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$CF_3S(O)_n$-Containing olefins in cyclopropanation reactions

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ABSTRACT

Cyclopropanation of trifluoromethyl(sulfinyl, sulfonyl) ethylenes was achieved by utilization of α-bromo- or α,α-dibromo 1,3-dicarbonyl compounds in the presence of bases. DBU was found to be the best choice to get satisfactory yields of cyclopropanes with $CF_3S(O)_n$ (n = 1, 2) groups if α-bromo-1,3-dicarbonyl compounds were used. A series of new cyclopropanes bearing trifluoromethylsulfinyl group were synthesized.

1. Introduction

Trifluoromethyl vinyl sulfoxide and trifluoromethyl vinyl sulfone are molecules under interest due to the strongly polarized (e.g., σ_p (CF_3SO) = 0.69, σ_p (CF_3SO_2) = 0.96) [1] double bonds, which makes these compounds attractive and promising precursors for the preparation of more complex molecules via modification of unsaturated part. Although both compounds were synthesized in our laboratory in 1967 [2], the properties of trifluoromethyl vinyl sulfoxide were not well investigated till 2010 [3,4], when we found the more suitable and efficient method for its preparation [3]. At the same time, trifluoromethyl vinyl sulfone was earlier studied in the addition reactions with N-, O-, S-, and C-nucleophiles [2,5,6] as well as in Diels-Alder reaction [7].

The cyclopropane ring is an important structural motif in diverse bioactive compounds [8–10] due to its uncommon bonding and as a result increasing drugs microsomal stability, brain permeability, bioavailability, metabolic stability, etc [9].

Cyclopropanes with trifluoromethylsulfonyl (triflyl) group were obtained using different synthetic methodologies: intramolecular base-mediated cyclization of γ-iodo-, γ-hydroxy-, or γ-triflyl alkyl triflones [11–13], the reaction of methyltrifluoromethylsulfone with 1,2-dibromoethane [14], cyclization of cyclic unsaturated triflones under fluoride activation [7]. α,α-Bis-triflylcyclopropanes were synthesized via reaction of arylhalonium bis(triflyl)methides with olefins [15–17] and interaction of dibromo(bis)trifluoromethylsulfonyl methane with ethylenes in the presence of tributylstibine [18].

To the best of our knowledge, cyclopropanes bearing trifluoromethylsulfinyl group were described to date in only one patent [19] by oxidation of corresponding cyclopropane trifluoromethylsulfides. In mentioned patent azoles derivatives bearing trifluoromethylsulfinyl- and (trifluoromethylsulfonyl)cyclopropyl fragments were shown to possess antifungal activity.

It is noteworthy to mention that direct cyclopropanation reactions starting from trifluoromethylsulfonyl ethylene and trifluoromethylsulfinyl ethylene stayed unknown.

Herein we report our results in the field of cyclopropanation reactions of trifluoromethylsulfinyl and trifluoromethylsulfonyl ethylenes.

2. Results and discussion

Various methods for carbene generating were well summarized in the reviews [20,21]. Nevertheless, the most common and easy route to functionalized carbenes/carbenoids for cyclopropanations remains decomposition of diazocompounds under the action of metal catalysts [22], for example, palladium diacetate [20,23,24] or dirhodium tetraacetate [25]. As a rule, reactions proceed in mild conditions with high yields.

Unfortunately, our attempts to introduce trifluoromethylsulfinyl ethylene **1** or trifluoromethylsulfonyl ethylene **2** into cyclopropanation reaction with ethyl diazoacetate in the presence of $Pd(OAc)_2$ or $Rh_2(OAc)_4$ failed. If the reaction of olefin **1** bearing $SOCF_3$ group with ethyl diazoacetate was carried out in the presence of $Pd(OAc)_2$ at an ambient temperature product formation was not observed. Ethylene **2** with SO_2CF_3 group in the same conditions reacted with ethyl diazoacetate mainly via 1,3-dipolar cycloaddition mechanism yielding, with high probability, the corresponding pyrazoline (according to LC-MS) contaminated by numerous side products that prevent its isolation in individual form. The reaction of compound **2** with ethyl diazoacetate in

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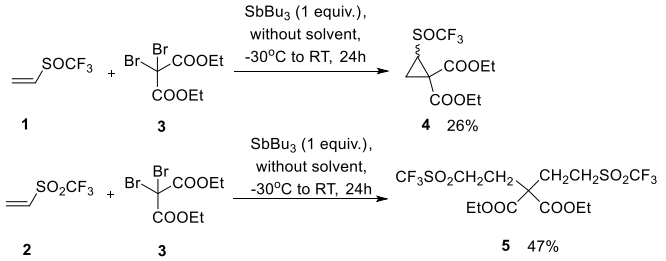


Scheme 1. The reaction of ethylenes **1** and **2** with diethyl α,α-dibromomalonate and tributylstibine.

the presence of $PdCl_2(dppf)_2$ led to the same result (according to LC-MS). Both olefins reacted with ethyl diazoacetate in the presence of $Rh_2(OAc)_4$ with the formation of complex mixtures of unidentified products.

The alternative route to functionalized cyclopropanes was shown to be cyclopropanation of electrophilic alkenes via ionic mechanism – Michael-Initiated Ring Closure (MIRC) reactions [26]. In particular cases, reactions of alkenes with diethyl dibromomalonate in the presence of stibines [27–29] and diethyl bromomalonate in the presence of bases could be mentioned [30,31].

Taking into account our previous results in cyclopropane synthesis starting from dibromo(bis)trifluoromethylsulfonyl methane and electron-deficient olefins under tributylstibine activation [18], we decided to apply such methodology to the $CF_3S(O)_n$-containing cyclopropanes preparation starting from ethylenes **1** and **2**. As model dibromide, we chose symmetrical diethyl α,α-dibromomalonate **3** (Scheme 1). It was found that compound **1** reacted with diethyl α,α-dibromomalonate and tributylstibine yielding two diastereomeric cyclopropanes in 26% total isolated yield. Surprisingly, the reaction of ethylene **2** with diethyl α,α-dibromomalonate and tributylstibine in the same conditions led to product **5** formation in 42% yield. NMR data of compound **5** is in accordance with the literature [6] and additionally, we confirmed its structure by X-ray analysis (Fig. 1).

We propose the following scheme for compound **5** formation (Scheme 2). Initially, dibromide **3** reacted with tributylstibine to form an ionic compound, which was added to the double bond of ethylene **2** to give intermediate **A**. In examples described in the literature [26,28] such intermediates underwent intramolecular nucleophilic substitution of bromine atom yielding corresponding cyclopropanes. The strong electron-withdrawing nature of CF_3SO_2-group may be the reason for anion stabilization and low rate of cyclization that allowed intermediate **A** to lose a second bromine atom with following addition to another molecule of ethylene **2**. As a result, after work-up compound **5** was obtained.

As far as absolutely different results were obtained for olefins under investigation, as well as cyclopropane **4** was isolated in low yield, other conditions for cyclopropanation reaction via ionic mechanism were tested. Thus, triphenylphosphine instead of tributylstibine was used, but no reaction occurred in this case.

