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通过锌催化区域选择性氧化反应实现 3-烯-1-炔的 1，4-官能团化

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摘要 γ-羟基或烷氧基取代的 α，β-不饱和羰基化合物广泛存在于众多天然产物和生物活性分子之中. 本工作通过锌催化的区域选择性的氮氧化合物氧化炔烃反应，实现了 3-烯-1-炔的 4-烷氧化-1-氧化官能团化. 该串联反应可以中等到良好的产率得到系列合成上很有用的 γ-烷氧基取代的 α，β-不饱和酰胺化合物.

关键词 氧化反应；1，4-官能团化；炔烃；串联反应

1,4-Functionalization of 3-En-1-ynes with Alcohols via Zinc-Catalyzed Regioselective *N*-oxide Oxidation

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Abstract γ-hydroxyl or γ-alkoxyl-substituted α,β-unsaturated carbonyls widely exist in a variety of natural products and bioactive molecules. Herein, we describe the realization of 1,4-functionalization of 3-en-1-ynes with alcohols through zinc-catalyzed regioselective *N*-oxide oxidation. This tandem reaction allows the practical synthesis of a range of valuable γ-alkoxyl-substituted α,β-unsaturated amides in moderate to good yields.

Keywords oxidation; 1,4-functionalization; alkynes; tandem reaction

γ-羟基或烷氧基取代的 α，β-不饱和羰基化合物是一类应用广泛的羰基化合物，存在于多种天然产物和生物活性分子之中(图 1)[1]. 此外，该类化合物可进一步化学转化，合成得到系列官能团化的羰基化合物[2]. 因此，γ-羟基或烷氧基取代的 α，β-不饱和羰基化合物的合成研究也受到了较多关注. 但是，目前制备该类 α，β-不饱和羰基化合物的方法还非常有限，且往往效率低下、步骤繁琐[3]. 因此，发展新的有效的合成 γ-羟基或烷氧基取代的 α，β-不饱和羰基化合物的方法具有重要的理论和现实意义.

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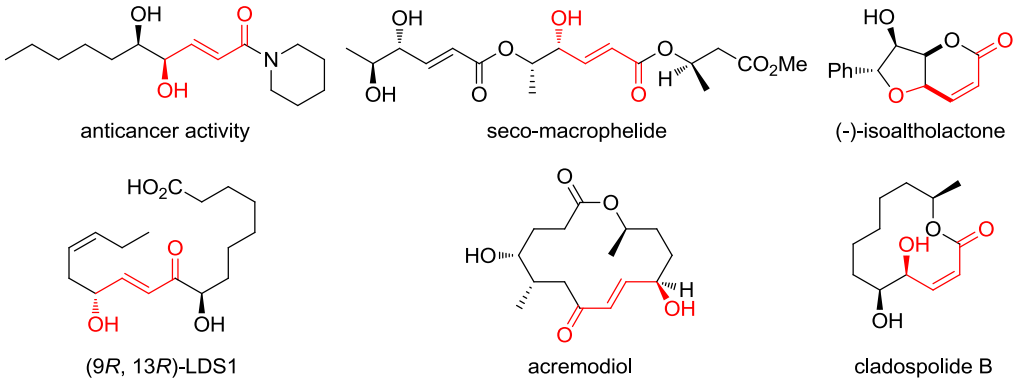


图 1 存在于生物活性分子中的 γ-羟基或烷氧基取代的 α，β-不饱和羰基化合物

Figure 1 γ-Hydroxyl or γ-alkoxyl-substituted α,β-unsaturated carbonyls in bioactive molecules

2014 年，Rai-shung Liu 小组发现，当使用 5 mol % $Zn(OTf)_2$ 作为催化剂，10 mol % 吡啶作为碱，2 当量的 Selectfluor 作为氧化剂时，3-烯-1-炔底物可方便转化成相应的 γ-羟基取代的 α，β-不饱和酰胺化合物(图 2a)[4]. 但是，该反应不足之处是反应过程中总会伴随着少量 1,4-二羰基化合物的生成. 在本课题组之前对炔酰胺化学的研究工作中[5,6]，我们实现了一系列廉价金属如锌、铜、铕等催化的炔酰胺氧化反应[7,8]引发的串联反应[9]，从而发展了一系列高效的炔酰胺的氧官能团化反应. 但是，上述氧官能团化反应目前仅局限于 1,2-双官能团化，尚未有相应的 1,4-氧官能团化反应报道. 受上述研究工作的启发，为了进一步拓宽该类廉价金属催化炔酰胺氧化反应的应用，我们设想使用来源易得的 3-烯-1-炔类化合物与各种醇反应，将有望实现基于该类烯炔的 1,4-氧官能团化反应，进而得到 γ-烷氧基取代的 α，β-不饱和酰胺化合物，为制备相关结构的功能分子提供一种更为绿色简洁的方法(图 2b).

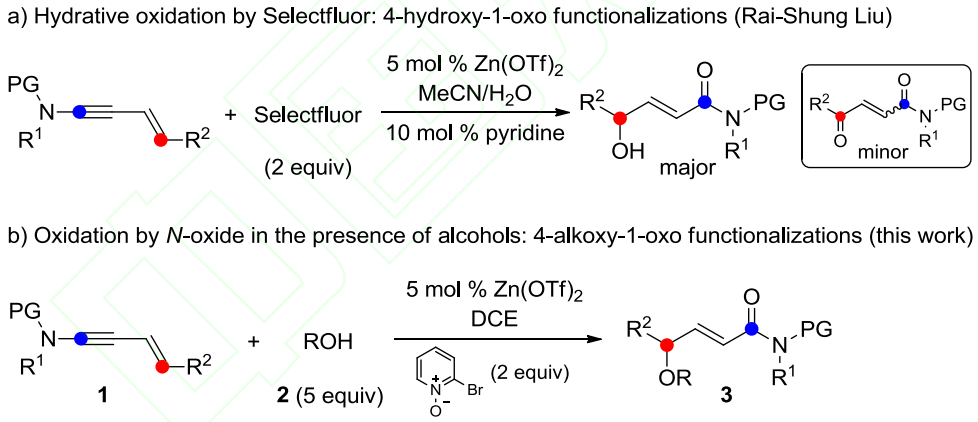


图 2 区域选择性的 3-烯 1-炔的 1，4-官能团化反应

Figure 2 Regioselective 1,4-functionalization of 3-en-1-ynes

1 结果与讨论

1.1 反应条件优化

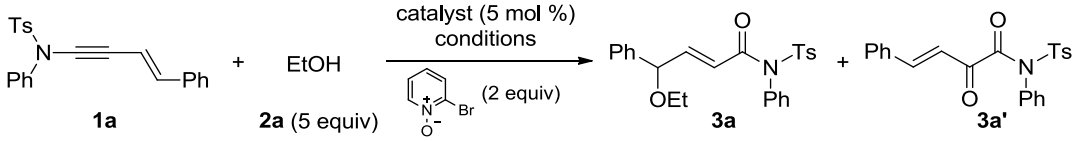
0.1 mmol 炔酰胺 **1a**，0.5 mmol 乙醇 **2a**，0.2 mmol 2-溴吡啶氮氧和 0.05 mmol PPh_3AuNTf_2 在 2 mL 1,2-二氯乙烷(DCE)中反应，用 TLC 监控反应，80 °C 搅拌反应 3 小时后，原料反应完全. 通过核磁氢谱内标分析反应体系发现目标产物 **3a** 产率 66%，副产物 **3a′**产率 22% (Table 1, Entry 1). 用上述投料比，以炔酰胺 **1a** 为模型底物，进行反应条件的优化，炔酰胺 **1a** 在不同条件下的反应结果见表 1.

研究发现，当使用其他金催化剂如 $IPrAuNTf_2$ 时，也能得到产物 **3a**，但副产物 **3a′**产率有所上升(Table 1, Entry 2).

接着，我们尝试不同的廉价金属催化剂，发现使用 $Cu(OTf)_2$、$Fe(OTf)_2$、$Zn(OTf)_2$ 和 $Sc(OTf)_3$ 作为催化剂时反应也都能得到产物 **3a**，并且几乎不产生过氧化副产物 **3a′**(Table 1, Entries 3~6), 其中使用 $Zn(OTf)_2$ 作为催化剂时的产率最高, 可达 72% (Table 1, Entry 5). 另外，我们也尝试了不同的反应溶剂如甲苯和氯苯(Table 1, Entry 7，Entry 8)，发现产率都会显著下降. 需要指出的是，当把乙醇的用量减少至 2 当量时，该类反应也能较好进行，产率稍有下降(Table 1, Entry 9).特别是，该类反应在 40 °C 下也能进行，产率几乎不变，只是反应时间会大大延长(Table 1, Entry 10).

