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# Synthesis of Trifluoromethylated Sultones from Alkenols Using a Copper Photoredox Catalyst

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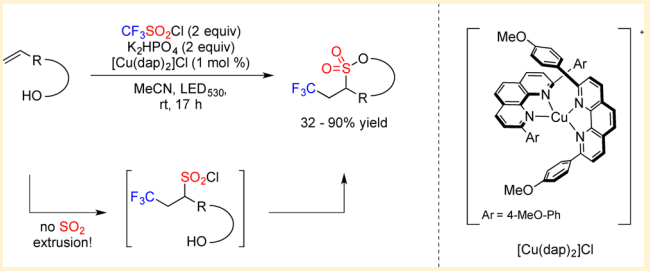
Supporting Information

**ABSTRACT:** A photo-redox-catalyzed procedure for the one-step formation of sultones from $\alpha,\omega$-alkenols and trifluoromethylsulfonyl chloride is described. Using $[Cu(dap)_2]Cl$ (1 mol %), a wide range of substrates can be cleanly converted to the target compounds, while commonly employed photoelectron transfer catalysts such as $[Ru(bpy)_3]Cl_2$ or *fac*-$Ir(ppy)_3$ fail in this transformation. The obtained fluorinated sultones are attractive as potential electrolyte additives or as structural motifs in drug synthesis, with the latter being demonstrated with the synthesis of a trifluoroethyl-substituted analogue of a benzoxathiin that has high anti-arrhythmic activity.




## INTRODUCTION

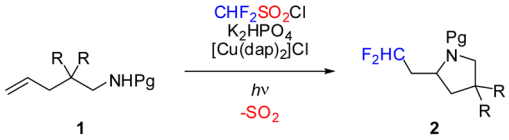
Since the discovery of internal esters of hydroxysulfonic acids, commonly known as "sultones", by Erdmann in 1888,[1] this compound class has been attractive for a variety of research fields including natural product synthesis and biologically active compounds, medicinal chemistry, and material science.[2] For instance, Metz et al.[3] could successfully demonstrate the application of sultones as key intermediates in natural product synthesis. Moreover, promising results against human immunodeficiency virus type 1 (HIV-1), human cytomegalovirus (HCMV), and varicellazoster virus (VZV) were demonstrated by Velázquez and co-workers.[4] Furthermore, sultones are applied in lithium-ion batteries (LIB) as an electrolyte additive[5] to overcome problems like low temperature and calendar life performance and safety issues for their application in electric vehicles. Especially in this context, the virtue of fluorine-containing sultone additives has been recognized.[6] Early approaches for sultone syntheses utilized the sulfonation of olefins with $SO_3$ and its adducts,[7] carbanion-mediated sulfonate coupling reactions,[8] or heating of the corresponding hydroxysulfonic acids in vacuum.[9] In the past decade, milder methodologies have been developed including ring-closure metathesis (RCM),[10] Diels–Alder reactions,[11] or rhodium-catalyzed C–H insertions.[12]

The incorporation of fluorinated moieties, particularly the trifluoromethyl ($CF_3$) group, into organic compounds and transition metal complexes can profoundly change their chemical, physical, and biological properties.[13] Consequently, various approaches including nucleophilic,[14] electrophilic,[15] and radical[16] strategies for installing a $CF_3$ moiety into organic molecules have been reported.

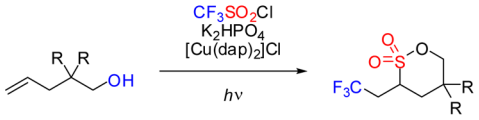
In recent years, rapid progress was made in the field of visible-light-mediated photoredox catalysis, which has established itself as a powerful technique for conducting free-radical transformations.[17] In this context, the visible-light-induced photocatalytic difunctionalization of alkenes proved to be an efficient approach for $CF_xR$-containing heterocycles.[18] Recently, a variety of pyrrolidines and lactones were efficiently synthesized by photoredox catalysis employing $[Cu(dap)_2]Cl$ (dap = 2,9-di(*p*-anisyl)-1,10-phenanthroline) and $CHF_2SO_2Cl$, as demonstrated by Dolbier and co-workers (Scheme 1).[19] In this case, however, the reaction proceeds with loss of sulfur dioxide without any sign of sultone or sulfamide formation.

**Scheme 1. Visible-Light-Mediated $[Cu(dap)_2]Cl$-Catalyzed Intramolecular Atom Transfer Radical Addition Processes**

**(a) Dolbier and co-workers: Intramolecular Aminotrifluoromethylation**




***(b) This work:***

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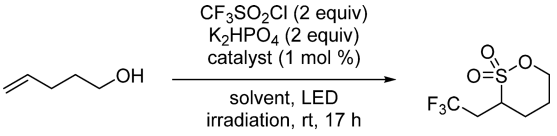
## RESULTS AND DISCUSSION

Following our interest in photocatalysis[20] and especially the application of environmentally benign copper complexes[21,22] for visible-light photoredox catalysis, we investigated the copper-catalyzed visible-light reaction of $CF_3SO_2Cl$ with terminal alkenes.[21] $[Cu(dap)_2]Cl$ was identified as a unique catalyst that, in contrast to other photoredox catalysts,[23] gives rise to a net addition of a trifluoromethyl and a chlorosulfonyl group to the alkene. Expanding the scope of this transformation, we report herein the one-step visible-light-mediated synthesis of $\alpha$-substituted trifluoromethylated sultones from $\alpha,\omega$-alkenols.

Using pent-4-en-1-ol (**3c**) as a benchmark substrate, we were delighted to find that in the presence of $[Cu(dap)_2]Cl$ (1 mol %) the reaction with triflyl chloride ($CF_3SO_2Cl$) indeed results in the smooth formation of sultone **4c** (Table 1, entry 1). Omitting the base, which is assumed to act as a scavenger for HCl that is formed in the course of the reaction, leads to a significant decrease in yield (entry 2). While the reaction proceeds well in $CH_2Cl_2$, DMF, or DMSO (entries 3–5), acetonitrile appears to be the optimal solvent (entry 1). Reducing the amount of $[Cu(dap)_2]Cl$ to 0.5 mol % (entry 6) was met with a reduction in yield: we reason that this is not a result of catalyst deactivation but rather due to deep coloring of the reaction solution with time that blocks the photoprocess. In contrast, net addition of $CF_3Cl$ was mainly observed besides unidentified side products and low yields of **4c** when well-established photoredox catalysts such as $[Ru(bpy)_3]Cl_2$ (bpy = 2,2′-bipyridyl) or *fac*-$Ir(ppy)_3$ (ppy = 4-pyrrolidinopyridine) were used (entries 11 and 12). These photocatalysts require irradiation at 455 nm. To rule out that the failure to form **4c** with these catalysts was due to the higher light energy, we also tested $[Cu(dap)_2]Cl$ at this wavelength, which proceeded cleanly but resulted in a slightly lower yield of **4c** (entry 13).

**Table 1. Optimization of Reaction Parameters for the Sultone Formation**[a]



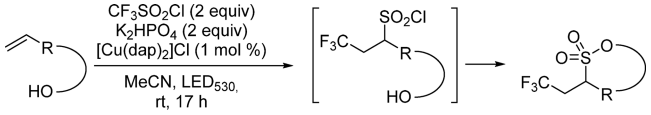

**3c** **4c**

| entry | catalyst | solvent | yield (%) |
|---|---|---|---|
| 1 | $[Cu(dap)_2]Cl$ | MeCN | 88 |
| 2[b] | $[Cu(dap)_2]Cl$ | MeCN | 34 |
| 3 | $[Cu(dap)_2]Cl$ | $CH_2Cl_2$ | 71 |
| 4 | $[Cu(dap)_2]Cl$ | DMF | 50 |
| 5 | $[Cu(dap)_2]Cl$ | DMSO | 61 |
| 6[c] | $[Cu(dap)_2]Cl$ | MeCN | 49 |
| 7[d] | $[Cu(dap)_2]Cl$ | MeCN | 4 |
| 8 | CuCl | MeCN | 2 |
| 9 | no catalyst | MeCN | nr |
| 10 | dap | MeCN | nr |
| 11[e] | $[Ru(bpy)_3]Cl_2$ | MeCN | 10 |
| 12[e] | *fac*-$Ir(ppy)_3$ | MeCN | 18 |
| 13[e] | $[Cu(dap)_2]Cl$ | MeCN | 66 |

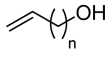
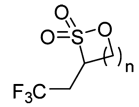
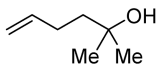
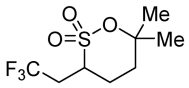
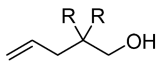
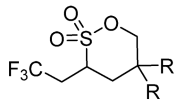
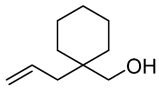
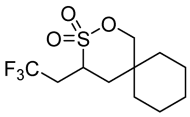
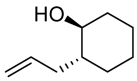
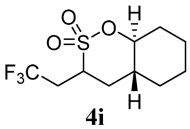
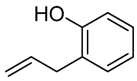
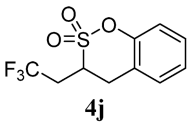
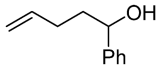
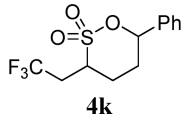
[a]Reaction conditions: 4-penten-1-ol **3c** (0.5 mmol, 1.0 equiv), $CF_3SO_2Cl$ (1.0 mmol, 2.0 equiv), $K_2HPO_4$ (1.0 mmol, 2.0 equiv), catalyst (1.0 mol %) in solvent (1.5 mL), irradiation at 530 nm (green LED) for 17 h. All yields are based on using benzotrifluoride as the internal standard. [b]Absence of $K_2HPO_4$. [c]Catalyst loading 0.5 mol %. [d]Dark reaction. [e]Irradiation at 455 nm (blue LED).

