Coplanarity by hydrogen bonding in well-defined oligoheterocycles

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COPLANARITY BY HYDROGEN BONDING IN WELL-DEFINED OLIGOHETEROCYCLES

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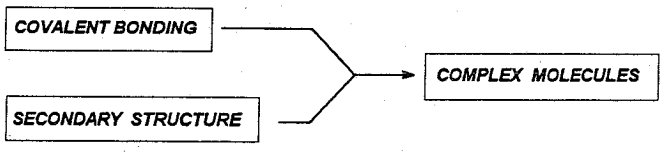
ABSTRACT

(Hetero)aryl-aryl coupling for covalent bonding and intramolecular hydrogen bond formation for establishing the secondary structure have been united to design and construct well-defined, functionalized macromolecules. The suitability of azaheterocyclic units to realize this concept is exemplified by star shaped discotic liquid crystalline compound **1** and ladder-type conjugated copolymers **2** and **3**.

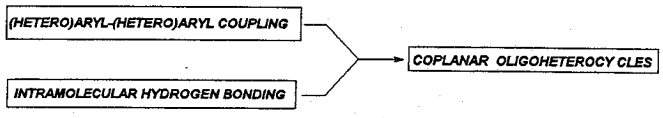
INTRODUCTION

A major challenge in modern organic chemistry is the development of well-defined, functionalized complex structures. Taking advantage of nature as a fruitful source of inspiration, not only nature-like compounds, but also artificial macromolecules are pursued as material. Together with miniaturization in technology, the synthesis of well-defined materials may contribute to overcome the gap between the microscopic and macroscopic world.[1] An appropriate combination of covalent bonding and secondary interactions is a prerequisite to successfully approach complex structures.

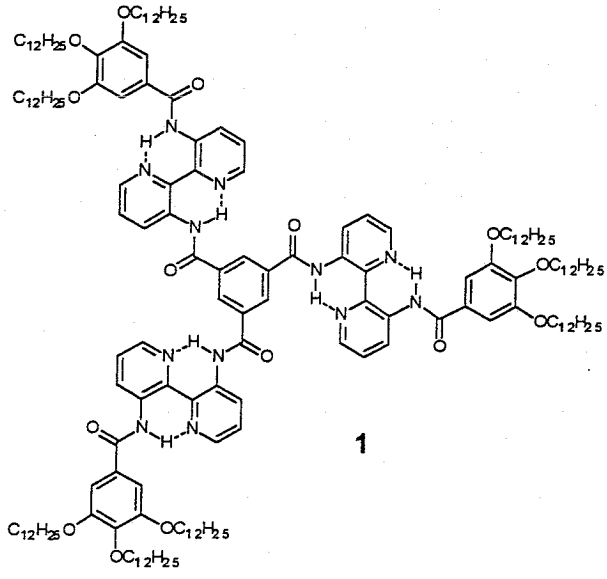


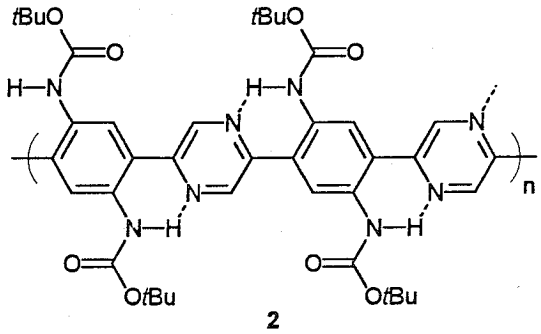
Covalent bonding is in general irreversible and determines the composition of the molecule. Properties, however, depend on the geometric organization of molecules and hence on the so-called secondary structure. The nature of interactions governing the spatial arrangement is often reversible and modifyable, and in particular examples controlled by cooperativity. Among these secondary interactions hydrogen bonding, metal-ligand formation, hydrophobic interactions and π-stacking are frequently intervening. These interactions are crucial instruments in the development of intermolecular, supramolecular chemistry.[2]

In this paper a survey is given of the first achievements in our laboratory in making oligoheterocycles provided with function and architecture by a combination of covalent linkage and *intra*molecular hydrogen bonding. The strategy to obtain the oligomeric backbones relies on symmetrical and asymmetrical (hetero)aryl-aryl coupling methodologies e.g. the ancient Ullmann[3a-b] reaction and the modern Stille[4] reaction, respectively. The strategy to use intramolecular hydrogen bonding is based on the observation that N-H :N interactions in six-membered conjugated cyclic arrangements may strongly govern the secondary structure not only in the crystalline but also in the liquid-crystalline phase and in solution.



In the first section, a screening of Ullmann and Stille reactions for some particular couplings of heterocycles is described, as an exploration to enter the field of oligoheterocyclic chemistry more experienced and intended to distill some fruitful guidelines therefrom. In the second section, the 2,2'-bipyridine-3,3'-diamine moiety is presented as a new building block for the construction of ordered structures by intramolecular hydrogen bonding.[5]





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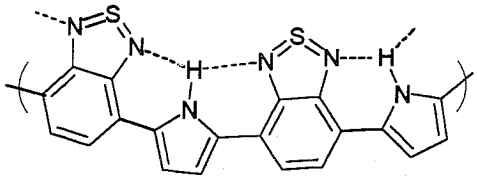


3

In the last three sections, which integrate linkage and order, we report i.a. on the synthesis and properties of star shaped discotic molecule **1** incorporating N-acylated 2,2'-bipyridine-3,3'-diamine moieties,[6] on ladder type alternating copolymer **2** of pyrazine and N-acylated 1,4-phenylenediamine[7] and, finally, on copolymer **3** composed of alternating pyrrole and 2,1,3-benzothiadiazole units.[8]

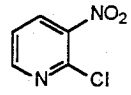
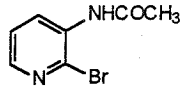
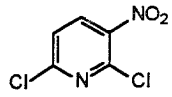
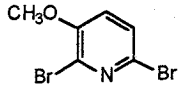
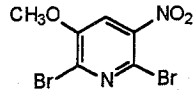
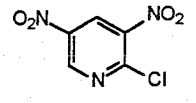
RESULTS AND DISCUSSION

1. Coupling methodologies for linking heterocyclic units

Selective linkage of (hetero)aromatic units requires in most cases the presence of transition metals. Oxidative homo-coupling procedures consume stoichiometric quantities of Cu^{II}, Pd^{II} or Fe^{III}; reductive ones of Cu^0 or Ni^0. The central role in such transformations of copper, especially in the Ullmann coupling, is, therefore, not surprising. Although in the past a lot of debate existed regarding the radical or ionic mechanism, it now seems generally accepted that ligand exchange in aryl-copper intermediates determines the course of the Ullmann reaction.[9] We investigated the scope and limitations of this reaction for specifically substituted 2-halopyridines. As can be deduced from Table 1, the observed reactivities and selectivities do not always corroborate the expectations. The results confirm the necessity of electron-withdrawing and chelating groups to be present. They also confirm the stronger and beneficial influence of *ortho*-substituents (entries 1, 2, 3, and 5). Entry 1 gives access to 3,3'-dinitro-2,2'-bipyridine, the key precursor for intramolecularly hydrogen bonded compounds described in sections 2 and 3. It is shown that by adaptation of the stoichiometry or temperature, selective dimerization of dihalides (entries 3 and 5) is feasible.[10] The success in entry 5 is important for several reasons. The dimer is a potential precursor for a lipophilic homologue of 2,2'-bipyridine-3,3'-diamine by demethylation followed by alkylation with a long alkyl halide and NO_2 reduction. Furthermore, it could eventually be transformed into a ladder type homopolymer composed of 2,6-linked pyridine units.

Table 1

Ullmann dimerization of selected 2-halopyridines

entry	substrate	method	yield	2,2'-bipyridine
1		A	85%	3,3'-dinitro-[5]
2		A	34%	N,N'-diacetyl-3,3-diamine
3		B	54%	6,6'-dichloro-3,3'-dinitro-
4		B	0%	
5		C	75%	6,6'-dibromo-5,5'-dimethoxy-3,3'-dinitro-
		A	0%	[polymer]
6		A	<10%	3,3',5,5'-tetranitro-
		D	0 %	[2(3,5-dinitro-pyridyl)copper]

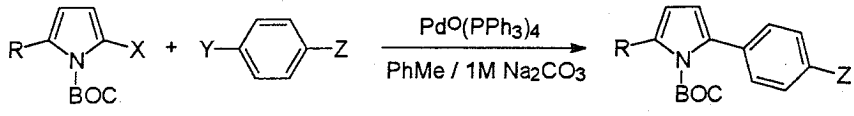
A: DMF, 100°C, excess Cu; B: DMF, 100°C, 1.25 eq Cu; C: DMF, 80°C, 1 eq Cu; D: DMF, 80°C, 0.5 eq Cu

To our surprise, we have not been able to obtain the bipyridine from the very electron-deficient 2-chloro-3,5-dinitropyridine (entry 6) in preparatively useful amounts. Copper tends to react rapidly with the substrate, but the tentative intermediate pyridylcopper[11] is in mild conditions stable towards electrophiles and under drastic conditions presumably even undergoing nucleophilic substitution. This is an example of an intrinsically very reactive substrate which nevertheless turns out to be unfavourable in a multi-step process due to alteration of rate-determining step.

