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Recognition and optical sensing of amines by a quartz-bound 7-chloro-4-quinolylazopillar[5]arene monolayer†

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Covalent bonding of 7-chloro-4-quinolylazo-octamethoxypillar[5]arene molecules to silylated quartz substrates readily produced a new chromogenic reusable pillararene-coated quartz slide, for the direct UV detection of "transparent" analytes in solution. This device provides an analyte-selective optical response towards linear (di)amines with a highly reproducible optical read-out.

Introduction

The construction of hybrid materials combining the robustness and inertness of inorganic substrates with the ample diversity of supramolecularly-active organic compounds is a topic of current academic and technological interest in connection with the development of stimuli-responsive materials (*e.g.*, switches, memory devices, logic gates, sensors, *etc.*).[1] Among these, substrates coated with molecular-based thin films – capable of detecting analytes at low concentrations – have received considerable attention in the context of sensing device construction,[2] following the pioneering work by Reinhoudt.[3] Cavitand-,[4] and calixarene-based[5] monolayers, for instance, owing to their electron-rich cavities, have been successfully used for the detection of ammonium-containing analytes,[6,7] but have shown rather poor or no affinity for amines and polyamines unless a spontaneous host-to-guest proton transfer takes place during the recognition/binding process.[8]

Despite the huge impact that pillararenes have had in the field of supramolecular chemistry[9] since their discovery in 2008,[10] with their scaffold being key to a number of different functional materials (*e.g.*, drug delivery systems,[11] supramolecular polymers,[12] light harvesting complexes,[13] photomodulated surfaces[14]), their potential as sensing agents for the detection of amine analytes has not yet been thoroughly explored. Very recently, the known proclivity of pillar[5]arenes to act as host molecules for alkanediamine neutral guests[15,16] has led to the preparation of pillar[5]arene-modified silver nanoparticles for the visual detection of spermine analogues[17] and the construction of a thiolated co-pillar[5]arene for the electrochemical sensing of linear biogenic amines.[18]

Given the UV- and fluorescence-transparency of both low molecular weight and biogenic amines and the usefulness of the latter in the direct monitoring/detection of foodstuff quality[19] and human health,[20] we have undertaken the design of an easy-to-make pillar[5]arene derivative containing a heteroarylazo chromophore suitable both as a sensing agent for "transparent" analytes and as a monolayer coating material.[21] The key benefits of monolayers rest on their ability to display and possibly enhance the intrinsic molecular properties of single molecules bound to a solid surface. Specific advantages of monolayer-based sensors include: (i) the need for only a small amount of sensing agent to generate a large active surface, (ii) the absence of sensing material consumption and (iii) the lack of diffusion limitations because the surface-confined molecules are in direct contact with the solution of the target analyte.[22] The aim of the present study was to obtain a sensing-device, namely a reusable pillararene-coated quartz slide, for the direct UV-vis and fluorescence detection of linear amines in solution. With this in mind, we have synthesised pillar[5]arene **QAP5** and we now wish to report its covalent immobilization on quartz substrates together with the ability of the resulting monolayer to detect linear (di)amino

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analytes (*i.e.*, *n*-butylamine, 1,8-diaminoctane and dansylcadaverine [5-dimethylaminonaphthalene-1-(*N*-(5-aminopentyl)) sulfonamide]).

Results and discussion

7-Chloro-4-quinolylazo-octamethoxypillar[5]arene (**QAP5**) was selected as a potential sensing agent to be anchored to quartz substrates in view of the chromogenic properties of the quinolylazo moiety.[23] The choice of **QAP5** as a sensing agent was also motivated by the additional advantage of using a molecule suitably equipped with a chromogenic moiety bearing a nucleophilic nitrogen atom capable of undergoing, at a later stage, covalent bond formation with silylated quartz surfaces, to ultimately yield a robust linkage with the solid substrate.