表 1 反应条件优化 [a]

Table 1 Optimization of reaction conditions



Entry	catalyst	Conditions	Yield[b]/% **3a**	Yield[b]/% **3a′**
1	$Ph_3PAuNTf_2$	DCE, 80 °C, 3 h	66	22
2	$IPrAuNTf_2$	DCE, 80 °C, 3 h	51	29
3	$Cu(OTf)_2$	DCE, 80 °C, 3 h	56	<1
4	$Fe(OTf)_2$	DCE, 80 °C, 3 h	57	<1
5	$Zn(OTf)_2$	DCE, 80 °C, 3 h	72	<1
6	$Sc(OTf)_3$	DCE, 80 °C, 3 h	59	<1
7	$Zn(OTf)_2$	toluene, 80 °C, 3 h	57	<1
8	$Zn(OTf)_2$	PhCl, 80 °C, 3 h	54	<1
9[c]	$Zn(OTf)_2$	DCE, 80 °C, 3 h	60	<1
10	$Zn(OTf)_2$	DCE, 40 °C, 8 h	70	<1

[a] Reaction run in vials; [**1a**] = 0.05 M. [b] Measured by ^{1}H NMR using diethyl phthalate as the internal standard. [c] 2 equiv of EtOH was used.

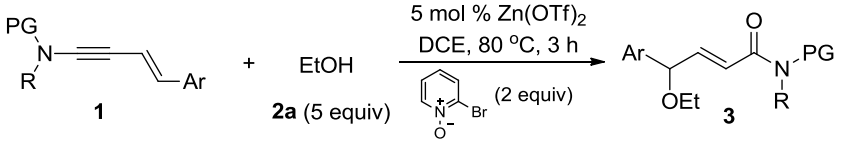
通过上述的条件优化，最终我们确定了该反应的最优条件是：2-溴吡啶氮氧(2 equiv)为氧化剂，溶剂为 1，2-二氯乙烷，$Zn(OTf)_2$ (5 mol %)为催化剂，反应温度 80℃，反应时间为 3 h (Table 1, Entry 5).

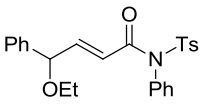
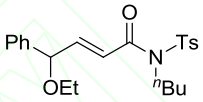
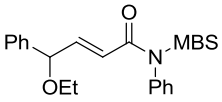
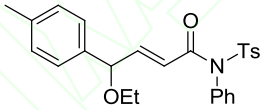
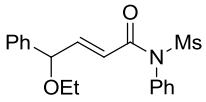
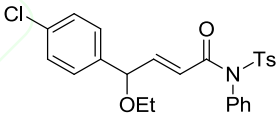
1.2 反应适用性研究

在最优化的反应条件下，我们对该区域选择性的氮氧化合物氧化炔烃反应的普适性进行了研究. 如表2所示，各种取代的α，β-不饱和炔酰胺底物都能很好地进行该反应，以中等到良好的产率得到相应的γ-烷氧基取代的α，β-不饱和羰基化合物(59%-83%). 首先，α，β-不饱和炔酰胺N上各种不同的保护基对反应体系都表现出良好的兼容性(Table 2, Entries 1~3). 对于R基团，无论是苯基还是正丁基，底物几乎都能以中等的产率转化成相应的目标产物**3a**和**3d** (Table 2, Entries 1, 4), 但是当R基团为正丁基时产率略低. 进一步考察Ar基团，当在苯环的对位，供电子的甲基取代时，产率明显上升(Table 2, Entry 5); 而若是吸电子的氯原子取代，对反应的结果差异很小，能以相当的产率得到所需产物**3f** (Table 2, Entry 6). 需要指出的是，当炔酰胺底物**1**中的Ar基团改为脂肪基时，反应产率明显降低(核磁产率<20%).

表 2 反应范围 [a]

Table 2 The reaction scope



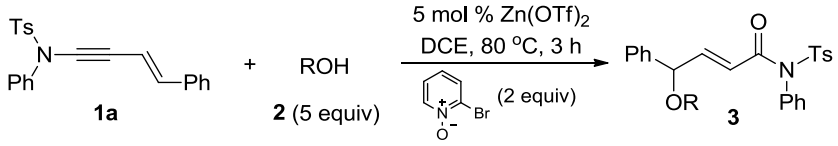
Entry	Product	**3**/Yield	Entry	Product	**3**/Yield
1		**3a**, 65%	4		**3d**, 59%
2		**3b**, 63%	5		**3e**, 83%
3		**3c**, 64%	6		**3f**, 66%

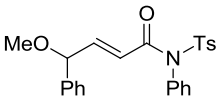
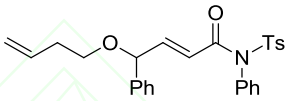
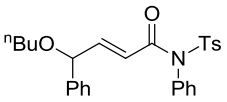
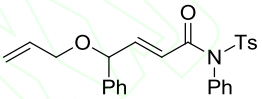
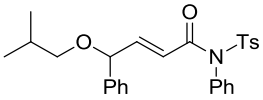
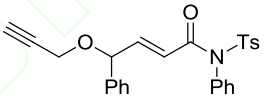
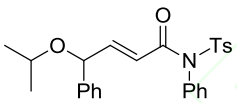
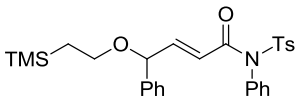
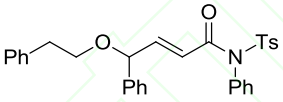
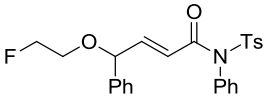
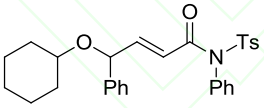
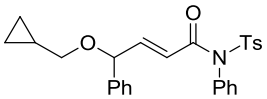
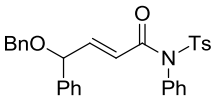
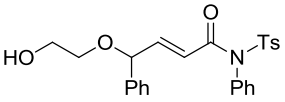
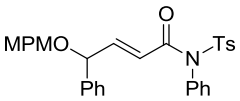
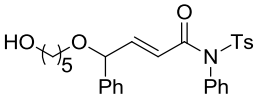
[a] Reactions run in vials; isolated yields are reported.

接下来，我们对该分子间反应的醇类底物普适性也进行了研究. 如表 3 所示，各种具有典型意义的醇类底物都能顺利地进行反应，均能以较高的产率得到相应的 γ-烷氧基取代的 α，β-不饱和羰基化合物(68%-86%). 对于简单醇，不论是直链或带支链的脂肪醇，底物几乎都能以较高的产率转化成目标产物 **3g~3k** (Table 3, Entries 1~5). 值得一提的是，当使用二级醇参与该反应时，也能以 80%的产率得到相应的产物 **3l** (Table 3, Entry 6). 进一步考察带有不同官能团的醇的反应，如含有苄基、对甲氧基苄基、炔基、TMS、氟原子和环丙基，发现该反应体系对其均有良好的兼容性，且都能以较高的产率得到所需的产物 **3m~3t** (Table 3, Entries 7~14). 最后，我们还尝试利用二元醇进行反应，在最佳条件下，也能分别以 72%和 80%的产率得到单取代的产物 **3u~3v** (Table 3, Entries 15~16)，进一步表明该反应对没有保护的羟基也能很好的兼容. 至此，该类廉价金属催化烯炔的 1,4-氧官能团化反应为 γ-烷氧基取代的 α，β-不饱和酰胺化合物的合成提供了一条简洁而高效的合成路径. 最后，还需要指出的是，当使用胺(如苯胺或苄胺)或酰胺(如 $TsNH_2$)取代醇时，该类反应产率很低(核磁产率<20%)，进一步的优化正在进行之中.

表 3 反应范围 [a]

Table 3 The reaction scope



Entry	Product	**3**/Yield	Entry	Product	**3**/Yield
1		**3g**, 73%	9		**3o**, 80%
2		**3h**, 78%	10		**3p**, 78%
3		**3i**, 83%	11		**3q**, 76%
4		**3j**, 72%	12		**3r**, 68%
5		**3k**, 84%	13		**3s**, 70%
6		**3l**, 80%	14		**3t**, 86%
7		**3m**, 81%	15		**3u**, 72%
8		**3n**, 70%	16		**3v**, 80%

[a] Reactions run in vials; isolated yields are reported.

该类 γ-烷氧基取代的 α，β-不饱和羰基化合物很容易通过一步简单的化学转化，得到各种脱保护的 γ-烷氧基或 γ-羟基取代的 α，β-不饱和羰基化合物. 比如，化合物 **3c** 与 Bu_3SnH 回流反应脱除甲基磺酸基，可得到相应的合成上有用的 α，β-不饱和单取代酰胺 **3ca**；化合物 **3n** 与 DDQ 室温反应可脱除甲氧苄基保护基，以 83%产率得到 γ-羟基

取代的 α，β-不饱和羰基化合物 **3na** (图 3).

