Diffuse Light Harvesting to Structured Information

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ABSTRACT

Efficient indoor light harvesters introduce a new design paradigm to Internet of Things (IoT) devices to maximize their ability to process, sense, and communicate data. Current employment of batteries or direct connection to the power grid can supply high power, but extended operation will require high maintenance and limit the deployment. By 2020, there may be as many as 30 billion devices connected to the internet and in most cases deployed indoors, all of which will require an energy source. We have developed a photovoltaic system to power a wireless sensor and to actually implement AI, such as a neural network utilising exclusively ambient light as power source. Wireless sensor nodes were powered by over 30% efficient dye-sensitized solar cells with an adapted sensitizer combination and with electrolyte redox mediator based on coordination copper complexes. Using a pretrained artificial neural network, we show that the collection in the magnitude of 10^{15} photons is needed for each inference. A 64 cm^2 photovoltaic area suffices to harvest enough energy to train and verify one epoch of MNIST datasets within less than 24 hours. Indoor light harvesters will lead to a new generation of self-powered IoT, capable of advanced machine learning.

Keywords: DSCs, Indoor Photovoltaics (IPVs), Copper Coordination Complexes, Indoor Light Harvesting, Machine Learning and IoT

1. EXTENDED SUMMARY

When materials absorb light, the energy from the photon is converted to potential energy of an electron and a hole. In semiconductors, these charge pairs are mobile and the basis of a solar cell is to extract the positive and negative charge at contacts and a current and voltage can be drawn to power a device. The amount of power generated depends on how quickly the charges can be separated and extracted. In most hybrid photovoltaic devices, the electron and hole are separated at the interface between an inorganic electron-transport layer (n-type semiconductor) and an organic hole-transport layer (p-type semiconductor) or redox mediator. The initial charge-separation step is very efficient in DSCs, but a lot of energy is lost transporting the charge and extracting it from the device.

A particular challenge in the field has been the replacement of iodine, which was the standard redox mediator in dye-sensitized solar cells, which led to substantial potential losses and corrosion. This limitation was addressed by replacing the iodine-based redox mediator based on new Cu complexes which exchange electrons rapidly with the dye molecules with very little energy required (overpotential).[1] A recently introduced new dye-sensitized solar cell (DSC) design with Cu complexes as a redox relay is capable of successfully regenerating dyes at only 0.1 eV overpotential.

To enable larger area production, the liquid electrolyte had to be replaced by a solid charge-transport material. The efficient copper coordination complex-based hole transport materials (HTMs) also demonstrate a whole new concept which give the most efficient solid-state DSC (ssDSC).[2] Fast charge separation in a variety of colored organic dyes and tuneable energy levels in Cu(II/I) redox systems combined with negligible recombinative processes allow DSCs to maintain a high photovoltage, which is especially important under ambient light. Further, co-sensitization of organic dyes enables absorption over a broad spectral range in the visible

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range and therefore adaption to the majority of light sources, which emit in the visible range. As a result, these DSCs outperform organic photovoltaics, silicon and thin-film GaAs technology under ambient light. Stable and record-breaking solar cell efficiencies of over 11% under 1 sun[3] were reached. In ambient conditions, 1000 lux indoor illumination the "zombie" photovoltaics showed a power conversion efficiency over 30% and 100 $\mu W/cm^2$ power output.[4] The conversion of ambient light offers broadly available energy and paves the way to extensive implementation of self-powered devices.[5]