With optimized conditions in hand, we examined the scope of the reaction (Table 2). Attempts to use allyl alcohol **3a** gave rise to a complex reaction mixture with only trace amounts of the desired $\beta$-sultone **4a** detectable (entry 1), a compound class that is known to have low stability.[24] The $\gamma$- and $\delta$-sultones **4b** and **4c** were obtained in good to excellent yields, while a drop in yield was observed for $\varepsilon$-sultone **4d** (entries 2–4). To demonstrate the viability of the method for preparative purposes, scale-up of **4b** and **4c** to gram quantities

**Table 2. Substrate Scope of Photo-redox-Catalyzed Intramolecular Formation of Sultone**[a]




**3** **13** **4**

| entry | alkene | | product | | yield (%) |
|---|---|---|---|---|---|
| |  | |  | | |
| 1 | n = 1 | **3a** | n = 1 | **4a** | <5 |
| 2 | n = 2 | **3b** | n = 2 | **4b** | 64 |
| 3 | n = 3 | **3c** | n = 3 | **4c** | 90 |
| 4 | n = 4 | **3d** | n = 4 | **4d** | 32 |
| 5 |  **3e** | |  **4e** | | 73 |
| 6 |  **3f** (R = Ph) | |  **4f** | | 73 |
| 7 | **3g** ($R = CO_2Et$) | | **4g** | | 50 |
| 8 |  **3h** | |  **4h** | | 74 |
| 9[b] |  **3i** | |  **4i** | | 90 |
| 10 |  **3j** | |  **4j** | | 67 |
| 11[c] |  **3k** | |  **4k** | | 67 |

[a]Reaction conditions: alkene **3** (1.0 mmol, 1.0 equiv), $CF_3SO_2Cl$ (2.0 mmol, 2.0 equiv), $K_2HPO_4$ (2.0 mmol, 2.0 equiv), $[Cu(dap]_2Cl$ (1.0 mol %) in MeCN (3.0 mL), irradiation at 530 nm (green LED) for 17 h. [b]Diastereomeric ratio of **4i** *syn*/*anti* = 44:56. [c]Diastereomeric ratio of **4k** *syn*/*anti* = 43:57.



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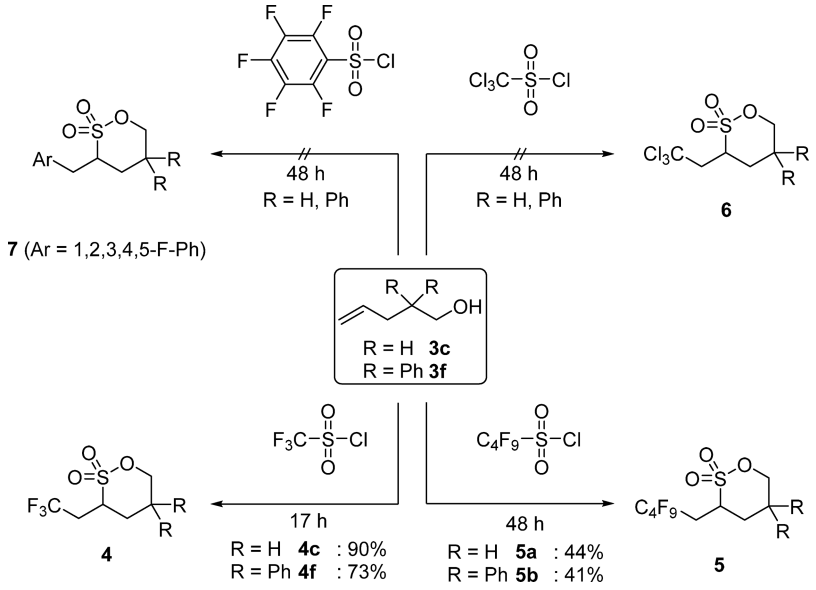
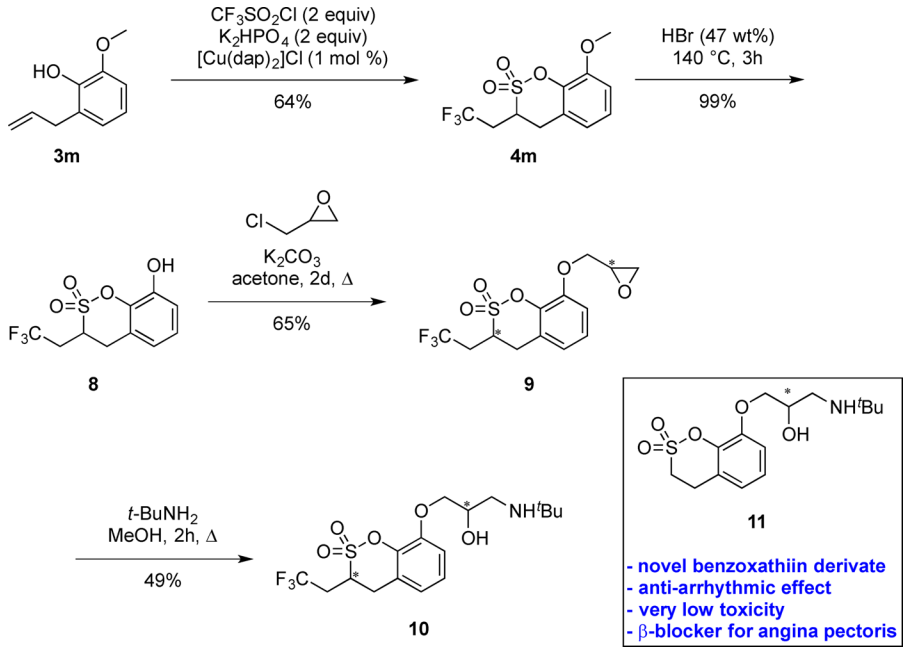
**Scheme 2. Various Sulfonyl Chlorides Tested for Sultone Synthesis**[a]




[a]For conditions, see Table 2.

**Scheme 3. Synthesis of Novel Benzoxathiin Derivative Derived from Visible-Light-Mediated Intramolecular Formation of Sultone as the Key Step**[a]




[a]Reaction conditions: (a) 2-allyl-6-methoxyphenol **3m** (1.0 equiv), $CF_3SO_2Cl$ (2.0 equiv), $K_2HPO_4$ (2.0 equiv), $[Cu(dap)_2]Cl$ (1.0 mol %), MeCN, irradiation at 530 nm (green LED), rt, 24 h, 64%; (b) HBr (47 wt %), 140 °C, 3 h, 99%; (c) epichlorohydrin (18.2 equiv), $K_2CO_3$ (2.2 equiv), anhydrous acetone, reflux, 2 days, 65% (dr = 50:50); *t*-$BuNH_2$, anhydrous MeOH, reflux, 2 h, 49% (20% overall yield after four steps).

was also demonstrated (see Supporting Information). Focusing on $\delta$-sultones, readily available pent-4-en-1-ols **3e**–**3k** being substituted in the 2- and/or 3-position gave rise to sultones **4e**–**4k**; however, methyl or phenyl substitution either in the 4- or 5-position led to complex reaction mixtures containing regio- and diastereomeric sultones, and in addition, trifluoromethylchlorination of the alkene was observed. In general, it should be noted that the trifluoromethylchlorosulfonylation of alkenes developed by us is sensitive to steric effects: substitution at the double bond or next to it leads to increasing amounts of $CF_3Cl$ addition, which is the general reaction mode for ruthenium- or iridium-based photocatalysts. An X-ray structure of **4f** confirmed the general structure of the sultones formed. Embedding a phenol moiety into the substrate was also possible, as demonstrated with the transformation of **3j** to **4j**, which is especially relevant for the synthesis of drug-like sultones (vide infra).

Next, different commercially available sulfonyl chlorides were tested for the introduction of various side chains (Scheme 2). Indeed, cyclization was observed for alkenols **3c**



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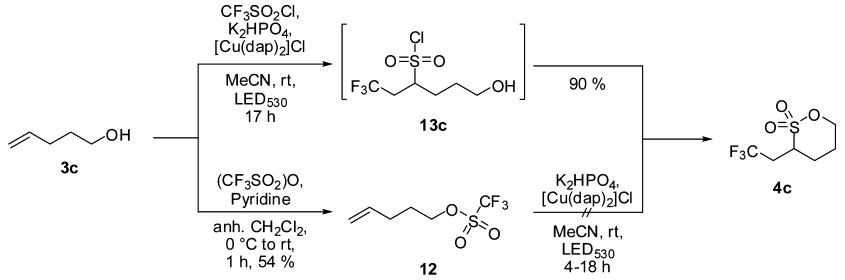
**Scheme 4. Mechanistic Studies: Trifluoromethylchlorosulfonylation versus Triflate Formation**




and **3f** when $C_4F_9SO_2Cl$ was employed, yielding perfluorobutane-containing sultones **5a** and **5b** in 41 and 44% yield, respectively, but longer reaction times were necessary to obtain full conversion. No conversion of the starting materials **3c** and **3f** was observed with pentafluorobenzenesulfonyl chloride. Use of $CCl_3SO_2Cl$ as the radical source led to a complex reaction mixture in which the desired product **6** could not be identified.

