

Azobenzene: Teaching an old dog some new tricks

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Introduction

The past decades have witnessed an increasing research effort in the development of light-responsive molecular systems and materials based on photochromic compounds such as spiropyrans, diarylethenes, and azobenzenes (ABs). Although the latter have been known to undergo *E-Z* isomerization upon UV and visible light irradiation for almost 80 years,¹ and several thousands of scientific papers have already been published on this topic, the azobenzene molecule is still good for a few surprises and can be taught some new “tricks”, given proper molecular design and creative integration into larger functional systems. In this letter, we will present some of our latest efforts in both of these directions, in particular with the inherent optimization of the photoswitch by *ortho*-fluorination (first section), the synthesis of covalent multiazobenzene architectures undergoing drastic geometrical modification (second section), and the creation of switching self-assembled lattices at surfaces (third section).

Optimization of azobenzenes by *ortho*-fluorination: All-visible light switches with very long-lived *Z* isomers and high photoconversions

In order to extend the scope of possible applications, it is critical that chemists optimize the intrinsic properties of their favorite photoactive compounds. The typical performance criteria of photochromic

compounds are photoconversions, quantum yields of isomerization, thermal half-life of the thermodynamically less stable isomer, fatigue resistance, and last but not least, the possibility to isomerize in both directions without UV light,² which is often damaging and penetrates only partially through most media.

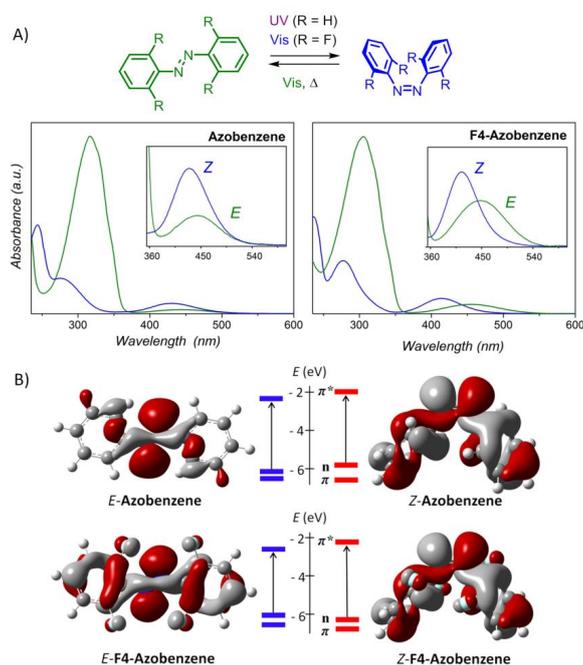


Figure 1. Comparison of electronic transitions in unsubstituted azobenzene (left) and *ortho*-tetrafluoroazobenzene (right). A) UV-vis absorption spectra in acetonitrile at 25 °C and B) energetic diagram of the π , n , and π^* orbitals, and representation of the n orbitals (HOMOs) calculated at the B3LYP/6-31G level of theory (arrows highlight $n \rightarrow \pi^*$ transitions).

Azobenzene is clearly a superior photoswitch in term of fatigue resistance, however, all the other criteria are typically not optimal. For example, although the $E \rightarrow Z$ photoconversion is typically high to very high (90-95%), the reverse $Z \rightarrow E$ photoconversion is often limited to 80-85%; the quantum yields are commonly not higher than 50%; the Z isomer persists only for a few hours to days in solution; and finally, UV light is typically essential to trigger the $E \rightarrow Z$ isomerization.