Cyclopropanation reactions with diethyl bromomalonate in the presence of a base (NaH or DBU) is widely used in fullerene chemistry and known as Bingel reaction [31,32]. Similar reactions with electron-deficient olefins and diethyl bromomalonate were also described [30]. We applied this methodology with some modifications to cyclopropanation reactions of ethylenes **1, 2**.

Experiments on compounds **1** and **2** interaction with diethyl bromomalonate and DBU were carried out in THF as a solvent. In comparison with described examples [30,31], reactions of ethylenes **1, 2** with diethyl bromomalonate/DBU proceeded with significant exothermic effect; the optimal temperature for interaction was found to be -30°C. Both olefins in these conditions gave cyclopropanes in moderate yields (Scheme 3).

If pyridine was used as the base in the reaction of olefin **1** with diethyl bromomalonate, no reaction occurred; with DABCO the reaction proceeded slowly with the low conversion of starting compounds. All the abovementioned results are summarized in Table 1.

It is evident from Table 1 that diethyl bromomalonate **6** combined with DBU is the most suitable reagent for cyclopropanation reactions starting from olefins **1** and **2**.

Cyclopropanation reactions of trifluoromethylsulfinyl ethylene **1** (Table 2) and trifluoromethylsulfonyl ethylene **2** (Table 3) using a variety of α-bromo dicarbonyl compounds as well as α-bromo malonodinitrile were performed following these optimization studies.

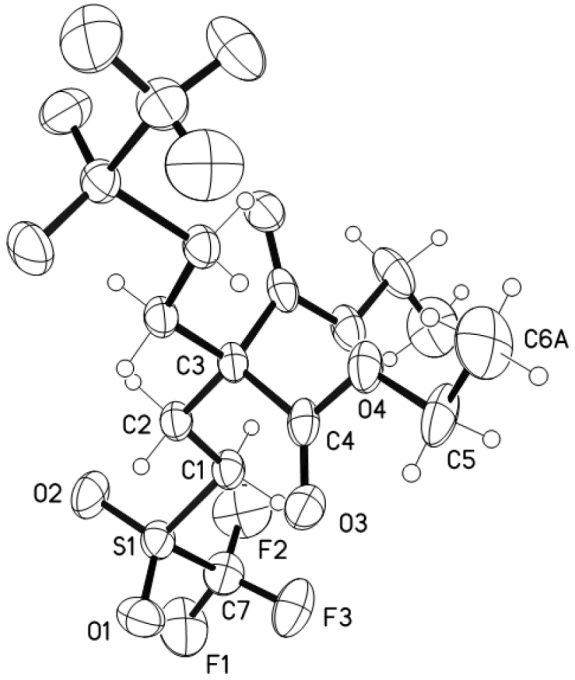
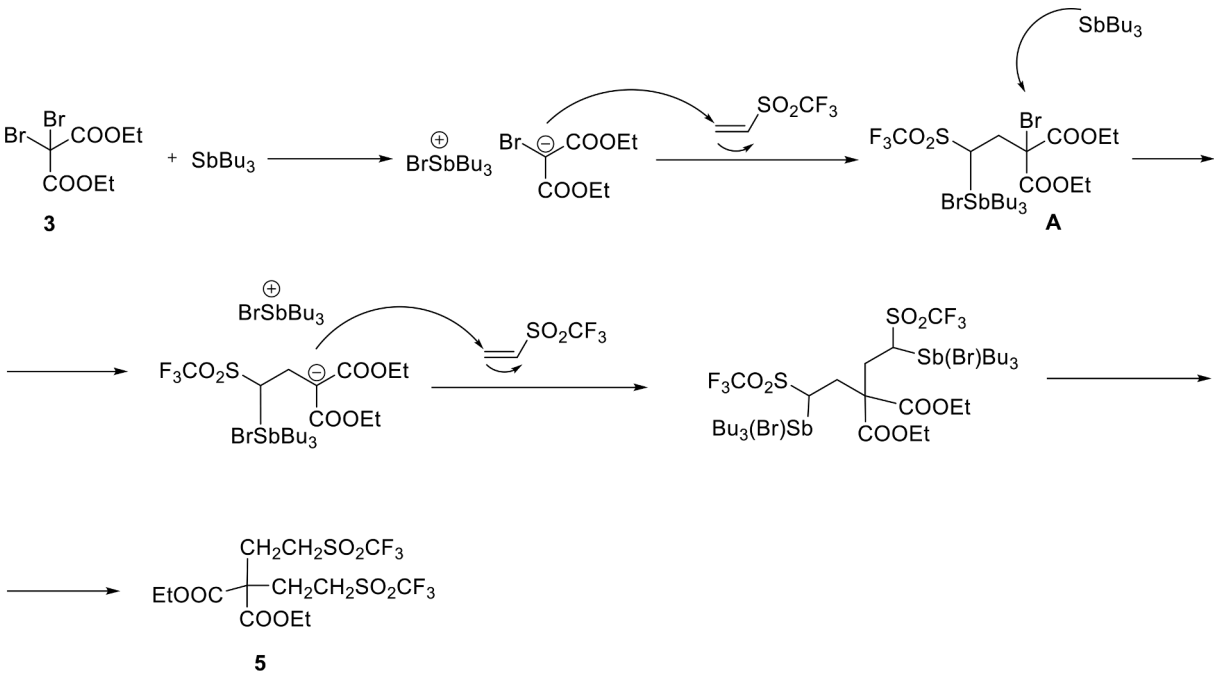
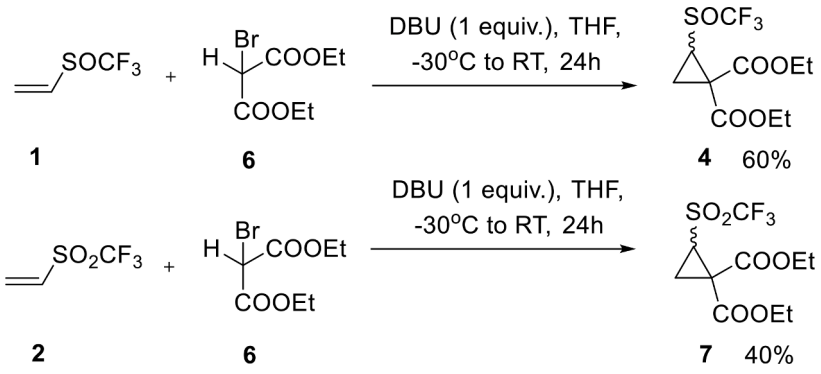


Fig. 1. Molecular structure of compound **5**. Ellipsoids are drawn at a 50% probability level.



Scheme 2. A possible scheme for compound **5** formation.



Scheme 3. The reaction of ethylenes **1** and **2** with diethyl α-bromomalonate and DBU.