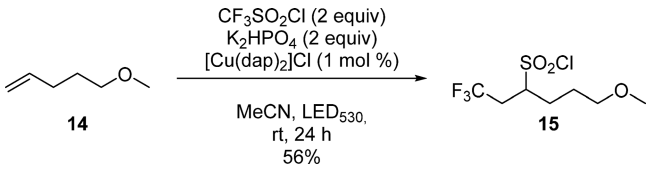
Benzoxathiins have been recognized as lead structures in medicinal chemistry due to their excellent pharmacological properties. In particular, **11**, being available in a seven-step sequence from *o*-vanilline, showed a concentration of 1 $\mu$mol 96.3% $\beta$-receptor blocking inhibition and anti-arrhythmic activity of 0.03 mg/kg ($ED_{50}$), while its toxicity is very low ($LD_{50}$ = 59.2 mg/kg intravenous, >500 mg/kg in stomach).[25]

Considering the benefits of fluoroalkyl group introduction into biologically active molecules,[26] based on the methodology reported here, the $CF_3CH_2$ analogue **10** could be efficiently synthesized in only four steps from commercially available *o*-eugenol **3m** (Scheme 3). The latter was converted under the standard conditions to sultone **4m** on a 3 mmol scale in 64% yield. Cleavage of the methoxy group with HBr and etherification with racemic epichlorohydrine gave rise to **9**, which upon treatment with *tert*-butylamine resulted in **10** as a 1:1 mixture of diastereomers in an overall yield of 20% over four steps.

In order to gain a deeper insight into the mechanism, a series of experiments were carried out (Scheme 4). Taking **3c** as a model compound, we tested if initially trifluorochlorosulfonylation to **13c** followed by cyclization takes place or if the triflate **12** is formed first, which is subsequently photochemically cleaved with concurrent cyclization to **4c**. The latter was ruled out by the independent synthesis of **12**, which resulted upon irradiation under the standard reaction conditions only in polymerization of the starting material.[27] Moreover, the reaction of **3c** with $CF_3SO_2Cl$ is sluggish, even in the presence of a base such as pyridine.

We therefore conclude that trifluoromethylsulfonylation of the alkene precedes sultone formation. In agreement with these findings, reacting **14** under the reaction conditions, trifluoromethylsulfonylation to **15** was observed (Scheme 5).

**Scheme 5. Trifluoromethylchlorosulfonylation of Protected $\alpha,\omega$-Alkenol 14**




While the overall process to sultones **4** proceeded cleanly, we identified as minor impurities (<5%) the corresponding sultines ($SO_2$ instead of $SO_3$), which could not be removed in the case of **4h** (see Supporting Information). The sultines could arise by reduction of the sultones; we therefore subjected the isolated $\delta$-sultone **4c** again under the reaction condition of its formation: no decomposition or further side reactions were observed, indicating that the sultones are photochemically stable. Most likely, the sultines arise from $CF_3SOCl$ that is present in commercially available trifluoromethanesulfonyl chloride due to incomplete oxidation of the corresponding sodium sulfinate, acid, or sulfinyl derivatives.[28]

A second impurity that was identified with the generation of **4g** is a sultone having a chlorine instead of a trifuoromethyl group incorporated (see Supporting Information), suggesting that under the photoredox conditions chlorine radicals are also generated that initiate sultone formation by addition to the alkene in **3**.

Taking these observations into account, the following mechanistic picture arises: photoexcited $[Cu(dap)_2]^{+*}$ reduces triflyl chloride by a single-electron transfer, thus generating a trifluoromethyl radical, which adds to alkene **3** to form the radical **18**. The Cu(II) species **19** formed concurrently in this process might coordinate and thus stabilize $SO_2Cl^-$, which then combines with **18** by a back-electron transfer to regenerate the Cu(I) catalyst **16** and to form **13**. The involvement of nucleophiles bound to Cu(II) has been recently shown by Fu et al. for the copper-mediated cross-coupling of an aryl thiol with an aryl halide induced by visible light.[29] Finally, an intramolecular cyclization of **13** produces the desired sultone **4** (Scheme 6).

Alternatively, radical **18** might initiate a radical chain process with $CF_3SO_2Cl$ to produce **13** and $\bullet CF_3$. This proposal would call for a rather unusual attack of **18** at sulfur in $CF_3SO_2Cl$. It should be noted that when $[Ru(bpy)_3]Cl_2$ is used instead of $[Cu(dap)_2]Cl$, trifluoromethyl *chlorination* instead of *chlorosulfonylation* is observed, which was explained by attack of radicals of type **18** onto chloride in $CF_3SO_2Cl$.[23] Given the lower oxidation potential of Cu(II) to Cu(I) ($E_{1/2}$ = 0.62 V vs SCE) compared to the potential for Ru(III) to Ru(II) ($E_{1/2}$ = 0.77 V vs SCE), in the ruthenium-catalyzed process, a more facile oxidation of **18** to its corresponding cation might be the key intermediate that takes up chloride.

## CONCLUSION

In conclusion, we have described a simple photo-redox-catalyzed procedure for the one-step synthesis of sultones **4a**–**4m** with trifluoroethyl substitution in the 3-position[30] from readily available $\alpha,\omega$-alkenols **3a**–**3m** in moderate to excellent yield using an inexpensive copper catalyst with low loading. The resulting sultones might have potential as lithium battery



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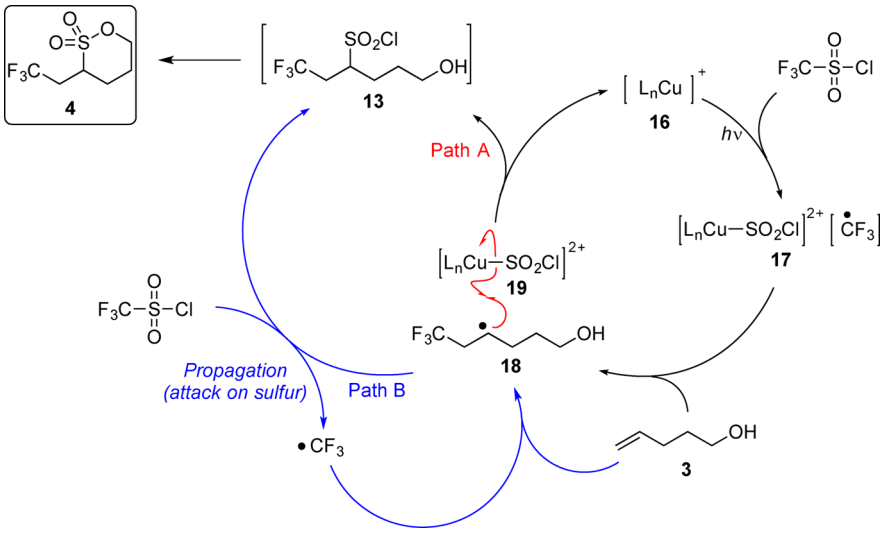
**Scheme 6. Proposed Mechanism**




additives, which is currently under investigation. Moreover, the trifluoroethyl-substituted benzoxathiin derivative **10** could be synthesized, which is an analogue of the highly potent *β*-blocker **11**.

## EXPERIMENTAL SECTION

**General Information.** All reactions were performed in flame-dried flasks under $N_2$ atmosphere using anhydrous solvents unless otherwise stated. Anhydrous solvents were prepared by established laboratory procedures. The commercially available chemicals were purchased in high quality and were used without further purification. All reactions were monitored by thin layer chromatography (TLC). Visualization was done with UV light ($\lambda$ = 254 nm) and staining with vanillin (6 g of vanillin in 100 mL of EtOH and 5 mL of $H_2SO_4$), sodium permanganate (1 g of $KMnO_4$ and 2 g of $Na_2CO_3$ in 100 mL of $H_2O$), PMA (1 g of ceric ammonium sulfate and 2.5 g of ammonium molybdate in 10 mL of $H_2SO_4$ and 90 mL of $H_2O$), or anisaldehyde (5 mL of *p*-anisaldehyde in 5 mL of $H_2SO_4$ and 100 mL of EtOH) followed by heating. All NMR spectra were recorded in $CDCl_3$ unless otherwise stated. Chemical shifts $\delta$ are reported in parts per million (ppm) relative to the signal of $CDCl_3$ (7.26 ppm for $^1$H, 77.16 ppm for $^{13}$C). High-resolution mass spectra were measured using electrospray ionization (ESI) or atmospheric pressure chemical ionization (APCI) with a quadrupole time-of-flight (Q-TOF) detector. The following compounds were synthesized according to the reported procedures, and the spectroscopical data are consistent with those reported: 2-methylhex-5-en-2-ol **3e**,[31] 2,2-diphenylpent-4-en-1-ol **3f**,[32] diethyl-2-allyl-2-(hydroxymethyl)-malonate **3g**,[33] (1-allylcyclohexyl)methanol **3h**,[34] *rel*-(1*R*,6*S*)-7-oxabicyclo[4.1.0]heptane,[35] *rel*-(1*S*,2*R*)-2-allylcyclohexan-1-ol **3i**,[36] 1-phenylpent-4-en-1-ol **3k**,[37] pent-4-en-1-yl trifluoromethanesulfonate **12**,[38] 2-(chloromethyl)tetrahydrofuran,[39] and 5-methoxypent-1-ene **14**.[40]