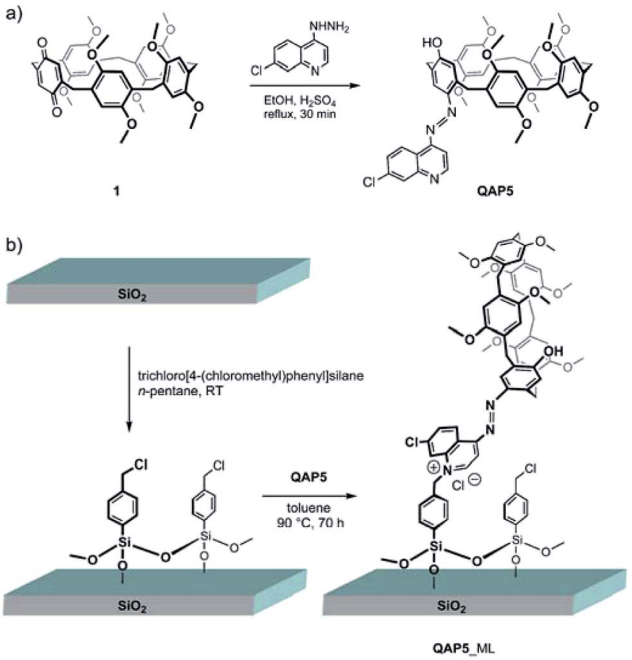
According to Scheme 1a, **QAP5** was obtained in a single step (55% yield) from pillar[4]arene[1]quinone[24] **1** and 7-chloro-4-hydrazinoquinoline. NMR spectroscopy (Fig. S3 and S4, ESI†) as well as single-crystal X-ray diffraction analysis (Fig. 1), unambiguously confirmed the structure of the novel pillararene. In the solid state **QAP5** adopts a semiregular pentagonal-prism shape (with dihedral angles between the hydroquinone-containing planes and the bridging-methylene mean-plane in the 80.88(7)–102.32(9)° range; ESI†). Several solvent molecules (tetrachloroethane (TCE), CH_3OH and H_2O; ESI†) either occlude or fill the hollow/cavity of the macrocycle.

The quinolylazo-pillar[5]arene monolayer (**QAP5**_ML) was synthesized by covalently grafting **QAP5** macrocycles to silylated quartz slides§ (Scheme 1b). The silylation reaction was carried out under a rigorously inert atmosphere, using trichloro[4-(chloromethyl)phenyl]silane as a convenient bifunctional coupling agent (CA) capable of covalently linking, *via* the nucleophilic quinoline nitrogen atom, the **QAP5** sensing agent to the quartz surface.[25]

This **QAP5**_ML was found to be insoluble in toluene, DMSO, CH_3CN, THF, Et_2O and EtOH, thermally robust and stable for long-term storage (*vide infra*). The successful siloxane-mediated immobilization of **QAP5**_ML onto quartz (and Si(100)) substrates was assessed by X-ray photoelectron spectroscopy (XPS), *via* elemental composition analysis of the surface. Data fitting of the O 1s binding-energy region of the **QAP5**_ML spectrum revealed the presence of two components one of high- and one of low-intensity assigned to the oxygen atoms of the SiO_2 substrate (532.6 eV) and the pillar[5]arene methoxy groups (530.8 eV), respectively (Fig. 2a). Similar fitting of the N 1s binding-energy region of the **QAP5**_ML experimental spectrum (Fig. 2b) showed the presence of three, equally intense, Gaussian components centred at 401.0, 399.9 and 399.2 eV which were respectively assigned to the quaternized nitrogen atom[26] of the quinoline moiety and the two nitrogen atoms of the azo group[27] adjacent to the quinoline and the phenol rings.

The reaction between **QAP5** and the chlorobenzyl-coated monolayer was not quantitative owing to the high molecular footprint of the pillararene (*vide infra*). The observed Cl/N XPS ratio of 3.2 ± 0.5 indicates ~11.9% yield, after taking into account the presence of one chlorine and three nitrogen atoms in **QAP5**. Physisorption was excluded on the basis of a control experiment carried out on a model substrate with a CA-uncoated hydrophilic SiO_2-terminated surface, which showed that exposure of the substrate to a 10^{-3} M toluene solution of **QAP5** (at 90 °C for 36 h) did not reveal any nitrogen signal, upon XPS analysis, thus excluding the presence of **QAP5** molecules on the substrate surface. AFM analysis of a **QAP5**_ML showed a uniform surface (Fig. S5, ESI†) with structure heights of 2.5 ± 0.15 nm, compatible with the dimension of a **QAP5** molecule covalently linked to a [4-(chloromethyl)phenyl]siloxane moiety (~2.15 nm, from molecular models).