Apart from the development of symmetrical methods to couple heterocycles, in the last decennia a huge amount

Table 2

Competitive Stille reactions with pyrrole substrates



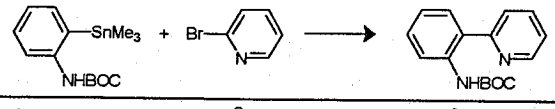
entry	R	X	Y	Z	reactivity
1	H	$SnMe_3$	I, Br, Cl	H	I > Br >>> Cl
2	Ph	$SnMe_3$	Br	NO_2, H, OMe	NO_2 > H > OMe
3	Ph	Br	$SnMe_3$	NO_2, H, OMe	NO_2 = H = OMe

of effort has been expended to develop reliable methods for the selective cross-coupling between (hetero)aromatic compounds. Most of the applied reactions are of a redox type and are usually catalyzed by Pd^0 or Ni^0. Worth-mentioning are the Ni^0-mediated Kumada coupling of aryl-Grignards, the Ni^0- or Pd^0-catalyzed Negishi coupling of arylzinc derivatives, the Pd^0-mediated Suzuki coupling of aryl boronates and Stille coupling of aryl stannanes. Aryl halides, -sulfonates, and -diazonium salts play the role of electrophilic partner. We have investigated the synthetic potential and some mechanistic implications of the Stille coupling to link specifically substituted pyrrole, pyrazine, pyridine, benzene, and 2,1,3-benzothiadiazole nuclei. Due to the extreme variation in experimental conditions, in oxidation state and ligands of the catalyst, and in supplements such as Cu^II or LiCl, it is almost impossible to predict optimal conditions for a given combination of reactants. The competitive occurrence of methyl shift, destannylation, dehalogenation, and reductive and oxidative homo-coupling complicates the situation even more. As far as the mechanism of the Stille coupling is concerned, usually a catalytic cycle is adopted in which four consecutive steps are recognized.[12] The reaction starts with oxidative addition of the electrophilic partner (halide,..) onto di-ligated palladium(0). Then rate determining transmetalation of the stannane into four-coordinated *trans* diarylpalladium occurs, followed by isomerization to the corresponding *cis* isomer. Finally, the diaryl compound is eliminated and the reactive di-ligated palladium(0) liberated, which restarts the catalytic cycle. We have investigated particular Stille reactions on pyrrole or pyridine substrates. In a series of competitive experiments with N-*t*-butoxycarbonyl-pyrrole derivatives (Table 2[13]), results appeared which are not completely in line with the generally accepted kinetics. Reaction of one equivalent of the N-BOC-2-trimethylstannylpyrrole (entry 1) with one equivalent of each chloro-, bromo- and iodobenzene gave the expected predominance of iodo coupling, although the ratio of 100% : 65% : 35% for remaining PhCl, PhBr, and PhI, respectively, points to a rate factor between iodide and bromide of less than 2. From a competitive experiment between N-BOC-5-phenyl-2-trimethylstannyl-pyrrole and bromobenzene, its *para*-methoxy and *para*-nitro analogues (entry 2), the accelerating effect of electron-withdrawing substituents on the halide becomes apparent: a ratio of 15 : 1 : 0 has been measured for Z = NO_2, H, and OCH_3, respectively. Interchange in the former case of the trimethylstannyl and bromo substituents (entry 3) obviously leads to the same coupling products; however, the observed ratio in this case was, 1 : 1 : 1! These results may suggest that -in the case of electron-rich pyrrole substrates- the transmetalation is not necessarily the rate-determining step:[12] a stannylated pyrrole derivative may be considered as very reactive in transmetalation, whereas a brominated pyrrole is rather unreactive in the oxidative addition onto Pd^0L_2. It is even not excluded that at a certain point the favoured first interaction becomes that between Pd^{II} and the stannyl compound. In this respect it is intriguing that the α-trimethylstannyl derivatives of N-BOC-pyrrole and of 2,2'-bithienyl in the presence of Pd^0 are prone to homo-coupling.[14a-c] In the same two-phase conditions and with the same Pd^0 catalyst as described in Table 2, N-BOC-2-trimethylstannyl-pyrrole has been linked to the electron-demanding heterocycle 4-bromo-2,1,3-benzothiadiazole in 78% yield (see section 5). Besides, Stille coupling involving electron-demanding heterocycles has been practiced extensively. We have studied in detail and optimized the reaction between 2-bromopyridine and N-BOC-2-trimethylstannyl-aniline with the aid of GC-monitoring. As shown in Table 3, the highest yield (94%) was obtained with 2 mol% $Pd^{II}(PPh_3)_2Cl_2$ in THF at reflux temperature in the presence of 5 mol% of CuBr (entry 2). In the absence of copper(I) no reaction occurred at all in these conditions. Changing the ligand to tetrakis(trifurylphosphine)-palladium(0) (entry 4) could not improve the yield. Interestingly, in this case the addition of CuBr remained without significant effect. This suggests that the role of Cu^I is either to scavenge triphenylphosphine or to reduce Pd^{II} to Pd^0, which may then enter the catalytic cycle.[15a-c]

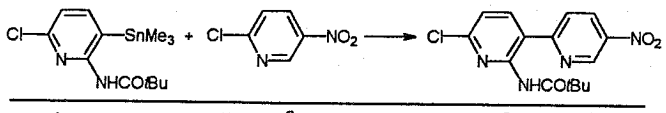
Applying the optimal conditions from entry 2, Stille reaction between the very electron-deficient 2-chloro-3,5-dinitropyridine, which fails to undergo Ullmann dimerization (Table 1), and N-BOC-2-trimethylstannyl-aniline yields 50% of the desired coupling product. To determine the reactivity of electron-demanding aryl-stannanes, a screening has been undertaken of the reaction between 2-chloro-5-nitropyridine and N-pivaloyl-2-amino-6-chloro-3-trimethylstannyl-pyridine (entries 5-8). In line with observations of Farina *et al.*[14a] concerning the coupling of phenyl derivatives, the outcome of the reactions is strongly dependent from the presence of oxygen (entry 5) and the nature of ligands and additives. Even without addition of CuBr, reaction occurs with the same catalyst as preferred in the 2-bromopyridine case, although only to a moderate extent and with the need of substantially more catalyst (entry 6).

Table 3

Screening of Stille reactions involving electron-deficient heterocycles



entry	conditions[a]			catalyst[c]	yield
	CuBr[b]	h	solv		%
1	0	22	THF	$Pd^{II}(PPh_3)_2Cl_2$	0
2	5	4.5	THF	$Pd^{II}(PPh_3)_2Cl_2$	94
3	0	4.5	THF	$Pd^{0}TFP^{d}$	57
4	5	22	THF	$Pd^{0}TFP^{d}$	76



entry	conditions[a]			catalyst[e]	yield
	CuBr[b]	h	solv		%
5	10	24	THF	$Pd^{II}(PPh_3)_2Cl_2$[f]	0
6	0	24	THF	$Pd^{II}(PPh_3)_2Cl_2$[g]	40
7	10	24	NMP	$Pd^{II}(PPh_3)_2Cl_2$	85
8	10	24	THF	$Pd^{0}TFP^{d}$	87

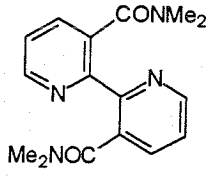
[a]Five repeated freeze thaw cycles to exclude oxygen; [b]in mol %; [c] 2.5 mol%; [d]TFP = trifurylphosphine; [e]5 mol%; [f]without freeze thaw cycles to exclude oxygen; [g]10 mol% catalyst

The use of NMP as solvent (entry 7) or of a Pd^0 catalyst with trifurylphosphine ligands in THF (entry 8), both in the presence of 10 mol% CuBr, equally improve the yield. From an electronic point of view the results suggest the trimethylstannyl group in six-membered azaheterocycles to be preferentially positioned at C-3 and in conjugation with an electron donor. The halide is in general a bromide since the iodides are often less available and the chlorides are only sufficiently reactive when positioned at C-2 and activated by conjugated electron-withdrawing substituents.

In conclusion, preparatively useful Ullmann coupling is restricted to activated halides, which means conjugated with electron-withdrawing groups or containing a labile C-X bond. The possibility to create an intermediate chelate is beneficial and the reaction is not susceptible to steric hindrance. The window for desired reactivity of substrates is not endless on the electrophilic side. As far as the Stille coupling is concerned, electrophilic halides (or sulfonates or diazonium salts) and nucleophilic stannanes seem to be favoured reaction partners. Homo-coupling of stannanes, however, becomes extremely important in very nucleophilic substrates. Finally, in contrast to the Ullmann coupling, steric hindrance, especially on the halide, may strongly retard the desired reaction.

2. Intramolecular hydrogen bonding in N-acylated 2,2'-bipyridine-3,3'-diamines[5]

To improve and govern the conjugative properties of oligoheterocycles, we aimed at the development of building blocks or motifs which can be easily incorporated in larger structures, and are capable of imposing the geometry by conformational locking. This search started with a contradictory observation: whereas 2,2'-bipyridine-3,3'-dicarbonamide **4** is readily mono-methylated with methyl iodide in boiling acetonitrile, the corresponding bis(acetylamino) derivative **5** is completely reluctant to N-methylation under those conditions. Of course this can not be rationalized by simple electronic considerations.



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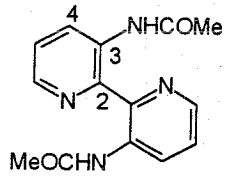
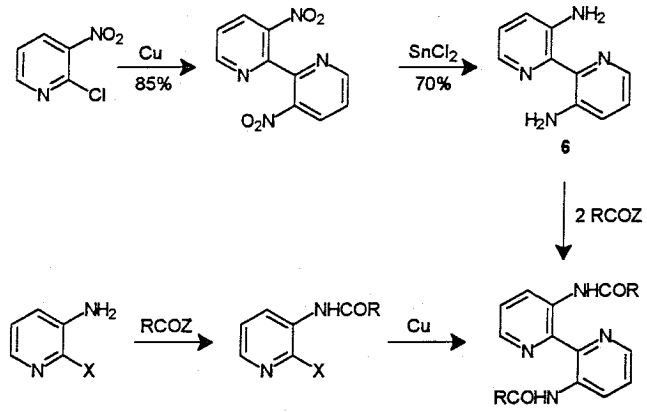


5

The ^1H NMR-spectral data of compound **5** in $CDCl_3$ revealed exceptional downfield absorptions for the NH and H-4 signals at 13.2 and 9.1 ppm, respectively. This pointed to intramolecular hydrogen bonding in solution and prompted us to investigate N-acylated 2,2'-bipyridine-3,3'-diamines,[5] the properties of which are dealt with after a description of their synthesis. As indicated in Scheme 1, molecules like **5** may in principle be accessible via a convergent or a divergent pathway. The success of the reductive dimerization of 2-chloro-3-nitropyridine (85% yield) and -in contrast- the low yield of the corresponding coupling of even a simple acetylamino

Scheme 1



Synthetic approach to N,N'-diacylated 2,2'-bipyridine-3,3-diamines

precursor strongly favoured the divergent approach. This has made 2,2'-bipyridine-3,3'-diamine, **6**,[16] our key precursor for all N-acylated compounds discussed below. In Table 4 relevant ^{1}H NMR data are collected regarding **6** and some of its typical derivatives. The dramatic deshielding of 6 - 9 ppm for the N-H proton signal and ±2 ppm for the H-4 proton signal, respectively, upon acylation of **6,** may only be rationalized by adopting a controlled conformation in solution. In contrast to the well-known and frequently applied *cisoid* conformation of 2,2'-bipyridine in complexes with metal ions from Pd, Ru or Cu, the N-acylated 2,2'-bipyridine-3,3'-diamines are locked in a *transoid*, planar arrangement due to extremely efficient intramolecular hydrogen bonding as shown in Fig. 1.