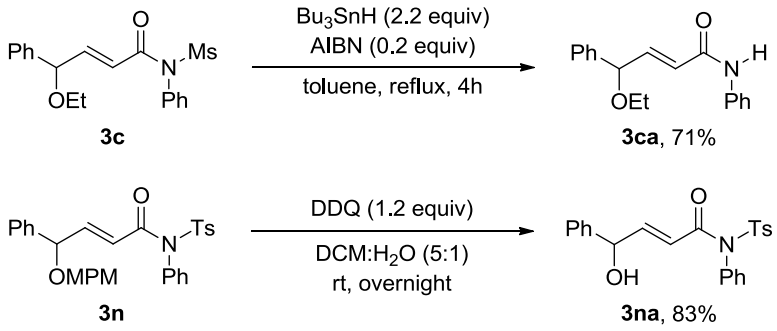


图 3 产物的进一步衍生化

Figure 3 Product elaboration

最后，基于之前在炔酰胺氧化反应的系列研究结果[6]，我们也提出了该类反应的可能机理，如图 4 所示. 首先，氧化剂 2-溴吡啶氮氧进攻 $Zn(OTf)_2$ 活化的炔酰胺底物 **A** 得到烯基锌中间体 **B**，该中间体再经分子间的 S_N2' 进攻[9]便可得到 α 位锌取代的酰胺中间体 **C**. 中间体 **C** 再经质子化脱金属，即可得到最终的 γ-烷氧基取代的 α，β-不饱和酰胺 **3a**，同时产生锌催化剂，进入下一个反应循环.

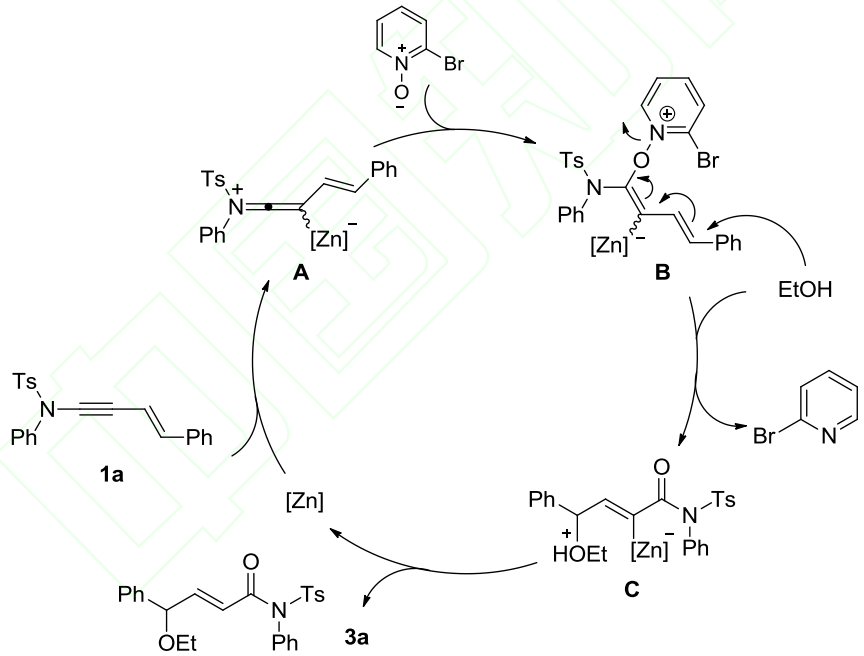


图 4 可能的反应机理

Figure 4 Plausible reaction mechanism

2 结论

综上所述，我们成功实现了具有挑战性的锌催化区域选择性氧化 3-烯-1-炔的 1，4-官能团化反应，以中等到良好的产率得到了各种官能团化的 γ-烷氧基取代的 α，β-不饱和羰基化合物. 特别是，该类反应利用简单的无机盐 $Zn(OTf)_2$ 作为催化剂，从而避免使用价格昂贵的贵金属催化剂. 此外，该反应还具有底物普适性广、官能团兼容性好、操作简单等优点，为构建十分有用的 γ-羟基或烷氧基取代的 α，β-不饱和羰基化合物提供了一种有效、简洁的合成方法.

3 实验部分

3.1 仪器与试剂

锌催化剂以及反应原料均购自安耐吉、阿拉丁、阿达玛斯等公司，所有药品和试剂均为分析纯. ^{1}H NMR 和 ^{13}C NMR(内标为 TMS，溶剂为 $CDCl_3$)使用 Bruker AV-400 或 Bruker AV-500 型核磁共振仪测定. MS 使用 ESI-QTOF 型高分辨质谱仪测定.

3.2 实验方法

室温条件下，在 10 mL 的圆底烧瓶中依次加入 0.2 mmol 炔酰胺 **1**，1.0 mmol 醇 **2**，0.4 mmol 2-溴吡啶氮氧，0.01 mmol $Zn(OTf)_2$ 和 4 mL 1,2-二氯乙烷，混合均匀后于 80 °C 反应 3 h。反应结束后减压旋去溶剂，得到浅黄色油状物，混合物再经柱层析(乙酸乙酯/石油醚 20:1~10:1)分离提纯得目标产物酰胺 **3a**~**3v**。

(*E*)-4-乙氧基-*N*,4-二苯基-*N*-对甲苯磺酰基丁-2-烯酰胺(**3a**): 淡黄色油状物. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.90 (d, 2H, *J* = 8.4 Hz), 7.51 – 7.45 (m, 3H), 7.31 (d, 2H, *J* = 8.4 Hz), 7.26 – 7.22 (m, 5H), 7.10 – 7.07 (m, 2H), 6.91 (dd, 1H, *J* = 5.2 Hz, *J* = 15.2 Hz), 5.73 (dd, 1H, *J* = 1.2 Hz, *J* = 15.2 Hz), 4.67 (dd, 1H, *J* = 1.2 Hz, *J* = 15.2 Hz), 3.32 – 3.22 (m, 2H), 2.43 (s, 3H), 1.02 (t, 3H, *J* = 6.8 Hz); ^{13}C NMR (100 MHz, $CDCl_3$) δ 165.0, 148.6, 144.8, 138.9, 136.1, 136.0, 130.3, 129.3, 129.2, 128.5, 126.8, 120.6, 80.5, 64.4, 21.6, 15.0; IR (neat): 3358, 2962, 2922, 2852, 1691, 1594, 1482, 1451, 1358, 1260, 1154, 1087, 1027, 798; HRESIMS Calcd for $[C_{25}H_{25}NNaO_4S]^+$ (M + Na^+) 458.1397, found 458.1395.

(*E*)-4-乙氧基-*N*-[(4-甲氧基苯基)磺酰基]-*N*,4-二苯基丁-2-烯酰胺(**3b**): 淡黄色油状物. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.98 – 7.93 (m, 2H), 7.51 – 7.45 (m, 3H), 7.31 – 7.20 (m, 5H), 7.10 – 7.07 (m, 2H), 7.00 – 6.95 (m, 2H), 6.91 (dd, 1H, *J* = 5.2 Hz, *J* = 15.2 Hz), 5.73 (dd, 1H, *J* = 1.6 Hz, *J* = 15.2 Hz), 4.68 (d, 1H, *J* = 5.2 Hz), 3.87 (s, 3H), 3.33 – 3.22 (m, 2H), 1.02 (t, 3H, *J* = 7.2 Hz); ^{13}C NMR (100 MHz, $CDCl_3$) δ 164.9, 163.8, 148.5, 138.9, 136.0, 131.5, 130.3, 129.8, 129.6, 128.5, 128.0, 126.8, 120.7, 113.8, 80.4, 64.3, 55.6, 14.9; IR (neat): 3445, 2915, 2848, 1674, 1647, 1485, 1356, 1263, 1164, 1079, 815; HRESIMS Calcd for $[C_{25}H_{25}NNaO_5S]^+$ (M + Na^+) 474.1346, found 474.1345.

