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Synthesis of silacyclopent-2-en-4-ols via intramolecular [2 + 2] photocycloaddition of benzoyl(allyl)silanes†

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Organosilicon compounds are versatile units with a wide range of uses from medicinal chemistry to the field of organic electronics. An unprecedented method for the synthesis of novel diaryl-substituted silacyclopentenols via blue-light promoted intramolecular [2 + 2] photocycloaddition of acyl silanes is herein disclosed. Additionally, the present findings demonstrate the influence of the olefin substituents in controlling the regioselectivity of the intramolecular Paternò–Büchi reaction, providing silacycles different from previously reported ones. The high degree of functionalization of these compounds makes them attractive precursors to other synthetically challenging silacyclopentanes.

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Introduction

The incorporation of silicon into an organic molecule can alter some of its physical and chemical properties, making organosilicon compounds attractive candidates for medicinal chemistry.^{1,2} Although silicon is an isostere of sp³-hybridised carbon, replacing carbon by silicon can: alter reactivity, increase lipophilicity, induce different conformations and increase ring sizes.¹ Organosilicons have the tendency to form penta- and hexa-coordinated species^{3,4} and labile Si–O, Si–N and Si–H bonds in aqueous media. Moreover, polarised C–Si bonds have increased reactivity as compared to C–C bounds. Because of these features, organosilicon compounds have shown considerable potential in the medicinal chemistry field over the past 55 years.¹ The virtually simple replacement of carbon by silicon in a known drug or scaffold has been widely explored in the design of new bioactive compounds.^{5,6} Drastic changes in the pharmacological profiles of silicon bioisoster of venlafaxine,⁷ haloperidol⁸ and bexarotene⁹ have been previously reported, including improvements in the selectivity profile or lower toxicity of the drug metabolites.

Notwithstanding the role of silicon in drug discovery,² organosilicon compounds have also gained notoriety in molecular electronics¹⁰ and polymer science.¹¹ Conjugated organosilicon materials are particularly promising for the organic electronics and photonics field.¹² The insertion of silicon atoms in conjugated organic motifs changes the HOMO and LUMO energy levels, creating a new broad class of important semiconductors. The 5-membered conjugated silacycle silole is a particularly interesting building block in this research area and in the development of silicon-containing polymers.¹³ Given the natural abundance of silicon and its lack of intrinsic toxicity, processes targeting the synthesis of organosilanes¹⁴ and the modification of C–Si bonds are becoming more available.¹⁵ Despite the versatility and importance of silacycles, methods for their preparation are somewhat scarce.¹⁶ Silacyclobutanes (SCBs) are generally synthesised by the convenient intramolecular silylation of *in situ* prepared Grignard reagents.¹⁶ Due to their high ring strain and Lewis acidity, SCBs are often used as precursors to other organosilicon compounds through ring opening/expansion reactions catalysed by transition metals.^{16,17} Even though ring expansion of SCBs can also provide silacyclopentanes under specific conditions, the most direct method for their synthesis consists in the addition of metal treated 1,3-butadienes to dichlorosilanes.^{18,19} The synthesis of silacyclopentenones through palladium-catalysed silylene-1,3-diene [4 + 1] cycloaddition²⁰ allows flexibility on substitution of the cyclopentene core.

Considering the importance of the cyclopentane motif in bioactive compounds,^{21–26} we reasoned that new methods for the preparation of 5 membered-ring silacycles are needed for several fields of molecular sciences. From a synthetic perspec-

