Dendritic Ligands for Magnetic Suspensions in Liquid Crystals

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Abstract: The synthesis of long-chain, aliphatic and space-filling dendritic ligands containing (pro)mesogenic, aliphatic or nitrile biphenyl moieties for the stabilization of magnetic nanoparticles in liquid crystal hosts is described. A Negishi or Sonogashira cross-coupling is exploited as a key step in the synthetic sequence. These synthetic procedures enable the synthesis of various ligands which can be easily adapted to different types of liquid crystals [e.g. 4-pentyl-4′-cyanobiphenyl (5CB)]. For instance, a three-step sequence (i.e. etherification, Sonogashira–Hagihara cross-coupling and Steglich-esterification) yields a dendritic ligand in 77 % overall yield starting from literature known compounds. The length of the ligand is important to stabilize the magnetic nanoparticles, and, therefore, the length of the ligand may be easily modified by this approach. Indeed, the established synthesis can readily tackle this issue.

Introduction

Suspensions of magnetic nanoparticles (MNPs) in liquid crystals (LCs) combine physical properties of both materials. These properties of the hybrid materials include electro-optical, magneto-optical (static and dynamic) and magneto-rheological properties not observed for the individual components.[1] In 1970, Brochard and de Gennes suggested that doping of LCs with shape-anisotropic MNPs leads to an increase in magnetic susceptibility $\chi$.[2] For the first time, the macroscopic collective behavior of ferromagnetic $\gamma$-Fe$_2$O$_3$ nanorods (500 × 70 nm) in N-(4-methoxy-benzylidene)-4-butylaniline (MBBA, Figure 1) was then demonstrated experimentally by Amer et al. in 1983.[3] In 2013, a ferromagnetic nematic phase with spontaneous magnetization was realized by Mertelj et al. embedding ferromagnetic BaFe$_{11.5}$Sc$_0.5$O$_{19}$ nanodiscs (70 × 5 nm) in 4-pentyl-4′-cyanobiphenyl (5CB, Figure 1).[4]

Despite the great interest in colloidal suspensions of MNPs in LCs, applications have been mainly hampered by a relatively low colloidal stability and a strong tendency to form aggregates. Examples in the literature have reported on the formation of aggregates [in particular for high particle concentrations (> 0.01 wt.-%)] leading to inhomogeneous particle distribution or even macroscopic phase separation.[5] Phase separation is caused by gravitational forces, magnetic field gradients and/or magnetic dipole-dipole interactions. Lower particle concentrations minimize potential interactions and thus the number and size of aggregates.[3,4] In order to prevent particle aggregation and phase separation, specific (pro)mesogenic ligands have been introduced to functionalize the particle surface.

The role of these (pro)mesogenic ligands is not only the steric repulsion by a large exclusion volume, but also the "smoothing out" of the disturbance of the local LC director caused by the nanoparticles (especially at the MNP-LC interface).[6] Therefore, it is no coincidence that the most stable colloidal LCs have been obtained either with ligands bearing mesogenic entities or a combination of (pro)mesogenic and aliphatic ligands. Ligands exploited for the stabilization of nanoparticles in LCs are typically composed of three major structural parts: a) an anchoring group (e.g., carboxyl, phosphates and amines), b) an aliphatic linker/spacer connecting the binding group with c) the (pro)mesogenic unit. The choice of the (pro)mesogenic unit depends on the LC and may consist, e.g.,
of a biphenyl residue bearing either a nitrile or an octyloxy end group in case of 8OCS, respectively (Figure 1).

The functionalization of magnetic nanorods with an octyl-oxybiphenyl-based ligand, for example, was shown to significantly reduce aggregation, as compared to their oleic acid-coated counterparts.[17] Likewise a ligand consisting of a 4-cyanobiphenyl residue and an aliphatic C7- or C15-spacer, respectively, was previously demonstrated to stabilize 2.5 nm size CoFe2O4 MNPs in 5CB.[8] Increasing the linker length from C7 to C15, lead to a larger exclusion volume and thus to better steric stabilization and allowed for the stabilization of higher MNP concentrations in the LC (i.e. without macroscopic aggregation in an external magnetic field). This suggests that a longer aliphatic spacer may allow for the stabilization of larger MNPs or achieving higher MNP concentrations. If the MNPs are introduced into the LC, the mutual molecular alignment not only disturbs the local LC order in the vicinity of the MNPs, but also disturbs the originally isotropic, (pro)mesogenic ligand shell of the MNP from spherical to tactoidal, which can also lead to MNP agglomeration.[9]

Dendritic ligands with a tree-like architecture may tackle this problem of equatorial ligand depletion on the nanoparticle surface. Derrmortière et al. have reported on the functionalization of MNPs with a dendritic ligand which leads to the formation of a magnetic hybrid material with birefringent, optical properties.[10] Yet, the stabilization of the MNPs in a LC host was not investigated. Vashchenko et al. have reported a seven-step synthesis of (pro)mesogenic ligands with linear and dendritic structures, topologies and properties but also to develop synthesis methods that are complicated, deliver only small amounts of the target ligand and thus limit the overall application. Hence, it is not only important to design organic ligands with specific structures, topologies and properties but also to develop synthetic procedures that are both simple and versatile at the same time. Herein, we describe a practical approach for the synthesis of (pro)mesogenic ligands with linear and dendritic structures and compare alternative approaches. We address the spacer length and the space-filling nature of these ligands. The synthetic procedures described herein range from the synthesis of the linear ligand 1 to the simple, three-step synthesis of the dendritic ligand 2 with an overall yield of 77 % (Figure 1).

