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# 三氟甲磺酸酐介导炔酰胺与吡啶加成反应的研究

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**摘要** 基于三氟甲磺酸酐介导炔酰胺与吡啶加成反应, 建立了含烯胺结构吡啶季铵盐的合成方法. 经过 13 个底物拓展验证, 采用该方法制备含烯胺结构吡啶季铵盐的收率在 65%～90%之间. 该方法中吡啶氮原子高区域选择性地与炔酰胺叁键的 $\alpha$ 位进行加成, 且产物以 $Z$ 构型为主($Z$∶$E$>20∶1).
**关键词** 炔酰胺; 吡啶; 加成反应; 吡啶季铵盐

# Trifluoromethyl Sulfonic Anhydride Mediated Addition of Pyridine with Ynamides

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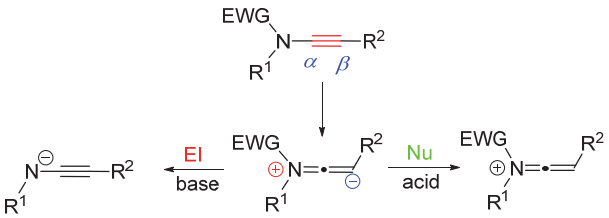
**Abstract** A convenient approach to pyridine quaternary ammonium salts containing enamine fragment has been developed, which features a trifluoromethyl sulfonic anhydride mediated regioselective addition process of pyridine with ynamides. Using this method, a variety of substituted pyridine quaternary ammonium salts containing enamine fragment **3a**～**3m** were prepared in moderate to excellent yields with high regioselectivities ($Z$∶$E$ up to 20∶1).
**Keywords** ynamides; pyridine; addition reaction; pyridine quaternary ammonium salt

制备简单、性质稳定的炔酰胺, 其分子中的氮原子以 $\sigma$ 键形式分别与酰基和炔基相连, 产生独特 p-π 共轭体系, 该体系受吸电子型酰基调控, 直接改变了两个炔键碳的反应活性[1-2]. 从而使炔酰胺结构中叁键 $\alpha$ 位碳原子具有亲电性, $\beta$ 位碳原子具有亲核性[3]. 使用不同酸、碱活化炔酰胺时, 反应活性位点会有所不同, 使炔酰胺在反应中出现较高的区域选择性(Scheme 1). 在炔酰胺参与的反应中, 多种活化模式被广泛研究, 主要包括金属试剂活化[4]、布朗斯特酸活化[5]、路易斯酸活化[6]、亲电试剂(卤素)活化[7]、碳正离子活化[8]. 既可作为亲电试剂又可作为亲核试剂的炔酰胺被广泛用于加成反应、氧化反应、还原反应、环加成反应、关环复分解反应(RCM)反应、自由基反应和金属催化的环异构化反应中[9]. 近年来, 本课题组也将炔酰胺用于亚胺鎓的加成环化, 与吲哚、酮的选择性加成, 与伯胺、仲胺的氢胺化反应及叔胺导向的芳环 $sp^2$ 杂化 C—H 活化加成反应中[10].




**图式 1** 炔酰胺结构中三键的电性分析
**Scheme 1** Electrical analysis of three bonds in ynamides

2-氨基吡啶、吡啶鎓盐及吡啶 *N*-氧化物也被用来与炔酰胺进行反应. 例如 Cossy 和 Meyer 课题组[11]实现了碱催化下缺电子的炔酰胺与稳定的吡啶鎓卤化物发生 1,3-偶极环加成反应, 合成了一系列 2-氨基吲哚并嗪化

