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Introduction

Tellurophene has gained growing interest as a structural element of polymeric materials for organic electronics and other applications with features such as narrow band gaps, low LUMO levels, high charge carrier mobilities, the redox capability of Te, and Te–Te interactions.^{1,2} Studies of tellurophene-containing small molecules focused on their redox and photochemical reactivity,³ photoluminescence properties,⁴ and anion

recognition ability through chalcogen bonds⁵ have also emerged (Chart 1). In these studies, the synthesis and functionalization of substituted tellurophenes have been achieved using a variety of methods, such as the cyclization of 1,3-diyne with sodium telluride⁶ and zirconacyclopentadiene transfer to $\text{TeCl}_2 \cdot \text{bpy}$.^{2c,7}

In contrast to the extensive studies on tellurophenes, benzo-fused tellurophenes and other tellurium-bridged aromatic systems, unlike their sulfur and selenium congeners,⁸ have been much less explored.^{4b,9} Indeed, there remains a scarcity of synthetic methods for making such tellurium compounds,¹⁰ as the C–S and C–Se bond-forming methods can not always be extended to C–Te bond formation.¹¹ Sashida developed a benzo[b]tellurophene synthetic route *via* the trapping of *ortho*-alkynylaryllithium with elemental tellurium and subsequent intramolecular cyclization (Scheme 1a).¹² Rivard extended the zirconacycle transfer method to achieve benzo[b]tellurophene synthesis *via* a zirconaindene intermediate (Scheme 1b).^{4b} However, these methods may not be suitable for the rapid preparation of diversely functionalized benzotellurophenes. Likewise, synthetic methods for making other tellurium-bridged (hetero)aromatic systems remain scarce.^{9a,13}

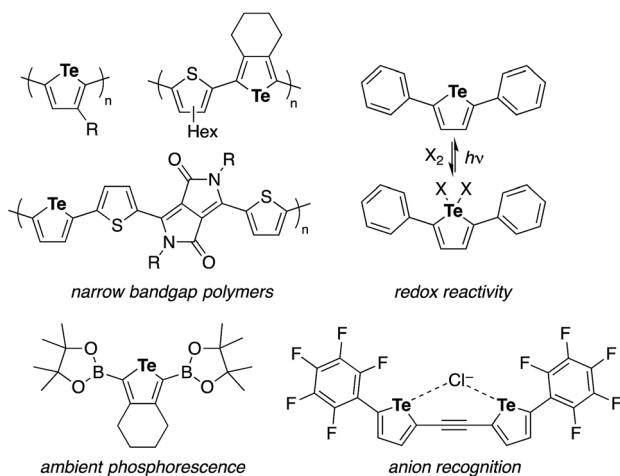
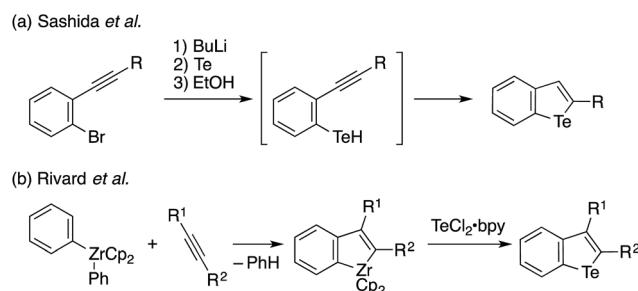


Chart 1 Examples of tellurophene-based polymers and small molecules.

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† Electronic supplementary information (ESI) available. CCDC 1523262–1523264. For ESI and crystallographic data in CIF or other electronic format see DOI: [10.1039/c7sc01162h](https://doi.org/10.1039/c7sc01162h)



Scheme 1 Reported synthetic approaches for benzotellurophenes.

