EurJOC
European Journal of Organic Chemistry

A Journal of ChemPubSoc Europe

Accepted Article

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To be cited as: *Eur. J. Org. Chem.* 10.1002/ejoc.202000130

Link to VoR: http://dx.doi.org/10.1002/ejoc.202000130

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FULL PAPER

Synthetic strategy for tetraphenyl-substituted all-*E*-carotenoids with improved molecular properties

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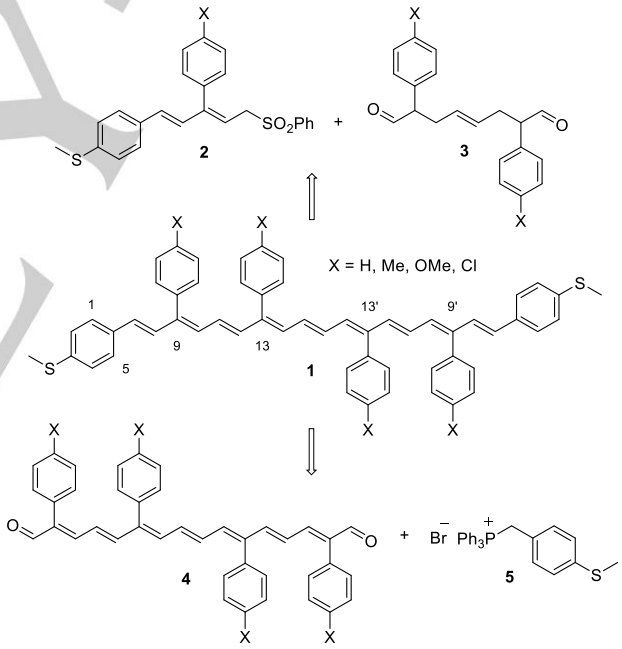
Abstract: The synthetic method of tetraphenyl-substituted all-*E*-carotenes **1** with improved properties of antioxidant and molecular electronic conductance was developed through the formation of tetraphenyl-substituted all-*E*-apocarotenedial **4**. The synthesis highlighted the preparation of novel subunits containing phenyl substituent(s) with *E*-configuration starting from the key (*E*)-4-chloro-2-phenylbut-2-enal (**10**), utilizing conjugation effect with formyl group or easy recrystallization of sulfone compounds. Sulfone-mediated coupling methods of Julia and modified Julia-Kocienski olefinations utilizing the subunits were demonstrated to produce tetraphenyl-substituted apocarotenedials **4**. The major all-*E*-forms (73~85% selectivity) were easily purified by SiO_2 chromatography and trituration with Et_2O due to the presence of the polar formyl groups. The olefination of all-*E*-apocarotenedials **4** and Wittig salt **5** provided all-*E*-9,9´,13,13´-tetraphenylcarotenes **1**.

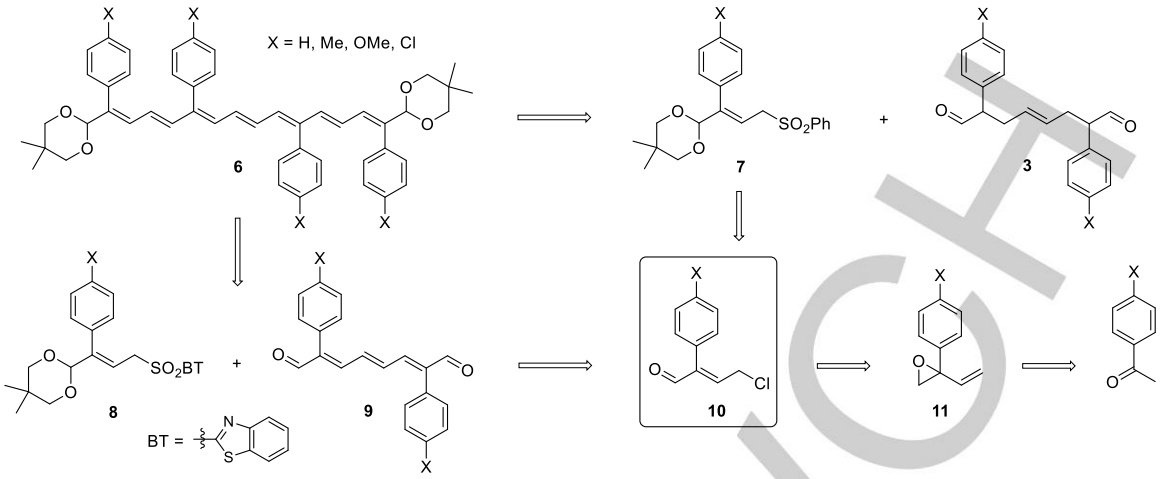
Introduction

Carotenoids are characterized by extensive conjugation of carbon-carbon double bonds, which affords visible transition between HOMO and LUMO levels of π-electrons with small energy gap.[1] It also allows delocalization of π-electrons to offer improved electronic conductance.[2] Carotenoids are thus utilized as natural red dyes for foodstuffs and may serve as efficient organic molecular wires as demonstrated by the energy-transferring efficiency in photosynthetic system.[3] Instability of carotenoids under aerobic condition, which inversely explains the antioxidant activity of carotenoids,[4] was a major problem in utilization of these valuable natural compounds for organic electronic materials. However, the instability was proven to be mitigated by replacement of the methyl groups along the polyene chain by phenyl substituents,[5] which not only improved the antioxidant activity in scavenging reactive oxygen species,[6] but also diversified the conducting ability of the chain by differing electronic nature of the substituent group in the phenyl rings.[7]



Scheme 1. Synthetic plan for 9,9´,13,13´-tetraphneyl substituted carotene **1**.

The conductance of single molecular wires, which can be measured by a STM (scanning tunneling microscopy) break junction method,[8] is largely dependent on the intrinsic decay constant as well as the length of the chain.[9] We demonstrated that the conductance can be modulated for 9,9´,13,13´-tetraphenyl carotene **1** (Scheme 1) by changing the substituent groups for improving intrinsic decay constant, while maintaining the same chain length.[10] It was thus anticipated that carotenoid **1** would serve as efficient organic molecular wires with variable conductance, which may find wide applications in the areas of bioelectronics and photovoltaic cells etc.



Scheme 2. Disconnection approaches to diacetal **6** of fully conjugated all-(*E*)- polyenedial **4**.

The synthesis of 9,9´,13,13´-tetraphenyl carotene **1** was not easy especially in controlling all-*E* configuration of the carbon-carbon double bonds. It seemed that steric interactions between bulky phenyl-substituents and polyene chain enforced not only high dihedral angles for the phenyl-substituents,[10] but also various *Z*-configurations of the carbon-carbon double bonds. We herein report our strategy for synthesizing 9,9´,13,13´-tetraphenyl carotene **1** with the *para*-phenyl substituent X of different electronic nature. Special focus was on the controlling all-*E* configuration of the carotenoid by utilizing conjugation effect with carbonyl groups and easy purification by the polar end groups.

Results and Discussion

The synthesis of 9,9´,13,13´-tetraphenyl-substituted carotene **1** was initially designed based on the sulfone-mediated olefination method[11] between allylic sulfone **2** with a phenyl substitution and 2,7-diphenyloct-4-enedial **3** (Scheme 1). The key building block **2** was prepared in a stereo-selective manner and purified by facile crystallization.[12] As an extension of biomimetic approach utilizing the basic C_5 isopentenyl building block,[13] the corresponding unit with phenyl substitution was prepared and transformed to dienyl sulfone **2**.[12] The 2:1 coupling between **2** and **3**, and protection of the resulting hydroxyl groups, followed by olefination through the double elimination of sulfone and protected hydroxyl groups produced the conjugated polyene compound.[11] It was, however, unfortunate that carotene **1** was not able to be clearly identified due to the presence of multiple stereoisomers (see ^{1}H NMR in page S-110 of Supporting Information). Unlike to the synthesis of carotene with 13,13´-diphenyl substitution,[7] the carotene with 9,9′,13,13′-tetraphenyl substitution was difficult in producing all-*E* configuration, presumably due to the steric interactions with the phenyl substituents.

