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Army Science Planning Strategy Meeting on Integrated Nanophotonics

by Michael Gerhold and James Joseph

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Army Research Office, DEVCOM Army Research Laboratory

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14. ABSTRACT The Army Science Planning and Strategy Meeting on integrated nanophotonics was held 4–6 November 2020 online through Microsoft Teams software. There were approximately 50 attendees, including 15 US Army/Department of Defense scientists and engineers and 35 academic researchers. Nanophotonics refers to the study of light and its interaction with matter on the nanometer scale, and photonic integrated circuits (PICs) are devices that route and manipulate light in a way analogous to electronic circuits. PICs have demonstrated utility in specific applications such as signal routing in optical communications. However, more complex all-optical capabilities require bulk optics that suffer from large size, weight, power, and cost as necessary nanophotonic components either do not exist or cannot be integrated readily. The purpose of this meeting was to identify investment opportunities in integrated nanophotonic basic and applied research to enable game-changing technologies both in the classical and quantum regimes. This report details the content of that meeting and subsequent findings of import to the Army research community. This report includes a discussion of the presentations and panels that met in various sessions, followed by some discussion of the field, including findings for future investment.					
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1. Introduction

The Army Science Planning and Strategy Meeting (ASPSM) on integrated nanophotonics was held 4–6 November 2020 online through Microsoft Teams software. There were approximately 50 attendees, including 15 US Army/Department of Defense (DOD) scientists and engineers (S&Es) and 35 academic researchers. Nanophotonics refers to the study of light and its interaction with matter on the nanometer scale, and photonic integrated circuits (PICs) are devices that route and manipulate light in a way analogous to electronic circuits. PICs have demonstrated utility in specific applications such as signal routing in optical communications. However, more complex all-optical capabilities require bulk optics that suffer from large size, weight, power, and cost (SWaP-C) as necessary nanophotonic components either do not exist or cannot be integrated readily. The purpose of this meeting was to identify investment opportunities in integrated nanophotonic basic and applied research to enable game-changing technologies both in the classical and quantum regimes. This report details the content of that meeting and subsequent findings of import to the Army research community. This report includes a discussion of the presentations and panels that met in various sessions, followed by some discussion of the field, including findings for future investment.

2. Integrated Nanophotonics

Photonics holds the key to enormous technological advances in information processing and computing. The bosonic nature of photons combined with far-more numerous optical degrees of freedom (DoFs) holds tremendous scaling potential far beyond the limits imposed by the fermionic-related limitations of electronics. The simple binary charge state of electrons cannot compete with the photonic DoFs (such as polarization, spatial modes, frequency, and others.) In addition, photon loss introduces dramatically less heat into the system than resistive Joule heating, virtually eliminating that scaling barrier (and signature). While near-term photonic systems will use only one DoF, additional DoFs hold promise for future expansion over the long term. The primary challenge of photonics is full replacement of electronic functions. While Defense Advanced Research Projects Agency (DARPA) has begun a massive program for photonics to overtake electronics for the first time, aiming at Pb/s chip edge data-communication bandwidths, the scaling, multiple DoFs, and quantum possibilities promise even far greater benefits in the future. Such advances are essential for multidomain operations by promising a feasible path toward efficient, compact computing at the edge, secure communications, truly optimized logistics, and other capabilities. This workshop explored how future classical and quantum photonics can be used in lieu of electronics and how to make the discoveries necessary to get there.

Integrated nanophotonics has the opportunity to impact three forms of information processing: analog, digital, and quantum. Analog photonics builds upon well-known Fourier optics techniques, yet current efforts suggest new discoveries will likely enable massive miniaturization, performance improvements, and novel approaches that go beyond Fourier optics. Digital data-based optical processing is similar to that used in computing. New, promising scientific and engineering opportunities have emerged after several failures over the last two decades that use both analog and digital data. Quantum integrated photonics is an emerging area but is building momentum as DOD-led discoveries advancing quantum information are combined with advances from classical integrated photonics. In all three contexts there are two key advances that new and forthcoming discoveries will dramatically propel new technologies in this area. First, scaling. While many functions can be implemented on large optical tables, these are not suitable for technological implementation—especially for the Army. The advent of PICs yields compactness necessary for technology and additional foundational knowledge development is necessary to enable full functionality at this scale as well as to push into fully planar, quasi-3-D (multiplanar) and full 3-D implementations. Second, DoFs. While current photonic implementations focus on amplitude or polarization, future initiatives can combine these with multiple frequencies, orbital angular momentum (OAM) and other properties of light, and a bosonic particle. One can envision, for example, parallel computation on a single integrated processor. This workshop explored these advances in each of these directions and the initiatives necessary to enable the integrated photonics technology the Army needs to win.

