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Light and Chemically Driven Molecular Machines Showing a Unidirectional Four-State Switching Cycle

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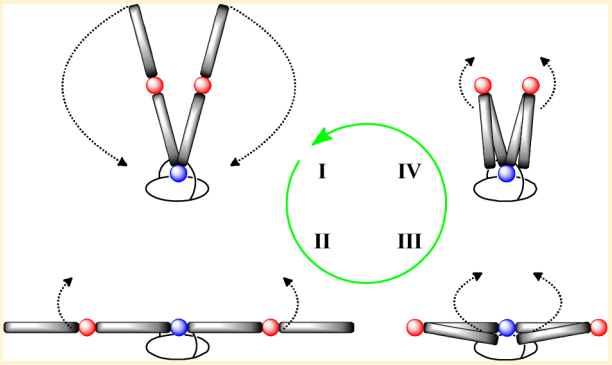
Supporting Information

ABSTRACT: The imitation of macroscopic movements at the molecular level is a key step in the development of nanomachines. The challenge is the synthesis of molecules that are able to transform external stimuli into a direction-controlled mechanical movement. The more complex such motion sequences are, the more difficult is the construction of the corresponding nanomachine. Here, we present a system that demonstrates a unidirectional, four-state switching cycle that bears similar characteristics to the arm movements of a human breaststroke swimmer. Like the latter, the molecules have a torso and two arms. The arms consist of bipyridine units and can be folded and stretched by addition and removal of copper ions. The unidirectional rotation of the arms is achieved by light-induced switching of an azo unit.



INTRODUCTION

In recent years, a large variety of synthetic molecular machines have been published.[1] The design of artificial molecular machines often takes inspiration from the macroscopic world.[2] Here, the aim and challenge are to construct a single molecule that shows mechanical motion caused by external stimulation resembling the movement of its macroscopic pendant. These attempts have yielded analogues of rotors,[3] gears,[4] clutches,[5] shuttles,[6] ratchets,[7] elevators,[8] muscles,[9] etc.[10] Furthermore, several entirely synthetic molecular motors have been designed to convert energy into a controlled rotary motion.[11] As stimuli, chemical energy,[12] light energy,[13] electron-transfer processes,[14] or a combination of different types of energy[15] has been used.

A special challenge is the construction of molecular machines showing unidirectional, multi-state switching cycles. The problem in the design of such systems is that the path of leaving the starting state must differ from the path returning back to the starting point,[16] as otherwise no mechanical work is performed during one cycle. Therefore, a system is needed that, on one hand, is flexible enough to allow a complex motion sequence and, on the other hand, is so rigid that the movements are controlled in a single direction.

Here, we present the design of two entirely synthetic machines that demonstrate unidirectional, four-state switching cycles that bear similar characteristics to the arm movements of a human breaststroke swimmer. They are single organic molecules having a size of about 2 nm and consisting of a peptidic scaffold (torso) and two flexible arms. The arms can be moved by external stimuli, and the direction of the movement is controlled by the chiral scaffold. The sequence of motion shows, analogously to the arm movements of a human breaststroke swimmer, four states that can be observed by CD and UV spectroscopy.

RESULTS AND DISCUSSION

Structure, Concept, and Principle of the Molecular Machine. The targeted unidirectional nanomachine should pass through a cycle of four states. Such a cycle (**I** → **II** → **III** → **IV** → **I**), together with the structure, concept, and principle of the nanomachine, is depicted in Figure 1. The system consists of a scaffold, which must be chiral to control the direction of motion, two arms, and two types of hinge (blue and red circles in Figure 1). Staying with the comparison of this system with the arm movements of a human breaststroke swimmer, the scaffold corresponds to the human torso and the arms represent human arms. The blue hinge corresponds to the shoulder joints, and the red hinges represent the elbow joints.

In state **I**, both arms are stretched forward. During the transition from state **I** to state **II**, a rotation of the stretched arms around the blue hinge occurs. This motion can also be considered to be the power stroke of a breaststroke swimmer. It is of the utmost importance that this motion is directed (unidirectional); this means that in our case the right arm in Figure 1 must rotate only clockwise, whereas the left arm must move counterclockwise. The second stroke is the folding of the two arms around the two red hinges (**II** → **III**). In the third

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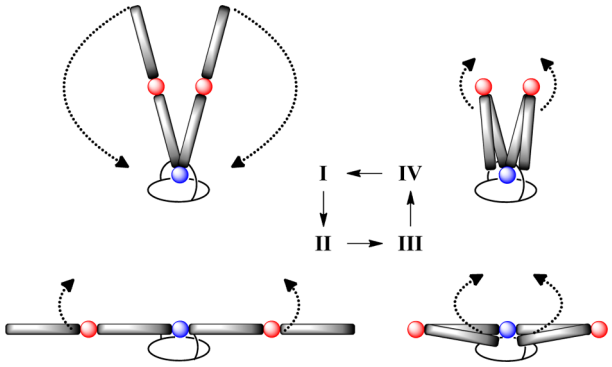

Figure 1. Structure, concept, and principle of the nanomachine. The nanomachine consists of a torso and two arms. The arms can be unidirectionally rotated around the blue hinge. The stretching/folding of the two arms takes place around the two red hinges. Sequence of motions: **I** → **II** (directed motion of the forward-stretched arms from the front to the side; power stroke), **II** → **III** (folding of the arms), **III** → **IV** (rotation of the folded arms), and **III** → **IV** (stretching of the arms).

stroke, a rotation of the folded arms around the blue hinge takes places (**III** → **IV**) whereby the direction occurs in exactly the inverse fashion as that in the first step. The fourth stroke is the stretching of the arms, which leads back to starting state **I** and completes the swimming cycle (**IV** → **I**).

We intended to build the targeted nanomachine in two steps. The first step was the development of a unidirectional switch consisting of a chiral scaffold and a hinge that performs the rotation of the arms unidirectionally (blue hinge in Figure 1). If the direction of motion was successfully proved, then we wanted to attach the two arms, with each possessing a further hinge (red hinges in Figure 1), in a second step.

Synthesis and Functionality of the Unidirectional Switch. For the synthesis of the unidirectional switch, we combined a chiral imidazole-containing macrocycle with an azobenzene unit. Imidazole-containing macrocycles[17] based on marine peptides[18] have already been successfully used for the synthesis of molecular machines in which the direction of motion plays an important role.[19−21] Azobenzenes are very popular light-driven switching units due to their high reversibility and high photostability, which offer a multitude of switching cycles.[22] Furthermore, they show a high-amplitude change between the stretched *trans* form and the more compact *cis* isomer, and the direction of movement is controllable.[23,24]

For our approach, it is important that the orientation of the arms relative to each other can be controlled in both states. That means that the arms are first stretched forward and that after the switching process they should be turned by 90° and point to the side. A system that meets these requirements is a *meta*-substituted azobenzene unit attached to a chiral imidazole-containing clamp.[23b] The synthesis of this system is depicted in Figure 2a. The oxidative coupling of aniline **1** leads to 4-fold-