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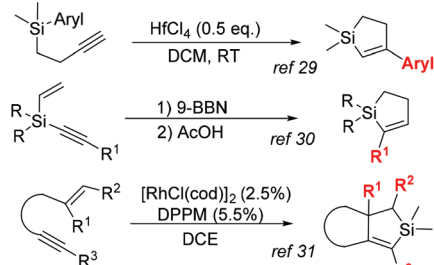
tive, achieving the cyclopentene moiety would be preferable due to potentially further functionalization of the double bond, such as asymmetric oxidative transformations.^{27,28} Silacyclopent-2-enes are especially challenging as the ring is usually constructed from a highly functionalised silane (Scheme 1a),^{29–31} imposing limitations on the degree of substitution on the cyclic core. Further modifications of silacyclopent-2-enes have also been reported^{32–35} but additional functionalization of the cyclopentene ring is rare and synthetic flexibility on olefin substitution is often limited. Amongst the aforementioned scaffold, silacyclopent-2-enes bearing an allylic alcohol are of particular interest. Tomooka's group has utilised such compounds in the synthesis of various functionalised silacyclopentanes, some presenting biological activity, *via* Mitsunobu, Tsuji–Trost, and other transformations.^{34,35} Additionally, similar silacyclopent-2-en-4-ols have been used in the synthesis of a polyol motif present in several natural products.³⁶

In 2008, Portella *et al.* reported a photochemical [2 + 2] cycloaddition of acylsilanes (Scheme 1b).³⁷ Upon irradiation, acyl(allyl)silanes undergo intramolecular Paternò–Büchi reaction, producing bicyclic oxetanes in moderate to good yields and providing a new method for the synthesis of SCBs. While new 1-alkyl-6-oxa-2-silabicyclo[2.2.0]hexanes could be prepared by this way, irradiation of benzoyl(allyl)silane resulted in an intractable reaction mixture. Since the relative stability of the triplet biradical intermediates in the Paternò–Büchi reaction plays an important role in its stereo- and regioselectivity,^{38,39}

we envisioned that substitution on the olefin moiety with a radical stabilising group could tame the reactivity of the intermediates, altering the reaction profile observed by Portella. This could alter the regioselectivity of the cycloaddition, and the subsequent oxetane ring-opening would eventually yield silacyclopentenols (Scheme 1c).

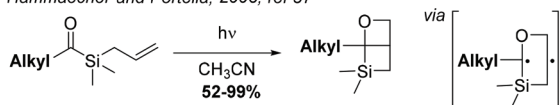
Acylsilanes have attracted immense scientific interest since their first preparation by Brook in 1957.⁴⁰ Despite the extensive research conducted on these compounds in the past few decades,^{41–43} novel methodologies that utilize acylsilanes as powerful reagents in organic chemistry are still being reported.^{44–46} Experimentally, the use of aromatic acylsilanes is particularly attractive as they do not undergo side reactions involving the carbonyl α -carbon.⁴⁷ Moreover, they show an absorption maximum at around 425 nm, thus allowing photoexcitation using visible blue light. The handling of acylsilanes requires special precautions as they are known to undergo Brook rearrangement to a reactive carbene after photoirradiation or thermal conditions. This carbene has been shown to undergo insertion reactions in polarised heteroatom-hydrogen bonds,^{48,49} cycloadditions to aldehydes⁵⁰ and alkynes,^{51,52} cross-coupling reaction with organoboronic esters⁵³ and even C–H insertions^{54–56} under harsher conditions. Carbene formation and its subsequent reactions are then possible competitive destructive pathways to the [2 + 2] photocycloaddition. This influence can be minimised by using dry, aprotic solvents and by protecting free alcohols or amines in the acylsilane starting material.

a) Previous methods for the construction of silacyclopent-2-enes rings



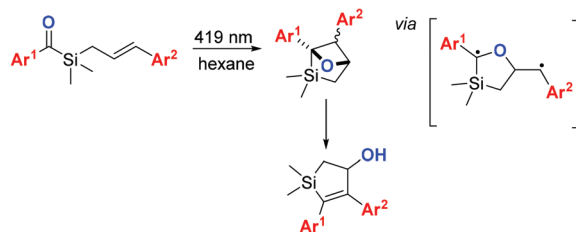
b) Previously reported 2+2 photocycloaddition of acyl(allyl)dimethylsilanes

Hammaeher and Portella, 2008, ref 37



c) Unreported 2+2 photocycloaddition of benzoyl(allyl)dimethylsilanes

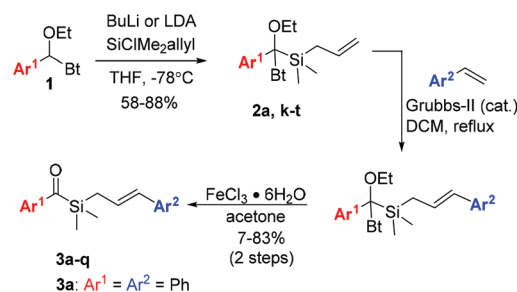
towards construction of silacyclopent-2-enes



Scheme 1 Methods for construction of silacyclopent-2-enes and photocycloaddition of acylsilanes.