Results and Discussion
Linear (pro)mesogenic ligands

The aliphatic ligand 1 exhibiting a (pro)mesogenic octyl-biphosphyl structural motif was obtained from iodide 3 in a three-step synthetic procedure (Scheme 1). The octyl group was introduced via a Sonogashira cross-coupling reaction, yielding alkyne 4 in 90 % yield after column chromatography.[12] Subsequently, the Pd-catalyzed hydrogenation of the triple bond in 4 led to alcohol 5.[13] Eventually, the alcohol 5 and the commercial bromide 6 were treated with NaH. Since the alcohols of 5 showed a poor solubility, tetrabutylammonium sulfate was employed as phase transfer agent. Nucleophilic substitution gave ligand 1 in an overall yield of 69 %[8]


Long-chain ligands (n > 15) via Negishi cross-coupling

As mentioned earlier, the length of the aliphatic spacer influences nanoparticle stabilization, and the increase in chain length allows for stabilization of higher particle concentrations.[8] However, the etherification described in Scheme 1 is limited to n-bromocarbonic acids. As the chain length of the n-bromocarbonic acids increases, the solubility in common organic solvents decreases. Therefore, an alternative synthetic pathway is required to build up ligands with longer alkyl spacers (–CH2–)n, n > 15. Here, a (Sp3)2-C(Sp3)2-Negishi cross-coupling of the corresponding methyl ester was employed to synthesize ligands with a spacer length of n = 17, 25.[14] First, as described earlier for bromide 9c, a modified procedure of a Mitsunobu reaction of alcohol 4 and 5, and 11-bromoundecan-1-ol (8) with disopropyl azodicarboxylate (DIAD) gave bromide 9a and 9c in 87 % and 94 % yield, respectively (Scheme 2).[10]

Scheme 2. Mitsunobu reaction of 11-bromoundecan-1-ol (8) and alcohol 4, 5 and 7, respectively.

Then, 9c was treated with the commercial compound 10a via C(Sp3)2-C(Sp3)2-Negishi cross-coupling to form the long-chain aliphatic ester 11a (Scheme 3). Compound 10b was obtained as a colorless solid (99 %) from the corresponding carboxylic acid in a mixture of methanol with a catalytic amount of H2SO4.[15] Using the same reaction conditions in the Negishi cross-coupling, bromide 9c and compound 10b resulted in the formation
of the poorly soluble ester 11b. Thus, ester 11b could only be assigned with a ¹H NMR experiment not with a ¹³C NMR experiment.


The poor solubility of the esters 11a and 11b made their transesterification even more difficult and attempts to deprotect them with TFA or LiOH in THF/MeOH (1:1) led to a precipitate. These precipitates were insoluble in common organic solvents (halogenated solvents, DMSO, DMF etc.). Hence, they could neither be further characterized nor directly exploited as ligands in the stabilization of magnetic nanoparticles. In order to overcome the issue of poor ligand solubility while maintaining large exclusion volumes of the ligands, a protocol for dendritic ligands was established in the following using a Sonogashira cross-coupling.

Synthesis of dendritic (pro)mesogenic ligands

A terminal anchoring group of the (pro)mesogenic ligand binds to the nanoparticle surface. Thereby, the binding efficiency depends strongly on both the type of anchoring group and the inorganic core. Several types of anchoring groups (e.g., carboxyl, amine) have been employed to directly bind organic ligands to the inorganic core of Co, CoFe₂O₄ or Fe₃O₄ nanoparticles, respectively. Alternatively, functional groups such as, hydroxyl[16], alkynyl[17], allyl[18] may be employed for covalent coupling to polymer-coated MNPs. In order to enable the functionalization of different types of nanoparticles with (pro)mesogenic ligands, we aimed for a scalable and variable method for a broad application spectrum and a high tolerance for functional groups. Therefore, a Sonogashira cross-coupling was investigated as a key step in the synthetic sequence of the (pro)mesogenic ligands.[12]

Triols 12a and 12b were obtained via deprotection of the corresponding methoxy derivatives with Br₂ (Table 1).[19]

Those triols were further reacted with bromides 9a, 9b and 9c, respectively, under reflux in a suspension of anhydrous acetone and K₂CO₃ under inert conditions (Table 1).[10] In the case of iodide 13d the yield could be increased by roughly 10% via exclusion of light.

Table 1. Results of the etherification of triol 12a and 12b and bromides 9a, 9b, 9c. Yields were determined after column chromatography.

<table>
<thead>
<tr>
<th>R</th>
<th>X</th>
<th>Product</th>
<th>Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>-H</td>
<td>I</td>
<td>13a</td>
<td>75%</td>
</tr>
<tr>
<td>-CH₃</td>
<td>Br</td>
<td>13b</td>
<td>90%</td>
</tr>
<tr>
<td>-CN</td>
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<tr>
<td>-CN</td>
<td>I</td>
<td>13d</td>
<td>82%</td>
</tr>
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Dendritic ligands via Sonogashira cross-coupling

The hydroxyl and alkynyl group are orthogonal in the Sonogashira cross-coupling. The alkynyl group should be addressable via a two-step protocol of a TMS-protected alkyne in a Sonogashira cross-coupling and deprotection with K₂CO₃ in MeOH/THF.[20] For the carboxyl group, a benzyl protected carboxylic acid was introduced which may be removed by reduction with H₂/Pd.[21] First, alkyne 14a was obtained from undec-10ynoic acid and benzyl bromide in DMF with K₂CO₃ at ambient temperature (not shown). After 1 day, the combined organic phase was washed, dried with Na₂SO₄ and the solvent removed under high vacuum to give reactant 14a in a yield of 95%. Table 2 summarizes the results of the Sonogashira cross-coupling of 13b–13d with different alkynes 14a–14c, the reaction conditions and the corresponding yields.