The UV-vis spectra (Fig. S6a and S6b; ESI†) of the pillarene as such ([**QAP5**] = 1.8 × 10^{-7} M, in toluene) and as a quartz-immobilized monolayer (**QAP5**_ML) display very similar



Scheme 1 The syntheses of: (a) 7-chloro-4-quinolylazo-octamethoxypillar[5]arene (**QAP5**) and (b) the corresponding quartz-grafted monolayer (**QAP5**_ML).

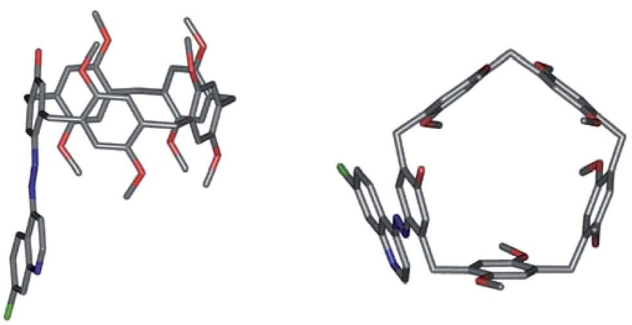


Fig. 1 Side (left) and top (right) views of the solid-state structure of **QAP5**. Hydrogen atoms and solvent molecules have been omitted for the sake of clarity.

§ For XPS and AFM characterizations, monolayers were also prepared by grafting quinolylazo-pillar[5]arene molecules onto silylated Si(100) slides (ESI†).

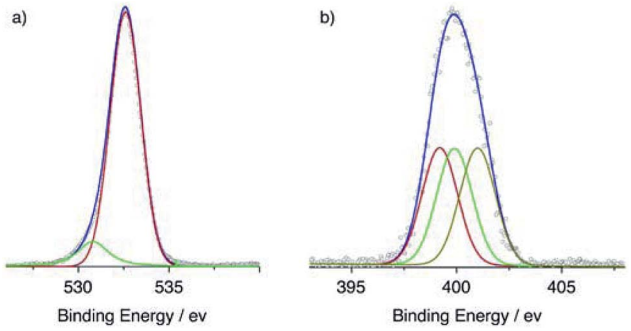


Fig. 2 Al-Kα excited XPS of the **QAP5**_ML in the O 1s and N 1s energy-regions, panels (a) and (b), respectively. Structures due to K$\alpha_{3,4}$ satellites were subtracted from the spectra. Open circles, present in both panels, indicate the experimental data points. Panel (a) the green and red traces refer to the Gaussian components at 530.8 and 532.6 eV, respectively. The blue trace, superimposed on the experimental data points, represents the sum of the two Gaussian components. Panel (b) the red, green and yellow traces refer to the Gaussian components centred at 401.0, 399.9 and 399.2 eV, respectively. The blue trace superimposed on the experimental datapoints refers to the sum of the three Gaussian components.

absorption bands (λ_{max} 384.2 and 406.0 nm, respectively). A **QAP5**_ML surface coverage of 5.4×10^{13} molecules per cm^2 was then calculated from the absorption intensity of the monolayer (5.7×10^{-3} O.D.), by means of the Lambert–Beer law (ε = 31 700 M^{-1} cm^{-1} for a toluene solution of **QAP5**), ultimately corresponding to a pillararene footprint of 185 Å^2, compatible with the value estimated from X-ray measurements (120 Å^2) for **QAP5**.[28]