Results and discussion

To investigate our hypothesis, cinnamyl silane **3a** was synthesised (Scheme 2). Initial investigations using the dithiane umpolung approach failed as the harsh conditions required for the deprotection of the dithiane moiety were incompatible with the olefin group. Inspired by Portella's success in the synthesis of acyl(allyl)silanes using benzotriazole hemiaminals as umpolung equivalents of aldehydes,^{37,57} we adopted a similar synthetic pathway. This strategy, originally developed by Katritzky,⁵⁸ benefits from facile late-stage hydrolysis of the hemiaminals to the corresponding carbonyls. Olefin cross-metathesis was performed on intermediate **2a**, as the acylsilane moiety seems to inhibit the Grubbs catalyst.⁵⁷



Scheme 2 Synthesis of benzoylsilanes **3**.

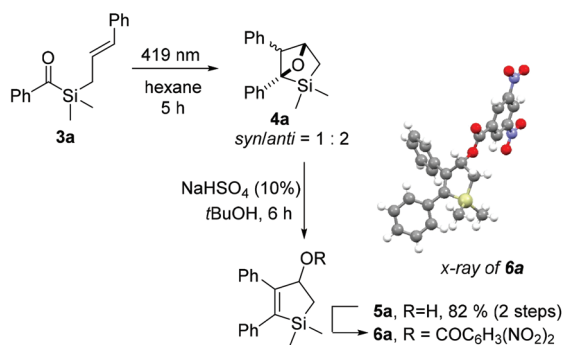


Gratifyingly, **3a** was obtained in reasonable 53% yield after hydrolysis. Compound **3a** was irradiated with blue-light for 5 hours in dry hexane, and complete consumption of the starting material was observed (Scheme 3). NMR analysis showed that oxetane **4a** was cleanly obtained as a mixture of two diastereoisomers (*syn/anti* = 1 : 2), resulting from the [2 + 2] photocycloaddition reaction. Notably, reverse regioselectivity in the Paternò–Büchi reaction was observed by Portella *et al.*³⁷ for unsubstituted acyl(allyl)silanes (Scheme 1b).

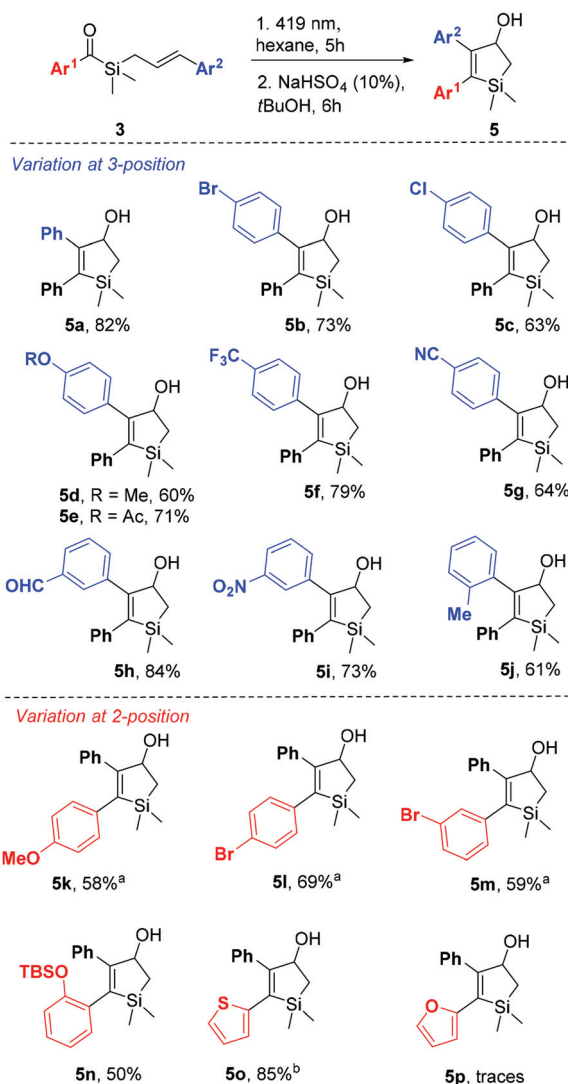
Compound **4a** proved to be unstable to silica column purification and overall acidic conditions, producing alcohol **5a** and other products. After optimization, we found that treating **4a** with catalytic NaHSO₄ in *tert*-butanol leads to complete and selective isomerization to **5a**, in 82% overall yield. Its structure was proven through esterification with 3,5-dinitrobenzoylchloride to yield **6a** and following single crystal X-ray diffraction analysis of the obtained ester.