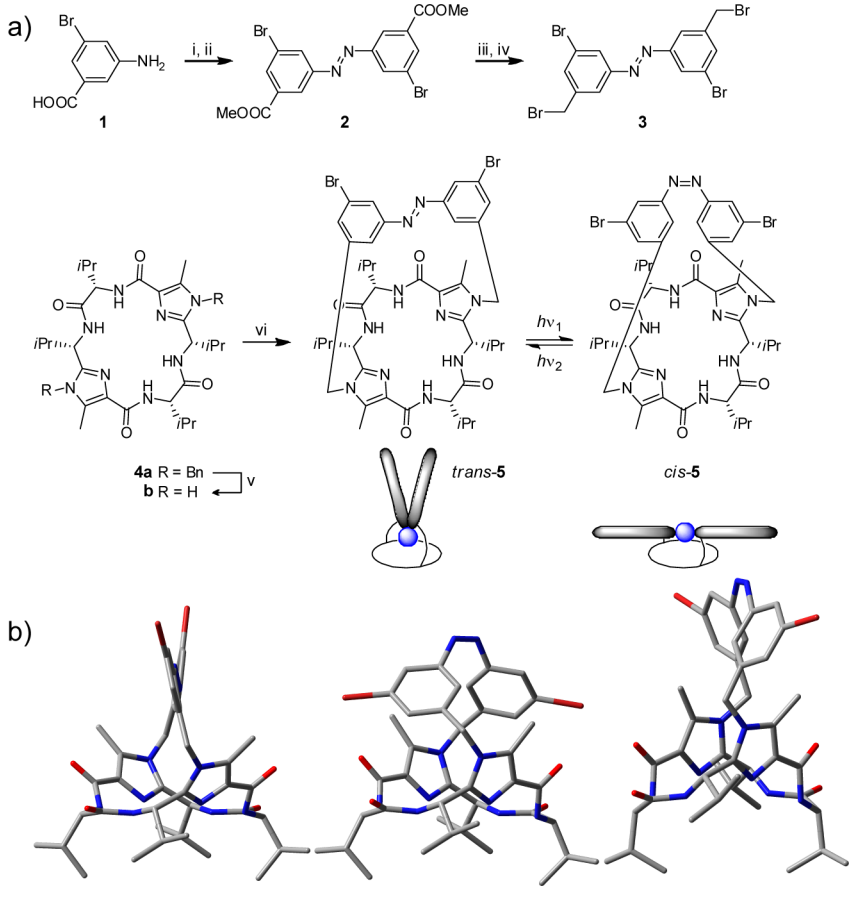

Figure 2. (a) Synthesis of unidirectional switch **5**. Reaction conditions: (i) MeOH, $SOCl_2$, 96%; (ii) MnO_2, toluene, 70 °C, 56%; (iii) $LiAlH_4$, dichloromethane, 0 °C, 96%; (iv) Ph_3P, NBS, THF, 85%; (v) H_2, $Pd(OH)_2/C$, DCM/MeOH, 95%; (vi) Cs_2CO_3, **3**, acetonitrile, Δ, 84%. (b) Molecular structures of *trans*-**5**, *cis*-(*P*)-**5**, and *cis*-(*M*)-**5** calculated by means of B3LYP/6-31G*.

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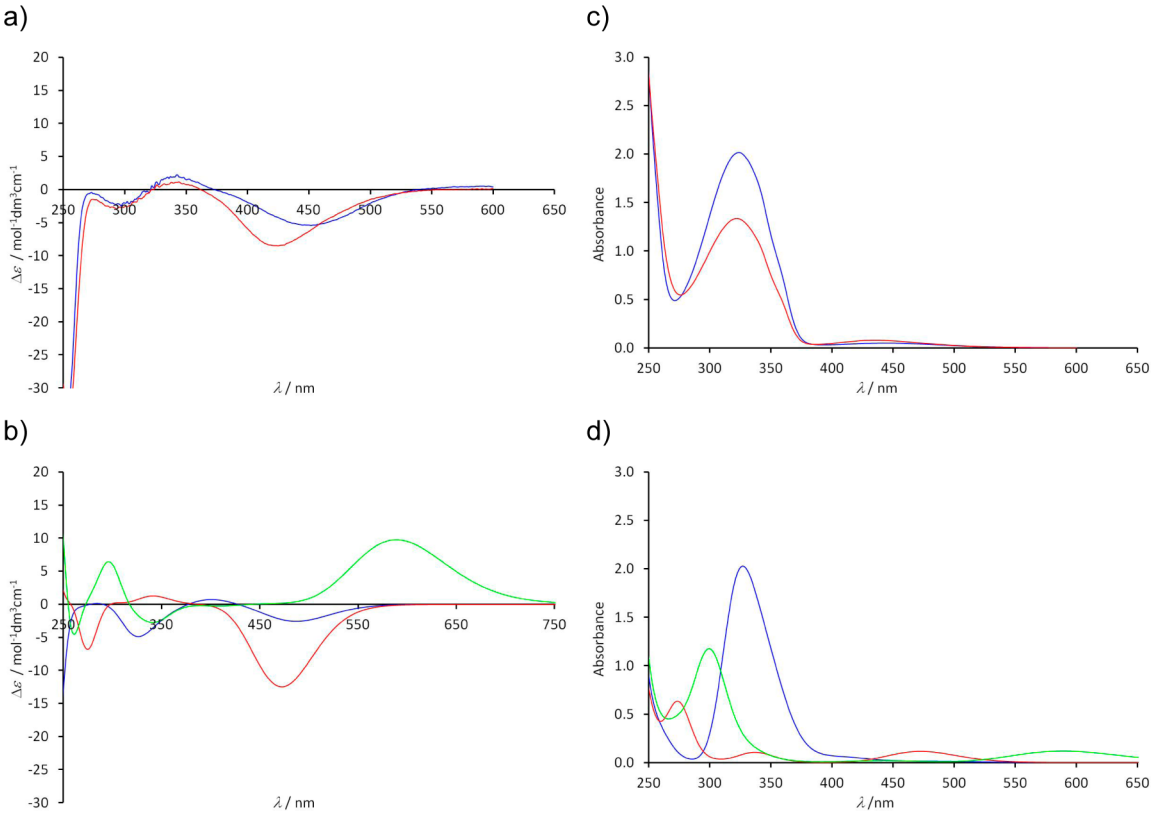

Figure 3. (a) CD spectrum of azo switch **5** before (blue) and after (red) irradiation (λ = 365 nm, 10 s; c = 1.0 × 10^{-4} M in DCM). (b) CD spectra of *trans*-**5** (blue), *cis*-(*P*)-**5** (red) and *cis*-(*M*)-**5** (green) calculated using TD-B3LYP/6-31G*. (c) UV spectrum of azo switch **5** before (blue) and after (red) irradiation (λ = 365 nm, 10 s; c = 1.0 × 10^{-4} M in DCM). (d) UV spectra of *trans*-**5** (blue), *cis*-(*P*)-**5** (red), and *cis*-(*M*)-**5** (green) calculated using TD-B3LYP/6-31G*.

substituted azobenzene **2**. Diester **2** can be transformed via two steps into benzylic bromide **3**, which was reacted with chiral clamp **4b** to the desired azo switch, **5**. Chiral clamp **4b** was synthesized from commercially available clamp **4a** by hydrogenation.[19]

To investigate the motion during the switching process, the structures of the three possible isomers, *trans*-**5**, *cis*-(*P*)-**5**, and *cis*-(*M*)-**5**, were geometrically optimized by means of B3LYP/6-31G* (Figure 2b). Subsequently, their CD and UV spectra were simulated on the basis of time-dependent density functional theory (TD-DFT) with the B3LYP functional and by employing the 6-31G* basis set. In Figure 2b, the calculated structures are depicted. It turned out that the *cis*-(*P*) form is more stable by 83 kJ/mol than the *cis*-(*M*) isomer. This huge energy difference is responsible for the unidirectionality of the switching process: Starting from the *trans* isomer, only the more stable *cis*-(*P*) isomer is formed during the switching process. Furthermore, the orientation of the bromine atoms in the isomers is ideal for using **5** to construct a molecular machine imitating the mechanical motion sequence of the arms of a human breaststroke swimmer. In the *trans* isomer, the bromine arms point forward, whereas in the *cis*-(*P*) isomer, they are turned by 90° and point to the right and left sides, respectively. Furthermore, we managed to grow crystals of *trans*-**5**, which were investigated by X-ray analysis. A comparison shows that the DFT-calculated conformation of the switching units matches well with the one found in the solid state (Figures S1 and S2).

The unidirectionality of the switching process of **5** was investigated using HPLC, NMR, CD, and UV spectroscopy (Figures 3 and S3−S5). In the UV spectra, the switching process can be observed by the decrease of the absorption band at ca. 330 nm (Figure 3c). This change in the $\pi \rightarrow \pi^*$ band is typical for isomerization of azobenzene derivatives.[22a] The experimentally measured CD spectrum of *trans*-**5** matches quite well with the simulated one (Figure 3). In the simulated CD spectrum of *cis*-(*M*)-**5**, a positive Cotton effect of the n → π^* transition at values above 400 nm is found. For the *cis*-(*P*) isomer, a negative Cotton effect of the n → π^* transition is predicted, which is consistent with the measured spectrum. Furthermore, the obtained cross-peaks in the ^{1}H−^{1}H NOESY NMR spectrum of *cis*-**5** can be explained only if the formed *cis* isomer adopts *P* configuration (Figure S4). Accordingly, the light-induced switching process is indeed unidirectional, as *trans*-**5** is undoubtedly transformed only into *cis*-(*P*)-**5**. The NMR spectra as well as the HPLC spectra confirm that only one *cis* isomer is formed by irradiation with 365 nm light (Figures S3 and S5). It is also apparent, however, that the extent of the switching process is lower than usually observed for azobenzene units. Only 20% of **5** is switched by irradiation with 365 nm light (Figure S5). The reverse isomerization from *cis*-(*P*)-**5** to *trans*-**5** is triggered by irradiation with 405 nm light (Figure S3). The switching process is repeatable almost any number of times without a noticeable change in the spectra.