Owing to the ability of pillar[5]arenes to host solvent molecules inside their cavity[29] and as a result impede analyte entry, preliminary UV-vis tests were carried out to assess the response of **QAP5** and **QAP5**_ML to the addition of model (di)amines (*i.e.*, *n*-butylamine, 1,8-diaminoctane and dansylcadaverine) in different solvents. Initial attempts, using **QAP5**, to sense/detect *n*-butylamine or 1,8-diaminoctane in toluene solution were to no avail, as the pillararene/amine mixtures under screening produced no significant UV-vis spectral changes (Fig. S6b, ESI†). Similarly unsatisfactory results were obtained in CH_3CN, where the same **QAP5**/amine mixtures were found to be sparingly soluble. DMSO was also judged to be unsuitable as it promoted the ionization of the phenol moiety to the corresponding phenolate anion (Fig. S6b, ESI†). Further UV-vis studies were carried out in TCE, which is known to be too bulky to fit inside the pillar[5]arene cavity.[30] In this solvent **QAP5** showed a single absorption band (λ_{max} = 397.2 nm; ε = 24 000 M^{-1} cm^{-1}). Aspecific interactions between *n*-butylamine and the simple 7-chloro-4-quinolylazophenol chromophore (**QA**) – lacking the pillararene macrocyclic scaffold – were preliminarily ruled out on the basis of the insignificant spectral variation observed in the chromophore spectrum upon addition of an excess of amine (Fig. S7, ESI†). Addition of increasing amounts (up to 50–100 equiv.) of *n*-butylamine, 1,8-diaminooctane and dansylcadaverine (Fig. S8–S10, ESI†) to a TCE solution of **QAP5** produced, in all instances, a sizeable optical response consistent with a (small but significant) red shift (from 397.2 nm to 408.4, 407.6 and 403.4 nm for *n*-butylamine, 1,8-diaminoctane, and dansylcadaverine, respectively) as well as an hyperchromic effect (*ca.*, 14, 3 and 20% for *n*-butylamine, 1,8-diaminooctane and dansylcadaverine, respectively).

Based on this initial screening, (di)amine detection by **QAP5** was closely looked into by ^{1}H NMR spectroscopy using deutero TCE (TCE-d_2) as the solvent of choice. Addition of increasing aliquots of analyte (up to ~5 equiv.) to 1.0 mM solutions of **QAP5** produced steady shifts of selected resonances (*e.g.*, Ar*H* at δ = 7.80 ppm), thus allowing the determination of the pertinent binding constants (K_{ass} = 286 ± 20 and 509 ± 40 M^{-1} for *n*-butylamine and 1,8-diaminoctane, respectively) under a fast host–guest association/dissociation regime (see Fig. S11 and S12 in the case of 1,8-diaminoctane, ESI†). Fluorescence spectroscopy was alternatively used for the determination, in TCE, of the binding constant between **QAP5** and dansylcadaverine (K_{ass} = (4.3 ± 0.4) × 10^4 M^{-1}), by looking at the quenching of the amine emission (at λ = 510 nm) upon addition of increasing amounts of pillararene (Fig. S13–S14, ESI†).

The ability of **QAP5**_ML to sense the model (di)amines in TCE solutions was tested spectrophotometrically (Fig. 3). However, owing to the presence of toluene molecules (used as the solvent in the **QAP5**-coating step) tightly hosted inside the pillararene cavity,[29b] it was deemed necessary to prime the monolayer (see the Experimental section) to expel these residual solvent molecules from the monolayer binding/recognition sites. Successful monolayer priming was ultimately confirmed by a shift in the **QAP5**_ML absorption from 384.2 to 397.0 nm. Dipping of the monolayer (5 min) into either *n*-butylamine, 1,8-diaminoctane or dansylcadaverine TCE solutions consistently caused a red shift of the original **QAP5**_ML band (λ_{max} = 397.0 nm), as well as, a substantial hyperchromic effect. In particular, the endo-cavity inclusion of *n*-butylamine, 1,8-diaminoctane and dansylcadaverine inside the **QAP5**_ML cavities, was diagnostically revealed by the presence of new absorption bands centred at 422.6 (8% intensity increase), 426.4 (47%) and 445.6 nm (21%), respectively. These data indicate that, depending on the amine included inside the **QAP5**_ML cavities,

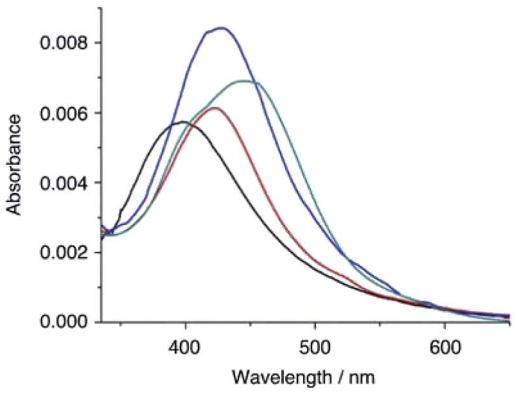


Fig. 3 UV-vis spectra of a **QAP5**_ML before (black trace) and after immersion in 100 ppm TCE solutions of *n*-butylamine, 1,8-diaminooctane and dansylcadaverine (red, blue and dark cyan traces, respectively).

