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Recyclable Heterogeneous Supported Copper-Catalyzed Coupling of Thiols with Aryl Halides: Base-Controlled Differential Arylthiolation of Bromoiodobenzenes

Sukalyan Bhadra,[a] Bojja Sreedhar,[b] and Brindaban C. Ranu[a,*]

[a] Department of Organic Chemistry, Indian Association for the Cultivation of Science, Jadavpur, Kolkata – 700 032, India
Fax: (+91)-33-2473-2805; e-mail: ocbcr@iacs.res.in
[b] Inorganic Chemistry Division, Indian Institute of Chemical Technology, Hyderabad – 500 007, India

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Abstract: Alumina-supported copper sulfate efficiently catalyzes the *S*-arylation of aromatic, heteroaromatic and aliphatic thiols with aryl as well as heteroaryl halides under aerobic, ligand-free conditions. This protocol provides an easy access to a variety of thioethers as well as unsymmetrical bis-thioethers by base-controlled differential coupling of thiols with iodo- and bromo-substituents in an aromatic halide. The catalyst is inexpensive, non-air sensitive, environmentally friendly and recyclable.

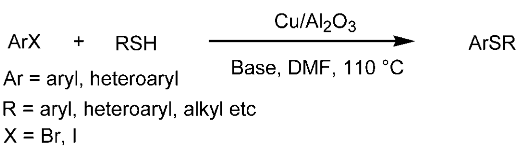
Keywords: aryl-sulfur bond; cross-coupling; heterogeneous catalyst; recycling; unsymmetrical organic sulfides

Introduction

The formation of aryl-sulfur, aryl-nitrogen and aryl-oxygen bonds is of much importance because of the presence of these bonds in many molecules of biological and material interest.[1] The transition metal-catalyzed coupling of aryl halides with thiols, phenols and amines are one of the most powerful tools for the construction of these bonds.[2] Among these three aryl-heteroatom bonds, aryl-sulfur bond formation is relatively complicated because of the associated oxidative S–S coupling reaction and deactivation of metal catalysts by sulfur compounds. A variety of Pd,[3] Cu,[4] Co,[5] Ni[6] and more recently Fe[7] catalysts, usually in presence of a ligand has been used for aryl-sulfur bond formation by the coupling of aryl halides with thiols. However, the high cost and air sensitivity of Pd catalysts and often tedious procedure for the preparation of ligands restrict their applications in large-scale processes. On the other hand, in general, Co and Ni catalysts are associated with toxicity. The Cu-mediated reactions sometimes require the use of Cu salts in a more than stoichiometric amount, high temperature and long reaction time. Thus, development of alternative inexpensive, ligand-free, non-air sensitive and recyclable catalysts for this useful reaction is highly desirable in the context of environmental and industrial cocerns.

Catalysis by a metal, anchored on a heterogeneous support, has received tremendous attention in recent times.[8] The primary advantages of using a heterogeneous catalyst compared to a homogeneous counterpart are ease of separation of product, reusability of catalyst, improved efficiency due to stable active site and better steric control of a reaction intermediate.[9]

As a part of our program to utilize heterogeneous catalysts for useful reactions[10] we report here an alumina-supported Cu(II)-catalyzed,[11,12] ligand-free coupling of aryl halides and thiols in presence of a base (Scheme 1).



Scheme 1. Cross-coupling of aryl halides and thiols.

Results and Discussion

The catalyst was prepared by stirring an aqueous solution of $CuSO_4$ and basic alumina followed by removal of water under reduced pressure at 120 °C. EDX (energy dispersive X-ray) spectra (Figure 1) of the light green powder confirmed the presence of Cu and

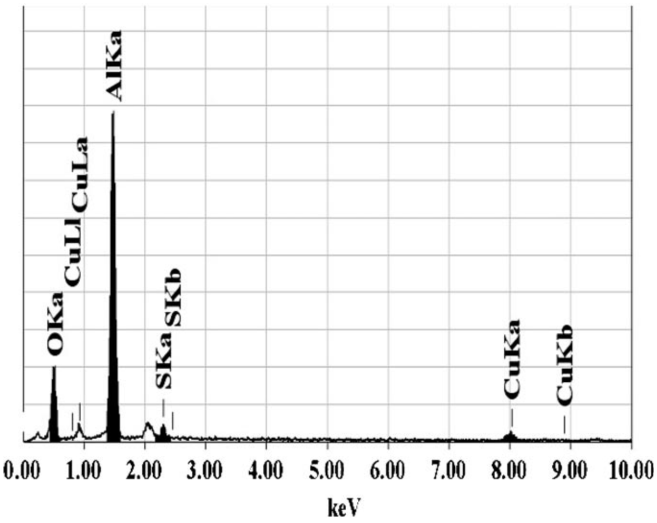


Figure 1. EDX spectra of the catalyst.

Al. FESEM (field emission scanning electron microscopy) (Figure 2) and AFM (atomic force microscopy) images (Figure 3, *top* and *bottom*) illustrate its morphology.

To optimize the reaction conditions, the coupling of iodobenzene with thiophenol was studied. The best results for this reaction were obtained using 5 mol% catalyst in DMF at 100–110 °C in presence of K_2CO_3 (Table 1, a), whereas the coupling of bromobenzene and thiophenol proceeded efficiently in the presence of Cs_2CO_3 (Table 1, b).

The reaction is not very effective using $CuSO_4$ alone without anchoring it on basic alumina. The reaction of iodobenzene and thiophenol using $CuSO_4$ alone provides only 35% yield, whereas the reaction with bromobenzene gives even lower yield (10%). The reaction using a mixture of alumina and $CuSO_4$ also did not show much improvement. Use of basic alumina as support is found to give best results in terms of yield and reaction time compared to neutral

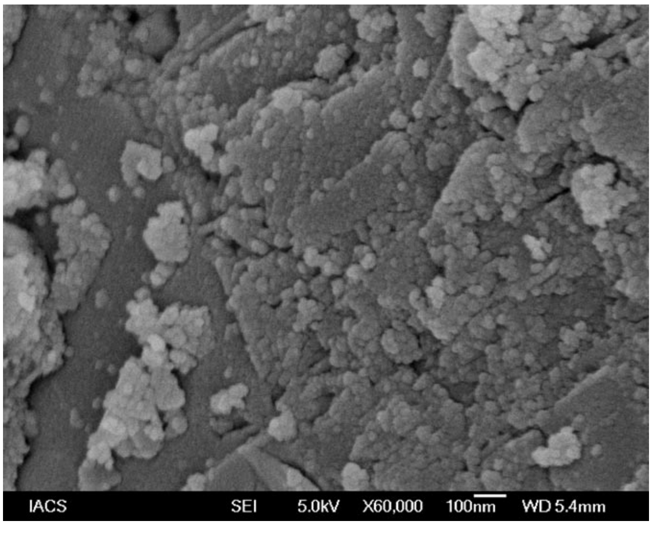


Figure 2. SEM image of Cu/Al_2O_3 catalyst.