(*E*)-4-乙氧基-*N*-(甲磺酰基)-*N*,4-二苯基丁-2-烯酰胺(**3c**): 淡黄色油状物. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.50 – 7.45 (m, 3H), 7.32 – 7.25 (m, 5H), 7.14 (dd, 2H, *J* = 1.6 Hz, *J* = 7.6 Hz), 7.07 (dd, 1H, *J* = 5.2 Hz, *J* = 15.2 Hz), 5.79 (dd, 1H, *J* = 1.6 Hz, *J* = 15.2 Hz), 4.76 (d, 1H, *J* = 5.2 Hz), 3.45 (s, 3H), 3.25 – 3.26 (m, 2H), 1.04 (t, 3H, *J* = 6.8 Hz); ^{13}C NMR (100 MHz, $CDCl_3$) δ 166.1, 149.4, 138.7, 135.1, 130.0, 129.9, 129.8, 128.6, 126.9, 120.2, 80.5, 64.4, 41.8, 15.0; IR (neat): 3450, 2974, 2928, 1687, 1640, 1593, 1490, 1454, 1320, 1279, 1155, 964; HRESIMS Calcd for $[C_{19}H_{21}NNaO_4S]^+$ (M + Na^+) 382.1083, found 382.1089.

(*E*)-*N*-叔丁基-4-乙氧基-4-苯基-*N*-对甲苯磺酰基丁-2-烯酰胺(**3d**): 淡黄色油状物. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.72 (d, 2H, *J* = 8.4 Hz), 7.35 – 7.20 (m, 7H), 6.90 – 6.86 (m, 2H), 4.87 (d, 1H, *J* = 4.0 Hz), 3.83 (t, 2H, *J* = 7.6 Hz), 3.48 – 3.39 (m, 2H), 2.41 (s, 3H), 1.75 – 1.66 (m, 2H), 1.42 – 1.31 (m, 2H), 1.22 (t, 3H, *J* = 6.8 Hz), 0.94 (t, 3H, *J* = 7.6 Hz); ^{13}C NMR (100 MHz, $CDCl_3$) δ 165.4, 148.5, 144.5, 139.1, 137.0, 129.6, 128.5, 128.0, 127.5, 127.0, 120.6, 80.6, 64.4, 46.5, 32.1, 21.5, 19.9, 15.2, 13.6; IR (neat): 3443, 2960, 2925, 1682, 1634, 1355, 1280, 1165, 1084, 826; HRESIMS Calcd for $[C_{23}H_{29}NNaO_4S]^+$ (M + Na^+) 438.1710, found 438.1719.

(*E*)-4-乙氧基-*N*-苯基-4-(对甲苯基)-*N*-对甲苯磺酰基丁-2-烯酰胺(**3e**): 淡黄色油状物. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.90 (d, 2H, *J* = 8.0 Hz), 7.53 – 7.45 (m, 3H), 7.31 (d, 2H, *J* = 8.4 Hz), 7.26 – 7.23 (m, 2H), 7.06 (d, 2H, *J* = 8.0 Hz), 6.97 (d, 2H, *J* = 8.0 Hz), 6.90 (dd, 1H, *J* = 5.2 Hz, *J* = 15.2 Hz), 5.72 (dd, 1H, *J* = 0.8 Hz, *J* = 15.2 Hz), 4.64 (d, 1H, *J* = 5.2 Hz), 3.31 – 3.19 (m, 2H), 2.43 (s, 3H), 2.29 (s, 3H), 1.01 (t, 3H, *J* = 6.8 Hz); ^{13}C NMR (100 MHz, $CDCl_3$) δ 164.9, 148.7, 144.7, 137.8, 136.0, 135.9, 135.8, 130.3, 129.7, 129.5, 129.2, 129.1, 126.8, 120.4, 80.2, 64.1, 21.6, 21.0, 14.9; IR (neat): 3443, 2974, 2925, 1692, 1639, 1488, 1364, 1174, 1161, 1088, 913, 814; HRESIMS Calcd for $[C_{26}H_{27}NNaO_4S]^+$ (M + Na^+) 472.1553, found 472.1550.

(*E*)-4-(4-氯苯基)-4-乙氧基-*N*-苯基-*N*-对甲苯磺酰基丁-2-烯酰胺(**3f**): 淡黄色油状物. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.89 (d, 2H, *J* = 8.0 Hz), 7.55 – 7.44 (m, 3H), 7.39 – 7.31 (m, 2H), 7.30 – 7.20 (m, 4H), 7.02 (d, 2H, *J* = 8.4 Hz), 6.85 (dd, 1H, *J* = 5.2 Hz, *J* = 15.2 Hz), 5.70 (dd, 1H, *J* = 1.2 Hz, *J* = 15.2 Hz), 4.65 (d, 1H, *J* = 4.8 Hz), 3.31 – 3.21 (m, 2H), 2.43 (s, 3H), 1.01 (t, 3H, *J* = 7.2 Hz); ^{13}C NMR (100 MHz, $CDCl_3$) δ 164.7, 147.9, 144.9, 137.4, 135.9, 135.8, 133.8, 130.2, 129.8,

129.6, 129.3, 129.1, 128.6, 128.1, 121.1, 79.6, 64.4, 21.6, 14.9; IR (neat): 3445, 2974, 2926, 1691, 1641, 1596, 1488, 1454, 1364, 1162, 1088, 1015, 932, 912, 813; HRESIMS Calcd for $[C_{25}H_{24}ClNNaO_4S]^+$ (M + Na^+) 492.1007, found 492.1018.

(*E*)-4-甲氧基-*N*,4-二苯基-*N*-对甲苯磺酰基丁-2-烯酰胺(**3g**): 淡黄色油状物. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.89 (d, 2H, *J* = 8.0 Hz), 7.53 – 7.45 (m, 3H), 7.32 – 7.20 (m, 7H), 7.09 – 7.06 (m, 2H), 6.90 (dd, 1H, *J* = 5.2 Hz, *J* = 15.2 Hz), 5.74 (dd, 1H, *J* = 1.2 Hz, *J* = 15.2 Hz), 4.57 (dd, 1H, *J* = 0.8 Hz, *J* = 5.2 Hz), 3.12 (s, 3H), 2.42 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 164.9, 148.2, 144.8, 138.3, 136.0, 135.8, 129.6, 129.3, 129.2, 128.6, 120.6, 82.2, 56.5, 21.6; IR (neat): 3446, 3063, 2929, 2825, 1690, 1639, 1597, 1488, 1454, 1362, 1162, 1088, 980, 896, 813; HRESIMS Calcd for $[C_{24}H_{23}NNaO_4S]^+$ (M + Na^+) 444.1240, found 444.1238.

(*E*)-4-丁氧基-*N*,4-二苯基-*N*-对甲苯磺酰基丁-2-烯酰胺(**3h**): 淡黄色油状物. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.91 (d, 2H, *J* = 8.4 Hz), 7.53 – 7.47 (m, 3H), 7.31 (d, 2H, *J* = 8.4 Hz), 7.27 – 7.22 (m, 5H), 7.08 (d, 2H, *J* = 8.0 Hz), 6.90 (dd, 1H, *J* = 4.8 Hz, *J* = 15.2 Hz), 5.76 (dd, 1H, *J* = 1.6 Hz, *J* = 15.2 Hz), 4.67 (d, 1H, *J* = 4.8 Hz), 3.25 – 3.15 (m, 2H), 2.42 (s, 3H), 1.40 – 1.33 (m, 2H), 1.21 – 1.12 (m, 2H), 0.80 (t, 3H, *J* = 7.2 Hz); ^{13}C NMR (100 MHz, $CDCl_3$) δ 165.0, 148.8, 144.8, 138.9, 136.0, 135.9, 130.3, 129.3, 129.2, 128.5, 126.8, 120.3, 80.5, 68.6, 31.6, 21.6, 19.2, 13.8; IR (neat): 3443, 2960, 2925, 2853, 1682, 1634, 1355, 1280, 1165, 1084; HRESIMS Calcd for $[C_{27}H_{29}NNaO_4S]^+$ (M + Na^+) 486.1710, found 486.1713.

(*E*)-4-异丁氧基-*N*,4-二苯基-*N*-对甲苯磺酰基丁-2-烯酰胺(**3i**): 淡黄色油状物. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.91 (d, 2H, *J* = 8.4 Hz), 7.52 – 7.46 (m, 3H), 7.31 (d, 2H, *J* = 8.4 Hz), 7.28 – 7.23 (m, 5H), 7.09 – 7.06 (m, 2H), 6.90 (dd, 1H, *J* = 4.8 Hz, *J* = 15.2 Hz), 5.78 (dd, 1H, *J* = 1.6 Hz, *J* = 15.2 Hz), 4.66 (dd, 1H, *J* = 1.6 Hz, *J* = 4.8 Hz), 3.01 – 2.92 (m, 2H), 2.42 (s, 3H), 1.71 – 1.61 (m, 1H), 0.71 (t, 6H, *J* = 6.4 Hz); ^{13}C NMR (100 MHz, $CDCl_3$) δ 165.0, 148.8, 144.8, 138.9, 136.1, 136.0, 130.3, 129.3, 129.2, 128.5, 126.8, 120.1, 80.5, 75.5, 28.5, 21.6, 19.1, 19.0; IR (neat): 3445, 2956, 2923, 1689, 1639, 1482, 1462, 1372, 1280, 1155, 1086; HRESIMS Calcd for $[C_{27}H_{29}NNaO_4S]^+$ (M + Na^+) 486.1710, found 486.1705.