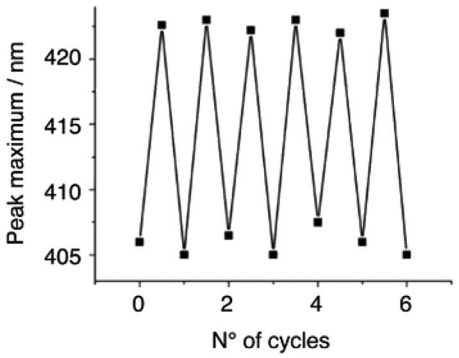


Fig. 4 Peak position variations for the QAP5_ML upon sequential 5 min. Dipping in a 100 ppm TCE solution of *n*-butylamine followed by rinsing (10 min) with TCE.

the grafted pillarazo derivative returns an analyte-selective optical response (λ_{max}).

In analogy with very closely structurally-related pillar[5]arene derivatives, the host–guest complexation between **QAP5** and uncharged aliphatic amines and diamines is believed to occur *via* the formation of 1 : 1 pseudorotaxane-type complexes.[15] The threading of the guests inside **QAP5** most likely involves multiple C–H$\cdots\pi$ interactions between the aliphatic chain of the (di)amine and the pillar[5]arene cavity, as well as hydrophobic interactions.[15c,31] The additional formation of hydrogen bonds between the primary amino group(s) and the oxygen atoms on the pillararene rims may also provide further stabilization to the pseudorotaxane. As a result, analyte detection relies on the transient presence of the guest inside the **QAP5** cavity and consequently on the strength of the concomitant host–guest interactions which in turn affect the absorption spectrum of the chromogenic pillararene.

The detection limit for the current prototypical device is 100 ppm. Longer contact periods of the **QAP5**_ML with the amine solutions did not change the optical absorbance. This detection limit is most likely related to the relatively weak absorption intensity of the 7-chloro-4-quinolylazo chromophore present in **QAP5** (ε = 24 000 in TCE). In all instances, reactivation of the monolayer with TCE (see the Experimental section), produces full recovery of the optical absorbance, as verified by UV-vis spectroscopy. Fig. 4 shows that the ability of the monolayer to sense *n*-butylamine remains substantially unchanged after several exposure/recovery cycles. Remarkably, heating of the **QAP5**_ML at 100 °C, in the presence of air for 10 days, does not affect its performance. Similarly, sensitivity was not compromised when the sensor was left in air at room temperature for a period as long as 4 months.

Experimental

Materials and methods

General. Commercial reagent grade chemicals were used as received without any further purification. Pillar[4]arene[1]quinone **1** was prepared according to a published procedure.[24] Melting points were determined on a Kofler hot stage apparatus and are uncorrected. Column chromatography was performed on silica gel (230–400 mesh).

NMR spectroscopy. Unless otherwise stated, ^{1}H and ^{13}C NMR spectra were acquired at 25 °C in deuterotetrachloroethane (TCE-d_2) at 500 and 125 MHz, respectively. Chemical shifts are reported in ppm and are referenced to the residual solvent (δ_H 5.98 ppm and δ_C 73.78 ppm); coupling constant (J) values are given in Hz.

^{1}H NMR titration studies were carried out at a fixed **QAP5** concentration (1 mM) and samples were routinely prepared by dissolving solid **QAP5** in TCE-d_2. Stock solutions of *n*-butylamine and 1,8-diaminooctane (20 mM) were, in turn, prepared by using the above-mentioned 1 mM **QAP5** TCE-d_2 solution as a convenient solvent so that, during the titration, the host concentration did not vary upon addition of increasing aliquots of the guest. The association constants were calculated by a nonlinear regression method (assuming a 1 : 1 complexation model) using the WinEQNMR.[32]

UV-vis spectroscopy. Absorption spectra were recorded at 25 °C on a V-650 Jasco spectrophotometer (±0.2 nm resolution) by using spectrophotometric grade solvents. Quartz cells with a 1 cm optical path were used for measurements in solution; quartz monolayers (**QAP5**_ML) were directly mounted onto the spectrophotometer. Routinely, 3 to 5 different solutions or monolayers were used for each determination.