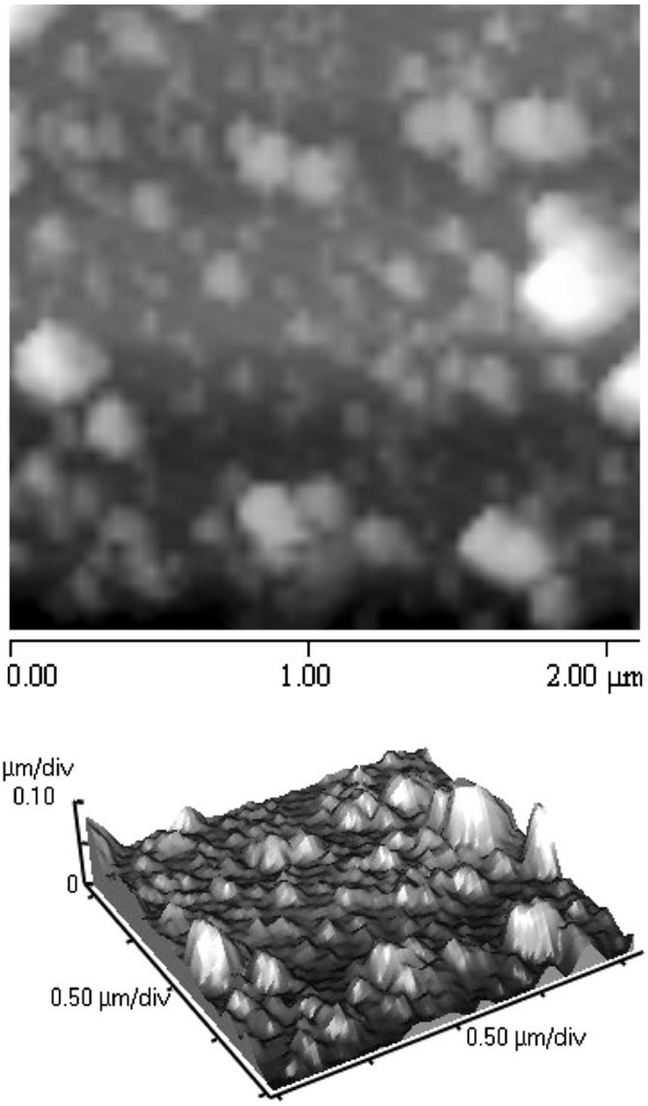


Figure 3. (*Top*) AFM image of Cu/Al_2O_3 catalyst. (*Bottom*) AFM topological image of the catalyst.

Table 1. Optimization of reaction conditions.

(**a**) $PhI + PhSH \xrightarrow{Cu/Al_2O_3} PhSPh$ (**b**) $PhBr + PhSH \xrightarrow{Cu/Al_2O_3} PhSPh$

Solvent	Temp. [°C]	Base	Yield [%]	Solvent	Temp. [°C]	Base	Yield [%]
Toluene	105	K_2CO_3	68	DMF	110	K_2CO_3	0
THF	65	K_2CO_3	46	H_2O	100	K_2CO_3	<10
DMF	**110**	**K_2CO_3**	**97**	DMF	110	K_3PO_4	43
H_2O	100	K_2CO_3	21	**DMF**	**110**	**Cs_2CO_3**	**95**
DMF	110	K_3PO_4	87	DMF	110	NaOH	54
DMF	110	Cs_2CO_3	94	Toluene	105	Cs_2CO_3	62
DMF	110	NaOH	82	THF	65	Cs_2CO_3	52

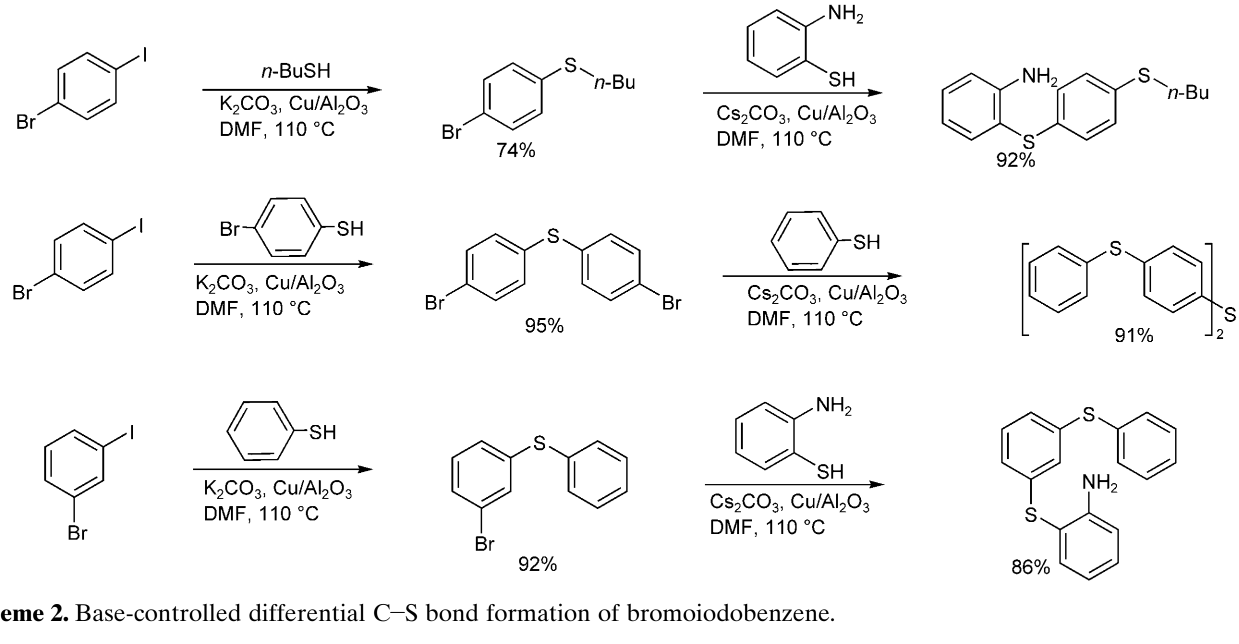
alumina, zeolite and hydrotalcite. The other Cu(II) salts such as $Cu(OAc)_2$, $Cu(NO_3)_2$, $Cu(OTf)_2$ and $CuCl_2$ in place of $CuSO_4$ did not produce good results when anchored on basic alumina.

Several substituted aryl iodides underwent coupling with a variety of functionalized thiols in the presence of K_2CO_3 to produce the corresponding diaryl/aryl-alkyl sulfides. The results are summarized in Table 2.

Both electron-donating and electron-withdrawing group-substituted iodobenzenes participated in this reaction with similar efficiency. A heteroaryl iodide underwent arylthiolation efficiently (Table 2, entry 16). Aliphatic thiols also coupled with aryl iodides under these conditions (Table 2, entries 14 and 15), which is difficult to achieve.[7b] The sterically hindered *ortho*-substituted iodobenzoic acid underwent arylthiolation without any difficulty (Table 2, entry 9). This Cu catalyst was also found to be very effective for coupling of aryl iodides with thiols bearing heterocyclic moieties (Table 2, entries 11, 17 and 18). This reaction is of much importance as these heterocyclic sulfides are very useful compounds.[13] Nevertheless, this coupling is rarely addressed by earlier methods.[7b] This Al_2O_3-supported Cu catalyst is highly chemoselective, demonstrating exclusive coupling of −SH with −I without any parallel coupling with −OH present in the aryl ring of the thiol (Table 2, entries 4 and 5). The substituted fluoro, chloro and bromo functionalities in aryl iodides remained inert under these conditions using K_2CO_3 as base (Table 2, entries 6, 10, 11, 12, 14, 15). Very interestingly, the coupling of thiols with bromobenzenes proceeded efficiently in the presence of Cs_2CO_3 (Table 1, b). Thus several substituted bromobenzenes were treated with various functionalized thiols to provide the corresponding sulfides (Table 3). A heteroaryl bromide, *ortho*-substituted bromobenzene and heteroaryl thiols were compatible in this coupling too. Under these conditions the Br substituent couples selectively with SH without any reaction with the $-NH_2$ present in the aryl ring of the thiol (Table 3, entry 4). On the other hand, reaction of 4-chlorothiophenol with 2-bromoaniline is limited to coupling of SH with Br only without any self-coupling of bromoaniline (Table 3, entry 5). Taking advantage of the base-controlled highly selective arylthiolation of iodo- and bromobenzenes we then focused our attention to the sequential coupling of iodobromobenzenes. Thus, iodobromobenzene was coupled with *n*-butyl thiol in the presence of K_2CO_3 followed by treatment with 2-aminothiophenol in the presence of Cs_2CO_3 leading to a benzene derivative substituted with two different thio-moieties at two ends.