Synthesis and Functionality of the Molecular Machines Imitating the Motion Sequence of a Breaststroke Swimmer. On the basis of unidirectional switch **5**, we intended to design light and chemically driven nanomachines by attaching additional arms whose shape is controlled by the addition/removal of metal ions (cf. Figure 1). As arms, we

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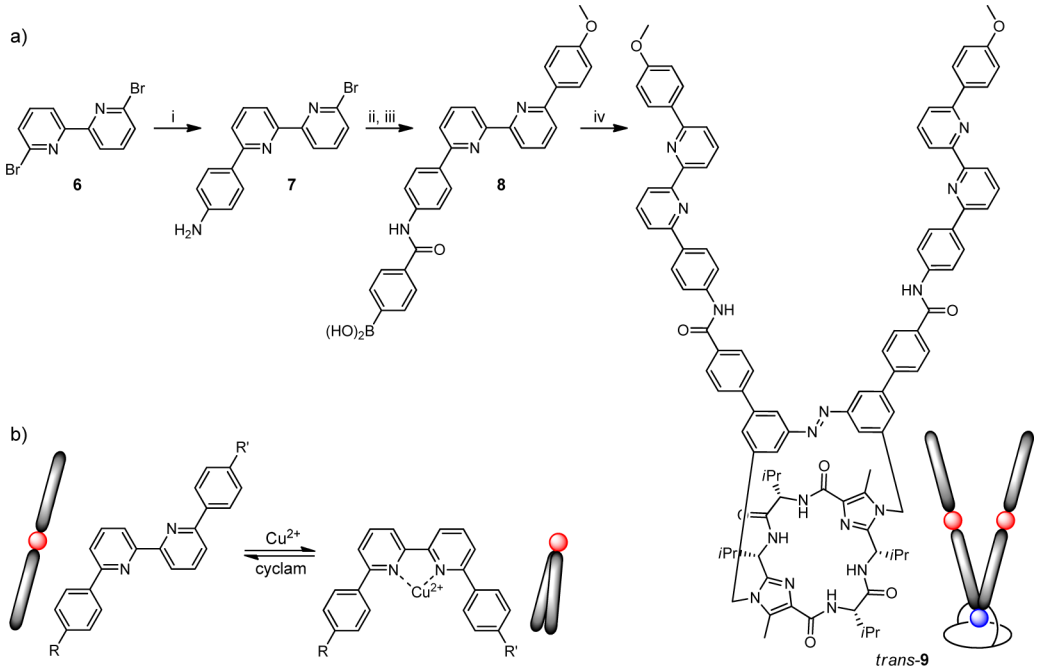
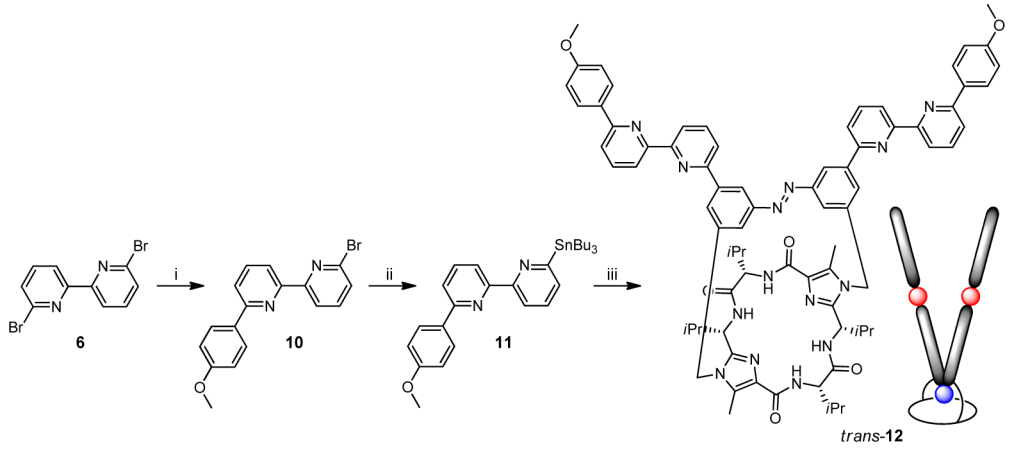
Scheme 1. (a) Synthesis of Unidirectional Nanomachine 9 and (b) Motion Principle of the Bipyridine Arms of Nanoswimmer 9[a]



[a](a) Reaction conditions: (i) 4-aminophenylboronic acid pinacol ester, $Pd(PPh_3)_4$, K_2CO_3, H_2O/dioxane, Δ, 31%; (ii) 4-methoxyphenylboronic acid, $Pd(PPh_3)_4$, K_2CO_3, H_2O/dioxane, Δ, 66%; (iii) 4-chlorocarbonylbenzeneboronic anhydride, THF, 71%; (iv) *trans*-**5**, $Pd(PPh_3)_4$, K_2CO_3, H_2O/dioxane, 365 nm, Δ, 34%. (b) Complexation of the bipyridine units with Cu^{2+} causes the folding of the arms (right); the addition of cyclam leads back to the opened arms (left).

Scheme 2. Synthesis of Unidirectional Nanomachine 12[a]



[a]Reaction conditions: (i) 4-methoxyphenylboronic acid, $Pd(PPh_3)_4$, K_2CO_3, H_2O/dioxane, Δ, 71%; (ii) *n*-BuLi, $ClSnBu_3$, tetrahydrofuran, −78 °C; (iii) *trans*-**5**, $Pd(PPh_3)_4$, toluene, 365 nm, Δ, 49%.

decided to use 6,6′-substituted 2,2′-bipyridines, as they are known to be completely and reversibly switchable (Scheme 1b).[25] Because noncomplexed 2,2′-biypridine units have an N−C−C−N dihedral angle of about 180°, the substituents in positions 6 and 6′ point in different directions and the 2,2′-biypridine arm is opened. The addition of salts containing metal ions, for example, Cu^{2+}, leads to a complexation that is accompanied by rotation around the C−C bipyridine bond axis.[26] In the complex, the N−C−C−N dihedral angle is ca. 0°, the substituents in position 6 and 6′ point into the same direction (Scheme 1b), and the 2,2′-biypridine arm is folded. The reversibility of this movement, the opening of the arms, is achieved chemically by the addition of cyclam, which complexes Cu^{2+} ions better than bipyridine units.[20]

For linking the arms with the chiral scaffold, we chose two approaches: In the first nanomachine (**9**, Scheme 1), the bipyridine unit is separated from the azobenzene by a rigid spacer. Here, the additional rigid spacer should ensure that the two switching systems are spatially separated from each other to avoid hindrance during the switching process. In the second nanomachine (**12**, Scheme 2), the bipyridine unit is directly bound to the *meta* position of the azobenzene.

The synthesis of light and chemically driven nanomachine **9** is depicted in Scheme 1a and basically corresponds to a Suzuki

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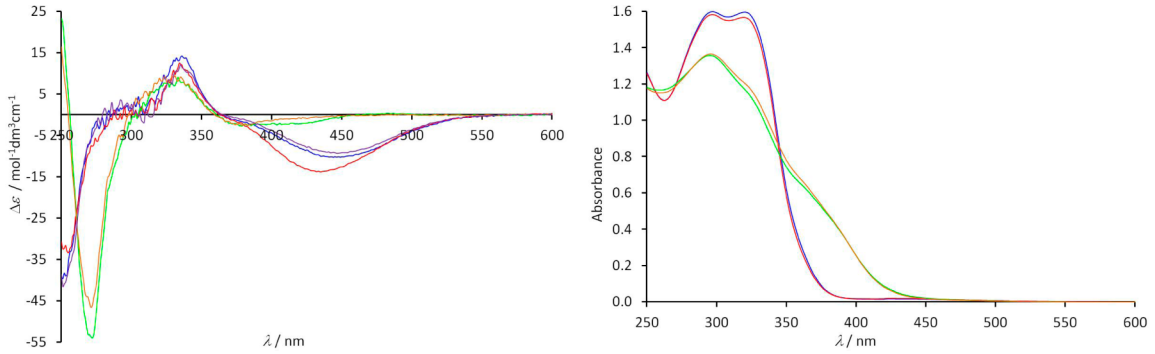

Figure 4. CD (left) and UV spectra (right) of states **I**–**IV** of light and chemically driven switch **9** in dichloromethane/acetonitrile (90:10; $c = 2.0 \times 10^{-5}$ M) at 20 °C. During a four-stroke swimming cycle, the states are progressed through in the following order: **I** (blue) → **II** (red) → **III** (orange) → **IV** (green) → **I** (violet). Transition from state **I** to state **II** is caused by irradiation with 365 nm light (10 s). Transition from state **II** to state **III** is caused by the addition of 3.2 equiv of Cu^{2+}. Transition from state **III** to state **IV** is caused by irradiation with 405 nm light (10 s). Transition from state **IV** to state **I** is caused by the addition of 10 equiv of cyclam.