Fluorescence spectroscopy. Luminescence measurements were carried out using a Varian Cary Eclipse fluorescence spectrophotometer with different λ_{exc} (in the 290–420 nm range, 10 nm steps) at 1 nm resolution and at room temperature. The emission was recorded at 90° with respect to the exciting line beam using 10 : 10 slit-widths. The association constant for the dansylcadaverine⊂**QAP5** complex was calculated by a nonlinear regression method (assuming a 1 : 1 complexation model) using the MicroMath Scientist program.

X-ray photoelectron spectroscopy. XPS spectra were measured with a PHI 5600 Multi Technique System, at a 45° electron take-off angle relative to the surface plane.[33] Samples were excited with Al-Kα radiations. Structures due to the K$\alpha_{3,4}$ satellite radiation were subtracted from the spectra prior to data processing. XPS peak intensities were obtained after Shirley background removal. The experimental uncertainties in the binding energies lie within ±0.4 eV. Deconvolution of the spectra was carried out by fitting the experimental profiles with a series of symmetrical Gaussian envelopes after subtraction of the background. Least-squares-fitting data refinement was carried out until the highest possible correlation between the experimental spectrum and the theoretical profile was reached. The residual or agreement factor R ($R = [\Sigma(F_{obs} - F_{calc})^2/\Sigma(F_{obs})^2]^{1/2}$), after minimization of the $\Sigma(F_{obs} - F_{calc})^2$ function, converged to a value of 0.02.

Atomic force microscopy. AFM micrographs were obtained with a Solver P47 NT-MTD instrument. The noise level before and after each measurement was 0.01 nm. The monolayer characterization was performed in a high-amplitude mode (tapping mode) to avoid any potential modification of the grafted layer on the surfaces, caused by the interactions with the tip (nominal curvature radius 10 nm).

Synthetic procedures

Synthesis of 7-chloro-4-quinolylazo-octamethoxypillar[5]arene (QAP5). A hot solution of 7-chloro-4-hydrazinoquinoline (158 mg, 0.818 mM) in EtOH/H_2O (1 : 1, 4 mL) containing 900 μL of conc. H_2SO_4 was added dropwise to a boiling solution of the known pillar[4]arene[1]quinone[24] **1** (294 mg, 0.408 mM) in EtOH (30 mL) under stirring. The starting red-coloured solution of **1** quickly darkened. After 30 min reflux the solution was stirred overnight at room temperature. The reaction mixture was concentrated to dryness and the resulting residue was partitioned between water and CH_2Cl_2. The organic layer was washed with a saturated $NaHCO_3$ solution, dried over anhydrous Na_2SO_4 and subjected to column chromatography (eluent CH_2Cl_2/AcOEt 100 : 0 to 95 : 5, v/v) to afford two main fractions:

Fraction A gave 7-chloro-4-quinolylazo-octamethoxypillar[5]arene *O*-ethyl ether (8–10% yield) as red crystals (mp 109–110 °C, from EtOH): ^{1}H NMR δ 9.00 (d, 2-QuinH, J = 4.4 Hz, 1H), 8.80 (d, 5-QuinH, J = 8.8 Hz, 1H), 8.19 (d, 8-QuinH, J = 2.2 Hz, 1H), 7.90 (s, ArH, 1H), 7.64 (dd, 6-QuinH, J = 8.8, 2.2 Hz, 1H), 7.51 (d, 3-QuinH, J = 4.4 Hz, 1H), 6.65, 6.645, 6.639, 6.62 (4 × s, ArH, 1H each), 6.60 (s, ArH, 2H), 6.58, 6.54, 6.52 (3 × s, ArH, 1H each), 4.46, 3.86, 3.76, 3.75, 3.74 (5 × s, $ArCH_2Ar$, 2H each), 3.79 (q, OCH_2CH_3, J = 7.0 Hz, 2H), 3.54, 3.52, 3.51, 3.504, 3.496, 3.47, 3.43, 3.30 (8 × s, OCH_3, 3H each) and 0.86 (t, J = 7.0 Hz, OCH_2CH_3, 3H) ppm; ^{1}H NMR (CD_2Cl_2) δ 9.02 (d, 2-QuinH, J = 5.0 Hz, 1H), 8.84 (d, 5-QuinH, J = 9.0 Hz, 1H), 8.17 (d, 8-QuinH, J = 2.0 Hz, 1H), 8.04 (s, ArH, 1H), 7.66 (d, 3-QuinH, J = 5.0 Hz, 1H), 7.59 (dd, 6-QuinH, J = 9.0, 2.0 Hz, 1H), 7.09 (s, ArH, 1H), 6.89 (s, ArH, 2H), 6.88, 6.86, 6.824, 6.817, 6.71, 6.56 (6 × s, ArH, 1H each), 4.40, 3.83, 3.73, 3.67, 3.64 (5 × s, $ArCH_2Ar$, 2H each), 4.11 (q, OCH_2CH_3, J = 6.5 Hz, 2H), 3.80, 3.78, 3.77, 3.73, 3.72, 3.69, 3.56, 3.11 (8 × s, OCH_3, 3H each) and 1.51 (t, J = 6.5 Hz, OCH_2CH_3, 3H) ppm; ^{13}C NMR δ 160.7, 153.4, 152.1, 150.8, 150.7, 150.56, 150.52 (×2), 150.48, 150.47, 150.42, 150.1, 144.9, 143.9, 135.4, 129.1, 128.7, 128.5, 128.4, 128.3 (×2), 128.2, 128.0, 127.57, 127.56, 127.54, 125.2, 123.8, 118.1, 114.0, 113.9, 113.8 (×2), 113.7, 113.6, 112.4, 105.2, 63.2, 55.82 (×2), 55.76, 55.68, 55.64 (×2) 55.5 (×2), 30.4, 30.2, 29.8, 29.7, 29.6 and 13.8 ppm; ESI MS m/z 923.7 (M^+, 100%). Anal. calcd for $C_{54}H_{54}ClN_3O_9$: C, 70.16; H, 5.89; Cl, 3.83; N, 4.55. Found: C, 69.83; H, 6.02; Cl, 3.75; N, 4.45.

Fraction B yielded the desired **QAP5** as red-brown crystals (mp 105–108 °C, from MeOH) (201 mg, 55% yield); ^{1}H NMR δ 9.02 (d, J = 4.9 Hz, 2-QuinH, 1H), 8.79 (d, J = 9.0 Hz, 5-QuinH, 1H), 8.20 (s, ArH, 1H), 7.92 (s, OH, 1H), 7.80 (s, 8-QuinH, 1H), 7.63 (dd, J = 9.0, 1.8 Hz, 6-QuinH, 1H), 7.56 (d, J = 4.9 Hz, 3-QuinH, 1H), 6.91, 6.78, 6.69, 6.64, 6.63, 6.61, 6.59, 6.54, 6.49 (9 × s, ArH, 1H each), 4.41, 3.87, 3.78, 3.75 (4 × s, ratio 1 : 1 : 1 : 2, $ArCH_2Ar$, 10H), 3.85, 3.66, 3.533, 3.525, 3.46, 3.44, 3.36 and 3.29 (8 × s, OCH_3, 3H each) ppm. ^{13}C NMR δ 159.1, 153.5, 152.1, 151.9, 150.9, 150.8, 150.7, 150.6, 150.5, 150.3, 150.0, 147.9, 145.4, 144.3, 135.5, 130.0, 128.9, 128.4, 128.2, 128.1, 128.0, 127.9, 127.6, 126.0, 125.6, 125.1, 123.7, 117.7, 116.9, 114.5, 114.4, 114.1, 114.0, 113.7, 112.8, 105.6, 56.5, 55.93, 55.86, 55.82, 55.77, 52.5, 30.4, 30.2, 29.9, 29.8 and 29.4 ppm. ESI MS m/z 895.4 (M^+, 100%). Anal. calcd for $C_{52}H_{50}ClN_3O_9$: C, 69.67; H, 5.62; Cl, 3.95; N, 4.69. Found: C, 69.73; H, 5.75; Cl, 4.07; N, 4.81.