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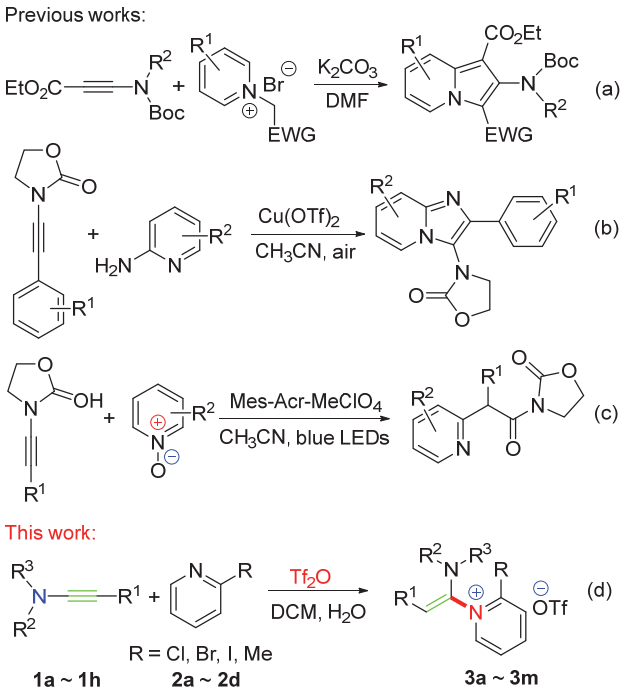
合物(Scheme 2a). Sridhar 课题组[12]基于三氟甲磺酸铜催化炔酰胺与 2-氨基吡啶的分子间选择性胺化反应，建立了咪唑并[1,2-*a*]吡啶化合物的合成方法(Scheme 2b). Deng 课题组[13]基于光催化下吡啶 *N*-氧化物与炔酰胺的酰胺烷基化反应，建立了 2-吡啶基酰胺化合物合成方法(Scheme 2c). 根据已有的研究结果，推测吡啶的氮原子能独立地与炔烃酰胺中的叁键发生加成反应，生成一种含有烯胺结构的吡啶鎓盐. 本文报道这一研究结果(Scheme 2d).




**图式 2** 炔酰胺与吡啶的加成反应

**Scheme 2** Addition process of ynamides with pyridine

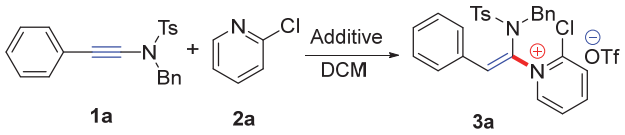
## 1 结果与讨论

首先，以炔酰胺 **1a** 和 2-氯吡啶 **2a** 作为底物对加成反应条件进行优化(表 1). 实验结果表明，当以催化量的稀土金属路易斯酸三氟甲磺酸钪或三氟甲磺酸铒为催化剂时，反应不能进行(表 1, Entries 1, 2). 可能是由于金属路易斯酸酸性较弱所致. 当化学计量的三氟甲磺酸被使用时，反应体系较为复杂，无法分离出单一化合物(表 1, Entry 3). 当使用化学计量的三氟甲磺酸酐时，反应 1 h 后经水淬灭和 $C^{18}$ 色谱柱分离以 85%的收率得到产物 **3a**(表 1, Entry 4). 需要说明的是延长反应时间至 2 h，反应的收率可能因纯化损失略有降低(75%，表 1, Entry 5)，因此，选择 1 h 开展研究.

获得较佳反应条件后，探索了底物的适用范围，实验结果如表 2 所示. 2 位卤素(氯、溴、碘)取代吡啶均能与炔酰胺 **1a** 顺利进行加成反应，以 85%～90%的收率生成了吡啶盐 **3a**, **3b** 和 **3c**，反应具有很好的区域选择性，且产物以 *Z* 式为主. 对位甲氧基和溴取代的炔酰胺 **1b** 和 **1c** 与 2-氯吡啶也能顺利在 $Tf_2O$ 介导下进行加成，分别以 90%和 86%的收率生成了加成产物吡啶盐 **3d** 和 **3e**,