(*E*)-4-异丙氧基-*N*,4-二苯基-*N*-对甲苯磺酰基丁-2-烯酰胺(**3j**): 淡黄色油状物. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.91 (d, 2H, *J* = 8.4 Hz), 7.52 – 7.45 (m, 3H), 7.31 (d, 2H, *J* = 8.0 Hz), 7.27 – 7.19 (m, 5H), 7.10 – 7.08 (m, 2H), 6.92 (dd, 1H, *J* = 5.2 Hz, *J* = 15.2 Hz), 5.74 (dd, 1H, *J* = 1.6 Hz, *J* = 15.2 Hz), 4.80 (t, 1H, *J* = 4.0 Hz), 3.45 – 3.38 (m, 1H), 2.43 (s, 3H), 0.98 (d, 3H, *J* = 6.0 Hz), 0.93 (d, 3H, *J* = 6.0 Hz); ^{13}C NMR (100 MHz, $CDCl_3$) δ 165.0, 149.3, 144.8, 139.4, 136.0, 130.3, 129.3, 129.2, 128.5, 126.8, 120.4, 77.7, 69.7, 22.2, 21.9, 21.6; IR (neat): 3447, 2918, 2843, 1684, 1635, 1488, 1363, 1275, 1161, 1088, 913; HRESIMS Calcd for $[C_{26}H_{27}NNaO_4S]^+$ (M + Na^+) 472.1553, found 472.1561.

(*E*)-4-苯乙氧基-*N*,4-二苯基-*N*-对甲苯磺酰基丁-2-烯酰胺(**3k**): 淡黄色油状物. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.95 (d, 2H, *J* = 8.4 Hz), 7.58 – 7.48 (m, 3H), 7.38 – 7.20 (m, 10H), 7.07 – 7.02 (m, 4H), 6.92 (dd, 1H, *J* = 5.2 Hz, *J* = 15.2 Hz), 5.80 (d, 1H, *J* = 15.2 Hz), 4.71 (d, 1H, *J* = 4.8 Hz), 3.45 (t, 2H, *J* = 6.8 Hz), 2.74 (t, 2H, *J* = 6.8 Hz), 2.46 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 164.8, 148.4, 144.7, 138.6, 138.4, 135.9, 135.8, 130.2, 129.7, 129.5, 129.2, 129.1, 128.7, 128.4, 128.1, 127.9, 126.7, 126.0, 120.2, 80.5, 69.5, 36.1, 21.5; IR (neat): 3443, 3062, 2921, 2853, 1691, 1639, 1597, 1488, 1453, 1363, 1174, 1162, 1088, 913, 809; HRESIMS Calcd for $[C_{31}H_{29}NNaO_4S]^+$ (M + Na^+) 534.1710, found 534.1712.

(*E*)-4-环己氧基-*N*,4-二苯基-*N*-对甲苯磺酰基丁-2-烯酰胺(**3l**): 淡黄色油状物. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.91 (d, 2H, *J* = 8.4 Hz), 7.50 – 7.45 (m, 3H), 7.31 (d, 2H, *J* = 8.0 Hz), 7.27 – 7.21 (m, 5H), 7.11 – 7.09 (m, 2H), 6.92 (dd, 1H, *J* = 4.4 Hz, *J* = 14.8 Hz), 5.78 (dd, 1H, *J* = 1.6 Hz, *J* = 15.2 Hz), 4.86 (dd, 1H, *J* = 1.2 Hz, *J* = 4.8 Hz), 3.13 – 3.08 (m, 1H), 2.43 (s, 3H), 1.69 – 1.58 (m, 1H), 1.54 – 1.36 (m, 4H), 1.21 – 1.05 (m, 5H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 165.1, 149.5, 144.8, 139.5, 136.1, 130.3, 129.3, 129.2, 128.5, 126.8, 120.3, 75.2, 32.2, 31.6, 25.6, 23.6, 23.5, 21.6; IR (neat): 3438, 2929, 2852, 2691, 1639, 1448, 1364, 1280, 1174, 1161, 1088, 814; HRESIMS Calcd for $[C_{29}H_{31}NNaO_4S]^+$ (M + Na^+) 512.1866, found 512.1867.

(*E*)-4-(苄基氧基)-*N*,4-二苯基-*N*-对甲苯磺酰基丁-2-烯酰胺(**3m**): 淡黄色油状物. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.90 (d, 2H, *J* = 8.4 Hz), 7.53 – 7.49 (m, 2H), 7.31 – 7.19 (m, 11H), 7.10 – 7.06 (m, 2H), 7.05 – 7.03 (m, 2H), 6.92 (dd, 1H, *J* = 5.2 Hz, *J* = 15.2 Hz), 5.85 (dd, 1H, *J* = 1.6 Hz, *J* = 15.2 Hz), 4.77 (dd, 1H, *J* = 1.6 Hz, *J* = 5.2 Hz), 4.33 (m, 2H), 2.43 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 164.9, 148.2, 144.8, 138.2, 137.6, 135.9, 130.3, 129.8, 129.6, 129.3, 129.1, 128.6, 128.2, 127.5, 127.1, 126.9, 120.7, 79.4, 70.0, 21.6; IR (neat): 3365, 2919, 2849, 1689, 1630, 1597, 1493, 1451, 1358, 1154, 1089; HRESIMS Calcd for $[C_{30}H_{27}NNaO_4S]^+$ (M + Na^+) 520.1553, found 520.1552.

(*E*)-4-[(4-甲氧基苄基)氧基]-*N*,4-二苯基-*N*-对甲苯磺酰基丁-2-烯酰胺(**3n**): 淡黄色油状物. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.90 (d, 2H, *J* = 8.4 Hz), 7.54 – 7.46 (m, 3H), 7.31 – 7.20 (m, 7H), 7.11 – 7.08 (m, 2H), 6.98 (d, 2H, *J* = 8.8 Hz), 6.92 (dd, 1H, *J* = 4.8 Hz, *J* = 15.2 Hz), 6.78 (d, 2H, *J* = 8.4 Hz), 5.82 (dd, 1H, *J* = 1.6 Hz , *J* = 15.2 Hz), 4.74 (dd, 1H, *J* = 1.2 Hz , *J* = 4.8 Hz), 4.25 (d, 1H, *J* = 11.6 Hz), 4.29 (d, 1H, *J* = 12.0 Hz), 3.77 (s, 3H), 2.41(s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 164.9, 159.0, 148.3, 144.8, 138.8, 135.9, 130.3, 129.8, 129.6, 129.5, 129.3, 129.1, 128.8, 128.5, 128.1, 126.9, 120.7, 79.0, 69.7, 55.1, 21.5; IR (neat): 3436, 3003, 2932, 1691, 1611, 1531, 1488, 1362, 1247, 1173, 1087, 1032, 814; HRESIMS Calcd for $[C_{31}H_{29}NNaO_5S]^+$ (M + Na^+) 550.1659, found 550.1655.

(*E*)-4-(丁-3-烯基氧基)-*N*,4-二苯基-*N*-对甲苯磺酰基丁-2-烯酰胺(**3o**): 淡黄色油状物. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.90 (d, 2H, *J* = 8.0 Hz), 7.53 – 7.45 (m, 3H), 7.31 (d, 2H, *J* = 8.4 Hz), 7.26 – 7.22 (m, 5H), 7.09 – 7.06 (m, 2H), 6.90 (dd, 1H, *J* = 4.8 Hz, *J* = 15.2 Hz), 5.76 (dd, 1H, *J* = 1.6 Hz, *J* = 15.2 Hz), 5.65 – 5.55 (m, 1H), 4.95 – 4.90 (m, 2H), 4.68 (dd, 1H, *J* = 1.2 Hz, *J* = 4.8 Hz), 3.30 – 3.20 (m, 2H), 2.42 (s, 3H), 2.16 – 2.11 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 165.0, 148.5, 144.8, 134.8, 130.3, 129.8, 129.6, 129.3, 129.2, 128.5, 128.1, 126.8, 120.3, 116.4, 80.5, 68.1, 34.0, 21.6; IR (neat): 3389, 3067, 2920, 1692, 1641, 1596, 1488, 1364, 1187, 1174, 1162, 1119, 1088, 983, 814; HRESIMS Calcd for $[C_{27}H_{27}NNaO_4S]^+$ (M + Na^+) 484.1553, found 484.1550.