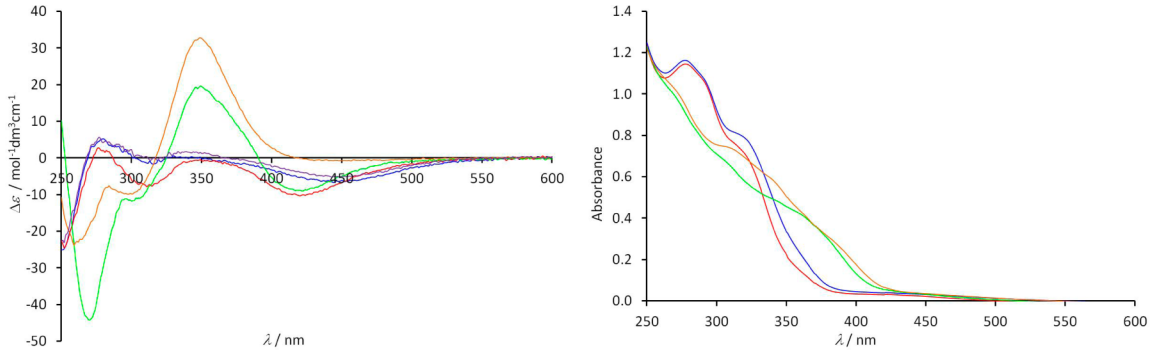

Figure 5. CD (left) and UV spectra (right) of states **I**–**IV** of light and chemically driven switch **12** in dichloromethane/acetonitrile (90:10; $c = 2.0 \times 10^{-5}$ M) at 20 °C. During a four-stroke swimming cycle, the states are progressed through in the following order: **I** (blue) → **II** (red) → **III** (orange) → **IV** (green) → **I** (violet). Transition from state **I** to state **II** is caused by irradiation with 365 nm light (10 s). Transition from state **II** to state **III** is caused by the addition of 2.4 equiv of Cu^{2+}. Transition from state **III** to state **IV** is caused by irradiation with 405 nm light (10 s). Transition from state **IV** to state **I** is caused by the addition of 44 equiv of cyclam.

coupling[27] of two bipyridine arms with the unidirectional switch, *trans*-**5**. The so-obtained nanomachine (*trans*-**9**) adopts state **I**; this means that both arms are stretched forward (cf. Figure 1). The synthesis of nanomachine **12** takes place according to a similar principle (Scheme 2). Here, stannane **11**, which can be synthesized in two steps from 6,6′-dibromo-2,2′-dipyridyl (**6**), is reacted with switch *trans*-**5** using a Stille coupling. The so-obtained nanomachine, **12**, also adopts state **I**.

After successful nanomachine synthesis, we wanted to first test if light-induced switching of the systems can still be achieved. Therefore, we analyzed the two systems via HPLC, NMR, CD, and UV spectroscopy (Figures S6–S11). In all spectra, the switching process can be proven. In the UV spectra, a decrease of the $\pi \rightarrow \pi^*$ band at ca. 330 nm can be observed. However, this effect is not very distinct for switch **9** (Figures S6 and S7). The unidirectionality of the process can be seen in the NMR spectra: Only one of the two diastereomeric *cis* isomers is found (Figures S8 and S9). The negative Cotton effects of the $n \rightarrow \pi^*$ transition at values above 400 nm can be ascribed to the *cis*-(*P*) isomers (Figures S6 and S7). Accordingly, irradiation with 365 nm light leads to the transition from state **I** (*trans*-**9**/*trans*-**12**) to state **II** (*cis*-(*P*)-**9**/*cis*-(*P*)-**12**).

Furthermore, a comparison of systems **9** and **12** shows that the extent of light-induced switching is different for the two machines. In the case of switch **9**, only ca. 20% is involved in the switching process (Figures S8 and S10). However, in system **12**, ca. 30% of the azobenzene units are switched by light (Figures S9 and S11). We ascribe this to the fact that in the case of **9** a part of the irradiated light is absorbed by the rigid spacers so that less light is available for excitation of the azobenzene unit.

Irradiation with 405 nm light returns state **II** to initial state **I** (*trans*-**9**/*trans*-**12**). This switching processes are repeatable almost any number of times without a noticeable change in the spectra.

In the second step, we wanted to test if the bipyridine units of nanomachines **9** and **12** can also be switched. Therefore, the nanomachines were titrated with different metal ions in DCM/MeCN and analyzed by CD and UV spectroscopy. Additionally, the metal complexes were investigated by mass spectrometry. Here, complete conversion was achieved only with copper ions, and the corresponding metal complexes were detected by ESI+. In the UV spectra, the formation of copper–bipyridine complexes can be easily observed by means of an increase of the absorption band at ca. 370 nm and a decrease of the band at 320 nm (Figures S12 and S13). For switch **9**, complete conversion is reached at 3.15 equiv; for switch **12**, only 2.15 equiv is necessary.

Even in the CD spectra, the formation of copper complexes can be observed. As expected, the bipyridine complex units in switch **12**, which are closer to the chiral clamp, show more distinct changes in the Cotton effects (Figures S12 and S13).

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After titration, the solutions were examined by mass spectrometry. In addition to the dinuclear complexes (**9***Cu_2^{2+}, **12***Cu_2^{2+}), the mononuclear complexes (**9***Cu^{2+}, **12***Cu^{2+}) can be unambiguously proven. The addition of the strong copper ion binder cyclam leads to the original (not complexed) compounds (Figures S12 and S13). Thus, titrations with Cu^{2+} ions and cyclam show that the bipyridine arms can be folded (*trans*-**9***Cu_2^{4+}; state **IV**) and reopened (state **I**, *trans*-**9**), as expected (Figures S12 and S13).

The combination of both switches using the different stimuli subsequently allows several cycles to be performed for light and chemically driven switches **9** and **12**. The UV and CD spectra for the first cycle are depicted in Figures 4 and 5. The starting point is the *trans* isomers (state **I**), which are transformed in the first stroke into state **II** (*cis*-(*P*) isomers) by irradiation with 365 nm light. This switching process is observable by the decrease of the absorption bands at 330 nm in the UV spectra and the more negative Cotton effect at 420 nm. During the second stroke, the addition of Cu^{2+} ions causes the folding of the arms (copper complexes of the *cis*-(*P*) isomers), which corresponds to state **III**. In the UV spectra, this process can be observed by means of the bathochromic shifts of the bipyridine bands to 380 nm. Rotation of the folded arms is triggered by irradiation with 405 nm light, and state **IV** (copper complexes of the *trans* isomers) is formed in the third stroke. This reisomerization becomes noticeable by an increase of the absorption band at 330 nm in the UV spectra. The so-recorded spectra are consistent with the ones obtained by titration of the *trans* isomers with Cu^{2+} (Figures S12 and S13). Addition of cyclam leads to the stretching of the arms, resulting in the *trans* isomers, which correspond to state **I**. The fourth stroke completes the cycle. The spectra are again identical with those of the starting compounds; this makes the case for the existence of a reversible cycle. The cycle can be repeated several times. The number of cycles is not limited by the system but by the measurement technique: With increasing overall concentration of all of the components, the absorption of the entire system is too high to obtain meaningful CD signals in the desired part of the spectra.

CONCLUSIONS

We have shown that we were able to design molecular machines that demonstrate unidirectional, four-state switching cycles that bear similar characteristics to the arm movements of a human breaststroke swimmer. They are based on a peptidic, macrocyclic scaffold that controls the direction of motion. The arms performing the swimming movements are rotated around one hinge and are stretched and folded by another hinge. The first hinge is a *meta*-substituted azobenzene attached to the chiral scaffold and can be switched by light. The arms are bipyridine units that are either directly attached or connected via rigid spacers to the azobenzene unit. The bipyridine units are stimulated by Cu^{2+} ions. The movements of these machines are triggered by alternating addition of chemicals and irradiation with light. The limiting factor for the repeatability of the cycles is the dilution effect caused by the addition of solutions, which worsens the recording of the spectra. The rate-limiting factor is the time to record the spectra for each cycle. The current work is a promising small step to an artificial nanoswimmer that is propelled in solution by an external stimuli.

EXPERIMENTAL SECTION

Computational Study. All calculations were performed by using the program package Gaussian 09.[28] The geometrical parameters of *trans*-**5**, *cis*-(*P*)-**5**, and *cis*-(*M*)-**5** were optimized without symmetry restriction by means of density functional theory (DFT). For the DFT method, we used the B3LYP[29−31] functional and the 6-31G*[32] basis set. Frequency calculation revealed that the optimized structures have no imaginary frequency.