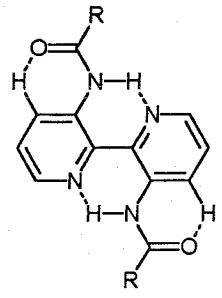
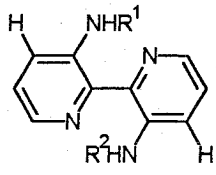


Fig. 1
Intramolecular hydrogen bonding in N,N-diacylated-2,2'-bipyridines

Apart from an N-H :N hydrogen bond, also a C-H :O secondary interaction may be envisaged. The combination of N-H :N bond, preferential *transoid* secondary amide conformation, and partial double bond character of the amidic bond coplanarize the amide carbonyl and C-4-H groups. This is translated in an additional strong deshielding of H-4. The conformational preference of the carbonyl group is further supported by a significant downfield ASIS (anisotropic solvent induced shift) of H-4 in dibenzoyl compound **8** in toluene-d_8 ($\Delta\delta$ 0.28 ppm). The parent diamino compound **6** does not show intramolecular hydrogen bonding in solution as indicated by the broad singlet in common for both NH_2 protons. When a solution of diamine **6** in acetone-d_6 is cooled to -60°C, however, the NH_2 signal splits into two NH signals located at about 6 and 9 ppm, respectively. The downfield one is assigned to the NH involved in intramolecular hydrogen bonding.

Single crystal structures of compound **6**, N-benzoyl derivative **11** and the corresponding N,N'-dicinnamoyl analogue, all show *transoid*, hydrogen bonded arrangements with pyridine rings not deviating more than 7° from coplanarity.[17] Finally, IR-data of solid **6** in KBr reveal two different NH stretching vibrations at 3346 and 2928 cm^{-1}, the latter of which is assigned to the NH involved in intramolecular hydrogen bonding. In the diacylated compounds **5** and **7-10** the corresponding signals appear between 3000 and 2750 cm^{-1}.

Table 4
Relevant ^{1}H NMR data in $CDCl_3$ regarding bipyridinediamine **6** and N-acylated derivatives



entry	R^1	R^2	comp	N-H	H-4	pK_a R^1OH
1	H	H	**6**	6.26[a]	7.01	15.7
2	CO-O*t*Bu	CO-O*t*Bu	**7**	12.16	8.80	~ 7
3	CO-Me	CO-Me	**5**	13.15	9.10	4.75
4	CO-Ph	CO-Ph	**8**	14.59	9.42	4.19
5	CO-CO_2Me	CO-CO_2Me	**9**	15.18	9.24	1.23
6	CO-CF_3	CO-CF_3	**10**	15.55	9.23	0.23
7	CO-Ph	H	**11**	14.74	9.30	
				6.62[a]	7.11	
8	CO-O*t*Bu	H	**12**	12.43	8.80	
				6.35[a]	7.11	

[a] This refers to an average value for two NH protons, one of which only can be involved in intramolecular hydrogen bonding,

The strength of the hydrogen bonding in N-acylated 2,2'-bipyridine-3,3'-diamines is further substantiated by their chemical and physical behaviour. Treatment of these compounds with polar solvents, acetic acid and 4-

dimethylaminopyridine leaves the hydrogen bonds unaffected. The addition of trifluoroacetic acid (pK_a 0.23), however, lifts the coplanarity by protonation of the pyridine nitrogen. This is immediately translated in the disappearance of any NH signal above 10 ppm and a substantial shielding of H-4. Temperature dependent NMR in toluene-d_8 and even in DMSO-d_6 shows only a minor shielding when raising the temperature ($\Delta\delta$ < 0.006 ppm/K) and no collapse of the hydrogen bond up to 110°C! Concentration dependent measurements in the range 0.15 - 0.015 M do not show any significant alteration of the NH position ($\Delta\delta$ < 0.01 ppm). A quantitative estimate of the hydrogen bond strength can not be calculated from the NMR measurements and in general is difficult to obtain for intramolecular bonds. A final and strong argument supporting the proposed strength of the intramolecular hydrogen bonds considered is the lack of cooperativity. Indeed, comparison of di-BOC and dibenzoyl derivatives **7** and **8** with their corresponding monoacylated homologues **12** and **11,** respectively, (Table 4, entries 2, 4, 8, and 7), learns that the NH signal even undergoes a slightly upfield shift as a result of the second acylation! The rationale behind this observation is that cooperativity is only operative and significant when one interaction is weak in terms of energy. The slightly upfield shift of the NH signal caused by the second acylation may be attributed to concomitant weakening of the hydrogen bond donor capacity of the pyridine nitrogen already involved in hydrogen bonding.

This brings us to the influence of substituents on the strength of the hydrogen bonds and the corresponding effect on the position of the N-H signals in NMR. The data on selected analogues in Table 4 (entries 1 - 6) undeniably prove the existence of a logic relationship between the pK_a value of the corresponding acid R^1-OH and the observed δ value for NH. The maximal strength of a hydrogen bond is reached when the N-H-N system is degenerate, in other words, when no distinction can be made between hydrogen bond donor and acceptor. As becomes clear from the resonance and tautomeric structures depicted in Fig. 2, the pyridine ring will remain in the examples shown in Table 4 the proton acceptor and the secondary amide the proton donor. Indeed, structures **IA** and **IIB** describe better the two tautomers than their non-aromatic resonance structures **IB** and **IIA**, respectively. Tautomer **IA** is energetically more favoured than **IIB** due to charge separation in the latter. This implies that substituents enhancing the basicity of the pyridine N and substituents enhancing the acidity of the secondary amide NH strengthen hydrogen bonding and, therefore, give rise to higher δ values in ^{1}H NMR. The effect of substitution on the bipyridine moiety is obviously more ambiguous than that on the acyl moiety.

In conclusion, N-acylated 2,2'-bipyridine-3,3'-diamines and analogous compounds incorporating a six-membered, conjugated N-H :N hydrogen bonding motif of high stability in solution, may represent useful building blocks for macro-organic structures and within supramolecular chemistry. In the next sections this motif is applied to the design and development of more complex structures.

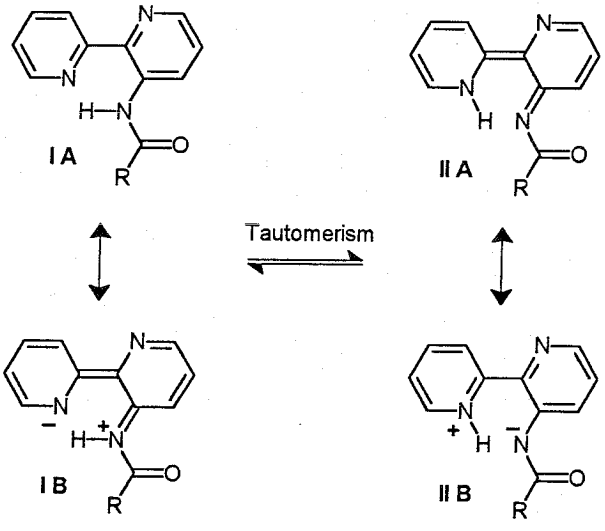


Fig. 2
Tautomeric and resonance structures in N-acylated 2,2'-bipyridine-3,3'-diamines

3. Star shaped discotic liquid crystals based on 2,2'-bipyridine-3,3'-diamine

The first application of the concept of combined covalent and secondary bonding to arrive at complex ordered structures provided with function, concerns a particular star-shaped molecule incorporating three 2,2'-bipyridine-3,3'-diamine units which shows LC behaviour in a very broad temperature range. Emphasizing the development of ordered macrostructures, one has to solve the problem of intractability due to a high degree of symmetry, especially when directed interactions are present. One way to guarantee processability is to take advantage of a fourth aggregation state between the isotropic liquid and crystalline state, called liquid crystalline phase. Apart from the well-established nematic and smectic mesophases of rod like molecules, also discotic mesophases exist, as was discovered in 1977[18a-b] for certain symmetrical hexasubstituted benzenes. Such discotic mesophases are formed when the outer tails loose their order (i.e. melt) while the rigid cores remain stacked due to strong interactions between the discs.[19] Within the discotic mesophases the highest degree of order is attained in ordered columnar mesophases with hexagonal, rectangular or oblique arrays, as shown in Fig. 3. With the exception of a few examples,[20a-d] most discotic molecules exhibit liquid