Recently, we developed methods for the synthesis of benzo-thiophenes and benzoselenophenes based on the cobalt-catalyzed addition of an arylzinc reagent to an alkyne involving 1,4-cobalt migration (migratory arylzincation), which affords an *ortho*-alkenylarylzinc species as a key intermediate (Scheme 2a).^{14,15} The iodination of this zinc intermediate is followed by the reaction of the resulting aryl iodide and elemental sulfur or selenium under copper-catalyzed Ullmann-type conditions, allowing for the two-step synthesis of benzo-thiophene or benzoselenophene (route a). Only when an electron-rich arylzinc reagent is employed can the zinc intermediate be directly converted to the corresponding benzothiophene using stoichiometric CuI and elemental sulfur (route b). Our attempt to synthesise benzotellurophene using elemental tellurium *via* route a or b was futile.

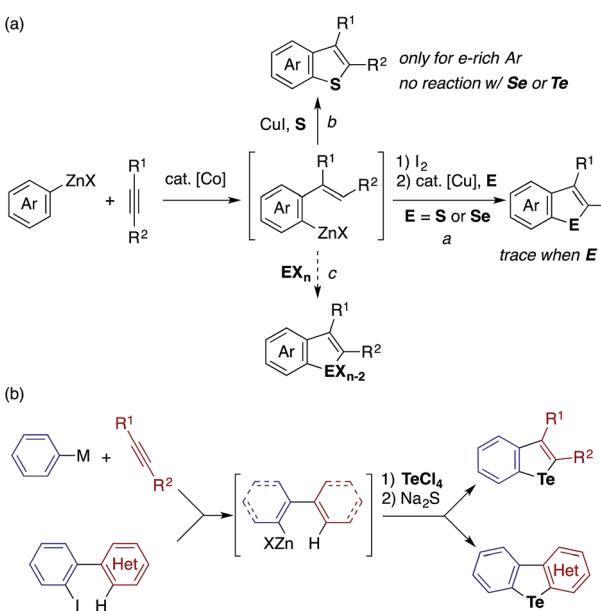
We envisioned that the above limitation in our previous benzochalcogenophene synthesis could be removed using stronger chalcogen electrophiles (EX_n), such as $TeCl_4$, $SeCl_4$, and SCl_2 , to intercept the zinc intermediate (route c). If successful, the electrophilic trapping of the zinc intermediate might be followed by intramolecular dehydrohalogenative cyclization onto the olefinic moiety to furnish benzochalcogenophene.¹⁶ Our study along this line allowed us not just to develop a modular one-pot method for benzotellurophene synthesis, but also to establish the sequential electrophilic telluration of $C(sp^2)$ -Zn and $C(sp^2)$ -H bonds as a general approach to tellurium-bridged aromatic systems (Scheme 2b). Being moderately nucleophilic, the $C(sp^2)$ -Zn bond undergoes selective monosubstitution of $TeCl_4$, which is followed by the intramolecular telluration of the proximal alkenyl or (hetero)aryl $C(sp^2)$ -H bond to form a telluracycle. A variety of functionalized benzotellurophenes can be synthesized in a one-pot manner

starting from arylzinc or aryl Grignard reagents and alkynes by way of cobalt- or nickel-catalyzed (migratory) arylmetalation.^{14,17} Furthermore, 2-heterobiarylzinc reagents that were generated from the corresponding iodides gave rise to a series of heteroarene-fused benzotellurophenes.