The CD and UV spectra of *trans*-**5**, *cis*-(*P*)-**5**, and *cis*-(*M*)-**5** were simulated with time-dependent density functional theory (TD-DFT),[33] using the B3LYP functional and the 6-31G* basis set. TD-DFT calculations were performed at the optimized ground-state geometry (B3LYP/6-31G*) of the compounds. The energy, oscillator strength, and rotatory strength were calculated for each of the 200 lowest singlet excitations.

General Remarks. All chemicals were reagent grade and were used as purchased. Reactions were monitored by TLC analysis with silica gel 60 F254 thin-layer plates. Flash chromatography was carried out on silica gel 60 (230−400 mesh). ^{1}H, ^{13}C, and 2D NMR spectra were recorded on 300, 500, and 600 MHz spectrometers. All chemical shifts (δ) are given in ppm. The spectra were referenced to the peak for the protium impurity in the deuterated solvents indicated in brackets in the analytical data. HRMS spectra were recorded using a time-of-flight (TOF) detector. Two high-power light-emitting diodes (LEDs) were used for the light-induced switching processes. The first light source irradiates 365 nm light, and the second one, 405 nm. Chiral clamp **4a** was purchased from Squarix GmbH.

Synthesis of Methyl 3-Amino-5-bromobenzoate (13). Aniline **1** (718 mg, 3.30 mmol) was dissolved in methanol and cooled to 0 °C. $SOCl_2$ (4.8 mL, 66.7 mmol) was added dropwise to the solution, and the mixture was allowed to reach room temperature overnight. The volatiles were removed in vacuo, and the remaining solid was dissolved in water. A saturated solution of $NaHCO_3$ was added until a pH of 7 was reached. The aqueous solution was extracted several times with ethyl acetate. The combined organic phases were dried over $MgSO_4$ and concentrated in vacuo to give **13** (730 mg, 3.17 mmol, 96%) as a grayish solid. mp 97−98 °C. ^{1}H NMR (500 MHz, $CDCl_3$): δ 7.52 (dd, $^4J_{H,H}$ = 1.4 Hz, $^4J_{H,H}$ = 1.4 Hz, 1 H, H_{ar}), 7.25 (dd, $^4J_{H,H}$ = 1.4 Hz, $^4J_{H,H}$ = 2.2 Hz, 1 H, H_{ar}), 6.99 (dd, $^4J_{H,H}$ = 2.0 Hz, $^4J_{H,H}$ = 2.0 Hz, 1 H, H_{ar}), 3.89 (s, 3 H, CH_3), 3.83 (bs, 2 H, NH_2) ppm. ^{13}C NMR (125 MHz, $CDCl_3$): δ 166.0, 147.7, 132.6, 122.9, 122.3, 121.6, 114.6, 52.3 ppm. HRMS (ESI+) $[C_8H_8{}^{79}BrNO_2 + Na]^+$ calcd, 251.9636; found, 251.9624. IR (ATR): 3410, 3329, 3220, 3095, 2953, 1708, 1636, 1601, 1467, 1444, 1430, 1308, 1273, 1242, 1187, 1089, 1003, 914, 896, 853, 833, 768, 729, 669 cm^{-1}. UV/vis (DCM): λ_{max} (log ε) = 324 (3.49) nm.

Synthesis of 2. Aniline **13** (1.52 g, 6.60 mmol) was dissolved in toluene (25 mL), and MnO_2 (13.2 mmol, 1.15 g) was added. The reaction mixture was warmed to 70 °C and stirred in the dark for several days at that temperature. Afterward, the reaction mixture was filtered over Celite, and the solvent was removed in vacuo. Column chromatography of the residue on silica gel (dichloromethane) led to diester **2** (436 mg, 29%) as an orange solid and to starting material **13** (841 mg, 1.84 mmol, 56%). mp 175−176 °C. ^{1}H NMR (500 MHz, $CDCl_3$) *trans* isomer: δ 8.53 (dd, $^4J_{H,H}$ = 1.6 Hz, $^4J_{H,H}$ = 1.6 Hz, 2 H, H_{ar}), 8.31 (dd, $^4J_{H,H}$ = 1.7 Hz, $^4J_{H,H}$ = 1.7 Hz, 2 H, H_{ar}), 8.23 (dd, $^4J_{H,H}$ = 1.8 Hz, $^4J_{H,H}$ = 1.8 Hz, 2 H, H_{ar}), 3.99 (s, 6 H, CH_3) ppm; *cis* isomer: δ 8.00 (dd, $^4J_{H,H}$ = 1.7 Hz, $^4J_{H,H}$ = 1.7 Hz, 2 H, H_{ar}), 7.39 (dd, $^4J_{H,H}$ = 1.6 Hz, $^4J_{H,H}$ = 1.6 Hz, 2 H, H_{ar}), 7.19 (dd, $^4J_{H,H}$ = 1.8 Hz, $^4J_{H,H}$ = 1.8 Hz, 2 H), H_{ar}, 3.89 (s, 6 H, CH_3) ppm. ^{13}C NMR (125 MHz, $CDCl_3$): δ 165.0, 152.8, 135.1, 132.9, 128.9, 124.2, 123.2, 52.7 ppm. HRMS (ESI+) $[C_{16}H_{12}{}^{79}Br^{81}BrN_2O_4 + Na]^+$ calcd, 478.9041; found, 478.9029. IR (ATR): 3444, 3074, 3035, 2964, 2850, 1841, 1793, 1732, 1563, 1446, 1432, 1280, 1242, 1203, 1183, 1103, 995, 922, 907, 887, 836, 763, 730, 683 cm^{-1}. UV/vis (DCM): λ_{max} (log ε) = 318 (4.21), 444 (2.73) nm.

Synthesis of 3,3′-Dibromo-5,5′-di(hydroxymethyl)-azobenzene (14). A solution of $LiAlH_4$ in THF (2 M, 0.36 mL, 0.75 mmol) was added to **2** (56 mg, 0.12 mmol) in anhydrous

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dichloromethane at 0 °C under argon, and the mixture was stirred for 3 h at 0 °C. Then, dichloromethane (20 mL) and water (1.0 mL) were added to the reaction mixture. The organic layer was separated, and the aqueous solution was extracted several times with dichloromethane. The combined organic phases were dried over $MgSO_4$ and concentrated in vacuo to yield diol **14** (96%, 46 mg, 0.11 mmol) as an orange solid, which was used for the next step without further purification. mp 186−188 °C. ^{1}H NMR (500 MHz, CD_3OD) *trans* isomer: δ 7.92 (m, 2 H, H_{ar}), 7.90 (m, 2 H, H_{ar}), 7.70 (m, 2 H, H_{ar}), 4.71 (s, 4 H, CH_2) ppm; *cis* isomer: δ 7.37 (m, 2 H, H_{ar}), 6.90 (m, 2 H, H_{ar}), 6.84 (m, 2 H, H_{ar}), 4.50 (s, 4 H, CH_2). ^{13}C NMR (125 MHz, CD_3OD): δ 154.7, 147.0, 133.4, 124.4, 124.1, 122.2, 63.9 ppm. HRMS (ESI+) $[C_{14}H_{12}{}^{79}Br^{81}BrN_2O_2 + Na]^+$ calcd, 422.9143; found, 422.9149. IR (ATR): 3305, 3082, 2922, 2855, 1659, 1602, 1575, 1450, 1434, 1358, 1307, 1253, 1218, 1132, 1097, 1020, 987, 903, 854, 821, 733, 685 cm^{-1}. UV/vis (DCM): λ_{max} (log ε) = 323 (4.19), 442 (2.79) nm.

Synthesis of 3. Triphenylphosphine (231 mg, 0.88 mmol) and *N*-bromosuccinimide (157 mg, 0.88 mmol) were added to a solution of diol **14** (92 mg, 0.23 mmol) in tetrahydrofuran at 0 °C under an argon atmosphere. The mixture was allowed to reach room temperature overnight. The volatiles were removed in vacuo, and the remaining solid was subjected to column chromatography (silica gel, *n*-hexane/dichloromethane, 10:2) to afford **3** (103 mg, 0.20 mmol, 85%) as an orange solid. mp 185−187 °C. ^{1}H NMR (500 MHz, $CDCl_3$) *trans* isomer: δ 7.99 (m, 2 H, H_{ar}), 7.91 (m, 2 H, H_{ar}), 7.68 (m, 2 H, H_{ar}), 4.52 (s, 4 H, CH_2) ppm; *cis* isomer: δ 7.35 (m, 2 H, H_{ar}), 7.01 (m, 2 H, H_{ar}), 6.69 (m, 2 H, H_{ar}), 4.28 (s, 4 H, CH_2) ppm. ^{13}C NMR (125 MHz, $CDCl_3$): δ 153.1, 140.7, 134.6, 125.1, 123.4, 123.3, 31.2 ppm. HRMS (ESI−) $[C_{14}H_{10}{}^{79}Br_2{}^{81}Br_2N_2 + {}^{81}Br]^-$ calcd, 606.6700; found, 606.6656. IR (ATR): 3124, 3089, 3055, 3027, 2973, 2923, 2859, 1799, 1779, 1598, 1557, 1429, 1306, 1268, 1241, 1209, 1140, 1121, 1089, 996, 979, 908, 880, 823, 689, 660 cm^{-1}. UV/vis (DCM): λ_{max} (log ε) = 324 (4.28), 446 (2.74) nm.