It is noteworthy to mention that ethyl bromoacetate bearing only one electron-withdrawing group is inefficient in the reaction with ethylene **1** and DBU as the conversion of ethylene **1** was low and only tar formation was observed. The reaction of olefin **1** with α-bromo malonodinitrile was accompanied by significant tar formation as well, thus product **11** was isolated with only 70% purity and low yield after two column chromatography processes. In the case of 2-bromo-1-phenylbutane-1,3-dione traces of product **13** were detected in the crude reaction mixture by ^{1}H NMR, but due to large quantities of tar, we were not able to isolate it from the reaction mixture. Compounds **4** and **9** were formed as two diastereomers, which were separated by column chromatography to give single diastereomers with 85% de. Diastereomers of cyclopropanes **10** were not separated by column chromatography; the only series of fractions with different diastereomers ratios were obtained. Two out of the three diastereomers of product **12** were isolated in pure form after column chromatography; the third one was obtained as the mixture with another diastereomer.

Interestingly, compound **15** was formed as one diastereomer according to ^{1}H NMR of the crude reaction mixture. Diastereomers of compounds **17** and **18** were separated by column chromatography to give pure ones with >99% de. Similar to the reaction of α-bromo malonodinitrile with olefin **1**, its reaction with ethylene **2** led to tar formation and product **16** was isolated from the reaction mixture with low yield.

The structure of synthesized compounds was proved by 2D NMR and APT spectra using product **14** as an example (see Supporting Information).

3. Conclusions

In conclusion, cyclopropanation reactions starting from trifluoromethylsulfinyl ethylene **1** and trifluoromethylsulfonyl ethylene **2** were studied. It was shown that olefins **1** and **2** reacted with α-bromo dicarbonyl compounds with DBU as a base to give cyclopropanes bearing functional groups in moderate yields. A series of new cyclopropanes with trifluoromethylsulfinyl group were synthesized.

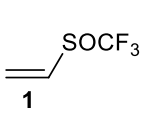
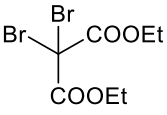
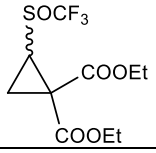
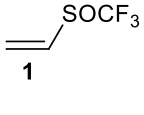
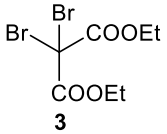
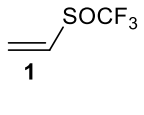
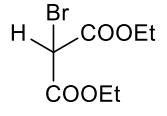
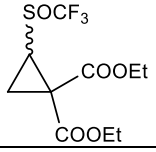
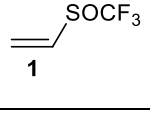
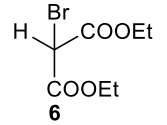
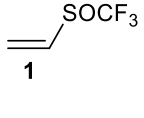
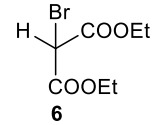
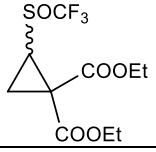
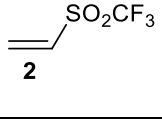
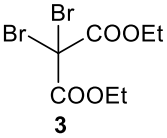
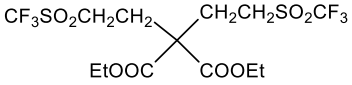
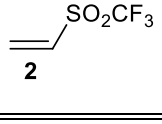
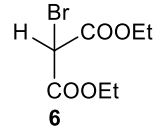
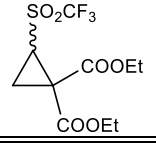
4. Experimental

4.1. General information

Reactions were carried out under dry argon using flame-dried glassware. THF was distilled over sodium immediately before use.

Tributylstibine [33], diethyl dibromomalonate [34], dibenzyl

Table 1
Optimization of the cyclopropanation reactions of ethylenes **1** and **2**.

Entry	Ethylene	Bromomalonate	Base	Product	Total isolated yield, %
1	 **1**	 **3**	$SbBu_3$[a]		26
2	 **1**	 **3**	PPh_3[b]	-	0
3	 **1**	 **6**	DBU[b]		60
4	 **1**	 **6**	pyridine[b]	-	0
5	 **1**	 **6**	DABCO[b]		0
6	 **2**	 **3**	$SbBu_3$[a]		47
7	 **2**	 **6**	DBU[b]		40

[a]Reactions were carried out at -30°C to RT without solvent.
[b]Reactions were carried out in THF at -30°C to RT.

malonate [35], dibenzyl bromomalonate [36], diethyl bromomalonate [30], α-bromomalonodinitrile [37], ethyl α-bromoacetoacetate [38] were prepared according to the literature procedures.

Purification of products by column chromatography (CC) was performed on Silica gel, 70-230 mesh 60A (Aldrich), or neutral activated (Brockmann activity I) aluminium oxide 60A (Aldrich). ^{1}H NMR spectra were recorded at 500 MHz with Bruker AVANCE DRX 500 instrument, or 300 MHz with Bruker AC-300, or 400 MHz with Varian UNITY – Plus 400 spectrometer, or 600 MHz with Agilent ProPulse 600 instrument. ^{19}F NMR spectra were recorded on Varian UNITY – Plus 400 spectrometer at 376.5 MHz or 470 MHz with Bruker AVANCE DRX 500 instrument or 188 MHz with Bruker AC-200. Chemical shifts are given in ppm relative to Me_4Si and CCl_3F, respectively, as internal or external standards. ^{13}C NMR-spectra (proton decoupled) were recorded on a Bruker AVANCE DRX 500 instrument at 125.7 MHz, or on Varian UNITY – Plus 400 spectrometer at 100.6 MHz, or 150.8 MHz with Agilent ProPulse 600 instrument. Melting points were determined in open capillaries using the SMP3 instrument (Stuart Scientific Bibby Sterlin Ltd, Stone, Staffordshire, UK). Elemental analysis was performed in the Analytical Laboratory of the Institute of Organic Chemistry, NAS of Ukraine, Kyiv.

4.2. Preparation of α-bromo-pivaloylacetonitrile

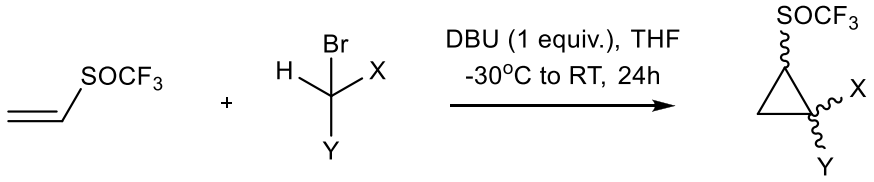
To the solution of pivaloylacetonitrile (1 g, 8 mmol) in dioxane (20 mL) bromine (1.28 g, 8 mmol) in dioxane (40 mL) was added dropwise over 2 h at room temperature. The reaction mixture was stirred at room temperature until complete discolouration occurred, then diluted by methyl-*tert*-butyl ether (MTBE) (60 mL), washed with 10% $NaHCO_3$ solution (3 × 15 mL), water (3 × 15 mL), and dried over $MgSO_4$. Solvents were removed on the rotor evaporator to yield 2.13 g (85%) of desired product, which was used for further reactions without purification.

Spectroscopic data were in agreement with the literature [39].