Intelligent wireless devices are rapidly evolving into indispensable assistants in numerous facets of our world (the Internet of Things, IoT).[6] Merged with machine learning, wireless sensor networks are poised to advance the interchange of information in smart homes, offices, cities or factories. The first prototype of a self-powered wireless sensor powered by five serial 3.2 cm^2-sensitized cells is illuminated with 1000 lux fluorescent light to drive a microcontroller with a small supercapacitor as an energy buffer. Wireless communication is established through low-power nRF24L01+. All benchmarks execute a workload inside a PID-control loop using the internal microcontroller voltage as a set point, determining intermittent sleep intervals. Four benchmarks were executed as core workloads: Temperature measurement, Heartbeat wireless communication, Dhrystone MIPS, and MNIST inference. Results were wirelessly transmitted to a connected base station. Under 1000 lux illumination, the wireless sensor transmitted temperature data every 16 seconds, well-ranging within common battery-driven wireless sensors. Heartbeat packages were constantly sent every 282ms. Machine-learning capabilities were benchmarked using a pretrained two-layer network to predict a down-sampled 14x14 MNIST dataset which is received wirelessly at device startup. Inferences are averaged over 100 computations, resulting in 0.947 mJ per inference, translating to 2.72 10^{15} photons per inference.[7]

Photovoltaic (PV) devices will be a key element in harvesting environmental energy. Given that autonomous and smart IoT devices are envisioned to be deployed widely in the ambient environment, combining high efficiency and low cost with non-toxic materials is of paramount importance to sustainability.[8]

REFERENCES

[1] Saygili, Y., Söderberg, M., Pellet, N., Giordano, F., Cao, Y., Muñoz-García, A. B., Zakeeruddin, S. M., Vlachopoulos, N., Pavone, M., Boschloo, G., Kavan, L., Moser, J.-E., Grätzel, M., Hagfeldt, A., and Freitag, M., "Copper Bipyridyl Redox Mediators for Dye-Sensitized Solar Cells with High Photovoltage," *Journal of the American Chemical Society* **138**, 15087–15096 (Nov. 2016).

[2] Freitag, M., Daniel, Q., Pazoki, M., Sveinbjörnsson, K., Zhang, J., Sun, L., Hagfeldt, A., and Boschloo, G., "High-efficiency dye-sensitized solar cells with molecular copper phenanthroline as solid hole conductor," *Energy & Environmental Science* **8**, 2634–2637 (Aug. 2015).

[3] Cao, Y., Saygili, Y., Ummadisingu, A., Teuscher, J., Luo, J., Pellet, N., Giordano, F., Zakeeruddin, S. M., Moser, J.-E., Freitag, M., Hagfeldt, A., and Grätzel, M., "11% efficiency solid-state dye-sensitized solar cells with copper(II/I) hole transport materials," *Nature Communications* **8**, 1–8 (June 2017).

[4] Freitag, M., Teuscher, J., Saygili, Y., Zhang, X., Giordano, F., Liska, P., Hua, J., Zakeeruddin, S. M., Moser, J.-E., Grätzel, M., and Hagfeldt, A., "Dye-sensitized solar cells for efficient power generation under ambient lighting," *Nature Photonics* **11**, 372–378 (June 2017).

[5] Mathews, I., Kantareddy, S. N. R., Sun, S., Layurova, M., Thapa, J., Correa-Baena, J.-P., Bhattacharyya, R., Buonassisi, T., Sarma, S., and Peters, I. M., "Self-Powered Sensors Enabled by Wide-Bandgap Perovskite Indoor Photovoltaic Cells," *Advanced Functional Materials* **29**(42), 1904072 (2019).

[6] Mathews, I., King, P. J., Stafford, F., and Frizzell, R., "Performance of III–V Solar Cells as Indoor Light Energy Harvesters," *IEEE Journal of Photovoltaics* **6**, 230–235 (Jan. 2016).

[7] Michaels, H., Rinderle, M., Freitag, R., Benesperi, I., Edvinsson, T. E., Socher, R., Gagliardi, A., and Freitag, M., "Dye-sensitized solar cells under ambient light powering machine learning: Towards autonomous smart sensors for the internet of things," *Chemical Science* (2020).

[8] Benesperi, I., Michaels, H., and Freitag, M., "The researcher's guide to solid-state dye-sensitized solar cells," *Journal of Materials Chemistry C* **6**, 11903–11942 (Nov. 2018).