Upconverting Nanoparticle Relays for Signal Restoration in Resonance Energy Transfer Networks

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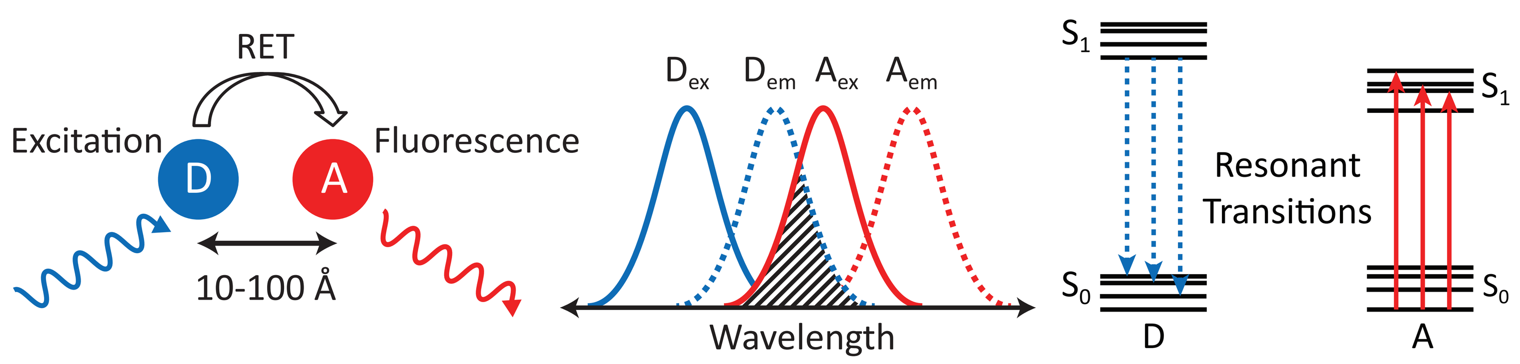
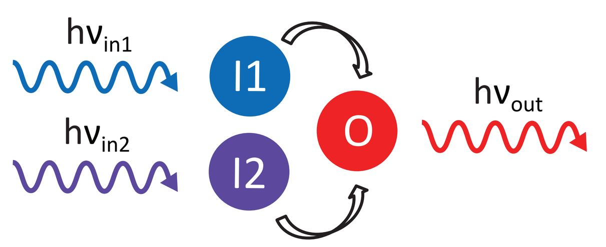
Background

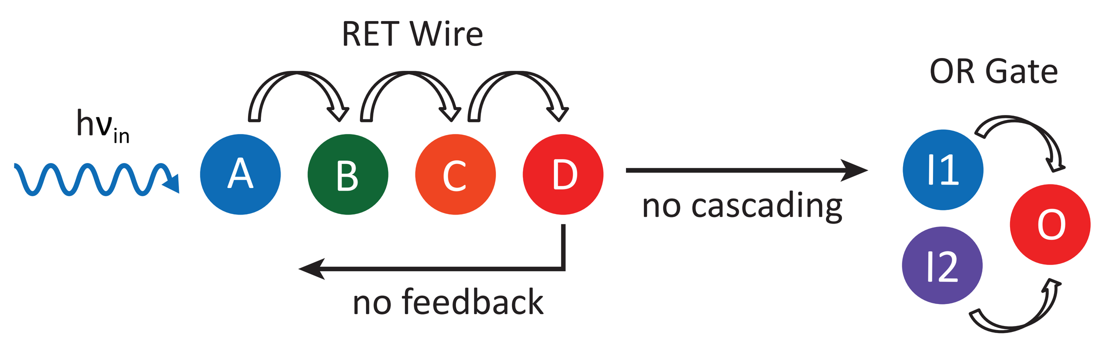
Resonance energy transfer (RET) is a weak dipole-dipole coupling that allows an excited fluorophore to non-radiatively donate its energy to a neighboring fluorophore. The donor's emission must overlap the acceptor's excitation and the molecules must be 1-10 nm apart.



Fluorophores can be spatially arranged into networks that perform Boolean logic using RET (RET Logic) [1]. For example, an OR gate is composed of two distinctly addressable donors (I1 and I2) that can each transfer to a single acceptor (O).