Synthesis of *trans*-5. Cesium carbonate (326 mg, 1.00 mmol) was added to a solution of clamp **4b** (25 mg, 0.045 mmol) and dibromide **3** (42 mg, 0.080 mmol) in anhydrous acetonitrile (25 mL), and the mixture was refluxed at 90 °C for 4 h under an argon atmosphere. After cooling to room temperature, dichloromethane (60 mL) and water (15 mL) were added. The organic layer was washed with water, dried over $MgSO_4$, and concentrated in vacuo. Column chromatography of the residue on silica gel (dichloromethane/ethyl acetate/methanol, 75:25:1) provided compound *trans*-**5** (35 mg, 0.038 mmol, 84%) as an orange solid. mp > 350 °C. ^{1}H NMR (600 MHz, $CDCl_3$): δ 7.90 (s, 2 H, H_{ar}), 7.52 (s, 2 H, H_{ar}), 7.42 (d, $^3J_{H,H}$ = 10.5 Hz, 2 H, N*H*), 7.12 (d, $^3J_{H,H}$ = 5.9 Hz, 2 H, N*H*), 5.90 (s, 2 H, H_{ar}), 5.36 (d, $^2J_{H,H}$ = 17.4 Hz, 2 H, CH_2), 4.98 (d, $^2J_{H,H}$ = 17.5 Hz, 2 H, CH_2), 4.97 (m, 2 H, C*H*), 4.61 (dd, $^3J_{H,H}$ = 8.0 Hz, $^3J_{H,H}$ = 10.5 Hz, 2 H, C*H*), 2.53−2.48 (m, 2 H, C*H*), 2.31−2.25 (m, 2 H, C*H*), 2.18 (s, 6 H, CH_3), 1.16 (d, $^3J_{H,H}$ = 6.7 Hz, 6 H, CH_3), 1.15 (d, $^3J_{H,H}$ = 6.7 Hz, 6 H, CH_3), 0.93 (d, $^3J_{H,H}$ = 6.2 Hz, 6 H, CH_3), 0.92 (d, $^3J_{H,H}$ = 6.6 Hz, 6 H, CH_3) ppm. ^{13}C NMR (151 MHz, $CDCl_3$): δ 171.1, 162.4, 153.0, 145.9, 138.7, 134.7, 131.2, 130.6, 125.7, 123.5, 117.9, 59.2, 51.3, 46.5, 33.0, 31.4, 19.6, 19.0, 18.5, 17.5, 10.1 ppm. HRMS (ESI+) $[C_{42}H_{52}{}^{79}Br^{81}BrN_{10}O_4 + Na]^+$ calcd, 943.2417; found, 943.2419. IR (ATR): 3389, 3073, 2963, 2930, 2873, 2358, 1660, 1593, 1504, 1463, 1428, 1388, 1371, 1333, 1256, 1223, 1140, 1091, 1048, 1029, 991, 952, 881, 858, 819, 765, 731, 688 cm^{-1}. UV/vis (DCM): λ_{max} (log ε) = 324 (4.30), 445 (2.69) nm. CD (DCM): λ_{max} ($\Delta\varepsilon$) = 251 (−34.89), 273 (−0.85), 297 (−2.87), 343 (+1.79), 452 (−5.81 M^{-1} cm^{-1}) nm.

Synthesis of 7. 4-Aminophenylboronic acid pinacol ester (646 mg, 2.95 mmol) was dissolved in dioxane (10.0 mL) under an argon atmosphere. $Pd(PPh_3)_4$ (23 mg, 0.020 mmol), an aqueous solution of potassium carbonate (saturated; 1.0 mL), and 6,6′-dibromo-2,2′-dipyridyl (**6**) (926 mg, 2.95 mmol) were added to the solution. The reaction mixture was warmed to 80 °C and stirred at that temperature overnight. After cooling to room temperature, dichloromethane (60 mL) and water (10 mL) were added. The phases were separated, and the aqueous layer was extracted several times with dichloromethane. The organic layers were combined and dried over $MgSO_4$, the solvent was removed, and the crude product was purified by column chromatography over silica gel (*n*-hexane/ethyl acetate, 1:1) to give **7** (301 mg, 0.92 mmol, 31%) as a white solid. mp 120−121 °C. ^{1}H NMR (600 MHz, $CDCl_3$): δ 8.58 (dd, $^4J_{H,H}$ = 0.7 Hz, $^3J_{H,H}$ = 7.8 Hz, 1 H, H_{ar}), 8.26 (dd, $^4J_{H,H}$ = 0.8 Hz, $^3J_{H,H}$ = 7.8 Hz, 1 H, H_{ar}), 7.97 (d, $^3J_{H,H}$ = 8.9 Hz, 2 H, H_{ar}), 7.81 (t, $^3J_{H,H}$ = 8.0 Hz, 1 H, H_{ar}), 7.68 (m, 2 H, H_{ar}), 7.48 (dd, $^4J_{H,H}$ = 0.8 Hz, $^3J_{H,H}$ = 8.1 Hz, 1 H, H_{ar}), 6.79 (d, $^3J_{H,H}$ = 8.9 Hz, 2 H, H_{ar}), 3.85 (s, 2 H, NH_2) ppm. ^{13}C NMR (151 MHz, $CDCl_3$): δ 157.8, 156.5, 153.7, 147.6, 141.4, 139.1, 137.5, 129.5, 128.1, 127.7, 119.8, 119.6, 118.6, 115.0 ppm. HRMS (ESI+) $[C_{16}H_{12}{}^{79}BrN_3 + Na]^+$ calcd, 348.0112; found, 348.0105. IR (ATR): 3427, 3411, 3300, 3199, 1641, 1606, 1591, 1572, 1547, 1519, 1459, 1448, 1426, 1415, 1373, 1344, 1320, 1285, 1273, 1227, 1185, 1168, 1147, 1124, 1108, 1092, 1070, 1048, 1012, 983, 960, 929, 904, 853, 836, 816, 808, 784, 720, 680, 657 cm^{-1}. UV/vis (DCM): λ_{max} (log ε) = 299 (4.43) nm.

Synthesis of 4-(6′-(4-Methoxyphenyl)-[2,2′-bipyridin]-6-yl)-aniline (15). 4-Methoxyphenylboronic acid (152 mg, 1.00 mmol) was dissolved in dioxane (7.0 mL) under an argon atmosphere. $Pd(PPh_3)_4$ (5.0 mg, 0.004 mmol), an aqueous solution of potassium carbonate (saturated; 0.7 mL), and bromide **7** (150 mg, 0.46 mmol) were added to the solution. The reaction mixture was warmed to 80 °C and stirred at that temperature overnight. After cooling to room temperature, dichloromethane (60 mL) and water (10 mL) were added. The phases were separated, and the aqueous layer was extracted several times with dichloromethane. The organic layers were combined and dried over $MgSO_4$, the solvent was removed, and the crude product was purified by column chromatography over silica gel (*n*-hexane/ethyl acetate, 1:1) to give **15** (107 mg, 0.30 mmol, 66%) as a white solid. mp 246−247 °C. ^{1}H NMR (600 MHz, $CDCl_3$): δ 8.53 (d, $^3J_{H,H}$ = 7.7 Hz, 1 H, H_{ar}), 8.49 (d, $^3J_{H,H}$ = 7.3 Hz, 1 H, H_{ar}), 8.13 (d, $^3J_{H,H}$ = 8.8 Hz, 2 H, H_{ar}), 8.02 (d, $^3J_{H,H}$ = 8.5 Hz, 2 H, H_{ar}), 7.85 (m, 2 H, H_{ar}), 7.71 (dd, $^4J_{H,H}$ = 0.7 Hz, $^3J_{H,H}$ = 7.8 Hz, 1 H, H_{ar}), 7.68 (dd, $^4J_{H,H}$ = 0.7 Hz, $^3J_{H,H}$ = 7.8 Hz, 1 H, H_{ar}), 7.04 (d, $^3J_{H,H}$ = 8.8 Hz, 2 H, H_{ar}), 6.81 (d, $^3J_{H,H}$ = 8.6 Hz, 2 H, H_{ar}), 3.89 (s, 3 H, CH_3), 3.84 (s, 2 H, NH_2) ppm. ^{13}C NMR (151 MHz, $CDCl_3$): δ 160.5, 156.3, 156.0, 155.9, 155.7, 147.4, 137.4, 137.3, 132.2, 129.9, 128.2, 128.1, 119.4, 119.0, 118.8, 118.3, 115.1, 114.1, 55.4 ppm. HRMS (ESI+) $[C_{23}H_{19}N_3O + Na]^+$ calcd, 376.1426; found, 376.1430. IR (ATR): 3459, 3371, 3215, 3000, 2962, 2932, 2907, 2837, 1602, 1561, 1512, 1457, 1433, 1373, 1300, 1286, 1266, 1244, 1178, 1157, 1129, 1115, 1086, 1026, 987, 963, 908, 841, 819, 792, 742 cm^{-1}. UV/vis (DCM): λ_{max} (log ε) = 294 (4.57) nm.