Several bis-thioethers were achieved by this sequence as illustrated in Scheme 2. This reaction has enormous scope for an easy access to a library of bis-thioethers and will have much potential in organic synthesis. For example, the poly-(*p*-phenylene sulfide) polymers are commercially very important materials because of their uses as thermoplastics, fire retardants etc.[14]

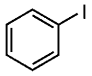
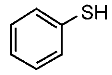
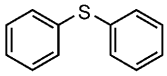
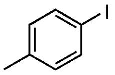
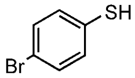
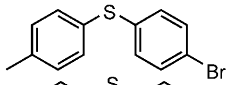
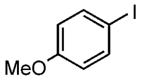
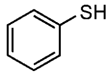
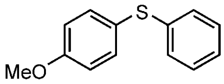
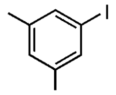
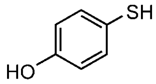
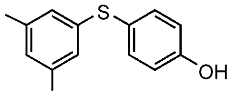
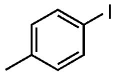
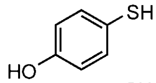
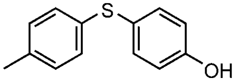
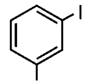
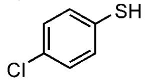
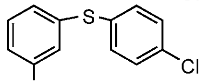
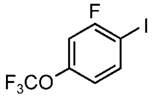
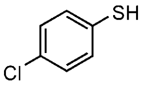
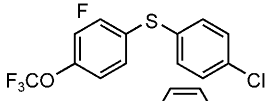
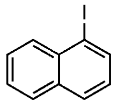
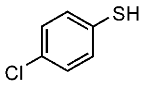
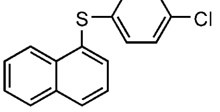
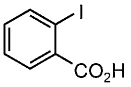
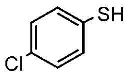
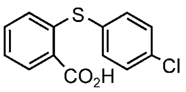
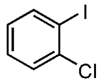
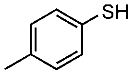
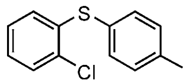
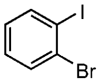
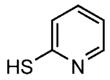
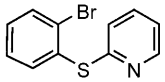
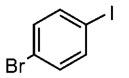
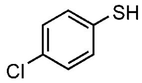
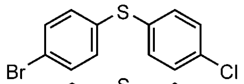
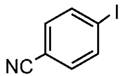
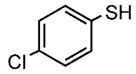
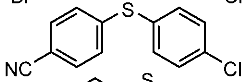
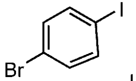
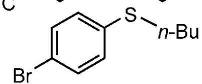
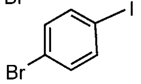
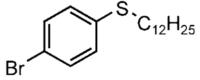
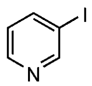
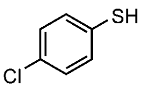
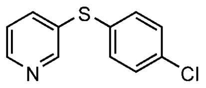
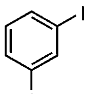
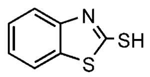
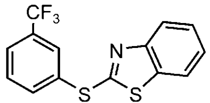
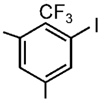
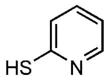
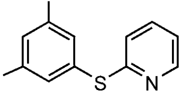
In general, the reactions are very clean and high yielding. No ligand has been used. No diaryl/dialkyl disulfide was found in any of these coupling reactions. The $CuSO_4/Al_2O_3$ catalyst is very robust and not air-sensitive. The reactions were carried out in ordinary DMF (no drying is necessary) without the requirement of an inert atmosphere. No appreciable leaching of catalyst was detected as measured by ICP-MS (inductively coupled plasma mass spectrometry) and



Scheme 2. Base-controlled differential C−S bond formation of bromoiodobenzene.

Table 2. Cu-catalyzed C-S cross-coupling of aryl iodides.[a]

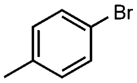
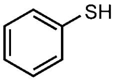
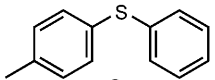
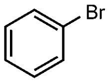
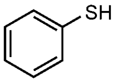
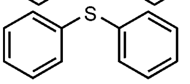
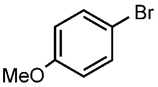
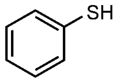
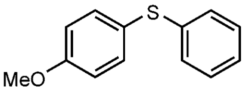
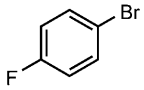
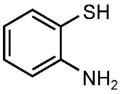
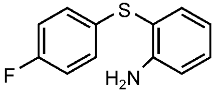
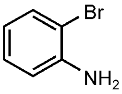
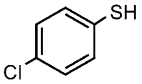
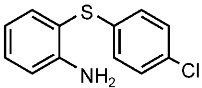
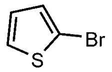
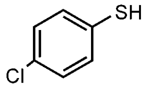
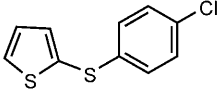
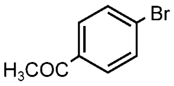
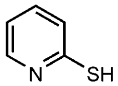
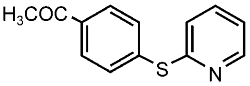
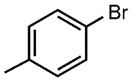
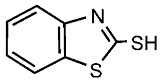
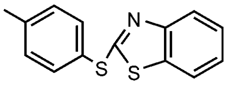
$$\text{ArI} + \text{RSH} \xrightarrow[\text{K}_2\text{CO}_3\text{, DMF, 110 °C}]{\text{Cu/Al}_2\text{O}_3} \text{ArSR}$$

Entry	ArI	RSH	ArSR	Time [h]	Yield [%][b]	Ref.
1				7	97	[4g]
2				7.5	95	[4e]
3				10	84	[4g]
4				8	90	[4h]
5				8.5	94	[16]
6				7	98	
7				8	92	
8				7	91	[4g]
9				8.2	89	
10				7	97	[4g]
11				7.5	95	
12				7	98	[4g]
13				7	96	[16]
14		n-BuSH		8.5	74	[6b]
15		$C_{12}H_{25}SH$		8.5	70	[17]
16				8	96	
17				7	97	
18				8	96	

[a] *Reaction conditions:* ArI (1.0 equiv.), RSH (1.1 equiv.), Cu/Al_2O_3 (5 mol%), K_2CO_3 (2 equiv.), DMF (3 mL), 110 °C. [b] Isolated yield of pure product.