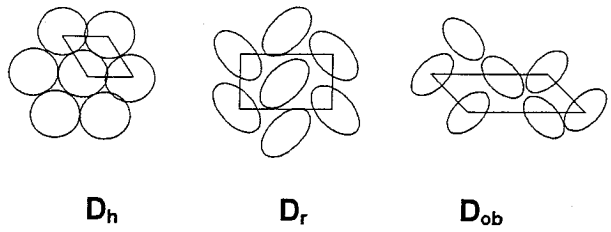
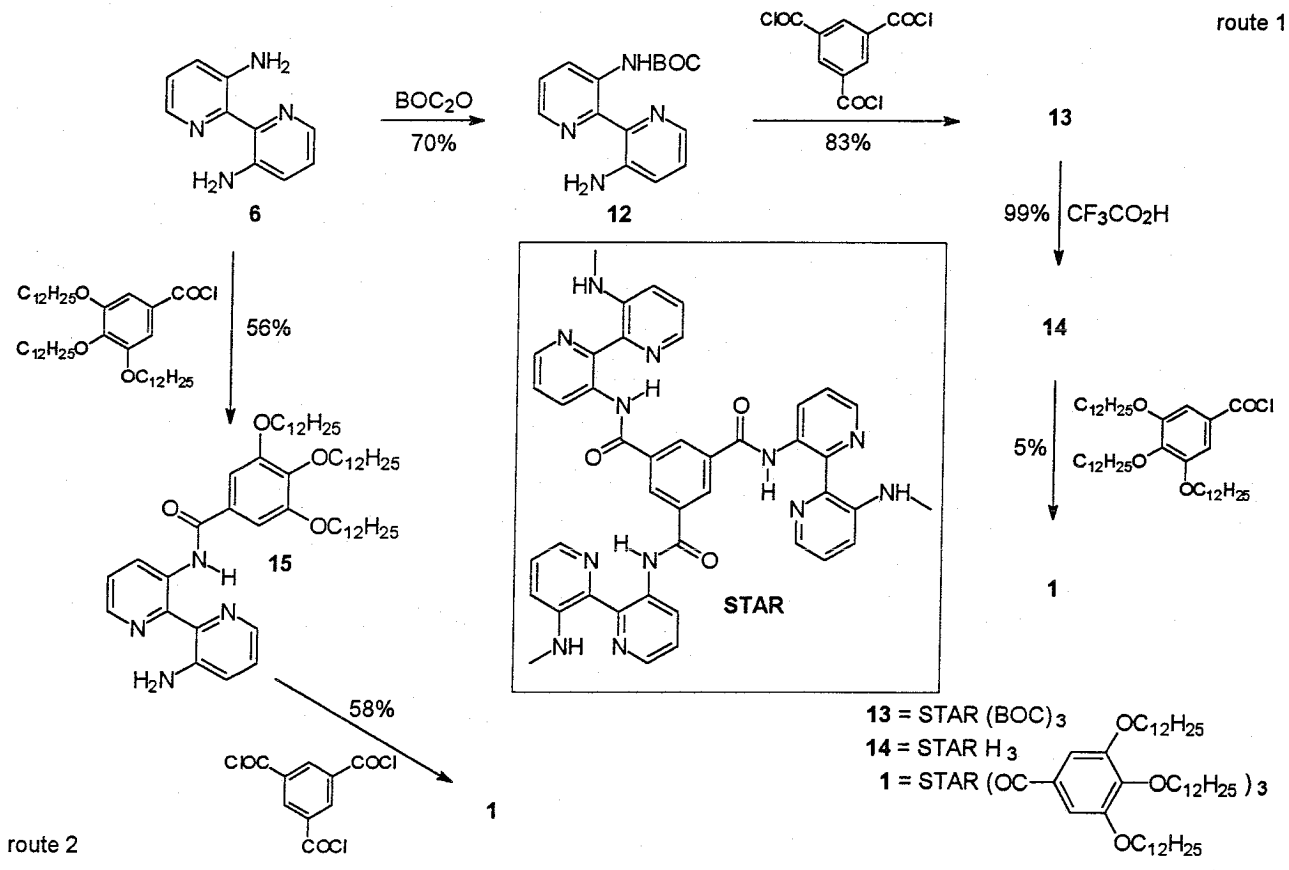


Fig. 3
Two-dimensional ordered columnar mesophases

crystalline behaviour at elevated temperature only and often in a narrow temperature range. To enhance applicability, liquid crystallinity at or close to room temperature in a broad temperature range is desirable. The design of such compounds has in our opinion to rely on a large central core characterized by a high degree of planarity and capable of perpendicular interactions and on sufficient and adequately sized tails to ensure processability and phase separation. Although a wide variety of central cores is actually known to induce discotic LC behaviour, the use of intramolecular hydrogen bonding to induce planarity in the central core is -to our knowledge- unprecedented. Starting from bipyridinediamine **6**, the synthesis of star shaped molecule **1** was pursued by a divergent (route 1) and a convergent (route 2) approach as depicted in Scheme 2. The initial preference for route 1 was based on the -fortunately wrong- expectation that monoacylation of 2,2'-bipyridine-3,3'-diamine would occur nearly statistically, thus forcing us to subject the reaction mixture to column chromatographical purification of either compound **12** or **15**. This would obviously be easier in the BOC than in the 3,4,5-tris(dodecyloxybenzoyl) case. It turns out, however, that monoacylation with BOC_2O in boiling THF occurs selectively and affords the mono- and di-BOC compounds in a 6 : 1 ratio when applying a slight excess of reactant (1.1 eq). Subsequent treatment of mono-BOC derivative **12** with trimesoyl chloride furnishes protected core **13** of the designed discotic material. Deprotection of **13** with trifluoroacetic acid in dichloromethane is straightforward and additional neutralization gives triamine **14** as a sparingly soluble solid. Reaction thereof with 3,4,5-tris(dodecyloxy)benzoyl chloride[19] in THF at reflux temperature affords target compound **1** in a disappointingly low yield of 5% after purification. Fortunately, we could circumvent this preparative

Scheme 2



Divergent and convergent routes to discotic compound **1**

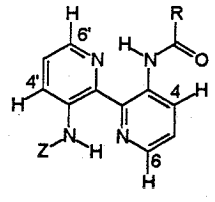
problem by the convergent approach (route 2). Unexpectedly, also acylation with 3,4,5-tris(dodecyloxy)-benzoyl chloride in diethyl ether between 0 and 20°C occurs selectively (equally 6 : 1 ratio mono- vs di-acylation). Thus, intermediate **15** has been obtained in 56% yield after chromatographic purification. Threefold amidation of **15** with trimesoyl chloride ultimately gives the target compound **1** in 58% isolated yield, which means that the overall yield with respect to bipyridinediamine **6** amounts to 32%. Compound **1** precipitates as a white solid from an ice-cold solution in chloroform by addition of acetone. At room temperature it behaves as a waxy, slightly yellow and strongly birefringent substance. According to GPC, a purity of > 99.6% with respect to higher and lower molecular weight material has been determined.

The equal selectivity in both mono-*t*-butoxycarbonylation and mono-tris(dodecyloxy)benzoylation has undoubtedly to do with the pronounced effect of acylation of one NH_2 group on the nucleophilicity of the remaining, remote NH_2 group. Since already one N-acylation prompts the molecule to adopt a planar conformation by strong intramolecular hydrogen bonding, the second acylation may evidently be retarded significantly. It is certainly worthwhile to further investigate the topic of selectivity in symmetric bi- or polyfunctional compounds as a function of the developing secondary structure.

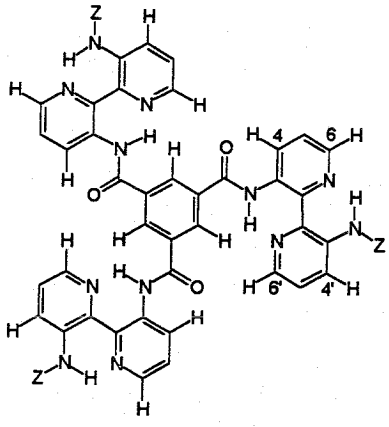
The characterization of **1** and its intermediates is primarily relying on ^{1}H NMR analysis, the relevant data of which are collected in Table 5. The data are in line with those presented in Table 4 (section 2). Once again, the more electron-withdrawing acyl moiety induces the more pronounced deshielding of the intramolecularly bonded NH proton. The ^{1}H NMR data of star shaped tris (bipyridine) compounds **13** and **1** strongly resemble those of their mono-(bipyridine) analogues **12** and **15**. In the star shaped compounds special attention deserve -besides the NH protons- the identical protons of the trimesoyl centre, the H-4 protons belonging to the inner pyridine rings, and the H-6' protons belonging to the outer pyridine rings. The inner N-H protons in target molecule **1** (15.5 ppm) are located at lower field than expected solely on the basis of the data collected in Table 4. The H-4 signal at 9.56 ppm is the most deshielded one we have ever encountered for this type of pyridine proton. The peak position of the central trimesoyl protons at 9.16 is also exceptional when compared to the more electron-deficient trimesoyl trichloride (δ 9.0) and trimethyl ester (δ 8.6), and to N,N',N"-triphenyl-benzene-1,3,5-tricarbonamide (δ 8.7).[6] Of course, the location of this signal in the spectrum not only depends on the electron-withdrawing character of the substituents but also on the degree of coplanarity of the benzene ring and the carbonyl moieties, and eventually on conformational interlocking of the acyl substituents. Most significantly, protons H-6', the α-protons of the outer pyridine rings, feature signals at 9.03 ppm, 0.65 ppm downfield with respect to the H-6 protons of the inner pyridine rings and 0.62 ppm downfield with respect to the comparable protons in dibenzoyl derivative **8**! All these data convincingly demonstrate that in solution the central part of molecule **1** is to a high degree planar and prefers an arrangement in which the amide conformations are all *anti* with respect to their mutual carbonyl orientation (C_3 symmetry). The preference for an all *anti* conformation would also be in agreement with forcefield calculations with CHARMm indicating that in *m*-phthaloylamides the *anti* conformer is 20 kJ/mol more stable than the two *syn* conformers.[21] Another planar conformation is excluded for steric reasons; any considerably out-of-plane conformation does not account for the exceptionally downfield positions of the inner NH and the H-6' protons. The tentatively assigned conformation as shown in structure **1** may fully account for all observations since the incremental deshielding associated with the star shape of the molecule may relate to the interaction of NH

Table 5

^{1}H NMR comparison of star shaped with linear N-acylated 2,2'-bipyridinediamines[a]



15 R = 3,4,5-tris(dodecyloxy) phenyl, Z = H
12 R = O-*t*-Bu, Z = H
8 R = Ph, Z = CO Ph



1 Z = 3,4,5-tris(dodecyloxy)benzoyl
13 Z = BOC
14 Z = H

entry	comp	NH in	NH' out	H-4 in	H-4' out	H_{trim} cent	H-6 out	H-6' in
1	**1**	15.49	14.36	9.56	9.38	9.16	8.38	9.03
2	**13**	15.33	12.77	9.44	8.90	9.10	8.38	8.90
3	**14**[b]	15.79	7.77	9.46	7.47	9.23	8.50	8.60
4	**15**	14.28	6.56	9.25	7.12	--	8.33	8.00
5	**12**	12.43	6.35	8.76	7.11	--	8.24	8.02
6	**8**	14.59	--	9.42	--	--	8.41	--

[a] Measured in $CDCl_3$; [b] measured in DMF-d_7

and H-6' with the adjacent carbonyl group of the trimesoyl centre. This means that a triangular core with a side of approximately 20 Å constitutes the central rigid part of star shaped molecule **1**, whereas the nine dodecyloxy tails are to be considered as the flexible part with an approximate length of 16 Å in the extended zigzag conformation, as is visualized in a CPK model in Fig. 4. The presence of order in solution has been further substantiated by the ^{1}H NMR behaviour in toluene-d_8. At room temperature coalescence of the signals corresponding to the core protons is observed, which disappears upon heating to 80°C under concomitant downfield shifting. Finally, a strong tendency to gelation in hexane suggests a specific interaction of the tails with this kind of solvent.