In order to tackle the visible light activation issue, and following pioneering work by Herges³ and Woolley,⁴ we decided to explore the possibility to separate the E and Z isomers' $n \rightarrow \pi^*$ absorption bands, which typically overlap in ABs (see Figure 1A). We anticipated that introducing electron withdrawing groups (EWG) *ortho* to the N=N would decrease the electronic repulsion occurring between the N lone pairs in the Z form, therefore stabilizing its n -orbital and eventually increasing the $n \rightarrow \pi^*$ gap of the Z isomer (compared to the $n \rightarrow \pi^*$ gap of the E isomer). Encouraged by DFT calculations (see Figure 1B), we opted for F atoms, which, in addition to being σ -withdrawing and π -donating at the same time, are rather small and therefore do not significantly twist the typically planar E isomer.^{5,6}

As expected, the E and Z isomers' $n \rightarrow \pi^*$ absorption bands of *ortho*-tetrafluoroazobenzene significantly split with a 40 nm separation of the absorption maxima (see Figure 1A). This feature allows for triggering E - Z isomerizations with visible light only (green for $E \rightarrow Z$ and blue for $Z \rightarrow E$). Further EWGs (such as ester groups) introduced *para* to the N=N work in concert with the *ortho*-F and lead to a superior photoswitchable compound, which exhibits a 50 nm separation of the $n \rightarrow \pi^*$ bands. Such a high separation makes possible to address both isomers selectively and as a consequence very high photoconversions (up to 97%) can be reached in both directions. On the contrary, electron donating groups (EDGs) such as N-acyls introduced in *para*-positions counterbalance the effects of the *ortho*-fluorine atoms by pushing electron density into the N=N bond. The separation of the $n \rightarrow \pi^*$ bands is

reduced to 22 nm and eventually the two isomers cannot be selectively excited in the visible range, leading to only 69% $Z \rightarrow E$ photoconversion (when irradiated at 440 nm).

A very attractive, though totally unexpected additional feature of F-ABs is the very high thermal stability of the Z isomers: a half-life ($\tau_{1/2}$) of 2 years (!) measured at room temperature in DMSO *vs.* a few days for unsubstituted ABs. This effect can be partly attributed to the pronounced stabilization of the n-orbital of the Z isomer (while the n-orbital of the transition state is less stabilized), which eventually leads to a larger barrier for the thermal $Z \rightarrow E$ reaction and place ortho F-ABs among the most stable azobenzenes ever reported.

Noteworthy, in addition to offering visible-light addressability, isomerizing ABs *via* $n \rightarrow \pi^*$ transitions is also quite efficient (quantum yields of typically $\Phi = 0.3-0.5$ *via* $n \rightarrow \pi^*$ *vs.* $\Phi = 0.1-0.2$ *via* $\pi \rightarrow \pi^*$ transitions).

In summary, *ortho*-fluoroazobenzenes constitute a new class of photoswitches with outstanding properties. The high level of bistability combined with the possibility to isomerize without UV-light opens many possibilities in life-sciences, for example in the growing field of photopharmacology,⁷ whose aim is to activate/deactivate drugs with (ideally NIR) light, but also in materials science, where many photo-responsive systems would benefit from sun-light harvesting or activation.

Covalent multiazobenzene architectures: Maximizing the photodeformation of individual molecules

Integrating azobenzene photoswitches into the backbone of oligomers and polymers with well-defined shapes offers some interesting possibilities, in particular for amplifying mechanical motion of single macromolecules and creating cooperative systems, where only a few switching event triggers dramatic changes in a particular self-assembly.

Our efforts in that direction focused on the integration of ABs into rigid-rod polymers and monodisperse foldamers (see Figure 2).

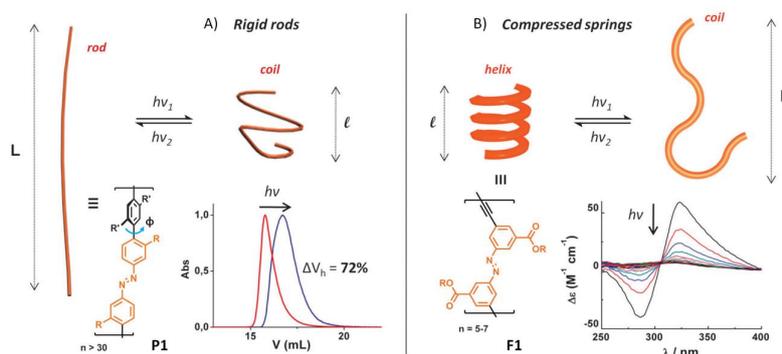


Figure 2. Large photodeformation of anisotropic macromolecules. A) Poly(*para*-phenylene)s rigid rods' light-induced shrinking, accompanied with a decrease in their hydrodynamic volume of $\Delta V_h = 72\%$. B) Oligo(*meta*-phenylene ethynylene) chiral foldamers' light-induced extension, accompanied with the vanishing of circular dichroism signals.