The bromides 13b and 13c led to the benzylic esters 15a and 15b in moderate yields, respectively. In the case of # 2, 49% of product 15b were obtained as a colorless solid and 19% of bromide 13c were recovered. An increase of the yield was expected with iodide 13d under similar conditions.[22] Indeed, the reaction already took place at room temperature and monitoring by thin layer chromatography indicated that the reaction was completed after 3 h to give ester 15b in 84% yield. If DMF was replaced by toluene and used as solvent, the yield could be further increased for 14b and 14c, respectively.[23] All products were obtained as pure compounds after purification with column chromatography and showed good solubility in common organic solvents (e.g. halogenated solvents).

Deprotection of ester 15a was carried out with hydrogen using Pd on charcoal as a catalyst to give the dendritic ligand
Table 2. Results of the Sonogashira cross-coupling of halides 13b–13d with different alkynes 14a–14c. Yields were determined after column chromatography.

<table>
<thead>
<tr>
<th>#</th>
<th>R</th>
<th>X</th>
<th>Alkyne</th>
<th>Condition</th>
<th>Product</th>
<th>Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-C6H17</td>
<td>Br</td>
<td>−Bn</td>
<td>NEt3, DMF</td>
<td>90 °C, 0.5 h</td>
<td>15a</td>
</tr>
<tr>
<td>2</td>
<td>-CN</td>
<td>Br</td>
<td>−Bn</td>
<td>NEt3, DMF</td>
<td>90 °C, 0.5 h</td>
<td>15b</td>
</tr>
<tr>
<td>3</td>
<td>-CN</td>
<td>I</td>
<td>14a</td>
<td>NEt3, DMF</td>
<td>r.t., 3 h</td>
<td>15b</td>
</tr>
<tr>
<td>4</td>
<td>-CN</td>
<td>I</td>
<td>14b</td>
<td>HNEt3, tol</td>
<td>r.t., 20 h</td>
<td>15c</td>
</tr>
<tr>
<td>5</td>
<td>-CN</td>
<td>I</td>
<td>14c</td>
<td>HNEt3, tol</td>
<td>r.t., 20 h</td>
<td>15d</td>
</tr>
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</table>

16 in quantitative yield (Scheme 4). In addition to the deprotection, the triple bond was also hydrogenated. In contrast, the reduction of ester 15b bearing aromatic nitrile groups caused a by-product (approx. 10 %). Unfortunately, this by-product could neither be separated via column chromatographic purification nor removed sufficiently via recrystallization.

It has been previously demonstrated that the reductive deprotection with hydrogen and Pd works well alongside an aromatic nitrile group. Using a Pd catalyst poisoned with Hünig’s base, Mandel et al. succeeded in selectively reducing a triple bond in the presence of an aromatic nitrile group, while the aromatic nitrile was not reduced. Therefore, we investigated this reduction initially using 18 (Scheme 5) as a model compound. Starting from triflate 17 and benzyl ester 14a, the Pd-mediated cross-coupling led by addition of lithium chloride (1.3 equivalent) to model compound 18. Without lithium chloride, no cross-coupling was observed under the chosen reaction conditions. Then, 18 was hydrogenated exploiting the described poisoned Pd catalyst (0.1 wt.-%) in methanol. After 12 h, the 1H-NMR spectrum revealed the complete conversion of the triple to the single bond – ester 19a was obtained (Scheme 5). After 24 h, < 0.3 % of the ester group was deprotected. However, under these conditions, a reduction of the nitrile group to the amine was also observed. Thus, this approach was not suitable for the selective deprotection of the benzyl group of ester 15b.

Therefore, an alternative strategy was developed in which a terminal carboxyl anchoring group was introduced for dendritic ligands bearing nitriles as end group of the (pro)mesogenic unit. First, a Sonogashira cross-coupling under the same reaction conditions as described before (GP-5) was performed with iodide 13d and propargyl alcohol (20) yielding the dendritic ligand 15e (Scheme 6). Ligand 15e is suitable for covalent coupling to polymer-coated nanoparticles. Second, we estab...
Scheme 5. Synthesis of model compound 18 and its hydrogenation with a poisoned Pd(5 %/C) catalyst led to the selective hydrogenation of the triple bond. The quantitative conversion to ester 19a was assigned via $^1$H NMR experiment.

Scheme 6. Synthesis of dendritic ligand 15e via Sonogashira cross-coupling. Esterification of 15e and a) succinic anhydride (21a) and b) succinic acid (21b) yielded dendritic ligand 2. Established a) an esterification$^{[28]}$ of dendritic ligand 15e and succinic anhydride (21a) and b) a Steglich esterification$^{[29]}$ of dendritic ligand 15e and succinic acid (21b). Both methods gave the dendritic ligand 2 in excellent yields simply by washing the combined organic phases. The overall yield starting from literature known triol 12b is 77 % (in the case of method b). Since various dicarboxylic acids are commercially available, it should be possible to obtain the corresponding dendritic ligands with different spacer lengths also in good overall yields.