4.3. Preparation of 2-bromo-1-phenyl-1,3-butanedione

N-Bromosuccinimide (1.65 g, 9.3 mmol) was added to the solution of 1-phenyl-1,3-butanedione (1.5 g, 9.3 mmol) in dichloromethane (20 mL). The reaction mixture was stirred at room temperature for 48 h. The solution was washed with 10% HCl solution (3 × 10 mL), water (3 × 10 mL), and dried over $MgSO_4$. The solvent was removed on the rotor evaporator to yield 2.1 g (94%) of desired product, which was used for

Table 2
Cyclopropanation reactions of trifluoromethylsulfinyl ethylene 1.



1 **4,8-13**

Entry	X	Y	Product (diastereomers ratio)	Total yield (%)[a]
1	H	COOEt	**8**	0[b]
2	COOEt	COOEt	**4** (1:7)[d]	60
3	COOBn	COOBn	**9** (1:15)[d]	55
4	CN	$COBu^t$	**10** (1.3:2:1)[d]	30
5	CN	CN	**11** (one diastereomer)[e]	15
6	$COCH_3$	$COOCH_3$	**12** (1:1:1)[d]	30
7	$COCH_3$	COPh	**13**	0[c]

[a] Isolated yield.

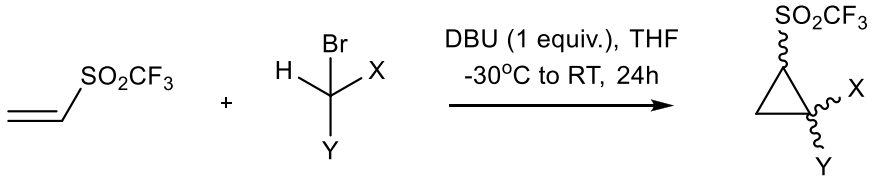
[b] Only tar formation was observed as well as a large quantity of starting olefin **1** was detected in the reaction mixture.

[c] Only tar formation was observed, the product was not isolated from the reaction mixture by column chromatography.

[d] Diastereomers ratio obtained in the crude reaction mixture according to ^{1}H NMR integration ratio.

[e] Only one diastereomer with 70% purity was isolated from the reaction mixture by two column chromatography processes.

Table 3
Cyclopropanation reactions of trifluoromethylsulfonyl ethylene 2.



2 **7, 14-18**

Entry	X	Y	Product (diastereomers ratio)	Total yield (%)[a]
1	COOEt	COOEt	**7**	40
2	COOBn	COOBn	**14**	47
3	CN	$COBu^t$	**15** (one diastereomer)[b]	60
4	CN	CN	**16**[c]	10
5	$COCH_3$	$COOCH_3$	**17** (3:1)[d]	27
6	$COCH_3$	COPh	**18** (1:1)[d]	30

[a] Isolated yield.

[b] Only one diastereomer was formed according to ^{1}H NMR of the crude reaction mixture.

[c] Significant tar formation was observed, the product was isolated from the reaction mixture by column chromatography with ~90% purity.

[d] Diastereomers ratio obtained in the crude reaction mixture according to ^{1}H NMR integration ratio.

further reactions without purification.

Spectroscopic data were in agreement with the literature [40].

4.4. General procedure for cyclopropanation reactions using diethyl dibromomalonate and tributylstibine (Method A)

Diethyl dibromomalonate (6.3 mmol) was placed into the flask and tributylstibine (6.9 mmol) was added dropwise at -30°C followed by the addition of ethylene **1** or **2** (6.9 mmol) at the same temperature. The reaction mixture was gently warmed to room temperature and then stirred for 24 h. To separate products from Sb-containing compounds column chromatography on Al_2O_3 using MTBE as eluent was performed. All fractions were combined, the solvent was removed *in vacuo*.

In the case of ethylene **1** column chromatography of the residue on silica (eluent pentane – MTBE, 100:5) led to corresponding diastereomeric cyclopropanes **4** as colourless oils. Yield of first diastereomer 0.20 g (10%), second one 0.30 g (16%); total yield 0.5 g (26%).

In the case of ethylene **2** addition of pentane led to the formation of the product **5** precipitate. The precipitate was filtered off, washed with pentane, and dried on air to give pure compound **5** as a white solid. Yield 0.7 g (47%).

*Diethyl 2,2-bis(2-(trifluoromethylsulfonyl)ethyl)malonate (**5**)*. mp 65-66°C (Lit. 67-68°C) [6]. ^{1}H NMR ($CDCl_3$, 400 MHz) δ 1.26-1.29 (m, 6H, $2CH_3$), 2.35-2.39 (m, 4H, $2CH_2$), 3.39-3.44 (m, 4H, $2CH_2$), 4.23-4.28 (m,

4H, $2CH_2$). ^{19}F NMR ($CDCl_3$, 376.5 MHz) δ -78.25 (s). ^{13}C NMR ($CDCl_3$, 125.7 MHz) δ 168.0, 118.9 (q, $^1J_{C\text{-}F} = 328.1$ Hz, CF_3), 62.5, 54.5, 45.4, 25.5, 13.4. Anal. Calcd for $C_{13}H_{18}F_6O_6S_2$: C, 34.82; H, 4.05; S, 14.30. Found: C, 34.84; H, 4.04; S, 14.29.

4.5. General procedure for cyclopropanation reactions using α-bromo dicarbonyl compounds or α-bromo malonodinitrile and DBU (Method B)

To the solution of ethylene **1** or **2** (7 mmol) in THF (10 mL) solution of α-bromo dicarbonyl compound or α-bromo malonodinitrile (7 mmol) in THF (10mL) was added at -30°C. To the resulting mixture solution of DBU (7 mmol) in THF (10 mL) was added dropwise with such a rate to keep the temperature in the range -30÷-25°C. After the addition of DBU reaction mixture was gently warmed to room temperature and then stirred for 24 h. Ether (30 mL) was added to the reaction mixture, the precipitate was filtered off, and organic solvents were removed *in vacuo*. Column chromatography of residue led to desired cyclopropanes isolation.

Diethyl 2-(trifluoromethylsulfinyl)cyclopropane-1,1-dicarboxylate ***(4)***. (Method B) Eluent pentane – MTBE, 100:5. After column chromatography yield of first diastereomer 0.30 g (15%), second one 0.93 g (45%); total yield 1.23 g (60%). Colourless oils.

First diastereomer:

^1H NMR ($CDCl_3$, 400 MHz) δ 1.28 (t, 6H, $J = 6.8$ Hz, $2CH_3$), 1.87 (dd, 1H, $J = 8.4$ Hz, 6.8 Hz, CH), 2.26 (t, 1H, $J = 6.8$ Hz, CH), 3.03 (t, 1H, J = 6.8 Hz, CH), 4.24 (q, 4H, $J = 6.8$ Hz, $2CH_2$). ^{19}F NMR ($CDCl_3$, 376.5 MHz) δ -73.42 (s). ^{13}C NMR ($CDCl_3$, 125.7 MHz) δ 167.4, 164.8, 125.2 (q, $^1J_{C\text{-}F} = 334.4$ Hz, CF_3), 62.9, 62.8, 37.9 (q, $J_{C\text{-}F} = 3.8$ Hz, C-$SOCF_3$), 33.1, 13.9, 13.8, 12.8. Anal. Calcd for $C_{10}H_{13}F_3O_5S$: C, 39.74; H, 4.34; S, 10.61. Found: C, 39.75; H, 4.34; S, 10.62.

