The Attojoule Challenge in Photonics/Optoelectronics: Materials, Devices, Modeling and Architectures

In Research & Development roadmaps for information technologies ranging from high-performance computing to embedded signal processing, power consumption and heat dissipation are emerging as critical engineering issues that could drive major shifts in materials, device designs, and architectures. For many of these challenges, the use of **optical signal formats** offers attractive prospects for achieving high degrees of connectivity and high-density communication with low heating/power consumption, and potentially reduced fabrication complexity relative to current electronic standards. For large-area sensor networks and "smart dust"-type applications, all-optical approaches could offer additional advantages of low-loss signal+power propagation over long distances.

Motivated by cumulative advances of the past few decades in nanofabrication and materials synthesis capabilities, forward-looking researchers have begun to work towards photonic and optoelectronic systems concepts based on switching energies at the **attojoule scale**, which in a sense is the lowest feasible energy scale for optical/optoelectronic approaches because of field quantization (individual photons). Even if we retain a focus on circuits and system architectures that are fundamentally based on classical (as opposed to quantum) information science, attojoule-scale systems incorporating optical signal formats must be modeled and designed using **quantum theory**. Having a rigorous physics foundation for continuing work on attojoule photonics/optoelectronics will help to ensure that we properly assess the impacts of quantum noise, and will furthermore enable us to consider architectures that leverage coherence (and possibly even low-level entanglement) on limited scales to improve performance or to improve size/weight/power metrics.

Building on this, of course, we need to develop optoelectronic and nonlinear-optical **materials and scalable device designs** that operate robustly at the attojoule energy scale, and **circuit design concepts** that leverage the advantages of optical signal formats while suppressing the effects of quantum noise--for example, through the use of coherent feedback. One can foresee that technical issues are bound to arise that tightly couple two, three, or even all four of these areas (materials, devices, modeling and architectures). For example, exciton number fluctuations in the small mode volume of a nanophotonic resonator could worsen the noise figure of a nonlinear optical device, whose impact would need to be assessed in the context of a functional circuit with complex feedback connections. Would it be better for the overall system design to increase the mode volume of the resonator (thus weakening its nonlinearity and raising the basic switching energy) or to add components to the circuit to compensate for the noise (thus increasing the system size/weight/power)?

As an intellectual domain, attojoule photonics/optoelectronics overlaps with quantum information science but remains quite distinct from it. Both fields require a technical infrastructure for modeling and simulation of device designs in which quantum mechanics plays a significant role, and they share a deep interest in the development of new materials that facilitate the realization of such devices. However, whereas in quantum information science there is a stringent requirement to develop device designs and circuit motifs that support the preservation of extensive entangled states over (computationally) significant time intervals, for attojoule photonics/optoelectronics there is no such need *a priori* and the engineering metrics remain more traditionally focused on issues such as size and weight, power consumption and heat dissipation, speed, robustness, and economy of manufacturing.

The primary new challenge that arises in attojoule photonics/optoelectronics is accommodating quantum noise associated with computing at the energy scale of individual photons. As quantum noise becomes a dominant consideration in component (*e.g.*, latch or relay) performance, we are motivated to consider radical changes in circuit architecture to better match the novel physics of attojoule-scale optical signals. Rather than considering straightforward but costly additions of redundancy and error correction to suppress quantum noise, there are opportunities to develop new quantum noise-tolerant architectures inspired by recent developments in message-passing algorithms, reservoir computing and neural network theory [1,2]. At the same time, the possibility for leveraging coherence (and possibly even entanglement) over limited time- and length-scales may enable "exotic" new design strategies for improving traditional metrics in the attojoule regime. For example, utilizing the coherent phase of optical signals (as opposed to their energy content only) to carry information within small clusters of devices (across which thermal variations and mechanical strains may be neglected) enables the use of simple beam-splitters to perform certain elementary logic operations in a completely passive way [3]. Likewise, coherent feedback strategies [4] may enable quantum noise suppression with minimal overhead of added components and power consumption. In order to perform complex computations our circuits must include complex and costly active/nonlinear components as well, however, the incorporation of optical interference (phase-based) phenomena and coherent feedback control may more efficient and economical overall circuit designs. Accurate, user-friendly and widely accessible numerical simulation tools will be crucial for exploring all such new ideas for managing quantum noise, including device design optimization and novel attojoule-scale architectures [5,6].