It was envisioned that conjugated polyenedials **4** with tetraphenyl substitution might be obtained in all-*E* configuration by effective conjugation with terminal formyl groups. The polar end groups would at least allow purification of the all-*E*-isomer by silica gel chromatographic separation. The synthetic plan for carotene **1** was thus revised through the formation of tetraphenyl-substituted all-*E*-polyenedial **4** (Scheme 1). The Wittig olefination between **4** and 4-(methylthio)benzyl phosphonium bromide **5** was conceived to produce all-(*E*)-9,9´,13,13´-tetraphenylcarotene **1**.

The synthesis of diacetal **6** of all-*E* polyenedial **4** was designed based on the sulfone-mediated coupling and olefination strategy (Scheme 2). Allylic phenyl sulfone **7** now became the key building block, which would couple with dialdehyde **3**.[14] Diacetal **6** was also planned to be synthesized by the “one-pot” Julia-Kocienski olefination between allylic benzothiazolyl (BT) sulfone **8** and 2,7-diphenyl-2,4,6-octatrienedial (**9**).[15] These newly devised building blocks **7**, **8**, and **9** were all planned to be synthesized from the common intermediate, 4-chloro-2-phenylbut-2-enal (**10**), which was proposed to be prepared by $CuCl_2$-mediated oxidative opening reaction of vinyl epoxide **11** with phenyl substitution.

The synthesis commenced from *para*-substituted acetophenones of different electronic nature (X = MeO, Me, H, Cl). Alpha-bromination was efficiently carried out using *N*-bromosuccinimide with catalytic TMS·OTf.[16] Vinyl Grignard addition to the carbonyl group produced bromohydrins **12** in 42–65% yields (Table 1), which were then treated with base to lead to vinyl epoxide **11**. $CuCl_2$-promoted regioselective oxidative ring opening of vinyl epoxides **11** was the key reaction for the preparation of chloro-aldehydes **10**.

The reaction was best carried out in the presence of LiCl at 80 °C for 1.5 h (entries 2, 5, and 9). Unlike to the case of vinyl epoxide with methyl substitution,[17] oxidation of the ring opening product was sluggish at 25 °C and allylic alcohols **13** were obtained exclusively as a mixture of *E*/*Z* isomers (entries 1, 4, and 8). The oxidation was progressed at 25 °C in the case of electron-rich MeO-substitution, and the reaction was better performed at 25 °C to reduce the amount of dechlorination product **14** (entry 6). The rate of oxidation was also dependent on the presence of LiCl, and a mixture of allylic alcohol **13** and conjugated aldehyde **10** was obtained in the absence of LiCl even at 80 °C (entry 3). It was unavoidable to obtain dechlorinated products **14**. Nevertheless, it was satisfactory that conjugated aldehydes **10** were exclusively *E* form by effective conjugation and obtained in the yield ranges of 54~64%.

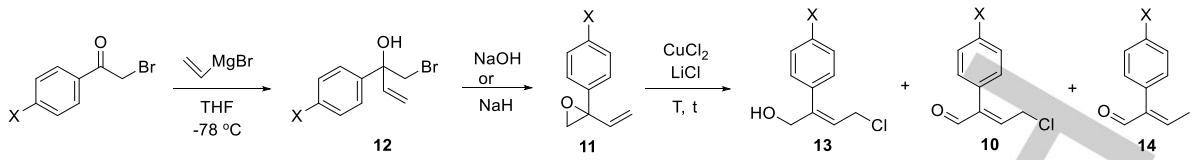


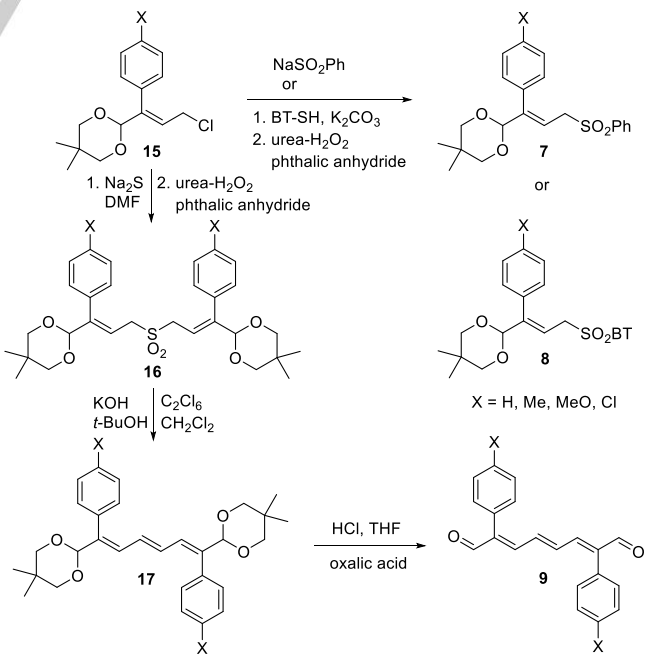
Table 1. Synthesis of chloro-aldehydes **10** through preparation and oxidative chlorination of phenyl-substituted vinyl epoxides **11**.

Entry	Compound	X	%Yield **12**[a]	Condition (Temp, time)	%Yield **13** (*E*:*Z*)[b]	% Yield *E*-**10**[b]	%Yield *E*-**14**[b]
1	**a**	H	58	25 °C, 2 d	77 (3:2)	-	-
2				80 °C, 1.5 h	-	59	8
3[c]				80 °C, 1.5 h	28 (3:2)	22	16
4	**b**	Me	62	25 °C, 2 d	48 (3:2)	-	-
5				80 °C, 1.5 h	-	58	8
6	**c**	MeO	42	25 °C, 2 d	-	54	14
7				80 °C, 1.5 h	-	40	20
8	**d**	Cl	65	25 °C, 2 d	66 (2:1)	-	-
9				80 °C, 1.5 h	-	64	13

[a] Purified (by SiO_2 chromatography) yield **12** of vinyl Grignard addition to α-bromoacetophenone. [b] Purified (by SiO_2 chromatography) yields after formation and oxidative chlorination of vinyl epoxides **11** from vinyl carbinols **12**. Compounds **10** and **14** were isolated as a mixture and the yields were calculated based on the ^{1}H NMR ratio. [c] LiCl (1 equiv.) was not added.

(*E*)-4-Chloro-2-phenylbut-2-enals (**10**) being prepared successfully, their acetals **15** were utilized for the preparation of the key building blocks **7**, **8**, and **9** (Scheme 3). Sulfonylation by $NaSO_2Ph$ in DMF produced the corresponding (*E*)-allylic benzenesulfones **7** (X = H, Me, MeO, Cl) in 35–46% yields from chloro-aldehydes **10** in 2 steps (Table 2). The solid products **7** were easily purified by recrystallization with EtOAc/hexane to give *E*-configuration. We also demonstrated one-pot Julia-Kocienski olefination for two cases (X = H, Me) for comparison with double elimination of the original Julia olefination (entries 1 and 2). Allylic BT-sulfones **8** were prepared in 60% yield (X = H) and 75% yield (X = Me) by sufurylation of 2-mercaptobenzothiazole in acetone with K_2CO_3 as base, followed by sulfur oxidation using mono peroxyphthalic acid, generated in situ by the reaction of urea-H_2O_2 (UHP) and phthalic anhydride in MeCN.[18] Allylic BT-sulfones **8** were consisted of a 3~4:1 mixture of *E*/*Z*-isomers, but the *E*-form can be easily purified by trituration with MeOH.

Novel 2,7-diphenyl-2,4,6-octatrienedials **9** are useful building blocks for the preparation of 13,13'-diphenyl carotenes not only by Julia-Kocienski olefination, but also by Wittig reaction. Dimerization of acetal-protected allylic chlorides **15** by Na_2S in DMF, followed by sulfur oxidation using mono peroxyphthalic acid (UHP and phthalic anhydride in MeCN) produced the corresponding allylic sulfones **16** in 29% (X = H) and 22% yields (X = Me) in 3 steps from chloro-aldehydes **10**. The 4:1 (*E*,*E*:*E*,*Z*) stereoisomeric ratio of **16** was believed to be sterically controlled by the substituents, but all-*E* form can be easily purified by trituration with MeOH as white solid. Ramberg-Bäcklund reaction of allylic sulfones **16** under the modified Meyers' condition (KOH and *t*-BuOH)[19] with chlorinating agent C_2Cl_6[20] in CH_2Cl_2 produced conjugated trienes **17** in 85% yield (X = H) and 76% yield (X = Me). Deprotection of neopentyl glycol by aqueous HCl with oxalic acid produced all-(*E*)-2,7-diphenylocta-2,4,6-trienedials **9** in 90% (X = H) and 74% yields (X = Me), which establishes conjugation of the formyl groups by means of the polyene.