On the engineering side, many of the basic research opportunities sought are hindered by a lack of tools necessary to implement theoretical ideas. Theoretical concepts are typically based on idealized systems rather than real materials. Integrated photonics provides an opportunity to study phenomena that are not accessible to optical scientists and engineers any other way. Translating from concepts to a real device in which the foundational research can be studied requires that nuances about optical materials, waveguide routing, and many other effects be managed concurrently. Thus, well-developed photonic design kits are necessary as an enabler of the basic research. Furthermore, foundries may not be able to process materials or produce exquisite structures in which the unique functions are accessible. These matters were an emphasis of the workshop.

On the science side, many exciting ideas are possible that provide additional novel approaches to integrated photonic functions. For example, until recently, photons are completely noninteracting. A recent discovery that using a cold Rydberg gas mediates interactions among photons allows a completely new approach to photonics, enabling such things as single-photon switches. Other nascent discoveries also of interest range from topological photonics to supersymmetric optics.

At the extreme limit of low-energy photonics are quantum effects. We are past the point where state-of-the-art demonstrations in quantum cryptography, communication, networking, imaging, and photonic implementations of quantum computation will be accomplished primarily with bulk optics. To develop these technologies, we must be able to manipulate and maintain the quantum state of light as well as generate, entangle, and detect at the single-photon level. Enabling quantum integrated photonics will likely require established engineering and the establishment of new engineering capability. Some integrated optical elements (silicon [Si] waveguides, microcavities, and microresonators for example) are compatible with current fabrication processes like optical fiber and semiconductors. Other capabilities require alternate materials (color centers in diamond for single-photon emission or nonlinear optical materials like periodically polled lithium niobate [PPLN]) to generate entangled photon pairs via spontaneous parametric down conversion or four-wave mixing. More exotic control platforms include plasmonics, atomic precision fabrication, and advanced metamaterials to name a few. These may provide advanced capabilities including active lensing, subwavelength field manipulation, and control of both gain and loss mechanisms. This is far from a complete list of the active research in this field, which is advancing apace and providing a wealth of basic science discovery.

This workshop highlighted exciting prospects of integrated photonics in the classical and quantum worlds and charted a path to enable it and demonstrate the critical importance for the Army and the DOD at large to position itself to advance and take advantage of the resulting revolutionary capabilities.

3. Meeting Summary

3.1 Overview from the Organizers: ARO Program Managers, Drs Michael Gerhold and James Joseph

Both the Army Research Office (ARO) Optoelectronics program (Electronics Branch) and the ARO Quantum Optics program (Physics Branch) have investments in fundamental studies related to integrated nanophotonics. Tasked to identify research investment opportunities, ARO project managers (PMs) organized this ASPSM. The meeting highlighted fundamental research at the cutting edge of academia, introduced stakeholders within the academic, Army labs, and research and development (R&D) environments, and brainstormed Army-relevant near and far future probable discoveries. The three-day virtual meeting was organized into a series of technical talks and breakout sessions. Instead of being limited by current travel restrictions, the ASPSM took advantage of technological efficiencies to host this meeting virtually and bring together leading experts to engage in a discussion that was at times highly energetic, inclusive, and informative.

A strong contingent of up-and-coming researchers, more-established distinguished professors, and Army personnel came together to participate in various technical and discussion sessions. The first plenary session was focused on opportunities for photonics in computing, advanced signal processing, and mathematical operations such as matrix multiplication and individual multiply and accumulate operations for matrix–vector multiplication. Generally, the session encompassed many opportunities for photonic information processing that go beyond what electronic microprocessors can do, particularly von Neumann processing used in central processing units (CPUs) of modern computers. Next, an Army introduction and information session afforded participants the opportunity to greet Army science and technology experts and learn about the US Army Combat Capabilities Development Command Army Research Laboratory, Army Centers, and Army Concepts groups. Four technical sessions were organized to highlight current and potential investment areas. The first was Materials and Devices I: New Capabilities that highlighted some recent advances and opportunities for scientific discovery in PICs. The second was Nonlinear Photonics, highlighting advances in frequency conversion, in particular frequency combs. Third, in the technical session Polaritons for Integrated Photonics, light–matter interactions interfacing photons with charged carriers that have significant mass were introduced as an opportunity for game-changing technologies. Exciton–polaritons were emphasized, spurred by an ARO Multidisciplinary University Research Initiative (MURI) titled *Toward Room Temperature Exciton-Polaritonics*. The last technical session, Materials and Devices 2: Smaller and Faster, was organized to highlight advances in nanoscale device capability. Such reduced scaling could make way for higher device densities and faster switching speeds. After the technical sessions, and on the last day of the meeting, attendees participated in a series of six breakout sessions to brainstorm future research directions.