**General Procedure for the Sultone Formation (GP-A).** An oven-dried Schlenk tube equipped with a magnetic stirring bar was charged with alkene **3** (1.0 mmol, 1.0 equiv), $[Cu(dap)_2]Cl$ (8.8 mg, 1.0 $\mu$mol, 1.0 mol %), and $K_2HPO_4$ (348 mg, 2.0 mmol, 2.0 equiv) in anhydrous MeCN (3 mL). The resulting suspension was degassed by three freeze−pump−thaw cycles followed by the addition of triflyl chloride (210 $\mu$L, 2.0 mmol, 2.0 equiv). The reaction mixture was irradiated under stirring for 17 h with a green light optical fiber (LED, $\lambda_{max}$ = 530 nm) at room temperature. The reaction mixture was quenched with water (3 mL), and the product was extracted with $CH_2Cl_2$. The combined organic layers were dried over anhydrous $Na_2SO_4$ and concentrated in vacuum. The residue was purified by filtration through a silica plug with $CH_2Cl_2$ as the eluent or by column chromatography on silica gel to yield the desired product.

**General Procedure for the Scale-Up of Sultones (GP-B).** The reactions were performed 10 times on a 5 mmol scale (=50 mmol). An oven-dried Schlenk tube equipped with a magnetic stirring bar was charged with alcohol (5.0 mmol, 1.0 equiv), $[Cu(dap)_2]Cl$ (44 mg, 5.0 $\mu$mol, 1.0 mol %), and $K_2HPO_4$ (1.76 g, 10.0 mmol, 2.0 equiv) in anhydrous MeCN (15 mL). The resulting suspension was degassed by three freeze−pump−thaw cycles followed by the addition of $CF_3SO_2Cl$ (1.1 mL, 10.0 mmol, 2.0 equiv). The reaction mixture was irradiated under stirring for 48 h with a green light plate (LED, $\lambda_{max}$ = 530 nm) at room temperature. The combined reaction solution of the overall 10 reactions was filtered through a silica plug with $CH_2Cl_2$ as the eluent and concentrated in vacuo. The residue was purified by distillation under reduced pressure to yield the desired product.

*3-(2,2,2-Trifluoroethyl)-1,2-oxathiolane 2,2-dioxide* ***4b***. Following GP-A, **4b** was prepared using but-3-en-1-ol **3b** (86 $\mu$L, 1.0 mmol, 1.0 equiv), $[Cu(dap)_2]Cl$ (8.8 mg, 1.0 $\mu$mol, 1.0 mol %), $K_2HPO_4$ (352 mg, 2.0 mmol, 2.0 equiv), and $CF_3SO_2Cl$ (210 $\mu$L, 2.0 mmol, 2.0 equiv) in anhydrous MeCN (3 mL). The reaction solution was filtered through a silica plug with $CH_2Cl_2$ as the eluent. The filtrate was concentrated under reduced pressure to afford **4b** as a colorless oil (102 mg, 50%). Following GP-B, **4b** was prepared using but-3-en-1-ol **3b** (430 $\mu$L, 5.0 mmol, 1.0 equiv), $[Cu(dap)_2]Cl$ (44 mg, 5.0 $\mu$mol, 1.0 mol %), $K_2HPO_4$ (1.76 g, 10.0 mmol, 2.0 equiv), $CF_3SO_2Cl$ (1.1 mL, 10.0 mmol, 2.0 equiv), and anhydrous MeCN (15 mL). The residue was purified by distillation under reduced pressure (1.4 mbar, oil bath temperature 150−170 °C, boiling point at 87−89 °C) to yield **4b** as a colorless oil (4.88 g, 48%): $R_f$ = not determinable; staining = not determinable (UV inactive); $^1$H NMR (600 MHz, $CDCl_3$) $\delta$ = 4.51 (ddd, $J$ = 9.2, 8.2, 3.3 Hz, 1H), 4.43 (td, $J$ = 9.1, 7.0 Hz, 1H), 3.50 (tdd, $J$ = 10.1, 7.9, 3.9 Hz, 1H), 2.95−2.87 (m, 1H), 2.83−2.78 (m, 1H), 2.51−2.41 (m, 2H); $^{19}$F NMR (282 MHz, $CDCl_3$) $\delta$ = −64.99 (s, 3F); $^{13}$C NMR (75 MHz, $CDCl_3$) $\delta$ = 125.3 (d, $J_{C-F}$ = 277.1 Hz), 67.2, 49.7 (q, $J_{C-F}$ = 2.8 Hz), 33.5 (q, $J_{C-F}$ = 30.8 Hz), 29.6; IR (neat, cm$^{-1}$) 2966, 2926, 1350, 1315, 1258, 1165, 1137, 1077, 993, 914, 792, 661, 631, 609, 496; HRMS (APCI) exact mass calcd for $C_5H_8F_3O_3S$ $m/z$ 205.0141, found $m/z$ 205.0140 $[M + H]^+$; GC analysis, purity 94%, $t_R$ = 5.491 min, wt($H_2O$) = 407 ppm.

*3-(2,2,2-Trifluoroethyl)-1,2-oxathiane 2,2-dioxide* ***4c***. Following GP-A, **4c** was prepared using pent-4-en-1-ol **3c** (102 $\mu$L, 1.0 mmol, 1.0 equiv), $[Cu(dap)_2]Cl$ (8.8 mg, 1.0 $\mu$mol, 1.0 mol %), $K_2HPO_4$ (352 mg, 2.0 mmol, 2.0 equiv), and $CF_3SO_2Cl$ (210 $\mu$L, 2.0 mmol, 2.0 equiv) in anhydrous MeCN (3 mL). The reaction solution was filtered through a silica plug with $CH_2Cl_2$ as the eluent. The filtrate



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was concentrated under reduced pressure to afford **4c** as a colorless oil (207 mg, 94%). Following GP-B, **4c** was prepared using pent-4-en-1-ol **3c** (510 μL, 5.0 mmol, 1.0 equiv), $[Cu(dap)_2]Cl$ (44 mg, 5.0 μmol, 1.0 mol %), $K_2HPO_4$ (1.76 g, 10.0 mmol, 2.0 equiv), $CF_3SO_2Cl$ (1.1 mL, 10.0 mmol, 2.0 equiv), and dry MeCN (15 mL). The residue was purified by distillation under reduced pressure (0.7 mbar, oil bath temperature 120 °C, boiling point at 83−84 °C) to yield **4c** as a colorless oil (7.72 g, 71%): $R_f$ = not determinable; staining = not determinable (UV inactive); $^1$H NMR (600 MHz, $CDCl_3$) $\delta$ = 4.61 (td, $J$ = 11.1, 2.9 Hz, 1H), 4.55 (dtd, $J$ = 11.4, 4.2, 1.8 Hz, 1H), 3.40 (tt, $J$ = 10.6, 3.5 Hz, 1H), 2.94 (dqd, $J$ = 15.3, 11.1, 2.9 Hz, 1H), 2.50−2.38 (m, 2H), 2.11 (dtd, $J$ = 14.4, 10.9, 3.7 Hz, 1H), 2.03−1.95 (m, 1H), 1.90 (ddq, $J$ = 15.2, 5.2, 3.5 Hz, 1H); $^{19}$F NMR (282 MHz, $CDCl_3$) $\delta$ = −63.86 (s, 3F); $^{13}$C NMR (75 MHz, $CDCl_3$) $\delta$ = 125.4 (q, $J_{C-F}$ = 277.2 Hz), 74.5, 53.7 (q, $J_{C-F}$ = 2.3 Hz), 32.5 (q, $J_{C-F}$ = 30.8 Hz), 28.3, 23.2; IR (neat, cm$^{-1}$) 2987, 1439, 1353, 1327, 1252, 1223, 1170, 1133, 1062, 1014, 939, 872, 794, 738; HRMS (ESI) exact mass calcd for $C_6H_{13}F_3NO_3S$ $m/z$ 236.0563, found $m/z$ 236.0565 $[M + NH_4]^+$; GC analysis, purity 95%, $t_R$ = 7.103 min, wt($H_2O$) = 134 ppm.