Second diastereomer:

^1H NMR ($CDCl_3$, 500 MHz) δ 1.29-1.36 (m, 6H, $2CH_3$), 1.87 (t, 1H, $J = 6.5$ Hz, CH), 1.99 (dd 1H, $J = 9$ Hz, 6.5 Hz, CH), 3.36 (dd, 1H, $J = 9$ Hz, 6.5 Hz, CH), 4.25-4.39 (m, 4H, $2CH_2$). ^{19}F NMR ($CDCl_3$, 376.5 MHz) δ -72.45 (s). ^{13}C NMR ($CDCl_3$, 125.7 MHz) δ 166.6, 165.5, 125.4 (q, $^1J_{C\text{-}F} = 335.6$ Hz, CF_3), 63.0, 62.9, 40.27 (q, $^3J_{C\text{-}F} = 3.8$ Hz, C-$SOCF_3$), 34.4, 16.6, 13.9, 13.8. Anal. Calcd for $C_{10}H_{13}F_3O_5S$: C, 39.74; H, 4.34; S, 10.61. Found: C, 39.75; H, 4.33; S, 10.60.

Diethyl 2-(trifluoromethylsulfonyl)cyclopropane-1,1-dicarboxylate ***(7)***. Eluent pentane – MTBE, 100:5. Yield 0.90 g (40%) (Method B). Colourless oil. ^1H NMR ($CDCl_3$, 600 MHz) δ 1.28-1.32 (m, 6H, 2CH3), 1.96 (dd, 1H, $J = 8.4$ Hz, 6 Hz, CH), 2.21 (t, 1H, $J = 6$ Hz, CH), 3.36 (t, 1H, $J = 8.4$ Hz, CH), 4.18-4.31 (m, 4H, $2CH_2$). ^{19}F NMR ($CDCl_3$, 376.5 MHz) δ -77.89 (s). ^{13}C NMR ($CDCl_3$, 150.8 MHz) δ 164.2, 160.8, 117.0 (q, $^1J_{C\text{-}F} = 327.2$ Hz, CF_3), 61.3, 60.7, 35.0 (q, $^3J_{C\text{-}F} = 1.5$ Hz, C-SO_2CF_3), 33.7, 15.9, 11.6, 11.4. Anal. Calcd for $C_{10}H_{13}F_3O_6S$: C, 37.74; H, 4.12; S, 10.07. Found: C, 39.75; H, 4.11; S, 10.08.

Dibenzyl 2-(trifluoromethylsulfinyl)cyclopropane-1,1-dicarboxylate ***(9)***. Eluent pentane – MTBE, 100:30. Yield 1.64 g (55%). White solid. mp 55-56°C.

Major diastereomer:

^1H NMR ($CDCl_3$, 500 MHz) δ 1.93 (t, 1H, $J = 6.5$ Hz, CH), 2.03 (dd, 1H, $J = 8.5$ Hz, 6.5 Hz, CH), 3.43 (t, 1H, $J = 8.5$ Hz, CH), 5.19 (s, 2H, CH_2), 5.27 (s, 2H, CH_2), 7.27-7.35 (m, 10H, ArH). ^{19}F NMR ($CDCl_3$, 376.5 MHz) δ -72.34 (s). ^{13}C NMR ($CDCl_3$, 125.7 MHz) δ 166.5, 165.4, 134.4, 134.3, 128.69, 128.68, 128.66, 128.6, 128.5, 128.3, 125.4 (q, $^1J_{C\text{-}F} = 335.6$ Hz, CF_3), 68.9, 68.6, 40.8 (q, $^3J_{C\text{-}F} = 3.8$ Hz, C-$SOCF_3$), 34.3, 17.1. Anal. Calcd for $C_{20}H_{17}F_3O_5S$: C, 56.34; H, 4.02; S, 7.52. Found: C, 56.35; H, 4.01; S, 7.51.

Minor diastereomer (as 7% impurity in the major one):

^1H NMR ($CDCl_3$, 500 MHz) δ 2.36 (t, 1H, CH), 3.09 (t, 1H, CH), 3.99 (t, 1H, CH), 5.19 (s, 2H, CH_2), 5.27 (s, 2H, CH_2), 7.27-7.35 (m, 10H, ArH). ^{19}F NMR ($CDCl_3$, 376.5 MHz) δ -72.78 (s).

1-Pivaloyl-2-(trifluoromethylsulfinyl)cyclopropane-1-carbonitrile ***(10)***. Eluent pentane – MTBE, 100:10. Yield of diasteremers mixture 0.56 g (30%). Colourless oil. Anal. Calcd for $C_{10}H_{12}F_3NO_2S$: C, 44.94; H, 4.53; S, 12.00. Found: C, 44.95; H, 44.51; S, 12.01.

First diastereomer:

^1H NMR ($CDCl_3$, 500 MHz) δ 1.39 (s, 9H, t-Bu), 2.05 (dd, 1H, $J = 8.5$ Hz, 6.0 Hz, CH), 2.36 (t, 1H, $J = 6.0$ Hz, CH), 3.32 (t, 1H, $J = 8.5$ Hz, CH). ^{19}F NMR ($CDCl_3$, 188 MHz) δ -72.85 (s). ^{13}C NMR ($CDCl_3$, 125.7 MHz) δ 201.4, 125.4 (q, $^1J_{C\text{-}F} = 335.6$ Hz, CF_3), 118.0, 46.0, 41.3 (q, $^3J_{C\text{-}F} = 3.8$ Hz, C-$SOCF_3$), 25.9, 21.6, 19.8.

Second diastereomer:

^1H NMR ($CDCl_3$, 300 MHz) δ 1.41 (s, 9H, t-Bu), 1.93 (t, 1H, $J = 6.0$ Hz, CH), 2.20 (dd, 1H, $J = 8.0$ Hz, 6.0 Hz, CH), 3.27 (t, 1H, $J = 8$ Hz, CH). ^{19}F NMR ($CDCl_3$, 188 MHz) δ -71.31 (s). ^{13}C NMR ($CDCl_3$, 125.7 MHz) δ 201.3, 125.1 (q, $^1J_{C\text{-}F} = 335.6$ Hz, CF_3), 116.3, 46.1, 43.8 (q, $^3J_{C\text{-}F} = 3.8$ Hz, C-$SOCF_3$), 25.9, 21.2, 20.9.

