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Article

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Copper-Catalyzed Tandem Sulfuration/Annulation of Propargylamines with Sulfur *via* C−N Bond Cleavage

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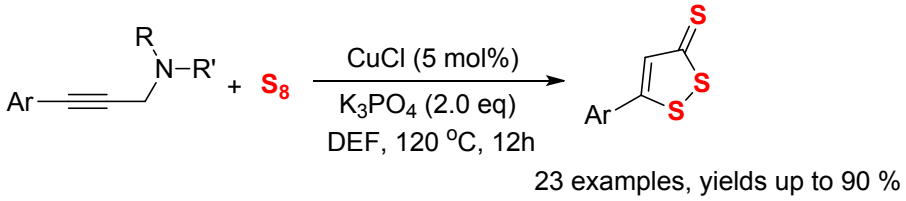
Abstract



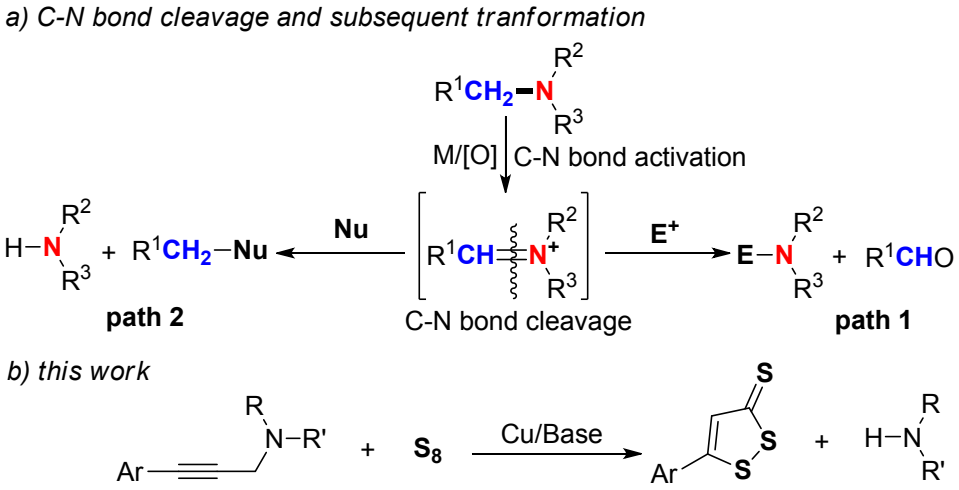
A copper-catalyzed aerobic oxidative sulfuration and annulation of propargylamines with elemental sulfur is described. The tandem reaction involves C-N bond cleavage and the formation of multiple C-S bonds, affording 1,2-dithiole-3-thiones in good to excellent yields with good functional group tolerance.

INTRODUCTION

Transition-metal-catalyzed C-N bonds activation and subsequent transformation have aroused much attention in synthetic chemistry since the C-N bond is one of the most abundant chemical bonds in organic compounds and biomacromolecules. [1] As a class of readily available chemical stocks, some tertiary amines are versatile building blocks and often used as nitrogen sources to construct new complex nitrogen-containing molecules *through* C−N bond cleavage and coupling reaction with electrophiles (**Scheme 1a**, path 1).[2] In addition, the released alkyl moiety could

also be used as the carbon source to be incorporated into organic molecules by reacting with nucleophiles during the C−N bonds cleavage of tertiary amines (**Scheme 1a**, path 2). [3] However, tertiary amines were less reported as alkyl group precursor although they were widely used as nitrogen source. We postulated whether some complex tertiary amines bearing a special functional group could undergo C−N bond cleavage and C-S bond formation to retain the major carbon fragment and release the secondary amines, which would be of great importance for the synthesis of sulfur-containing compounds.

Scheme 1. The C-N bond cleavage strategy

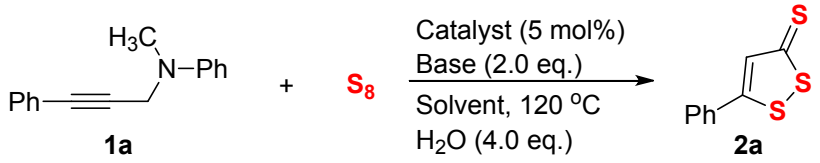


1,2-Dithiole-3-thiones exhibit significant biological activities including antitumor, antioxidant, antithrombotic, chemotherapeutic and radioprotective properties, [4] such as the commercial drugs oltipraz, [5] anethole dithiolethione (ADT) [6] and its analogues [7]. Furthermore, 1,2-dithiole-3-thiones were often used as versatile building blocks to assemble organic electronic conductors, [8] photoconductive materials [9] or semiconducting polymers. [10] Traditionally, these S-heterocyclics were prepared from multi-step reactions of β-ketoesters [11] or terminal alkynes [12] with various sulfurating reagents, which suffered from harsh reaction conditions or poor atom-economic sulfur surrogates. Inspired by our recent thioannulations for the synthesis of sulfur-heterocycles, [13] we herein wish to report a novel copper-catalyzed tandem sulfuration/annulation of propargylamines with elemental sulfur for the practical

synthesis of 1,2-dithiole-3-thiones *through* the C−N bond cleavage and the formation of multiple C-S bonds (**Scheme 1b**).

RESULTS AND DISCUSSION

Table 1. Optimization of the Reaction Conditions [a]



Entry	Catalyst	Base	Solvent	Yield (%)
1	CuCl	NaOAc	NMP	62
2	CuBr	NaOAc	NMP	58
3	CuI	NaOAc	NMP	55
4	CuOAc	NaOAc	NMP	42
5	Cu_2O	NaOAc	NMP	35
6	CuCl	$NaHCO_3$	NMP	63
7	CuCl	KOAc	NMP	65
8	CuCl	K_3PO_4	NMP	75
9	CuCl	KF	NMP	66
10	CuCl	K_3PO_4	DMSO	61
11	CuCl	K_3PO_4	DMF	ND
12	CuCl	K_3PO_4	DEF	88
13	CuCl	K_3PO_4	DMAc	58
14	CuCl	K_3PO_4	Toluene	trace
15	CuCl	K_3PO_4	DEF	NR [b]

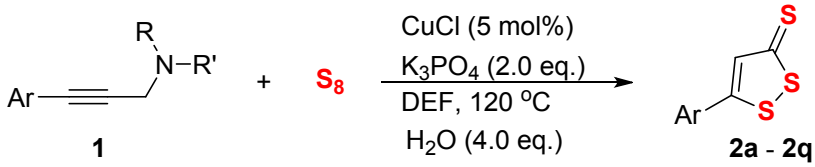
[a] Reaction conditions: **1a** (0.2 mmol), S_8 (0.3 mmol), catalyst (5 mol%), base (0.4 mmol), H_2O (4.0 eq.) and anhydrous solvent (2.0 mL), 120 °C, air, 12 h; isolated yield. [b] under N_2.