*3-(2,2,2-Trifluoroethyl)-1,2-oxathiepane 2,2-dioxide* ***4d***. Following GP-A, **4d** was prepared using hex-5-en-1-ol **3d** (120 μL, 1.0 mmol, 1.0 equiv), $[Cu(dap)_2]Cl$ (8.8 mg, 1.0 μmol, 1.0 mol %), $K_2HPO_4$ (352 mg, 2.0 mmol, 2.0 equiv), and $CF_3SO_2Cl$ (210 μL, 2.0 mmol, 2.0 equiv) in anhydrous MeCN (3 mL). The reaction solution was filtered through a silica plug with $CH_2Cl_2$ as the eluent. The filtrate was concentrated under reduced pressure to afford **3d** as a colorless oil (74 mg, 32%); $R_f$ = not determinable; staining = not determinable (UV inactive); $^1$H NMR (300 MHz, $CDCl_3$) $\delta$ = 4.45−4.23 (m, 2H), 3.50−3.39 (m, 1H), 3.06−2.87 (m, 1H), 2.52−2.31 (m, 1H), 2.30−2.18 (m, 1H), 2.16−2.05 (m, 2H), 2.05−1.92 (m, 1H), 1.86−1.66 (m, 2H); $^{19}$F NMR (282 MHz, $CDCl_3$) $\delta$ = −63.89 (s, 3F); $^{13}$C NMR (75 MHz, $CDCl_3$) $\delta$ = 125.7 (q, $J_{C-F}$ = 277.4 Hz), 71.1, 57.7 (q, $J_{C-F}$ = 2.2 Hz), 34.1 (q, $J_{C-F}$ = 30.2 Hz), 28.9, 28.5, 22.8; IR (neat, cm$^{-1}$) 2961, 2923, 2853, 1458, 1357, 1261, 1133, 1096, 1022, 800, 633; HRMS (APCI) exact mass calcd for $C_7H_{11}F_3O_3S$ $m/z$ 233.0454, found $m/z$ 233.0450 $[M + H]^+$.

*6,6-Dimethyl-3-(2,2,2-trifluoroethyl)-1,2-oxathiane 2,2-dioxide* ***4e***. Following GP-A, **4e** was prepared using 2-methylhex-5-en-2-ol **3e** (115 mg, 1.0 mmol, 1.0 equiv), $[Cu(dap)_2]Cl$ (8.8 mg, 1.0 μmol, 1.0 mol %), $K_2HPO_4$ (352 mg, 2.0 mmol, 2.0 equiv), and $CF_3SO_2Cl$ (210 μL, 2.0 mmol, 2.0 equiv) in anhydrous MeCN (3 mL). The reaction solution was filtered through a silica plug with $CH_2Cl_2$ as the eluent. The filtrate was concentrated under reduced pressure to afford **4e** as a yellowish solid (179 mg, 73%): $R_f$ = not determinable; staining = not determinable (UV inactive); $^1$H NMR (600 MHz, $CDCl_3$) $\delta$ = 3.27 (tt, $J$ = 10.7, 3.4 Hz, 1H), 2.97−2.89 (m, 1H), 2.40 (ddt, $J$ = 15.2, 12.6, 10.0 Hz, 2H), 2.26−2.19 (m, 1H), 1.94 (ddd, $J$ = 15.2, 11.8, 3.6 Hz, 1H), 1.87 (ddd, $J$ = 14.7, 5.5, 3.4 Hz, 1H), 1.63 (s, 3H), 1.53 (s, 3H); $^{19}$F NMR (376 MHz, $CDCl_3$) $\delta$ = −63.59 (s, 3F); $^{13}$C NMR (101 MHz, $CDCl_3$) $\delta$ = 125.6 (q, $J_{C-F}$ = 277.3 Hz), 93.2, 52.6 (q, $J_{C-F}$ = 2.3 Hz), 35.1, 32.6 (q, $J_{C-F}$ = 30.4 Hz), 30.4, 25.4, 25.1 (dd, $J_{C-F}$ = 2.5, 1.1 Hz); IR (neat, cm$^{-1}$) 2994, 2955, 1446, 1396, 1342, 1291, 1243, 1174, 1132, 1097, 1078, 1032, 875, 848, 778, 696, 545; HRMS (ESI) exact mass calcd for $C_8H_{14}F_3O_3S$ $m/z$ 247.0610, found $m/z$ 247.0611 $[M + H]^+$; mp 68−71 °C.

*5,5-Diphenyl-3-(2,2,2-trifluoroethyl)-1,2-oxathiane 2,2-dioxide* ***4f***. Following GP-A, **4f** was prepared using 2,2-diphenylpent-4-en-1-ol **3f** (238 mg, 1.0 mmol, 1.0 equiv), $[Cu(dap)_2]Cl$ (8.8 mg, 1.0 μmol, 1.0 mol %), $K_2HPO_4$ (352 mg, 2.0 mmol, 2.0 equiv), and $CF_3SO_2Cl$ (210 μL, 2.0 mmol, 2.0 equiv) in anhydrous MeCN (3 mL). Chromatography on silica gel (pentane/$CH_2Cl_2$, 2:1) afforded **4f** as a white solid (269 mg, 73%): $R_f$ (pentane/$CH_2Cl_2$, 3:1) = 0.25; staining = PMA (UV active); $^1$H NMR (600 MHz, $CDCl_3$) $\delta$ = 7.45−7.24 (m, 8H), 7.13−7.07 (m, 2H), 5.04 (dd, $J$ = 12.3, 2.7 Hz, 1H), 4.79 (d, $J$ = 12.4 Hz, 1H), 3.22 (tdd, $J$ = 10.5, 4.8, 2.8 Hz, 1H), 3.12−3.02 (m, 2H), 2.87 (dqd, $J$ = 15.2, 10.9, 2.8 Hz, 1H), 2.51−2.42 (m, 1H); $^{19}$F NMR (376 MHz, $CDCl_3$) $\delta$ = −63.22 (s, 3F); $^{13}$C NMR (101 MHz, $CDCl_3$) $\delta$ = 141.4, 140.3, 129.4, 129.1, 128.0, 127.9, 127.6, 127.1, 125.4 (d, $J_{C-F}$ = 277.5 Hz), 78.4, 50.9 (q, $J_{C-F}$ = 2.6 Hz), 32.4 (q, $J_{C-F}$= 30.5 Hz); IR (neat, cm$^{-1}$) 3064, 3030, 2960, 2874, 1739, 1603, 1495, 1448, 1361, 1316, 1260, 1174, 1141, 1014, 954, 928; HRMS (ESI) exact mass calcd for $C_{18}H_{17}F_3O_3S$ $m/z$ 370.0845, found $m/z$ 370.0847 $[M]^+$; mp 187−193 °C.

*Diethyl 3-(2,2,2-Trifluoroethyl)-1,2-oxathiane-5,5-dicarboxylate 2,2-dioxide* ***4g***. Following GP-A, **4g** was prepared using diethyl 2-allyl-2-(hydroxymethyl)malonate **3g** (230 mg, 1.0 mmol, 1.0 equiv), $[Cu(dap)_2]Cl$ (8.8 mg, 1.0 μmol, 1.0 mol %), $K_2HPO_4$ (352 mg, 2.0 mmol, 2.0 equiv), and $CF_3SO_2Cl$ (210 μL, 2.0 mmol, 2.0 equiv) in anhydrous MeCN (3 mL). Chromatography on silica gel (pentane/$CH_2Cl_2$, 5:1) afforded **4g** as a colorless oil (181 mg, 50%): $R_f$ (pentane/$CH_2Cl_2$, 5:1) = 0.42; staining = $KMnO_4$ (UV inactive); $^1$H NMR (600 MHz, $CDCl_3$) $\delta$ = 5.01−4.88 (m, 2H), 4.40−4.20 (m, 4H), 3.84−3.75 (m, 1H), 3.20−2.88 (m, 2H), 2.43−2.22 (m, 2H), 1.34−1.25 (m, 6H); $^{19}$F NMR (282 MHz, $CDCl_3$) $\delta$ = −63.57 (s, 3F); $^{13}$C NMR (75 MHz, $CDCl_3$) $\delta$ = 166.9, 166.3, 125.2 (q, $J_{C-F}$ = 277.7 Hz), 74.5, 63.2, 63.1, 57.1, 50.7 (q, $J_{C-F}$ = 2.2 Hz), 39.9, 34.1, 32.7 (q, $J_{C-F}$ = 31.0 Hz), 14.0; IR (neat, cm$^{-1}$) 2989, 1733, 1439, 1368, 1320, 1252, 1178, 1141, 1014, 965, 846, 801, 742, 697; HRMS (ESI) exact mass calcd for $C_{12}H_{18}F_3O_7S$ $m/z$ 363.0720, found $m/z$ 363.0721 $[M + H]^+$; GC analysis, purity 88%, $t_R$ = 11.933 min.

*4-(2,2,2-Trifluoroethyl)-2-oxa-3-thiaspiro[5.5]undecane 3,3-Dioxide* ***4h***. Following GP-A, **4h** was prepared using (1-allylcyclohexyl)-methanol **3h** (154 mg, 1.0 mmol, 1.0 equiv), $[Cu(dap)_2]Cl$ (8.8 mg, 1.0 μmol, 1.0 mol %), $K_2HPO_4$ (352 mg, 2.0 mmol, 2.0 equiv), and $CF_3SO_2Cl$ (210 μL, 2.0 mmol, 2.0 equiv) in anhydrous MeCN (3 mL). Chromatography on silica gel (pentane/$CH_2Cl_2$, 1:1) afforded **4h** as a yellowish oil (213 mg, 74%): $R_f$ (pentane/$CH_2Cl_2$, 2:1) = 0.40; staining = PMA (UV inactive); $^1$H NMR (600 MHz, $CDCl_3$) $\delta$ = 4.35 (d, $J$ = 11.4 Hz, 1H), 3.47 (ddt, $J$ = 13.4, 10.3, 3.5 Hz, 1H), 2.90 (dqd, $J$ = 15.3, 11.0, 2.9 Hz, 1H), 2.42−2.24 (m, 2H), 1.86−1.31 (m, 12H); $^{19}$F NMR (376 MHz, $CDCl_3$) $\delta$ = −64.00 (s, 3F); $^{13}$C NMR (101 MHz, $CDCl_3$) $\delta$ = 125.5 (q, $J_{C-F}$ = 277.4 Hz), 80.7, 49.7 (q, $J_{C-F}$ = 2.7 Hz), 39.4, 34.2, 33.9, 32.9 (q, $J_{C-F}$ = 30.4 Hz), 30.5, 26.0, 21.4, 20.9; IR (neat, cm$^{-1}$) 2933, 2863, 1454, 1361, 1320, 1267, 1170, 1003, 954, 910, 846, 805, 731; HRMS (ESI) exact mass calcd for $C_{11}H_{18}F_3O_3S$ $m/z$ 287.0923, found $m/z$ 287.0928 $[M + H]^+$; GC analysis, purity 88%, $t_R$ = 11.433 min.