Rigid rods such as poly(*para*-phenylene) derivative *E*-**P1** are anisotropic objects displaying high aspect ratio. Therefore, upon *E/Z* isomerization the rods significantly shrink and stretch in response to UV and visible light, respectively.⁸ The structural modification is accompanied with a marked decrease in their hydrodynamic volume ($\Delta V_h = 72\%$), as measured by light scattering, which list among the highest level of contraction reported for AB-based polymeric architecture. Large twist angles (Φ) were introduced into the rigid scaffold in order to electronically decouple the chromophores, an approach allowing for quantitative photoswitching in linear multi-azobenzene architectures.⁹

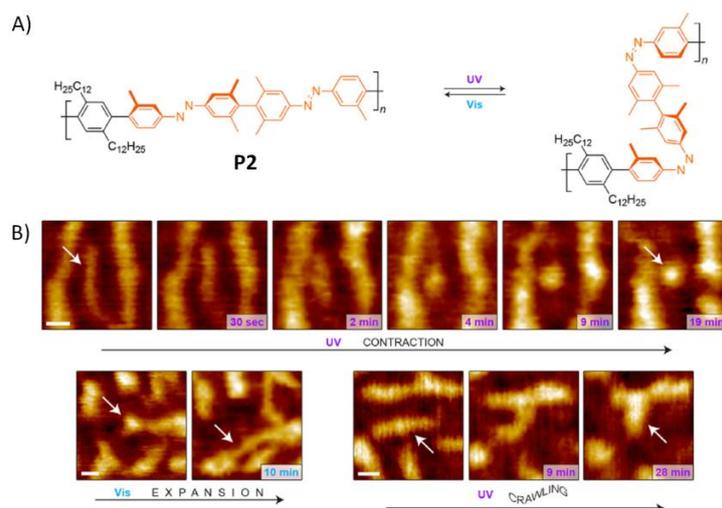


Figure 3. Photoinduced motion of single macromolecules at surfaces. A) Molecular structure of polymer **P2** and B) Surface force microscopy snapshots showing UV-induced contractions, blue light-induced expansions, and UV-induced contraction accompanied by crawling of single polymer chains (scale bars 20 nm).

Such articulated macromolecules could be isolated on templated surfaces and their photomovement observed at the single molecule level^{10,11} (see Figure 3). The dramatic contraction/expansion indirectly measured in solution by light scattering could be directly visualized by scanning force microscopy. In addition, more complex motion such as crawling events accompanying light-induced isomerization at the surface could also be identified. Taking these structures to the next hierarchical level, *i.e.* supramolecular assemblies, is currently underway.

On the other hand, synthetic molecular helices or *foldamers* such as oligo(*meta*-phenylene ethynylene) **F1** experience an efficient helix to coil transition as a result of the *E*→*Z* isomerization of the embedded azobenzenes.¹²⁻¹⁵ After optimizing the number¹² and location¹⁴ of

azobenzene photochromes per turn as well as the length of the oligomers,^{12,14} quantitative unfolding could be achieved, as observed by vanishing circular dichroism signals. Remarkably, the light-induced denaturation of the helices overcomes both intramolecular stacking interactions and solvophobic effects. In analogy to the macroscopic world, these multiazobenzene foldamers can be viewed as compressed molecular springs releasing potential energy upon unloading.