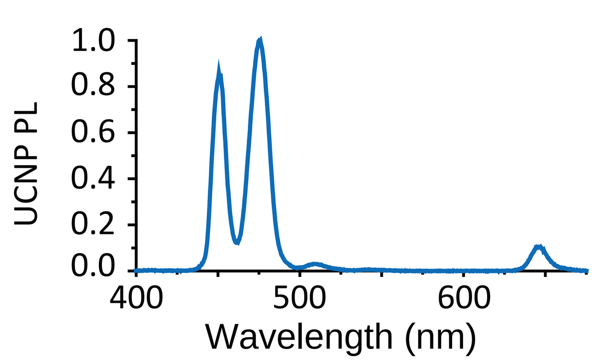


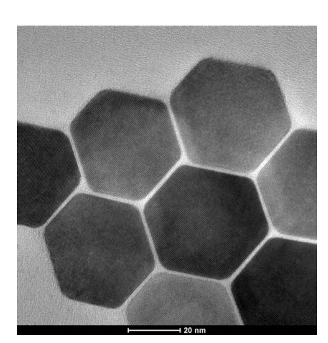
Problem: As excitons traverse a RET network, they lose energy due to the vibrational relaxation of each fluorophore. This loss prohibits the use of feedback and the cascading of RET networks.



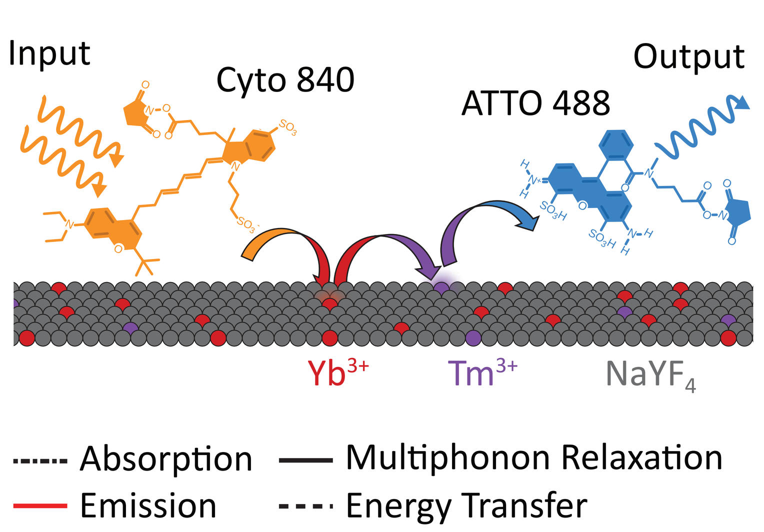
Without a way to restore this energy, it is difficult to build large-scale RET systems.

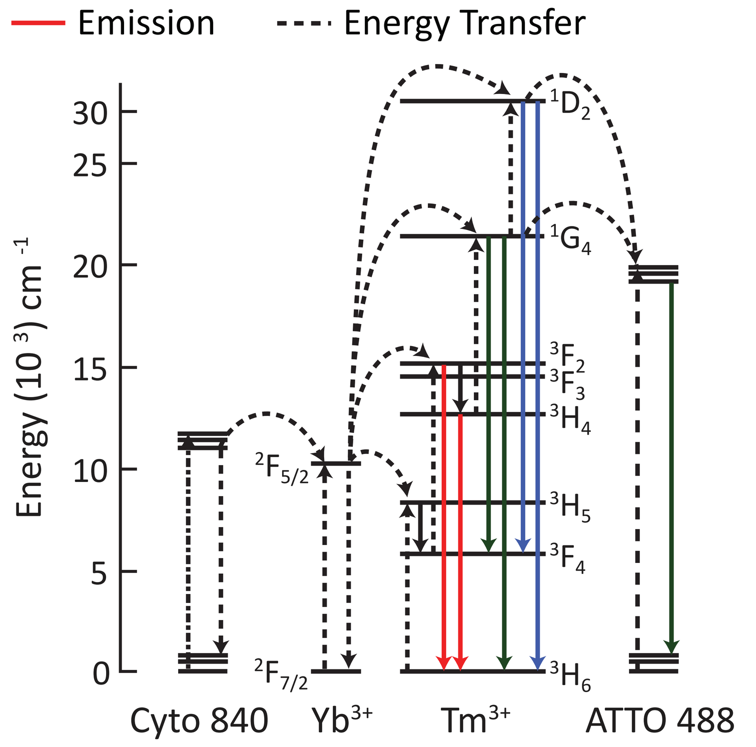
Upconverting nanoparticles (UCNPs) provide a way to restore this energy loss by converting near-infrared (NIR) photons (980 nm) into visible light using a set of lanthanide dopants (Yb^{3+} and Tm^{3+}) [2].