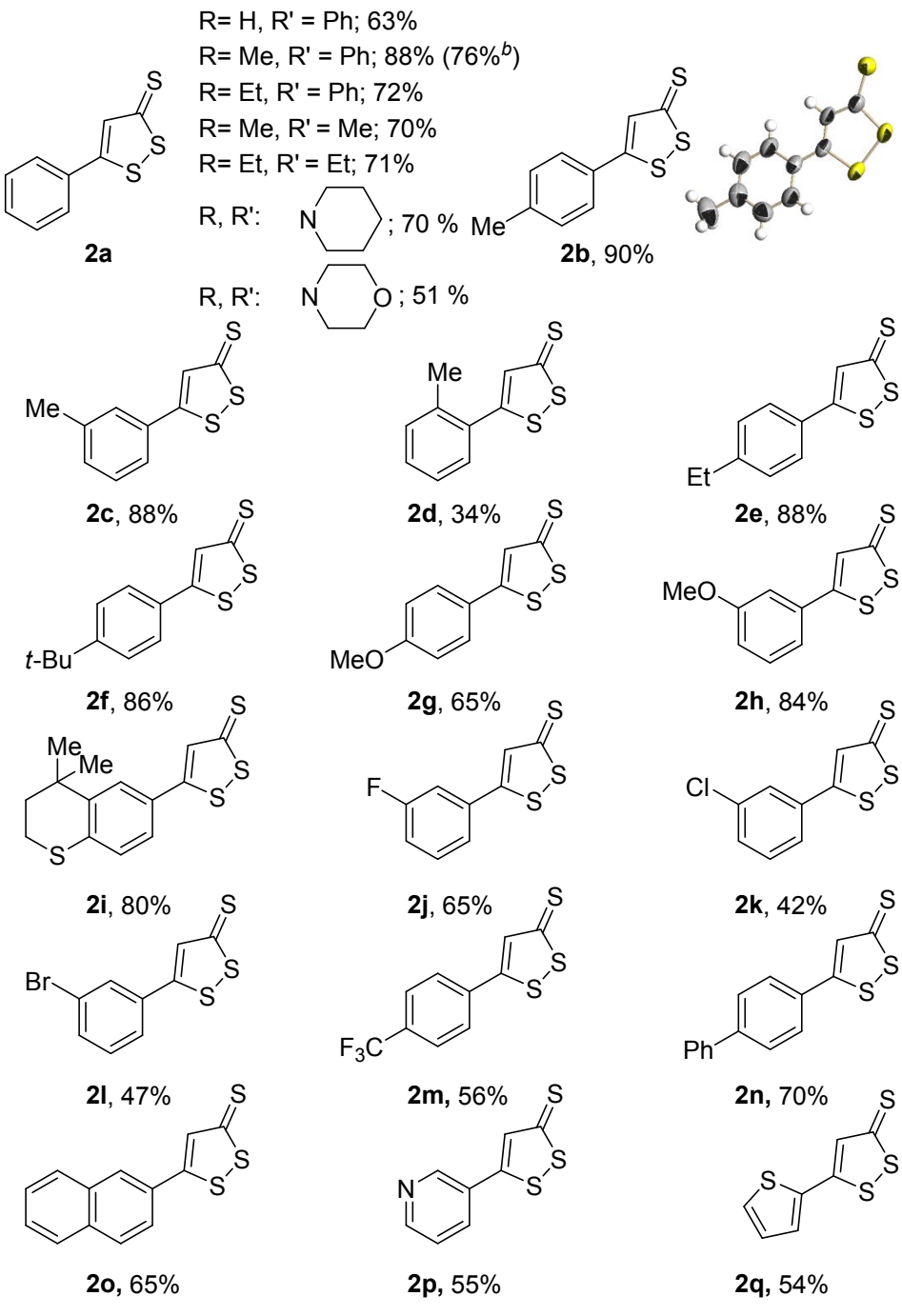
In view of the high efficiency of copper(I) catalyst in the C-S bond formation [14] and the cleavage of C-N bond [2a,2d], the model reaction of *N*-methyl-*N*-(3-phenylprop-2-yn-1-yl)aniline **1a** [15] with 1.5 equiv of sulfur was conducted in the presence of 5 mol % CuCl, 4.0 equiv H_2O, 2.0 equiv of NaOAc in *N*-methyl pyrrolidone (NMP) at 120 °C for 12 h (Table 1). We were pleased to find that the desired product **2a** could be isolated in 62% yield along with PhNHMe in 55% yield (entry 1). Encouraged by these results, various copper catalysts such as CuBr, CuI, CuOAc, and Cu_2O were investigated, but all were less active than CuCl

(entries 1-5). To further enhance the reaction yield, other bases including $NaHCO_3$, KOAc, K_3PO_4 and KF were also examined (entries 6-9), K_3PO_4 was found to be the optimal base and 75% yield of **2a** was obtained (entry 8). During the testing of different solvents, *N*,*N*-diethylformamide (DEF) was the most suitable by contrast with DMSO, DMF, *N*,*N*-dimethylacetamide (DMAc) and toluene (entries 10-14), and the product **2a** was isolated in 88% yield (entry 12). When DMF was used as solvent, a messy conversion was observed although all the propargylamines were consumed (entry 11). When the reaction was performed under N_2 atmosphere, no product could be detected and the substrate **1a** was totally recovered, demonstrating that the air play an essential role in the thioannulation (entry 15).