3.1.1 ARO Optoelectronics Program Relevance to Integrated Nanophotonics: Dr Michael Gerhold

The ARO Optoelectronics (OE) program emphasizes III-V semiconductor OE devices and complements investments from other funding agencies such as the Air Force Office of Scientific Research (AFOSR) that have focused on photonics that use organic materials and Si. The program is split into two thrusts: low-energy, high-speed OEs and high-intensity radiation. The latter is focused on laser regimes and adaptive optics approaches geared toward directed energy. While some of the work is relevant to future integrated photonics investment directions, it is not oriented toward nanoscale implementations. However, the first thrust does have that emphasis, especially toward data processing and neuromorphic computing (aka "neurophotonics"), where low energy and high speeds are critical. As described in the workshop overview, photonics can be made highly advantageous over electronics due to the distinct differences between bosons and fermions. Photons, which are bosons, are not limited as electrons are in terms of their ability to occupy the same space at the same time. They can be spatially and temporally coherent and use spatial and temporal frequency to multiply their information content. Fiber optic systems have used this capability to create very-high bandwidth systems for long-haul systems near the 1.55-micron transmission window of silica fibers. However, hollow core fibers recently progressed to similar low-loss levels (0.2 dB/km) and have been demonstrated to lengths of over 100 km.[1] They are therefore poised to be used for transformative information processing systems and need to be considered for future Army systems. Both classical and quantum information systems are relevant due to the potential for achieving low loss even in visible (VIS) and mid-infrared wavelength ranges. Integrated nanophotonic PICs should thus be considered based upon many semiconductor or alternative material systems with optical bandgaps ranging from the UV to THz frequencies.

Under Dr Gerhold's direction, the ARO OE program led to some of the highest-performing III-V lasers and detectors, generally at the microscale. A turning point toward nanoscale type of investments came notably when DARPA's Nanoscale Coherent Hyperopic Sources (NACHOS) program formed and started achieving progress. Dr Gerhold became involved around 2010 and co-led the program with DARPA. During this program, microfabrication etching and deposition processes were honed, enabling functional devices at the nanoscale. Attaining low nonradiative interfaces with active current-controlled devices, subwavelength-scale lasers were demonstrated for the first time.

III-V devices including modulators, detectors, LEDs, and lasers are still progressing very significantly in performance. However, their incorporation into PICs awaits advances at the basic and applied research levels. Incorporation of various III-V semiconductor-based, high-performance OE components onto a single planar platform can enable a huge opportunity to create miniaturized photonic sensing and data processing capability. Prior work on indium-phosphide-based PICs culminated in technology primarily aimed at interfaces with fiber optic networks. These operate at around 1.55 microns for long-haul networks due to the minimum loss window of silica fibers (0.2 dB/km). Army systems can benefit from many other wavelengths though, to improve bandwidth via multiplexing or lower-cost devices. In summary, the ARO OE program was a wide purview for the long-term vision of nanophotonics—many examples of current investment areas are highlighted in Section 3.3.

3.1.2 ARO Quantum Optics Program Relevance to Integrated Nanophotonics: Dr James Joseph

As part of its mission, the quantum optics (QO) program at ARO pursues high-risk–high-reward fundamental research investments in the realm of quantum photonics for transformational overmatch in support of the Warfighter. The program seeks to push beyond the state of the art in photonics and integrated optical platforms, seeking not only novel functionality, but also increased limits to sensitivity, stability, and robustness. In general, the program invests in research exploring fundamental studies of light, and light–matter interaction in the micro, nano, and subwavelength scale. Broadly, areas of interest that the program monitors include nonlinear photonics, topological photonics, plasmonics, polariton physics, and low-energy photonics. Also, necessary to advance the field is deeper understanding of synthetic photonic materials including but not limited to photonic crystals (PCs), disordered photonic systems, 2-D planar systems, and layered 2-D materials. The program is currently investigating specific questions relevant to integrated photonics regarding the roll intrinsic OAM and photon spin density can play in an integrated photonics platform and novel methods to generate tunable nonclassical light on chip. Incorporating these new understandings will enable the development of integrated quantum technology including efficient single and entangled photon sources and detectors, multispectral and optically tunable systems, and novel ways to use quantum mechanics to probe, image, or control matter.