**表 1** 炔酰胺与吡啶的反应条件优化 [a]

**Table 1** Screening of optimal conditions for the reaction of ynamides with pyridine

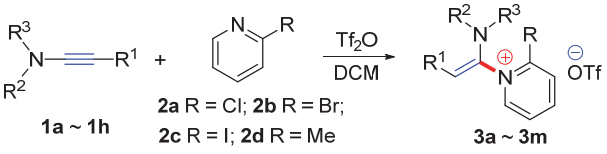


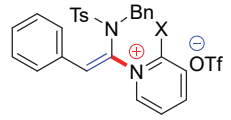

| Entry | Additive (equiv.) | Time/h | Yield[b]/% | *Z* : *E*[c] |
|---|---|---|---|---|
| 1 | $Sc(OTf)_3$ (0.2) | 10 | NR | — |
| 2 | $Er(OTf)_3$ (0.2) | 10 | NR | — |
| 3 | TfOH (1.1) | 1 | Complex | — |
| 4 | $Tf_2O$ (1.1) | 1 | 85 | >20 : 1 |
| 5 | $Tf_2O$ (1.1) | 2 | 75 | >20 : 1 |

[a] Reaction conditions: **1a** (0.20 mmol) and **2a** (0.24 mmol) were stirred in dichloromethane (DCM, 1.6 mL) for 5 min, then added additive agents. After a certain reaction time, quenched the reaction with water, then dried the product by distillation. [b] Isolated yield (isolated by $C^{18}$ chromatographic column). [c] *Z* : *E* values were determined by $^1$H NMR data of the crude product.

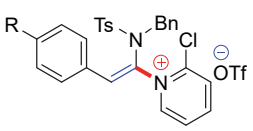
**表 2** 炔酰胺与吡啶反应底物拓展 [a]

**Table 2** Reaction substrate expansion of ynamides with pyridine

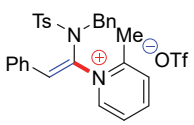


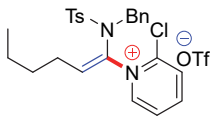
**3a** X = Cl, 85%, *Z*/*E* > 20:1
**3b** X = Br, 86%, *Z*/*E* > 20:1
**3c** X = I, 90%, *Z*/*E* > 20:1



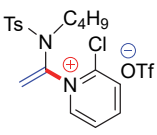
**3d** R = OMe, 90%, *Z*/*E* >20:1
**3e** R = Br, 86%, *Z*/*E* > 20:1



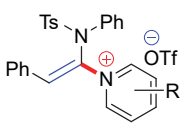
**3f** 88%, *Z*/*E* > 20:1



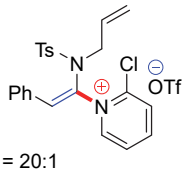
**3g** 75%, *Z*/*E* > 10:1



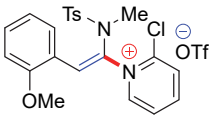
**3h** 65%



**3i** R = 2-Cl, 85%, *Z*/*E* = 20:1
**3j** R = 3-Cl, Complex
**3k** R = 4-Cl, Complex



**3l** 89%
*Z*/*E* > 20:1



**3m** 75%
*Z*/*E* > 20:1

[a] Reaction conditions: **1** (0.20 mmol) and **2** (0.24 mmol) were stirred in DCM (1.6 mL) for 5 min, then $Tf_2O$ (0.22 mmol) was added. After 1 h, the reaction was quenched with water, then the product was dried by distillation. [b] Isolated yield (isolated by $C^{18}$ chromatographic column). [c] *Z* : *E* values were determined by $^1$H NMR data of the product.