Returning to materials, we recall that strong optical nonlinearities are required to implement photonic signal processing at attojoule energy scales. While attojoule-scale switching dynamics can readily be observed in the context of atomic cavity quantum electrodynamics [7-9], the only solid-state integrated approaches that have been investigated so far rely on quantum dots or similar embedded optical emitters. Given manufacturing considerations for complex photonic/opto-electronic systems, it is not clear whether implantation, heterogeneous assembly or *in situ* growth of such dopants/vacancies can be made economically feasible at large scale. We are thus led to consider the potential of 1D materials such as transition-metal dichalcogenides (TMDs), whose unique properties can give rise to strong optical nonlinearities and whose mechanical structure may be more amenable to integration with planar (or pseudo-planar) nanophotonic circuits. There is still a lot of work to be done to understand the fundamental physics of TMDs well enough to predict the best achievable performance with large-area TMD monolayers in photonic/opto-electronic circuits under practical operating conditions (*e.g.*, temperature). For attojoule-scale applications there is a specific new challenge of understanding the optical noise figure that we may expect from optimized device designs, considering all relevant physics involved in the strong coupling of the TMD optoelectronic response to an ultra-small mode volume photonic resonator. At the same time, there are many practical issues to be addressed in terms of preparing large-area TMDs with optimal optical properties [10]. Such work on TMD-based attojoule devices may be complemented by parallel research on material systems such as lithium niobate.

The proposed workshop format will be a 1.5-day meeting at Stanford University in the timeframe of December 2018 – January 2019. The program of talks could draw upon local expertise at Stanford University, supplemented by four or five key invited speakers, to provide an overview of major challenges and opportunities in the field during the first day of the workshop. Then in the following half-day, the attendees could work to formulate a list of "major challenges" for attojoule photonics/opto-electronics and to propose ideas for vertically-integrated research collaborations that stretch across materials, devices, modeling and architectures to address them. The list of local and invited speakers would be determined by a small organizing committee; additional government and industrial attendees could be invited to contribute to the discussion.

References

1. Dmitri S. Pavlichin and Hideo Mabuchi, "Photonic circuits for iterative decoding of a class of low-density parity-check codes," New Journal of Physics **16**, 105017 (2014); http://iopscience.iop.org/article/10.1088/1367-2630/16/10/105017/meta
2. Nikolas Tezak and Hideo Mabuchi, "A coherent perceptron for all-optical learning," EPJ Quantum Technology **2**, 10 (2015); https://doi.org/10.1140/epjqt/s40507-015-0023-3

3. Hideo Mabuchi, "Nonlinear interferometry approach to photonic sequential logic," Appl. Phys. Lett. **99**, 153103 (2011); https://doi.org/10.1063/1.3650250
4. Hideo Mabuchi, "Coherent-feedback control strategy to suppress spontaneous switching in ultralow power optical bistability," Appl. Phys. Lett. **98**, 193109 (2011); https://doi.org/10.1063/1.3589994
5. Nikolas Tezak, Armand Niederberger, Dmitri S. Pavlichin, Gopal Sarma and Hideo Mabuchi, "Specification of photonic circuits using quantum hardware description language," Phil. Trans. Roy. Soc. A **370**, 5270-5290 (2012); http://rsta.royalsocietypublishing.org/content/370/1979/5270
6. Nikolas Tezak, Nina H. Amini, and Hideo Mabuchi, "Low-dimensional manifolds for exact representation of open quantum systems," Phys. Rev. A **96**, 062113 (2017); https://journals.aps.org/pra/abstract/10.1103/PhysRevA.96.062113
7. Michael A. Armen and Hideo Mabuchi, "Low-lying bifurcations in cavity quantum electrodynamics," Phys. Rev. A **73**, 063801 (2006); https://doi.org/10.1103/PhysRevA.73.063801
8. Joseph Kerckhoff, Michael A. Armen, Dmitri S. Pavlichin, and Hideo Mabuchi, "The dressed atom as binary phase modulator: towards attojoule/edge optical phase-shift keying," Optics Express 19, 6478-6486 (2011); http://www.etoponline.org/oe/fulltext.cfm?uri=oe-19-7-6478&id=211230
9. Joseph Kerckhoff, Michael A. Armen, and Hideo Mabuchi, "Remnants of semiclassical bistability in the few-photon regime of cavity QED," Optics Express 19, 24468-24482 (2011); https://www.osapublishing.org/oe/abstract.cfm?uri=oe-19-24-24468
10. Daniel B. S. Soh, Christopher Rogers, Dodd J. Gray, Eric Chatterjee and Hideo Mabuchi, "Optical nonlinearities of excitons in monolayer MoS_2," Phys. Rev. B **97**, 165111 (2018); https://doi.org/10.1103/PhysRevB.97.165111
11. Christopher Rogers, Dodd Gray, Nate Bogdanowicz and Hideo Mabuchi, "Laser Annealing for Radiatively Broadened MoSe2 grown by Chemical Vapor Deposition," arXiv:1804.07880 [cond-mat.mtrl-sci]; https://arxiv.org/abs/1804.07880