(*E*)-4-烯丙氧基-*N*-(甲基磺酰基)-*N*,4-二苯基丁-2-烯酰胺(**3p**): 淡黄色油状物. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.90 (d, 2H, *J* = 8.4 Hz), 7.51 – 7.45 (m, 3H), 7.31 (d, 2H, *J* = 8.4 Hz), 7.28 – 7.22 (m, 5H), 7.10 – 7.07 (m, 2H), 6.91 (dd, 1H, *J* = 5.2 Hz, *J* = 15.2 Hz), 5.78 (dd, 1H, *J* = 2.0 Hz, *J* = 15.2 Hz), 5.75 – 5.65 (m, 1H), 5.06 (dd, 1H, *J* = 1.2 Hz, *J* = 15.2 Hz), 5.04 – 5.01 (m, 1H), 4.75 (dd, 1H, *J* = 1.2 Hz, *J* = 15.2 Hz), 3.86 – 3.71 (m, 2H), 2.43 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 165.0, 148.3, 144.8, 133.9, 130.3, 129.8, 129.6, 129.3, 129.2, 128.6, 128.2, 126.9, 120.6, 79.6, 69.2, 21.6; IR (neat): 3435, 2920, 2849, 1691, 1640, 1596, 1488, 1363, 1174, 1162, 1087, 696, 573, 574; HRESIMS Calcd for $[C_{26}H_{25}NNaO_4S]^+$ (M + Na^+) 470.1397, found 470.1398.

(E)-*N*,4-二苯基-4-(丙-2-炔基氧基)-*N*-对甲苯磺酰基丁-2-烯酰胺(**3q**): 淡黄色油状物. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.90 (d, 2H, *J* = 8.4Hz), 7.52 – 7.45 (m, 3H), 7.31 (d, 2H, *J* = 8.0 Hz), 7.27 – 7.23 (m, 5H), 7.11 – 7.09 (m, 2H), 6.91 (dd, 1H, *J* = 5.2 Hz, *J* = 15.2 Hz), 5.75 (d, 1H, *J* = 16.4 Hz), 5.00 (d, 1H, *J* = 4.4 Hz), 3.97 (dd, 1H, *J* = 2.4 Hz, *J* = 15.6 Hz), 3.84 (dd, 1H, *J* = 2.4 Hz, *J* = 16.0 Hz), 2.43 (s, 3H), 2.34 (t, 1H, *J* = 2.4 Hz); ^{13}C NMR (100 MHz, $CDCl_3$) δ 164.8, 147.3, 144.9, 137.4, 135.9, 135.8, 130.3, 129.2, 128.6, 127.3, 121.3, 78.9, 74.9, 55.4, 21.6; IR (neat): 3285, 2921, 2853, 1659, 1636, 1591, 1496, 1454, 1364, 1165, 1081, 831; HRESIMS Calcd for $[C_{26}H_{23}NNaO_4S]^+$ (M + Na^+) 468.1240, found 468.1241.

(*E*)-*N*,4-二苯基-*N*-甲苯磺酰基-4-[2-(三甲基甲硅烷基)乙氧基]丁-2-烯酰胺(**3r**): 淡黄色油状物. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.97 (d, 2H, *J* = 8.4 Hz), 7.61 – 7.53 (m, 3H), 7.38 (d, 2H, *J* = 8.4 Hz), 7.35 – 7.29 (m, 5H), 7.17 – 7.14 (m, 2H), 6.98 (dd, 1H, *J* = 5.2 Hz, *J* = 15.2 Hz), 5.84 (dd, 1H, *J* = 1.2 Hz, *J* = 14.8 Hz), 4.75 (dd, 1H, *J* = 1.2 Hz, *J* = 5.2 Hz), 3.38 (t, 2H, *J* = 7.6 Hz), 2.50 (s, 3H), 0.88 – 0.79 (m, 2H), 0.04 (s, 9H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 165.0, 149.0, 144.8, 138.9, 136.0, 135.9, 130.3, 129.3, 129.2, 128.5, 126.9, 120.1, 80.4, 66.3, 21.6, 17.9, 1.31; IR (neat): 3445, 2952, 2920, 2851, 1694, 1639, 1488, 1454, 1366, 1248, 1175, 1161, 1088, 837; HRESIMS Calcd for $[C_{28}H_{33}NNaO_4SSi]^+$ (M + Na^+) 530.1792, found 530.1787.

(*E*)-4-(2-氟乙氧基)-*N*,4-二苯基-*N*-对甲苯磺酰基丁-2-烯酰胺(**3s**): 淡黄色油状物. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.90 (d, 2H, *J* = 8.4 Hz), 7.52 – 7.45 (m, 3H), 7.31 (d, 2H, *J* = 8.4 Hz), 7.27 – 7.22 (m, 5H), 7.11 – 7.08 (m, 2H), 6.91 (dd, 1H, *J* = 5.2 Hz, *J* = 15.2 Hz), 5.77 (dd, 1H, *J* = 1.6 Hz, *J* = 15.2 Hz), 4.77 (dd, 1H, *J* = 1.2 Hz, *J* = 5.2 Hz), 4.43 (t, 1H, *J* = 4.0 Hz), 4.31 (t, 1H, *J* = 4.0 Hz), 3.50 (t, 1H, *J* = 4.0 Hz), 3.43 (t, 1H, *J* = 4.0 Hz), 2.43 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 164.8, 147.7, 144.9, 138.1, 136.0, 135.8, 130.3, 129.3, 128.6, 126.9, 120.9, 82.6 (d, *J* = 168.8 Hz), 80.1, 67.5 (d, *J* = 19.8 Hz), 21.6; IR (neat): 3445, 2954, 2922, 1691, 1640, 1596, 1488, 1453, 1362, 1163, 1120, 1088, 912, 814; HRESIMS Calcd for $[C_{25}H_{24}FNNaO_4S]^+$ (M + Na^+) 476.1302, found 476.1309.

(*E*)-4-(环丙基甲氧基)-*N*,4-二苯基-*N*-对甲苯磺酰基丁-2-烯酰胺(**3t**): 淡黄色油状物. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.82 (d, 2H, *J* = 8.4Hz), 7.44 – 7.37 (m, 3H), 7.27 – 7.14 (m, 7H), 7.02 – 7.00 (m, 2H), 6.84 (dd, 1H, *J* = 5.2 Hz, *J* = 15.2 Hz), 5.65 (dd, 1H, *J* = 1.6 Hz, *J* = 15.2 Hz), 4.65 (d, 1H, *J* = 5.2 Hz), 3.04 – 2.96 (m, 2H), 2.33 (s, 3H), 0.82 – 0.72 (m, 1H),

0.33 – 0.29 (m, 2H), -0.07 – -0.11 (m, 2H); ^{13}C NMR (100 MHz,$CDCl_3$) δ 164.9, 148.6, 144.8, 138.8, 135.9, 135.8, 130.3, 129.2, 128.5, 126.8, 120.6, 80.0, 73.2, 21.6, 10.3, 2.8, 2.7; IR (neat): 3440, 2920, 2851, 1689, 1639, 1597, 1488, 1364, 1174, 1161, 1087, 1029, 812; HRESIMS Calcd for $[C_{27}H_{27}NNaO_4S]^+$ (M + Na^+) 484.1553, found 484.1555.

(*E*)-4-(2-羟基乙氧基)-*N*,4-二苯基-*N*-对甲苯磺酰基丁-2-烯酰胺(**3u**): 淡黄色油状物. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.89 (d, 2H, *J* = 8.0 Hz), 7.53 – 7.45 (m, 3H), 7.31 (d, 2H, *J* = 8.0 Hz), 7.29 – 7.19 (m, 5H), 7.09 – 7.06 (m, 2H), 6.90 (dd, 1H, *J* = 5.2 Hz, *J* = 15.2 Hz), 5.72 (dd, 1H, *J* = 1.6 Hz, *J* = 15.2 Hz), 4.73 (dd, 1H, *J* = 1.2 Hz, *J* = 5.2 Hz), 3.55 (t, 2H, *J* = 4.0 Hz), 3.32 (t, 2H, *J* = 4.8 Hz), 2.42 (s, 3H), 1.98 – 1.81 (m, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 164.7, 147.7, 144.9, 138.2, 135.8, 130.2, 129.3, 129.2, 128.6, 126.8, 120.8, 80.9, 69.9, 61.6, 21.6; IR (neat): 3442, 2912, 2850, 1691, 1682, 1644, 1488, 1361, 1275, 1158, 1087, 1014, 815; HRESIMS Calcd for $[C_{25}H_{25}NNaO_5S]^+$ (M + Na^+) 474.1346, found 474.1345.