Third diastereomer:

^1H NMR ($CDCl_3$, 300 MHz) δ 1.43 (s, 9H, t-Bu), 2.17 (dd, 1H, $J = 9.0$ Hz, 6.5 Hz, CH), 2.27 (t, 1H, $J = 6.5$ Hz, CH), 3.51 (t, 1H, $J = 9.0$ Hz, CH). ^{19}F NMR ($CDCl_3$, 188 MHz) δ -72.77(s). ^{13}C NMR ($CDCl_3$, 125.7 MHz) δ 202.6, 124.7 (q, $^1J_{C\text{-}F} = 335.6$ Hz, CF_3), 115.9, 46.1, 45.8 (q, $^3J_{C\text{-}F} = 3.8$ Hz, C-$SOCF_3$), 25.9, 21.5, 19.9.

2-(Trifluoromethylsulfinyl)cyclopropane-1,1-dicarbonitrile ***(11)***. First chromatography process: pentane – MTBE, from 100:0 to 0:100; second chromatography process: pentane – MTBE, 100:10. Yield 0.22 g (15%) with 70% purity. Colourless oil. ^1H NMR ($CDCl_3$, 400 MHz) δ 2.36 (dd, 1H, $J = 8.8$ Hz, 7.2 Hz, CH), 2.66 (t, 1H, $J = 7.2$ Hz, CH), 3.39 (t, 1H, $J = 8.8$ Hz, CH). ^{19}F NMR ($CDCl_3$, 188 MHz) δ -72.06 (s).

Methyl 1-acetyl-2-((trifluoromethylsulfinyl)cyclopropane-1-carboxylate ***(12)***. Eluent pentane – MTBE, 100:10. After column chromatography yield of first diastereomer 0.14 g (8%), second one 0.10 g (6%), and mixture of second and third diastereomers in 2:1 ratio 0.30 g (16%); total yield 0.54 g (30%). Colourless oils.

First diastereomer:

^1H NMR ($CDCl_3$, 400 MHz) δ 1.86 (t, 1H, $J = 7.2$ Hz, CH), 2.25 (t, 1H, $J = 6.4$ Hz, CH), 2.40 (s, 3H, CH_3), 3.08 (t, 1H, $J = 7.2$ Hz, CH), 3.82 (s, 3H, CH_3). ^{19}F NMR ($CDCl_3$, 376.5 MHz) δ -73.50 (s). Anal. Calcd for $C_8H_9F_3O_4S$: C, 37.21; H, 3.51; S, 12.42. Found: C, 37.22; H, 3.52; S, 12.40.

Second diastereomer:

^1H NMR ($CDCl_3$, 400 MHz) δ 1.92-1.98 (m, 2H, 2CH), 2.55 (s, 3H, CH_3), 3.50 (t, 1H, $J = 7.2$ Hz, CH), 3.82 (s, 3H, CH_3). ^{19}F NMR ($CDCl_3$, 376.5 MHz) δ -73.36 (s). ^{13}C NMR ($CDCl_3$, 125.7 MHz) δ 199.2, 167.8, 125.4 (q, $^1J_{C\text{-}F} = 335.6$ Hz, CF_3), 53.5, 42.7 (q, $^3J_{C\text{-}F} = 3.8$ Hz, C-$SOCF_3$), 39.6, 30.4, 29.7, 18.2. Anal. Calcd for $C_8H_9F_3O_4S$: C, 37.21; H, 3.51; S, 12.42. Found: C, 37.20; H, 3.50; S, 12.41.

Third diastereomer:

^1H NMR ($CDCl_3$, 500 MHz) δ 1.86-1.94 (m, 2H, 2CH), 2.42 (s, 3H, CH_3), 3.29 (dd, 1H, $J = 8.8$ Hz, 7.0 Hz, CH), 3.85 (s, 3H, CH_3). ^{19}F NMR ($CDCl_3$, 376.5 MHz) δ -73.73 (s). ^{13}C NMR ($CDCl_3$, 125.7 MHz) δ 198.3, 167.4, 125.4 (q, $^1J_{C\text{-}F} = 335.6$ Hz, CF_3), 53.4, 42.0 (q, $^3J_{C\text{-}F} = 3.8$ Hz, C-$SOCF_3$), 39.4, 29.02, 29.0, 18.8.

Dibenzyl 2-(trifluoromethylsulfonyl)cyclopropane-1,1-dicarboxylate ***(14)***. Eluent pentane – MTBE, 100:5. Yield 1.45 g (47%). White solid. mp 45-46°C. ^1H NMR ($CDCl_3$, 500 MHz) δ 2.02 (dd, 1H, $J = 8.5$ Hz, 6.0 Hz, CH), 2.31 (t, 1H, $J = 6.0$ Hz, CH), 3.45 (t, 1H, $J = 8.5$ Hz, CH), 5.16-5.29 (m, 4H, $2CH_2$), 7.25-7.37 (m, 10H, 10 ArH). ^{19}F NMR ($CDCl_3$, 376.5 MHz) δ -77.70 (s). ^{13}C NMR ($CDCl_3$, 125.7 MHz) δ 166.2, 162.9, 134.4, 134.1, 128.8, 128.7, 128.6, 128.5, 128.2, 119.3 (q, $^1J_{C\text{-}F} = 326.8$ Hz, CF_3), 69.0, 37.5, 35.9, 18.4. Anal. Calcd for $C_{20}H_{17}F_3O_6S$: C, 54.30; H, 3.87; S, 7.25. Found: C, 54.29; H, 3.88; S, 7.25.

1-Pivaloyl-2-(trifluoromethylsulfonyl)cyclopropane-1-carbonitrile ***(15)***. Eluent pentane – MTBE, 100:5. Yield 1.2 g (60%). White solid. mp 55-56°C. ^1H NMR ($CDCl_3$, 500 MHz) δ 1.44 (s, 9H, t-Bu), 2.21 (dd, 1H, $J = 8.5$ Hz, 6.5 Hz, CH), 2.38 (t, 1H, $J = 6.5$ Hz, CH), 3.33 (t, 1H, $J = 8.5$ Hz, CH). ^{19}F NMR ($CDCl_3$, 470 MHz) δ -76.95 (s). ^{13}C NMR ($CDCl_3$, 125.7 MHz) δ 200.4, 119.2 (q, $^1J_{C\text{-}F} = 326.8$ Hz, CF_3), 114.6, 46.2, 40.3, 25.9, 21.8, 21.6. Anal. Calcd for $C_{10}H_{12}F_3NO_3S$: C, 42.40; H, 4.27; S, 11.32. Found: C, 42.39; H, 4.28; S, 11.34.

2-(Trifluoromethylsulfonyl)cyclopropane-1,1-dicarbonitrile ***(16)***. Eluent pentane – MTBE, 100:15. Yield 0.16 g (10%) with 90% purity. Colourless oil. ^{1}H NMR (acetone-d6, 400 MHz) δ 2.92 (t, 1H, $J = 7.6$ Hz, CH), 3.08 (t, 1H, $J = 8.8$ Hz, CH), 4.78 (t, 1H, $J = 8.8$ Hz, CH). ^{19}F NMR ($CDCl_3$, 376.5 MHz) δ -76.48 (s). ^{13}C NMR (acetone-d6, 100.6 MHz) δ 119.7 (q, $^{1}J_{C\text{-}F} = 326.0$ Hz, CF_3), 112.3, 110.6, 39.2, 20.8, 7.2.