Moreover, deprotection of 15d with K$_2$CO$_3$ in MeOH/THF (1:1) yielded the dendritic ligand 23 (Scheme 7).$^{[20]}$ The
dendritic ligand 23 may be further exploited to functionize magnetic nanoparticles with (pro)mesogenic ligands via click chemistry.[138]

Conclusions

In summary, we have shown the synthesis of various (pro)mesogenic ligands with linear and dendritic structures using a Sonogashira cross-coupling reaction as a key step. Our approach represents a convenient and practical route which delivers the (pro)mesogenic ligands in good overall yields, minimizes the apparative effort and allows different end and anchoring groups to be introduced, respectively. This is an important issue with respect to the functionalization of MNPs in LC hosts and the future application of the resulting hybrid materials. For instance, the reductive deprotection of the benzyl ester 15a with H₂/Pd led to the quantitative formation of the dendritic ligand 16 with a carboxyl anchoring and an octyl end group. The dendritic ligand 15c with a terminal alkene was specifically designed for the future functionalization of polymer-coated nanoparticles (i.e. via cross metathesis) and received with an overall yield of 77 %. Moreover, the simple, three-step sequence of ethification, Sonogashira cross-coupling and esterification gave the (pro)mesogenic dendritic ligand 2 in an overall yield of 77 %. The dendritic ligand 2 with nitrile end group was specifically tailored for the stabilization of MNPs in LC hosts (e.g. SCB). The synthetic sequence is versatile and may be extended to dendritic ligands with various spacer length and end groups. This will allow for a systematic investigation of the relationships between ligand structure and particle stability in LC matrices, which will be a subject of our future investigations.

Experimental Section

General Remarks

All chemicals and reagents were obtained from commercial sources and used as received, unless otherwise noted. Dry solvents (i.e., acetone, dichloromethane, dimethylformamide, 1,3-dimethyl-2-imidazolidinone, dimethyl sulfoxide, methanol, tetrahydrofuran, toluene) were purchased from Sigma-Aldrich. Triethylamine and ethylamine were dried and stored over 3 Å molecular sieves.[20] Starting materials and reagents are purchased from commercial sources: Bis(triphenylphosphine) palladium(II) dichloride (99 %, Sigma-Aldrich), 11-bromoundecan-1-ol (99 %, abcr), 5-bromo-1,2,3-trimethoxybenzene (98 %, TCI), copper(I) iodide (98 %, abcr), dicyclohexylcarbodiimid (99 % abcr), diisopropyl azodicarboxylate (94 %, abcr), N,N′-diphenyl-4-ol (Alfa Aesar 98 %), 5-iodo-1,2,3-trimethoxybenzene (98 %, Alfa Aesar), lithium chloride (99.9 %, Sigma-Aldrich), lithium bromide (99.9 %, Sigma-Aldrich), lithium chloride (99.9 %, Sigma-Aldrich), methyl 7-bromomethanoate (98 %, abcr), oct-1-yn-1-ene (97 %, Alfa aesar), sodium hydroxide (60 % dispersion, Sigma-Aldrich), sucinic acid (99 %, Sigma-Aldrich), succinic anhydride (99 % Arcos organics), trimethylsilylacetylene (98 % Arcos organics), triphenylphosphate (99 % Sigma-Aldrich), undec-10-ynoic acid (95 %, Sigma-Aldrich). Manipulations under inert conditions were performed under an atmosphere of dry argon (6.0; Linde AG, Germany) using dry glassware and syringe-cannula techniques which were argon flushed.

Analytical thin layer chromatography (TLC) was performed on TLC-PET-sheets (pore size 60 Å, 25 μm). Components were visualized by observation either under UV light (254 nm or 365 nm) or by dyeing with KMnO₄ solution. Flash column chromatography was carried out using silica gel (pore size 60 Å, 40–63 μm) purchased from Sigma Aldrich. Melting points (not corrected) were measured with a Melting Point B-540 Büchi. ¹H-NMR spectra were recorded at room temperature on a Bruker Avance III 300 (250 MHz) and a Bruker Avance III 400 (400 MHz). The spectra were recorded in CDCl₃ and d6-DMSO, respectively, as indicated in each case. Chemical shifts (δ) were reported in parts per million (ppm) and referenced to the remaining non-deuterated solvent signals of the deuterated solvents.[21] The following abbreviations are used to indicate the signal multiplicity: s (singlet), d (doublet), t (triplet), dd (doublet of doublet), dt (doublet of triplet), b (broad signal), m (multiplet). All NMR spectra were integrated and processed using the software MestReNova. The coupling constants (J) are reported in Hertz. NMR spectra are provided in the supporting information (SI). Accurate mass spectra (MS) were determined at the MS facility of the Institute of Organic Chemistry, Heidelberg University. All ionization methods (EI+, DART+, ESI−, MALDI+/−) were applied using following mass spectrometers: Bruker FT-ICR Apex-Qe, Bruker Autoflex Speed TOF and JEOL JMS-700. The signal intensity of mass spectral peaks is given relatively to the base peak intensity. IR spectra of the samples were recorded as pellets in potassium carbonate with the FT-IR-spectrometer Varian 660-IR (Agilent Technologies, USA). The position of the peaks is indicated in wavenumbers ν in cm⁻¹. The following abbreviations are used to characterize the signals: s (strong), m (medium), w (weak) and b (broad). Elementary analysis was determined using a vario MIKRO cube by Elementar.