With the optimal reaction conditions in hand, we next explored the substrate scope of the thioannulation by testing a variety of propargylamines (Table 2). Various secondary and tertiary *N*-phenylpropargyl amines were compatible with this transformation. For example, *N*-phenylpropargyl aniline, *N*-methyl and *N*-ethyl anilines underwent the annulation smoothly to afford product **2a** in 63-88% yields. Aliphatic *N*,*N*-dimethyl, *N*,*N*-diethyl amines and cyclic piperidine, morpholine were also compatible with the reaction to give product **2a** in 51-71% yields. Moreover, the thioannulation is feasible to scale-up and a 76% yield was obtained. Subsequently, the substitution effect of alkyne moiety of *N*-propargylamines was evaluated. The results showed that electron-rich and electron-poor aryl group could be tolerated well. For example, *para* or *meta*- methyl, ethyl, *tert*-butyl, methoxyl substituted phenyl afforded the products **2b**-**2h** in good to excellent yields. Moreover, the structure of product **2b** was confirmed by X-ray single crystal diffraction analysis. Even steric *ortho*-tolyl substituted substrate **1d** underwent the thioannulation smoothly to give product **2d** in acceptable yield (34% yield). The commercial prescription drug anethole dithiolethione (ADT) **2g** could be easily prepared in 65% yield through this tandem sulfuration/annulation strategy. Substrate **1i** with a dimethylthiochroman-6-yl group yielded the corresponding polysulfide **2i** in 80% yield. *Meta*- F, Cl and Br substituted phenyl delivered the corresponding 1,2-dithiole-3-thiones **2j**-**2l** in 42-65%

Table 2. Scope with respect to *N*-propargylamines [a]





[a] Reaction conditions: **1** (0.2 mmol), S_8 (0.3 mmol), CuCl (5 mol%), K_3PO_4 (0.4 mmol), H_2O (4.0 eq.) and anhydrous DEF (2.0 mL), 120 °C, air, 12 h; isolated yield; R=Me, R'=Ph if not mentioned; [b] **1a** (5 mmol, 1.1 g).

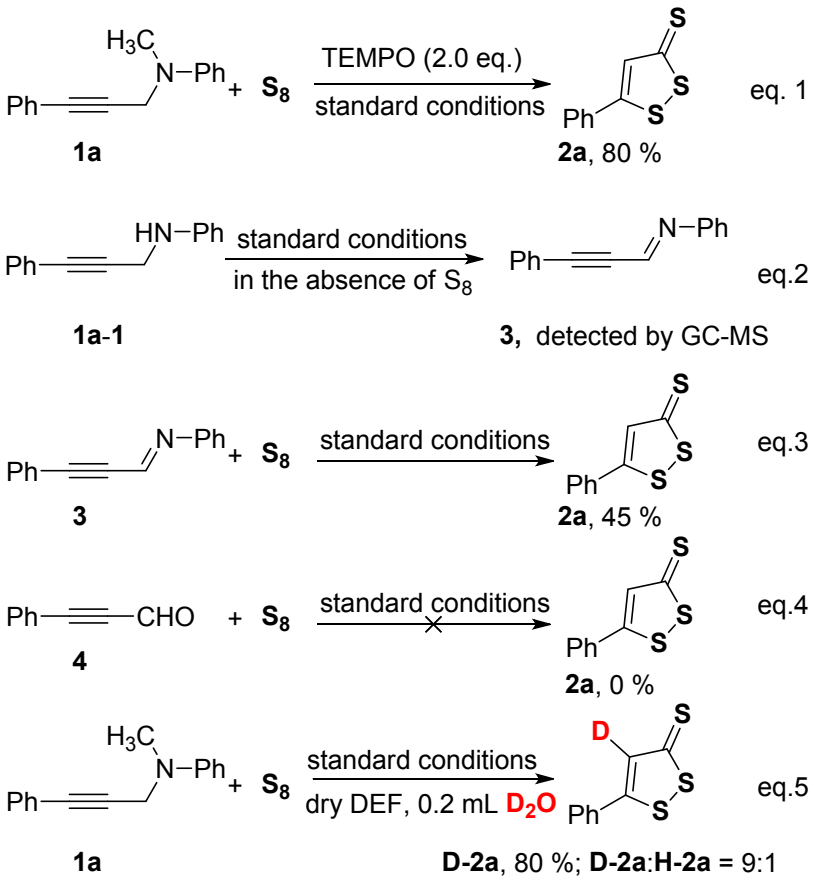
-yields, and the halo group might provide potential handles for further transformation. The propargylamine 1m bearing strong electron-withdrawing CF3 group afforded product **2m** in 56% yield. Moreover, the reaction of polycyclic aryl and heteroaryl substituted N-propargylamines also proceeded smoothly. For instance, 1,1'-biphenyl, naphthalen-1-yl, pyridin-3-yl and thiophen-2-yl provided the products **2n**-**2q** in 54%-70% yields.

To probe the reaction mechanism, some control experiments were conducted as shown in **Scheme 2**. First, the reaction of aniline **1a** with S_8 was carried out under the standard conditions by adding 2 equiv. of 2,2,6,6-tetramethylpiperidine oxide (TEMPO). The product **2a** was still isolated in 80% yield (**Scheme 2**, eq. 1), suggesting that this transformation might not proceed through a free radical pathway. Imine **3** was found to be generated by GC-MS analysis when the reaction of *N*-(3-phenylprop-2-yn-1-yl)aniline **1a-1** was conducted in the absence of S_8 under the optimal reaction condition (eq. 2). Treatment of imine **3** with S_8 gave the desired product **2a** in 45% yield (eq. 3). However, the reaction of 3-phenylpropiolaldehyde **4** with S_8 did not work under the standard conditions (eq. 4). These results implied that imine **3** might be the key intermediate in the thioannulation. Furthermore, when the reaction of **1a** with S_8 was carried out in anhydrous DEF and 0.2 mL D_2O, the deuterated product **D-2a** was observed and the product was obtained in 80% yield with a 9:1 ratio (**D-2a**: **H-2a**, according to NMR), showing that the proton was derived from water in the solvent (eq. 5).

