Palladium-Catalyzed Carbonylative Lactonization of Propargyl Alcohols with Organic Dichalcogenides and Carbon Monoxide

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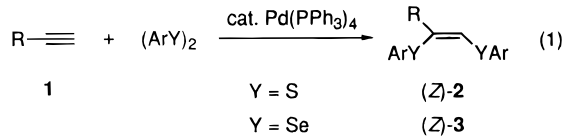
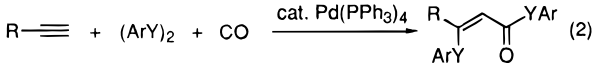
The reaction of propargylic alcohols with diaryl disulfides and carbon monoxide in the presence of tetrakis(triphenylphosphine)palladium leads to a novel thiolative lactonization to afford β-(arylthio)-α,β-unsaturated lactones in moderate to good yields. Similar conditions can be employed with homopropargylic alcohols, giving the corresponding δ-lactones with a β-arylthio group successfully. The reaction using diaryl diselenides in lieu of diaryl disulfides also attains a similar one-pot thiolation/lactonization sequence to provide the corresponding β-selenobutenolides (**7**).

Introduction

Although the utility of transition metal catalysts for effecting a wide variety of synthetic transformations using heteroatom compounds, such as organic silicon,[1] tin,[2] and boron[3] compounds, is well established, the use of these catalysts for synthetic reactions of group 16 heteroatom compounds has remained largely unexplored.[4] This is partly due to the widespread belief that sulfur and selenium compounds often bind strongly to the catalysts, thus poisoning them and making catalytic reactions ineffective. On the contrary, we have recently revealed a series of reactions involving such a mismatched combination of chalcogen compounds and transition metal catalysts.[5] These reactions clearly demonstrate the efficacy of the transition metal catalysts in the synthetic reactions of organic sulfides and selenides. For example, diaryl dichalcogenides add stereoselectively to terminal acetylenes in the presence of palladium(0) catalyst, as shown in eq 1.[5i] When the same reaction is carried out under the pressure of carbon monoxide, the carbonylative addition of diaryl dichalcogenides to acetylenes takes place with excellent regio- and stereoselectivity (eq 2).[5i]



1 Y = S (*Z*)-**2**; Y = Se (*Z*)-**3**



Y = S (*Z*)-**4**; Y = Se (*Z*)-**5**

In the case of acetylenes possessing a hydroxyl group in the "R" of acetylenes at a proper position, double bond isomerization, followed by intramolecular cyclization, has been found to take place, giving α,β-unsaturated β-chalcogenolactones (**6** and **7**) successfully (eq 3). Reported herein is a novel thiolative lactonization of propargylic

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(1) For example, see: (a) Hiyama, T.; Kusumoto, T. In *Comprehensive Organic Synthesis*; Trost, B. M., Ed.; Pergamon: Oxford, 1991; Vol. 8, p 763. (b) Ojima, I. In *The Chemistry of Organic Silicon Compounds*; Patai, S., Rappoport, Z., Eds.; John Wiley & Sons: Chichester, 1989; Part 2, p 1479. (c) Hevesi, L. In *Comprehensive Organic Functional Group Transformations*; Katritzky, A. R., Meth-Cohn, O., Rees, C. W., Eds.; Elsevier Science: Cambridge, 1995; Vol. 2, p 899. (d) Murai, S.; Chatani, N. *J. Synth. Org. Chem., Jpn.* **1993**, *51,* 421. (e) Recatto, C. A. *Aldrichimica Acta* **1995**, *28,* 85.

(2) (a) Stille, J. K. *Angew. Chem., Int. Ed. Engl.* **1986**, *25*, 508. (b) Mitchell, T. N. *Synthesis* **1992**, 803. (c) Pereyre, M.; Quintard, J.-P.; Rahm, A. *Tin in Organic Synthesis*; Butterworths: London, 1987. (d) Harrison, P. G. *Chemistry of Tin*; Blackie & Son: New York, 1989.

(3) (a) Burgess, K.; Ohlmeyer, M. J. *Chem. Rev. (Washington, D.C.)* **1991**, *91*, 1179. (b) Beletskaya, I.; Pelter, A. *Tetrahedron* **1997**, *53*, 4957. (C) Suzuki, A.; Miyaura, N. *J. Synth. Org. Chem., Jpn.* **1993**, *51*, 1043.

(4) (a) Murahashi, S.-I.; Yano, T. *J. Am. Chem. Soc.* **1980**, *102*, 2456. (b) Okamura, H.; Miura, M.; Kosugi, K.; Takei, H. *Tetrahedron Lett.* **1980**, *21*, 87. (c) Dzhemilev, U. M.; Kunakova, R. V.; Gaisin, R. L. *Izv. Akad. Nauk SSSR, Ser. Khim.* **1981**, *11*, 2655. (d) Hutchins, R. O.; Learn, K. *J. Org. Chem.* **1982**, *47*, 4380. (e) McKervey, M. A.; Ratananukul, P. *Tetrahedron Lett.* **1982**, *23*, 2509. (f) Godleski, S. A.; Villhauer, E. B. *J. Org. Chem.* **1984**, *49*, 2246. (g) Antebi, S.; Alper, H. *Tetrahedron Lett.* **1985**, *26*, 2609. (h) Auburn, P. R.; Whelan, J.; Bosnich, B. *J. Chem. Soc., Chem. Commun.* **1986**, 146. (i) Cristau, H. J.; Chabaud, B.; Labaudiniere, R.; Christol, H. *J. Org. Chem.* **1986**, *51*, 875. (j) Antebi, S.; Alper, H. *Organometallics* **1986**, *5*, 596. (k) Goux, C.; Lhoste, P.; Sinou, D. *Tetrahedron Lett.* **1992**, *33*, 8099. (l) Takahashi, H.; Ohe, K.; Uemura, S.; Sugita, N. *J. Organomet. Chem.* **1987**, *334*, C43. (m) Osakada, K.; Yamamoto, T.; Yamamoto, A. *Tetrahedron Lett.* **1987**, *28*, 6321. (n) Carpita, A.; Rossi, R.; Scamuzzi, B. *Tetrahedron Lett.* **1989**, *30*, 2699. (o) Luh, T. Y.; Ni, Z. J. *Synthesis* **1990**, 89. (p) Fukuzawa, S.; Fujinami, T.; Sakai, S. *Chem. Lett.* **1990**, 927. (q) Kano, K.; Takeuchi, M.; Hashimoto, S.; Yoshida, Z. *Chem. Lett.* **1990**, 1381. (r) Ishiyama, T.; Nishijima, K.; Miyaura, N.; Suzuki, A. *J. Am. Chem. Soc.* **1993**, *115*, 7219. (s) Keim, W.; Herwig, J. *J. Chem. Soc., Chem. Commun.* **1993**, 1592. (t) Totland, K.; Alper, H. *J. Org. Chem.* **1993**, *58*, 3326. (u) Khumtaveeporn, K.; Alper, H. *J. Org. Chem.* **1994**, *59*, 1414. (v) Bäckvall, J.-E.; Ericsson, A. *J. Org. Chem.* **1994**, *59*, 5850. (w) Besenyei, G.; Németh, S.; Simándi, L. I. *Tetrahedron Lett.* **1994**, *35*, 9609. (x) Han, L.-B.; Choi, N.; Tanaka, M. *J. Am. Chem. Soc.* **1996**, *118*, 7000.