Synthetic Procedures

Synthesis of Alkyne 4 via Sonogashira Cross-Coupling: Iodide 3 (100 g, 3.38 mmol), Pd(PPh₃)₂Cl₂ (120 mg, 0.17 mmol), and copper iodide (64.0 mg, 0.34 mmol) were added to a vial with a magnetic stirrer bar and purged with argon. Then, degassed NET₃ (5 mL) and 1-octyne (550 mL, 411 mg, 3.73 mmol) were added and the reaction mixture was stirred at 60 °C for 2 d. Et₂O (100 mL) was added and the organic phase was washed with sat. NH₄Cl solution and brine. The combined organic phase was washed with CaCl₂ and the solvent was removed. After column chromatography (pentane/EtOAc = 1:5) and removing the solvent under high vacuum, 834 mg (90 %) of alkyne 4 were obtained as an off-white solid. Rₖ = 0.23 (pentane/EtOAc, 15:1); m.p. 125 °C; ¹H NMR (250 MHz, CDCl₃); δ = 7.53–7.39 (m, 6H, ArH), 6.96–6.84 (m, 2H, ArH), 4.88 (s, 1H, -OH), 2.43 (2, 2JHH = 7.0 Hz, C(C₃H₇)), 1.64 (dd, 2JHH = 15.0, 7.1 Hz, C₃(C₃H₇)), 0.98–0.85 (m, 3H, CH₃). 13C NMR (63 MHz, CDCl₃); δ = 155.3, 139.8, 133.4, 132.0, 128.4, 128.5, 122.5, 115.8, 91.2, 80.6, 31.5, 28.9/28.8, 19.7, 14.2. IR (KBr): ν = 3402 (bs), 3041 (w), 2954 (m), 2928 (m), 2856 (m), 1610 (m), 1597 (m), 1497 (m), 1467 (m), 1447 (m), 1430 (w), 1376 (m), 1320 (w), 1261 (m), 1116 (w), 1135 (w), 820 (s), 551 (w), 519 (m). MS (ESI, neg.): m/z calcd. for C₂₀H₂₀O₂H: 277.1598, found 277.1597; elemental analysis calcd. (%): C, 86.12; H 7.89; found: C 86.17 H 7.81.

Pd-Catalyzed Hydration of Alkyne 4 to Alcohol 5: Palladium on charcoal (10 % Pd/C, 185 mg) was added to a solution of alkyne 4 (700 mg, 3.38 mmol) in EtOAc (40 mL). The flask was charged with H₂ (10 % in argon) and the reaction mixture was vigorously stirred at ambient conditions. After 15 h, Pd/C was filtered off and the
solvent was removed by rotary evaporation. After column chromatography (pentane/EtOAc = 10:1) and removing the solvent under high vacuum, 673 mg (95 %) of alcohol 5 were obtained as colorless solid. Rf = 0.49 (pentane/EtOAc, 10:1); m.p. 140 °C; 1H NMR (250 MHz, CDCl3); δ = 7.54 – 7.40 (m, 4H, Ar-H), 7.26 – 7.18 (m, 2H, Ar-H), 6.96 – 6.82 (m, 2H, Ar-3,5-H), 4.73 (s, 1H, OH), 2.63 (dd, JH,H = 8.8, 6.7 Hz, 2H, Ar-CH2), 1.73 – 1.54 (m, 2H, Ar-CH2-CH2), 1.43 – 1.22 (m, 10H, -(CH2)n), 2.94 (m, 3H, -CH3). 13C NMR (63 MHz, CDCl3); δ = 154.9, 141.7, 138.2, 134.2, 128.3, 126.7, 115.7, 35.7, 32.1, 31.7, 29.7, 29.5, 29.4, 22.8, 14.3. IR (KBr): ν = 3420 (bs), 3031 (w), 2957 (w), 2920 (m), 1610 (m), 1501 (m), 1454 (w), 1378 (w), 1266 (m), 1245 (w), 814 (m), 785 (w), 506 (w). MS (ESI, neg.): m/z calcd. for C20H26O: C 85.06 H 9.28; found C 85.18 H 9.19.

Bromide 9b: Using the general procedure GP-1, DIAD (82.8 mg, 0.54 μl, 41 mmol), 11-bromoundecan-1-ol (8) (98.0 mg, 0.39 mmol), alcohol 4 (100 mg, 0.35 mmol), PPh3 (102 mg, 0.39 mmol) and THF (0.4 ml) yielded 171 mg (94 %) bromide 9b as colorless solid after column chromatography (DCM stabilized with amylene). Rf = 0.80 (DCM, stabilized with amylene); m.p. 62–67 °C; 1H NMR (250 MHz, CDCl3); δ = 7.48 (t, JH,H = 8.8 Hz, 4H, Ar-H), 7.29–7.16 (m, 2H, Ar-H), 6.95 (d, JH,H = 8.5 Hz, 2H, 2H, 1H), 3.99 (t, JH,H = 6.4 Hz, 2H, OCH2), 3.41 (t, JH,H = 6.9 Hz, 2H, BrCH2), 2.63 (t, JH,H = 7.9 Hz, 2H, ArCH2), 1.92 – 1.75 (m, 4H, -CH2-CH2), 1.71–1.58 (m, 2H, -CH2-CH2), 1.56–1.22 (m, 22H, -CH2-CH2), 0.88 (t, JH,H = 7.9 Hz, -CH2-CH2). 13C NMR (63 MHz, CDCl3); δ = 158.6, 141.5, 138.3 133.7, 128.0, 126.7, 114.8, 68.2, 35.7, 34.2, 33.0, 32.1, 31.7, 29.7, 29.6, 29.5, 29.4, 28.9, 28.3, 26.2, 22.7, 19.6, 14.2. IR (KBr): ν = 2919 (bs), 2849 (m), 1509 (w), 1529 (m), 1496 (m), 1466 (m), 1437 (w), 1391 (w), 1293 (m), 1252 (m), 1197 (m), 1178 (m), 1030 (m), 1010 (m), 828 (s), 724 (m), 652 (m), 564 (w), 521 (m). MS (DART, pos.): m/z calcd. for C12H8Br2+: 511.2570; found 511.2574; elemental analysis calcd. (%) for C12H8Br2: C 72.78 84.7; found C 72.33 H 6.8.