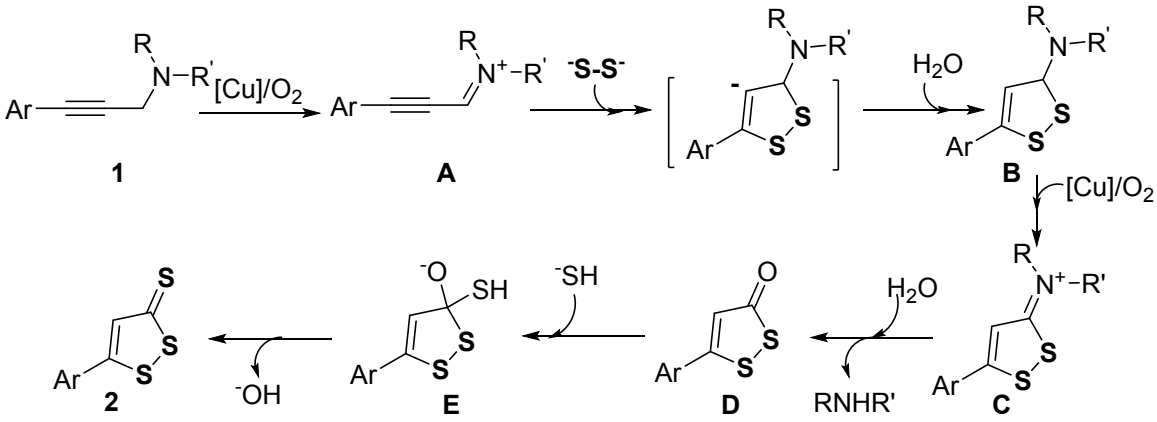
Based on the obtained experimental results, a possible mechanism is proposed for this copper-catalyzed tandem reaction (**Scheme 3**). Firstly, the copper-catalyzed oxidative dehydrogenation of propargylamines **1** occurs under air atmosphere to give the imine **A**. [2a, 3c] The disproportionation reaction of S_8 in the presence of K_3PO_4 releases $^-$S-S$^-$ and $^-$SH. [16] Then, the simultaneous nucleophilic additions of $^-$S-S$^-$ to the carbon-carbon triple bond and C=N bond of **A** and the following protonation afford the cyclization intermediate **B**. The further copper-catalyzed dehydrogenative oxidation of **B** produces imine **C**, which undergoes hydrolysis to yield

1,2-dithiol-3-one **D** along with secondary amines. [1a, 1b] Finally, the nucleophilic addition of $^{-}$SH to ketone moiety of **D** and subsequent elimination deliver the target product **2**.

Scheme 2. Control experiments



Scheme 3. Possible Mechanism



CONCLUSIONS

In summary, we have developed a copper-catalyzed tandem sulfuration and annulation of propargylamines with cheap and relatively safe elemental sulfur using air as oxidant. A variety of tertiary arylpropargylamines were firstly applied to prepare the 1,2-dithiole-3-thiones in good to excellent yields through this thioannulation process. This protocol provides a novel method for the synthesis of polysulfides *via* the cleavage C-N bonds and the formation of multi C-S bonds, and also offers a facile and efficient route to construct the key moiety of commercial drug anethole dithiolethione (ADT).

EXPERIMENTAL SECTION

General Information

Chemicals were either purchased or purified by standard techniques. ^{1}H NMR and ^{13}C{^{1}H} NMR spectra were measured on a 500 MHz spectrometer (500 MHz for ^{1}H and 125 MHz for ^{13}C) or a 400 MHz spectrometer(400 MHz for ^{1}H), using $CDCl_3$ as the solvent with tetramethylsilane (TMS) as an internal standard at room temperature. Chemical shifts are given in δ relative to TMS, the coupling constants J are given in Hz. High resolution mass spectra were recorded on an ESI-Q-TOF mass spectrometry. All reactions under air atmosphere were conducted using standard Schlenk techniques. Melting points were measured on X4 melting point apparatus and uncorrected. Column chromatography was performed using EM Silica gel 60 (300-400 mesh).

General Procedure for the Synthesis of Propargylamines 1a-1q [15]

To a mixture of CuBr (35.8 mg, 0.25 mmol), *N*, *N*-dimethylaniline (1210 mg, 10.0 mmol) and phenylacetylene (510 mg, 5.0 mmol) was added *tert*-butyl hydroperoxide (0.9 mL, 5.5M in decane) under nitrogen over 30 seconds at room temperature. The reaction temperature was raised to 100 ^{o}C over 15 min. The resulting mixture was stirred at the same temperature for 3 hour. After the reaction

mixture was cooled to room temperature, the mixture was poured into ethyl acetate and evaporated under a vacuum. The residue was purified by flash column chromatography (petroleum ether/ethyl acetate = 50:1) to afford the desired products **1a-1q**.

General Procedure for the Synthesis of 1,2-Dithiole-3-thiones 2a-2q

To a flame-dried Schlenk tube with a magnetic stirring bar was charged with **1** (44.2 mg, 0.2 mmol), H_2O (4.0 eq), S_8 (76.8mg, 0.3mmol), CuCl (1.0 mg, 5 mol %), K_3PO_4 (84.8 mg, 2 equiv) in anhydrous DEF (2 mL) under air atmosphere. The reaction mixture was stirred at 120 °C for 12 hours. After the reaction was finished, the mixture was poured into ethyl acetate, which was washed with brine (2 x 15 mL). After the aqueous layer was extracted with ethyl acetate, the combined organic layers were dried over anhydrous Na_2SO_4 and evaporated under *vacuum*. The residue was purified by flash column chromatography using petroleum ether/ethyl acetate =50:1 as the eluent to afford the desired products **2a**-**2q**.

General Procedure for the Synthesis of Compound 3 [17]

To a solution of aniline (0.47 g, 5.0 mmol) in CH_2Cl_2 (10 mL) in the presence of molecular sieves 4 A (MS 4 A) (2 g) was added a solution of 3-phenyl-2-propynal (0.65g, 5.0 mmol) in CH_2Cl_2 (10 mL) at 0 °C. The reaction mixture was warmed to r.t. and stirred for 1 h. Then the reaction mixture was filtered and the solvents were evaporated under vacuum. The residue was purified by flash column chromatography (petroleum ether/ethyl acetate=50:1) to afford the desired products **3.**

N-methyl-N-(3-phenylprop-2-yn-1-yl)aniline (**1a**): [15] yellow oil (718.3 mg, 65% yield); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.40 - 7.37 (m, 2H), 7.32 - 7.27 (m, 5H), 6.93 (d, J = 8.4 Hz, 2H), 6.85 - 6.81 (m, 1H), 4.28 (s, 2H), 3.05 (s, 3H).

N-(3-phenylprop-2-yn-1-yl)aniline (**1a-1**): [3d] yellow oil (590.0 mg, 57% yield); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.41 - 7.38 (m, 2H), 7.29 - 7.28 (m, 3H), 7.25 - 7.21 (m, 2H), 6.81 - 6.77 (m, 1H), 6.74(d, J = 8.0 Hz, 2H), 4.15 (s, 2H).