(5) (a) Ogawa, A.; Kawakami, J.; Sonoda, N.; Hirao, T. *J. Org. Chem.* **1996**, *61*, 4161. (b) Ogawa, A.; Sonoda, N. *J. Synth. Org. Chem., Jpn.* **1996**, *54*, 894. (c) Ogawa, A.; Takeba, M.; Kawakami, J.; Ryu, I.; Kambe, N.; Sonoda, N. *J. Am. Chem. Soc.* **1995**, *117*, 7564. (d) Ogawa, A.; Sonoda, N. *J. Synth. Org. Chem., Jpn.* **1993**, *51*, 815. (e) Kuniyasu, H.; Ogawa, A.; Sonoda, N. *Tetrahedron Lett.* **1993**, *34*, 2491. (f) Kuniyasu, H.; Ogawa, A.; Sato, K.; Ryu, I.; Kambe, N.; Sonoda, N. *J. Am. Chem. Soc.* **1992**, *114*, 5902. (g) Kuniyasu, H.; Ogawa, A.; Sato, K.; Ryu, I.; Sonoda, N. *Tetrahedron Lett.* **1992**, *33*, 5525. (h) Kuniyasu, H.; Ogawa, A.; Higaki, K.; Sonoda, N. *Organometallics* **1992**, *11*, 3937. (i) Kuniyasu, H.; Ogawa, A.; Miyazaki, S.; Ryu, I.; Kambe, N.; Sonoda, N. *J. Am. Chem. Soc.* **1991**, *113*, 9796.

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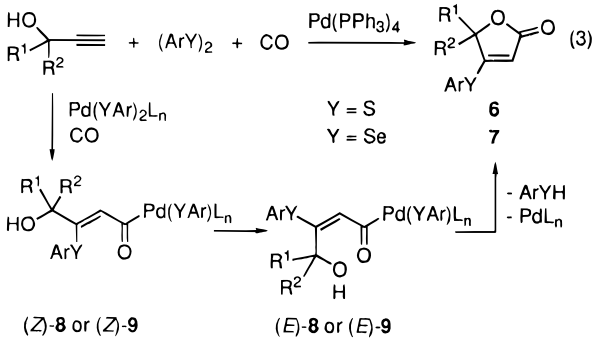
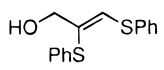
alcohols, which has also been attained by the combination of organic dichalcogenides and palladium catalysts.[6]

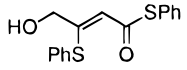


Results and Discussion

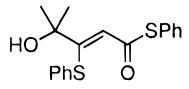
The reaction of 2-propyn-1-ol (**1a**) with diphenyl disulfide and carbon monoxide in the presence of tetrakis(triphenylphosphine)palladium at 100 °C for 50 h provided 43% of 3-(phenylthio)-2-buten-4-olide (**6a**) with the formation of (*Z*)-1,2-bis(phenylthio)-3-hydroxy-1-propene ((*Z*)-**2a**, 35%) (entry 1 in Table 1). However, 1,3-bis(phenylthio)-4-hydroxy-2-buten-1-one (**4a**) was not detected at all under these reaction conditions.



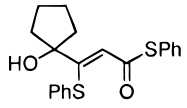
2a



4a



4c

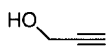
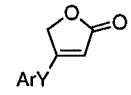
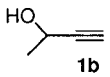
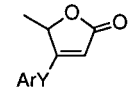
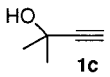
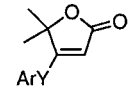
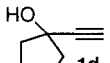
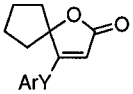
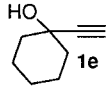
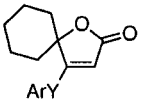
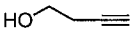
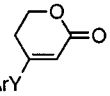


4d

The scope and limitations of this palladium-catalyzed carbonylative lactonization of a series of hydroxyacetylenes are summarized in Table 1. When diphenyl diselenide was used in place of diphenyl disulfide, a similar lactonization took place to provide 3-(phenylseleno)-2-buten-4-olide (**7a**) (entry 2). $Pd(PPh_3)_2Cl_2$ was also effective as a catalyst for this carbonylative lactonization with $(PhSe)_2$ (entry 3).[7] Introduction of a trifluoromethyl group on the para position of diaryl diselenide improved the yield of the butenolide (entry 5).