Bromide 9c: Using the general procedure GP-1, DIAD (5.69 g, 5.52 ml, 38.1 mmol), 11-bromoundecan-1-ol (8) (7.08 g, 29.9 mmol), alcohol 7 (0.1 g, 25.6 mmol), PPh3 (7.39 g, 28.2 mmol) and THF (20 ml) gave 10.9 g (99 %) bromide 9c as colorless solid after column chromatography (DCM stabilized with amylene). Rf = 0.80 (DCM, stabilized with amylene); m.p. 78 °C; 1H NMR (250 MHz, CDCl3); δ = 7.67 (q, JH,H = 8.4 Hz, 4H, Ar-H), 7.58–7.47 (m, 2H, Ar-H), 6.99 (d, JH,H = 8.3 Hz, 2H, 2H, 1H), 3.91 (t, JH,H = 6.4 Hz, 2H, OCH2), 2.69 (t, JH,H = 7.9 Hz, 2H, ArCH2), 1.81–1.74 (m, 4H, -CH2-CH2), 1.54–1.22 (m, 16H, -CH2-CH2).
Ester 11a: Using the general procedure GP-2, zinc powder (79 mg, 1.2 mmol), iodine (10 mg, 0.06 mol), DMI (0.8 mL), methyl 7-bromopentadecanoate (10a) (178 mg, 0.8 mmol), PEPPSI-IPr (3.4 mg,1 mol-%), LiBr (139 mg, 0.8 mmol), dry THF (1.6 mL), bromide 9c (214 mg, 0.5 mmol) provided 157 mg (64 %) of ester 11a as colorless solid. 

Bromide 13b: Using the general procedure GP-3, triol 12a (315 mg, 2.50 mmol), bromide 9b (3.75 g, 8.75 mmol), K₂CO₃ (3.46 g, 25.00 mmol) and tetrabutylammonium hydrogenosulfate (5 mg), dry acetone (60 mL) provided the crude product. Then, DCM (600 mL) was added, the combined organic phase was washed with water (2 x 250 mL), brine (150 mL), dried with Na₂SO₄ Celite® was activated and the solvent was removed in vacuo. After column chromatography (DCM; stabilized with amylene) and removing the solvent under vacuum, 2.83 g (90 %) of bromide 13b were obtained as colorless solid. 

Bromide 13c: Using the general procedure GP-3, triol 12a (985 mg, 3.91 mmol), bromide 9c (7.50 g, 17.55 mmol), K₂CO₃ (7.41 g, 53.66 mmol) and tetrabutylammonium hydrogenosulfate (11 mg), dry acetone (140 mL) provided the crude product. After washing with acetone (2 x 80 mL) and EtOAc (2 x 80 mL), the crude product was taken up onto Celite®. After column chromatography (DCM, stabilized with amylene) and removing the solvent under high vacuum, 4.17 g (81 %) of bromide 13c were obtained as colorless solid. 

**General Procedure for Etherification (GP-3):** Triol 12a-b (1.0 equiv.), bromide 9a-c (3.5 equiv.), K₂CO₃ (35 equiv.) and tetrabutylammonium hydrogenosulfate (1 mol-%) were added under argon to dry acetone and the reaction mixture was stirred under reflux. After 3 days, the residue was collected.
1.52–1.12 (m, 12H, (CH₂)₆), 0.97–0.79 (m, 9H, CH₃). 13C NMR (63 MHz, CDCl₃): δ = 158.6, 153.9, 141.5, 138.3, 137.4, 133.6, 128.9, 128.1, 126.7, 115.7, 114.8, 110.1, 35.7, 32.1, 29.8, 29.7, 29.6, 29.5, 29.4, 29.3, 26.2, 26.2, 22.8. IR (KBr): ν = 3030 (w), 2918 (s), 2850 (s), 1608 (s), 1583 (m), 1530 (w), 1467 (m), 1422 (m), 1383 (m), 1253 (m), 1218 (m), 1180 (m), 1123 (m), 1040 (m), 1000 (m), 861 (m), 810 (m), 720 (m), 691 (w), 593 (w), 577 (w), 501 (w). MS (MALDI, pos.): m/z calc. for C₃₀H₅₁Br₂N₂O₇: 1509.018; found 1509.005; elemental analysis calc. (%) for C₇₈H₇₂Br₂N₂O₇: C 78.79 ± 0.15; H 9.55; found C 78.32 ± 0.07.

**Synthesis of Alkylene 14a:** Benzyl bromide (750 μL, 1078 mg, 6.30 mmol) was added dropwise to a mixture of under-dec-10-ynoic acid (1092 mg, 6.00 mmol), anhydrous K₂CO₃ (1.42 g, 9.00 mmol) and dry DMF (9 mL) and after completion, the reaction mixture was stirred at ambient temperature. After 1 day, ethyl acetate (50 mL) was added and the combined organic phase was washed with H₂O (2 × 50 mL) and brine (2 × 50 mL) and dried with Na₂SO₄. After removing the solvent under high vacuum, 1.49 g (95%) of alkylene 14a were obtained as yellow liquid. γ(ν) (D2O) = 1.51; 1H NMR (250 MHz, CDCl₃): δ = 7.53 (bs, 5H, Ar-H), 5.11 (s, 2H, CH₂), 2.34 (d, 3JH,H = 7.6 Hz, 2H, C=CH₂CH₂), 2.17 (td, 3JH,H = 7.0 Hz, 2H, 2H, COO-CH₂), 1.94 (t, 3JH,H = 7.4 Hz, 1H, C=CH₂), 1.66 (q, 3JH,H = 7.0 Hz, 6H, 2H, CH₂), 1.45–1.19 (m, 8H, (CH₂)₆), 13C NMR (63 MHz, CDCl₃): δ = 173.8, 136.2, 128.7, 128.3, 84.9, 68.2, 66.2, 34.4, 29.2, 29.2, 29.0, 28.8, 28.6, 25.1, 18.5. IR (KBr): ν = 3300 (m), 2932 (m), 2857 (m), 2117 (w), 1737 (s), 1587 (w), 1499 (m), 1461 (m), 1383 (m), 1352 (m), 1258 (m), 1235 (m), 1166 (m), 1099 (m), 1003 (m), 910 (m), 826 (m), 751 (m), 737 (m), 698 (m), 632 (m), 507 (m), 339 (m). MS (EI, m/z): calc. for C₉₆H₇₅N₃O₈₁: 1438.876; found 1438.868; elemental analysis calc. (%) for C₉₆H₇₅N₃O₈₁: C 79.37 H 8.88; found C 78.96 H 8.81.