Methyl 1-acetyl-2-((trifluoromethylsulfonyl)cyclopropane-1-carboxylate ***(17)***. Eluent pentane – MTBE, 100:10. Yield of first diastereomer 0.35 g (18%), second one 0.17 g (9%); total yield 0.52 g (27%). Colourless oils.

First diastereomer:

^{1}H NMR ($CDCl_3$, 400 MHz) δ 1.82 (dd, 1H, $J = 8.6$ Hz, 6 Hz, CH), 2.19 (t, 1H, $J = 6$ Hz, CH), 2.38 (s, 3H, CH_3), 3.37 (t, 1H, $J = 8.6$ Hz, CH), 3.85 (s, 3H, CH_3). ^{19}F NMR ($CDCl_3$, 376.5 MHz) δ -77.75 (s). ^{13}C NMR ($CDCl_3$, 100.6 MHz) δ 197.5, 165.4, 119.3 (q, $^{1}J_{C\text{-}F} = 327.0$ Hz, CF_3), 53.8, 41.6, 38.2, 28.2, 19.5. Anal. Calcd for $C_8H_9F_3O_5S$: C, 35.04; H, 3.31; S, 11.69. Found: C, 35.03; H, 3.30; S, 11.67.

Second diastereomer:

^{1}H NMR ($CDCl_3$, 301.5 MHz) δ 1.95 (dd, 1H, $J = 8.6$ Hz, 6 Hz, CH), 2.25 (t, 1H, $J = 6$ Hz, CH), 2.49 (s, 3H, CH_3), 3.43 (dd, 1H, $J = 8.6$ Hz, 6 Hz, CH), 3.84 (s, 3H, CH_3). ^{19}F NMR ($CDCl_3$, 376.5 MHz) δ -79.25 (s). Anal. Calcd for $C_8H_9F_3O_5S$: C, 35.04; H, 3.31; S, 11.69. Found: C, 35.06; H, 3.32; S, 11.70.

1-Acetyl-1-benzoyl-2-(trifluoromethylsulfonyl)cyclopropane ***(18)***. Eluent pentane – MTBE, 100:5. Yield of first diastereomer 0.34 g (15%), second one 0.34 g (15%); total yield 0.68 g (30%). White solids.

First diastereomer:

$R_f = 0.17$, mp 67-68°C. ^{1}H NMR ($CDCl_3$, 400 MHz) δ 1. 88 (dd, 1H, $J = 8.4$ Hz, 6 Hz, CH), 2.2 (s, 3H, CH_3), 2.66 (t, 1H, J = 6 Hz, CH), 3.65 (t, 1H, J = 8.4 Hz, CH), 7.49 (t, 2H, ArH), 7.63 (t, 1H, ArH), 7.91 (d, 2H, ArH). ^{19}F NMR ($CDCl_3$, 376.5 MHz) δ -78.25 (s). ^{13}C NMR ($CDCl_3$, 125.7 MHz) δ 195.8, 190.1, 134.9, 134.2, 129.3, 129.2, 119.3 (q, $^{1}J_{C\text{-}F} = 326.8$ Hz, CF_3), 49.7, 36.9, 30.0, 17.4. Anal. Calcd for $C_{13}H_{11}F_3O_4S$: C, 48.75; H, 3.46; S, 10.01. Found: C, 48.74; H, 3.45; S, 10.00.

Second diastereomer:

$R_f = 0.12$, mp 77-78°C. ^{1}H NMR ($CDCl_3$, 400 MHz) δ 1.91 (dd, 1H, $J = 8$ Hz, 6 Hz, CH), 2.2 (s, 3H, CH_3), 2.31 (t, 1H, $J = 6$ Hz, CH),), 3.72 (t, 1H, $J = 8$ Hz, CH), 7.52 (t, 2H, ArH), 7.65 (t, 1H, ArH), 7.99 (d, 2H, ArH). ^{19}F NMR ($CDCl_3$, 376.5 MHz) δ -78.02 (s). ^{13}C NMR ($CDCl_3$, 125.7 MHz) δ 198.3, 189.4, 135.1, 134.9, 129.4, 129.3, 119.3 (q, $^{1}J_{C\text{-}F} = 326.8$ Hz, CF_3), 46.3, 38.1, 28.7, 19.8. Anal. Calcd for $C_{13}H_{11}F_3O_4S$: C, 48.75; H, 3.46; S, 10.01. Found: C, 48.77; H, 3.47; S, 10.02.

4.6. X-ray data for compound 5

Crystal data for **5**: $C_{13}H_{18}F_6O_8S_2$, M = 480.39,monoclinic, space group C2/c, $a = 23.978(10)$, $b = 8.723(4)$, $c = 10.055(6)$Å, $\beta = 103.350(17)°$, V = 2046.2(17)Å^3, Z = 4, $d_c = 1.559$ g•cm^{-3}, $\mu = 0.351$ mm^{-1}, F(000) = 984, crystal size ca. 0.17 × 0.28 × 0.38 mm. All crystallographic measurements were performed at temperature 173K on a Bruker Smart Apex II diffractometer operating in the ω scans mode. The intensity data were collected within the range of $1.8 \leq \theta \leq 25.0°$ using Mo-K_α radiation ($\lambda = 0.71078$ Å). The intensities of 7064 reflections were collected (1736 unique reflections, $R_{merg} = 0.0392$). The structure were solved by direct methods and refined by the full-matrix least-squares technique in the anisotropic approximation for non-hydrogen atoms using the Bruker SHELXTL program package [41]. The C6 atom of the ethyl group is disordered over two position A and B with occupancies 58 and 42% respectively. All CH hydrogen atoms were placed at calculated positions and refined as 'riding' model. Convergence was obtained at R1 = 0.0368 and wR2 = 0.0993 for 1327 observed reflections with $I \geq 2\sigma(I)$, R1 = 0.0529 and wR2 = 0.1113, GOF = 1.041 for 1736 independent reflections, 142 parameters, the largest and minimal peaks in the final difference map 0.25 and –0.28 e/Å^3. Full crystallographic details have been deposited at Cambridge Crystallographic Data Centre (CCDC). Any request to the CCDC for these materials should quote the full literature citation and reference number CCDC 2052156.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.jfluchem.2021.109802.