产物同样以 *Z* 构型为主. 2-甲基吡啶也能顺利进行反应, 以 88%的收率生成了 *Z*-**3f** (*Z*∶*E*>20∶1). 直链炔酰胺 **1d** 也能与 2-氯吡啶反应, 但产物的 **3g** 收率有所下降(收率为 75%), 产物的顺反异构比例也下降(*Z*∶*E* 约为 10∶1). 末端炔酰胺也能与2-氯吡啶在这个条件下反应, 但**3h**收率只有65%. 当炔酰胺中苄基换为苯基时, 产物 **3i** 的顺反比例及收率变化不大, 而当吡啶上的甲基在间位或者对位时, 反应体系较为复杂. 当炔酰胺中苄基换为烯丙基时, 加成所生成的吡啶盐**3l**在收率和选择性上均没有明显变化(89%, *Z*∶*E*>20∶1); 但当 *N*-苄基替换为 *N*-甲基时, 加成产物 **3m** 的收率降低为 75% (*Z*∶*E*>20∶1).

为了进一步确定化合物 **3a**～**3m** 的结构, 化合物 **3a** 经乙醇和水体系培养晶体, 结构分析表明: 吡啶中氮原子加成到炔酰胺中 *α* 碳上, 且产物是以 Z 构型为主的三氟甲磺酸盐(图 1). [14]

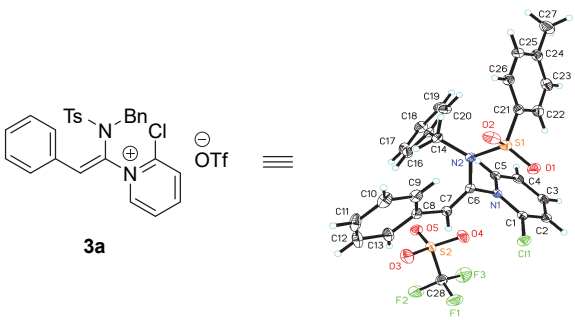
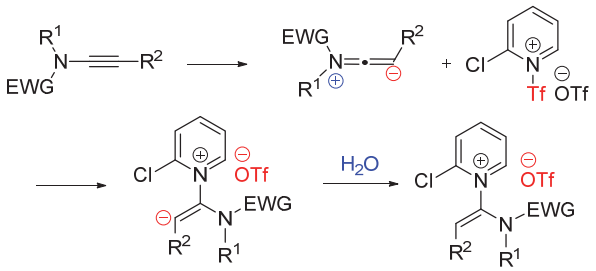



**图 1** 化合物 **3a** 的晶体结构
**Figure 1** Crystal structure of compound **3a**

根据以上反应结果和参考文献[15], 推测该反应机理: 二氯吡啶首先与三氟甲磺酸酐结合, 再与炔酰胺的联烯亚胺活性中间体反式加成, 接着体系被水淬灭, 直接生成吡啶取代的稳定中间体−吡啶烯胺结构化合物 (Scheme 3).




**图式 3** 炔酰胺与吡啶加成反应机理推测
**Scheme 3** Speculation on the reaction mechanism of ynamides with pyridine

## 2 结论

本研究基于三氟甲磺酸酐介导的炔酰胺与吡啶的加成反应, 建立了吡啶烯胺三氟甲磺酸盐的合成新方法. 经过 13 个底物的拓展, 以 65%～90%收率合成了化合物 **3a**～**3m**. 这一方法具有理想的区域选择性, 产物以 *Z*-式为主(*Z*∶*E* 可达到 20∶1).

## 3 实验部分

### 3.1 仪器与试剂

红外谱图以 Nicolet-FT-IR360 傅立叶变换红外光谱仪, $CH_2Cl_2$ 液膜法测定; 核磁谱图以 MERCURY-400 型核磁共振仪测定, TMS 为内标, $CD_3OD$ 为溶剂; 高分辨质谱以 HP6890/5973 型质谱仪测定, ESI 光源. 柱层析所用吸附剂为市售的普通 $C^{18}$ 填料, 洗脱剂为不同体积比例的甲醇与水. 用于反应的溶剂均经过重蒸处理; 甲醇柱层析和后处理用溶剂均为市售分析纯化学试剂.