Table 3. Cu-catalyzed C–S cross coupling of aryl bromides.[a]

$$\mathrm{ArBr} + \mathrm{RSH} \xrightarrow[\mathrm{Cs_2CO_3,\ DMF,\ 110\ ^\circ C}]{\mathrm{Cu\text{-}Al_2O_3}} \mathrm{ArSR}$$

Entry	ArBr	RSH	ArSR	Time [h]	Yield [%][b]	Ref.
1				8	94	6a
2				7.5	95	4g
3				10	73	4g
4				8	94	
5				8.5	91	4g
6				8	93	
7				8.5	93	
8				8	91	

[a] *Reaction conditions:* ArBr (1.0 equiv.), RSH (1.1 equiv.), Cu/Al_2O_3 (5 mol%), Cs_2CO_3 (1.5 equiv.), DMF (3 mL), 110 °C.

[b] Isolated yield of pure product.

control experiments. The catalyst in DMF was heated for 8 h in the presence of K_2CO_3 and the supernetant liquid after centrifuging did not show any catalytic activity for a coupling reaction of iodobenzene and thiophenol. The catalyst is recyclable and in fact, it was reused for eight times without any loss of efficiency (Cu content in fresh catalyst: 0.517 mmol g^{-1}, Cu content in recovered catalyst after 8th cycle: 0.503 mmol g^{-1}as measured by ICP-MS). This procedure is compatible with a variety of functionalities such as OMe, OCF_3, CO_2H, CF_3, CN, NH_2 etc.

This Cu/Al catalyst is also effective for the *O*-arylation of phenols and *N*-arylation of amines by aryl halides as illustrated in Table 4 and Table 5.

Recently, we reported a similar coupling reaction of aryl iodide and thiophenol using copper nanoparticles under ligand-free conditions.[4g] However, the present procedure using the supported Cu(II) catalyst provides a wider scope using a variety of halides and thiols, phenols and amines, sequential thioarylation, low catalyst loading and recyclability of catalyst.

To investigate the mechanism of this reaction a few experiments were carried out. The X-ray photoelectron spectroscopic (XPS) study of the fresh and used Cu/Al_2O_3 catalyst at the Cu 2*p* level shows the 2$p_{3/2}$ lines at 934.7 and 934.6 eV, respectively, which indicates that Cu is in the +2 oxidation state before and after the reaction (Figure 4). To find the intermediate, when thiophenol was treated with the catalyst in the absence of any base, a dirty white complex was

Table 4. Cu-catalyzed C–O cross-coupling of aryl iodides.[a]

$$\mathrm{Ar^1I} + \mathrm{Ar^2OH} \xrightarrow[\mathrm{Cs_2CO_3,\ DMF,\ 110\,^\circ C}]{\mathrm{Cu/Al_2O_3}} \mathrm{Ar^1OAr^2}$$

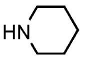
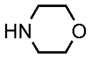
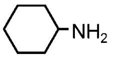
Entry	Ar^1	Ar^2	Time [h]	Yield [%][b]	Ref.
1	C_6H_5	C_6H_5	12	83	[18]
2	4-CH_3-C_6H_4	C_6H_5	9	82	[18]
3	naphthyl	4-MeO-C_6H_4	10	81	[19]
4	3-CH_3CO-C_6H_4	C_6H_5	10	78	[18]

[a] *Reaction conditions:* Ar^{1}I (1.0 equiv.), Ar^{2}OH (1.2 equiv.), Cu/Al_2O_3 (5 mol%), Cs_2CO_3 (2 equiv.), DMF (3 mL), 110 °C.

[b] Isolated yield of pure product.

Table 5. Cu-catalyzed C-N cross-coupling of aryl halides.[a]

$$\underset{X = Br, I}{ArX} + R^1NHR^2 \xrightarrow[K_2CO_3,\ H_2O,\ 100\,°C]{Cu/Al_2O_3} ArNR^1R^2$$

Entry	Ar	R^1NHR^2	Time [h]	Yield [%][b]	Ref.
1	C_6H_5		8	85	[20]
2	$4\text{-}CH_3O\text{-}C_6H_4$		9	82	[20]
3	$4\text{-}CH_3\text{-}C_6H_4$	$C_6H_{13}NH_2$	8	92[c]	[21]
4	C_6H_5		9	78[c]	[22]

[a] *Reaction conditions:* ArI/ArBr (1.0 equiv.), R^1NHR^2 (1.2 equiv.), Cu/Al_2O_3 (5 mol%), K_2CO_3 (2 equiv.), H_2O (4 mL), 100 °C.

[b] Isolated yield of pure product.

[c] Only mono-arylated product.

formed, which shows the appearance of a new band at 2800–3000 cm^{-1} by FTIR (Figure 5, *top* and *middle*) due to aromatic C-H stretching indicating the addition of thiophenol to the complex and this peak disappeared after the reaction (Figure 5, *bottom*). The complex **II** was isolated and when it was treated with iodobenzene, no reaction occurred in the absence of K_2CO_3 or Cs_2CO_3. In the presence of a base, the corresponding sulfide was obtained. Obviously, the base has a decisive role in this addition-elemination step. Based on these observations we speculate that in the presence of K_2CO_3/Cs_2CO_3, complex **II**[15] undergoes oxidative addition with iodobenzene to give a transient complex **III** which on reductive elimination *via* **IV** provided the product and regenerated the catalyst (Scheme 3). We explain the differential coupling of −I and −Br groups using K_2CO_3 and Cs_2CO_3 respectively, by the fact that the bromo substituent being relatively less reactive than iodo substituent, is not likely to undergo oxidative addition in the presence of the milder base K_2CO_3 and thus a stronger base, Cs_2CO_3, is required to polarize the aryl-Br bond for further reaction.

Conclusions

In summary, we have developed an efficient protocol for the *S*-arylation of aromatic, heteroaromatic and aliphatic thiols with aryl as well as heteroaryl iodides and bromides using a heterogeneous Al_2O_3-supported Cu catalyst under aerobic, ligand-free conditions. Such a wide scope demonstrated by a single catalyst has not been reported earlier and this procedure provides a convenient route to a variety of substituted organic sulfides. The most attractive feature of this protocol is the base-controlled differential coupling of thiols with iodo- and bromo-substituents in an aryl halide providing unsymmetrical bis-thioethers. To the best of our knowledge, we are not aware of any report demonstrating such differential *S*-arylation in this type of coupling reactions. In addition, this novel Cu-catalyzed *S*-arylation protocol is of potential industrial significance because of its high yields, simplicity in operation, scaling up to multogram quantitites, and environmental (no leaching of catalyst) and economical advantages using commercially available DMF, an inexpensive, stable and recyclable heterogeneous catalyst, no inert atmosphere and no special device for reaction. Further investigations on other useful applications of this catalyst are in process.