Realising the potential of the photocycloaddition–isomerization sequence as a direct and selective way to obtain 2,3-aryl-substituted silacyclopent-2-en-4-ols, we synthesised a series of acylsilanes **3** to be submitted to the same transformation (Scheme 2). Sila-hemiaminals **2** were obtained in very good yields, containing a wide range of functional groups in the aryl moiety. Nitro-substituted aromatics however failed to add to the silylchloride reagent, presumably due to the low nucleophilicity of the lithiated intermediate. Issues related with the instability of the lithiated anion of **1** bearing electron-rich groups in Ar¹ were overcome by *t*BuLi addition to a stirring solution of **1** and silyl chloride. The syntheses proceeded with cross-metathesis of intermediates **2** with styrenes. Low to moderate yields were obtained in some cases due to incomplete conversion of **2**, as the dimerization of styrene to stilbene was a fast competitive reaction. 2-Pyrididyl, 4-cyano- and 4-dimethylamine-benzene resulted in complete deactivation of the catalyst, as no reactions were observed after several days at reflux. The detrimental effect of nitrogen bases and N-heterocycles in metathesis reaction is known and still a problematic issue in this field.⁵⁹

Despite the synthetic challenges, a series of seventeen aryl-substituted acylsilanes **3** were obtained and tested in the intra-



Scheme 3 [2 + 2] photocycloaddition of cinnamyl silane **3a**, acid-catalysed isomerization to **5a**, and crystal structure of 3,5-dinitro-benzoylated **6a**.



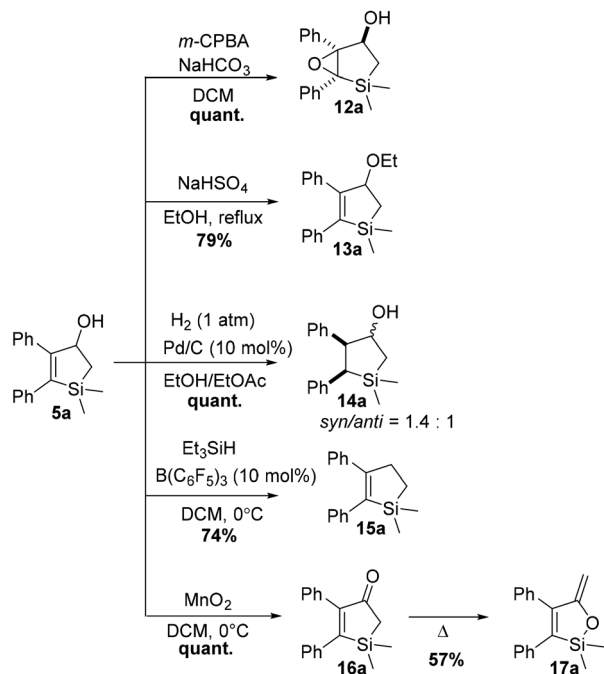
Scheme 4 Scope of the [2 + 2] photocycloaddition of benzoylsilanes **3**. ^a PPTS (10%) was used instead of NaHSO₄. ^b No acid treatment was needed.

molecular [2 + 2] photocycloaddition reaction (Scheme 4). The reaction scope appears to be quite vast, withstanding electron withdrawing and electron donating substituents, as well as *ortho*, *meta* and *para* substitution. Gratifyingly, both variations at 3- and 2-positions of the 2,3-diaryl-silacyclopent-2-ene-4-ol could be performed. The reaction tolerates the presence of substituents prone for further derivatization such as acetyl (**5e**), nitrile (**5g**), aldehyde (**5h**) and silyl ether (**5n**). Formation of sulfur heterocycle derivative **5o** contrasts with its oxygen homologue **5p**, for which only traces could be observed. Also *ortho*-methyl substitution on the ketone side (Ar¹) led to the recovery of starting material even after 8 hours of irradiation.