Results and discussion

The feasibility of the sequential telluration of $C(sp^2)$ -Zn and $C(sp^2)$ -H bonds was first demonstrated by the one-pot synthesis of benzotellurophenes from arylzinc reagents and alkynes capitalizing on the cobalt-catalyzed migratory arylzincation (Table 1).¹³ As a typical example, the reaction of a 4-methoxyphenylzinc reagent (**1a**) and 5-decyne (**2a**) in the presence of a $CoCl_2$ -Xantphos catalyst was followed by the treatment of the resulting *ortho*-alkenylarylzinc species with $TeCl_4$ at 90 °C and then with aqueous Na_2S at room temperature, affording a benzotellurophene **3aa** in 58% yield. Na_2S is considered to reduce $Te(IV)$ to $Te(II)$ in the last step.^{13b} The putative $Te(IV)$ intermediate, *i.e.*, the 1,1-dichlorobenzotellurophene derivative, was detected using mass spectrometry (ESI) analysis of the reaction mixture before the addition of Na_2S . We obtained the product **3aa** even without the addition of Na_2S , albeit in a significantly lower yield (<30% GC yield). It should be noted that the use of a $Te(II)$ electrophile, such as $TeCl_2$ -bipy instead of $TeCl_4$, resulted in an even poorer yield of **3aa** (<10% GC yield). It is also worth noting that all of the attempts using other chalcogen electrophiles such as $SeCl_4$, SCl_2 , S_2Cl_2 , $SOCl_2$, or SO_2Cl_2 in place of $TeCl_4$ failed to produce the corresponding benzochalcogenophene derivative.¹⁸

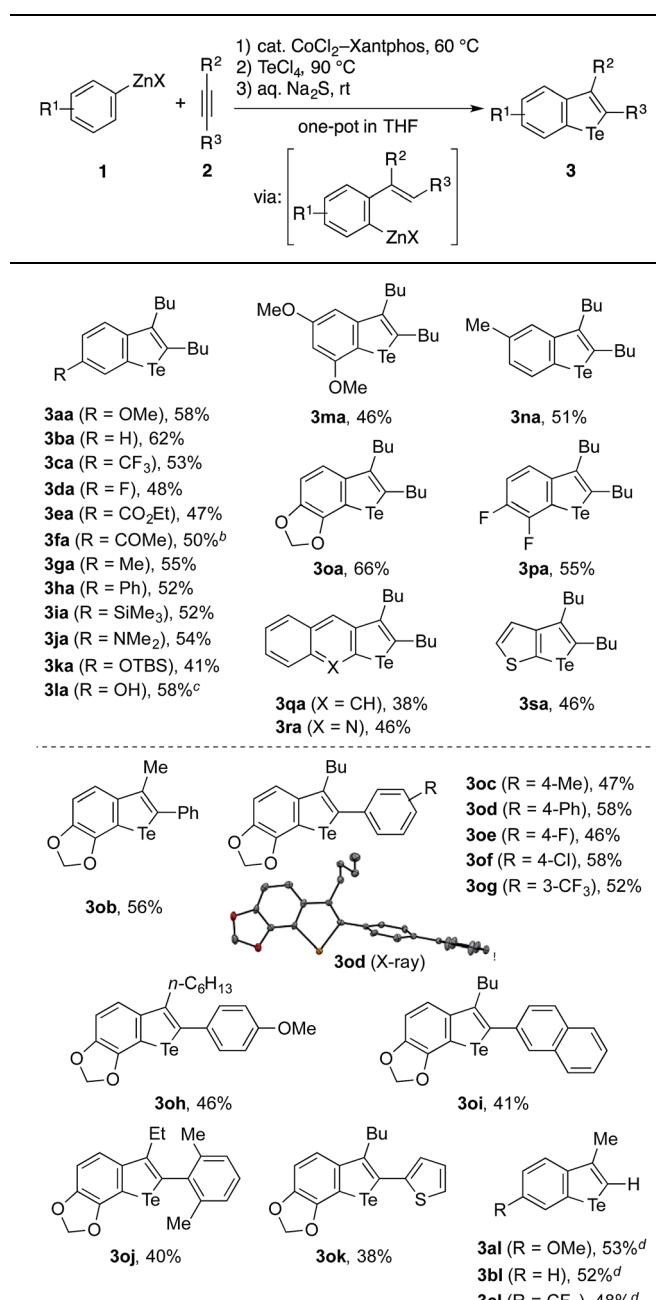
A wide variety of arylzinc reagents could be employed for the one-pot cyclization with **2a** and $TeCl_4$, affording the corresponding benzotellurophenes **3ba**-**3qa** in moderate to good yields. In particular, the method allowed for the installation of various functional groups, both electron-donating and electron-withdrawing, to the 6-position of the benzotellurophene core. The benzotellurophenes **3na**-**3qa** were obtained with exclusive regioselectivity as a result of regioselective 1,4-cobalt migration to the less hindered position (for **3na** and **3qa**) or the position proximal to the ether oxygen or the fluorine atom (for **3oa** and **3pa**).¹⁴ The reactions of 2-quinolinyl- and 3-thienylzinc reagents with **2a** allowed for the preparation of the corresponding fused tellurophenes **3ra** and **3sa** in moderate yields. Besides these 2,3-dialkylbenzotellurophenes, a series of 2-aryl-3-alkylbenzotellurophenes **3ob**-**3ok** could be synthesized in decent yields from the 3,4-methylenedioxyphenylzinc reagent and the corresponding aryl(alkyl)acetylenes. Furthermore, the use of 1-trimethylsilyl-1-propyne as the alkyne reactant resulted in a loss of the trimethylsilyl group during the cyclization process, thus furnishing 3-methylbenzotellurophenes **3al**-**3cl**. The generally moderate efficiency of the present synthesis of benzotellurophenes and other telluracycles (*vide infra*) is mainly attributed to the moderate efficiency of the electrophilic trapping of the organozinc intermediate with $TeCl_4$, which results in its protonated derivative as the major byproduct. It is worth noting that the crystal packing of the benzotellurophene **3od**