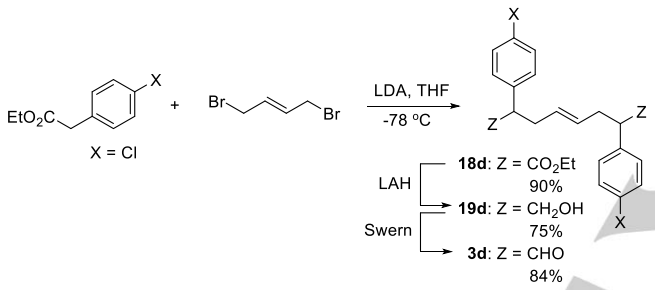
Scheme 3. Preparation of allylic sulfones **7**, **8** and conjugated trienedials **9** from acetal **15**.

Table 2. Reaction yields (%) of the compounds according to Scheme 3.

Entry	X	*E*-**7**[a]	**8** (*E*:*Z*)[a]	**16** (*E*,*E*:*E*,*Z*)[a]	**17**	**19**
1	**a**: H	42	60 (4:1)	29 (4:1)	85	90
2	**b**: Me	35	75 (3:1)	22 (4:1)	76	74
3	**c**: MeO	46				
4	**d**: Cl	43				

[a] Yields starting from chloro-aldehydes **10**.

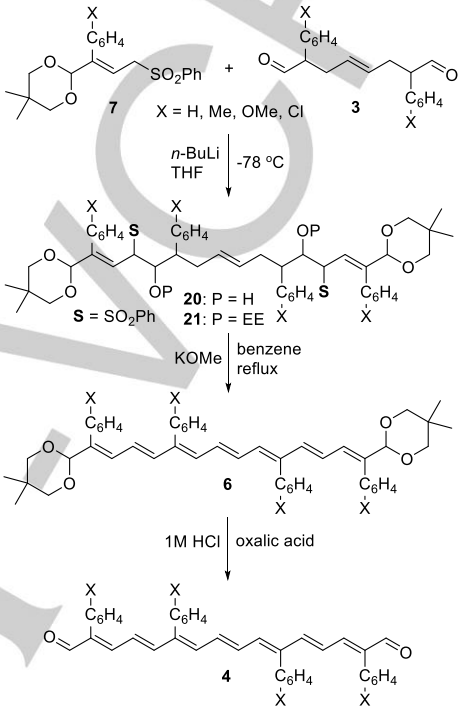
The synthesis of 2,7-diphenyloct-4-enedials **3** (Z = CHO, X = H, Me, MeO) has been reported.[14] Its *p*-chlorophenyl analogue **3d** (Z, CHO, X = Cl) was prepared uneventfully according to the above procedure as demonstrated in Scheme 4. The LDA-promoted 2:1 coupling between ethyl *p*-chlorophenylacetate and 1,4-dibromobut-2-ene at -78 °C produced diester **18d** in 90% yield. LAH reduction to diol **19d** (75% yield) and Swern oxidation (oxalyl chloride, DMSO, and Et_3N) provided dial **3d** in 84% yield.



Scheme 4. Preparation of 2,7-di(*p*-chlorophenyl)oct-4-enedial **3d**.

All the required building blocks were ready to assemble tetraphenyl-substituted conjugated polyenedials **4**. Scheme 5 and Table 3 respectively delineated the sulfone olefination strategy utilizing the double elimination method[11] and the yield of each reaction for the preparation of all-(*E*)-2,6,11,15-tetraphenylhexadeca-2,4,6,8,10,12,14-heptaenedials **4** (X = H, Me, MeO, Cl). Coupling was initiated from allylic sulfone **7** by deprotonation with *n*-BuLi, and reaction with dial **3** produced diols **20** in 58~84% yields. The reaction was carried out at -78 °C for several hours and quenched with water to prevent both possible retro-reaction at higher temperature and hydrolysis of the acetal groups under acidic condition. The hydroxyl groups in the coupling product **20** was protected with ethyl vinyl ether in CH_2Cl_2 by catalytic pyridinium *p*-toluene sulfonate (PPTS) to give 1-ethoxyethyl ethers (EE) **21**, which upon the elimination condition (KOMe, benzene reflux) for benzenesulfonyl ($PhSO_2$) and 1-ethoxyethoxy (EEO) groups produced fully conjugated polyene diacetal **6** in 76~90% yields (2 steps from diol **20**). The all-*E*-isomer was the major product from this reaction sequence. *Pars pro toto*, the stereo-isomeric ratio was analyzed by HPLC for **6b**. Three peaks were observed in the ratio of 6.4: 1.0: 0.1 with all-*E*-configuration as the major product (85%, calculated by the ratio).

Hydrolysis of the acetal groups was effective by addition of oxalic acid in aqueous acidic THF solution. Tetraphenyl-substituted heptaenedials **4** were obtained in 73~88% yields. Three stereo-isomers were generally obtained with all-*E*-configuration as the major product. The yields of all-*E*-heptaenedial **4** were notified in Table 4 (inside the parentheses). It was noticeable that non-all-*E*-configurations were still obtained in the fully conjugated polyenedials, which were not isomerized to all-*E* form, but decomposed under forcing thermal or acidic conditions. Nevertheless, all-*E*-products were separable by SiO_2 chromatography and further purified by trituration from Et_2O



Scheme 5. Synthesis of conjugated polyenedial **4** by sulfone-mediated coupling and double elimination.

Table 3. %Yield of the compounds according to the scheme 5.

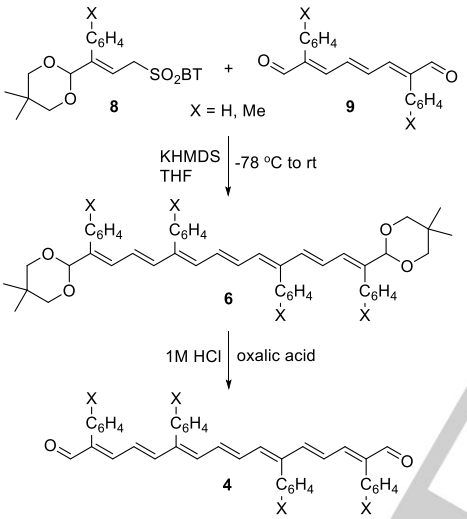
Entry	X	**20**	**6**	**4**[a]
1	**a**: H	84	81	88 (37)
2	**b**: Me	72	76[b]	75 (41)
3	**c**: MeO	71	90	73 (48)
4	**d**: Cl	58	80	77 (40)

[a] The recrystallization yield of all-(*E*)-apocarotenedial **4** in parenthesis. [b] The stereo-isomeric ratio was measured by HPLC as 6.4: 1.0: 0.1 with the all-*E* major.

2,6,11,15-Tetraphenylhexadeca-2,4,6,8,10,12,14-heptaenedials **4** (X = H, Me) were also prepared by the Julia-Kocienski olefination between allylic BT-sulfone **8** and trienedial **9** as described in Scheme 6. Table 4 reported the isolated yield of each reaction product and its *E*/*Z* stereoisomeric ratio by HPLC. Julia-Kocienski olefination was carried out with KHMDS base at –78 °C for 2 h and then at room temperature for overnight to produce fully conjugated polyene diacetal **6a** (X = H) in 33% yield and **6b** (X = Me) in 42% yield with all-*E* product as the major product. The all-*E* selectivity was compared with that of the previous double elimination method in the case of **6b** (85% *vide*

supra). Three peaks were observed in the ratio of 11: 1: 3 with 73% all-*E*-configuration for **6b** by Julia-Kocienski olefination. The double elimination method was slightly better in producing more all-*E* product **6b** than the Julia-Kocienski olefination.