Synthesis of 8. 4-Chlorocarbonylbenzeneboronic anhydride (90%, 61 mg, 0.33 mmol) was dissolved in tetrahydrofuran (8 mL) under an argon atmosphere. Aniline **15** (67 mg, 0.19 mmol) dissolved in tetrahydrofuran (5 mL) was added dropwise at room temperature. Pyridine (0.08 mL) was added dropwise at room temperature, and the resulting mixture was stirred overnight. The precipitate was separated by filtration and air-dried to yield **8** (68 mg, 0.14 mmol, 71%) as a white solid. mp > 250 °C. ^{1}H NMR (600 MHz, DMSO-d_6): δ 10.43 (s, 1 H, N*H*), 8.51 (m, 2 H, H_{ar}), 8.29 (d, $^3J_{H,H}$ = 8.2 Hz, 2 H, H_{ar}), 8.23 (d, $^3J_{H,H}$ = 8.8 Hz, 2 H, H_{ar}), 8.07−8.03 (m, 3 H, H_{ar}), 8.00−7.99 (m, 3 H, H_{ar}), 7.97−7.94 (m, 4 H, H_{ar}), 7.11 (d, $^3J_{H,H}$ = 8.9 Hz, 2 H, H_{ar}), 3.85 (s, 3 H, CH_3) ppm. ^{13}C NMR (151 MHz, DMSO-d_6): δ 165.7, 160.2, 155.1, 155.0, 154.9, 154.8, 140.2, 138.3, 138.2, 136.0, 133.9, 133.5, 130.9, 127.9, 126.9, 126.5, 120.2, 119.8, 119.6, 118.7, 118.5, 114.1, 55.2 ppm. HRMS (ESI+) $[C_{30}H_{24}BN_3O_4 + Na]^+$ calcd, 524.1758; found, 524.1752. IR (ATR): 3280, 1639, 1607, 1589, 1564, 1528, 1513, 1468, 1436, 1396, 1355, 1328, 1299, 1274, 1173, 1135, 1114, 1083, 1027, 1012, 914, 843, 813, 788, 754, 742, 699, 670 cm^{-1}. UV/vis (MeOH): λ_{max} (log ε) = 292 (4.73), 319 (4.65) nm.

Synthesis of *trans*-9. Boronic acid **8** (60 mg, 0.12 mmol) was dissolved in dioxane (4.0 mL) under an argon atmosphere. $Pd(PPh_3)_4$ (1.0 mg, 0.001 mmol), an aqueous solution of potassium carbonate (saturated; 0.4 mL), and azo compound *trans*-**5** (22 mg, 0.024 mmol) were added to the solution. The reaction mixture was stirred under an argon atmosphere for 1 day at 80 °C under simultaneous irradiation with UV light (λ = 365 nm). After cooling to room temperature, dichloromethane (60 mL) and water (10 mL) were added. The phases were separated, and the aqueous layer was extracted several times with

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dichloromethane. The organic layers were combined and dried over $MgSO_4$, the solvent was removed, and the crude product was purified by column chromatography over silica gel (dichloromethane/ethyl acetate, 75:25) to provide *trans*-**9** (13.7 mg, 0.008 mmol, 34%) as an orange solid. mp > 350 °C. ^{1}H NMR (600 MHz, $CDCl_3$): δ 8.58 (dd, $^4J_{H,H}$ = 0.7 Hz, $^3J_{H,H}$ = 7.8 Hz, 2 H, H_{ar}), 8.55 (dd, $^4J_{H,H}$ = 0.7 Hz, $^3J_{H,H}$ = 7.8 Hz, 2 H, H_{ar}), 8.24 (d, $^3J_{H,H}$ = 8.7 Hz, 4 H, H_{ar}), 8.14 (d, $^3J_{H,H}$ = 8.8 Hz, 4 H, H_{ar}), 8.11 (s, 2 H, H_{ar}), 8.04 (m, 6 H, H_{ar}), 7.92−7.86 (m, 8 H, H_{ar}), 7.81−7.78 (m, 6 H, H_{ar}), 7.73 (dd, $^4J_{H,H}$ = 0.7 Hz, $^3J_{H,H}$ = 7.8 Hz, 2 H, H_{ar}), 7.62 (s, 2 H, H_{ar}), 7.49 (d, $^3J_{H,H}$ = 10.6 Hz, 2 H, N*H*), 7.21 (d, $^3J_{H,H}$ = 5.9 Hz, 2 H, N*H*), 7.05 (d, $^3J_{H,H}$ = 8.9 Hz, 4 H, H_{ar}), 6.03 (s, 2 H, N*H*), 5.48 (d, $^2J_{H,H}$ = 17.2 Hz, 2 H, CH_2), 5.11 (d, $^2J_{H,H}$ = 17.3 Hz, 2 H, CH_2), 5.05 (dd, $^3J_{H,H}$ = 3.9 Hz, $^3J_{H,H}$ = 5.8 Hz, 2 H, C*H*), 4.66 (dd, $^3J_{H,H}$ = 7.8 Hz, $^3J_{H,H}$ = 10.5 Hz, 2 H, C*H*), 3.90 (s, 6 H, CH_3), 2.58−2.52 (m, 2 H, C*H*), 2.35−2.29 (m, 2 H, C*H*), 2.25 (s, 6 H, CH_3), 1.19 (d, $^3J_{H,H}$ = 6.7 Hz, 6 H, CH_3), 1.18 (d, $^3J_{H,H}$ = 6.7 Hz, 6 H, CH_3), 0.96 (d, $^3J_{H,H}$ = 8.5 Hz, 6 H, CH_3), 0.94 (d, $^3J_{H,H}$ = 7.0 Hz, 6 H, CH_3) ppm. ^{13}C NMR (151 MHz, $CDCl_3$): δ 171.2, 165.1, 162.6, 160.5, 156.06, 156.03, 155.77, 155.51, 153.1, 145.9, 143.1, 141.8, 138.7, 137.69, 137.60, 137.53, 135.7, 134.9, 134.3, 132.1, 130.5, 128.2, 127.9, 127.73, 127.68, 126.9, 121.2, 120.2, 119.8, 119.6, 119.4, 118.8, 118.7, 114.1, 59.3, 55.4, 51.4, 47.1, 33.0, 31.4, 19.7, 19.0, 18.6, 17.5, 10.2 ppm. HRMS (ESI+) $[C_{102}H_{96}N_{16}O_8 + Na]^+$ calcd, 1695.7495; found, 1695.7505. IR (ATR): 3384, 2962, 2927, 2872, 1667, 1597, 1564, 1514, 1463, 1434, 1402, 1390, 1372, 1317, 1302, 1248, 1178, 1152, 1104, 1085, 1043, 1028, 988, 953, 897, 847, 823, 796, 763, 743, 697, 667 cm^{-1}. UV/vis (DCM/CH_3CN, 9:1): λ_{max} (log ε) = 297 (4.90), 320 (4.90), 426 (2.94) nm. CD (DCM/CH_3CN, 9:1): λ_{max} ($\Delta\varepsilon$) = 252 (−27.34), 332 (+9.78), 444 (−7.60 M^{-1} cm^{-1}) nm.