Scheme 2 Approaches to benzochalcogenophenes via cobalt-catalyzed migratory arylzincation (a) and a summary of the telluracycle synthesis developed in this study (b).



Table 1 One-pot benzotellurophene synthesis based on the Co-catalyzed migratory arylzincation of alkynes^a



^a The reaction was performed using 0.5 mmol of **2a** as the limiting agent. See the ESI for the detailed procedure. ^b The starting arylzinc reagent was protected in the form of *p*-anisidine imine. ^c The starting arylzinc reagent was protected with a Boc group, which was removed during the reaction. ^d 1-Trimethylsilyl-1-propyne was used as the alkyne.

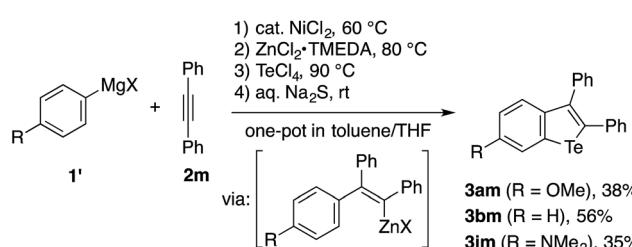
displayed a rather short Te–Te distance of 3.67 Å, indicating that there were significant Te–Te interactions.^{1,19}

Because migratory arylzincation is not applicable to a diarylalkyne due to the substantial *E/Z* isomerization of the alkynylcobalt intermediate and incomplete 1,4-cobalt migration,¹⁴ the above protocol did not allow for the synthesis of a 2,3-diarylbenzotellurophene. This gap can be filled by a modified

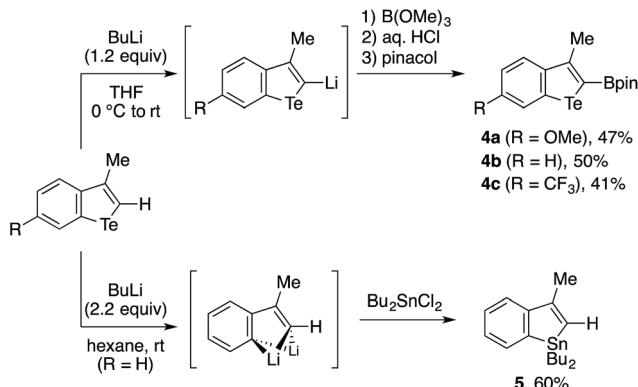
protocol employing a normal arylmetalation reaction instead of the migratory arylzincation (Scheme 3). Thus, a one-pot sequence of the nickel-catalyzed arylmagnesiation of diphenylacetylene (**2m**),^{17,20} the transmetalation of the resulting alkynylmagnesium species with ZnCl₂·TMEDA (TMEDA = *N,N,N',N'*-tetramethylethylenediamine), and treatment with TeCl₄ and aqueous Na₂S allowed for the preparation of 2,3-diphenylbenzotellurophenes **3am**, **3bm**, and **3jm** in moderate yields. It should be noted that the Mg-to-Zn transmetalation is essential for this protocol. The omission of this step resulted in only a trace amount of the desired benzotellurophene due to multiple substitution reactions on Te(IV) with the alkynylmagnesium species, as indicated from the GCMS analysis of the crude product.