When diphenyl disulfide was used, the carbonylative lactonization of α,α-disubstituted propargyl alcohols **6c** and **6d** proceeded in poor yields, and instead, (*Z*)-**4c** and (*Z*)-**4d** were formed as the major products, in 38% and 58% yields, respectively (entries 8 and 10). In contrast, the corresponding reaction between **1c** and $(PhSe)_2$ gave the desired lactone **7c** in moderate yield (entry 9). Spirocyclic lactones with a *β*-arylseleno group (**7d** and **7e**) could also be prepared upon similar treatment of **1d** and **1e** (entries 11 and 12). The present one-pot lactonization was then applicable to a homopropargyl alcohol (**1f**), which provided the corresponding *δ*-lactones (**6f** and **7f**) in good yields (entries 13 and 14).

Table 1. Carbonylative Lactonization of Propargyl and Homopropargyl Alcohols with Diaryl Disulfides and Diselenides[a]

entry	substrate	$(ArY)_2$	product	yield, %[b]
1		$(PhS)_2$		**6a** 43
2[d]	**1a**	$(PhSe)_2$		**7a** 36[e]
3		$(PhSe)_2$		**7a** 53[c]
4		$(p\text{-}MeC_6H_4Se)_2$		**7a'** 56[f]
5		$(p\text{-}CF_3C_6H_4Se)_2$		**7a"** 74
6		$(PhS)_2$		**6b** 52
7	**1b**	$(PhSe)_2$		**7b** 54
8		$(PhS)_2$		**6c** 16
9	**1c**	$(PhSe)_2$		**7c** 57
10		$(PhS)_2$		**6d** 14[g]
11	**1d**	$(PhSe)_2$		**7d** 70
12	 **1e**	$(PhSe)_2$		**7e** 62
13		$(PhS)_2$		**6f** 64
14	**1f**	$(PhSe)_2$		**7f** 66[h]

[a] Unless otherwise noted, a mixture of substrate (1 mmol), $(ArY)_2$ (1 mmol), $Pd(PPh_3)_4$ (2 mol%), and PhH (1 mL) was stirred at 100 °C for 50 h under the pressure of CO (60 atm). [b] Isolated yield. [c] NMR yield. [d] $Pd(PPh_3)_2Cl_2$ (2 mol%), CO (20 atm). [e] 3,3-Bis(phenylseleno)butan-4-olide (12%) was also obtained. [f] 3,3-Bis(*p*-methylphenylseleno)butan-4-olide (13%) was also obtained. [g] 1-[1,2-Bis(phenylthio)ethenyl]cyclopentene was obtained in 6% yield. [h] 3,3-Bis(phenylseleno)pentan-5-olide (10%) was also obtained.

A mechanistic pathway of this one-pot lactonization is likely to involve the following processes (Scheme 1): (i) $(PhS)_2$ adds oxidatively to low-valent palladium complex to form "$Pd(SPh)_2L_n$";[8] (ii) insertion of acetylene (**1a**) into the Pd−S bond forms a *cis*-vinylpalladium (**10a**) regio- and stereoselectively; (iii) introduction of carbon monoxide into the palladium−carbon bond of **10a** provides acylpalladium intermediate ((*Z*)-**8a**) (carbonylation step); (iv) double bond isomerization of (*Z*)-**8a** forms (*E*)-**8a** (isomerization step); and (v) (*E*)-**8a** cyclizes intramolecularly to give lactone (**6a**) and benzenethiol with the regeneration of the catalyst (cyclization step).

To obtain some information about the reaction pathway, the following experiments were made. When the palladium-catalyzed reaction of homopropargyl alcohol (**1f**) with $(PhS)_2$ in the presence of CO was carried out under controlled conditions (80 °C, 30 h), a stereoisomeric mixture of **4f** was formed in 28% yield besides lactone **6f** (46%) (entry 1 in Table 2; eq 4).[9,10] Upon subjection to

(6) For some examples of transition-metal-catalyzed carbonylative lactonization of olefinic or acetylenic alcohols, see: (a) Matsuda, I.; Ogiso, A.; Sato, S. *J. Am. Chem. Soc.* **1990**, *112*, 6120. (b) Matin, L. D.; Stille, J. K. *J. Org. Chem.* **1982**, *47*, 3630. (c) Cowell, A.; Stille, J, K. *J. Am. Chem. Soc.* **1980**, *102*, 4193. (d) Ali, B. E.; Alper, H. *J. Org. Chem.* **1991**, *56*, 5357. (e) Alper, H.; Leonard, D. *J. Chem. Soc., Chem. Commun.* **1985**, 511. (f) Murray, T. F.; Varma, V.; Norton, J. R. *J. Org. Chem.* **1978**, *43*, 353. (g) Murray, T. F.; Varma, V.; Norton, J. R. *J. Am. Chem. Soc.* **1977**, *99*, 8085.

(7) In the case of $(PhS)_2$, $Pd(PPh_3)_2Cl_2$ was ineffective (the yield of **6a** was 17%).

(8) The oxidative addition of $(PhS)_2$ to $Pd(PPh_3)_4$ easily proceeds even at room temperature, see: (a) Zanella, R.; Ros, R.; Graziani, M. *Inorg. Chem.* **1973**, *12*, 2736. (b) Rauchfuss, T. B.; Shu, J. S.; Roundhill, D. M. *Inorg. Chem.* **1976**, *15*, 2096.