In order to better understand the dramatic change in regioselectivity of the [2 + 2] photocycloaddition of **3a** compared to its terminal olefin analogues, DFT calculations were performed and the energies of the possible biradical intermediates com-







Scheme 8 Examples of chemical transformations of **5a**.

ence of catalytic palladium on carbon quantitatively yields the silacyclopentanol **14a** as mixture of two diastereoisomers (*syn/anti* = 1.4 : 1). Finally, inspired by the structural similarity of selective COX-2 enzyme inhibitors⁶⁰ derived from cyclopentane, the removal of the hydroxyl functionality of **5a** was attempted. Gratefully, use of Yamamoto's HSiEt₃/catalytic B(C₆F₅)₃ system⁶¹ allowed deoxygenation to **15a** in reasonable yield. The use of such compounds as bioisosteres of cyclopentanes could pave the way in the adoption of the new intramolecular [2 + 2] photocycloaddition in the silicon/carbon switch strategy. Oxidation of allylic alcohol **5a** was accomplished using excess MnO₂ in cold DCM, giving ketone **16a** quantitatively. Low temperatures are vital as **16a** proved to easily isomerize to the silyl enol ether **17a** under thermal conditions.

Conclusions

In conclusion, we have developed a methodology for the synthesis of novel 2,3-diaryl silacyclopent-2-en-4-ols. This strategy involved the synthesis of olefin-substituted benzoyl(allyl) silanes through the benzotriazole umpolung and metathesis reactions. Blue-light irradiation of these molecules promotes a [2 + 2] photocycloaddition reaction with complete regioselectivity, governed by the stability of the biradical intermediate as supported by computational calculations. Acid-promoted isomerization yields, to the best of our knowledge, the so far unavailable 2,3-disubstituted silacyclopentenols. Moreover, this study expands the rather short collection of intramolecular Paternò-Büchi reaction examples while demonstrating the influence of the olefin substituents in controlling

the regioselectivity of such reaction. The obtained compounds may be used as versatile precursors to other silacyclopentanes that could find their use in the silicon/carbon switch approach in medicinal chemistry as bioisosteres of bioactive cyclopentanes, or as organosilicon motifs in organic electronics.

Conflicts of interest

There are no conflicts to declare.

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Notes and references

- 1 A. K. Franz and S. O. Wilson, *J. Med. Chem.*, 2013, **56**, 388–405.
- 2 E. Rémond, C. Martin, J. Martinez and F. Cavelier, *Chem. Rev.*, 2016, **116**, 11654–11684.
- 3 A. D. Dilman and S. L. Ioffe, *Chem. Rev.*, 2003, **103**, 733–772.
- 4 S. Rendler and M. Oestreich, *Synthesis*, 2005, 1727–1747.
- 5 R. Tacke and S. Dörrich, *Atypical Elements in Drug Design*, 1st edn, 2014.
- 6 R. Ramesh and D. S. Reddy, *J. Med. Chem.*, 2017, **61**, 3779–3798.
- 7 O. Daiss, C. Burschka, J. S. Mills, J. G. Montana, G. A. Showell, J. B. H. Warneck and R. Tacke, *Organometallics*, 2006, **25**, 1188–1198.
- 8 R. Tacke, F. Popp, B. Müller, B. Theis, C. Burschka, A. Hamacher, M. U. Kassack, D. Schepmann, B. Wünsch, U. Jurva and E. Wellner, *ChemMedChem*, 2008, **3**, 152–164.
- 9 J. B. Bauer, W. P. Lippert, S. Dörrich, D. Tebbe, C. Burschka, V. B. Christie, D. M. Tams, A. P. Henderson, B. A. Murray, T. B. Marder, S. A. Przyborski and R. Tacke, *ChemMedChem*, 2011, **6**, 1509–1517.
- 10 T. A. Su, H. Li, R. S. Klausen, N. T. Kim, M. Neupane, J. L. Leighton, M. L. Steigerwald, L. Venkataraman and C. Nuckolls, *Acc. Chem. Res.*, 2017, **50**, 1088–1095.
- 11 R. L. N. Hailes, A. M. Oliver, J. Gwyther, G. R. Whittell and I. Manners, *Chem. Soc. Rev.*, 2016, **45**, 5358–5407.
- 12 S. A. Ponomarenko and S. Kirchmeyer, *Adv. Polym. Sci.*, 2011, **235**, 33–110.
- 13 J. Chen and Y. Cao, *Macromol. Rapid Commun.*, 2007, **28**, 1714–1742.
- 14 J. V. Obligacion and P. J. Chirik, *Nat. Rev. Chem.*, 2018, **2**, 15–34.