Deprotection of acetal was carried out by addition of oxalic acid in aqueous acidic (1M HCl) THF solution to provide tetraphenyl-substituted heptaenedials **4a** (X = H) in 60% yield and **4b** (X = Me) in 38% yield. Three stereoisomers were obtained again with all-*E*-configuration as the major product. The *E*/*Z*-isomeric ratio was measured by HPLC for **4b** as 4: 1: 0.2. The all-*E* selectivity for **4b** was calculated to be 77%, which was almost same as that for **6b** (73%) within experimental errors. It seemed that aldehyde groups did not practically improve the all-*E* selectivity for the poly(hepta)ene chain by conjugation upon hydrolysis of the acetal groups. The polar aldehyde groups rather allowed facile separation of the all-*E* product by SiO_2 chromatography and further purification by trituration from Et_2O.



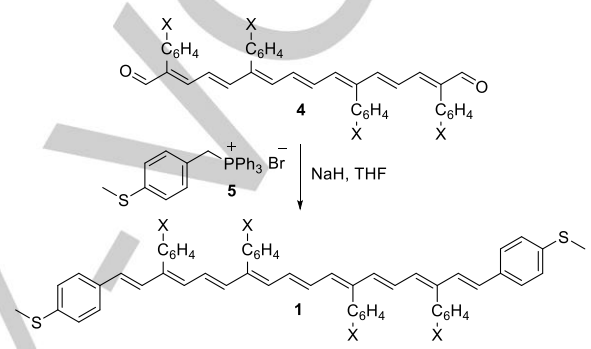
Scheme 6. Synthesis of conjugated polyenedial **4** by Julia-Kocienski olefination.

Table 4. %Yield and stereoisomeric ratio (HPLC) of the compounds according to the scheme 6.

Entry	X	**6** (all-*E*:*Z*s')	**4** (all-*E*:*Z*s')
1	**a**: H	33 (3: 1)	60 (11: 1: 2)
2	**b**: Me	42 (11: 1: 3)	38 (4: 1: 0.2)

The final synthesis of 9,9´,13,13´-tetraphenyl carotene **1** was carried out by the Wittig reaction of the above tetraphenyl-substituted all-*E*-apocarotenedials **4** and the phosphonium salt **5** containing a methylthio group for the application to the molecular wires (Scheme 7). The olefination was carried out using NaH as base at room temperature. The Wittig reaction products were initially purified by SiO_2 flash column chromatography to give an inseparable mixture of *E*/*Z*-isomers of carotene **1**. All-*E*-carotene **1** can be separated and purified from the above mixture by trituration with a proper solvent system (THF/MeOH or CH_2Cl_2/MeOH or even acetone) due to lower solubility than the *Z*-isomers. The isolated yields were reported in Table 5, and analytical samples were prepared after several trituration procedures.

The UV absorption wave lengths for 9,9´,13,13´-tetraphenyl all-*E*-apocarotenedials **4** and all-*E*-carotenes **1** were listed according to the group X of the benzene substituents in Table 5. It is noteworthy that the polar effect of the methoxy substituent narrowed the energy gap between HOMO and LUMO of π-electrons to give higher UV absorption wave length for **4c** and **1c**.[7] The trend in UV absorption values for carotene **1**, which can be correlated with the energy gaps between HOMO and LUMO, coincides exactly with that of the conductance values of the molecular wire **1**, measured by STM break junction method.



Scheme 7. Synthesis of tetraphenyl-substituted all-(*E*)-carotenes **1** from all-(*E*)-polyenedial **4**.

Table 5. Yield of carotenes **1** from polyenedials **4** according to the scheme 7 and their UV (λ_{max}) values.

Entry	X	**1** (%)[a]	UV (λ_{max}) **4**	UV (λ_{max}) **1**	Conductance[b]
1	**a**: H	46	473 nm	504 nm	2.99×10^{-4} G_0
2	**b**: Me	21	478 nm	508 nm	4.50×10^{-4} G_0
3	**c**: MeO	15	491 nm	513 nm	4.84×10^{-4} G_0
4	**d**: Cl	26	475 nm	501 nm	2.17×10^{-4} G_0

[a] The isolated yield of all-(*E*)-carotene **1** after SiO_2 chromatography and trituration with THF/MeOH (CH_2Cl_2/MeOH or acetone). [b] The conductance values were taken from the reference No. [10].

Conclusion

The synthetic method of 9,9´,13,13´-tetraphenyl all-*E*-carotenes **1** has been developed through the formation of tetraphenyl-substituted all-*E*-apocarotenedials **4**. A terminal formyl group allowed *E*-configuration for short (up to three) carbon-carbon double bonds by conjugation and for long (up to seven) carbon-carbon double bonds by easy purification using SiO_2 chromatography and trituration with Et_2O. The novel building blocks **7**, **8**, and **9** containing phenyl substituent(s) were devised and synthesized from the key intermediate, (*E*)-4-chloro-2-phenylbut-2-enal (**10**), which was prepared by $CuCl_2$/LiCl-mediated oxidative ring opening of 2-phenyl-2-vinyloxirane (**11**). The *E*-configuration was obtained exclusively for **9** and **10** by

conjugation with the formyl group and for **7** and **8** by facile recrystallization of the sulfone compound.

Diacetal **6** of tetraphenyl-substituted all-*E*-apocarotenedials **4** were synthesized by the sulfone-mediate coupling between allylic sulfone **7** and dial **3** with phenyl substituent(s), followed by double eliminations of sulfones and the protected hydroxyl groups. The Julia-Kocienski olefination between allylic BT-sulfone **8** and trienedial **9** with phenyl substituent(s) was also demonstrated for the synthesis of diacetal **6**. The all-*E*-isomer was the major product from these reaction sequences (85~73% selectivity). Hydrolysis of the acetal groups provided three *E*/*Z*-stereoisomeric apocarotenedials **4**, among which the major all-*E*-isomers were easily purified by SiO_2 chromatography and trituration with Et_2O. The olefination of all-*E*-apocarotenedials **4** with phosphonium salt **5** provided 9,9´,13,13´-tetraphenyl carotenes **1**, from which all-*E*-isomers were obtained by purification using SiO_2 chromatography and trituration with an appropriate solvent system. Tetraphenyl-substituted all-*E*-carotenes **1** are stabilized molecular wires which may find wide applications in the area of bioelectronics and photovoltaic cells.

Experimental Section

General Experimental. Reactions were performed in a well-dried flask under Argon atmosphere unless noted otherwise. Solvents used as reaction media were dried over pre-dried molecular sieve (4 Å) by microwave oven. Solvents for extraction and chromatography were reagent grade and used as received. The column chromatography was performed with silica gel 60 (70-230 mesh) using a mixture of EtOAc/hexane as eluent. ^{1}H and ^{13}C NMR spectra were respectively recorded on a 400 MHz and 100 MHz NMR spectrometer in deuterated chloroform ($CDCl_3$) with tetramethylsilane (TMS) as an internal reference unless noted otherwise. High resolution mass spectroscopy was performed using magnetic sector analyzer. All the new compounds were identified by ^{1}H and ^{13}C NMR, IR, and High-Resolution Mass Spectroscopy. Identity of the known compounds was established by the comparison of their ^{1}H and ^{13}C NMR peaks with the authentic values

1-Bromo-2-phenylbut-3-en-2-ol (12a). To a stirred solution of α-bromoacetophenone (7.00 g, 35.2 mmol) in THF (70 mL) at -78 ºC was added 1M THF solution of vinyl magnesium bromide (52.8 mL, 52.8 mmol). The mixture was stirred vigorously at that temperature for 2.5 h and quenched with 1M HCl solution. The mixture was extracted with Et_2O, dried over anhydrous Na_2SO_4, filtered and concentrated under reduced pressure. The crude product (7.30 g) was purified by SiO_2 flash column chromatography to give vinyl carbinol **12a** (4.66 g, 20.5 mmol) in 58% yield as yellow oil. Data for **12a**: R_f = 0.59 (8:2 hexane:EtOAc); ^{1}H NMR δ = 2.70 (br s, 1H), 3.79 (A of ABq, *J* = 10.6 Hz, 1H), 3.81 (B of ABq, *J* = 10.6 Hz, 1H), 5.31 (dd, *J* = 10.7, 0.8 Hz, 1H), 5.41 (dd, *J* = 17.1, 0.8 Hz, 1H), 6.17 (dd, *J* = 17.1, 10.7 Hz, 1H), 7.27–7.42 (m, 3H), 7.45–7.50 (m, 2H) ppm; ^{13}C NMR δ = 44.2, 75.6, 115.9, 125.6, 127.8, 128.5, 140.6, 142.2 ppm; IR (KBr) 3446, 3026, 2970, 1447, 1366, 1217 cm^{-1}; HRMS (CI$^+$) calcd for $C_{10}H_{12}OBr$ 227.0071, found 227.0069.