*rel-(4aR,8aS)-3-(2,2,2-Trifluoroethyl)octahydrobenzo[e][1,2]-oxathiine 2,2-Dioxide* ***4i***. Following GP-A, **4i** was prepared using *rel*-(1*S*,2*R*)-2-allylcyclohexan-1-ol **3i** (140 mg, 1.0 mmol, 1.0 equiv), $[Cu(dap)_2]Cl$ (8.8 mg, 1.0 μmol, 1.0 mol %), $K_2HPO_4$ (352 mg, 2.0 mmol, 2.0 equiv), and $CF_3SO_2Cl$ (210 μL, 2.0 mmol, 2.0 equiv) in anhydrous MeCN (3 mL). The reaction solution was filtered through a silica plug with $CH_2Cl_2$ as the eluent. The filtrate was concentrated under reduced pressure to afford **4i** as a mixture of diastereomers as a yellowish oil (245 mg, *syn*/*anti* = 44:56, 90% overall yield): $R_f$ = not determinable; staining = not determinable (UV inactive); $^1$H NMR (600 MHz, $CDCl_3$) $\delta$ = 4.38−4.29 (m, 2H), 3.53−3.48 (m, 1H), 3.38 (ddt, $J$ = 12.3, 7.0, 3.3 Hz, 1H), 2.91−2.87 (m, 1H), 2.62 (dd, $J$ = 10.2, 5.1 Hz, 1H), 2.36−2.31 (m, 1H), 2.26−2.18 (m, 2H), 2.06 (ddt, $J$ = 16.4, 8.3, 3.6 Hz, 3H), 1.84 (q, $J$ = 3.2 Hz, 2H), 1.81−1.66 (m, 8H), 1.56−1.48 (m, 2H), 1.30−1.22 (m, 4H), 1.14−1.04 (m, 2H); $^{19}$F NMR (376 MHz, $CDCl_3$) $\delta$ = −63.53 (s, 3F, minor), −64.42 (s, 3F, major); $^{13}$C NMR (101 MHz, $CDCl_3$) $\delta$ = 125.6 (q, $J_{C-F}$ = 277.3 Hz), 125.5 (q, $J_{C-F}$ = 277.4 Hz), 89.2, 89.0, 54.2 (q, $J_{C-F}$ = 2.5 Hz), 52.0 (q, $J_{C-F}$ = 2.4 Hz), 40.7, 35.4, 34.7, 32.4, 32.8 (q, $J_{C-F}$ = 30.5 Hz), 32.0 (q, $J_{C-F}$ = 30.0 Hz), 31.6, 31.5, 30.2, 30.0, 24.9, 24.7, 24.0, 23.9; IR (neat, cm$^{-1}$) 2941, 2866, 1454, 1357, 1256, 1137, 977, 910, 883, 831, 753, 667; HRMS (APCI) exact mass calcd for $C_{10}H_{19}F_3NO_3S$ $m/z$ 290.1032, found $m/z$ 290.1036 $[M + NH_4]^+$; GC analysis, purity 90%, $t_R$ = 10.853 min (two diastereomers).

*3-(2,2,2-Trifluoroethyl)-3,4-dihydrobenzo[e][1,2]oxathiine 2,2-Dioxide* ***4j***. Following GP-A, **4j** was prepared using 2-allylphenol **3j** (134 mg, 1.0 mmol, 1.0 equiv), $[Cu(dap)_2]Cl$ (8.8 mg, 1.0 μmol, 1.0 mol %), $K_2HPO_4$ (352 mg, 2.0 mmol, 2.0 equiv), and $CF_3SO_2Cl$ (210 μL, 2.0 mmol, 2.0 equiv) in anhydrous MeCN (3 mL). The reaction solution was filtered through a silica plug with $CH_2Cl_2$ as the eluent. The filtrate was concentrated under reduced pressure to



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afford **4j** as a yellowish oil (178 mg, 67% yield): $R_f$ (pentane/$CH_2Cl_2$, 3:1) = 0.20; staining = PMA (UV active); $^1$H NMR (300 MHz, $CDCl_3$) $\delta$ = 7.39−7.05 (m, 4H), 3.83 (dddd, $J$ = 10.8, 8.0, 5.3, 2.6 Hz, 1H), 3.70 (dd, $J$ = 17.0, 5.4 Hz, 1H), 3.41 (dd, $J$ = 17.1, 8.3 Hz, 1H), 3.09 (dqd, $J$ = 15.1, 10.8, 2.6 Hz, 1H), 2.61−2.43 (m, 1H); $^{19}$F NMR (282 MHz, $CDCl_3$) $\delta$ = −63.81 (s, 3F); $^{13}$C NMR (75 MHz, $CDCl_3$) $\delta$ = 151.1, 129.9, 129.2, 126.2, 125.4 (q, $J_{C-F}$ = 277.3 Hz), 119.3, 118.9, 50.4 (q, $J_{C-F}$ = 2.6 Hz), 32.5 (q, $J_{C-F}$ = 28.9 Hz), 32.3; IR (neat, cm$^{-1}$) 3071, 2960, 1618, 1584, 1457, 1491, 1375, 1327, 1260, 1186, 1148, 1096, 1010, 924, 876, 816, 790, 757, 719, 670; HRMS (EI) exact mass calcd for $C_{10}H_9F_3O_3S$ $m/z$ 266.0219, found $m/z$ 266.0208 [M]$^+$; GC analysis, purity 89%, $t_R$ = 10.411 min.

*6-Phenyl-3-(2,2,2-trifluoroethyl)-1,2-oxathiane 2,2-Dioxide* ***4k***. Following GP-A, **4k** was prepared using 1-phenylpent-4-en-1-ol **3k** (150 mg, 0.9 mmol, 1.0 equiv), [Cu(dap)$_2$]Cl (8.1 mg, 1.0 $\mu$mol, 1.0 mol %), $K_2HPO_4$ (320 mg, 1.8 mmol, 2.0 equiv), and $CF_3SO_2Cl$ (195 $\mu$L, 1.8 mmol, 2.0 equiv) in anhydrous MeCN (2.5 mL). Chromatography on silica gel (hexanes/EtOAc, 5:1) afforded **4k** as a colorless liquid (181 mg, 67%): $R_f$ (hexanes/EtOAc, 7:3) = 0.4; staining = anisaldehyde (UV active); $^1$H NMR (300 MHz, $CDCl_3$) $\delta$ = 7.34 (tdd, $J$ = 9.3, 6.6, 4.3 Hz, 6H), 7.23 (td, $J$ = 7.7, 1.8 Hz, 4H), 4.90−4.74 (m, 2H), 3.56 (dddd, $J$ = 11.6, 10.3, 7.3, 4.1 Hz, 1H), 3.29−3.18 (m, 2H), 3.17−3.02 (m, 2H), 3.01−2.76 (m, 3H), 2.75−2.67 (m, 1H), 2.57−2.30 (m, 4H), 2.22−2.10 (m, 1H); $^{19}$F NMR (282 MHz, $CDCl_3$) $\delta$ = −64.93 (s, 3F), −64.97 (s, 3F); $^{13}$C NMR (75 MHz, $CDCl_3$) $\delta$ = 134.5, 134.3, 129.6, 129.4, 129.1, 129.0, 127.8, 127.7, 125.2 (q, $J_{C-F}$ = 277.2 Hz), 81.3, 79.9, 52.1 (q, $J_{C-F}$ = 2.9 Hz), 49.8 (q, $J_{C-F}$ = 2.9 Hz), 41.1, 41.1, 35.7, 33.2 (q, $J_{C-F}$ = 7.4 Hz); IR (neat, cm$^{-1}$) 3068, 3034, 2956, 1609, 1498, 1454, 1394, 1349, 1320, 1260, 1163, 1077, 1033, 992, 842, 753; HRMS (ESI) exact mass calcd for $C_{12}H_{14}F_3O_3S$ $m/z$ 294.0700, found $m/z$ 294.0611 [M + H]$^+$.