### 3.2 实验方法

在 25 mL 单口瓶中加入炔烃酰胺 **1a**～**1h** (0.20 mmol, 1.0 equiv.), 氩气保护后加入二氯甲烷(1.6 mL)和吡啶化合物 **2a**～**2d** (0.24 mmol, 1.2 equiv.), 室温下搅拌 5 min 后滴加三氟甲磺酸酐(0.22 mmol, 1.1 equiv.), 室温反应 1 h 后体系用水淬灭后蒸干, 用 $C^{18}$ 色谱柱(甲醇/水, *V*∶*V*=40∶60)纯化.

(*Z*)-1-(1-((*N*-苄基-4-甲基苯基)磺酰胺基)-2-苯基乙烯基)-2-氯吡啶三氟甲磺酸盐(**3a**): 粘稠状物, 106.1 mg, 产率 85%. $^1$H NMR (400 MHz, $CD_3OD$) *δ*: 8.56 (t, *J*=7.2 Hz, 1H), 8.35～8.26 (m, 1H), 7.90～7.80 (m, 3H), 7.56～7.50 (m, 2H), 7.47～7.34 (m, 5H), 7.30～7.25 (m, 2H), 7.24～7.21 (m, 1H), 7.18～7.13 (m, 2H), 6.97～6.90 (m, 2H), 5.10～4.95 (m, 1H), 4.31～4.15 (m, 1H), 2.54 (s, 3H); $^{13}$C NMR (100 MHz, $CDCl_3$) *δ*: 150.2, 149.9, 147.8, 142.2, 135.6, 132.3, 132.0, 130.9, 130.6, 130.3, 130.2, 129.5, 129.3, 129.1, 129.0, 127.2, 126.4, 124.4, 103.9, 53.2, 21.7. HRMS (ESI-Orbitrap) calcd for $C_{27}H_{24}ClN_2O_2S$ 475.1242, found 475.1247.

(*Z*)-1-(1-((*N*-苄基-4-甲基苯基)磺酰胺基)-2-苯基乙烯基)-2-溴吡啶三氟甲磺酸盐(**3b**): 粘稠状物, 89.3 mg, 产率 86%. $^1$H NMR (400 MHz, $CD_3OD$) *δ*: 8.51～8.36 (m, 2H), 7.96～7.82 (m, 3H), 7.57～7.50 (m, 2H), 7.49～7.30 (m, 5H), 7.29～7.22 (m, 2H), 7.21～7.16 (m, 3H), 6.97～6.90 (m, 2H), 5.06 (d, *J*=14.4 Hz, 1H), 4.31～4.09 (m, 1H), 2.56 (s, 3H); $^{13}$C NMR (100 MHz, $CD_3OD$, rotamers) *δ*: 149.1, 147.8, 146.3, 143.0, 136.5, 136.3, 135.6, 133.4, 132.3, 132.0, 131.4, 130.9, 130.6, 130.4, 130.3, 130.2, 129.5, 129.3, 129.0, 127.5, 120.2, 104.0, 52.8, 21.7. HRMS (ESI-Orbitrap) calcd for $C_{27}H_{24}BrN_2O_2S$ 519.0736, found 519.0730.

(*Z*)-1-(1-((*N*-苄基-4-甲基苯基)磺酰胺基)-2-苯基乙

烯基)-2-碘吡啶三氟甲磺酸盐(**3c**): 粘稠状物, 128.9 mg, 产率 90%. $^1$H NMR (400 MHz, $CD_3OD$) $\delta$: 8.82～8.74 (m, 1H), 7.82～7.75 (m, 1H), 7.67～7.62 (m, 1H), 7.53～7.45 (m, 3H), 7.44～7.37 (m, 1H), 7.33～7.22 (m, 9H), 7.17～7.13 (m, 3H), 4.90～4.53 (m, 2H), 2.42 (s, 3H); $^{13}$C NMR (100 MHz, $CD_3OD$) $\delta$: 146.9, 141.9, 137.2, 136.2, 132.9, 132.4, 131.9, 131.4, 131.3, 131.2, 130.9, 130.2, 130.1, 130.0, 128.5, 128.0, 126.5, 115.9, 115.3, 114.9, 53.6, 21.5. HRMS (ESI-Orbitrap) calcd for $C_{27}H_{24}IN_2O_2S$ 567.0598, found 567.0597.