Experimental Section

Preparation of Cu/Al_2O_3 Catalyst

To a well-stirred aqueous solution of $CuSO_4{\cdot}5H_2O$ (1.0 g, 4 mmol $CuSO_4{\cdot}5H_2O$ dissolved in 25 mL of water) basic alu-

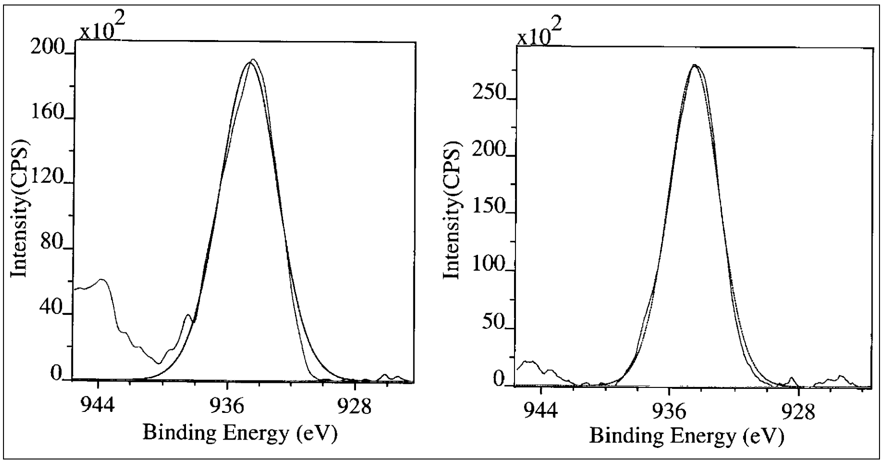


Figure 4. XPS of Cu $2p_{3/2}$ for (*left*) Cu/Al_2O_3 fresh catalyst; (*right*) Cu/Al_2O_3 used catalyst.

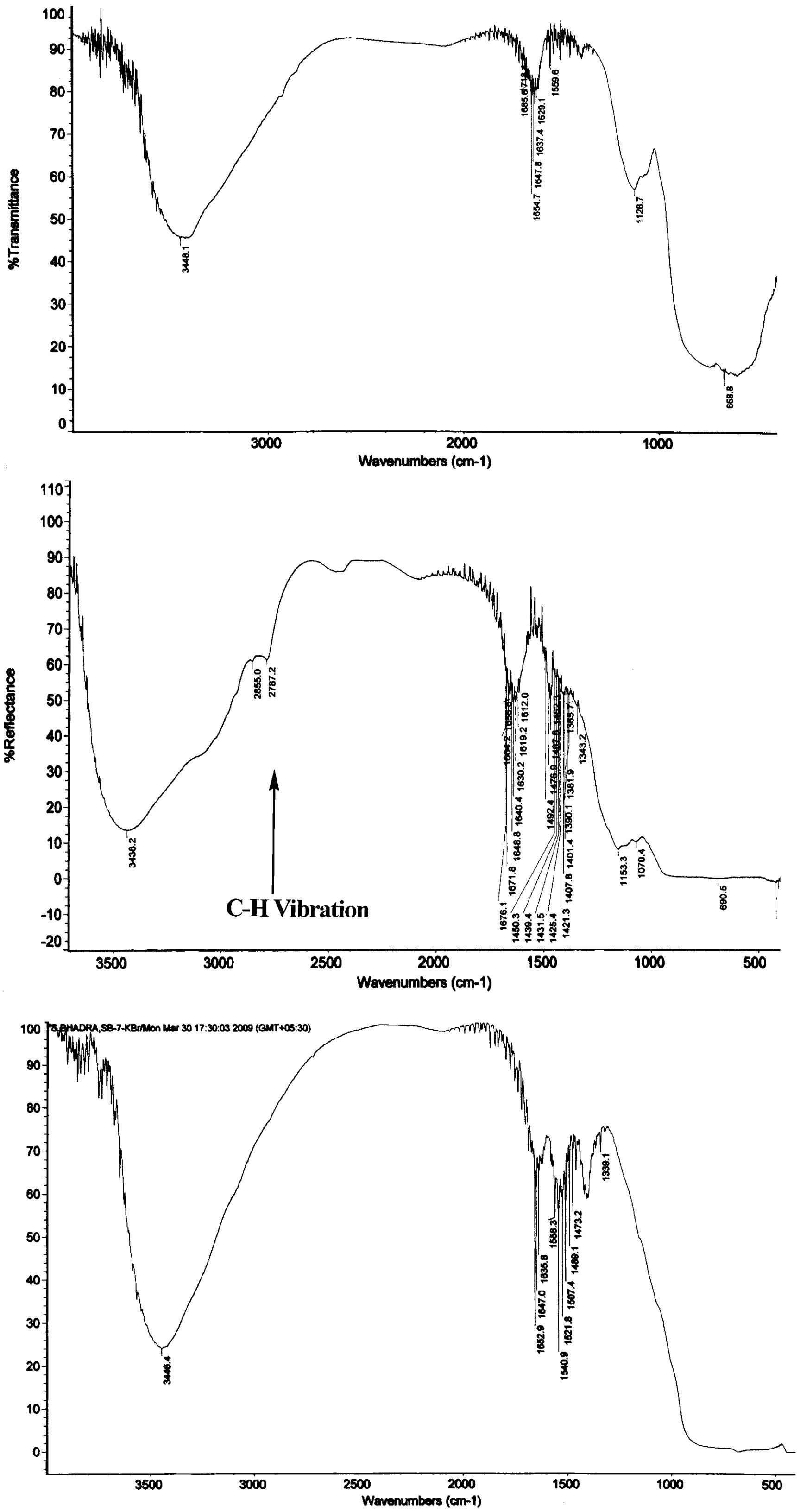
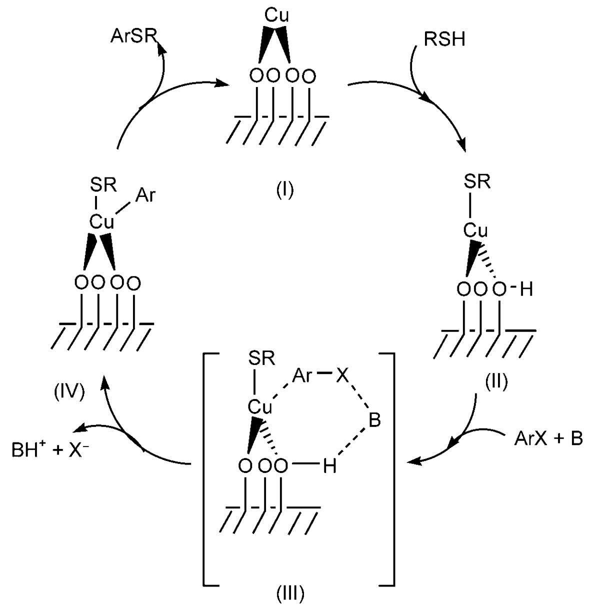


Figure 5. (*Top*) FT-IR spectrum of the fresh Cu/Al_2O_3 catalyst. (*Middle*) FT-IR spectrum of Cu/Al_2O_3-thiophenol complex. (*Bottom*) FT-IR spectrum of used catalyst.



Scheme 3. Possible reaction pathway.

mina (6.5 g) was added and the resulting solution was stirred at an ambient temperature for 2 h. The excess water was evaporated on a rotary-evaporator under reduced pressure followed by drying under high vacuum at 120 °C for 8 h to get the Cu/Al_2O_3 catalyst as a light green powder. (Copper content of the fresh catalyst: 0.517 mmol g^{-1} as measured by ICP-MS).