A full description of the OE and QO program interests can be found in the ARO Broad Agency Announcement (BAA) at https://www.arl.army.mil/wp-content/uploads/2020/10/W911NF-17-S-0002-ARO-BAA-Amendment-08.pdf.

3.2 Workshop Overview (of Technical Presentations)

3.2.1 Plenary Session: Neuromorphic Photonic Computing

3.2.1.1 Benjamin Lev, Stanford University: Associative Memory with Confocal Cavity Quantum Electrodynamics (QED) Neural Networks

Prof Lev introduced the concept of confocal cavities for cold atoms.[2] Specifically, the talk focused on realization of associative memory using these confocal multimode cavity systems consisting of Bose-condensed atoms. The basic idea is that the different modes of the cavity act as synapses and the atomic spin ensembles and their connectivity act as the neurons. The neural network (NN) relies on the connectivity between the spin states of the atoms and can be probed via the incident and output light patterns. In this system, the position of the atomic ensembles can be tuned and this results in the system emulating ferromagnetic and spin-glass regimes. From a computing standpoint, the main advantage is that natural spin relaxation in these atomic clouds is physically equivalent to deepest descent dynamics in a NN. The computing regime referred to here is reservoir computing and it is quite different from integrated nanophotonics per se, but was included due to the nanoscale interactions and the possibility of further integration of the approach with concurrent advances in atomic–photonic circuits, for example, DARPA's A-PHI (Atomic-Photonic Integration) program, currently in its second year.

3.2.1.2 Vinod Menon, City College (City University of New York): Polariton Lattices for Neuromorphic Computing

Prof Menon introduced using exciton–polaritons (strongly coupled states of excitons and cavity photons) in semiconductors as a platform to carry out reservoir computing. The talk initially focused on current work in the area of realizing Hamiltonian simulators using polariton condensates, and it was followed by discussion on reservoir computing. Unlike traditional NNs, reservoir computing relies on a random network of nodes with fixed bi-directional coupling that eliminates the need for training of the network. What is trained in this context is the matrix that is applied to the output of the system. By introducing nonlinearity in the system, one can introduce nonlinear cuts to the higher-dimensional data. In this case, the naturally interacting exciton–polaritons provided the nonlinearity (NL). The nodes of the network may be realized in the momentum space. Problems such as linear classifiers can be solved using this approach. Challenges include the number of nodes that can be realized in momentum space as well as the sensitivity to laser instabilities that affect the system performance.

3.2.1.3 Marin Soljacic, Massachusetts Institute of Technology (MIT): Photonics for Deep-Learning and Ising Problems

Prof Soljacic described integrated photonic NNs and the types of problems they have addressed. He explained the value proposition of using Si photonics to implement NNs.[3] He then proceeded to show how similar Si photonics designs can also be used to find ground states of Ising Hamiltonians very efficiently.[4] He described how these works provided inspiration to implement a novel class of NNs, which use unitary (instead of regular) matrices for deep learning.[5] This mitigates the exploding and vanishing gradient problem from which conventional NNs often suffer. He concluded with a vision that the excellent correspondence between the numerical and real experiments in photonics presents a particularly suitable training ground for developing new artificial intelligence (AI) algorithms for science.[6]

3.2.1.4 Dirk Englund, MIT: Large-Scale Photonics for Machine Intelligence: Bits to Qubits

Prof Englund focused on optical neural networks (ONNs) realized using integrated Si photonic platforms. He discussed a toolbox of large-scale programmable photonic circuits consisting of a large array of integrated Mach Zehnder interferometers (MZIs) realizing quantum photonic operations on chip. The end applications include deep neural networks (DNNs) with stationary weights, as well as output stationary DNNs that could operate below the thermodynamic limit. The "Holy Grail" would be the realization of a quantum ONN. He presented approaches for realizing quantum optical circuits by integrating diamond (Si and germanium [Ge] vacancies) with an aluminum nitride (AlN) platform.[7] Use of quantum ONNs for one-way repeaters was also discussed (see Hamerly et al., Bogaerts et al., and Steinbrecher et al.[8–10]).