**General Procedure for the Sonogashira Cross-Coupling in DMF (GP-4):** Compound 13b–d (1.0 equiv.), PdCl₂(PPh₃)₂ (35 mol-%), copper iodide (38 mol-%) and a magnetic stirrer bar were added to a vial and purged with argon. Then, degassed DMF, NEt₃ and alkylene 14a (3.05 equiv.) were added and the reaction mixture was stirred. After completion of the reaction, isopropyl alcohol was added. The crude product was collected and washed with isopropyl alcohol. Then, crude⁶ and DCM were added and the solvent was removed.

**Benzyl Ester 15b:** Using the general procedure GP-4, iodoide 13d (400 μL, 1.08 mmol), PdCl₂(PPh₃)₂ (38 mol-%), copper iodide (15 mol-%) and the magnetic stirrer bar were added to a vial and purged with argon. Then, degassed DMF, NEt₃ and alkylene 14a (3.05 equiv.) were added and the reaction mixture was stirred. After completion of the reaction, isopropyl alcohol was added. The crude product was collected and washed with isopropyl alcohol. Then, crude⁶ and DCM were added and the solvent was removed.

**General Procedure for the Sonogashira Cross-Coupling in Toluene (GP-5):** Iodoide 13d (1.0 equiv.), Pd(PPh₃)₂Cl₂ (47.5 mol-%), copper iodide (15 mol-%) and the magnetic stirrer bar were added to a vial and purged with argon. Then, degassed DMF, NEt₃ and alkylene 14a (3.05 equiv.) were added and the reaction mixture was stirred. After completion of the reaction, isopropyl alcohol was added. The crude product was collected and washed with isopropyl alcohol. Then, crude⁶ and DCM were added and the solvent was removed. Column chromatographic purification (DCM) gave the dendritic ligand 15c.

**Dendritic Ligand 15c:** Using the general procedure GP-4, iodoide 13d (1.00 g, 772 μmol), Pd(PPh₃)₂Cl₂ (22.0 mg, 36.7 μmol), copper iodide (22.0 mg, 116 μmol), toluene (5.5 mL), HNEt₂ (400 μL) hex-1-en-5-yne (322 mg, 440 μL, 4.01 mmol) provided 865 mg (89%) of dendritic ligand 15c as a weak yellow waxy solid after removing the solvent under high vacuum. Rᵣ = 0.45 (DCM); m.p. 63 °C; 1H NMR (250 MHz, CDCl₃): δ = 7.65 (q, 3JH,H = 8.2 Hz, 12H, Ar-H), 7.51 (dd, 3JH,H = 8.8 Hz, 2H, Ar-H), 6.60 (s, 2H, Ar-H), 5.19–4.99 (m, 2H, 2H, CH₂=CH₂), 3.96 (dt, 3JH,H = 13.7 Hz, 12H, OCH₃), 1.91–1.62 (m, 4H, C=CH₂CH₂), 1.61–1.17 (m, 42H, (CH₂)₆), 1.53 (m, (CH₂)₆), 1.52–1.07 (m, 84H, (CH₂)₆), 0.88 (t, 3JH,H = 6.4 Hz, 9H, CH₃). 13C NMR (63 MHz, CDCl₃): δ = 173.8, 158.6, 141.5, 138.3, 133.6, 128.9, 128.1, 126.7, 118.6, 114.8, 113.4, 35.7, 32.1, 29.7, 29.6, 29.5, 29.4, 29.3, 26.2, 26.2, 22.8, 14.2. IR (KBr): ν = 3030 (w), 2920 (s), 2851 (s), 1737 (m), 1608 (m), 1572 (m), 1530 (w), 1501 (s), 1466 (m), 1418 (m), 1384 (w), 1254 (m), 1121 (m), 1041 (m), 811 (m), 721 (m), 696 (m), 501 (m). MS (MALDI, pos.): m/z calc. for C₉₆H₇₅N₃O₈₂: 1699.2577; found 1699.2577; elemental analysis calc. (%) for C₉₆H₇₅N₃O₈₂: C 82.63 H 9.84; found C 82.62 H 9.92.
Dendritic Ligand 15e: Using the general procedure GP-4, iodide 13e (1.1 g, 859 μmol, Pd(PPh3)2Cl2 (25.0 mg, 42.8 μmol), copper iodide (250 mg, 1.31 mmol), toluene (6 mL), HNEt2 (440 μL) and propargyl alcohol (21) (250 mg, 260 μg, 428 μmol) provided 0.2 g (97%) of dendritic ligand 15e as colorless solid after removing the solvent under high vacuum. 22 mg (2% of iodide 13d) were recovered. Rf = 0.42 (DCM); m.p. 103 °C; 1H NMR (250 MHz, CDCl3); δ = 7.77–7.57 (m, 12H, Ar-H), 7.55–7.42 (m, 4H, 6.98 (dd, 3JH,H = 8.9 Hz, 2.4 Hz, 6H, Ar-H), 6.64 (s, 2H, Ar-H), 4.47 (s, 2H, HO-CH2), 4.12–3.83 (m, 12H, OCH2), 1.91–1.62 (m, 14H, (CH2)4), 1.61–1.71 (m, 4H, (CH2)4, 13C NMR (63 MHz, CDCl3); δ = 159.9, 153.0, 145.3, 139.2, 132.7, 131.3, 128.4, 127.1, 119.2, 117.1, 115.2, 110.3, 110.1, 86.1, 73.6, 69.2, 68.3, 51.7, 30.4, 29.8, 29.7, 29.7, 29.5, 29.4, 29.3, 24.2 (m, IR (KBr): 6 = 3451 (bm), 3042 (w), 2918 (m), 2850 (m), 2227 (m), 1722 (m), 1653 (m), 1573 (m), 1540 (m), 1436 (m), 1424 (m), 1391 (m), 1341 (m), 1291 (m), 1291 (m), 1191 (m), 1114 (m), 1055 (m), 1032 (m), 999 (m), 852 (m), 816 (m), 719 (w), 661 (w), 562 (m), 531 (m) (MS (MALDI, pos.); m/z: ccalc. for C81H79N2O2Si + H+: 1264.7464; found 1264.7583; elemental analysis calcld. (%) for C81H79N2O2Si: C 78.82 H 8.05 N 3.32; found C 78.58 H 8.21 N 3.11.