(*E*)-4-Chloro-2-phenylbut-2-enal (10a). To a stirred solution of bromohydrin **12a** (4.66 g, 20.5 mmol) in THF (20 mL) was added aqueous solution (5 mL) of NaOH (1.92 g, 41.0 mmol). The reaction mixture was stirred vigorously at room temperature for 3 h, extracted with EtOAc (25 mL×3), dried over anhydrous Na_2SO_4, filtered, and concentrated to give vinyl epoxide **11a** (3.00 g). Data for **11a**: ^{1}H NMR δ = 3.03 (A of ABq, *J* = 5.6 Hz, 1H), 3.10 (B of ABq, *J* = 5.6 Hz), 5.26 (d, *J* = 17.2 Hz, 1H), 5.34 (d, *J* = 10.8 Hz, 1H), 6.05 (dd, *J* = 17.2, 10.8 Hz, 1H), 7.29–7.42 (m, 5H) ppm.

To a stirred solution of epoxide **11a** (0.49 g, 3.35 mmol) in EtOAc (30 mL) were added $CuCl_2{\cdot}2H_2O$ (0.70 g, 4.11 mmol) and LiCl (0.17 g, 4.11 mmol). The mixture was then heated to reflux for 1.5 h and cooled to room temperature. The mixture was diluted with hexane (100 mL), filtered through a short pad of SiO_2, and rinsed with a 1:1 solution of EtOAc and hexane (100 mL). The filtrate was concentrated under reduced pressure and purified by SiO_2 flash chromatography to give a 7.4:1 mixture (0.40 g) of chloroaldehyde **10a** (calcd 0.36 g, 1.98 mmol, 59%) and dechlorinated aldehyde **14a** (calcd 0.04 g, 0.27 mmol, 8%) as brown oils. Data for **10a**: R_f = 0.52 (8:2 hexane:EtOAc); ^{1}H NMR δ = 4.26 (d, *J* = 7.6 Hz, 2H), 6.76 (t, *J* = 7.6 Hz, 1H), 7.18–7.22 (m, 2H), 7.37–7.44 (m, 3H), 9.71 (s, 1H) ppm; ^{13}C NMR δ = 39.7, 128.5, 128.8, 129.2, 130.6, 144.6, 146.5, 192.7 ppm; IR (KBr) 3069, 2993, 2830, 2722, 1773, 1695, 1643, 1503, 1440, 1376, 1241, 1074, 974, 920, 835, 776, 694, 672 cm^{-1}; HRMS (CI$^+$) calcd for $C_{10}H_9ClO$ 181.0420, found 181.0415.

(*E*)-4-Chloro-2-phenylbut-2-en-1-ol (13a). To a stirred solution of epoxide **11a** (0.50 g, 3.42 mmol) in EtOAc (10 mL) were added $CuCl_2{\cdot}2H_2O$ (0.70 g, 4.10 mmol) and LiCl (0.17 g, 4.10 mmol). The mixture was stirred vigorously at room temperature for 2 d and quenched with 1M HCl solution. The mixture was extracted with Et_2O, dried over anhydrous Na_2SO_4, filtered and concentrated under reduced pressure. The crude was purified by SiO_2 flash column chromatography to give a 3:2 (*E*:*Z*) mixture of chloroallylic alcohol **13a** (0.48 g, 2.63 mmol) in 77% yield as yellow liquid. Data for **13a**: ^{1}H NMR (major *E*-isomer) δ = 1.92 (br s, 1H), 4.01 (d, *J* = 7.6 Hz, 2H), 4.35 (s, 2H), 5.96 (t, *J* = 8.0 Hz, 1H), 7.21–7.26 (m, 2H), 7.30–7.40 (m, 3H) ppm; (minor *Z*-isomer) δ = 1.92 (br s, 1H), 4.33 (d, *J* = 8.0 Hz, 2H), 4.61 (s, 2H), 6.06 (t, *J* = 8.0 Hz, 1H), 7.31–7.47 (m, 5H) ppm; ^{13}C NMR (major *E*-isomer) δ = 41.3, 66.4, 122.1, 126.5, 128.1, 128.5, 136.3, 145.2 ppm; (minor *Z*-isomer) δ = 39.9, 59.3, 126.1, 128.0, 128.0, 128.5, 139.4, 143.4 ppm; IR (KBr) 3369, 3070, 3037, 2935, 2868, 1702, 1499, 1452, 1222, 1113, 1018, 782, 714 cm^{-1}; HRMS (EI) calcd for $C_{10}H_{11}ClO$ 182.0498, found 182.0500.

(*E*)-5,5-Dimethyl-2-(1-phenyl-3-(phenylsulfonyl)prop-1-en-1-yl)-1,3-dioxane (7a). An 8:1 mixture (2.47 g) of **10a** (calcd 2.24 g, 12.4 mmol) and dechlorinated aldehyde **14a**, neopentyl glycol (1.92 g, 18.5 mmol), and *p*-TsOH (117 mg, 0.62 mmol) in benzene was heated to reflux for 3 h under a reflux condenser equipped with a Dean-Stark column. The mixture was cooled to room temperature, diluted with Et_2O, washed with 1M NaOH (50 mL×3) and with brine. The aqueous layer was extracted with Et_2O again. The combined organic layer was dried over anhydrous Na_2SO_4, filtered, and concentrated under reduced pressure to give the crude acetal product (3.30 g), which was an 8:1 mixture of chloro-acetal **15a** and dechlorinated acetal as yellow oil. Data for chloro-acetal **15a**: R_f = 0.72 (8:2 hexane:EtOAc); ^{1}H NMR δ = 0.72 (s, 3H), 1.17 (s, 3H), 3.50 (d, *J* = 10.8 Hz, 2H), 3.68 (d, *J* = 10.8 Hz, 2H), 4.20 (d, *J* = 8.0 Hz, 2H), 5.02 (s, 1H), 6.21 (t, *J* = 8.0 Hz, 1H), 7.28–7.41 (m, 5H) ppm.

To a stirred solution of the above crude acetal (3.30 g) in DMF was added benzenesulfinic acid sodium salt (2.43 g, 18.4 mmol). The mixture was stirred at room temperature for 20 h, and then 60 ºC for 2 h. Most of solvent was removed under reduced pressure. The crude product was dissolved in CH_2Cl_2, washed with brine and with H_2O, dried over anhydrous Na_2SO_4, filtered, and concentrated under reduced pressure. The crude product (4.70 g) was solidified upon addition of a 1:9 mixture of EtOAc:hexane. The product was filtered, rinsed with a 1:9 solution of EtOAc:hexane, and air-dried to give (*E*)-sulfone **7a** (1.93 g, 5.20 mmol) in 42% yield as light-brown solid. Data for **7a**: m.p.: 131–133 ºC; ^{1}H NMR δ = 0.71 (s, 3H), 1.11 (s, 3H), 3.44 (d, *J* = 10.8 Hz, 2H), 3.62 (d, *J* = 10.8 Hz, 2H), 3.78 (d, *J* = 8.0 Hz, 2H), 4.91 (s, 1H), 6.13 (t, *J* = 8.0 Hz, 1H), 6.76–6.82 (m, 2H), 7.16–7.24 (m, 3H), 7.49–7.55 (m, 2H), 7.63–7.68 (m, 1H), 7.76–7.81 (m, 2H) ppm; ^{13}C NMR δ = 21.7, 22.9, 30.2, 56.3, 77.4, 102.1, 117.2, 127.7, 128.0, 128.6, 128.6, 129.0, 133.6, 135.0, 138.4, 136.5 ppm; IR (KBr) 2956, 2919, 2900, 2852, 1740, 1449, 1395, 1306, 1145, 1128, 1081, 1017, 991 cm^{-1}; HRMS (CI$^+$) calcd for $C_{21}H_{25}O_4S$ 373.1474, found 373.1469.