(*E*)-4-[(5-羟戊基)氧基]-*N*,4-二苯基-*N*-对甲苯磺酰基丁-2-烯酰胺(**3v**): 淡黄色油状物. ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.90 (d, 2H, *J* = 8.4 Hz), 7.53 – 7.45 (m, 3H), 7.26 – 7.19 (m, 2H), 7.18 – 7.08 (m, 5H), 7.11 – 7.08 (m, 2H), 6.90 (dd, 1H, *J* = 5.2 Hz, *J* = 15.2 Hz), 5.74 (dd, 1H, *J* = 0.8 Hz, *J* = 15.2 Hz), 4.66 (d, 1H, *J* = 4.4 Hz), 3.57 – 3.54 (m, 2H), 3.25 – 3.16 (m, 2H), 2.42 (s, 3H), 1.78 – 1.56 (m, 1H), 1.50 – 1.38 (m, 4H), 1.34 – 1.19 (m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 164.9, 148.6, 144.8, 138.7, 135.9, 130.3, 129.7, 129.5, 129.2, 129.1, 128.5, 128.0, 126.7, 120.4, 80.5, 68.6, 62.5, 32.2, 29.2, 22.1, 21.5; IR (neat): 3439, 2920, 2856, 1634, 1493, 1451, 1356, 1274, 1176, 1165, 1084, 816; HRESIMS Calcd for $[C_{28}H_{31}NNaO_5S]^+$ (M + Na^+) 516.1815, found 516.1811.

(*E*)-4-乙氧基-*N*,4-二苯基丁-2-烯酰胺(**3ca**): 室温条件下, 在10 mL 的反应管中依次加入0.2 mmol 酰胺**3c**, 0.04 mmol AIBN, 0.44 mmol 三丁基锡氢和4 mL 甲苯, 混合均匀后加热回流, 均匀搅拌反应4 h, 反应结束后减压旋去溶剂, 混合物再经柱层析得到无色油状产物**3ca**[10]. ^{1}H NMR (400 MHz, $CDCl_3$) δ7.91 – 7.76 (m, 1H), 7.68 – 7.43 (m, 2H), 7.40 – 7.20 (m, 7H), 7.19 – 7.07 (m, 1H), 6.95 (dd, 1H, *J* = 4.8 Hz, *J* = 15.0 Hz), 6.26 (d, 1H, *J* = 8.8 Hz), 4.85 (d, 1H, *J* = 4.0 Hz), 3.59 – 3.41 (m, 2H), 1.26 – 1.18 (m, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 165.0, 145.1, 139.2, 138.3, 129.1, 128.9, 128.5, 127.0, 124.4, 123.8, 120.3, 81.3, 63.8, 15.3. HRESIMS Calcd for $[C_{18}H_{19}NNaO_2]^+$ (M + Na^+) 304.1308, found 304.1311.

(*E*)-4-羟基-*N*,4-二苯基-*N*-对甲苯磺酰基丁-2-烯酰胺(**3na**): 室温条件下，在10 mL 的反应管中依次加入0.1 mmol 酰胺**3n**, 0.5 mL DCM, 0.1 mL H_2O, 0.12 mmol 2,3-二氯-5,6-二氰基苯醌(DDQ), 混合均匀后在室温条件下搅拌反应2 h. 反应结束后加入10 mL $Na_2S_2O_3$淬灭, 乙醚萃取, 有机相用$NaHCO_3$洗, 饱和NaCl洗, $MgSO_4$干燥, 过滤, 减压旋去溶剂, 混合物再经柱层析(V(石油醚)/V(乙酸乙酯)=3/1), 得到无色油状产物**3na**. 该化合物是已知化合物，其谱图数据与文献报道的一致[4]. ^{1}H NMR (400 MHz, $CDCl_3$) δ7.88 (d, 2H, *J* = 8.4 Hz), 7.52 – 7.43 (m, 3H), 7.34 – 7.22 (m, 7H), 7.11 (d, 2H, *J* = 7.6 Hz), 6.96 (dd, 1H, *J* = 4.8 Hz, *J* = 15.2 Hz), 5.82 (dd, 1H, *J* = 1.6 Hz, *J* = 14.8 Hz), 5.13 (d, 1H, *J* = 4.0 Hz), 2.42 (s, 3H), 2.23 – 2.06 (m, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 165.0, 149.6, 144.8, 140.4, 135.9, 135.7, 130.2, 129.9, 129.7, 129.3, 129.2, 128.6, 128.2, 126.3, 119.8, 73.1, 21.6.

辅助材料(Supporting Information) 化合物**3a~3v**，**3ca**和**3na**的氢谱和碳谱. 这些材料可以免费从本刊网站(http://sioc-journal.cn/) 上下载.

References

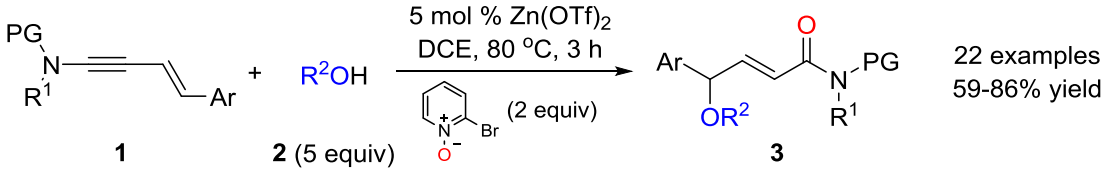
[1] For selected examples, see: (a) Heravi, M. M.; Zadsirjan, V.; Esfandyari, M.; Lashaki, T. B. *Tetrahedron: Asymmetry* **2017**, *28*, 987.
(b) Takayasu, Y.; Ogura, Y.; Towada, R.; Kuwahara, S. *Biosci. Biotechnol. Biochem*. **2016**, *80*, 1459.
(c) Srinivas, C.; Kumar, P.; China, R. B.; Jayathirtha, R. V.; Naidu, V.; Ramakrishna, S.; Diwan, P. V. *Bioorg. Med. Chem. Lett.* **2009**, *19*, 5915.
(d) Nakamura, H.; Ono, M.; Yamada, T.; Numata, A.; Akita, H. *Chem. Pharm. Bull.* **2002**, *50*, 303.

[2] For selected examples, see: (a) Nidhiry, J. E.; Prasad, K. R. *Synlett* **2014**, *25*, 2585.
(b) Son, S.; Fu, G. C. *J. Am. Chem. Soc*. **2008**, *130*, 2756.
(c) Cooksey, J. P.; Kocienski, P. J.; Li, Y.; Schunk, S.; Snaddon, T. N. *Org. Biomol. Chem*. **2006**, *4*, 3325.

[3] For selected examples, see: (a) Sutar, R. L.; Sen, S.; Eivgi. O.; Segalovich, G.; Schapiro, I.; Reany, O.; Lemcoff, N. G. *Chem. Sci.* **2018**, *9*, 1368.
(b) Ziegler, D. T.; Fu, G. C. *J. Am. Chem. Soc*. **2016**, *138*, 12069.
(c) Ammann, S. E.; Liu, W.; White, M. C. *Angew. Chem. Int. Ed*. **2016**, *55*, 9571.
(d) Kikuchi, H.; Hoshikawa, T.; Kurata, S.; Katou, Y.; Oshima, Y. *J. Nat. Prod*. **2016**, *79*, 1259.