- 15 T. Komiyama, Y. Minami and T. Hiyama, *ACS Catal.*, 2017, **7**, 631–651.
- 16 Q. C. Mu, J. Chen, C. G. Xia and L. W. Xu, *Coord. Chem. Rev.*, 2018, **374**, 93–113.
- 17 H. Chen, Y. Chen, X. Tang, S. Liu, R. Wang, T. Hu, L. Gao and Z. Song, *Angew. Chem., Int. Ed.*, 2019, **58**, 4695–4699.
- 18 G. Manuel, P. Mazerolles and E. T. J. Florence, *J. Organomet. Chem.*, 1971, **30**, 5–19.
- 19 G. K. Henry, R. Shinimoto, Q. Zhou and W. P. Weber, *J. Organomet. Chem.*, 1988, **350**, 3–8.
- 20 T. Ohmura, K. Masuda, I. Takase and M. Sugimoto, *J. Am. Chem. Soc.*, 2009, **131**, 16624–16625.
- 21 D. S. Straus and C. K. Glass, *Med. Res. Rev.*, 2001, **21**, 185–210.
- 22 S. M. Roberts, M. Gabriella and E. S. Sickel, *J. Chem. Soc., Perkin Trans. 1*, 2002, 1735–1742.
- 23 H. Almahli, *Curr. Top. Med. Chem.*, 2017, **17**, 2903–2912.
- 24 Z. Sevcikova, M. Pour, D. Novak, J. Ulrichova and J. Vacek, *Mini-Rev. Med. Chem.*, 2014, **14**, 322–331.
- 25 B. Heasley, *Curr. Org. Chem.*, 2014, **18**, 641–686.
- 26 S. P. Simeonov, P. M. Nunes, K. Guerra, V. B. Kurteva and C. A. M. Afonso, *Chem. Rev.*, 2016, **116**, 5744–5893.
- 27 H. C. Kolb, M. S. VanNieuwenhze and K. B. Sharpless, *Chem. Rev.*, 1994, **94**, 2483–2547.
- 28 A. Pfenniger, *Synthesis*, 1986, 89–116.
- 29 N. Asao, T. Shimada, T. Shimada and Y. Yamamoto, *J. Am. Chem. Soc.*, 2001, **123**, 10899–10902.
- 30 B. Wrackmeyer, O. L. Tok and R. Kempe, *Inorg. Chim. Acta*, 2005, **358**, 4183–4190.
- 31 T. Ohmura, I. Sasaki and M. Sugimoto, *Org. Lett.*, 2019, **21**, 1649–1653.
- 32 A. C. Stevens and B. L. Pagenkopt, *Org. Lett.*, 2010, **12**, 3658–3661.
- 33 D. Liu and S. A. Kozmin, *Angew. Chem., Int. Ed.*, 2001, **40**, 4757–4759.
- 34 K. Igawa, D. Yoshihiro, Y. Abe and K. Tomooka, *Angew. Chem., Int. Ed.*, 2016, **55**, 5814–5818.
- 35 K. Igawa, A. Kuroo, D. Yoshihiro, Y. Yamanaka and K. Tomooka, *Synlett*, 2017, **28**, 2445–2448.
- 36 D. Liu and S. A. Kozmin, *Org. Lett.*, 2002, **4**, 3005–3007.
- 37 C. Hammaeher and C. Portella, *Chem. Commun.*, 2008, 5833.
- 38 M. Abe, T. Kawakami, S. Ohata and K. Nozaki, *J. Am. Chem. Soc.*, 2004, **126**, 2838–2846.