Scheme 1. A Proposed Reaction Pathway for the Palladium-Catalyzed Lactonization of 1a with $(PhS)_2$ and CO

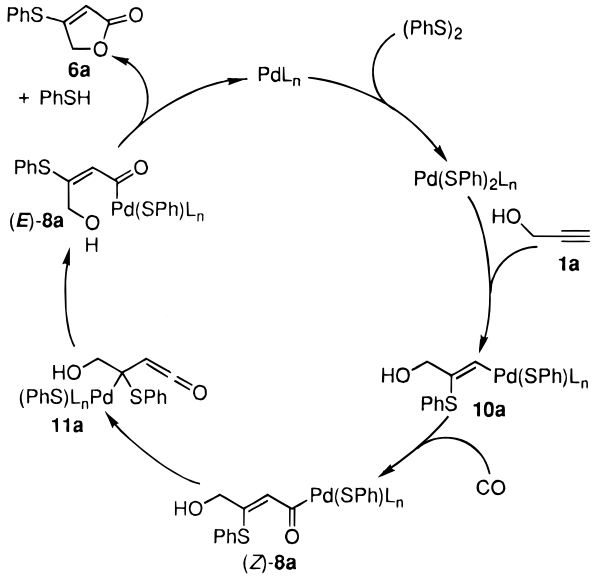
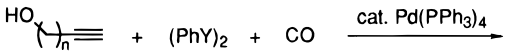
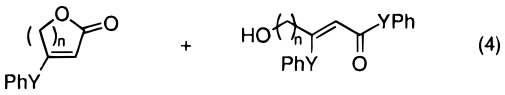


Table 2. Palladium-Catalyzed Reaction of Hydroxyacetylenes with CO and $(PhY)_2$ (Y = S, Se)[a]



1f (n = 2)
1g (n = 3)



(4)

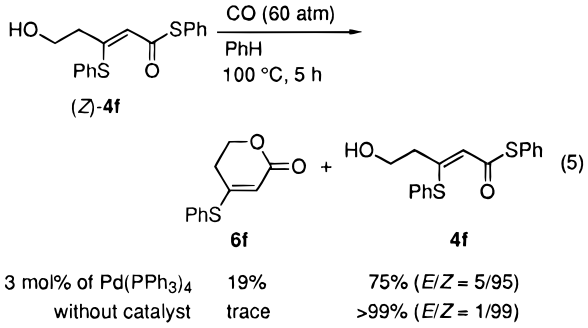
6f (n = 2, Y =S) **4f** (n = 2, Y =S)
6g (n = 3, Y =S) **4g** (n = 3, Y =S)
7g (n = 3, Y =Se) **5g** (n = 3, Y =Se)

entry	$(PhY)_2$, equiv	substrate	conditions	yield %[b] lactone	yield %[b] chalcogenoester
1	1 (Y = S)	**1f**	80 °C, 30 h	46	28 (*E*/*Z* = 47/53)
2	1 (Y = S)	**1g**	100 °C, 50 h	trace	41 (*E*/*Z* = 62/38)
3	1 (Y = Se)	**1g**	100 °C, 50 h	trace	56 (*E*/*Z* = 36/64)

[a] Substrate (1 mmol), $(PhS)_2$ (1 or 4 mmol), CO (60 atm), and $Pd(PPh_3)_4$ (2 mol %). [b] Determined by ^1H NMR.

the lactonization conditions, 4-pentyn-1-ol (**1g**) did not provide the corresponding seven-membered lactone (**6g**), but instead the carbonylation product **4g** was formed as a mixture of *E*- and *Z*-isomers (62/38) (entry 2). A similar result was obtained in the reaction using $(PhSe)_2$ (entry 3).[11] Considering that the carbonylative addition of disulfides (or diselenides) to acetylenes bearing no hydroxy group provides *Z*-isomers of **4** (or **5**) with excellent stereoselectivity (eq 2), these results may indicate that the presence of a hydroxyl group in **4** (or **5**) is crucial for the isomerization of (*Z*)-isomers into (*E*)-isomers.[8]

To elucidate whether the palladium catalyst is essential for the isomerization step and/or the cyclization step, the palladium(0)-catalyzed reaction of isolated (*Z*)-**4f** was carried out in the presence of carbon monoxide (eq 5). When a solution of (*Z*)-**4f** in benzene was heated



3 mol% of $Pd(PPh_3)_4$	19%	75% (*E*/*Z* = 5/95)
without catalyst	trace	>99% (*E*/*Z* = 1/99)

at 100 °C for 5 h in the presence of $Pd(PPh_3)_4$ under pressurized CO,[12] lactone **6f** was obtained in 19% yield along with small amounts of (*E*)-**4f**. Since the oxidative addition of thioester **4f** to palladium(0) species proceeds very slowly under the conditions employed, the yields were not very high, but both isomerization and cyclization were observed. On the other hand, a similar reaction in the absence of the palladium(0) catalyst resulted in almost quantitative recovery of the starting (*Z*)-**4f**. Although the precise mechanism of the double bond isomerization remains unclear, a possible pathway may include the formation of ketene species (**11a**), in which the palladium would undergo intramolecular coordination by the hydroxyl group (see Scheme 1).

In conclusion, the palladium-catalyzed reactions of propargyl alcohols with diaryl disulfides and diselenides under pressurized carbon monoxide allow the one-pot preparation of butenolides possessing ArS and ArSe groups at the β position, respectively, which result should be applicable to the development of further transformations.[13] This paper again demonstrates the utility of transition metal catalysts in the synthetic reactions of chalcogen compounds.

Experimental Section

Acetylenes and palladium complexes were obtained commercially, and the former were purified by distillation if necessary. Diaryl disulfides were obtained commercially and were purified by recrystallization from EtOH or *n*-hexane and dried in vacuo. Diphenyl diselenide was prepared according to the literature[14] and was recrystallized from *n*-hexane. A similar procedure was employed for the syntheses of bis(*p*-methylphenyl) diselenide and bis(*p*-trifluoromethylphenyl)

(9) The palladium-catalyzed carbonylative addition of disulfides and diselenides to acetylenes bearing no hydroxyl group proceeded with high stereoselectivity. For example, the reaction of 1-octyne (1 mmol) with $(PhS)_2$ (1 mmol) in the presence of $Pd(PPh_3)_4$ (0.02 mmol) under pressure of CO (60 atm) at 80 °C for 39 h gave (*Z*)-1,3-bis(phenylthio)-2-nonen-1-one stereoselectively in 84% yield; see ref 5i.