(*E*)-2-((3-(5,5-Dimethyl-1,3-dioxan-2-yl)-3-phenylallyl)sulfonyl)benzo[*d*]thiazole (8a). To a stirred solution of chloro-acetal **15a** (5.00 g, 18.74 mmol) in acetone (60 mL) were added 2-mercaptobenzothiazole (2.51 g, 14.99 mmol) and anhydrous K_2CO_3 (3.89 g, 28.11 mmol). The mixture was stirred at room temperature for 21 h under argon atmosphere, and most of solvent was removed under reduced pressure. The crude product was dissolved in EtOAc, washed with H_2O. The aqueous layer was extracted with EtOAc, and the combined organic layer was dried over anhydrous Na_2SO_4, filtered, and concentrated under reduced pressure to give yellow brown oil, which was purified by SiO_2 flash column chromatography (5–40% EtOAc in hexane) to give a 4:1 *E*:*Z* mixture of benzothiazolyl sulfide (6.91 g, 17.38 mmol) in 60% yield as sticky solid. The *E*-isomer was further purified by trituration with Et_2O as white solid [R_f = 0.71 (4:1 hexane:EtOAc)]; ^{1}H NMR δ = 0.71 (s, 3H), 1.14 (s, 3H), 3.48 (d, *J* = 11.2 Hz, 2H), 3.66 (d, *J* = 11.2 Hz, 2H), 4.00 (d, *J* = 7.6 Hz, 2H), 5.02 (s, 1H), 6.29 (t, *J* = 7.6 Hz, 1H), 7.25–7.31 (m, 1H), 7.31–7.39 (m, 5H), 7.37–7.43 (m, 1H), 7.72–7.76 (m, 1H), 7.82–7.86 (m, 1H) ppm.

The mixture of Urea-H_2O_2 (1.07 g, 11.34 mmol) and phthalic anhydride (0.84 g, 5.67 mmol) in MeCN (40 mL) was stirred vigorously at room temperature for 1.5 h to give a clear solution. A solution of the above allylic sulfide (0.75 g, 1.89 mmol) in CH_2Cl_2 (10 mL) was added to the above solution. The mixture was stirred at room temperature under argon atmosphere for 20 h. Most of solvent was removed under reduced pressure, and the crude product was dissolved in CH_2Cl_2. The solid residue was filtered off, and the filtrate was concentrated under reduced pressure to give a 4:1 *E*:*Z* mixture of the corresponding sulfone **8a** (0.91 g, 2.12 mmol) in 100% yield as sticky solid. The *E* isomer was purified by trituration with MeOH in 83% yield (0.67g, 1.56mmol) as white solid. The mother liquor was concentrated under reduced pressure to give the *Z*-isomer exclusively. Data for **8a**: R_f = 0.27 (4:1 hexane:EtOAc); m.p.: 135–137 ºC; ^{1}H NMR δ = 0.69 (s, 3H), 1.08 (s, 3H), 3.42 (d, *J* = 10.4 Hz, 2H), 3.60 (d, *J* = 10.4 Hz, 2H), 4.22 (d, *J* = 7.6 Hz, 2H), 4.94 (s, 1H), 6.18 (t, *J* = 7.6 Hz, 1H), 6.96–7.00 (m, 2H), 7.16–7.22 (m, 2H), 7.23–7.28 (m, 1H), 7.58–7.67 (m, 2H), 8.00–8.04 (m, 1H), 8.16–8.18 (m, 1H) ppm; ^{13}C NMR δ = 21.7, 22.9, 30.1, 54.9, 77.4, 102.1, 115.6, 122.2, 125.6, 127.5, 128.0, 128.2, 128.7, 134.7, 137.1, 147.7, 152.6, 165.0 ppm; IR (KBr) 2956, 2848, 1472, 1394, 1331, 1215, 1144, 1122, 1085, 1018, 992, 969, 906, 854, 757, 705, 667, 664 cm^{-1}; HRMS (ESI) calcd for $C_{22}H_{23}NO_4S_2Na$ 452.0961, found 452.0960.

2,2'-((1*E*,1'*E*)-Sulfonylbis(1-phenylprop-1-ene-3,1-diyl))bis(5,5-dimethyl-1,3-dioxane) (16a). To a stirred solution of chloro-acetal **15a** (3.09 g, 11.58 mmol) in DMF (25 mL) was added $Na_2S{\cdot}9H_2O$ (1.39 g, 5.79 mmol). The mixture was stirred vigorously at room temperature for 22 h, diluted with EtOAc, washed with 10% $NaHCO_3$ solution, dried over anhydrous Na_2SO_4, filtered, and concentrated under reduced pressure to give a crude product as yellow oil, which was purified by SiO_2 flash column chromatography (3–10% EtOAc in hexane) to give disulfide (2.38 g, 4.81mmol) in 42% overall yield as yellow oil [R_f = 0.58 (4:1 hexane:EtOAc)]; ^{1}H NMR δ = 0.71 (s, 6H), 1.13 (s, 6H), 3.06 (d, *J* = 8.0 Hz, 4H), 3.46 (d, *J* = 10.8 Hz, 4H), 3.64 (d, *J* = 10.8 Hz, 4H), 4.92 (s, 2H), 5.95 (t, *J* = 8.0 Hz, 2H), 7.24–7.40 (m, 10H) ppm.

The mixture of UHP (4.21 g, 44.76 mmol) and phthalic anhydride (3.31g, 22.38 mmol) in MeCN (70 mL) was stirred vigorously at room temperature for 2 h, and a solution of the above disulfide (3.69 g, 7.46 mmol) in CH_2Cl_2 (20 mL) was slowly added. The mixture was stirred at room temperature for 18 h, and most of solvent was removed under reduced pressure. The crude product was dissolved in CH_2Cl_2, and undissolved solid was filtered off by a filter paper. The filtrate was diluted with CH_2Cl_2, washed H_2O, dried over anhydrous Na_2SO_4, filtered, and concentrated under reduced pressure to give a crude product as yellow oil, which was purified by SiO_2 flash column chromatography (20–70% EtOAc in hexane) to give a 4:1 *E*,*E*:*E*,*Z* mixture of the corresponding sulfone **16a** (2.67 g, 5.07 mmol) in 68% overall yield as sticky solid. The *E*,*E*-isomer was further purified by trituration with MeOH as white solid. Data for **16a**: m.p.: 163–165 ºC; R_f = 0.66 (3:2 hexane:EtOAc); ^{1}H NMR δ = 0.72 (s, 6H), 1.12 (s, 6H), 3.45 (d, *J* = 10.8 Hz, 4H), 3.62 (d, *J* = 8.0 Hz, 4H), 3.64 (d, *J* = 10.8 Hz, 4H), 4.94 (s, 2H), 6.00 (t, *J* = 8.0 Hz, 2H), 7.23–7.27 (m, 4H), 7.31–7.37 (m, 6H) ppm; ^{13}C NMR δ = 21.8, 23.0, 30.2, 52.5, 77.5, 102.4, 116.8, 128.0, 128.3, 128.9, 135.0, 146.6 ppm; IR (KBr) 3012, 2956, 2844, 1469, 1394, 1364, 1308, 1230, 1215, 1118, 1088, 1014, 988, 969, 909, 854, 749, 700, 667 cm^{-1}; HRMS (FAB) calcd for $C_{30}H_{39}O_6S$ 527.2467, found 527.2473.