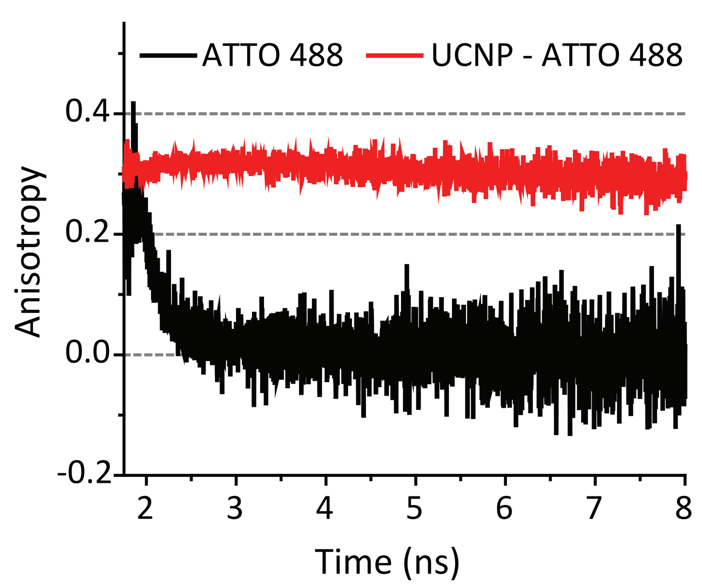
Relay Design and Assembly





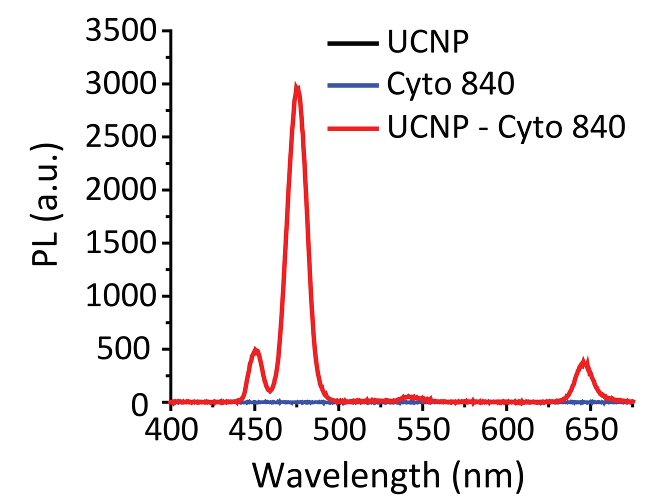
We have designed a UCNP based RET relay that converts multiple low energy excitons from a NIR absorbing fluorophore (Cyto 840) into a single high energy exciton accepted by a visible fluorophore (ATTO 488).

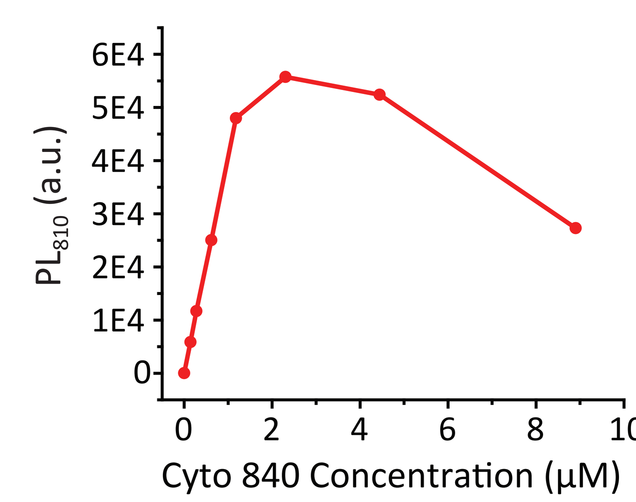
To assemble the relay, fluorophores are directly adsorbed to the UCNPs. Adsorption was confirmed by colorimetric comparison of centrifuged free dye, UCNPs, and UCNP-dye complexes, and time-resolved fluorescence anisotropy measurements.