(10) When the carbonylative thiolation of propargyl alcohols such as **1a** was carried out at 100 °C for 24 h, the formation of (*Z*)-**4a** (17%) and **6a** (25%) was confirmed. In this case, however, no (*E*)-**4a** was detected at all by ^1H NMR spectrometer, probably because five-membered cyclization proceeded very smoothly, compared with the six-membered cyclization.

(11) The carbonylative addition of $(PhSe)_2$ to 1-octyne under similar reaction conditions (100 °C, 50 h) gave 1,3-bis(phenylseleno)-2-nonen-1-one in 57% yield (*E*/*Z* = 1/99) with the concomitant formation of some unidentified materials.

(12) In the absence of carbon monoxide, palladium-catalyzed decarbonylation occurred competitively. For a relating report, see: Wenkert, E.; Chianelli, D. *J. Chem. Soc., Chem. Commun.* **1991**, 627 and ref 4m.

(13) (a) Tanikaga, R.; Yamasita, H.; Kaji, A. *Synthesis* **1986**, 416. (b) Barua, N. C.; Schmidt, R. R. *Synthesis* **1986**, 1067. (c) Trost, B. M.; Lavoie, A. C. *J. Am. Chem. Soc.* **1983**, *105*, 5075. (d) Magnus, P.; Quagliato, D. *J. Org. Chem.* **1985**, *50*, 1621. (e) Comasseto, J. V. *J. Organomet. Chem.* **1983**, *253*, 131. (f) Paulmier, C. *Selenium Reagents and Intermediates in Organic Synthesis*; Pergamom Press: Oxford, 1986.

(14) Reich, H. J.; Renga, J. M.; Reich, I. L. *J. Am. Chem. Soc.* **1975**, *97*, 5434.

diselenide. Benzene was purified by distillation from sodium (>8%)−lead alloy before use. ^{1}H NMR spectra of $CDCl_3$ solutions were recorded on a JEOL JNM-GSX-270 (270 MHz) spectrometer. ^{13}C NMR spectra of $CDCl_3$ solutions were also recorded on a JEOL JNM-GSX-270 (68 MHz) spectrometer. Chemical shifts in the ^{1}H NMR and ^{13}C NMR spectra were determined relative to Me_4Si. IR spectra were recorded on a Perkin-Elmer Model 1600 spectrometer. Mass spectra were recorded on a JEOL JMS-DX303 apparatus. Purification of products was performed by using MPLC with Merck 25−40 mm mesh silica gel (Art 9390) and preparative TLC with Wakogel B-5F silica gel (or recycling preparative HPLC (Japan Analytical Industry Co., Ltd. Model LC-908, JAIGEL-1H and -2H (GPC), length 600 mm, i.d. 20 mm, eluent $CHCl_3$)). High-resolution mass spectra (HRMS) and combustion analyses were performed in the Instrumental Analysis Center of the Faculty of Engineering, Osaka University. Registry numbers are provided by the author.

Palladium-Catalyzed One-Pot Carbonylative Lactonization: General Procedure (Table 1, entry 1). To a 50 mL stainless steel autoclave equipped with a magnetic stirring bar were placed diphenyl disulfide (1.0 mmol), 2-propyn-1-ol (**1a**) (1.0 mmol), tetrakis(triphenylphosphine)palladium ($Pd(PPh_3)_4$) (0.02 mmol), and benzene (1 mL). The apparatus was charged with carbon monoxide at 60 atm, and the mixture was heated at 100 °C for 50 h with magnetic stirring. The resulting brown precipitate was removed by filtration through Celite, and the filtrate was concentrated under reduced pressure. The crude mixture was analyzed by using a ^{1}H and ^{13}C NMR spectrometer and then was separated by MPLC (silica gel, 25−40 mm, length 310 mm, i.d. 25 mm, *n*-hexane/ether as eluent) followed by HPLC to provide 83 mg of 3-(phenylthio)-2-buten-4-olide (**6a**) (43%, CA Registry No. 57061-30-0).[15]

The following compounds were prepared according to the general procedure. The reaction listed in Table 2 was also carried out under similar reaction conditions. The structures of lactones obtained were characterized unambiguously on the basis of analytical and spectral data.

3-(Phenylseleno)-2-buten-4-olide (7a) (Table 1, entry 2): yellow oil; ^{1}H NMR (270 MHz, $CDCl_3$) δ 4.72 (s, 2 H), 5.76 (s, 1 H), 7.39−7.48 (m, 3 H), 7.63−7.66 (m, 2 H); ^{13}C NMR (68 MHz, $CDCl_3$) δ 73.51, 115.60, 123.32, 130.01, 130.10, 136.00, 164.50, 171.80; IR (NaCl) 3058, 2932, 1770, 1742, 1567, 1440, 1249, 1150, 1008, 884, 845, 744, 692 cm^{-1}; mass spectra (EI) *m*/*z* 240 (M^+, 100). Anal. Calcd for $C_{10}H_8O_2Se$: C, 50.23; H, 3.37. Found: C, 49.98; H, 3.41.

3-[(*p*-Methylphenyl)seleno]-2-buten-4-olide (7a′) (Table 1, entry 4): yellow oil; ^{1}H NMR (270 MHz, $CDCl_3$) δ 2.39 (s, 3 H), 4.70 (d, J = 1.7 Hz, 2 H), 5.75 (t, J = 1.7 Hz, 1 H), 7.21 (d, J = 7.9 Hz, 2 H), 7.51 (d, J = 7.9 Hz, 2 H); ^{13}C NMR (68 MHz, $CDCl_3$) δ 21.22, 73.61, 115.46, 119.73, 130.88, 136.05, 140.62, 165.09, 172.00; IR (NaCl) 3024, 2924, 1774, 1743, 1569, 1490, 1249, 1149, 1007, 883, 846, 807, 725, 697 cm^{-1}; mass spectrum (EI) *m*/*z* 254 (M^+, 100). Anal. Calcd for $C_{11}H_{10}O_2Se$: C, 52.19; H, 3.98. Found: C, 52.37; H, 4.08.