General Procedure for Coupling of Thiophenol with Aryl Iodide

To a solution of iodobenzene (204 mg, 1 mmol) and thiophenol (121 mg, 1.1 mmol) in DMF (3 mL) was added K_2CO_3 (276 mg, 2 mmol) and Cu-Al_2O_3 catalyst (100 mg, 5 mol%) and the mixture was heated at 110 °C (oil bath) for a period of time required for completion (TLC). The reaction mixture was allowed to cool and diluted with Et_2O (30 mL) followed by washing with aqueous (10%) NaOH solution (2 × 2 mL) and brine. The organic phase was dried (Na_2SO_4) and evaporated to leave the crude product which was purified by column chromatography over silica gel (hexane) to provide pure diphenyl sulfide as a colourless oil; yield: 181 mg (97%). The spectroscopic data (^1H NMR and ^{13}C NMR) of this product are in good agreement with those of an authentic sample.

This procedure was followed for all the reactions listed in Table 2. The coupling with aryl bromide was carried out by the same procedure using CS_2CO_3 (1.5 equiv.) in place of K_2CO_3 (Table 3).

Recovery of Catalyst

After the reaction was over, the reaction mixture was centrifuged and filtered. The residue was washed with water (5 × 3 mL) followed by acetone (3 × 4 mL). The solid was then dried at 100 °C for 8 h for further use. The catalyst was recycled for 8 times for the coupling reaction of iodobenzene and thiophenol without any loss of activity (Figure 6). The Cu content of the catalyst after 8th cycle is found to be 0.503 mmol g^{-1} compared to that of the fresh catalyst as 0.517 mmol g^{-1} as detected by ICP-MS analysis.

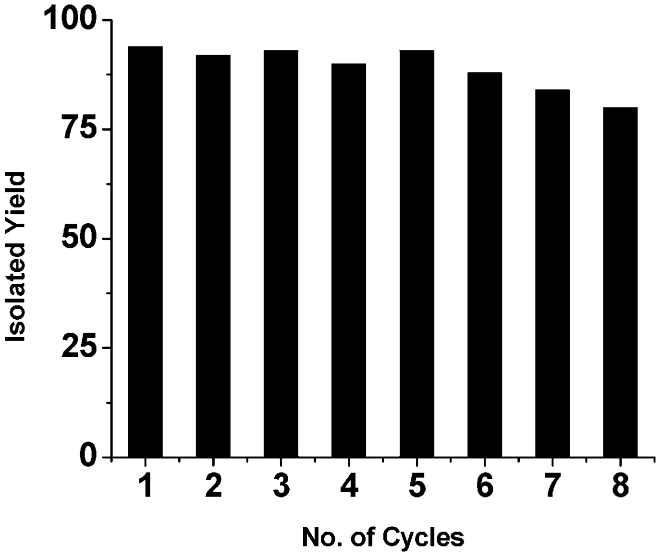


Figure 6. Recyclability chart of the Cu/Al_2O_3 catalyst.

Although the representative experimental procedure was based on a mmol scale, this procedure was also effective for multigram (10 g) scale reactions with uniform results.

The known compounds were identified by comparison of their spectra with those of authentic samples (see references in Tables 2–5). The unknown compounds were properly characterized by their spectroscopic data (IR, ^1H NMR, ^{13}C NMR and HR-MS) data and elemental analysis and these data are provided below in order of their entries in the respective Tables.

1-Fluoro-3-(4-chlorophenylsulfanyl)benzene (Table 2, entry 6): Yellow liquid; IR (neat): $\nu = 3039$, 1486, 1474, 1103, 754, 619 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$): $\delta = 6.93$–7.00 (m, 2H), 7.07 (d, 1H, $J = 7.86$ Hz), 7.23–7.44 (m, 5H); ^{13}C NMR (75 MHz, $CDCl_3$): $\delta = 113.9$ (d, $J_{C,F} = 22.5$ Hz), 116.8 (d, $J_{C,F} = 22.5$ Hz), 125.5, 129.4, 129.7 (2C), 130.5 (d, $J_{C,F} = 8.5$ Hz), 133.9 (2C), 138.5 (d, $J_{C,F} = 7.65$ Hz), 163.0 (d, $J_{C,F} = 247.5$ Hz); anal. calcd. for $C_{12}H_8ClFS$: C 60.38, H 3.38; found: C 60.67, H 3.32.

1-(4-Chlorophenylsulfanyl-4-trifluoromethoxybenzene (Table 2, entry 7): Yellow liquid; IR (neat): $\nu = 3018$, 1489, 1475, 1261, 1215, 1170, 758 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$): $\delta = 7.16$ (d, 2H, $J = 8.4$ Hz), 7.27–7.35 (m, 6H); ^{13}C NMR (75 MHz, $CDCl_3$): $\delta = 118.8$, 121.9 (2C), 129.7 (2C), 132.2 (2C), 132.8 (2C), 133.7, 133.9, 148.5; anal. calcd for $C_{13}H_8ClF_3OS$: C 51.25, H 2.65; found: C 51.17, H 2.67.

2-(4-Chlorophenylthio)benzoic acid (Table 2, entry 9): White solid (mp 162–163 °C); IR (KBr): $\nu = 3320$, 1676, 1558, 1462, 1315, 1253, 900, 813, 744 cm^{-1}; ^1H NMR (300 MHz, DMSO-d_6): $\delta = 6.75$ (d, 1H, $J = 8.04$ Hz), 7.21 (t, 1H, $J = 7.38$ Hz), 7.36 (t, 1H, $J = 8.04$ Hz), 7.55 (m, 4H), 7.93 (d, 1H, $J = 7.38$ Hz), 13.27 (bs, 1H); ^{13}C NMR (75 MHz; DMSO-d_6): $\delta = 127.1$, 127.9, 130.3 (2C), 130.8, 131.4, 132.4, 136.5 (2C), 140.8, 167.3; HR-MS: $m/z = 286.9903$, calcd. for $C_{13}H_9ClO_2S$ $[M+Na]^+$: 286.9909.

2-(2-Bromophenylsulfanyl)pyridine (Table 2, entry 11): Colourless liquid; IR (neat): $\nu = 3047$, 1573, 1448, 1417, 1116, 1020, 754 cm^{-1}; ^{1}H NMR (300 MHz, CDCl$_3$): $\delta = 6.91$ (d, 1H, $J = 7.9$ Hz), 7.02 (t, 1H, $J = 6.08$ Hz), 7.23 (t, 1H, $J = 7.45$ Hz), 7.32 (t, 1H, $J = 7.45$ Hz), 7.48 (t, 1H, $J = 7.62$ Hz), 7.62 (d, 1H, $J = 7.62$ Hz), 7.68 (d, 1H, $J = 7.90$ Hz), 8.43 (s, 1H); ^{13}C NMR (75 MHz, CDCl$_3$): $\delta = 120.4$, 122.1, 128.3, 129.4 (2C), 130.4, 132.8, 133.8, 136.4, 136.9, 149.8, 159.2; HR-MS: $m/z = 295.9646$, calcd. for $C_{11}H_8BrNS$ $[M+H]^+$: 265.9639.

3-(4-Chlorophenylthio)pyridine (Table 2, entry 16): Yellow oil; IR (neat): $\nu = 3070$, 3043, 1566, 1473, 1406, 1091, 1014, 819, 704 cm^{-1}; ^{1}H NMR (300 MHz, CDCl$_3$): $\delta = 7.23$–7.28 (m, 5H), 7.57–7.60 (m, 1H), 8.47–8.55 (m, 2H); ^{13}C NMR (75 MHz, CDCl$_3$): $\delta = 122.8$, 128.3 (2C), 131.2, 131.4 (2C), 131.9, 132.6, 136.8, 146.6, 149.5; HR-MS: $m/z = 222.0139$, calcd. for $C_{11}H_8ClNS$ $[M+H]^+$: 222.0156.