UCNP-Cyto 840 Characterization

To demonstrate the first half of the relay, the photoluminescence (PL) from a sample of UCNP-Cyto 840 when excited at 810 nm was compared to two negative controls consisting of the individual constituents at the same concentrations.



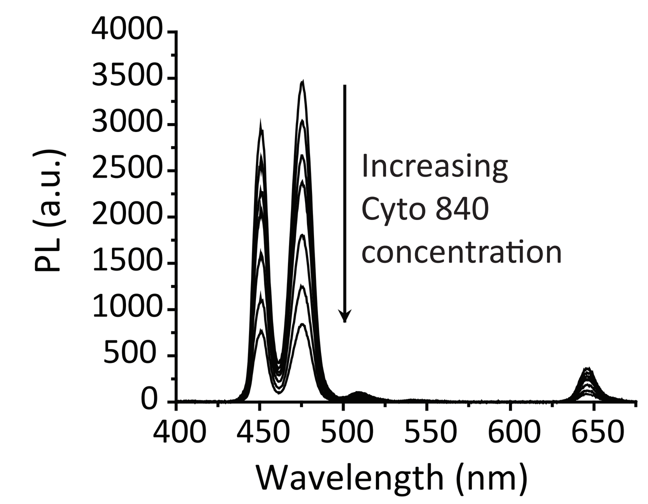


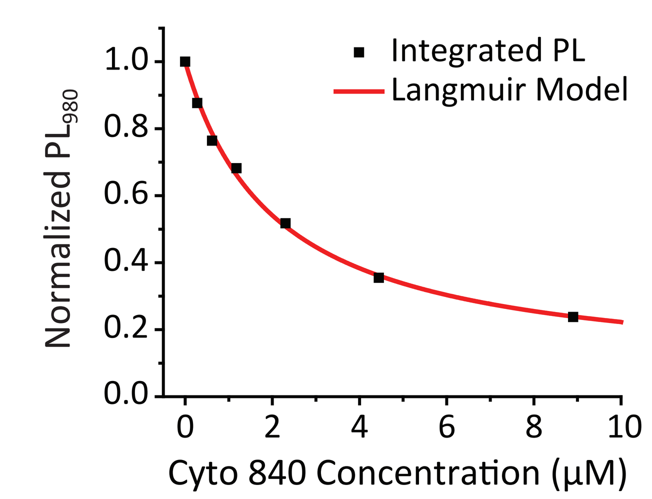
UCNP PL can be optimized by varying the Cyto 840 assembly concentration.

Direct excitation of the UCNP-Cyto 840 complexes at 980 nm shows that Cyto 840 also quenches UCNP emission. This quenching can be captured by a modified Langmuir adsorption model:

$$\text{Normalized } PL_{980} = 1 - q\theta_{cyto} = 1 - \frac{qK_{cyto}[C]}{1 + K_{cyto}[C]} \qquad K_{cyto} = 479335 \quad q = 0.94$$