Deprotection for Dendritic Ligand 16: Palladium on charcoal (10 % Pd/C, 120 mg) was a solution of benzyl ester 15a (150 mg, 880 μmol) in THF (70 mL). The flask was charged with H2 (10 % in argon) and the reaction mixture was vigorously stirred at ambient conditions. After 12 h, Pd/C was filtered off and the solvent was removed by rotary evaporation. After removing the solvent under high vacuum, 142 mg (99 %) of dendritic ligand 16 were obtained as colorless solid. M.p. 98–101 °C; 1H NMR (250 MHz, CDCl3); δ = 7.75–7.40 (m, 12H, Ar-H), 7.21 (d, δJH,H = 7.9 Hz, 6H, Ar-H), 6.93 (dd, δJH,H = 8.8 Hz, 2.1 Hz, Ar-H), 6.36 (s, 2H, Ar-H), 4.03–3.87 (m, 12H, O-CO2H), 2.70–2.56 (m, 6H, Ar-CH2), 2.57–2.41 (m, 4H, 2.34 (t, δJH,H = 7.5 Hz, 2H, 1.77 (h, δJH,H = 6.1, 5.7 Hz, 12H, CH2OH), 1.61 (q, δJH,H = 7.5 Hz, 10H, (CH2)4, 1.54–1.12 (m, 9H, (CH2)3, 0.92–0.83 (m, 9H, (CH2)3, 13C NMR (63 MHz, CDCl3); δ = 189.9, 166.3, 161.3, 158.6, 157.0, 141.5, 138.9, 128.9, 128.6, 116.4, 88.4, 62.7, 32.1, 31.7, 29.8, 29.7, 29.6, 29.4, 26.2, 22.8, 14.3 (IR (KBr): ν = 3436 (bm), 3030 (w), 2919 (s), 2851 (s), 1708 (m), 1608 (m), 1583 (m), 1502 (m), 1466 (m), 1436 (m), 1384 (m), 1255 (m), 1214 (m), 1180 (m), 1121 (m), 1043 (m), 812 (m), 722 (m), 593 (m), 500 (m). MS (MALDI, neg.); m/z: ccalc. for C110H164O8 CH2Cl2: –H+; 1713.2722; found 1613.234; elemental analysis calcld. (%) for C110H164O8: C 77.18 H 7.54 N 3.18; found C 76.91 H 7.82 N 3.13.

Synthesis of Dendritic Ligand 23: Silane 15e (385 mg, 0.30 mmol) and K2CO3 (150 mg, 1.09 mmol) were added to dry MeOH/THF = 1:1 (20 mL) and the reaction mixture was stirred at room temperature. After 3.5 h, n-hexane (50 mL) was added and the precipitate was collected. The combined organic phase was washed with MeOH (50 mL). After column chromatography (DCM, stab. with amylene) and removing the solvent under high vacuum, 349 mg (96 %) of dendritic ligand 23 were obtained as a colorless solid. Rf = 0.29 (DCM, stab. with amylene); m.p. 62 °C; 1H NMR (250 MHz, CDCl3); δ = 7.80–7.58 (m, 12H, Ar-H), 7.51 (dd, δJH,H = 8.8 Hz, J = 2.0 Hz, 6H, 6.98 (dd, δJH,H = 8.8 Hz, 2.4 Hz, 6H, Ar-H), 6.69 (s, 2H, Ar-H), 4.09–3.81 (m, 12H, OCH2CH2), 3.00 (s, 1H, C-H), 1.92–1.64 (m, 12H, (CH2)3), 1.55–1.14 (m, 42H, (CH2)3), 13C NMR (63 MHz, CDCl3); δ =
Keywords: Cross-coupling · Dendrons · (Pro)mesogenic units · Liquid crystals · Organic-inorganic hybrid material

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