- 39 F. Kong, B. Zhai and Q. Song, *Photochem. Photobiol. Sci.*, 2008, **7**, 1332–1336.
- 40 A. G. Brook, *J. Am. Chem. Soc.*, 1957, **79**, 4373–4375.
- 41 A. Ricci and A. Degl'Innocenti, *Synthesis*, 1989, 647–660.
- 42 P. C. B. Page, S. S. Klair and S. Rosenthal, *Chem. Soc. Rev.*, 1990, **19**, 147.
- 43 H.-J. Zhang, D. L. Priebbenow and C. Bolm, *Chem. Soc. Rev.*, 2013, **42**, 8540–8571.
- 44 J. Y. Lv, Z. Xu, Z. J. Zheng, L. Li, Y. M. Cui, J. Cao, K. F. Yang and L. W. Xu, *RSC Adv.*, 2017, **7**, 54934–54938.
- 45 F. G. Zhang and I. Marek, *J. Am. Chem. Soc.*, 2017, **139**, 8364–8370.
- 46 L. Capaldo, R. Riccardi, D. Ravelli and M. Fagnoni, *ACS Catal.*, 2018, **8**, 304–309.
- 47 A. G. Brook and J. M. Duff, *Can. J. Chem.*, 1973, **51**, 352–360.
- 48 J. M. Duff and A. G. Brook, *Can. J. Chem.*, 1973, **51**, 2869–2883.
- 49 H. Watanabe, T. Kogure and Y. Nagai, *J. Org. Chem.*, 1972, **43**, 285–291.
- 50 A. G. Brook and J. B. Pierce, *Can. J. Chem.*, 1971, **49**, 1622–1628.
- 51 H. J. Zhang, P. Becker, H. Huang, R. Pirwerdjan, F. F. Pan and C. Bolm, *Adv. Synth. Catal.*, 2012, **354**, 2157–2161.
- 52 P. Becker, D. L. Priebbenow, H. J. Zhang, R. Pirwerdjan and C. Bolm, *J. Org. Chem.*, 2014, **79**, 814–817.
- 53 K. Ito, H. Tamashima, N. Iwasawa and H. Kusama, *J. Am. Chem. Soc.*, 2011, **133**, 3716–3719.
- 54 A. R. Bassindale, A. G. Brook and J. Harris, *J. Organomet. Chem.*, 1975, **90**, C6–C8.
- 55 B. Fund and F. Summer, *J. Org. Chem.*, 1982, **47**, 2668–2670.
- 56 Z. Shen and V. M. Dong, *Angew. Chem., Int. Ed.*, 2009, **48**, 784–786.
- 57 C. Hammaeher, J. Bouillon and C. Portella, *Tetrahedron*, 2009, **65**, 5527–5534.
- 58 A. R. Katritzky, H. Lang, Z. Wang, Z. Zhang and H. Song, *J. Org. Chem.*, 1995, **60**, 7619–7624.
- 59 K. Lafaye, C. Bosset, L. Nicolas, A. Guérinot and J. Cossy, *Beilstein J. Org. Chem.*, 2015, **11**, 2223–2241.
- 60 D. B. Reitz, J. J. Li, M. B. Norton, E. J. Reinhard, J. T. Collins, G. D. Anderson, S. A. Gregory, C. M. Koboldt, W. E. Perkins, K. Seibert and P. C. Isakson, *J. Med. Chem.*, 1994, **37**, 3878–3881.
- 61 V. Gevorgyan, J. X. Liu, M. Rubin, S. Benson and Y. Yamamoto, *Tetrahedron Lett.*, 1999, **40**, 8919–8922.