(1*E*,3*E*,5*E*)-1,6-Bis(5,5-dimethyl-1,3-dioxan-2-yl)-1,6-diphenylhexa-1,3,5-triene (17a). To a stirred solution of allylic sulfone **16a** (1.52 g, 2.89 mmol) in *t*-BuOH (25 mL) and CH_2Cl_2 (50 mL) were added C_2Cl_6 (1.37 g, 5.78 mmol) and pulverized KOH (1.62 g, 28.90 mmol). The mixture was stirred at room temperature for 1 d under argon atmosphere and quenched with 10% $NaHCO_3$ solution. The mixture was extracted with CH_2Cl_2, dried over anhydrous Na_2SO_4, filtered, and concentrated under reduced pressure to give crude trienedial acetal as yellow-brown solid, which was further purified by trituration with MeOH to give **17a** (1.13 g, 2.45 mmol) in 85% overall yield as white solid. Data for **17a**: R_f = 0.62 (4:1 hexane:EtOAc); ^{1}H NMR δ = 0.71 (s, 6H), 1.18 (s, 6H), 3.49 (d, *J* = 10.4 Hz, 4H), 3.66 (d, *J* = 10.4 Hz, 4H), 5.03 (s, 2H), 6.45–6.52 (m, 2H), 6.52–6.58 (m, 2H), 7.28–7.39 (m, 10H) ppm; ^{13}C NMR δ = 21.8, 23.1, 30.2, 77.7, 103.4, 127.4, 128.0, 129.5, 129.9, 132.3, 137.0, 139.2 ppm; IR (KBr) 3012, 2956, 2844, 1469, 1390, 1364, 1305, 1215, 1107, 1085, 1014, 980, 962, 928, 891, 749, 697, 667 cm^{-1}; HRMS (ESI) calcd for $C_{30}H_{36}O_4Na$ 483.2506, found 483.2504.

(2*E*,4*E*,6*E*)-2,7-diphenylocta-2,4,6-trienedial (9a). To a stirred solution of diacetal **17a** (0.67 g, 1.45 mmol) in THF (5 mL) were added 1 M HCl solution (10 mL) and oxalic acid (366 mg, 4.06 mmol). The mixture was stirred vigorously at room temperature for 1 d. Light yellow oil was formed in the lower phase upon standing, which was extracted with CH_2Cl_2, washed with H_2O, dried over anhydrous Na_2SO_4, filtered, and concentrated under reduced pressure to give yellow solid. The crude product was purified by SiO_2 flash column chromatography (10–25% EtOAc in hexane) to give all-*E*-dialdehyde **9a** (374 mg, 1.30 mmol) in 90% yield as light yellow solid. Data for **9a**: m.p.: 165–168 ºC; R_f = 0.30 (4:1 hexane:EtOAc); ^{1}H NMR δ = 7.03–7.13 (m, 4H), 7.24–7.28 (m, 4H), 7.40–7.50 (m, 6H), 9.70 (s, 2H) ppm; ^{13}C NMR δ = 128.5, 128.8, 129.8, 131.9, 136.9, 144.1, 146.4, 192.8 ppm; IR (KBr) 3012, 2926, 2848, 2714, 1674, 1595, 1495, 1442, 1416, 1372, 1267, 1196, 1085, 1025, 1006, 980, 749, 716, 667 cm^{-1}; HRMS (ESI) calcd for $C_{20}H_{16}O_2Na$ 311.1043, found 311.1044.

(1*E*,7*E*,13*E*)-1,14-Bis(5,5-dimethyl-1,3-dioxan-2-yl)-1,5,10,14-tetraphenyl-3,12-bis(phenylsulfonyl)tetradeca-1,7,13-triene-4,11-diol (20a). To a stirred solution of allylic sulfone **7a** (3.50 g, 9.63 mmol) in THF (30 mL) at -78 ºC was added 1.6M hexane solution of *n*-BuLi (6.6 mL, 10.6 mmol). The mixture was stirred vigorously at that temperature for 15 min, and a solution of 2,7-diphenyloct-4-endial (**3a**) (1.28 g, 4.38 mmol) in THF (10 mL) was added. The reaction mixture was stirred at -78 ºC for 1.5 h and quenched with H_2O (20 mL). The mixture was extracted with Et_2O, washed with brine, dried over anhydrous Na_2SO_4, filtered, and concentrated under reduced pressure. The crude product (4.91 g) was purified by SiO_2 flash column chromatography to give the coupling diol **20a** (3.80 g, 3.67 mmol) in 84% yield as clumsy white solid. Data for coupling diol **20a**: R_f = 0.34~0.47 (6:4 hexane:EtOAc); ^{1}H NMR δ = 0.71 (s, 6H), 1.12 (s, 6H), 1.86–2.43 (m, 8H), 3.50–3.70 (m, 8H), 3.55–3.96 (m, 2H), 4.14–4.30 (m, 2H), 4.78 (br s, 2H), 4.90–5.08 (m, 2H), 5.84–6.38 (m, 2H), 6.38–7.76 (m, 30H) ppm; IR (KBr) 3505, 3058, 2957, 2848, 1735, 1696, 1600, 1502, 1444, 1395, 1365, 1306, 1211, 1143, 1123, 1080, 1017 985, 906 cm^{-1}; HRMS (FAB$^+$) calcd for $C_{62}H_{69}O_{10}S_2$ 1037.4332, found 1037.4324.

2,2'-((1*E*,3*E*,5*Z*,7*E*,9*Z*,11*E*,13*E*)-1,5,10,14-tetraphenyltetradeca-1,3,5,7,9,11,13-heptaene-1,14-diyl)bis(5,5-dimethyl-1,3-dioxane) (6a).

[Method A: double elimination] To a stirred solution of the coupled diol **20a** (3.77 g, 3.63 mmol) in CH_2Cl_2 (50 mL) at 0 ºC were added ethyl vinyl

ether (7.0 mL, 72.7 mmol) and pyridinium *para*-toluenesulfonate (182 mg, 0.73 mol). The mixture was stirred vigorously at 0 ºC to room temperature for 11.5 h. The reaction mixture was cooled to 0 ºC again, and ethyl vinyl ether (7.0 mL) was added. Stirring for 3 h, the mixture was diluted with CH_2Cl_2, washed with 10% $NaHCO_3$ solution, dried over anhydrous Na_2SO_4, filtered, and concentrated under reduced pressure to give crude bis(1-etoxyethyl ether) **21a** (5.40 g) as bright yellow oil. R_f = 0.56 (6:4 hexane:EtOAc).

To a stirred solution of 1-ethoxyethyl protected sulfone **21a** (5.40 g) in benzene (50 mL) and cyclohexane (50 mL) was added KOMe (6.41 g, 91.4 mmol). The mixture was heated at reflux for 15 h and cooled to room temperature. The mixture was quenched with H_2O and extracted with Et_2O. The aqueous layer was extracted again with Et_2O, and the combined organic layer was dried over anhydrous Na_2SO_4, filtered, and concentrated under reduced pressure to give the crude product (4.05 g), which was purified by SiO_2 flash column chromatography to provide **6a** (2.11 g, 2.94 mmol) in 81% yield as dark reddish solid. Data for **6a**: R_f = 0.49 (8:2 hexane:EtOAc); m.p.: 158–161 ºC; ^{1}H NMR δ = 0.72 (s, 6H), 1.20 (s, 6H), 3.51 (d, *J* = 10.8 Hz, 4H), 3.67 (d, *J* = 10.8 Hz, 4H), 5.05 (s, 2H), 6.06 (dd, *J* = 15.2, 11.6 Hz, 2H), 6.18–6.30 (m, 4H), 6.55 (d, *J* = 15.2 Hz, 2H), 6.64 (d, *J* = 11.6 Hz, 2H), 7.03–7.10 (m, 4H), 7.12–7.33 (m, 16 H) ppm; ^{13}C NMR δ = 21.8, 23.1, 30.2, 77.7, 103.7, 127.2, 127.2, 127.7, 128.0, 128.6, 129.2, 129.7, 130.2, 132.2, 133.1, 136.8, 137.2, 138.3, 139.3, 143.1 ppm; IR (KBr) 3030, 2971, 2924, 2849, 1741, 1651, 1556, 1542, 1459, 1363, 1220, 1128, 1097, 1014, 960, 695 cm^{-1}; HRMS (FAB$^+$) calcd for $C_{50}H_{52}O_4$ 716.3866, found 716.3871.

(2*E*,4*E*,6*Z*,8*E*,10*Z*,12*E*,14*E*)-2,6,11,15-Tetraphenylhexadeca-2,4,6,8,10,12,14-heptaenedial (4a). To a stirred solution of polyenediacetal **6a** (2.62 g, 3.65 mmol) in THF (35 mL) were added oxalic acid (823 mg, 9.14 mmol) and 1M HCl solution (35 mL). The mixture was stirred vigorously at room temperature for 22 h, and then extracted with Et_2O. The etheral extract was washed with 10% $NaHCO_3$ solution, dried over anhydrous Na_2SO_4, filtered, and concentrated under reduced pressure to give the crude product (2.61 g) as dark red solid.