3-[[(*p*-Trifluoromethyl)phenyl]seleno]-2-buten-4-olide (7a′) (Table 1, entry 5): mp 48−49 °C (a white solid); ^{1}H NMR (270 MHz, $CDCl_3$) δ 4.78 (s, 2 H), 5.80 (s, 1 H), 7.69 (d, J = 7.7 Hz, 2 H), 7.82 (d, J = 7.7 Hz, 2 H); ^{13}C NMR (68 MHz, $CDCl_3$) δ 73.52, 116.61, 123.43 (q, J = 273 Hz), 126.89 (q, J = 3.8 Hz), 128.06, 132.30 (q, J = 33 Hz), 136.31, 162.71, 171.45; IR (KBr) 3067, 2970, 1783, 1736, 1571, 1249, 1166, 1124, 1006, 834, 702, 596, 500, 438 cm^{-1}; mass spectrum (EI) *m*/*z* 308 (M^+, 100). Anal. Calcd for $C_{11}H_7O_2F_3Se$: C, 43.02; H, 2.30. Found: C, 43.24; H, 2.43.

4-Methyl-3-(phenylthio)-2-buten-4-olide (6b) (Table 1, entry 6): CA Registry No. 75717-37-2.[16] ^{13}C NMR (68 MHz, $CDCl_3$) δ 20.00, 79.20, 110.75, 127.86, 130.15, 130.48, 134.48, 170.95, 173.73; mass spectrum (EI), *m*/*z* 206 (M^+, 100).

4-Methyl-3-(phenylseleno)-2-buten-4-olide (7b) (Table 1, entry 7): yellow oil; ^{1}H NMR (270 MHz, $CDCl_3$) δ 1.51 (d, J = 6.8 Hz, 3 H), 5.10 (q, J = 6.8 Hz, 1 H), 5.48 (s, 1 H), 7.39−7.48 (m, 3 H), 7.62−7.65 (m, 2 H); ^{13}C NMR (68 MHz, $CDCl_3$) δ 20.23, 80.72, 115.70, 124.49, 130.11, 130.22, 135.91, 170.84; IR (NaCl) 3057, 2982, 2929, 1746, 1571, 1163, 1056, 931, 743, 692 cm^{-1}; mass spectrum (EI) *m*/*z* 254 (M^+, 100). Anal. Calcd for $C_{11}H_{10}O_2Se$: C, 52.19; H, 3.98. Found: C, 52.23; H, 4.02.

4, 4-Dimethyl-3-(phenylthio)-2-buten-4-olide (6c) (Table 1, entry 8): CA Registry No. 84246-67-3.[17] ^{13}C NMR (68 MHz, $CDCl_3$) δ 26.62, 86.30, 109.66, 128.02, 130.14, 130.46, 134.60, 170.02, 177.98; mass spectrum (EI) *m*/*z* 220 (M^+, 100).

1,3-Bis(phenylthio)-4-methyl-4-hydroxy-2-penten-1-one ((Z)-4c): mp 103−104 °C (yellow solid); ^{1}H NMR (270 MHz, $CDCl_3$) δ 1.53 (s, 6 H), 2.27 (s, 1 H), 6.91 (s, 1 H), 7.09−7.36 (m, 10 H) (NOE experiment: Irradiation of methyl singlet at δ 1.53 resulted in a 23% enhancement at δ 6.91 (vinyl singlet)); ^{13}C NMR (68 MHz, $CDCl_3$) δ 29.19, 75.20, 125.56, 126.87, 127.67, 128.96, 129.04, 129.22, 130.10, 134.38, 134.90, 157.41, 186.57; IR (KBr) 3496, 2979, 1672, 1585, 1479, 1440, 1037, 762, 746, 689 cm^{-1}. Anal. Calcd for $C_{18}H_{18}O_2S_2$: C, 65.42; H, 5.49; S, 19.40. Found: C, 65.05; H, 5.32; S, 19.32.

4,4-Dimethyl-3-(phenylseleno)-2-buten-4-olide (7c) (Table 1, entry 9): oil; ^{1}H NMR (270 MHz, $CDCl_3$) δ 1.57 (s, 6 H), 5.29 (s, 1 H), 7.41−7.47 (m, 3 H), 7.61−7.64 (m, 2 H); ^{13}C NMR (68 MHz, $CDCl_3$) δ 26.89, 87.52, 114.46, 124.59, 130.06, 130.17, 135.98, 169.87, 176.02; IR (NaCl) 3058, 2980, 1749, 1573, 1240, 1117, 980, 923, 812, 835, 744, 691 cm^{-1}; mass spectra (CI), *m*/*z* 269 ($M^+ + 1$, 100). Anal. Calcd for $C_{12}H_{12}O_2Se$: C, 53.94; H, 4.53. Found: C, 53.76; H, 4.70.

4-(Phenylthio)-1-oxaspiro[4.4]-3-nonen-2-one (6d) (Table 1, entry 10): mp 59−61 °C (a white solid); ^{1}H NMR (270 MHz, $CDCl_3$) δ 1.79−2.38 (m, 8 H), 5.16 (s, 1 H), 7.46−7.57 (m, 5 H); ^{13}C NMR (68 MHz, $CDCl_3$) δ 25.15, 38.66, 96.36, 110.66, 128.12, 130.20, 130.40, 134.77, 170.31, 175.44; IR (KBr) 2966, 1754, 1572, 1472, 1440, 1270, 1148, 938, 832, 762, 598, 586 cm^{-1}; mass spectrum (EI) *m*/*z* 246 (M^+, 61). Anal. Calcd for $C_{14}H_{14}O_2S$: C, 68.27; H, 5.73; S, 13.02. Found: C, 68.33, H, 5.69; S, 12.96.