(*Z*)-1-(1-((*N*-苄基-4-甲基苯基)磺酰胺基)-2-(4-甲氧基苯基)乙烯基)-2-氯吡啶三氟甲磺酸盐(**3d**): 粘稠状物, 117.7 mg, 产率 90%. $^1$H NMR (400 MHz, $CD_3OD$) $\delta$: 8.56～8.46 (m, 1H), 8.35～8.14 (m, 1H), 7.92～7.72 (m, 3H), 7.50～7.30 (m, 5H), 7.24～7.13 (m, 3H), 7.01～6.87 (m, 2H), 6.85～6.71 (m, 3H), 5.18～4.92 (m, 1H), 4.40～4.20 (m, 1H), 3.84 (s, 3H), 2.52 (s, 3H); $^{13}$C NMR (100 MHz, $CD_3OD$) $\delta$: 163.5, 149.9, 149.3, 143.2, 135.8, 132.3, 131.9, 130.7, 130.7, 130.5, 130.4, 129.1, 128.9, 128.0, 123.3, 115.6, 114.9, 114.4, 103.7, 56.0, 55.6, 21.6. HRMS (ESI-Orbitrap) calcd for $C_{28}H_{26}ClN_2O_3S$ 505.1347, found 505.1345.

(*Z*)-1-(1-((*N*-苄基-4-甲基苯基)磺酰胺基)-2-(4-溴苯基)乙烯基)-2-氯吡啶三氟甲磺酸盐(**3e**): 粘稠状物, 120.7 mg, 产率 86%. $^1$H NMR (400 MHz, $CD_3OD$) $\delta$: 8.53 (t, $J$=8.0 Hz, 1H), 8.25～8.17 (m, 1H), 7.97～7.88 (m, 1H), 7.78～7.63 (m, 2H), 7.53～7.32 (m, 8H), 7.27～7.17 (m, 3H), 7.00～6.90 (m, 2H), 5.05～4.93 (m, 1H), 4.87～4.47 (m, 1H), 2.54 (s, 3H); $^{13}$C NMR (100 MHz, $CD_3OD$) $\delta$: 150.4, 147.6, 136.9, 135.4, 133.4, 133.1, 132.0, 131.8, 131.4, 131.0, 130.6, 130.4, 129.0, 128.5, 127.4, 126.5, 112.5, 103.4, 53.9, 21.8. HRMS (ESI-Orbitrap) calcd for $C_{27}H_{23}BrClN_2O_2S$ 553.0347, found 553.0341.

(*Z*)-1-(1-((*N*-苄基-4-甲基苯基)磺酰胺基)-2-苯基乙烯基)-2-甲基吡啶三氟甲磺酸盐(**3f**): 粘稠状物, 106.0 mg, 产率 88%. $^1$H NMR (400 MHz, $(CD_3)_2OD$) $\delta$: 7.54～7.47 (m, 2H), 7.44～7.39 (m, 2H), 7.25～7.17 (m, 8H), 7.12～7.06 (m, 4H), 6.87～6.81 (m, 2H), 6.10 (s, 1H), 4.61～4.57 (m, 2H), 2.44 (s, 3H), 2.38 (s, 3H); $^{13}$C NMR (100 MHz, $(CD_3)_2OD$, rotamers) $\delta$: 145.0, 144.7, 138.5, 138.2, 137.9, 136.3, 134.9, 133.3, 130.4, 130.1, 129.6, 129.2, 129.1, 129.0, 128.9, 126.0, 52.4, 51.5, 21.5, 21.4. HRMS (ESI-Orbitrap) calcd for $C_{28}H_{27}N_2O_2S$ 455.1788, found 455.1781.