The aqueous layer together with red emulsion was extracted with CH_2Cl_2. The CH_2Cl_2 layer was dried over anhydrous Na_2SO_4, filtered, and concentrated under reduced pressure to give mostly all-*E*-polyene compound **4a** (567 mg) as dark red solid, which was further purified by trituration with diethyl ether to give pure all-*E*-**4a** (222 mg). The crude product (2.61 g) obtained from etheral extraction was purified by SiO_2 flash column chromatography (4:1 hexane:EtOAc) to give the mono-deprotected aldehyde (259 mg, R_f = 0.44) and three stereoisomers of polyenedial in the following amounts: 478 mg (0.88 mmol, 24% yield, R_f = 0.35), 427 mg (R_f = 0.25, all-*trans*), and 531 mg (0.97 mmol, 27% yield, R_f = 0.16). The SiO_2 in the column was flushed again with 300 mL of 9:1 CH_2Cl_2:acetone to give all-*E*-**4a** (86 mg, R_f = 0.25). The total amount of the combined all-*E*-**4a** (R_f = 0.25) was 735 mg (1.35 mmol, 37% yield). The total yield of the polyenedial was 1.74 g (3.20 mmol) in 88% yield. Data for all-*E*-hexadecahepta-2,4,6,8,10,12,14-enedial (**4a**): R_f = 0.25 (4:1 hexane:EtOAc); ^{1}H NMR δ = 6.35 (dd, *J* = 14.8, 11.8 Hz, 2H), 6.32–6.42 (m, 2H), 6.44–6.54 (m, 2H), 6.91 (d, *J* = 14.8 Hz, 2H), 7.07–7.15 (m, 4H) 7.10 (d, *J* = 11.8 Hz, 2H), 7,20–7.40 (m, 6H) 9.63 (s, 2H) ppm; ^{13}C NMR δ = 127.9, 127.9, 128.1, 128.1, 128.3, 129.5, 129.7, 132.3, 134.2, 136.0, 137.0, 140.6, 143.8, 145.5, 148.9, 192.9 ppm; IR (KBr) 2922, 2853, 1672, 1648, 1598, 1549, 1457, 1384, 1267, 1103, 1022, 803 cm^{-1}; UV (c = 1.18×10^{-6} M in CH_2Cl_2) λ (ε) 444 (65,600), 473 (102,000), 503 (95,000) nm ; HRMS (FAB$^+$) calcd for $C_{40}H_{33}O_2$ 545.2481, found 545.2493.

6a and 4a [Method B: Julia-Kocienski coupling and hydrolysis] To a stirred solution of allylic BT-sulfone **8a** (479 mg, 1.12 mmol) and dialdehyde **9a** (115 mg, 0.40 mmol) in THF (20 mL) at -78 ºC under argon atmosphere was added 1M THF solution of KHMDS (1.12 mL, 1.12 mmol). The mixture was stirred vigorously at that temperature for 2 h and warmed to and stirred at room temperature for 10 h. The mixture was diluted with Et_2O, washed with 10% NH_4Cl solution, dried over anhydrous Na_2SO_4, filtered, and concentrated to give red solid, which was purified by SiO_2 flash chromatography (0–15% EtOAc in hexane) to give the coupling product **6a** (90.2 mg, 0.13 mmol) in 33% yield as red solid [R_f = 0.54–0.49 in 4:1 EtOAc:hexane]. The E/Z isomeric ratio was analyzed as 3: 1 by HPLC.

To a stirred solution of acetal coupling product **6a** (75.0 mg, 0.10 mmol) in THF (5 mL) were added 1M HCl (15 mL) solution and oxalic acid (27.0 mg, 0.30mmol). The mixture was stirred at room temperature for 12 h. The mixture was extracted with CH_2Cl_2, dried over anhydrous Na_2SO_4, filtered, and concentrated under reduced pressure to give red solid, which was purified by SiO_2 flash column chromatography (7–30% EtOAc in hexane) to give dialdehydes **4a** (total 31.7 mg, 0.06 mmol) in 60% yield. The E/Z isomeric ratio was analyzed as 11: 1: 2 by HPLC.

(((1*E*,3*Z*,5*E*,7*Z*,9*E*,11*Z*,13*E*,15*Z*,17*E*)-3,7,12,16-Tetraphenyloctadeca-1,3,5,7,9,11,13,15,17-nonaene-1,18-diyl)bis(4,1-phenylene))bis(methylsulfane) (1a). To a stirred suspension of NaH (60% oil suspension, 115 mg, 2.88 mmol) in THF (20 mL) was added 4-methylthiobenzyl triphenylphosphonium bromide (**5**) (690 mg, 1.44 mmol). The mixture was stirred at room temperature for 15 min, a solution of dial **4a** (256 mg, 0.48 mmol) in THF (20 mL) was added. The reaction mixture was stirred at room temperature overnight, diluted with Et_2O, washed with 1M HCl, 10% $NaHCO_3$ solution, and with brine. The aqueous layer was extracted with CH_2Cl_2, and the combined organic layer was dried over Na_2SO_4, filtered, and concentrated. The crude product (992 mg) was purified by SiO_2 chromatography (R_f = 0.68 at 8:2 EtOAc:hexane), followed by trituration with CH_3OH/CH_2Cl_2 to give all-*E*-polyene **1a** (153 mg, 0.19 mmol) as red-purple solid. The mother liquor was concentrated and purified by SiO_2 flash column chromatography to give **1a** (192 mg, 0.24 mmol). The SiO_2 in the column was flushed again with 9:1 CH_2Cl_2:acetone (300 mL) and was concentrated to give all-*E*-**1a** (21 mg, 0.027 mmol). The combined total yield of all-*E*-**1a** was 174 mg (0.22 mmol) in 46% yield. Data for **1a** (X = H): ^{1}H NMR δ = 2.46 (s, 6H), 5.86 (dd, *J* = 15.0, 12.0 Hz, 2H; H^{11}), 6.14 (d, *J* = 15.8 Hz, 2H; H^7), 6.18–6.23 (m, 2H; H^{15}), 6.23–6.29 (m, 4H; H^{14}), 6.47 (d, *J* = 12.0 Hz, 2H; H^{10}), 6.48 (d, *J* = 15.0 Hz, 2H; H^{12}), 6.97 (d, *J* = 15.8 Hz, 2H; H^8), 7.02 (d, *J* = 8.0 Hz, 4H), 7.07 (d, *J* = 8.0 Hz, 4H), 7.14 (d, *J* = 8.4 Hz, 4H), 7.20–7.27 (m, 12H), 7.25 (d, *J* = 8.4 Hz, 4H) ppm; UV (c = 4.55×10^{-6} M in CH_2Cl_2) λ (ε) 477 (182,000), 504 (200,000), 538 (142,000) nm; IR (KBr) 3027, 2972, 2920, 2853, 1738, 1653, 1558, 1487, 1437, 1372, 1229, 1213, 1090, 968 cm^{-1}; HRMS (FAB$^+$) calcd for $C_{56}H_{48}S_2$ 784.3197, found 784.3212.

Acknowledgements

This work was supported by the National Research Foundation of Korea through the Basic Science Research Program (No. NRF-2016R1A2B4007684) and partly by 2019 Research Fund of Myongji University.

Keywords: carotenoids • conducting material • olefination • synthesis design • total synthesis

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10.1002/ejoc.202000130

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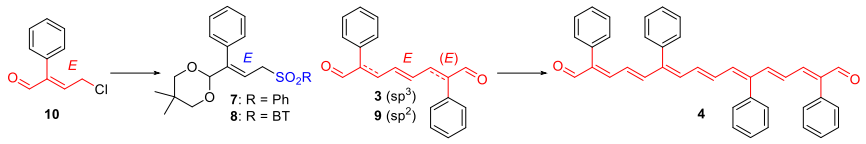
Carotenoid Wires



Tetraphenyl-substituted carotenoids with improved antioxidant and electronic conducting properties than natural carotenoids were synthesized through the formation of all-*E*-apocarotenedials (**4**), which were prepared by the sulfone-mediated olefinations of the novel building blocks **7** and **3**, or **8** and **9** with *E*-configurations. (*E*)-4-Chloro-2-phenylbut-2-enal (**10**) was the key material for the syntheses.