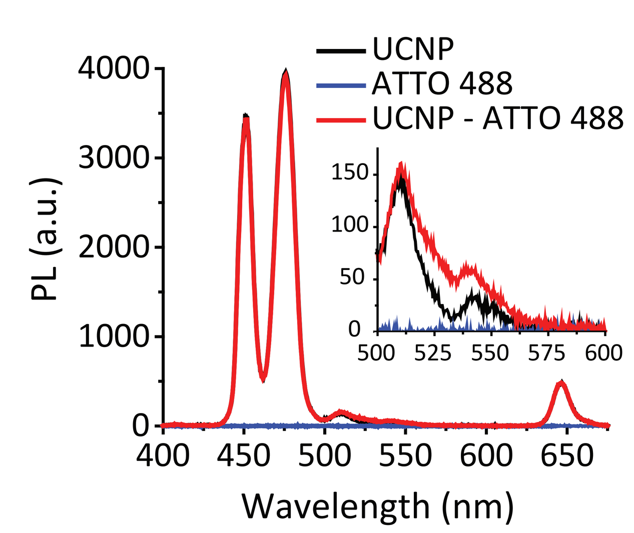
Peak PL_{810} corresponds to θ_{cyto} = 52% occupancy



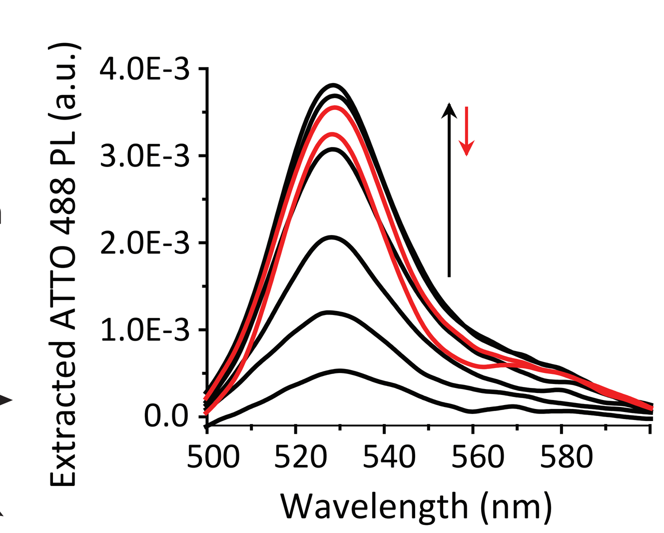


UCNP-ATTO 488 Characterization

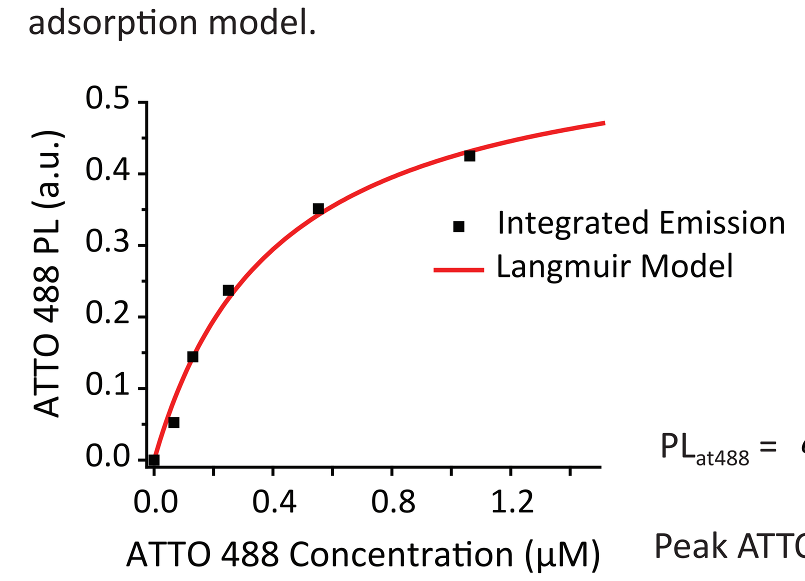
To demonstrate the second half of the relay, the PL from a sample of UCNP-ATTO 488 when excited at 980 nm was compared to two negative controls consisting of the individual constituents at the same concentrations.