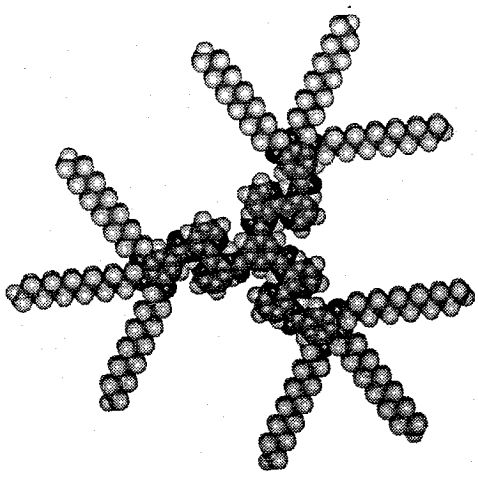


Fig. 4
CPK model of star shaped compound **1**

Subsequently, the expected LC behaviour of compound **1** has been investigated by polarization microscopy, DSC (differential scanning calorimetry), refractive index measurements, and X-ray analysis. Polarization microscopy indicates that **1** is already discotic liquid crystalline at room temperature, whereas the clearance temperature is reached at no less than 373°C. The isotropic phase reversibly returns into the LC phase on cooling. DSC measurements show transition temperatures of 9 and 355°C for the melting and clearance points, respectively. In a cooling run a small metastable region is observed since crystallization then occurs at -3°C. Enthalpic changes of 56 and 27±2 kJ/mol associated with the melting and clearing temperatures, respectively, have been calculated. Birefringence measurements on an oriented film of **1** at 20°C allow the accurate determination of two refractive indices η of 1.598 and 1.463, perpendicular and parallel to the rubbing direction, reflecting the strong anisotropy of ordered ensembles of molecules. This phenomenon corroborates the observation of birefringent textures in the polarization microscope. X-Ray diffraction measurements are consistent with a discotic, ordered mesophase in which a columnar packing is present. Inter column spacings of 40 Å and interdisc spacings of 3.4 Å could be deduced from the diffraction pattern as shown in Fig. 5. Although the exact packing could not be ascertained unambiguously and no homeotropic areas could be observed during microscopy, recent comparison with the corresponding nonakis(octadecyl) representative points to the presence of a discotic hexagonal ordered mesophase.

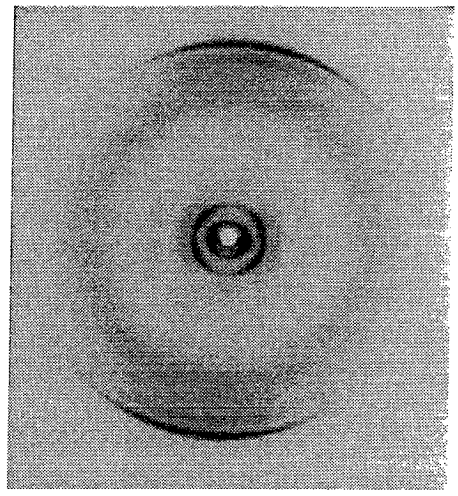


Fig. 5
Diffraction pattern of star shaped discotic material **1**

In conclusion, we have been able to design a new class of discotic molecules based on a central core owing its rigidity to strong intramolecular hydrogen bonding in three N-acylated 2,2'-bipyridine-3,3'-diamine fragments and to the conformational preference of the central trimesoyl unit. The length of the trialkoxybenzoyl tails is variable. Star shaped compound **1** exerts liquid crystalline discotic behaviour in a temperature range of 350°C. The liquid crystalline packing belongs to the highest ordered arrays, most probably the hexagonal D_{ho}.

4. Ladder type oligomers and polymers based on 1,4-phenylenediamine

Polyarylenes are promising structures for application in electronic devices.[22] Unsubstituted polyarylenes tend, however, to be insoluble and thus hard to process. Substituted polyarylenes on the other hand may show enhanced processability but usually at the expense of coplanarity and hence degree of conjugation. This dilemma lead to the development of conjugated ladder polymers, π-conjugated structures with an uninterrupted sequence of rings joined by covalent bonds.[23a-b] We anticipated that one of the two covalent bonds in ladder polymers might be replaced by a hydrogen bond. The advantages of such an approach would be the self-

assembly of the ladder structure between coupling neighbouring aromatic units and the reversibility of the hydrogen bonding, allowing manipulation of the secondary structure. Taking into account the intramolecular hydrogen bond motif developed in section 2, we have chosen alternating copolymer **2** as a first target of π-conjugated polymers with a self-assembled ladder structure. Repeated linkage of pyrazine and N,N'-di-BOC-1,4-phenylenediamine units in a 2,5-fashion would afford an alternating copolymer with the desired ladder structure (Fig. 6).

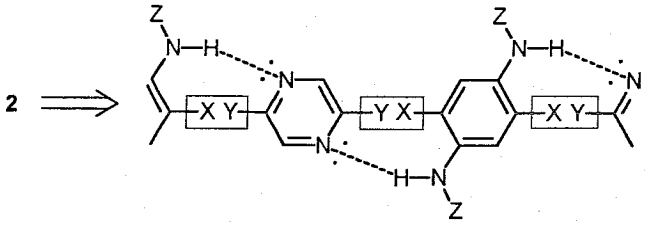
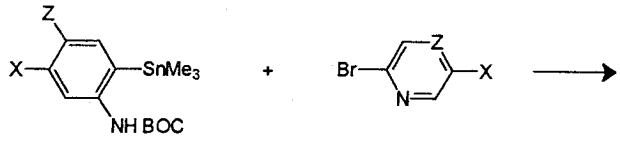


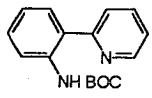
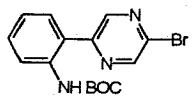
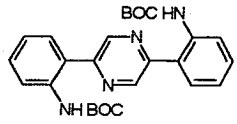
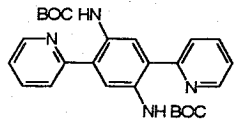
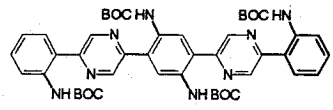
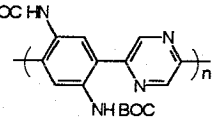
Fig. 6
Conceptual approach to ladder copolymer **2**

The synthetic approach is based on the Stille methodology and, therefore, requires copolymerization of appropriate dihalides and distannanes. This type of copolymerization succeeds for phenyl with thiophene,[24] quinoxaline with thiophene,[25] and phenyl with pyrrole[26] units. Our strategy relies on a step-by-step approach from co-dimer via co-pentamer to copolymer. Initially the *t*-butoxycarbonyl (BOC) group has been selected as acyl group for several reasons. According to the data gathered from the bipyridinediamine work described in sections 2 and 3, this group induces significant but not maximal strengthening of the hydrogen bond donor capacity when compared to the NH_2 group. Likewise, it enhances the processability, is compatible with the introduction of the required halo and trimethylstannyl substituents, and is easily removed either thermally or under the influence of trifluoroacetic acid. The coupling products have all been prepared according to the optimized conditions worked out for the model Stille coupling between N-BOC-2-trimethylstannyl-aniline and 2-bromopyridine (section 1). In Table 6 a survey is depicted of Stille reactions which have given rise to the model oligomers **16** - **20** and to target polymer **2**. Fair yields varying between 60 and 80% have been obtained with only one exception: the selective mono-coupling of N-BOC-2-trimethylstannyl-aniline with 2,5-dibromo-pyrazine. Despite the use of 2 eq of the pyrazine, co-dimer **17** has been isolated in only 17% yield. The main byproduct, co-trimer **18**, has been isolated in 25% yield, which implies that at least two thirds of the stannane has been incorporated in both compounds. The preference for co-trimer formation reflects the higher reactivity in the

Table 6
$Pd(PPh_3)_2Cl_2$ / CuBr catalyzed Stille reactions[a] for the construction of ladder type co-oligomers **16** - **20** and copolymer **2**



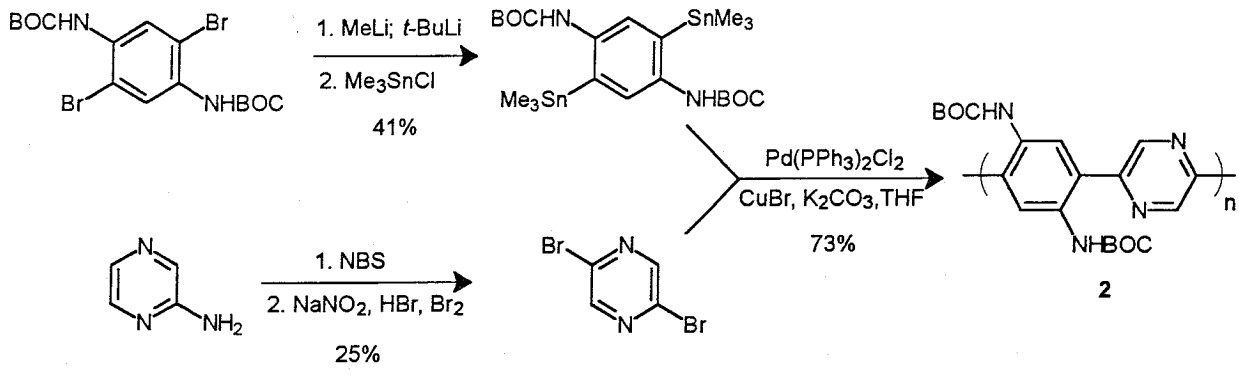
21 X = Z = H
22 X = Me_3Sn, Z = NHBOC
23 X = H, Z = CH
24 X = Br, Z = N
17 X = 2(BOC-NH-Ph), Z = N

entry	stannane	halide	product	yield
1	**21**	**23**	 **16**	84
2	**21** 1 eq	**24** 2 eq	 **17**	17[b]
3	**21** 2 eq	**24** 1 eq	 **18**	63
4	**22** 1 eq	**23** 2 eq	 **19**	60
5	**22** 1 eq	**17** 2 eq	 **20**	72
6[c]	**22**	**24**	 **2**	73

[a] The conditions are: 2.5 - 4 mol% Pd catalyst per function, 5 - 10 mol% CuBr per function, 4.5 - 24 h reflux in THF, freeze thaw cycling to exclude oxygen; [b] accompanied by 25% of co-trimer **18**; [c] 10 mol% catalyst, 2 eq K_2CO_3