References

[1] C. Hansch, A. Leo, R.W. Taft, Chem. Rev. 91 (1991) 165–195, https://doi.org/10.1021/cr00002a004.
[2] I.L. Knunyants, I.N. Rozhkov, A.M. Alexandrov, L.M. Yagupolskii, J. Gen. Chem. USSR (Engl. Transl.) 37 (1967) 1210–1213.
[3] L.V. Sokolenko, I.I. Maletina, L.M. Yagupolskii, Yu.L. Yagupolskii, Synlett 14 (2010) 2075–2078, https://doi.org/10.1055/s-0030-1258515.
[4] L.V. Sokolenko, Yu.L. Yagupolskii, Yu.G. Vlasenko, L.N. Babichenko, V.O. Lipitskij, E. Anselmi, E. Magnier, Tet. Lett. 56 (2015) 1259–1262, https://doi.org/10.1016/j.tetlet.2015.01.136.
[5] Yu.A. Fialkov, A.M. Aleksandrov, L.M. Yagupolskii, J. Gen. Chem. USSR (Engl. Transl.) 38 (1968) 1697–1700.
[6] A. Haas, V. Popov, J. Fluor. Chem. 20 (1982) 99–105, https://doi.org/10.1016/S0022-1139(00)84022-1.
[7] T. Billard, B. Langlois, M. Essers, G. Haufe, Coll. Czech. Chem. Comm. 73 (2008) 1814–1824, https://doi.org/10.1135/cccc20081814.
[8] L. Clemens, Tetrahedron 75 (2019) 4365–4383, https://doi.org/10.1016/j.tet.2019.06.043.
[9] T.T. Talele, J. Med. Chem. 59 (2016) 8712–8756, https://doi.org/10.1021/acs.jmedchem.6b00472.
[10] I.A. Novakov, A.S. Babushkin, A.S. Yablokov, M.B. Nawrozkii, O.V. Vostrikova, D. S. Sheikin, A.S. Mkrtchyan, K.V. Balakin, Russ. Chem. Bull. 67 (2018) 395–418, https://doi.org/10.1007/s11172-018-2087-6.
[11] A. Mahadevan, P.L. Fuchs, J. Am. Chem. Soc. 117 (1995) 3272–3273, https://doi.org/10.1021/ja00116a032.
[12] J.B. Hendrickson, G.J. Boudreaux, P.S. Palumbo, J. Am. Chem. Soc. 108 (1986) 2358–2366, https://doi.org/10.1021/ja00269a037.
[13] J.B. Hendrickson, K.W. Bair, R. Bergeron, A. Giga, P.L. Skiper, D.D. Stembach, J. A. Wareing, Org. Prep. Proced. Int. 9 (1977) 173–207, https://doi.org/10.1080/00304947709356878.
[14] S. Zhu, Q. Chu, X. Guolin, C. Qin, X. Yong, J. Fluor. Chem. 91 (1998) 195–198, https://doi.org/10.1016/S0022-1139(98)00240-1.
[15] S. Zhu, Q. Chen, J. Chem. Soc. Chem. Comm. 20 (1990) 1459–1460, https://doi.org/10.1039/C39900001459.
[16] N.Tada M.Ochiai, T. Okada, A. Sota, K. Miyamoto, J. Am. Chem. Soc. 130 (2008) 2118–2119, https://doi.org/10.1021/ja074624h.
[17] K. Miyamoto, S. Iwasaki, R. Doi, T. Ota, Y. Kawano, J. Yamashita, Y. Sakai, N. Tada, M. Ochiai, S. Hayashi, W. Nakanishi, M. Uchiyama, J. Org.Chem. 81 (2016) 3188–3198, https://doi.org/10.1021/acs.joc.6b00142.
[18] Yu.L.Yagupolskii N.V.Pavlenko, Russ. J. Gen. Chem. 64 (1994) 1148–1151.
[19] K. Stroech, D. Bielefeldt, M. Plempel (Bayer AG), DE 3732388 A1 (1989) p. 16.
[20] M.P. Doyle, Chem. Rev. 86 (1986) 919–939, https://doi.org/10.1021/cr00075a013.
[21] W. Wu, Z. Lin, H. Jiang, Org. Biomol. Chem. 16 (2018) 7315–7329, https://doi.org/10.1039/C8OB01187G.
[22] H.M.L. Davies, E.G. Antoulinakis, in Organic Reactions; L.E. Overman, Ed.; John Wiley & Sons. Inc.: New York, 2001; Vol. 57, pp 1-326. doi:10.1002/0471264180.or057.01.
[23] U. Mende, B. Radüchel, V. Skuballa, H. Vorbrüggen, Tetrahedron Lett. 16 (1975) 629–632, https://doi.org/10.1016/S0040-4039(00)71939-3.
[24] M.W. Majchrzak, A. Kotelko, J.B. Lambert, Synthesis (1983) 469–470, https://doi.org/10.1055/s-1983-30385.
[25] M.P. Doyle, D. Van Leusen, W.H. Tamblyn, Synthesis (1981) 787–789, https://doi.org/10.1055/s-1981-29593.
[26] H. Lebel, J-F. Marcoux, C. Molinaro, A.B. Charette, Chem. Rev. 103 (2003) 977–1050, https://doi.org/10.1021/cr010007e.
[27] C. Chen, Y-Z. Huang, Y. Shen, Tet. Lett. 29 (1988) 1033–1036, https://doi.org/10.1016/0040-4039(88)85328-0.
[28] C. Chen, Y. Liao, Y-Z. Huang, Tetrahedron 45 (1989) 3011–3020, https://doi.org/10.1016/S0040-4020(01)80128-9.
[29] Y-Z. Huang, Acc. Chem. Res. 25 (1992) 182–187, https://doi.org/10.1021/ar00016a002.
[30] W.J. Frazee, S. Thorimbert, M. Malacria, Dimethyl bromomalonate. Encyclopedia of Reagents for Organic Synthesis, John Wiley & Sons, 2007.
[31] Yu. Biglova, A. Mustafin, RSC Advances 9 (2019) 22428–22498, https://doi.org/10.1039/C9RA04036F.
[32] A. Herrmann, M. Rüttimann, C. Thilgen, F. Diederich, Helvetica Chimica Acta 78 (1995) 1673–1704, https://doi.org/10.1002/hlca.19950780705.

[33] W.J.C. Dyke, W.C. Davies, W.J. Jones, J. Chem. Soc. (1930) 463–467, https://doi.org/10.1039/JR9300000463.
[34] M.L. Meketa, Y.R. Mahajan, S.M. Weinreb, Tet. Lett. 46 (2005) 4749–4751, https://doi.org/10.1016/j.tetlet.2005.05.055.
[35] S. Wolfe, S. Ro, C-K. Kim, Z. Shi, Can. J. Chem. 79 (2001) 1238–1258, https://doi.org/10.1139/v01-100.
[36] Z. Santa, J. Nagy, J. Nyitrai, Tetrahedron Asymmetry 17 (2006) 3111–3127, https://doi.org/10.1016/j.tetasy.2006.11.034.
[37] Organic Synth. 75 (1998) 210–212, https://doi.org/10.15227/orgsyn.075.0210.
[38] J.F. Okonya, R.V. Hoffman, M.C. Johnson, J. Org. Chem. 67 (2002) 1102–1108, https://doi.org/10.1021/jo010630z.
[39] S. Muto, A. Itai, (Institute of Medicinal Molecular Design, Inc.), EP 1535609 A1, (2005), p. 106.
[40] A.T. Khan, M.A. Ali, P. Goswami, L.H. Choudhury, J. Org. Chem. 71 (2006) 8961–8963, https://doi.org/10.1021/jo061501r.
[41] G. Sheldrick, ActaCryst., Sect. A 64 (2008) 112–122, https://doi.org/10.1107/S0108767307043930.