N-ethyl-N-(3-phenylprop-2-yn-1-yl)aniline (**1a-2**): [18] yellow solid (599.3 mg, 51% yield); m.p. 51-53 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.40 - 7.38 (m, 2H), 7.29 (m, 5H), 6.93 - 6.91 (m, 2H), 6.80 - 6.79 (m, 1H), 4.25 (s, 2H), 3.53 (q, *J* = 7.0 Hz, 2H), 1.27 (t, *J* = 7.0 Hz, 3H).

N,N-dimethyl-3-phenylprop-2-yn-1-amine (**1a-3**): [19] yellow oil (302.1 mg, 38% yield); ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.440 - 7.435 (m, 2H), 7.30 (m, 3H), 3.48 (s, 2H), 2.38 (s, 6H).

N,N-diethyl-3-phenylprop-2-yn-1-amine (**1a-4**): [20] yellow oil (327.3 mg, 35% yield); ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.43 - 7.42 (m, 2H), 7.30 - 7.29 (m, 3H), 3.65 (s, 2H), 2.64 (q, *J* = 7.0 Hz, 4H), 1.13 (t, *J* = 7.0 Hz, 6H).

1-(3-phenylprop-2-yn-1-yl)piperidine (**1a-5**): [20] yellow oil (626.9 mg, 63% yield); ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.44 - 7.43 (m, 2H), 7.290 - 7.287 (m, 3H), 3.49 (s, 2H), 2.58 (s, 4H), 1.65 - 1.64 (m, 4H), 1.45 (s, 2H).

4-(3-phenylprop-2-yn-1-yl)morpholine (**1a-6**): [20] yellow oil (532.7 mg, 53% yield); ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.44 - 7.43 (m, 2H), 7.303 - 7.299 (m, 3H), 3.77 (s, 4H), 3.51 (s, 2H), 2.65 (s, 4H).

N-methyl-N-(3-(p-tolyl)prop-2-yn-1-yl)aniline (**1b**): [15] yellow oil (787.3 mg, 67% yield); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.31 - 7.27 (m, 4H), 7.08 (d, *J* = 8.0 Hz, 2H), 6.93 (d, *J* = 8.4 Hz, 2H), 6.84 - 6.81 (m, 1H), 4.27 (s, 2H), 3.05 (s, 3H), 2.33 (s, 3H).

N-methyl-N-(3-(m-tolyl)prop-2-yn-1-yl)aniline (**1c**): [21] yellow oil (775.5 mg, 66% yield); ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.29 - 7.26 (m, 2H), 7.19 - 7.14 (m, 3H), 7.08 - 7.06 (m, 1H), 6.92 - 6.90 (m, 2H), 6.82 - 6.79 (m, 1H), 4.24 (s, 2H), 3.02 (s, 3H), 2.28 (s, 3H).

N-methyl-N-(3-(o-tolyl)prop-2-yn-1-yl)aniline (**1d**): [21] yellow oil (693.3 mg, 59% yield); ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.29 - 7.20 (m, 3H), 7.10 - 7.00 (m, 3H), 6.87 - 6.86 (m, 2H), 6.76 - 6.74 (m, 1H), 4.23 (s, 2H), 2.97 (s, 3H), 2.23 (s, 3H).

N-(3-(4-ethylphenyl)prop-2-yn-1-yl)-N-methylaniline (**1e**): [21] yellow oil (896.4 mg, 72% yield); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.31 - 7.27 (m, 4H), 7.11 - 7.09 (m, 2H), 6.93(d, *J* = 8.0 Hz, 2H), 6.84 - 6.80 (m, 1H), 4.26 (s, 2H), 3.04 (s, 3H), 2.62 (q, *J* = 7.6 Hz, 2H), 1.21 (t, *J* = 7.6 Hz, 3H).

N-(3-(4-(tert-butyl)phenyl)prop-2-yn-1-yl)-N-methylaniline (**1f**): [21] yellow solid (1024.9 mg, 74% yield); m.p. 54-56 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.31 - 7.28 (m, 6H), 6.94 (d, *J* = 8.0 Hz, 2H), 6.84 - 6.81 (m, 1H), 4.26 (s, 2H), 3.04 (s, 3H), 1.29 (s, 9H).

N-(3-(4-methoxyphenyl)prop-2-yn-1-yl)-N-methylaniline (**1g**):[15] yellow solid (853.4 mg, 68% yield); m.p. 70-72 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.34 - 7.28 (m, 4H), 6.93 (d, *J* = 8.0 Hz, 2H), 6.84 - 6.79 (m, 3H), 4.26 (s, 2H), 3.79 (s, 3H), 3.05 (s, 3H).

N-(3-(3-methoxyphenyl)prop-2-yn-1-yl)-N-methylaniline (**1h**): yellow oil (903.6 mg, 72% yield); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.31 - 7.27 (m, 2H), 7.20 - 7.16 (m, 1H), 6.98 - 6.90 (m, 4H); 6.86 - 6.81 (m, 2H), 4.27 (s, 2H), 3.78 (s, 3H), 3.05 (s, 3H); ^{13}C{^{1}H} NMR (125 MHz, $CDCl_3$) δ 159.4, 149.4, 129.4, 129.2, 124.5, 124.2, 118.4, 116.8, 114.8, 114.6, 85.0, 84.3, 55.4, 43.5, 38.8; HRMS (ESI) Calcd for $C_{17}H_{18}NO^+$ ($[M + H]^+$) 252.1383, found 252.1388.

N-(3-(4,4-dimethylthiochroman-6-yl)prop-2-yn-1-yl)-N-methylaniline (**1i**): yellow solid (1219.8 mg, 76% yield); m.p. 71-73 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.37 - 7.36 (m, 1H), 7.31 - 7.27 (m, 2H), 7.05 - 7.02 (m, 1H), 6.99 - 6.97 (m, 1H), 6.93 (d, *J* = 8.0 Hz, 2H), 6.84 - 6.80 (m, 1H), 4.26 (s, 2H), 3.04 (s, 3H), 3.02 (m, 2H), 1.92 (t, *J* = 6.4 Hz, 2H), 1.30 (s, 6H); ^{13}C{^{1}H} NMR (125 MHz, $CDCl_3$) δ 149.5, 142.0, 132.8, 129.9, 129.3, 129.2, 126.5, 118.5, 118.3, 114.6, 84.6, 84.2, 43.6, 38.8, 37.5, 33.1, 30.1, 23.3; HRMS (ESI) Calcd for $C_{21}H_{24}NS^+$ ($[M + H]^+$) 322.1624, found 322.1616.