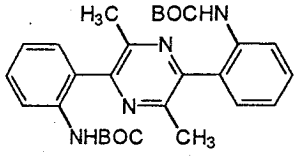
Stille coupling of co-dimer **17** compared to 2,5-dibromo-pyrazine. It is tempting to assume that the 2-*t*-butoxy-carbonylamino-phenyl substituent exerts a stronger activating effect than the bromo substituent due to intramolecular hydrogen bonding with the pyrazine moiety. The 72% yield in the case of co-pentamer **20** (entry 5) compares favourably with the 63% obtained for co-trimer **18**, presumably for the aforementioned reason. The synthetic scheme leading to copolymer **2** is depicted in Scheme 3. It relies on the preparation of N,N'-di-BOC-

Scheme 3

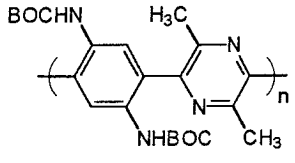


Reaction sequence leading to ladder copolymer **2**

2,5-bis(trimethylstannyl)-1,4-phenylenediamine from a tetraanion described by Tour *et al.*[27] and of 2,5-dibromopyrazine from 2-aminopyrazine. The Stille copolymerization between stannane and bromide is conducted in the conditions optimized for the corresponding co-oligomers **16 - 20** (Table 6). Copolymer **2** has been obtained in fair yield after washing of the organic phase with aqueous base, concentration and successive soxhlet extraction of the residue with hexane, methanol and chloroform. Evaporation of the latter extract yields copolymer **2** as an orange solid in up to 73%. From size exclusion chromatography (SEC) an M_n of ± 2500 (13 - 15 aromatic units) can be deduced, whereas the polydispersity is 1.67. Interestingly, the copolymers seem to contain primarily an odd number of aromatic units: this may reflect once more the tendency of 2,5-dibromopyrazine to react twice and reminds to the observations described earlier for entries 2, 3, and 5 from Table 6. The thermal stability of the copolymer was limited due to the presence of thermally removable BOC groups. Up to 220°C no weight loss was observed by thermogravimetric analysis, between 220 and 550°C the calculated loss of the BOC groups was observed without further decomposition. The properties of the deprotected copolymer have not yet been investigated, although it may serve as a source of a variety of N-acylated analogues. Apart from the Stille coupling products summarized in Table 6, methylated analogues **25** and **26** of co-trimer **18** and copolymer **2**, respectively, have also been synthesized to better correlate the analytical data with the degree of coplanarity and conjugation and with hydrogen bond strength.



25



26

For the characterization of the Stille coupling products ^{1}H NMR, UV-Vis, and CV-measurements have shown to be of special relevance, as is demonstrated in Table 7. The ^{1}H NMR data of the aforementioned oligomers and polymers are consistent with the proposed secondary structure. The intra-molecular hydrogen bonds in which pyrazine is the a hydrogen bond acceptor (entries 3 - 5, δ_{NH} 10.5-10.7) seem to be weaker than those involving pyridine (entries 1 and 2, δ_{NH} 11.1 - 11.2); those involving 3,6-dimethyl-pyrazine (entries 6 and 7, δ_{NH} 8.6 - 8.7) are very weak as indicated by a relative shielding of 2 ppm with respect to pyrazine despite the higher electron density at N. Obviously, considerable steric hindrance is detrimental for coplanarity and efficient hydrogen bonding. Complementary results are obtained for the H-3 protons of the benzene moieties. In the coplanar structures (entries 1 - 5) the signal on a terminal ring is found at δ 8.3 - 8.4, and on a central ring at δ 8.7 - 8.8. In the 3,6-dimethylpyrazine derivatives (entries 6 - 7), however, a relative shielding of 1 ppm is observed for these protons.

Table 7

^{1}H NMR,[a] UV-Vis,[b] and CV[c] data on alternating pyrazine-phenylene ladder structures and models thereof

entry	compound	^{1}H NMR δ_{N-H}	^{1}H NMR δ_{H-3}	UV-Vis λ_{max}	CV E [V]
1	**16**	11.06	8.33	311	-
2	**19**	11.22	8.73	362	-1.94
3	**18**	10.52	8.36	360	-1.73
4	**20**	10.59	8.85	399	-1.60
		10.55	8.37		-1.41
5	**2**	10.7	8.7	440	-1.37
6	**25**	8.73	7.34	332	
7	**26**	8.6	7.8	367	

[a] Measured in $CDCl_3$; [b] measured in $CHCl_3$; [c] measured in 0.1M $Bu_4N^+PF_6^-$ in THF vs SCE.

The most intriguing questions are of course whether the lengthening of the oligomeric backbone indeed leads to enhanced conjugation and whether intramolecular hydrogen bonding is operative and contributes beneficially to conjugation. This aspect can be investigated by UV-Vis and CV measurements. In the series co-dimer (entry 1) to copolymer (entry 5) a steady increase in the λ_{max} values is observed. The decrease in absorption maximum energy observed upon addition of aromatic units compares well to other conjugated polymers. Extrapolation to a copolymer of infinite length suggests a λ_{max} of 475 nm, corresponding to a transition energy of 2.7 eV. This energy is clearly lower than that of polyphenylene (3.75 eV)[22] but is still far removed from that of a low band gap polymer. The intermediate λ_{max} value measured for copolymer **2** is consistent with the chain length calculated from SEC. The reduced effect of elongation of the backbone in the 3,6-dimethylpyrazine cases (entries 6 and 7, $\Delta\lambda_{max}$ 35 nm versus ± 80 nm in the comparable pyrazine entries 3 and 5) is consistent with the expected effect of intramolecular hydrogen bonding on coplanarity.

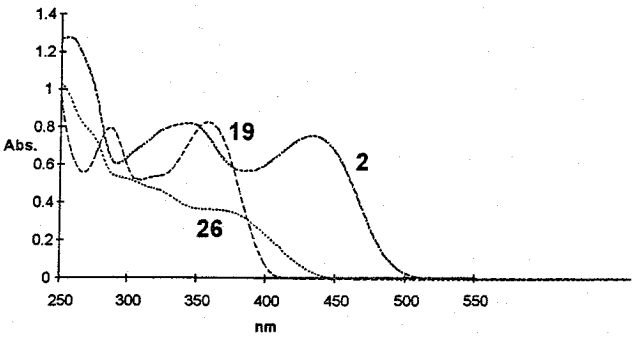


Fig. 7

UV-Vis spectra of co-trimer **19** and copolymers **2** and **26**

Finally, CV measurements have been undertaken to find out whether reversible oxidation or reduction is feasible and whether these ladder structures are to be considered as *n*- or *p*-type conjugated polymers. Cyclic voltammetry in THF indicates the tendency of the ladder structures to undergo reversible electrochemical reduction provided at least three aryl units are present. A steady decrease of the reduction potential in going from co-trimer **18** (entry 3) to copolymer **2** (entry 5), suggests delocalization of the added electron through the backbone. The impact of one pyrazine unit on the reduction potential seems to be larger than that of two pyridine units, as follows from a comparison of compounds **18** and **19** (entries 2 and 3). In contrast to reduction, no reversible oxidation could be measured, even not in CH_2Cl_2. Apparently the presence of pyrazine units inhibits oxidation of the phenylenediamine units.

In conclusion, an alternating ladder type copolymer **2**, composed of pyrazine and 1,4-phenylenediamine, has been designed and prepared using a Stille coupling with concomitant intramolecular hydrogen bond formation. Intramolecular hydrogen bonding planarizes the system to such an extent that a significant incremental bathochromic effect is observed upon elongation of the backbone. Although the chain length is limited, copolymer **2** shows an absorption maximum at 440 nm, which considerably surpasses the 340 nm found in polyphenylene. CV measurements illustrate that the electron-withdrawing character of the pyrazine unit, renders pyrazine-containing conjugated polymers *n*-type semiconductors.

5. Ladder type oligomers and polymers based on pyrrole

Pyrrole is not only the key subunit in many biologically important molecules such as hemoglobin and vitamin B_{12}, but also plays the role of monomeric unit for the strongly conducting material polypyrrole. The latter owes its conductivity to *p*-type doping. Structural knowledge on polypyrrole is, however, scarce due its intractability which prevents proper analysis. Only a few years ago the real development of methods to prepare well-defined oligopyrroles and alternating co-oligomers incorporating pyrrole has started. Important pioneering work has been performed by Martina *et al.*[28a-b] by the application of the BOC group as N-protective group and the implementation of the Stille coupling methodology in pyrrole chemistry. Elaboration of this approach proved to be very rewarding.[13] We considered the development of a low band gap copolymer based on the electron-rich pyrrole unit as a challenging and inspiring research topic. Two important concepts have been developed to attain a low band gap in conjugated polymers. One is based on the alternation of aromatic and quinoid units[29] and the other