2-[3-(Trifluoromethyl)phenylthio]benzo[*d*]thiazole (Table 2, entry 17): Colourless oil; IR (neat): $\nu = 3063$, 1461, 1426, 1323, 1130, 756, 695 cm^{-1}; ^{1}H NMR (300 MHz, CDCl$_3$): $\delta = 7.25$ (t, 1H, $J = 7.41$ Hz), 7.37 (t, 1H, $J = 7.41$ Hz), 7.52 (t, 1H, $J = 7.41$ Hz), 7.62–7.69 (m, 2H), 7.83–7.87 (m, 2H), 7.95 (s, 1H); ^{13}C NMR (75 MHz, CDCl$_3$): $\delta = 121.0$, 121.6, 122.3, 124.8, 126.4, 126.9, 130.3, 131.3, 131.6, 132.4, 135.7, 137.9, 153.7, 166.7; HR-MS: $m/z = 310.0120$, calcd. for $C_{14}H_8F_3NS_2$ $[M+H]^+$: 312.0156.

2-(3,5-Dimethylphenylthio)pyridine (Table 2, entry 18): Colourless oil; IR (neat): $\nu = 3041$, 2917, 1600, 1573, 1560, 1447, 1416, 1144, 1124, 849, 758, 688 cm^{-1}; ^{1}H NMR (300 MHz, CDCl$_3$): $\delta = 2.33$ (s, 6H), 6.89 (d, 1H, $J = 7.9$ Hz), 6.94–6.97 (m, 1H), 6.98 (s, 1H), 7.22 (s, 2H), 7.39–7.45 (m, 1H), 8.40–8.42 (m, 1H); ^{13}C NMR (75 MHz, CDCl$_3$): $\delta = 21.1$ (2C), 119.6, 121.1, 130.2, 130.9, 132.5 (2C), 136.6, 139.2 (2C), 149.4, 161.9; HR-MS: $m/z = 216.0845$, calcd. for $C_{13}H_{13}NS$ $[M+H]^+$: 216.0859.

2-(4-Fluorophenylsulfanyl)phenylamine (Table 3, entry 4): Colourless liquid; IR (neat): $\nu = 3317$, 2956, 1513, 1469, 1288, 1102, 1010, 811, 752 cm^{-1}; ^{1}H NMR (300 MHz, DMSO-d_6): $\delta = 5.40$ (broad, 2H), 6.55–6.60 (m, 1H), 6.79–6.82 (m, 1H), 7.10–7.18 (m, 5H), 7.29–7.32 (m, 1H); ^{13}C NMR (75 MHz, DMSO-d_6): $\delta = 113.0$, 115.4, 116.5 (d, 2C, $J_{C,F} = 22.5$ Hz), 117.2, 129.4 (2C), 131.5, 132.5, 137.2, 150.6, 161.0 (d, 1C, $J_{C,F} = 247.5$ Hz); HRMS: $m/z = 220.0598$, calcd. for $C_{12}H_{10}FNS$ $[M+H]^+$: 220.0625.

2-(4-Chlorophenylsulfanyl)thiophene (Table 3, entry 6): Colourless liquid; IR (neat): $\nu = 3057$, 1579, 1475, 1438, 1217, 1022, 738, 688 cm^{-1}; ^{1}H NMR (300 MHz, CDCl$_3$): $\delta = 7.11$–7.38 (m, 5H), 7.50–7.58 (m, 2H); ^{13}C NMR (75 MHz, CDCl$_3$): $\delta = 126.1$, 127.2 (3C), 127.6 (2C), 128.0, 131.3, 136.1, 137.1; HR-MS: $m/z = 225.9662$, calcd. for $C_{10}H_7ClS_2$ $[M+H]^+$: 226.9756.

1-[4-(Pyridin-2-ylsulfanyl)phenyl]ethanone (Table 3, entry 7): Colourless liquid; IR (neat): $\nu = 3046$, 3000, 1680, 1620, 1526, 1417, 1262, 1120, 1095, 826, 760 cm^{-1}; ^{1}H NMR (300 MHz, CDCl$_3$): $\delta = 2.56$ (s, 3H), 7.05–7.11 (m, 2H), 7.50–7.55 (m, 3H), 7.88–7.91 (m, 2H), 8.42–8.43 (m, 1H); ^{13}C NMR (75 MHz, CDCl$_3$): $\delta = 26.6$, 121.1, 123.5, 129.1 (2C), 132.7 (2C), 136.4, 137.1, 138.7, 150.0, 158.6, 197.2; HR-MS: $m/z = 230.0633$, calcd. for $C_{13}H_{11}NOS$ $[M+H]^+$: 230.0625.

2-*p*-Tolylsulfanylbenzothiazole (Table 3, entry 8): Colourless liquid; IR (neat): $\nu = 3065$, 1638, 1476, 1323, 1170, 1131, 1008, 756, 695 cm^{-1}; ^{1}H NMR (300 MHz, CDCl$_3$): $\delta = 2.34$ (s, 3H), 7.12–7.20 (m, 3H), 7.30 (t, 1H, $J = 7.32$ Hz), 7.53 (d, 3H, $J = 7.97$ Hz), 7.79 (d, 1H, $J = 7.97$ Hz); ^{13}C NMR (75 MHz, CDCl$_3$): $\delta = 21.4$, 120.7, 121.7, 124.1, 126.1, 126.2 (2C), 130.7 (2C), 135.4, 135.5 (2C), 154.0, 170.8; HR-MS: $m/z =$ 258.0425, calcd. for $C_{14}H_{11}NS_2$ $[M+H]^+$: 258.0411.

2-(4-Butylsulfanylphenylsulfanyl)phenylamine (Scheme 2, entry 1): Pale brown oil; IR (neat): $\nu = 3426$, 2252, 1665, 1108, 1051, 1026, 824, 762 cm^{-1}; ^{1}H NMR (300 MHz, CDCl$_3$): $\delta = 0.90$–0.96 (m, 3H), 1.38–1.50 (m, 2H), 1.56–1.67 (m, 2H), 2.87 (t, 3H, $J = 7.2$ Hz), 4.27 (broad, 2H), 6.75–6.83 (m, 2H), 7.04 (d, 2H, $J = 8.3$ Hz), 7.19–7.27 (m, 3H), 7.46 (d, 1H, $J = 7.6$ Hz); ^{13}C NMR (75 MHz, CDCl$_3$): $\delta =$ 13.7, 21.9, 31.3, 33.7, 115.6, 118.9, 121.9, 123.6, 126.2 (2C), 129.9 (2C), 131.1, 134.2, 137.3, 148.5; anal. calcd. for $C_{16}H_{19}NS_2$: C 66.39, H 6.62, N 4.84; found: C 66.20, H 6.51, N 4.81.