N-(3-(3-fluorophenyl)prop-2-yn-1-yl)-N-methylaniline (**1j**): [21] yellow oil (740.9 mg, 62% yield); ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.29 - 7.27 (m, 2H), 7.23 - 7.19 (m, 1H), 7.14 - 7.12 (m, 1H), 7.06 - 7.04 (m, 1H), 6.99 - 6.95 (m, 1H), 6.91 - 6.90 (m, 2H), 6.83 - 6.81 (m, 1H), 4.25 (s, 2H), 3.02 (s, 3H).

N-(3-(3-chlorophenyl)prop-2-yn-1-yl)-N-methylaniline (**1k**): [21] yellow oil (765.0 mg, 60% yield); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.34 (s, 1H), 7.30 - 7.22 (m, 4H), 7.18 - 7.14(m, 1H), 6.89 (d, *J* = 8.0 Hz, 2H), 6.83 - 6.80 (m, 1H), 4.24 (s, 2H), 3.01 (s, 3H).

N-(3-(3-bromophenyl)prop-2-yn-1-yl)-N-methylaniline (**1l**): [21] yellow oil (930.0 mg, 62% yield); ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.54 (s, 1H), 7.43 - 7.42 (m, 1H), 7.33 - 7.30 (m, 3H), 7.16 - 7.13 (m, 1H), 6.94 - 6.92 (m, 2H), 6.87 - 6.84 (m, 1H), 4.28 (s,

2H), 3.05 (s, 3H).

N-methyl-N-(3-(4-(trifluoromethyl)phenyl)prop-2-yn-1-yl)aniline (**1m**): yellow oil (895.9 mg, 62% yield); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.54 - 7.45 (m, 4H), 7.32 - 7.28 (m, 2H), 6.94 - 6.92 (m, 2H), 6.86 - 6.83 (m, 1H), 4.29 (s, 2H), 3.05 (s, 3H); ^{13}C{^{1}H} NMR (125 MHz, $CDCl_3$) δ 149.3, 132.1, 130.0 (q, $J_{C\text{-}F}$ = 32.5 Hz), 129.3, 127.0, 125.3, 121.9 (q, $J_{C\text{-}F}$ = 270.6 Hz), 118.5, 114.5, 87.9, 83.1, 43.5, 38.9. HRMS (ESI) Calcd for $C_{17}H_{15}F_3N^+$ ([M + H]$^+$) 290.1151, found 290.1145.

N-(3-([1,1'-biphenyl]-4-yl)prop-2-yn-1-yl)-N-methylaniline (**1n**):[15] yellow solid (1009.8 mg, 68% yield); m.p. 80-82 °C; ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.59 - 7.58 (m, 2H), 7.54 - 7.52 (m, 2H), 7.47 - 7.44 (m, 4H), 7.38 - 7.30 (m, 3H), 6.97 - 6.95 (m, 2H), 6.86 - 6.84 (m, 1H), 4.31 (s, 2H), 3.08 (s, 3H).

N-methyl-N-(3-(naphthalen-2-yl)prop-2-yn-1-yl)aniline (**1o**): yellow solid (935.0 mg, 69% yield); m.p. 91-93 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.91 (s, 1H), 7.81 - 7.73 (m, 3H), 7.50 - 7.42 (m, 3H), 7.34 - 7.30 (m, 2H), 6.97 (d, J = 8.4 Hz, 2H), 6.87 - 6.83 (m, 1H), 4.33 (s, 2H), 3.09 (s, 3H); ^{13}C{^{1}H} NMR (125 MHz, $CDCl_3$) δ 149.4, 133.1, 132.9, 131.7, 129.3, 128.7, 128.0, 127.84, 127.80, 126.7, 126.6, 120.5, 118.5, 114.6, 85.4, 84.8, 43.6, 38.9. HRMS (ESI) Calcd for $C_{20}H_{18}N^+$ ([M + H]$^+$) 272.1434, found 272.1434.

N-methyl-N-(3-(pyridin-3-yl)prop-2-yn-1-yl)aniline (**1p**): [22] yellow oil (266.4 mg, 24% yield); ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.61 (s, 1H), 8.50 - 8.49 (m, 1H), 7.65 - 7.63 (m, 1H), 7.31 - 7.28 (m, 2H), 7.20 - 7.18 (m, 1H), 6.92 - 6.91(m, 2H), 6.85 - 6.82 (m, 1H), 4.29 (s, 2H), 3.04 (s, 3H).

N-methyl-N-(3-(thiophen-2-yl)prop-2-yn-1-yl)aniline (**1q**): [22] black oil (249.7 mg, 22% yield); ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.33 - 7.30 (m, 2H), 7.22 - 7.21 (m, 1H), 7.16 (s, 1H), 6.94 - 6.93 (m, 3H), 6.87 - 6.84 (m, 1H), 4.30 (s, 2H), 3.05 (s, 3H).

5-phenyl-3H-1,2-dithiole-3-thione (**2a**):[13a] red solid (37.0 mg, 88% yield); m.p. 124-126 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.66 - 7.64 (m, 2H), 7.58 - 7.54 (m, 1H), 7.50 - 7.47 (m, 2H), 7.44 (s, 1H); ^{13}C{^{1}H} NMR (125 MHz, $CDCl_3$) δ 215.7, 173.0, 136.1, 132.3, 131.8, 129.7, 127.0; GC-MS (EI, 70 eV) m/z (%): 209.40 (73.22), 144.65 (100), 101.80 (35.32), 76.85 (12.18).

5-(p-tolyl)-3H-1,2-dithiole-3-thione (**2b**):[13a] red solid (40.3 mg, 90% yield); m.p. 117-119 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.54 (d, *J*= 8.4 Hz, 2H), 7.42 (s, 1H), 7.28 (d, *J*= 8.0 Hz, 2H), 2.41 (s, 3H); $^{13}C\{^1H\}$ NMR (125 MHz, $CDCl_3$) δ 215.5, 173.3, 143.2, 135.5, 130.4, 129.0, 126.9, 21.7; GC-MS (EI 70 ev) m/z (%): 223.40 (100), 209.40 (23.60), 158.60 (88.76), 144.65 (31.59).