The reaction chemistry of benzotellurophene and *n*-BuLi²¹ enabled the further transformations of the 3-methylbenzotellurophenes **3al**–**3cl** (Scheme 4). Thus, these benzotellurophenes were amenable to C2-lithiation using *n*-BuLi in THF, and the resulting 2-lithiobenzotellurophenes were readily transformed into 2-borylated benzotellurophenes **4a**–**4c**. Not unexpectedly, **4a**–**4c** and the other benzotellurophenes (Table 1 and Scheme 3) were not emissive in organic solvents.^{3a,4,8d} Among **4a**–**4c**, only **4c** exhibited weak luminescence at 525 nm in a THF/water mixture (1 : 9), presumably due to aggregation-induced emission.²² This luminescence was found to have a short lifetime in the order of ns (see the ESI†), and the relevance of this to the phosphorescent nature of Rivard's borylated (benzo)tellurophenes in the solid state⁴ remains to be explored. A treatment of **3bl** with excess *n*-BuLi in hexane resulted in double tellurium–lithium exchange,²¹ and subsequent trapping with Bu₂SnCl₂ furnished benzostannole **5** in 60% yield. The success of this conversion would hold promise for the use of benzotellurophenes as versatile precursors for different benzoheteroles,¹⁰ such as benzosilole²³ and benzophosphole.²⁴

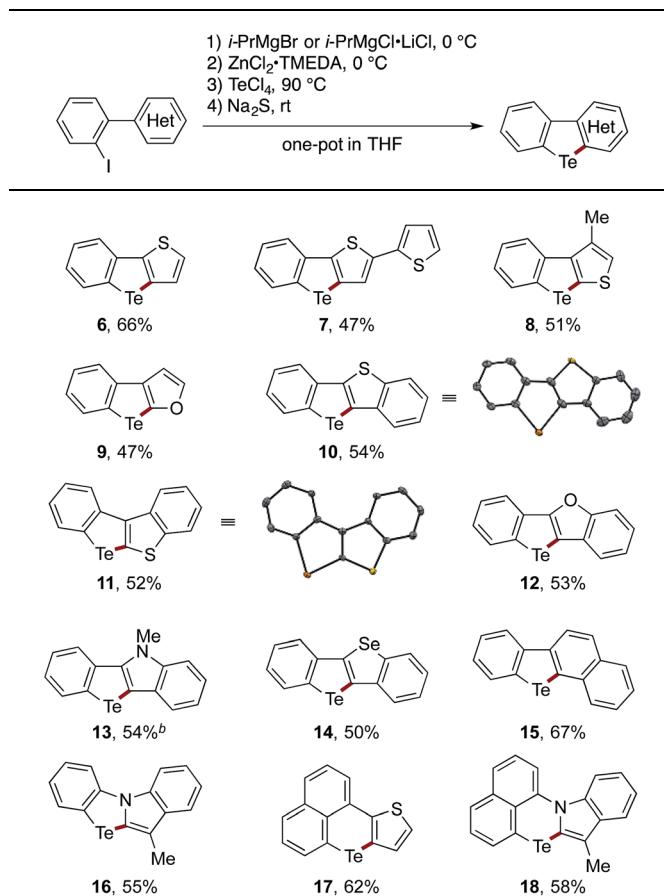
The scope of the sequential C(sp²)–Zn and C(sp²)–H telluration was further extended to the synthesis of tellurium-bridged heterobiaryls starting from 2-iodoheterobiaryls, which can be readily prepared in two steps from 2-bromoaniline and heteroarylboronic acids (Table 2). Iodine–magnesium exchange with *i*-PrMgBr or *i*-PrMgCl·LiCl was followed by Mg-to-Zn transmetalation and sequential treatment with TeCl₄ and Na₂S, thus furnishing benzotellurophenes fused with (benzo)thiophene, (benzo)furan, indole, or benzoselenophene **6**–**14** in decent yields. Again, the Mg-to-Zn transmetalation proved to be a crucial step, without which the double substitution on Te(IV)