4-(7-Chloro-4-quinolylazo)-2,5-dimethylphenol (QA). This model compound was obtained in 11% yield as a powdery orange solid (mp > 220 °C) from 2,5-dimethyl-1,4-quinone and 7-chloro-4-hydrazinoquinoline by following the procedure already described for **QAP5**: ^{1}H NMR (DMSO-d_6) δ 10.59 (bs, OH, 1H), 9.03 (d, J = 4.4 Hz, 2-QuinH, 1H), 8.82 (d, J = 9.3 Hz, 5-QuinH, 1H), 8.17 (d, J = 2.4 Hz, 8-QuinH, 1H), 7.78 (s, ArH, 1H), 7.77 (dd, J = 9.3, 2.3 Hz, 6-QuinH, 1H), 7.50 (d, J = 4.4 Hz, 3-QuinH, 1H), 6.84 (s, ArH, 1H), 2.66 and 2.19 (2 × s, CH_3, 3H each) ppm; ^{13}C NMR (DMSO-d_6) δ 161.8, 153.3, 153.0, 149.9, 144.3, 141.3, 134.9, 128.0, 127.8, 126.1, 124.0, 123.5, 118.7, 116.8, 105.9, 17.2 and 15.9 ppm: ESI MS m/z 283.0 (M^+, 100%). Anal. calcd for $C_{15}H_{10}ClN_3O$: C, 63.50; H, 3.55; Cl, 12.50; N, 14.81. Found: C, 63.87; H, 3.61; Cl, 12.72; N, 14.62.

Synthesis of the 7-chloro-4-quinolylazo-octamethoxy-pillar[5]arene-based monolayer (QAP5_ML). Fused silica (quartz) substrates were cleaned by immersion into a "piranha" solution (98% H_2SO_4 : 30% H_2O_2, 7 : 3 v/v) at 90 °C for 1 h and then left to cool to r.t. Substrates were repeatedly rinsed with double-distilled water and then kept in a H_2O : 30% H_2O_2 : NH_3 (5 : 1 : 1 v/v/v) mixture at r.t. for 1 h.[34] A final wash with double-distilled water, followed by drying under vacuum was then carried out just prior to deposition of the coupling agent. Si(100) substrates, were first cleaned with the above-mentioned piranha solution for 10 min at 90 °C, rinsed with double-distilled water for 5 min, etched in a 2.5% hydrofluoric acid aqueous solution for 150 s (both piranha and hydrofluoric acid solutions need to be handled with caution!), washed, dried under N_2 and then treated for 5 min with ozone (using a Fisher 500 ozone-generator system) to yield a SiO_2 thin (~10 Å) layer.[35] Both types of freshly cleaned substrates were transferred in a glove-box under a N_2 atmosphere and dipped, at r.t. for 1 h, in a *n*-pentane/trichloro[4-(chloromethyl)phenyl]silane (CA) (100 : 0.1, v/v) solution, to afford siloxane-coated substrates.[36] These substrates were washed with copious amounts of *n*-pentane, removed from the glove-box and heated to 135 °C for 15 min in an oven to complete the grafting of the coupling agent (CA). CA-grafted substrates were sonicated in *n*-pentane for 10 min, to remove any physisorbed CA, and subsequently dipped for 72 h in a stirred 8.56×10^{-4} M toluene solution of **QAP5** and kept at 90 °C. The monolayer thus obtained (**QAP5**_ML) was allowed to reach r.t. and then sonicated in turn with toluene, CH_3CN and THF to remove any residual unreacted **QAP5**.

Procedure for QAP5_ML priming/reactivation. The initial priming of the device was carried out by **QAP5**_ML immersion (60 min) in TCE at 90 °C, followed by washing in TCE and drying under a N_2 stream in order to remove any cavity-included toluene molecules (reaction solvent). **QAP5**_ML reactivation, after each sensing cycle, was accomplished by letting the device stand in TCE (10 min at 60 °C or 2 h at r.t.).

Conclusions

In conclusion, we have described a simple strategy for the construction of reliable quartz-supported pillararene-based

optical devices for the sensing of "transparent" analytes. In particular, a new pillararene-based sensing agent (**QAP5**) for the detection of UV-inactive or dansyl-derivatized linear (di)amines has been synthesized and covalently grafted to a silylated quartz substrate, with the resulting device displaying an analyte-selective optical response. Linear amine detection – in the 100 ppm range – involves simple immersion of the pillararene-coated quartz substrate (**QAP5**_ML) into a tetrachloroethane solution of the amine to be revealed. The synthesis of new quartz-bound monolayers based on pillararenes incorporating a variety of different chromogenic moieties is currently in progress.

Conflicts of interest

There are no conflicts to declare.

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