(*Z*)-1-(1-((*N*-苄基-4-甲基苯基)磺酰胺基)己-1-烯基)-2-氯吡啶三氟甲磺酸盐(**3g**): 粘稠状物, 102.4 mg, 产率 75%. $^1$H NMR (400 MHz, $CD_3OD$) $\delta$: 8.53 (t, $J$=7.6 Hz, 1H), 8.22 (d, $J$=8.0 Hz, 1H), 8.00～7.93 (m, 2H), 7.89～7.82 (m, 1H), 7.57～7.52 (m, 2H), 7.52～7.20 (m, 6H), 6.41 (t, $J$=7.2 Hz, 1H), 4.92～4.77 (m, 2H), 2.50 (s, 3H), 1.98～1.72 (m, 2H), 1.35～1.23 (m, 2H), 1.22～1.12 (m, 2H), 0.90～0.82 (m, 3H); $^{13}$C NMR (100 MHz, $CD_3OD$, rotamers) $\delta$: 150.1, 149.2, 147.3, 144.6, 143.4, 142.1, 139.1, 138.7, 136.8, 136.5, 131.8, 131.7, 130.7, 130.6, 130.4, 129.4, 129.3, 129.1, 128.9, 128.0, 127.1, 120.2, 104.9, 56.4, 52.5, 32.4, 31.0, 29.3, 28.0, 25.6, 23.7, 23.4, 21.6, 14.2, 14.0. HRMS (ESI-Orbitrap) calcd for $C_{25}H_{28}ClN_2O_2S$ 455.1555, found 455.1561.

1-(1-((*N*-丁基-4-甲基苯基)磺酰胺基)乙烯基)-2-氯吡啶三氟甲磺酸盐(**3h**): 粘稠状物, 71.2 mg, 产率 65%. $^1$H NMR (400 MHz, $CD_3OD$) $\delta$: 9.16 (d, $J$=6 Hz, 1H), 8.71 (t, $J$=7.6 Hz, 1H), 8.34 (d, $J$=8.8 Hz, 1H), 8.19 (t, $J$=6.8 Hz, 1H), 7.80～7.74 (m, 2H), 7.54～7.47 (m, 2H), 5.96 (d, $J$=2.8 Hz, 1H), 5.73 (d, $J$=3.2 Hz, 1H), 3.55～3.49 (m, 2H), 2.48 (s, 3H), 1.87～1.78 (m, 2H), 1.44～1.34 (m, 2H), 1.02～0.94 (m, 3H); $^{13}$C NMR (100 MHz, $CD_3OD$) $\delta$: 150.7, 149.5, 148.6, 147.4, 143.2, 134.0, 131.7, 131.4, 129.3, 127.5, 116.9, 53.3, 30.8, 21.6, 21.0, 13.9. HRMS (ESI-Orbitrap) calcd for $C_{21}H_{20}ClN_2O_2S$ 365.0929, found 365.0929.

(*Z*)-2-氯-1-(1-((*N*-苯基-4-甲基苯基)磺酰胺基)-2-苯基乙烯基)吡啶三氟甲磺酸盐(**3i**): 粘稠状固体, 102.7 mg, 产率 85%. $^1$H NMR (400 MHz, $CD_3OD$) $\delta$: 9.47～9.37 (m, 1H), 8.82～8.68 (m, 1H), 8.37～8.20 (m, 2H), 7.70～7.62 (m, 2H), 7.55～7.47 (m, 1H), 7.46～7.37 (m, 4H), 7.36～7.30 (m, 2H), 7.28～7.17 (m, 4H), 7.16～7.07 (m, 2H), 2.39 (s, 3H); $^1$H NMR (100 MHz, $CD_3OD$, rotamers) $\delta$: 151.1, 150.3, 148.6,147.3, 145.4, 137.3, 136.8, 135.6, 135.0, 132.7, 132.1, 131.8, 131.3, 131.1, 130.9, 130.8, 130.4, 130.1, 130.0, 129.9, 129.4, 129.0, 128.6, 128.2, 120.0, 112.6, 21.5. HRMS (ESI-Orbitrap) calcd for $C_{25}H_{28}ClN_2O_2S^+$ $[M]^+$ 455.1555, found 455.1551.