Scheme 3 One-pot benzotellurophene synthesis based on the Ni-catalyzed arylmagnesiation of diphenylacetylene.



Scheme 4 Transformations of 3-methylbenzotellurophenes.

Table 2 Conversion of 2-iodoheterobiaryls and related compounds to tellurium-bridged heteroaromatic systems^a

^a See the ESI for the detailed procedure. ^b *n*-BuLi was used instead of *i*-PrMgBr at –78 °C.

with the arylmagnesium species took place predominantly to afford a diaryltellurium derivative. Although the present protocol failed to convert 2-iodobiphenyl to the parent dibenzotellurophene in an appreciable yield, it allowed for the conversion of 2-(2-iodophenyl)naphthalene to benzo[*b*]naphtho[2,1-*d*]tellurophene **15** *via* the regioselective telluration of the

naphthalene 1-position. Furthermore, tellurium-bridged heteroarenes **16–18**, which feature non-tellurophene-type telluracycles, could also be synthesized in reasonable yields.

The planar structures of the benzothiophene-fused derivatives **10** and **11** were confirmed using X-ray crystallographic analysis.¹⁹ While **10** adopted a so-called sandwiched herringbone-type packing structure without significant Te–Te interactions (the shortest Te–Te distance being 6.80 Å),²⁵ **11** assumed a herringbone arrangement with close Te–Te contacts (3.71 Å) between the π-stacks (Fig. 1). This sharp difference suggests the importance of the molecular framework and the peripheral structures in achieving efficient Te–Te interactions in the condensed phase, which may be relevant for the potential application of tellurium-embedded polyaromatic systems in organic electronics.

We measured the UV absorption spectra of selected Te-bridged heterobiaryls, *i.e.*, compounds **10–15** and **17**, and also calculated their HOMO/LUMO levels and transition energies using TD-DFT calculations for reference (Table 3). The compounds **10**, **12**, and **14**, which can be regarded as Te/chalcogen-bridged stilbenes, exhibited a trend of increasing λ_{max} (the longest wavelength absorption maxima) upon changing the extra chalcogen atom from O to Se. This trend is in line with the trends observed for related chalcogen-bridged π-conjugated systems,^{25,26} and is also consistent with the trend of the lowest transition energies, which are largely represented by the HOMO–LUMO (π – π^*) transition (see the ESI† for details). Compound **11**, the cross-conjugated isomer of **10**, showed a distinctly shorter λ_{max} . Unlike the other compounds, the LUMO of **11** was found to be the C–Te σ^* -orbital, with the π^* -orbital being located at the LUMO+1 level. The non-tellurophene-type compound **17**, which is another structural isomer of **10**, exhibited absorption in the visible region, that is in agreement with a much lower transition energy. It is worth noting that none of these compounds were emissive in organic solvents.