Insight into the mechanism of the foldamers' denaturation was gained by incorporating only two azobenzene switching units within the foldamer backbone. By comparing the quantum yields of successive switching events a *cooperative* process could be uncovered in case when the azobenzene units are located near the core of the foldamer since the first switching event facilitates the subsequent one by intermediate unfolding resulting in a lowering of the isomerization barrier.¹³ In another foldamer series energy transfer from donor to acceptor azobenzene units was used to localize the excitation energy either at the core or at the periphery of the foldamer thereby initiating unfolding either from the inside-out or vice versa.¹⁵ Such optimized photoswitchable foldamers could be used to design efficient photoswitchable dual catalysts,¹⁶ where two units should be in close contact to be active, while light-induced denaturation would deactivate the catalyst.

Switching self-assembled lattices at surfaces

Interfacing molecular switches with conducting and semiconducting surfaces while preserving their photoactivity is an important challenge for the construction of light-responsive hybrid systems. Our approach relies on *physisorbed* self-assembled monolayers, with azobenzenes either oriented up-right (see Figure 4) or in a flat fashion (see Figure 5). Due to the large geometrical difference between the structures of the *E* and *Z* isomers, a necessary prerequisite for photoisomerization to occur in azobenzene-containing molecular layers is to provide sufficient free volume to the system. Decoupling the photochromic unit electronically from the conducting surface by avoiding a direct contact is also crucial to preserve the photoisomerization ability.

In our up-right oriented approach¹⁷ (see compound **3**) we used a terfluorene platform, equipped with COOH groups to direct the self-assembly via H-bonds and dodecyl chains to favor physisorption on highly oriented pyrolytic graphite (HOPG). This design provides free-space to the photoswitch and by scanning tunneling microscopy (STM) measurements at the solid-liquid interface we could confirm the self-assembly of **3** into linear polymers zipped together *via* alkyl chains' interdigitation. Upon UV-light irradiation, we observed a progressive change in the packing of the monolayer, indicating the transformation of the 2D crystal from *E*- to *Z*-azobenzenes.

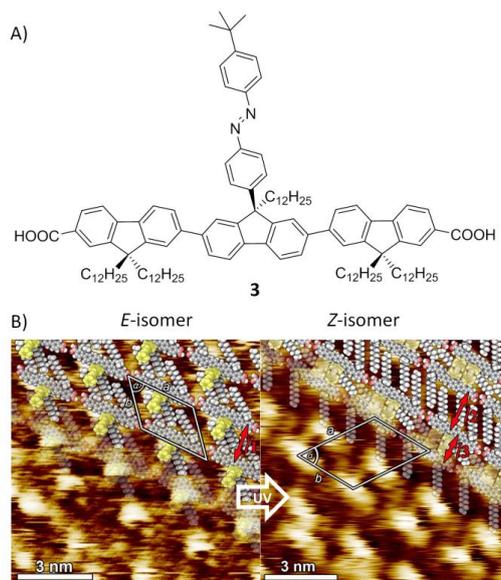


Figure 4. Photoswitching self-assembled physisorbed monolayers. A) Molecular structure of the terfluorene platform supported azobenzene derivative *E*-**3** and B) STM height image of **3** at the HOPG-phenyloctane interface in its *E*- (left) and *Z*-isomer (right), obtained upon UV irradiation for *ca.* 1 h.

The monolayer could be switched back *via* $Z \rightarrow E$ isomerization induced by blue light. However, in view of the dynamic nature of the system involving continuous desorption/adsorption and considering the large differences in the dimensions of the crystal lattices (unit cells) it is rather likely that the switching process occurs in solution and not when bound on the surface.