*8-Methoxy-3-(2,2,2-trifluoroethyl)-3,4-dihydrobenzo[e][1,2]-oxathiine 2,2-Dioxide* ***4m***. Following GP-A, **4m** was prepared using 2-allyl-6-methoxyphenol **3m** (492 mg, 3.0 mmol, 1.0 equiv), [Cu(dap)$_2$]Cl (26 mg, 3.0 $\mu$mol, 1.0 mol %), $K_2HPO_4$ (1.06 g, 6.0 mmol, 2.0 equiv), and $CF_3SO_2Cl$ (630 $\mu$L, 6.0 mmol, 2.0 equiv) in anhydrous MeCN (9 mL). Chromatography on silica gel (pentane/$CH_2Cl_2$, 7:1) afforded **4m** as a yellowish solid (566 mg, 64%): $R_f$ (hexanes/EtOAc, 5:1) = 0.36; staining = anisaldehyde (UV active); $^1$H NMR (300 MHz, $CDCl_3$) $\delta$ = 7.13 (t, $J$ = 8.0 Hz, 1H), 6.89 (dd, $J$ = 8.4, 1.4 Hz, 1H), 6.81−6.75 (m, 1H), 3.86 (d, $J$ = 1.5 Hz, 3H), 3.78 (ddt, $J$ = 10.6, 5.3, 2.6 Hz, 1H), 3.66 (dd, $J$ = 17.2, 5.4 Hz, 1H), 3.36 (dd, $J$ = 17.1, 8.0 Hz, 1H), 3.12−2.96 (m, 1H), 2.56−2.39 (m, 1H); $^{19}$F NMR (282 MHz, $CDCl_3$) $\delta$ = −63.84 (s, 3F); $^{13}$C NMR (75 MHz, $CDCl_3$) $\delta$ = 149.0, 140.5, 126.0, 125.4 (q, $J_{C-F}$ = 277.6 Hz), 120.8, 120.5, 111.5, 56.2, 50.3 (q, $J_{C-F}$ = 2.6 Hz), 32.6 (q, $J_{C-F}$ = 30.8 Hz), 32.4; IR (neat, cm$^{-1}$) 3019, 2982, 2948, 2844, 1618, 1588, 1480, 1372, 1323, 1279, 1204, 1144, 1111, 999, 954, 869, 801, 716, 686; HRMS (ESI) exact mass calcd for $C_{11}H_{11}F_3O_4S$ $m/z$ 296.0325, found $m/z$ 296.0319 [M]$^+$; mp 97−100 °C.

*3-(2,2,3,3,4,4,5,5,5-Nonafluoropentyl)-1,2-oxathiane 2,2-Dioxide* ***5a***. Following GP-A, **5a** was prepared using pent-4-en-1-ol **3c** (102 $\mu$L, 1.0 mmol, 1.0 equiv), [Cu(dap)$_2$]Cl (8.8 mg, 1.0 $\mu$mol, 1.0 mol %), $K_2HPO_4$ (352 mg, 2.0 mmol, 2.0 equiv), and perfluorobutanesulfonyl chloride (636 mg, 2.0 mmol, 2.0 equiv) in anhydrous MeCN (3 mL). The reaction solution was filtered through a silica plug with $CH_2Cl_2$ as the eluent. The filtrate was concentrated under reduced pressure to afford **5a** as a white solid (162 mg, 44%): $R_f$ = not determinable; staining = not determinable (UV inactive); $^1$H NMR (300 MHz, $CDCl_3$) $\delta$ = 4.70−4.49 (m, 2H), 3.52 (tdd, $J$ = 10.3, 3.9, 2.7 Hz, 1H), 3.01−2.79 (m, 1H), 2.54−2.26 (m, 2H), 2.22−2.11 (m, 1H), 2.11−1.96 (m, 1H), 1.91 (dtt, $J$ = 11.2, 5.4, 3.0 Hz, 1H); $^{19}$F NMR (282 MHz, $CDCl_3$) $\delta$ = −81.56 (td, $J$ = 9.6, 4.9 Hz, 3F), −109.36 to −117.15 (m, 2F), 124.74 (tq, $J$ = 9.5, 4.7, 4.2 Hz, 2F), −126.42 (dtd, $J$ = 24.7, 13.1, 12.1, 4.5 Hz, 2F); $^{13}$C NMR (75 MHz, $CDCl_3$) $\delta$ = 74.6, 53.0 (d, $J_{C-F}$ = 3.9 Hz), 29.4 (t, $J_{C-F}$ = 21.9 Hz), 29.1 (d, $J_{C-F}$ = 3.7 Hz), 23.5; IR (neat, cm$^{-1}$) 3088, 3031, 2996, 2962, 1600, 1584, 1497, 1448, 1376, 1337, 1227, 1193, 1172, 1133, 1111, 1081, 971, 931, 802, 738, 696, 513; HRMS (ESI) exact mass calcd for $C_9H_{10}F_9O_3S$ $m/z$ 369.0201, found $m/z$ 369.0200 [M + H]$^+$; mp 66−68 °C.

*3-(2,2,3,3,4,4,5,5,5-Nonafluoropentyl)-5,5-diphenyl-1,2-oxathiane 2,2-Dioxide* ***5b***. Following GP-A, **5b** was prepared using 2,2-diphenylpent-4-en-1-ol **3f** (238 mg, 1.0 mmol, 1.0 equiv), [Cu(dap)$_2$]Cl (8.8 mg, 1.0 $\mu$mol, 1.0 mol %), $K_2HPO_4$ (352 mg, 2.0 mmol, 2.0 equiv), and perfluorobutanesulfonyl chloride (636 mg, 2.0 mmol, 2.0 equiv) in anhydrous MeCN (3 mL). Chromatography on silica gel (pentane/$CH_2Cl_2$, 2:1) afforded **5b** as a white solid (218 mg, 41%): $R_f$ (pentane/$CH_2Cl_2$, 3:1) = 0.29; staining = PMA (UV active); $^1$H NMR (600 MHz, $CDCl_3$) $\delta$ = 7.47−7.24 (m, 8H), 7.15−7.06 (m, 2H), 5.06 (dd, $J$ = 12.4, 2.8 Hz, 1H), 4.82 (d, $J$ = 12.4 Hz, 1H), 3.34 (tdd, $J$ = 10.3, 4.8, 2.5 Hz, 1H), 3.17−3.05 (m, 2H), 2.86 (dddd, $J$ = 33.1, 16.9, 6.4, 2.4 Hz, 1H), 2.49−2.38 (m, 1H); $^{19}$F NMR (282 MHz, $CDCl_3$) $\delta$ = −81.50 (td, $J$ = 9.7, 4.8 Hz, 3F), 105.42−118.36 (m, 2F), −124.69 (dt, $J$ = 11.4, 4.4 Hz, 2F), −126.41 (ddd, $J$ = 26.1, 16.5, 11.8 Hz, 2F); $^{13}$C NMR (75 MHz, $CDCl_3$) $\delta$ = 141.4, 140.2, 129.4, 129.1, 128.0, 127.9, 127.6, 127.0, 78.4, 50.1 (d, $J_{C-F}$ = 3.7 Hz), 47.7, 40.3 (d, $J_{C-F}$ = 3.6 Hz), 29.2 (t, $J_{C-F}$ = 21.6 Hz); IR (neat, cm$^{-1}$) 2951, 2931, 2868, 2332, 2164, 2053, 1435, 1385, 1350, 1292, 1276, 1221, 1188, 1166, 1131, 1072, 1040, 1023, 1008, 931, 877, 855, 808, 786, 741, 696, 513; HRMS (ESI) exact mass calcd for $C_{21}H_{18}F_9O_3S$ $m/z$ 521.0827, found $m/z$ 521.0825 [M + H]$^+$; mp 111−115 °C.

*8-Hydroxy-3-(2,2,2-trifluoroethyl)-3,4-dihydrobenzo[e][1,2]-oxathiine 2,2-Dioxide* ***8***. A mixture of 8-methoxy-3-(2,2,2-trifluoroethyl)-3,4-dihydrobenzo[*e*][1,2]oxathiine 2,2-dioxide **4m** (500 mg, 1.7 mmol, 1.0 equiv) and hydrobromic acid (30 mL, 47 wt %) was heated at 140 °C for 3 h. After completion of the reaction as monitored by TLC, the mixture was cooled to room temperature and extracted with $Et_2O$ (3 × 30 mL). The combined organic layers were washed with once with brine (1 × 50 mL), dried over anhydrous $Na_2SO_4$, and concentrated under reduced pressure. The residue was recrystallized from pentane/$CH_2Cl_2$ (1:1) to obtain product **8** as a white solid (470 mg, 99%): $R_f$ (hexanes/EtOAc, 5:1) = 0.32; staining = anisaldehyde (UV active); $^1$H NMR (300 MHz, $CDCl_3$) $\delta$ = 7.10 (t, $J$ = 7.9 Hz, 1H), 6.96 (dd, $J$ = 8.2, 1.5 Hz, 1H), 6.76 (dt, $J$ = 7.8, 1.2 Hz, 1H), 5.43 (s, 1H), 3.85 (dddd, $J$ = 10.7, 8.0, 5.2, 2.6 Hz, 1H), 3.68 (dd, $J$ = 17.0, 5.2 Hz, 1H), 3.40 (dd, $J$ = 17.2, 8.1 Hz, 1H), 3.13−2.99 (m, 1H), 2.52 (ddt, $J$ = 15.1, 10.7, 9.6 Hz, 1H); $^{19}$F NMR (282 MHz, $CDCl_3$) $\delta$ = −63.80 (s, 3F); $^{13}$C NMR (75 MHz, $CDCl_3$) $\delta$ = 145.1, 139.2, 126.5, 125.3 (q, $J_{C-F}$ = 277.3 Hz), 120.7, 119.9, 116.1, 51.0 (q, $J_{C-F}$ = 2.3 Hz), 32.6 (q, $J_{C-F}$ = 31.0 Hz), 32.4; IR (neat, cm$^{-1}$) 3452, 2922, 2851, 2117, 1946, 1737, 1633, 1592, 1502, 1476, 1394, 1361, 1320, 1267, 1118, 1006, 939, 895, 790, 682; HRMS (EI) exact mass calcd for $C_{10}H_9F_3O_4S$ $m/z$ 282.0168, found $m/z$ 282.0166 [M]$^+$; mp 112−114 °C.

