−3863.
(30) McCallum, T.; Wu, X.; Lin, S. Recent Advances in Titanium Radical Redox Catalysis. *J. Org. Chem.* **2019**, *84*, 14369−14380.
(31) Zhang, Z.; Hilche, T.; Slak, D.; Rietdijk, N. R.; Oloyede, U. N.; Flowers, R. A.; Gansäuer, A. Titanocenes as Photoredox Catalysts Using Green-Light Irradiation. *Angew. Chem., Int. Ed.* **2020**, *59*, 9355−9359.
(32) Twilton, J.; Le, C.; Zhang, P.; Shaw, M. H.; Evans, R. W.; MacMillan, D. W. C. The merger of transition metal and photocatalysis. *Nat. Rev. Chem.* **2017**, *1*, 52.
(33) Skubi, K. L.; Blum, T. R.; Yoon, T. P. Dual Catalysis Strategies in Photochemical Synthesis. *Chem. Rev.* **2016**, *116*, 10035−10074.
(34) Prier, C. K.; Rankic, D. A.; MacMillan, D. W. C. Visible Light Photoredox Catalysis with Transition Metal Complexes: Applications in Organic Synthesis. *Chem. Rev.* **2013**, *113*, 5322−5363.
(35) Deng, Y.; Wei, X. J.; Wang, H.; Sun, Y.; Noël, T.; Wang, X. Disulfide-Catalyzed Visible-Light-Mediated Oxidative Cleavage of C═C Bonds and Evidence of an Olefin−Disulfide Charge-Transfer Complex. *Angew. Chem., Int. Ed.* **2017**, *56*, 832−836.
(36) Yoshimura, A.; Takamachi, Y.; Han, L. B.; Ogawa, A. Organosulfide-Catalyzed Diboration of Terminal Alkynes under Light. *Chem. - Eur. J.* **2015**, *21*, 13930−13933.
(37) Lin, S.; Chen, Y.; Li, F.; Shi, C.; Shi, L. Visible-light-driven spirocyclization of epoxides via dual titanocene and photoredox catalysis. *Chem. Sci.* **2020**, *11*, 839−844.
(38) Wang, P.-Z.; Chen, J.-R.; Xiao, W.-J. Hantzsch esters: an emerging versatile class of reagents in photoredox catalyzed organic synthesis. *Org. & Biomol. Chem.* **2019**, *17*, 6936−6951.