2-(3-Phenylsulfanylphenylsulfanyl)phenylamine (Scheme 2, entry 3): Brownish viscous oil; IR (neat): $\nu =$ 3470, 3369, 3059, 1606, 1568, 1477, 1438, 1307, 1159, 1072, 771, 748 cm^{-1}; ^{1}H NMR (300 MHz, CDCl$_3$): $\delta = 4.57$ (broad, 2H), 6.74–6.84 (m, 2H), 6.90–6.95 (m, 1H), 7.03–7.06 (m, 2H), 7.09–7.16 (m, 1H), 7.20–7.45 (m, 7H); ^{13}C NMR (75 MHz, CDCl$_3$): $\delta = 114.5$, 116.0, 119.5, 124.7, 127.1, 127.6, 129.3 (2C), 129.6, 131.3, 132.0 (2C), 134.5, 137.4, 137.6, 138.1, 147.9; anal. calcd. for $C_{18}H_{15}NS_2$: C 69.86, H 4.89, N 4.53; found: C 69.81, H 4.77, N 4.61.

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References

[1] a) D. N. Jones, in: *Comprehensive Organic Chemistry*, (Eds.: D. H. Barton, D. W. Ollis), Pergamon, New York, **1979**, Vol. 3; b) D. J. Procter, *J. Chem. Soc. Perkin Trans. 1* **2001**, 335–354.

[2] a) *Metal-Catalyzed Cross-Coupling Reactions*, (Eds.: F. Diederich, A. de Meijere), Wiley-VCH, Weinheim, **2004**; b) A. R. Muci, S. L. Buchwald, *Top. Curr. Chem.* **2002**, *219*, 131.

[3] a) M. A. Fernandez-Rodriguez, Q. Shen, J. F. Hartwig, *J. Am. Chem. Soc.* **2006**, *128*, 2180–2181; b) T. Itoh, T. Mase, *Org. Lett.* **2004**, *6*, 4587–4590; c) G. y-Li, *Angew. Chem.* **2001**, *113*, 1561–1564; *Angew. Chem. Int. Ed.* **2001**, *40*, 1513–1516; d) G. y-Li, G. Zheng, A. F. Noonan, *J. Org. Chem.* **2001**, *66*, 8677–8681; e) U. Schopfer, A. Schlapbach, *Tetrahedron* **2001**, *57*, 3069–3073.

[4] a) S. Jammi, S. Sakthivel, L. Rout, T. Mukherjee, S. Mandal, R. Mitra, P. Saha, T. Punniyamurthy, *J. Org. Chem.* **2009**, *74*, 1971–1976; b) H.-J. Xu, X.-y. Zhao, J. Deng, Y. Fu, Y.-S. Feng, *Tetrahedron Lett.* **2009**, *50*, 434–437; c) E. Sperotto, G. P. M. van Klink, J. G. de Vries, G. u. Koten, *J. Org. Chem.* **2008**, *73*, 5625–5628; d) H.-J. Xu, X.-y. Zhao, Y. Fu, Y.-S. Feng, *Synlett* **2008**, 3063–3067; e) P. Buranaprasertsuk, J. W. W. Chang, W.

Chavasiri, P. W. H. Chan, *Tetrahedron Lett.* **2008**, *49*, 2023–2025; f) L. Rout, T. K. Sen, T. Punniyamurthy, *Angew. Chem.* **2007**, *119*, 5679–5682; *Angew. Chem. Int. Ed.* **2007**, *46*, 5583–5586; g) B. C. Ranu, A. Saha, R. Jana, *Adv. Synth. Catal.* **2007**, *349*, 2690–2696, and references cited therein; h) F. Y. Kwong, S. L. Buchwald, *Org. Lett.* **2002**, *4*, 3517–3520; i) H. Zhang, W. Cao, D. Ma, *Synth. Commun.* **2007**, *37*, 25–35; j) K. Kauz, U. Schlotz, D. Ganzer, *Synlett* **2003**, 2428–2439; k) Y. J. Wu, H. He, *Synlett* **2003**, 1789–1790; l) N. Jung, S. Brase, *J. Comb. Chem.* **2009**, *11*, 47–71; m) M. Carril, R. SanMartin, E. Dominguez, I. Tellitu, *Chem. Eur. J.* **2007**, *13*, 5100–5105.

[5] Y.-C. Wong, T. T. Jayanth, C.-H. Cheng, *Org. Lett.* **2006**, *8*, 5613–5616.

[6] a) S. Jammi, P. Barua, L. Rout, P. Saha, T. Punniyamurthy, *Tetrahedron Lett.* **2008**, *49*, 1484–1487; b) N. Taniguchi, *J. Org. Chem.* **2004**, *69*, 6904–6906.

[7] a) W.-Y. Wu, J.-C. Wang, F.-Y. Tsai, *Green Chem.* **2009**, *11*, 326–329; b) A. Correa, M. Carril, C. Bolm, *Angew. Chem.* **2008**, *120*, 2922–2925; *Angew. Chem. Int. Ed.* **2008**, *47*, 2880–2883.

[8] L. Yin, J. Leibescher, *Chem. Rev.* **2007**, *107*, 133–173.

[9] a) B. C. Gates, *Chem. Rev.* **1995**, *95*, 511–522; b) D. E. Bergbreiter, *Med. Res. Rev.* **1999**, *19*, 439–450.

[10] B. C. Ranu, L. Adak, K. Chattopadhyay, *J. Org. Chem.* **2008**, *73*, 5609–5612.

[11] The $CuSO_4$-Al_2O_3 catalyst was prepared following a reported procedure.[12] The catalyst was characterized by FT-IR, AFM, FE-SEM, XPS and ICP-MS techniques.

[12] T. Sakamoto, H. Yonehara, C. Pac, *J. Org. Chem.* **1994**, *59*, 6859–6861.

[13] a) S. Sivaramakrishnan, K. S. Gates, *Bioorg. Med. Chem. Lett.* **2008**, *18*, 3076–3080; b) H. L. Holland, C. D. Turner, P. R. Andreana, D. Nguyen, *Can. J. Chem.* **1999**, *77*, 463–471; c) A. W. Erian, A. Konno, T. Fuchigami, *Tetrahedron Lett.* **1994**, *35*, 7245–7248.

[14] a) O. Goyot, M. Gingras, *Tetrahedron Lett.* **2009**, *50*, 1977–1981; b) Y. Ding, A. S. Hay, *Tetrahedron* **1997**, *53*, 15237–15246.

[15] B. M. Choudary, C. Sridhar, M. L. Kantam, G. T. Venkanna, B. Sreedhar, *J. Am. Chem. Soc.* **2005**, *127*, 9948–9949.

[16] C. Palomo, M. Oiarbide, R. Lopez, E. Gomez-Bengoa, *Tetrahedron Lett.* **2000**, *41*, 1283–1286.

[17] M. Lu, Y. Pan, Z. Peng, *Tetrahedron Lett.* **2002**, *43*, 7903–7906.

[18] O. Bistri, A. Correa, C. Bolm, *Angew. Chem.* **2008**, *120*, 596–598; *Angew. Chem. Int. Ed.* **2008**, *47*, 586–588.

[19] T. Sato, E. Yamada, Y. Akiyama, H. Inoue, K. Hata, *Bull. Chem. Soc. Jpn.* **1965**, *38*, 1225.

[20] J. L. Bolliger, C. M. Frech, *Tetrahedron* **2009**, *65*, 1180–1187.

[21] M. J. Cawley, F. Geoffrey, N. Cloke, R. J. Fitzmaurice, S. E. Pearson, J. S. Scott, S. Caddick, *Org. Biomol. Chem.* **2008**, *6*, 2820–2825.

[22] A. Prades, R. Corberan, M. Poyatos, E. Peris, *Chem. Eur. J.* **2008**, *14*, 11474–11479.