*8-(Oxiran-2-ylmethoxy)-3-(2,2,2-trifluoroethyl)-3,4-dihydrobenzo[e][1,2]oxathiine 2,2-Dioxide* ***9***. To a solution of **8** (400 mg, 1.4 mmol, 1.0 equiv) and epichlorohydrin (2 mL, 25.5 mmol, 18.2 equiv) in acetone (20 mL) was added $K_2CO_3$ (433 mg, 3.1 mmol, 2.2 equiv), and the mixture was heated at reflux for 2 days. Afterward, the solvent was removed in vacuo and the residue extracted with $CHCl_3$ (3 × 50 mL). The combined organic layers were washed with water (1 × 50 mL) followed by brine (1 × 50 mL), dried over anhydrous $Na_2SO_4$, and concentrated under reduced pressure. The residue was purified by chromatography on silica gel ($CH_2Cl_2$) to afford **9** as a white solid (312 mg, 65%) in a diastereomeric mixture of *syn*/*anti* = 50:50: $R_f$ ($CH_2Cl_2$) = 0.43; staining = $KMnO_4$ (UV active); $^1$H NMR (400 MHz, $CDCl_3$) $\delta$ = 7.12 (t, $J$ = 8.0 Hz, 1H), 6.94 (dd, $J$ = 8.3, 1.3 Hz, 1H), 6.81 (dd, $J$ = 7.8, 1.2 Hz, 1H), 4.28 (dt, $J$ = 11.3, 2.7 Hz, 1H), 4.02 (ddd, $J$ = 11.3, 5.5, 2.2 Hz, 1H), 3.79 (dddt, $J$ = 10.4, 7.8, 5.0, 2.4 Hz, 1H), 3.66 (dd, $J$ = 17.0, 5.4 Hz, 1H), 3.47−3.31 (m, 2H), 3.06 (dqd, $J$ = 15.2, 10.8, 2.6 Hz, 1H), 2.91 (t, $J$ = 4.5 Hz, 1H), 2.77 (ddd, $J$ = 4.9, 2.7, 0.9 Hz, 1H), 2.59−2.38 (m, 1H); $^{19}$F NMR (376 MHz, $CDCl_3$) $\delta$ = −63.84 (s, 3F), −63.85 (s, 3F); $^{13}$C NMR (101 MHz, $CDCl_3$) $\delta$ = 148.1, 148.1, 141.1, 126.1, 125.4 (q, $J_{C-F}$ = 277.5 Hz), 121.7, 121.7, 120.8, 120.8, 113.7, 113.7, 70.4, 70.3, 50.4 (ddd, $J_{C-F}$ = 5.4, 2.6, 1.5



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Hz), 50.3 (ddd, $J_{C-F}$ = 5.8, 2.6, 1.3 Hz), 50.1, 44.8, 44.8, 32.6 (q, $J_{C-F}$ = 28.0 Hz), 32.2 (q, $J_{C-F}$ = 28.0 Hz), 32.5, 32.5; IR (neat, $cm^{-1}$) 3097, 3004, 2933, 1621, 1588, 1480, 1372, 1327, 1267, 1193, 1152, 1118, 1010, 939, 887, 790, 719; HRMS (ESI) exact mass calcd for $C_{13}H_{17}F_3NO_5S$ $m/z$ 356.0774, found $m/z$ 356.0777 $[M + NH_4]^+$; mp 80−81 °C.

*8-(3-(tert-Butylamino)-2-hydroxypropoxy)-3-(2,2,2-trifluoroethyl)-3,4-dihydrobenzo[e][1,2]oxathiine 2,2-Dioxide* **10**. To a solution of **9** (200 mg, 0.6 mmol, 1.0 equiv) in anhydrous MeOH (40 mL) was added freshly distilled *tert*-butylamine (0.8 mL, 7.7 mmol, 12.9 equiv), and the mixture was heated at reflux for 2 h. Afterward, the solvent and the amine were removed in vacuo. The residue was purified by chromatography on silica gel ($CH_2Cl_2$) followed by recrystallization from pentane/$CH_2Cl_2$ (1:1) to obtain product **10** as a white solid (202 mg, 49%) in a diastereomeric mixture of *syn*/*anti* = 50:50: $R_f$ ($CH_2Cl_2$) = 0.13; staining = $KMnO_4$ (UV active); $^1$H NMR (600 MHz, $CDCl_3$) $\delta$ = 7.10 (t, $J$ = 7.9 Hz, 1H), 6.92 (d, $J$ = 8.0 Hz, 1H), 6.79 (d, $J$ = 7.7 Hz, 1H), 4.27 (dt, $J$ = 7.4, 3.4 Hz, 1H), 4.19 (td, $J$ = 9.0, 8.5, 4.4 Hz, 1H), 4.09−4.02 (m, 2H), 3.77 (dtd, $J$ = 10.7, 7.9, 5.1 Hz, 2H), 3.63 (dd, $J$ = 17.0, 5.4 Hz, 1H), 3.37−3.33 (m, 1H), 3.10 (dt, $J$ = 12.2, 3.3 Hz, 1H), 3.05−2.97 (m, 1H), 2.47 (ddd, $J$ = 24.9, 19.5, 9.6 Hz, 2H), 1.28 (s, 9H); $^{19}$F NMR (376 MHz, $CDCl_3$) $\delta$ = −63.82 (s, 3F), 63.84 (s, 3F); $^{13}$C NMR (151 MHz, $CDCl_3$) $\delta$ = 148.0, 140.8, 140.7, 126.0, 125.2 (q, $J_{C-F}$ = 277.4 Hz), 121.4, 121.3, 120.6, 120.6, 113.4, 113.4, 73.9, 73.8, 71.8, 71.7, 50.4−50.2 (m), 44.7, 44.7, 32.5 (q, $J_{C-F}$ = 30.9 Hz), 32.4, 27.2, 25.7; IR (neat, $cm^{-1}$) 3327, 2971, 2937, 2873, 2618, 1742, 1618, 1585, 1477, 1379, 1322, 1271, 1236, 1192, 1155, 1119, 1039, 1009, 945, 886, 841, 784, 769, 732, 664, 623, 581, 548; HRMS (ESI) exact mass calcd for $C_{17}H_{24}F_3NO_5S$ $m/z$ 412.1400, found $m/z$ 412.1404 $[M + H]^+$; mp 88−89 °C.

*3-(2,2,2-Trifluoroethyl)-1,2-oxathiane 2,2-Dioxide* **15**. Following GP-A, **15** was prepared using 5-methoxypent-1-ene **14** (100 mg, 1.0 mmol, 1.0 equiv), $[Cu(dap)_2]Cl$ (8.8 mg, 1.0 μmol, 1.0 mol %), $K_2HPO_4$ (352 mg, 2.0 mmol, 2.0 equiv), and $CF_3SO_2Cl$ (210 μL, 2.0 mmol, 2.0 equiv) in anhydrous MeCN (3 mL). Chromatography on silica gel (pentane/$Et_2O$, 5:1) afforded **15** as a colorless oil (150 mg, 56%): $R_f$ (pentane/$Et_2O$, 5:1) = 0.45; staining = $KMnO_4$ (UV inactive); $^1$H NMR (300 MHz, $CDCl_3$) $\delta$ = 3.93 (dtd, $J$ = 8.7, 5.8, 2.7 Hz, 1H), 3.44 (td, $J$ = 5.9, 2.2 Hz, 2H), 3.33 (s, 3H), 3.07 (dqd, $J$ = 15.5, 10.5, 2.7 Hz, 1H), 2.67−2.48 (m, 1H), 2.31 (dq, $J$ = 14.4, 7.2 Hz, 1H), 2.12 (dtd, $J$ = 15.1, 7.2, 6.7, 5.1 Hz, 1H), 1.91−1.81 (m, 2H); $^{19}$F NMR (282 MHz, $CDCl_3$) $\delta$ = −64.22 (s, 3F); $^{13}$C NMR (75 MHz, $CDCl_3$) $\delta$ = 125.0 (q, $J_{C-F}$ = 277.2 Hz), 71.7, 69.7 (q, $J_{C-F}$ = 2.3 Hz), 58.8, 35.0 (q, $J_{C-F}$ = 30.9 Hz), 28.1, 26.2; IR (neat, $cm^{-1}$) 2933, 2881, 2837, 1439, 1372, 1320, 1260, 1156, 1118, 1070, 1029, 902, 842, 772; HRMS (CI+) exact mass calcd for $C_7H_{13}ClF_3O_3S$ $m/z$ 269.0221, found $m/z$ 269.0220 $[M + H]^+$.

## ■ ASSOCIATED CONTENT

### Ⓢ Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.joc.6b01001.

Copies of $^1$H, $^{13}$C, and $^{19}$F NMR spectra and GC−MS spectra for all compounds (PDF)

X-ray crystallographic data for sultone **4f** (CIF)

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### Notes

The authors declare no competing financial interest.

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