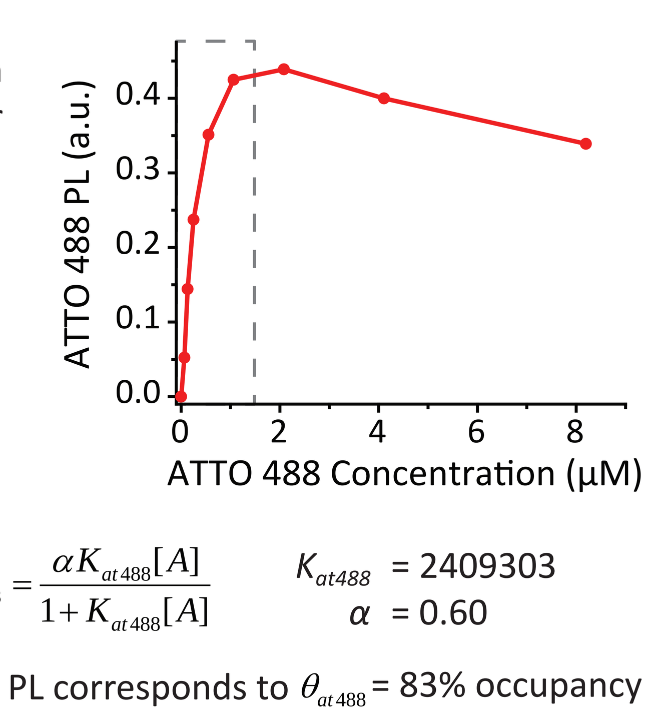


This PL can be extracted and plotted as a function of the ATTO 488 concentration.



Similar to Cyto 840 adsorption, ATTO 488 adsorption can also be captured by a modified Langmuir adsorption model.



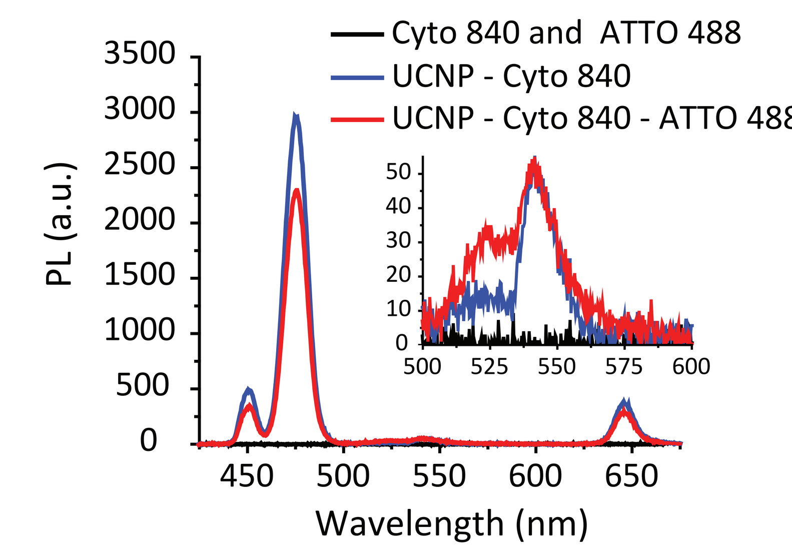


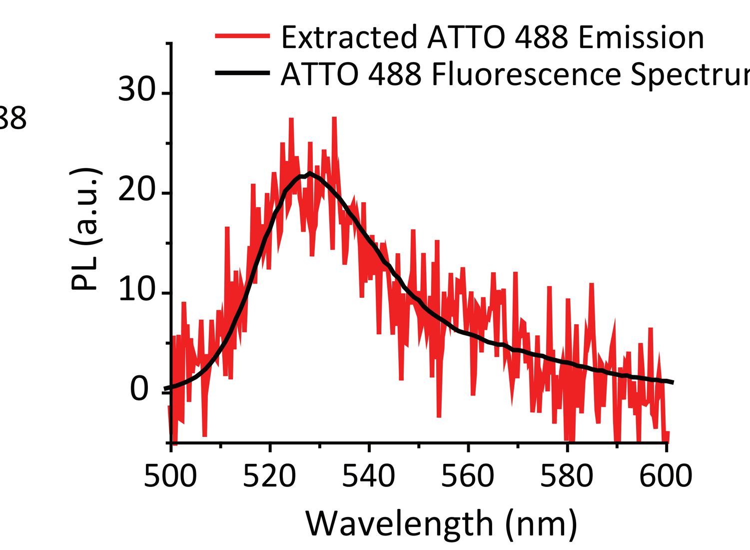
$$PL_{at488} = \alpha\theta_{at488} = \frac{\alpha K_{at488}[A]}{1 + K_{at488}[A]} \qquad K_{at488} = 2409303 \quad \alpha = 0.60$$