(*Z*)-1-(1-((*N*-烯丙基-4-甲基苯基)磺酰胺基)-2-苯基乙烯基)-2-氯吡啶三氟甲磺酸盐(**3l**): 粘稠状物, 102.1 mg, 产率 89%. $^1$H NMR (400 MHz, $CD_3OD$) $\delta$: 9.24～9.11 (m, 1H), 8.72 (t, $J$=8.0 Hz, 1H), 8.40 (d, $J$=8.4 Hz, 1H), 8.20 (t, $J$=6.8 Hz, 1H), 7.75～7.62 (m, 2H), 7.49～7.40 (m, 3H), 7.32～7.25 (m, 2H), 7.24～7.20 (m, 1H), 7.10～6.95 (m, 2H), 6.00～5.85 (m, 1H), 5.26～5.17 (m, 1H), 5.02～4.94 (m, 1H), 4.42～4.18 (m, 1H), 3.96～3.72

(m, 1H), 2.50 (s, 3H); $^{13}$C NMR (100 MHz, $CD_3OD$, rotamers) $\delta$: 150.5, 149.1, 147.6, 143.4, 136.1, 135.0, 133.9, 132.5, 131.9, 131.7, 131.6, 130.7, 130.3, 130.2, 130.1, 129.5, 128.9, 128.1, 127.7, 126.9, 124.8, 122.7, 119.5, 117.1, 103.6, 46.6, 21.6. HRMS (ESI-Orbitrap) calcd for $C_{23}H_{22}ClN_2O_2S$ 425.1085, found 425.1083.

(*Z*)-2-氯-1-(1-((*N*-甲基-4-甲基苯基)磺酰胺基)-2-(2-甲氧基苯基)乙烯基)吡啶三氟甲磺酸盐(**3m**): 粘稠状物, 86.7 mg, 产率 75%. $^1$H NMR (400 MHz, $CD_3OD$) $\delta$: 9.35 (d, $J$=5.6 Hz, 1H), 8,72 (t, $J$=8.0 Hz, 1H), 8.27～8.15 (m, 2H), 7.52～7.37 (m, 5H), 7.26～7.17 (m, 1H), 7.13～7.06 (m, 1H), 7.02～6.93 (m, 1H), 6.87～6.82 (m, 1H), 3.85 (s, 3H), 3.07 (s, 3H), 2.48 (s, 3H); $^{13}$C NMR (100 MHz, $CD_3OD$) $\delta$: 159.2, 159.0, 151.6, 150.6, 149.6, 148.3, 147.4, 144.7, 142.8, 135.6, 133.7, 132.0, 131.6, 131.3, 130.7, 129.8, 129.7, 128.2, 128.1, 127.4, 127.0, 126.6, 124.6, 121.6, 121.4, 120.1, 112.4, 111.5, 56.3, 55.9, 38.8, 29.2, 21.6, 21.4. HRMS (ESI-Orbitrap) calcd for $C_{22}H_{22}ClN_2O_3S$ 429.1034, found 429.1037.

**辅助材料(Supporting Information)** 化合物 **3a**～**3m** 的 $^1$H NMR 和 $^{13}$C NMR 图谱. 这些材料可以免费从本刊网站(http://sioc-journal.cn/)上下载.

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