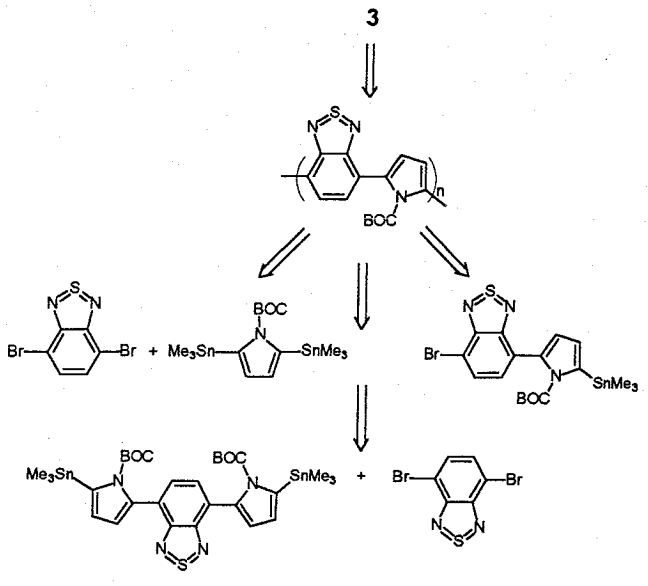
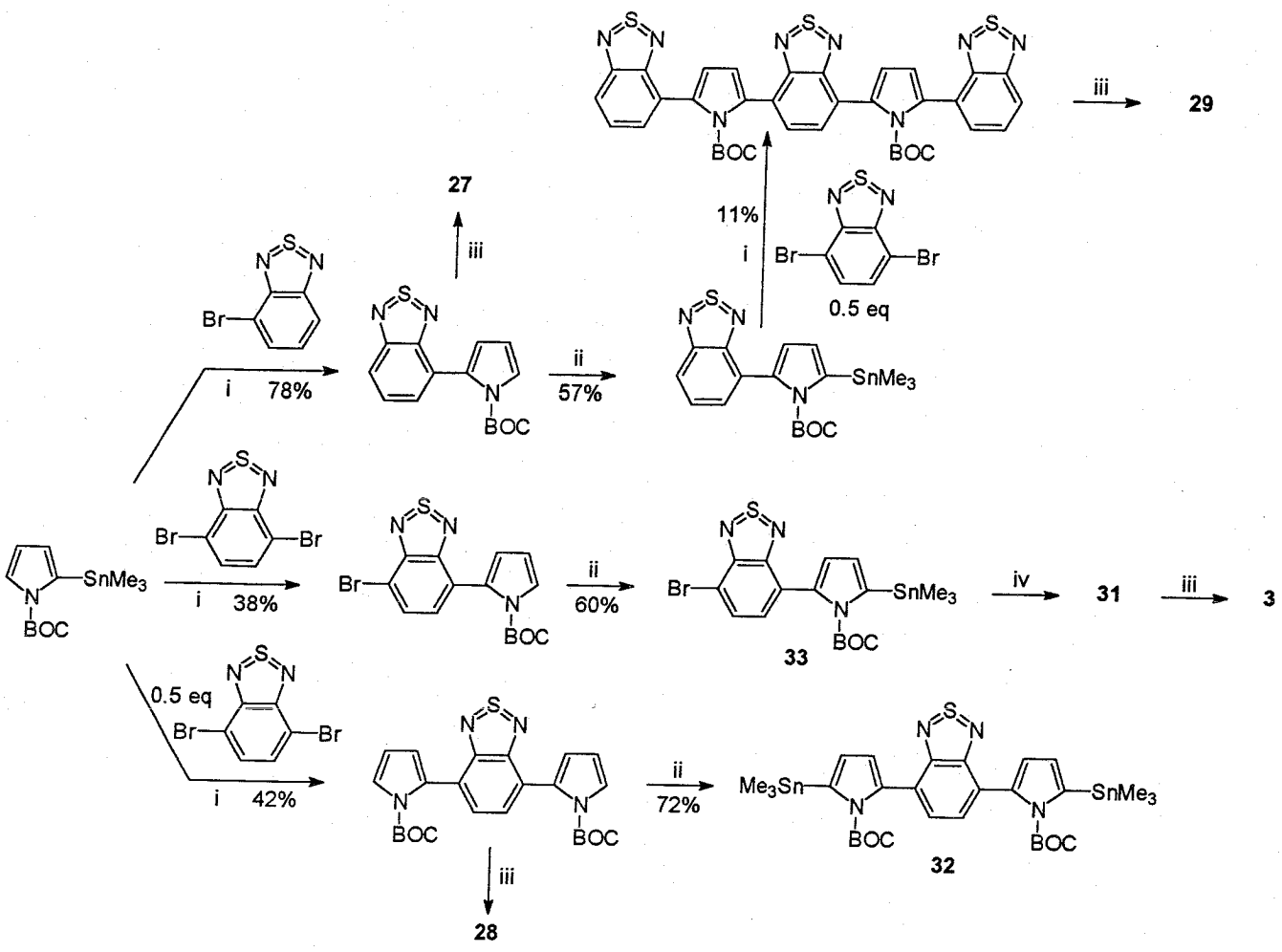


Fig. 8

Retrosynthetic approaches to ladder copolymer **3**

on the alternation of electron donors and acceptors (push-pull).[30] We wondered whether intramolecular hydrogen bonding in copolymers containing pyrrole might contribute to an enhanced degree of coplanarity and hence to lower the band gap. We designed, therefore, an alternating copolymer **3** composed of 2,1,3-benzothiadiazole as a strong electron acceptor and pyrrole as a strong electron donor. This copolymer might in principle represent a self-assembled ladder type structure comparable to the pyrazine-phenylenediamine copolymer **2** described in section 4. Differing from the strategy used in that section, however, is the absence of hydrogen bonding during the coupling of the aromatic units. The approach here leads to a pre-polymer (Fig. 8), which in a final thermolysis has to lose its N-protection to undergo self-assembly by intramolecular hydrogen bonding. Not only the outcome of a copolymerization of a distannane and a dihalide has been investigated but also that of a homopolymerization of an α-halo-ω-stannyl derivative. Stille homo-polymerizations are seldom described.[31] Following the same strategy as adopted in section 4, a step-by-step approach was chosen to attain a well-defined copolymer at the end. The preparation of the model compounds **27** - **30** has been effectuated using the same conditions as described previously for model pyrrole derivatives discussed in section 1 (Table 2). The synthetic route to the model compounds and the precursors of the polymer is depicted in Scheme 4. The benzothiadiazole unit is readily mono- or dibrominated at the phenyl nucleus, but anion formation with non-nucleophilic strong bases like LDA and LTMP to introduce trimethylstannyl groups is not of preparative use. This has suggested to locate the halide substituent onto the electron-withdrawing heterocycle and the stannyl group onto pyrrole, not unfavourable from electronic considerations. The reaction sequences are terminated by thermal N-deprotection, which occurs quantitatively between 190 and 200°C. The reduction in yield of the

Scheme 4



(i) $Pd(PPh_3)_4$, toluene-1M Na_2CO_3, 48 h reflux; (ii) 1. LTMP, -70°C, 2. Me_3SnCl; (iii) 200°C, 30 min; (iv) $Pd(PPh_3)Cl_2$, DMF, 75°C, 7 d

Synthetic approach to co-oligomers of pyrrole and 2,1,3-benzothiadiazole

Stille reactions when going to longer oligoheterocycles prompted us to screen both the conditions and the methodology for polymerization. In contrast to the alternating pyrazine - 1,4-phenylenediamine copolymerization, described in section 4, the obvious approach involving N-BOC-2,5-bis(trimethylstannyl)pyrrole and 4,7-dibromo-2,1,3-benzothiadiazole does not succeed due to the instability of the former substrate. An attempt to couple the distannylated derivative **32** of co-trimer **28** with 4,7-dibromo-2,1,3-benzothiadiazole has also failed (Scheme 4). Ultimately, preference has been given to a homo-polymerization of 7-bromo-4(5-trimethylstannyl-2-pyrrolyl)2,1,3-benzothiadiazole, **33**, as shown in Fig. 9. $Pd^{II}(PPh_3)_2Cl_2$ -mediated Stille coupling in DMF at 75°C for 7 days gives the N-BOC protected polymer **31**. The latter may be purified by precipitation in hexane and diethyl ether and subsequent chromatographic purification on silica gel by eluting consecutively with chloroform and THF. Concentration of the THF fraction affords pure copolymer **31** in 13% yield. A solution of this pre-polymer in chloroform has been subjected to SEC. Therefrom, an average number of repeating units of 8 can be estimated by comparison with defined oligomers and crude polymerization reaction mixtures. Spincasting chloroform solutions of **31** gives rise to a film, which upon heating at 200°C during 15 minutes affords copolymer **3** as a blue transparent film. Oxidative doping of this film with I_2 is partial and gives rise to an extremely broad near-infrared band centered around 2000 nm. The conductivity of the doped material amounts to 1 S/cm according to four probe measurements.

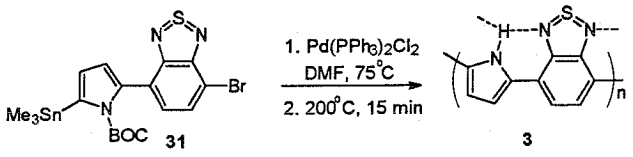
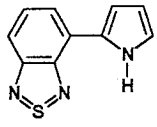
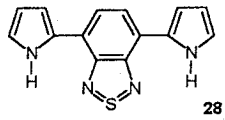
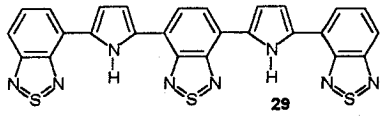
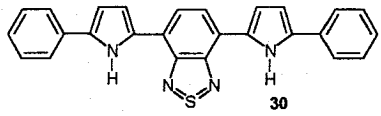
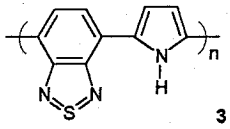


Fig. 9
Stille homo-polymerization to **3**

Firstly, the ^{1}H NMR and UV-Vis analysis of the model compounds **27-30** are discussed (Table 8). From all NMR data the position of the N-H protons in the deprotected co-oligomers is the most revealing. In $CDCl_3$ the co-dimer and co-trimer (entries 1 and 2), in which the pyrrole NH is terminal and may undergo just one hydrogen bonding interaction, a signal at δ 10.9 is detected. In comparison, α,α'-diphenyl terminated compound **30** (entry 4) features only a slightly deshielded NH signal at δ 11.2, despite the expected anisotropic effect of the additional aromatic ring. By contrast, in co-pentamer **29** (entry 3), where the pyrrole units are flanked by two benzothiadiazole units, a considerable downfield shift to δ 12.1 is observed. Copolymer **3** is too insoluble to be

Table 8
Significant ^{1}H NMR[a] and UV-Vis[b] data on alternating pyrrole and 2,1,3-benzothiadiazole co-oligomers

entry	compound	^{1}H NMR δ NH	UV-Vis λ_{max}
1	 **27**	10,9	442
2	 **28**	10.9	532
3	 **29**	12.1	599
4	 **30**	11.2	585
5	 **3**	-----	704[c]

[a] In $CDCl_3$; [b] in $CHCl_3$; [c] of film

measured in NMR. Although the N: H-N distance in this class of compounds is larger than in the hydrogen bonded structures described in sections 2 - 4 due to the wider angles in five-membered rings, the occurrence of intramolecular hydrogen bonding is without any doubt, albeit that its strength may be limited. From co-trimer **28** single crystals have been grown and the X-ray structure reveals coplanar heterocyclic units in an all-*cisoid* conformation, in agreement with the proposed intramolecular hydrogen bonding.[32]

The UV-data of these model compounds show a steady increase of λ_{max} with the number of (hetero)aryl units. While the co-dimer (entry 1) is yellow (λ_{max} 442 nm) in chloroform, the co-pentamer (entry 3) is purple (λ_{max} 599 nm). In comparison, the blue transparent film of co-polymer **3** (entry 5), features a λ_{max} at 704 nm. When a plot of the absorption maximum energies of the alternating co-oligomers **27-29** and of copolymer **3**, is made as a function of the reciprocal number of repeating units, a linear relationship is found with an extrapolated value of 1.6 eV, corresponding to λ_{max} 800 nm, for the polymer with infinite chain length. A major question remains whether the bathochromic shifts in this homologous series are primarily due to charge transfer

between electron donor and -acceptor, to intramolecular hydrogen bonding or simply to extended conjugation length. Interestingly, a significant solvatochromic shift was recorded for model compound **30** (entry 4). Whereas in chloroform λ_{max} appeared at 585 nm, a hypsochromic effect was observed in more polar solvents (EtOH: 562 nm, CH_3CN: 549 nm) and a bathochromic shift in less polar (cyclohexane: 607 nm). Although not a proof, these facts strongly point to the impact of intramolecular hydrogen bonding on electronic transitions in **3** and its lower homologues.