5-(m-tolyl)-3H-1,2-dithiole-3-thione (**2c**): [13a] red oil (37.0 mg, 88% yield); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.46 - 7.44 (m, 2H), 7.42 (s, 1H), 7.37 - 7.35 (m, 2H), 2.42 (s, 3H); $^{13}C\{^1H\}$ NMR (125 MHz, $CDCl_3$) δ 215.6, 173.3, 139.7, 135.9, 133.1, 131.7, 129.6, 127.6, 124.2, 21.5; GC-MS (EI 70 ev) m/z (%): 223.45 (100), 190.50 (6.79), 158.65 (89.92), 134.70 (7.57).

5-(o-tolyl)-3H-1,2-dithiole-3-thione (**2d**): [13a] red solid (15.2 mg, 34% yield); m.p. 123-125 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.43 - 7.39 (m, 2H), 7.33 - 7.27 (m, 2H), 7.13 (s, 1H), 2.43 (s, 3H); $^{13}C\{^1H\}$ NMR (125 MHz, $CDCl_3$) δ 216.1, 173.2, 139.5, 136.3, 131.6, 131.2, 130.9, 129.4, 126.6, 20.6; GC-MS (EI 70 ev) m/z (%): 224.35 (100), 190.55 (18.35), 158.65 (37.00), 127.75 (15.18).

5-(4-ethylphenyl)-3H-1,2-dithiole-3-thione (**2e**): [13a] red solid (41.9 mg, 88% yield); m.p. 115-116 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.57 (d, *J* = 8.4 Hz, 2H), 7.43 (s, 1H), 7.31 (d, *J* = 8.4 Hz, 2H), 2.71 (q, *J* = 7.8 Hz, 2H), 1.27 (t, *J* = 7.8 Hz, 3H); $^{13}C\{^1H\}$ NMR (125 MHz, $CDCl_3$) δ 215.6, 173.3, 149.4, 135.5, 129.2, 127.0, 29.0, 15.2; GC-MS (EI 70 ev) m/z (%): 237.40 (100), 208.45 (16.85), 172.55 (61.37), 144.65 (15.40).

5-(4-(tert-butyl)phenyl)-3H-1,2-dithiole-3-thione (**2f**): [13a] red solid (45.8 mg, 86% yield); m.p. 112-114 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.60 (d, *J* = 8.4 Hz, 2H), 7.50 (d, *J* = 8.8Hz, 2H), 7.45 (s, 1H), 1.35 (s, 9H); $^{13}C\{^1H\}$ NMR (125 MHz, $CDCl_3$) δ 215.6, 173.3, 156.3, 135.6, 129.0, 126.9, 126.8, 35.3, 31.2; GC-MS (EI 70 ev) m/z (%): 265.40 (100), 250.40 (53.78), 200.55 (19.86), 170.60 (8.36).

5-(4-methoxyphenyl)-3H-1,2-dithiole-3-thione (**2g**): [13a] red solid (31.2 mg, 65% yield); m.p. 109-111 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.63 - 7.59 (m, 2H), 7.38 (s, 1H), 6.99 - 6.95 (m, 2H), 3.87 (s, 3H); $^{13}C\{^1H\}$ NMR (125 MHz, $CDCl_3$) δ 215.2, 173.1, 163.1, 134.7, 128.7, 124.3, 115.1, 55.7; GC-MS (EI 70 ev) m/z (%): 239.40 (100),

206.50 (6.13), 174.60 (55.65), 131.75 (27.56).

5-(3-methoxyphenyl)-3H-1,2-dithiole-3-thione (**2h**): [13a] red solid (40.3 mg, 84% yield); m.p. 113-115 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.40 - 7.35 (m, 2H), 7.22-7.20 (m, 1H), 7.11 - 7.10 (m, 1H), 7.08 - 7.06 (m, 1H), 3.84 (s, 3H); $^{13}C\{^1H\}$ NMR (125 MHz, $CDCl_3$) δ 215.5, 172.8, 160.3, 136.1, 132.8, 130.8, 119.3, 117.8, 112.4, 55.6; GC-MS (EI 70 ev) m/z (%): 239.40 (100), 206.50 (8.15), 174.55 (56.39), 131.70 (19.75).

5-(4,4-dimethylthiochroman-6-yl)-3H-1,2-dithiole-3-thione (**2i**): red solid (49.6 mg, 80% yield); m.p. 128-130 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.61 (d, J = 2.0 Hz, 1H), 7.42 (s, 1H), 7.31 - 7.29 (m, 1H), 7.16 (d, J = 8.4 Hz, 1H), 3.09 - 3.06 (m, 2H), 1.98 - 1.95 (m, 2H), 1.35 (s, 6H); $^{13}C\{^1H\}$ NMR (125 MHz, $CDCl_3$) δ 215.1, 173.4, 143.3, 139.2, 134.9, 127.7, 127.4, 124.7, 124.2, 36.8, 33.3, 29.9, 23.4; GC-MS (EI 70 ev) m/z (%): 309.20 (100), 294.20 (23.75), 244.40 (46.67), 220.45 (7.44); HRMS (ESI) Calcd for $C_{14}H_{15}S_4^+$ ($[M + H]^+$) 311.0051, found 311.0053.

5-(3-fluorophenyl)-3H-1,2-dithiole-3-thione (**2j**): [13a] red solid (29.6 mg, 65% yield); m.p. 126-128 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.52 - 7.45 (m, 2H), 7.41 (s, 1H), 7.38 - 7.35 (m, 1H), 7.29 - 7.26 (m, 1H); $^{13}C\{^1H\}$ NMR (125 MHz, $CDCl_3$) δ 215.6, 170.9 , 163.1 (d, $J_{C\text{-}F}$ = 248.8 Hz), 136.6, 133.6, 131.5, 122.8, 119.1 (d, $J_{C\text{-}F}$ = 21.3 Hz), 114.1 (d, $J_{C\text{-}F}$ = 23.8 Hz); GC-MS (EI 70 ev) m/z (%): 227.40 (100), 162.55 (86.67), 119.75 (39.25), 94.80 (9.53).