Peak ATTO 488 PL corresponds to θ_{at488} = 83% occupancy

RET Relay Characterization

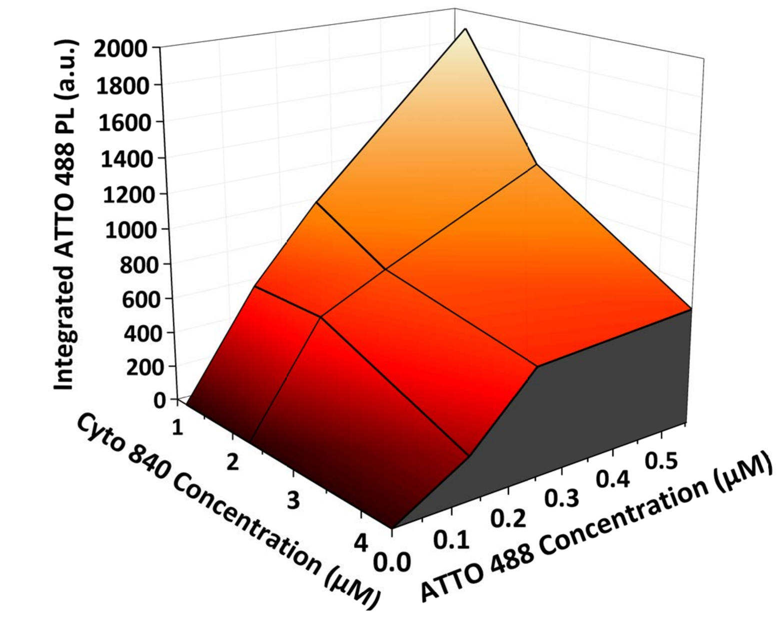
The RET relay was demonstrated by exciting the fully assembled construct at 810 nm and comparing the resulting PL to the UCNP-Cyto 840 and dye only controls. Additional PL in the ATTO 488 emission region matches that of the ATTO 488 fluorescence spectrum.





The decrease in UCNP emission for the relay sample above indicates that fluorophores compete for adsorption sites. To better understand this competition and to probe the relay performance as a function of the individual dye concentrations, we assembled nine different relays using three different Cyto 840 and ATTO 488 concentrations.

All nine relay configurations exhibited measurable ATTO 488 emission. When the Cyto 840 concentration is kept constant and the ATTO 488 concentration is raised, the ATTO 488 emission increases. The span of this increase depends on the Cyto 840 concentration. If the Cyto 840 concentration is high, it is difficult for ATTO 488 to compete for adsorption sites. If the Cyto 840 concentration is low, ATTO 488 more effectively competes with Cyto 840.



Conclusions

We have successfully designed and fabricated a nanoassembly, known as the RET relay, capable of converting many low energy excitons into a single high energy exciton. Using upconverting nanoparticles, the relay integrates and transfers energy from NIR absorbing fluorophores to visibly excited fluorophores. We have also demonstrated the following:

- an assembly procedure for adsorbing fluorophores to oleic acid capped UCNPs
- fluorophore adsorption can be accurately modeled as a Langmuir process
- energy transfer to and from the UCNP can be optimized based on fluorophore occupancy
- adsorption competition between fluorophores influences the performance of the RET relay

Further optimization of this device will make it a staple in RET network design by enabling the signal restoration between RET networks necessary for building more computationally complex integrated molecular circuits.

Acknowledgments

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References

1. C. Pistol, C. Dwyer, and A. R. Lebeck, "Nanoscale Optical Computing Using Resonance Energy Transfer Logic," IEEE Micro, vol. 28, pp. 7-18, 2008.
2. F. Wang and X. G. Liu, "Recent advances in the chemistry of lanthanide-doped upconversion nanocrystals," Chemical Society Reviews, vol. 38, pp. 976-989, 2009.