1,3-Bis(phenylthio)-3-(1′-hydroxycyclopentyl)-2-propan-1-one (4d): mp 87−88 °C (a light yellow solid); ^{1}H NMR (270 MHz, $CDCl_3$) δ 1.62−1.95 (m, 6 H), 2.04 (s, 1 H), 2.07−2.14 (m, 2 H), 6.96 (s, 1 H), 7.10−7.35 (m, 10 H); ^{13}C NMR (68 MHz, $CDCl_3$) δ 24.16, 39.97, 85.80, 125.97, 126.81, 127.68, 128.95, 129.02, 129.18, 129.93, 134.36, 135.06, 155.81, 186.49; IR (KBr) 3489, 3055, 2949, 1669, 1582, 1478, 1440, 1043, 1008, 754, 702, 579, 487 cm^{-1}; mass spectrum (EI), *m*/*z* 247 ($M^+ - 109$, 67). Anal. Calcd for $C_{20}H_{20}O_2S_2$; C, 67.38; H, 5.65; S 17.99. Found: C, 67.67; H, 5.68; S, 17.93.

4-(Phenylseleno)-1-oxaspiro[4.4]-3-nonen-2-one (7d) (Table 1, entry 11): mp 85−89 °C (a white solid); ^{1}H NMR (270 MHz, $CDCl_3$) δ 1.82−2.18 (m, 8 H), 5.33 (s, 1 H), 7.42−7.50 (m, 3 H), 7.60−7.70 (m, 2 H); ^{13}C NMR (68 MHz, $CDCl_3$) δ 25.09, 38.90, 97.61, 115.41, 124.67, 130.08, 130.22, 136.11, 170.14, 173.44; IR (KBr) 2966, 1736, 1564, 1442, 1246, 1149, 946, 922, 834, 752, 692, 578, 478 cm^{-1}; mass spectrum (EI), *m*/*z* 294 (M^+, 70). Anal. Calcd for $C_{14}H_{14}O_2Se$: C, 57.35; H, 4.81. Found: C, 57.18; H, 4.80.

4-(Phenylseleno)-1-oxaspiro[5.4]-3-decan-2-one (7e) (Table 1, entry 12): mp 101−106 °C (a white solid); ^{1}H NMR (270 MHz, $CDCl_3$) δ 1.65−2.05 (m, 10 H), 5.28 (s, 1 H), 7.35−7.51 (m, 3 H), 7.61−7.64 (m, 2 H); ^{13}C NMR (68 MHz, $CDCl_3$) δ 22.06, 24.46, 36.21, 89.27, 114.36, 124.73, 130.08, 130.22, 136.11, 170.36, 176.22; IR (KBr) 3044, 2932, 1740, 1568, 1269, 1251, 1211, 931, 888, 835, 754, 694, 578, 478 cm^{-1}; mass spectrum (EI), *m*/*z* 308 (M^+, 100). Anal. Calcd for $C_{15}H_{16}O_2Se$: C, 58.64; H, 5.25. Found: C, 54.43; H, 5.36.

3-(Phenylthio)-2-penten-5-olide (6f) (Table 1, entry 13): mp 71−73 °C (a yellow solid); ^{1}H NMR (270 MHz, $CDCl_3$) δ 2.59 (t, J = 6.1 Hz, 2 H), 4.39 (t, J = 6.1 Hz, 2 H), 5.32 (s, 1 H), 7.46−7.52 (m, 5 H); ^{13}C NMR (68 MHz, $CDCl_3$) δ 28.67, 65.68, 110.15, 127.03, 130.03, 130.49, 135.37, 161.06, 163.18; IR (KBr) 3056, 2893, 1708, 1591, 1472, 1398, 1290, 1210, 1202,

(15) (a) Andrès, D. F.; Dietrich, U.; Laurent, E. G.; Marquet, B. S. *Tetrahedron* **1997**, *53*, 647. (b) Hollingworth, G. J.; Perkins, G.; Sweeney, J. *J. Chem. Soc., Perkin Trans. 1* **1996**, 1913. (c) Townsend, C. A.; Christensen, S. B.; Davis, S. G. *J. Chem. Soc., Perkin Trans. 1* **1988**, 839.

(16) (a) Xiao, W.-J.; Alper, H. *J. Org. Chem.* **1997**, *62*, 3422. (b) Bakuzis, P.; Bakuzis, M. L. F. *J. Org. Chem.* **1981**, *46*, 235.

(17) Barbier, P.; Benezra, C. *Tetrahedron Lett.* **1982**, *23*, 3511.

1078, 1050, 746, 694, 631 cm^{-1}; mass spectrum (EI), *m*/*z* 206 (M^+, 100). Anal. Calcd for $C_{11}H_{10}O_2S$: C, 64.06; H, 4.89; S, 15.54. Found: C, 63.80; H, 5.03; S, 15.50.

3-(Phenylseleno)-2-penten-5-olide (7f) (Table 1, entry 14): yellow oil; ^1H NMR (270 MHz, $CDCl_3$) δ 2.61 (t, J = 6.1 Hz, 2 H), 4.37 (t, J = 6.1 Hz, 2 H), 5.64 (s, 1 H), 7.37−7.49 (m, 3 H), 7.58−7.61 (m, 2 H); ^{13}C NMR (68 MHz, $CDCl_3$) δ 29.65, 65.88, 114.99, 124.18, 129.98, 129.98, 136.50, 159.02, 162.43; IR (NaCl) 3057, 2990, 2945, 2894, 1715, 1590, 1284, 1214, 1080, 1048, 1022, 856, 743 cm^{-1}; mass spectrum (EI) *m*/*z* 254 (M^+, 19). Anal. Calcd for $C_{11}H_{10}O_2Se$: C, 52.19; H, 3.98. Found: C, 51.93; H, 4.12.