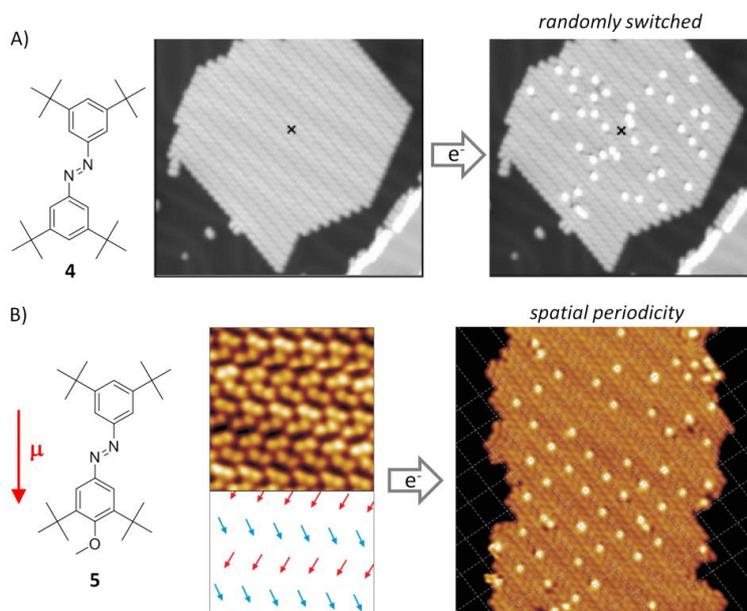


Figure 5. Electric field-induced isomerization of azobenzenes at surfaces. A) Electric pulses applied from the tip of a STM (localized at the cross) induce azobenzenes $E \rightarrow Z$ isomerization creating a random pattern of Z-isomers. B) When a dipole (μ) is introduced in the azobenzene derivative, a commensurability is established between the monolayer and the substrate, leading to the creation of a periodic array of

switched molecules upon scanning at elevated biased voltage (conditions: 10^{-10} mbar, 7 K, Au(111)).

In order to switch molecules in physisorbed monolayers directly at the surface without interfering desorption processes, interfaces in ultra-high vacuum environment are inevitably more suitable. Azobenzene was equipped with four *tert*-butyl "legs" in order to decouple the photochrome from the surface (compound **4**), and the resulting islands of densely packed building blocks on Au(111) analyzed by STM.¹⁸ In that case the switching was electronically induced by the STM tip, and the *Z*-isomers appear as bright protrusions randomly located within the islands. In order to create arrays of ordered *Z*-isomers, an additional feature needed to be integrated into the switch: a permanent intrinsic *dipole*. This was achieved by attaching one methoxy group *para* to the N=N (see compound **5**).¹⁹ Thanks to this new molecular property, a commensurability between the monolayer and the underlying substrate could be established, which defines the local switching ability of the molecules on the surface. Consequently, the same periodic lattices of *Z* isomers are created in repeated erasing and reswitching cycles. These results demonstrate a conceptually original approach to use self-assembled photoswitch arrays to simultaneously address single molecular entities on the length scale of few nanometers (nanopatterning).

Before concluding this letter, it should be emphasized that in order to create photoresponsive organic electronics, diarylethene photoswitches are arguably more promising candidates than ABs, as they require fewer free volume and therefore can be switched faster, in addition to offering a greater change in HOMO-LUMO gaps and relative levels, as recently demonstrated with the construction of light-addressable OFETs.^{20,21}

Conclusion

As illustrated in the previous sections, the azobenzene chromophore - despite being the oldest investigated photochromic family - remains

attractive for creating advanced light-responsive functional systems. Thanks to molecular design and extensive structure-switch relationship studies, we were able to dramatically improve the intrinsic photoswitching properties of azobenzenes, in particular addressability with visible light, high photoconversion in both switching directions, as well as thermal half life. Furthermore, we could successfully amplify the significant geometrical changes occurring during the course of photochemical *E-Z* isomerization in an individual azobenzene unit by exploiting macromolecular architectures, such as rigid rod as well as helically folding azobenzene main chain polymers. Beyond the (macro)molecular level, we could create assemblies of azobenzene switches organized on surfaces and use them to generate periodic nanoscale patterns. Based on these examples and our experience over the past decade it is fair to conclude by comparing azobenzenes some good red wine – it gets better with age!

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