5-(3-chlorophenyl)-3H-1,2-dithiole-3-thione (**2k**): [13a] black solid (20.4 mg, 42% yield); m.p. 106-108 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.63 (s, 1H), 7.55 - 7.52 (m, 2H), 7.45 - 7.41 (m, 1H), 7.40 (s, 1H); $^{13}C\{^1H\}$ NMR (125 MHz, $CDCl_3$) δ 215.6, 170.7, 136.6, 135.9, 133.4, 132.1, 131.0, 127.0, 125.1; GC-MS (EI 70 ev) m/z (%): 243.35 (100), 180.50 (26.50), 135.70 (22.01), 100.80 (13.06).

5-(3-bromophenyl)-3H-1,2-dithiole-3-thione (**2l**): [13a] red solid (27.2 mg, 47% yield); m.p. 123-125 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.79 (s, 1H), 7.69 - 7.67 (m, 1H), 7.60 - 7.58 (m, 1H), 7.39 - 7.35 (m, 2H); $^{13}C\{^1H\}$ NMR (125 MHz, $CDCl_3$) δ 215.6, 170.6, 136.6, 135.0, 133.7, 131.2, 129.9, 125.6, 123.8; GC-MS (EI 70 ev) m/z (%): 289.20 (100), 243.35 (15.47), 224.20 (68.15), 143.65 (17.62).

5-(4-(trifluoromethyl)phenyl)-3H-1,2-dithiole-3-thione (**2m**): [13a] red solid (31.1 mg,

56% yield); m.p. 109-111 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.80 - 7.75 (m, 4H), 7.44 (s, 1H); $^{13}C\{^1H\}$ NMR (125 MHz, $CDCl_3$) δ 215.7, 170.3, 137.1, 135.1, 133.8 (q, J_{C-F} = 32.5 Hz), 127.5, 126.8, 123.6 (q, J_{C-F} = 271.3 Hz); GC-MS (EI 70 ev) m/z (%): 277.20 (100), 258.20(4.36), 212.35 (76.20), 169.45 (6.90).

5-([1,1'-biphenyl]-4-yl)-3H-1,2-dithiole-3-thione (**2n**): [13a] red solid (40.0 mg, 70% yield); m.p. 119-122 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.75 - 7.70 (m, 4H), 7.64 - 7.62 (m, 2H), 7.51 - 7.47 (m, 3H); 7.44 - 7.41 (m, 1H); $^{13}C\{^1H\}$ NMR (125 MHz, $CDCl_3$) δ 215.6, 172.6, 145.2, 139.5, 135.8, 130.6, 129.2, 128.6, 128.3, 127.5, 127.2; GC-MS (EI 70 ev) m/z (%): 285.30 (100), 252.35 (8.70), 220.45 (71.56), 206.50 (10.21).

5-(naphthalen-2-yl)-3H-1,2-dithiole-3-thione (**2o**): [13a] red solid (33.8 mg, 65% yield); m.p. 68-71 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.18 (d, J = 1.2 Hz, 1H), 7.94 - 7.91 (m, 2H), 7.89 - 7.87 (m, 1H), 7.67 - 7.64 (m, 1H), 7.63 - 7.58 (m, 2H), 7.56 (s, 1H); $^{13}C\{^1H\}$ NMR (125 MHz, $CDCl_3$) δ 215.6, 172.9, 136.2, 134.9, 133.1, 129.7, 129.1, 129.0, 128.5, 128.1, 127.7, 127.3, 123.5; GC-MS (EI 70 ev) m/z (%): 259.30 (100), 226.40 (9.72), 194.50 (54.72), 151.65 (22.77).

5-(pyridin-3-yl)-3H-1,2-dithiole-3-thione (**2p**):[12g] red solid (23.2 mg, 55% yield); m.p. 150-152 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.93 (d, J = 2.4 Hz, 1H), 8.79 - 8.77 (m, 1H), 7.97 - 7.94 (m, 1H), 7.47 - 7.44 (m, 1H), 7.43 (s, 1H); $^{13}C\{^1H\}$ NMR (125 MHz, $CDCl_3$) δ 215.6, 168.7, 152.9, 147.5, 136.8, 134.1, 128.1, 124.2; GC-MS (EI 70 ev) m/z (%): 210.30 (79.82), 167.55 (2.43), 145.60 (100), 121.65 (9.91).

5-(thiophen-2-yl)-3H-1,2-dithiole-3-thione (**2q**):[13a] red solid (23.3 mg, 54% yield); m.p. 127-129 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.60 - 7.58 (m, 1H), 7.55 - 7.54 (m, 1H), 7.33 (s, 1H), 7.16 - 7.14 (m, 1H); $^{13}C\{^1H\}$ NMR (125 MHz, $CDCl_3$) δ 214.7, 165.2, 134.8, 134.1, 131.1, 129.3, 129.2; GC-MS (EI 70 ev) m/z (%): 215.35 (100), 150.55 (89.46), 126.65 (12.84), 107.75 (69.81).

phenyl-3H-1,2-dithiole-3-thione-4-d (**D-2a**): [13a] red solid (33.7 mg, 80% yield); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.66 - 7.64 (m, 2H), 7.50 – 7.47 (m, 2H), 7.44 (s, 0.10H); $^{13}C\{^1H\}$ NMR (125 MHz, $CDCl_3$) δ 215.7, 215.6, 172.9, 172.9, 136.04, 135.96, 135.8, 135.5, 132.3, 131.7, 129.7, 127.0; GC-MS (EI 70 ev) m/z (%): 210.35 (71.35), 144.60

(100), 102.75 (41.07), 76.80 (17.51).

(Z)-N,3-diphenylprop-2-yn-1-imine (**3**):[17] yellow solid (533.0 mg, 52% yield); m.p. 46-48 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.80 (s, 1H), 7.67 - 7.65 (m, 2H), 7.47 - 7.43 (m, 5H), 7.36 - 7.31 (m, 2H), 7.28 (m, 1H).

SUPPLEMENTARY INFORMATION

Copies of ^{1}H NMR or ^{13}C{^{1}H} NMR spectra for products **1a-1q**, **2a-2q** and X-ray data for compound **2b.** This material is available free of charge *via* the Internet at http://pubs.acs.org.

Supplementary crystallographic data was deposited at the Cambridge Crystallographic Data Centre (CCDC) under the number CCDC-1883614 (**2b**) and can be obtained free of charge from via www.ccdc.cam.ac.uk/data_request.cif.

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