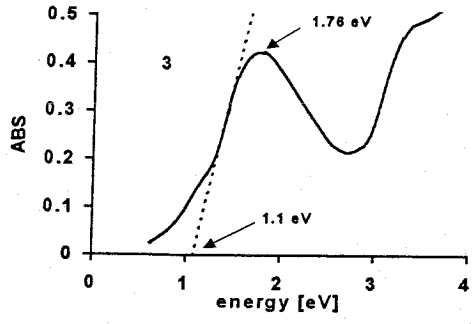


Fig. 10
Absorption spectrum of copolymer **3** and band-gap determination

In conclusion, an alternating, conjugated ladder copolymer composed of pyrrole and 2,1,3-benzothiadiazole units has been designed and prepared. It has an average length of 16 heterocyclic units and shows a λ_{max} at 704 nm. A λ_{max} of 800 nm represents presumably the maximal value attainable for a polymer of infinite chain length. Such a value approaches those obtained for homopolymers like poly-isothianaphthene[33] and for copolymers of bisbenzothiadiazole or thienopyrazine with electron-rich heterocycles like thiophene and N-methylpyrrole.[34]

CONCLUDING REMARKS AND OUTLOOK

The potential of the Ullmann and Stille coupling methodology involving electron-deficient (pyrazine, pyridine) and electron-rich (pyrrole) azaheterocycles has been examined. A limit in useful intrinsic reactivity of substrates is encountered in both cases. Too electron-deficient pyridylhalides do not undergo Ullmann coupling appropriately, while too electron-rich pyrrolylstannanes are too unstable to give preparatively useful yields in the Stille coupling.

Azaheterocyclic biaryls containing a 4-amino-1-azadiene fragment may feature very strong intramolecular hydrogen bonding, applicable as an ordering principle in the construction of well-defined larger systems. Apart from the applications described in this paper, the scope of the 2,2'-bipyridine-3,3'-diamine moiety as building block for well-organized macro- structures may be broadened by decorating this essential building block with appropriate lipophilic substituents at the C-5 and C-5' positions. This may give rise to the development of new ladder polymers and ladder macrocycles.

Three examples have been given of combined covalent linkage and intramolecular hydrogen bonding to develop well-defined and well-organized oligoheterocyclic structures. In the case of star shaped discotic compound **1** a fine tuning of the LC window by changing the length and/or nature of the lipophilic chains is necessary. A study of the interaction of this new class of discotic molecules with gel forming solvents, chiral environments, charge transfer, complexing and H-bond disrupting agents has to be undertaken.

As far as the *n*-type ladder co-oligomers and copolymer **2** derived from pyrazine and 1,4-phenylenediamine are concerned, intramolecular hydrogen bonding is convincingly demonstrated to be operative. A considerably larger bathochromic shift is observed upon addition of units than in simple polyphenylenes or polypyridines. To further substantiate the importance of hydrogen bonding for enhanced conjugation and low energy transitions, appropriate model compounds have to be selected, lacking the opportunity of intramolecular hydrogen bonding but with comparable donor-acceptor interactions not hampered by steric hindrance. The use of the *t*-butoxycarbonyl group in this first series offers the opportunity to readily replace the acylating group and, therefore, to strengthen the hydrogen bonds. The cyclic voltammetry results of copolymer **2** suggest an investigation of other, more electron-deficient ladder structures based on pyridine and pyrazine. Attention has also to be paid to the behaviour of the deprotected copolymer **2** in acidic, neutral and basic conditions. Finally, in the search for ladder copolymers based on pyrrole, preference presumably has to be given to electron-accepting heterocyclic partners prone to strong intramolecular hydrogen bonding and quinoid structure formation. One must realize, however, that the hydrogen bond donor is at the same time the electron donor. This implies that stronger hydrogen bonding is attended with weaker donor-π-acceptor interactions.

Although the two series of ladder oligomers ending in copolymers **2** and **3** differ strongly, the evolution of their absorption maximum energies with length seems to run parallel. Indeed the slope of a plot relating the energy to the inverse number of aryl units is almost identical. This might have far-reaching consequences for the future design of conjugated polymers of the *n* or intrinsic type.

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REFERENCES

1. D. Philp, J. Fraser-Stoddart, Angew. Chem. Int. Ed. Eng., 1996, 35, 1154 and references cited.
2. J.-M. Lehn, Angew. Chem., 1988, 100, 91 and references cited.
3. a. F. Ullmann, Ber., 1896, 29, 1878; b. P.E. Fanta, Synthesis, 1974, 9.
4. J.K. Stille, Angew. Chem., 1986, 98, 504.
5. A.R.A. Palmans, J.A.J.M. Vekemans, E.W. Meijer, Recl. Trav. Chim. Pays-Bas, 1995, 114, 277.
6. A.R.A. Palmans, J.A.J.M. Vekemans, H. Fischer, R.A. Hikmet, E.W. Meijer, Chem. Eur. J., submitted for publication.
7. D.A.P. Delnoye, R.P. Sijbesma, J.A.J.M. Vekemans, E.W. Meijer, J. Am. Chem. Soc., 1996, in press.
8. H.A.M. van Mullekom, J.A.J.M. Vekemans, E.W. Meijer, Chem. Commun., submitted for publication.
9. T. Cohen, I. Cristea, J. Am. Chem. Soc., 1976, 98, 748.
10. a. J.A.H. Mc Bride, P.M. Wright, B.J. Wakefield, Tetrahedron Lett., 1981, 22, 4545; b. R.D. Chambers, J. Hutchinson, W.K.R. Musgrave, J. Chem. Soc., 1965, 5040.
11. W.J. Thompson, J. Gaudino, J. Org. Chem., 1984, 49, 5237.
12. V. Farina, B. Krishnan, J. Am. Chem. Soc., 1991, 113, 9585.
13. L. Groenendaal, H.W.I. Peerlings, J.L.J. van Dongen, E.E. Havinga, J.A.J.M. Vekemans, E.W. Meijer, Macromolecules, 1995, 28, 116.
14. a. V. Farina, B. Krishnan, D.R. Marshall, G.P. Roth, J. Org. Chem., 1993, 20, 5434; b. G.P. Roth, V. Farina, L.S. Liebeskind, E. Peña-Cabrera, Tetrahedron Lett., 1995, 36, 2191; c. E.V. Dehmlow, A. Sleegers, Liebigs Ann. Chem., 1992, 953.
15. a. J.M. Sáa, G. Martorell, J. Org. Chem., 1993, 58, 1963; b. V. Farina, S. Kapadia, B. Krishnan, C. Wang, L.S. Liebeskind, J. Org. Chem., 1994, 59, 5905; c. A.M. Echavarren, N. Tamayo, D.J. Cardenas, J. Org. Chem., 1994, 59, 6075.
16. L. Kaczmarek, P. Nantka-Namirski, Acta Polon. Pharm., 1979, 6, 629.
17. To be published elsewhere.
18. a. S. Chandrasekhar, B. K. Sadashiva, K.A. Suresh, Pramana, 1977, 7, 471; b. S. Chandrasekhar, Liquid Crystals, 1993, 14, 3.
19. D.M. Collard, C.P. Lillya, J. Am. Chem. Soc., 1991, 113, 8577.
20. a. J.F van der Pol, E. Neeleman, J.W. Zwikker, R.J.M.Nolte, W. Drenth, Recl. Trav. Chim. Pays-Bas, 1988, 107, 615; b. P.G. Schouten, J.F van der Pol, J.W. Zwikker, W. Drenth, S.J. Picken, Mol. Cryst. Liq. Cryst., 1991, 195, 291); c. C. Metsendorf, H. Ringsdorf, Mol. Eng., 1992, 2, 189; d. J.A. Rego, S. Kumar, I.J. Dmochowski, H. Ringsdorf, Chem. Commun., 1996, 1031.
21. C. A. Hunter, D.H. Purviss, Angew. Chem., 1992, 104, 779.
22. T.A. Skotheim, Handbook of conducting polymers, M. Dekker, New York, 1986.
23. a. U. Scherf, K. Müllen, Macromolecules, 1992, 25, 3546; b. J.M. Tour, R. Wu, Macromolecules, 1992, 25, 1901.
24. Z. Bao, W. Chan, L. Yu, Chem. Mater., 1993, 5, 2.
25. T. Yamamoto, T. Kanbara, N. Ooba, S. Tomaru, Chem. Lett., 1994, 1709.
26. S. Martina, A.-D. Schlüter, Macromolecules, 1992, 25, 3607.
27. J.J.S, Lamba, J.M. Tour, J. Am. Chem. Soc., 1994, 116, 11723.
28. a. S. Martina, V. Enkelmann, A.-D. Schlüter, G. Wegner, Synth. Met., 1991, 41, 403; b. Ibidem, Synthesis, 1991, 613.
29. J.L. Brédas, A.J. Heeger, F. Wudl, J. Chem. Phys., 1986, 85, 4673.
30. E.E. Havinga, W. ten Hoeve, H. Wynberg, Synth. Met., 1993, 55-57, 299.
31. S. Martina, V. Enkelmann, G. Wegner, Synth. Met., 1992, 51, 299.
32. S.Tanaka, Y. Yamashita, Synth. Met., 1995, 69, 599.
33. F. Wudl, M. Kobayashi, A.J. Heeger, J. Org. Chem., 1984, 49, 3382.
34. C. Kitamura, S. Tanaka, Y. Yamashita, J. Chem. Soc., Chem. Commun., 1994, 1585.