(e) Xu, M.; Ren, T.-T.; Li, C.-Y. *Org. Lett*. **2012**, *14*, 4902.
(f) Sugiura, M.; Yagi, Y.; Wei, S.-Y.; Nakai, T. *Tetrahedron Lett.* **1998**, *39*, 4351.
(g) Brooks, P. B.; Marson, C. M. *Tetrahedron* **1998**, *54*, 9613.
(h) Tiecco, M.; Testaferri, L.; Tingoli, M.; Bagnoli, L.; Santi, C. *J. Chem. Soc. Chem. Commun*. **1993**, 637.
[4] Jadhav, A. H.; Gawade, S. A.; Vasu, D.; Dateer, R. B.; Liu, R.-S. *Chem. Eur. J*. **2014**, *20*, 1813.
[5] For recent reviews on ynamide reactivity, see: (a) Li, L.; Tan, T.-D.; Zhang, Y.-Q.; Liu, X.; Ye, L.-W. *Org. Biomol. Chem.* **2017**, *15*, 8483.
(b) Pan, F.; Shu, C.; Ye, L.-W. *Org. Biomol. Chem.* **2016**, *14*, 9456.
(c) Evano, G.; Theunissen, C.; Lecomte, M. *Aldrichimica Acta* **2015**, *48*, 59.
(d) Wang, X.-N.; Yeom, H.-S.; Fang, L.-C.; He, S.; Ma, Z.-X.; Kedrowski, B. L.; Hsung, R. P. *Acc. Chem. Res.* **2014**, *47*, 560.
(e) DeKorver, K. A.; Li, H.; Lohse, A. G.; Hayashi, R.; Lu, Z.; Zhang, Y.; Hsung, R. P. *Chem. Rev.* **2010**, *110*, 5064.
(f) Evano, G.; Coste, A.; Jouvin, K. *Angew. Chem., Int. Ed*. **2010**, *49*, 2840.
[6] For selected examples from our group, see: (a) Li, L.; Zhu, X.-Q.; Zhang, Y.-Q.; Bu, H.-Z.; Yuan, P.; Chen, J.; Su, J.; Deng, X.; Ye, L.-W. *Chem. Sci*. **2019**, *10*, 3213.
(b) Zhou, B.; Li, L.; Zhu, X.-Q.; Yan, J.-Z.; Guo, Y.-L.; Ye, L.-W. *Angew. Chem., Int. Ed.* **2017**, *56*, 4015.
(c) Shen, W.-B.; Xiao, X.-Y.; Sun, Q.; Zhou, B.; Zhu, X.-Q.; Yan, J.-Z.; Lu, X.; Ye, L.-W. *Angew. Chem., Int. Ed.* **2017**, *56*, 605.
(d) Li, L.; Chen, X.-M.; Wang, Z.-S.; Zhou, B.; Liu, X.; Lu, X.; Ye, L.-W. *ACS Catal.* **2017**, *7*, 4004.
(e) Zhou, B.; Zhang, Y.-Q.; Liu, X.; Ye, L.-W. *Sci. Bull.* **2017**, *62*, 1201.
(f) Shu, C.; Wang, Y.-H.; Shen, C.-H.; Ruan, P.-P.; Lu, X.; Ye, L.-W. *Org. Lett.* **2016**, *18*, 3254.
(g) Pan, Y.; Chen, G.-W.; Shen, C.-H.; He, W.; Ye, L.-W. *Org. Chem. Front.* **2016**, *3*, 491.
(h) Shu, C.; Wang, Y.-H.; Zhou, B.; Li, X.-L.; Ping, Y.-F.; Lu, X.; Ye, L.-W. *J. Am. Chem. Soc*. **2015**, *137*, 9567.
(i) Zhou, A.-H.; He, Q.; Shu, C.; Yu, Y.-F.; Liu, S.; Zhao, T.; Zhang, W.; Lu, X.; Ye, L.-W. *Chem. Sci*. **2015**, *6*, 1265.
(j) Li, L.; Shu, C.; Zhou, B.; Yu, Y.-F.; Xiao, X.-Y.; Ye, L.-W. *Chem. Sci*. **2014**, *5*, 4057.
[7] For reviews on catalytic intermolecular *N*-oxide oxidation of alkynes, see: (a) Zheng, Z.; Wang, Z.; Wang, Y.; Zhang, L. *Chem. Soc. Rev.* **2016**, *45*, 4448.
(b) Zhou, B.; Li, L.; Ye, L.-W. *Synlett* **2016**, 493.
(c) Yeom, H.-S.; Shin, S. *Acc. Chem. Res.* **2014**, *47*, 966.
(d) Zhang, L. *Acc. Chem. Res.* **2014**, *47*, 877.
(e) Xiao, J.; Li, X. *Angew. Chem., Int. Ed.* **2011**, *50*, 7226
[8] For recent representative examples, see: (a) Cai, J.; Wang, X.; Qian, Y.; Qiu, L.; Hu, W.; Xu, X. *Org. Lett.* **2019**, *21*, 369.
(b) Wei, H.; Bao, M.; Dong, K.; Qiu, L.; Wu, B.; Hu, W.; Xu, X. *Angew. Chem., Int. Ed.* **2018**, *57*, 17200.
(c) Yang, J.-M.; Zhao, Y.-T.; Li, Z.-Q.; Gu, X.-S.; Zhu, S.-F.; Zhou, Q.-L. *ACS Catal.* **2018**, *8*, 7351.
(d) Zhang, Y.-Q.; Zhu, X.-Q.; Chen, Y.-B.; Tan, T.-D.; Yang, M.-Y.; Ye, L.-W. *Org. Lett.* **2018**, *20*, 7721.
(e) Zhao, J.; Xu, W.; Xie, X.; Sun, N.; Li, X.; Liu, Y. *Org. Lett.* **2018**, *20*, 5461.
(f) Li, J.; Xing, H.-W.; Yang, F.; Chen, Z.-S.; Ji, K. *Org. Lett.* **2018**, *20*, 4622.
(g) Hamada, N.; Yamaguchi, A.; Inuki, S.; Oishi, S.; Ohno, H. *Org. Lett.* **2018**, *20*, 4401.
(h) M. Lin, L. Zhu, J. Xia, Y. Yu, J. Chen, Z. Mao, X. Huang, *Adv. Synth. Catal.* **2018**, *360*, 2280.
(i) Xu, Z.; Chen, H.; Wang, Z.; Ying, A.; Zhang, L. *J. Am. Chem. Soc.* **2016**, *138*, 5515.
(j) Zeng, X.; Liu, S.; Shi, Z.; Liu, G.; Xu, B. *Angew. Chem., Int. Ed*. **2016**, *55*, 10032.
(k) Zhang, Y.; Xue, Y.; Li, G.; Yuan, H.; Luo, T. *Chem. Sci*. **2016**, *7*, 5530.
(l) Wang, Y.; Zheng, Z.; Zhang, L. *J. Am. Chem. Soc.* **2015**, *137*, 5316.
(m) Chen, H.; Zhang, L. *Angew. Chem., Int. Ed*. **2015**, *54*, 11775.
(n) Ji, K.; Zheng, Z.; Wang, Z.; Zhang, L. *Angew. Chem., Int. Ed.* **2015**, *54*, 1245.
(o) Chen, M.; Chen, Y.; Sun, N.; Zhao, J.; Liu, Y.; Li, Y. *Angew. Chem., Int. Ed.* **2015**, *54*, 1200.
(p) Zheng, Z.; Zhang, L. *Org. Chem. Front.* **2015**, *2*, 1556.
(q) Ji, K.; Liu, X.; Du, B.; Yang, F.; Gao, J. *Chem. Commun*. **2015**, *51*, 10318.
(r) Li, L.; Zhou, B.; Ye, L.-W. *Youji Huaxue* **2015**, *35*, 655.
(s) Pan, F.; Liu, S.; Shu, C.; Lin, R.-K.; Yu, Y.-F.; Zhou, J.-M.; Ye, L.-W. *Chem. Commun*. **2014**, *50*, 10726.
(t) Shu, C.; Li, L.; Xiao, X.-Y.; Yu, Y.-F.; Ping, Y.-F.; Zhou, J.-M.; Ye, L.-W. *Chem. Commun.* **2014**, *50*, 8689.
[9] For examples on the ynamide oxidation by non-noble metal catalysis from our group, see: (a) Zhu, J.; Ren, X.; Tang, F.; Pan, F.; Ye, L.-W. *Youji Huaxue* **2019**, *39*, 10.6023/cjoc201811007.
(b) Zhu, B.-H.; Wang, C.-M.; Su, H.-Y.; Ye, L.-W. *Chin. J. Chem.* **2019**, *37*, 58.
(c) Wang, C.-M.; Qi, L.-J.; Sun, Q.; Zhou, B.; Zhang, Z.-X.; Shi, Z.-F.; Lin, S.-C.; Lu, X.; Gong, L.; Ye, L.-W. *Green Chem.* **2018**, *20*, 3271.
(d) Shen, W.-B.; Sun, Q.; Li, L.; Liu, X.; Zhou, B.; Yan, J.-Z.; Lu, X.; Ye, L.-W. *Nat. Commun.* **2017**, *8*, 1748.
(e) Pan, F.; Li, X.-L.; Chen, X.-M.; Shu, C.; Ruan, P.-P.; Shen, C.-H.; Lu, X.; Ye, L.-W. *ACS Catal.* **2016**, *6*, 6055.
(f) Ruan, P.-P.; Shen, C.-H.; Li, L.; Liu, C.-Y.; Ye, L.-W. *Org. Chem. Front.* **2016**, *3*, 989.
(g) Li, L.; Zhou, B.; Wang, Y.-H.; Shu, C.; Pan, Y.-F.; Lu, X.; Ye, L.-W. *Angew. Chem., Int. Ed.* **2015**, *54*, 8245.
[10] Wang, G.; Huang, Z.; Negishi, E.-I. *Org. Lett.* **2008**, *10*, 3223.

(Editor)



The realization of the 1,4-functionalization of 3-en-1-ynes with alcohols through zinc-catalyzed regioselective *N*-oxide oxidation is described. This tandem reaction allows the practical synthesis of a range of valuable γ-alkoxyl-substituted α,β-unsaturated amides in moderate to good yields.