Synthesis of 10. 4-Methoxyphenylboronic acid (330 mg, 2.17 mmol) was dissolved in dioxane (10.0 mL) under an argon atmosphere. $Pd(PPh_3)_4$ (23 mg, 0.020 mmol), an aqueous solution of potassium carbonate (saturated; 1.0 mL), and 6,6′-dibromo-2,2′-dipyridyl (**6**) (1.025 g, 3.26 mmol) were added to the solution. The reaction mixture was warmed to 80 °C and stirred at that temperature overnight. After cooling to room temperature, dichloromethane (60 mL) and water (10 mL) were added. The phases were separated, and the aqueous layer was extracted several times with dichloromethane. The organic layers were combined and dried over $MgSO_4$, the solvent was removed, and the crude product was purified by column chromatography over silica gel (*n*-hexane/ethyl acetate, 10:1) to give **10** (526 mg, 1.54 mmol, 71%) as a white solid. mp 128−129 °C. ^{1}H NMR (600 MHz, $CDCl_3$): δ 8.59 (d, $^3J_{H,H}$ = 7.2 Hz, 1 H, H_{ar}), 8.31 (d, $^3J_{H,H}$ = 7.8 Hz, 1 H, H_{ar}), 8.09 (d, $^3J_{H,H}$ = 8.9 Hz, 2 H, H_{ar}), 7.84 (t, $^3J_{H,H}$ = 7.8 Hz, 1 H, H_{ar}), 7.72 (d, $^3J_{H,H}$ = 7.8 Hz, 1 H, H_{ar}), 7.69 (t, $^3J_{H,H}$ = 7.8 Hz, 1 H, H_{ar}), 7.49 (d, $^3J_{H,H}$ = 7.8 Hz, 1 H, H_{ar}), 7.03 (d, $^3J_{H,H}$ = 8.9 Hz, 2 H, H_{ar}), 3.89 (s, 3 H, CH_3) ppm. ^{13}C NMR (151 MHz, $CDCl_3$): δ 160.6, 157.7, 156.2, 153.9, 141.5, 139.1, 137.7, 131.8, 128.2, 127.9, 120.1, 119.9, 119.0, 114.1, 55.4 ppm. HRMS (ESI+) $[C_{17}H_{13}{}^{79}BrN_2O + Na]^+$ calcd, 363.0109; found, 363.0094. IR (ATR): 3087, 3040, 3006, 2971, 2933, 2838, 1608, 1572, 1548, 1516, 1462, 1422, 1375, 1325, 1301, 1278, 1249, 1180, 1165, 1152, 1128, 1116, 1068, 1032, 985, 957, 904, 835, 821, 784, 739, 718, 657 cm^{-1}. UV/vis (DCM): λ_{max} (log ε) = 284 (4.37) nm.

Synthesis of 11. To a solution of bromide **10** (177 mg, 0.52 mmol) in dry tetrahydrofuran (8.0 mL) was added a solution of *n*-butyllithium in hexane (0.30 mL, 2.5 M, 0.75 mmol) dropwise under argon at −78 °C. The resulting mixture was stirred for 1 h before adding $ClSnBu_3$ (0.27 mL, 1.00 mmol) at −78 °C. The solution was stirred at this temperature for 45 min and subsequently quenched with a saturated solution of NH_4Cl. After phase separation, the aqueous phase was extracted with dichloromethane. The combined organic layers were dried over $MgSO_4$ and concentrated in vacuo to yield stannane **11** (280 mg, 0.51 mmol, 98%) as a yellowish oil, which was used for the next step without further purification. ^{1}H NMR (300 MHz, $CDCl_3$): δ 8.44 (m, 2 H, H_{ar}), 8.12 (d, $^3J_{H,H}$ = 9.0 Hz, 2 H, H_{ar}), 7.83 (t, $^3J_{H,H}$ = 7.8 Hz, 1 H, H_{ar}), 7.66 (m, 2 H, H_{ar}), 7.41 (dd, $^4J_{H,H}$ = 1.3 Hz, $^3J_{H,H}$ = 7.3 Hz, 1 H, H_{ar}), 7.03 (d, $^3J_{H,H}$ = 9.0 Hz, 2 H, H_{ar}), 3.89 (s, 3 H, CH_3), 1.61 (m, 6 H, CH_2), 1.36 (m, 6 H, CH_2), 1.16 (m, 6 H, CH_2), 0.90 (t, $^3J_{H,H}$ = 7.4 Hz, 9 H, CH_3) ppm. HRMS (ESI+) $[C_{29}H_{40}N_2O^{120}Sn + H]^+$ calcd, 553.2241; found, 553.2246.

Synthesis of *trans*-12. $Pd(PPh_3)_4$ (3.0 mg, 0.002 mmol) was added to a toluene solution (8 mL) of a mixture of azo compound *trans*-**5** (25 mg, 0.027 mmol) and stannane **11** (83 mg, 0.150 mmol) under an argon atmosphere. The reaction mixture was stirred under argon for 4 days at 95 °C by simultaneous irradiation with UV light (λ = 365 nm). After cooling to room temperature, the mixture was evaporated to dryness under reduced pressure. Column chromatography of the residue on silica gel (dichloromethane/ethyl acetate/methanol, 75:25:6) provided *trans*-**12** (17.0 mg, 0.013 mmol, 49%) as an orange solid. mp > 350 °C. ^{1}H NMR (600 MHz, $CDCl_3$/CD_3OD): δ 8.54 (d, $^3J_{H,H}$ = 7.9 Hz, 2 H, H_{ar}), 8.46 (d, $^3J_{H,H}$ = 7.7 Hz, 2 H, H_{ar}), 8.43 (s, 2 H, H_{ar}), 8.26 (s, 2 H, H_{ar}), 8.03 (d, $^3J_{H,H}$ = 8.8 Hz, 4 H, H_{ar}), 7.94 (d, $^3J_{H,H}$ = 10.7 Hz, 2 H, N*H*), 7.91 (t, $^3J_{H,H}$ = 7.8 Hz, 2 H, H_{ar}), 7.84 (m, 4 H, H_{ar}), 7.67 (d, $^3J_{H,H}$ = 7.4 Hz, 2 H, H_{ar}), 7.43 (d, $^3J_{H,H}$ = 7.2 Hz, 2 H, N*H*), 6.96 (d, $^3J_{H,H}$ = 8.8 Hz, 4 H, H_{ar}), 6.04 (s, 2 H, H_{ar}), 5.50 (d, $^2J_{H,H}$ = 17.2 Hz, 2 H, CH_2), 5.17 (d, $^2J_{H,H}$ = 17.2 Hz, 2 H, CH_2), 5.01 (d, $^3J_{H,H}$ = 4.0 Hz, 2 H, C*H*), 4.44 (d, $^3J_{H,H}$ = 9.4 Hz, 2 H, C*H*), 3.80 (s, 6 H, CH_3), 2.35−2.30 (m, 2 H, C*H*), 2.17−2.10 (m, 2 H, C*H*), 2.16 (s, 6 H, CH_3), 1.08 (d, $^3J_{H,H}$ = 6.5 Hz, 6 H, CH_3), 1.07 (d, $^3J_{H,H}$ = 6.5 Hz, 6 H, CH_3), 0.91 (d, $^3J_{H,H}$ = 7.0 Hz, 6 H, CH_3), 0.89 (d, $^3J_{H,H}$ = 7.0 Hz, 6 H, CH_3) ppm. ^{13}C NMR (151 MHz, $CDCl_3$/CD_3OD): δ 171.6, 163.0, 160.4, 156.2, 156.1, 155.3, 154.5, 152.9, 145.9, 141.0, 137.84, 137.54, 137.45, 135.1, 131.8, 130.1, 128.1, 126.8, 120.51, 120.46, 120.3, 119.7, 118.99, 118.85, 113.9, 59.8, 55.2, 50.9, 47.1, 33.5, 31.4, 19.3, 19.2, 18.0, 17.7, 9.9 ppm. HRMS (ESI+) $[C_{76}H_{78}N_{14}O_6 + Na]^+$ calcd, 1305.6127; found, 1305.6135. IR (ATR): 3305, 2955, 2921, 2852, 1737, 1660, 1606, 1564, 1514, 1462, 1430, 1374, 1337, 1301, 1251, 1174, 1090, 1056, 1027, 843, 799, 743, 720 cm^{-1}. UV/vis (DCM): λ_{max} (log ε) = 278 (4.61), 425 (2.89) nm. CD (DCM): λ_{max} ($\Delta\varepsilon$) = 253 (−19.35), 279 (+2.61), 314−2.34), 448 (−5.94 M^{-1} cm^{-1}) nm.

■ ASSOCIATED CONTENT

Supporting Information

Molecular structures of *cis*-(*P*)-**5**, *cis*-(*M*)-**5**, and *trans*-**5**; CD, HPLC, NMR and UV spectra; Cartesian coordinates and absolute energies of *cis*-(*P*)-**5**, *cis*-(*M*)-**5**, and *trans*-**5**; ^{1}H and ^{13}C NMR spectra of the new compounds; crystal structure data of *trans*-**5**; complete ref 28; and CIF file for *trans*-**5**. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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