(*Z*)-1,3-Bis(phenylthio)-5-hydroxy-2-penten-1-one ((*Z*)-4f) (Table 2, entry 1): CA Registry No. 148787-89-7.[5e] This compound was prepared under more moderate reaction conditions (80 °C, 24 h) than those of listed in Table 2. The attempt to isolate (*E*)-**4f** was unsuccessful, because it gradually decomposed to **6f** and PhSH during purification by preparative TLC. mp 110−112 °C (a white solid); ^1H NMR (270 MHz, $CDCl_3$) δ 1.46 (t, J = 5.4 Hz, 1 H), 2.41 (t, J = 6.4 Hz, 2 H), 3.58, (q, J(average) = 5.9 Hz, 2 H), 6.35 (s, 1 H), 7.34−7.55 (m, 10 H) (NOE experiment: Irradiation at methylene triplet of δ 2.41 resulted in a 28% enhancement at δ 6.35 (vinyl singlet)); ^{13}C NMR (68 MHz, $CDCl_3$) δ 39.20, 60.95, 118.64, 127.93, 129.05, 129.23, 129.27, 129.69, 130.07, 134.60, 135.62, 157.15, 185.16; IR (KBr) 3531, 2872, 1641, 1537, 1476, 1439, 1111, 1073, 1046, 842, 748, 706 cm^{-1}; mass spectrum (CI), *m*/*z* 317 ($M^+ + 1$, 100). Anal. Calcd for $C_{17}H_{16}O_2S_2$: C, 64.53; H, 5.10; S, 20.26. Found: C, 64.46; H, 5.09; S, 20.12.

(*Z*)-1,3-Bis(phenylthio)-6-hydroxy-2-hexen-1-one ((*Z*)-4g) (Table 2, entry 2): pale yellow oil; ^1H NMR (270 MHz, $CDCl_3$) δ 1.42 (br s, 1 H), 1.57 (quint, J = 7.6, 6.1 Hz, 2 H), 2.23 (t, J = 7.6 Hz, 2 H), 3.36 (t, J = 6.1 H, 2 H), 6.30 (s, 1 H), 7.36−7.53 (m, 10 H) (NOE experiment: Irradiation of methylene triplet at δ 2.23 resulted in a 25% enhancement at δ 6.30 (vinyl singlet)); ^{13}C NMR (68 MHz, $CDCl_3$) δ 32.03, 32.76, 61.19, 117.47, 128.07, 129.00, 129.13, 129.13, 129.60, 130.13, 134.61, 135.71, 161.03, 185.06; IR (NaCl) 3398, 3057, 2943, 1667, 1548, 1477, 1440, 1111, 1078, 1023, 828, 748, 707, 690 cm^{-1}; mass spectrum (EI), *m*/*z* 330 (M^+, 2), 221 ($M^+ - SPh$, 100). Anal. Calcd for $C_{18}H_{18}O_2S_2$: C, 65.42; H, 5.49; S, 19.40. Found: C, 65.21; H, 5.51; S, 19.12. This compound was prepared under more moderate reaction conditions (80 °C, 24 h) than those of listed in Table 2.

1,3-Bis(phenylseleno)-6-hydroxy-2-hexen-1-one (5g) (Table 2, entry 3): (*Z*)-isomer: mp 98−100 °C (a light yellow solid); ^1H NMR (270 MHz, $CDCl_3$) δ 1.55 (quintet, J = 6.1 Hz, 7.6 Hz, 2 H), 1.70 (br s, 1 H), 2.26 (t, J = 7.6 Hz, 2 H), 3.29 (t, J = 6.1 Hz, 2 H), 6.71 (s, 1 H), 7.30−7.65 (m, 10 H) (NOE experiment: Irradiation of the methylene triplet at δ 2.26 resulted in a 21% enhancement of the signal at δ 6.71 (vinyl singlet)); ^{13}C NMR (68 MHz, $CDCl_3$) δ 32.35, 33.99, 61.06, 122.49, 126.58, 127.08, 128.83, 129.24, 129.29, 129.45, 135.74, 137.23, 161.95, 187.69; IR (KBr) 3326, 3055, 2937, 1664, 1546, 1532, 1085, 809, 742, 693 cm^{-1}; mass spectrum (CI), *m*/*z* 427 ($M^+ + 1$, 8). Anal. Calcd for $C_{18}H_{18}O_2Se_2$: C, 50.96; H, 4.27. Found: C, 51.01; H, 4.34.

(*E*)-Isomer could not be obtained in pure form, so only spectral analyses were performed. (*E*)-isomer: ^1H NMR (270 MHz, $CDCl_3$) δ 1.87 (quintet, J = 5.9, 7.3 Hz, 2 H), 2.07 (br s, 1 H), 2.88 (t, 2 H, J = 7.3 Hz), 3.62 (t, 2 H, J = 5.9 Hz), 5.94 (s, 1 H), 7.30−7.66 (m, 10 H); ^{13}C NMR (68 MHz, $CDCl_3$) δ 31.69, 32.55, 61.09, 123.48, 126.03, 126.87, 128.88, 129.32, 129.94, 130.07, 135.69, 136.72, 163.43, 187.74; IR (NaCl) 3368, 3056, 2942, 2874, 1693, 1564, 1557, 1476, 1438, 1338, 1038, 1020, 738, 690 cm^{-1}; mass spectrum (CI), *m*/*z* 427 ($M^+ + 1$, 8).

Cyclization of (*Z*)-4f in the Presence of $Pd(PPh_3)_4$ (eq 5). In a 50-mL stainless steel autoclave equipped with a magnetic stirring bar were placed (*Z*)-**4f** (14.4 mg, 0.05 mmol), $Pd(PPh_3)_4$ (1.2 mg, 0.001 mmol), and benzene (0.1 mL). The apparatus was charged with carbon monoxide (60 atm), the resulting mixture was heated at 100 °C for 5 h, and the reaction mixture was filtered through Celite and evaporated in vacuo. The formation of **6f** (19%) was confirmed by ^1H NMR spectroscopy.

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