The utility of the present Te-bridging protocol was further demonstrated using a stepwise synthesis of a bis-tellurium-bridged ladder molecule **22** (Scheme 5). The thiophene-fused benzotellurophene **6** was subjected sequentially to bromination, Suzuki–Miyaara coupling with a 2-aminophenylboron reagent, and diazotization–iodination to afford a new 2-iodoheterobiaryl **21**. With **21** in hand, the second tellurium bridge

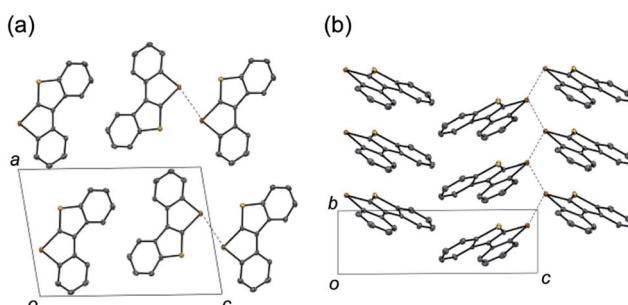
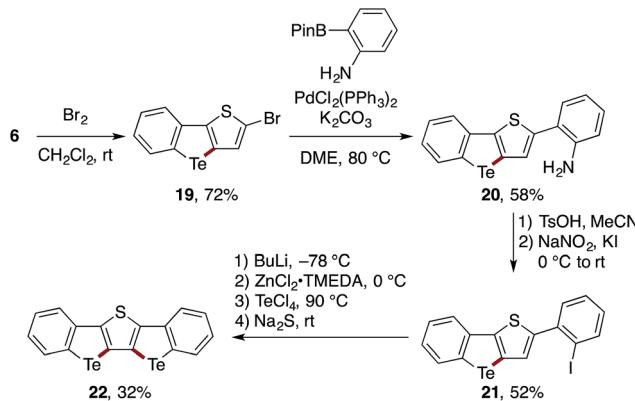
Fig. 1 Packing structures of **11** in the (a) ac-plane and (b) bc-plane. The dotted lines indicate the Te–Te contacts (3.71 Å).

Table 3 UV absorption data and the calculated HOMO/LUMO levels of Te-bridged heterobiaryls

Cmpd	λ_{max}^a (nm)	ϵ^a ($10^4 \text{ M}^{-1} \text{ cm}^{-1}$)	E_{HOMO}^b (eV)	E_{LUMO}^b (eV)	$\Delta E (f)^c$ (eV)
10	348	0.51	-5.67	-1.55	3.65 (0.0992)
11	321	0.73	-5.71	-1.49	4.08 (0.1116)
12	334	0.85	-5.66	-1.45	3.79 (0.1493)
13	348	0.68	-5.23	-1.21	3.56 (0.1878)
14	356	0.61	-5.66	-1.60	3.58 (0.0902)
15	363	0.25	-5.64	-1.54	3.58 (0.0575)
17	425	0.31	-5.10	-1.71	2.98 (0.1492)

^a The longest wavelength absorption maxima from absorption spectra in MeOH. ^b Calculated using DFT at the level of B3LYP/6-311G* (SDD for Te).

^c The lowest significant transition energies determined using TD-DFT calculations ($f > 0.05$; f = oscillator strength).



Scheme 5 Synthesis of the bis-tellurium-bridged ladder molecule 22.

was constructed using *n*-BuLi instead of *i*-PrMgBr as the metatating agent, thus affording the ladder product 22, albeit in a modest yield.²⁷

Conclusions

In summary, we have established the sequential electrophilic telluration of $\text{C}(\text{sp}^2)\text{-Zn}$ and $\text{C}(\text{sp}^2)\text{-H}$ bonds as a simple and versatile approach for the construction of tellurium-bridged aromatic systems. The combination of the transition metal-catalyzed (migratory) arylmetalation of alkynes and sequential telluration offers a method for the expedient synthesis of functionalized benzotellurophenes starting from arylmetal reagents and alkynes. The sequential telluration also enables the facile conversion of 2-iodoheterobiaryls into heteroarene-fused benzotellurophenes and other Te-bridged aromatics, most of which are unprecedented in the literature and have been synthesized for the first time. We envision that electrophilic aromatic telluration will open access to an even greater variety of novel Te-containing heterocycles, and that the present study will stimulate further studies on the synthesis, properties, and application of such compounds.

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27 Attempts to simultaneously construct the two tellurium bridges of 22 starting from a teraryl diiodide precursor have not been successful.