3.2.2 Technical Session 1: Materials and Devices 1: New Capabilities

3.2.2.1 Zetian Mi, University of Michigan: Aluminum Nitride (AlN) Integrated Nanophotonics

Prof Mi presented AlN as an alternate material for use in integrated photonic devices such as light sources, modulators, and detectors operating in UV and VIS wavelengths. He argued that an alternate material is necessary in some cases due to the challenges associated with conventional integrate photonics materials like silicon nitride (SiN) and lithium niobate (LN). The challenges include high loss below 500 nm and low damage thresholds among others. Prof Mi presented that low-quality AlN can be overcome with advanced growth techniques such as ultrahigh-temperature molecular-beam epitaxy (MBE). With these techniques, high-quality (Q) AlN can be grown directly on sapphire substrate with an atomically smooth surface and reduced dislocations. Quality factors as high as 2.8 million have been reported in AlN ring resonators on sapphire.[11] High-Q microring resonators (MRRs) can be manufactured in the VIS and UV as well. Finally, AlN has strong second- and third-order NLs, which enables the previously mentioned device capabilities.

3.2.2.2 Liang Feng, University of Pennsylvania (U Penn): Symmetry-Driven Photonics for New Active Functionality On-Chip

Prof Feng discussed novel device physics enabled by non-Hermitian photonics based on parity-time (PT) symmetry and 2-D topological photonics. Dr Feng presented his work developing an integrated microlaser that produces OAM beams with the ability to switch between OAM modes. In conjunction with Prof Ritesh Agarwal, he also demonstrated photocurrent detection of OAM light. Dr Feng also presented work on photonic switching in non-Hermitian photonic topological insulators. In these structures, regions of gain and loss are created with external fields to reroute topologically protected edge states constraining photon propagation to specific paths enabling all-to-all optical routing.[12] These devices were fabricated with indium gallium arsenide phosphide (InGaAsP) and operated at approximately 1500 nm. While these studies are early-stage investigations of fundamental physics, future device capabilities are easily envisioned.

3.2.2.3 Sahin Ozdemir, Pennsylvania State University: Plasmonics with Quantum State of Light

Prof Ozdemir presented on the potential for plasmonics to study quantum sciences in a nanophotonics platform. He suggests that even though plasmonic systems have high photon loss, they offer engineering advantages such as compactness, power efficiency, and ease of fabrication as well as fundamental advantages by providing a medium for interactions to occur. Also under consideration should be hybrid plasmonic–photonic systems. It has been shown that quantum correlations survive plasmonic losses when photons are converted into plasmons. Single photon to plasmon interconversion and quantum interference have been demonstrated as well. Dr Ozdemir suggests that photon losses can be mitigated by the correct application space. Examples of state of the art here are entanglement distillation—the process by which a larger number of entangled particles is reduced to smaller number of maximally entangled pairs (95 ±0.01% fidelity to a maximally entangled state—or random number generation [2.37 Mbits/s]).[13] Plasmonic waveguides have been used to integrate single-photon sources into PIC architectures. These early demonstrations indicate that plasmonic or photon–plasmon hybrid PICs are possible.

3.2.2.4 Jelena Vuckovic, Stanford University: New Photonics Enabled by Optimization and Machine Learning

Jelena Vuckovic presented the state of the art in inverse design in nanophotonics. Prof Vuckovic's group at Stanford has had great success in using this method to design and fabricate grating couplers, wavelength demultiplexer, spatial mode converter, dielectric laser accelerators, and nonreciprocal pulse routers. Fabrication can be done in Si, diamond, and silicon carbide (SiC) thus far. Foundry fabrication (specifically AIM Photonics) is available for inverse designs from a specialized software package (SPINS) developed at Stanford.[14] A typical spacial mode splitter from the foundry, for example, would have bandwidth greater than 200 nm, insertion loss of 1.5 dB per device, and a minimum feature size of 90–100 nm. Inverse design and fabrication in diamond and SiC—which host quantum emitters—enables more complex and compact quantum photonic circuits as well as efficient generation of nonlinear effects such as frequency combs, second harmonic generation, and four-wave mixing. Next-generation algorithms currently in development are using machine learning (ML) to accelerate simulations of Maxwell's equations—a necessary element of the inverse design algorithm.

3.2.2.5 Michael Fanto, Air Force Research Laboratory/Rochester Institute of Technology: Nonlinear Optics in Photonic Ultra-Wide Bandgap Circuits

Dr Fanto presented recent work on integrated nonlinear optics (NLOs) toward integrated quantum photonics. Integrated photonic waveguides provide a scalable and stable platform for the implementation of quantum photon sources and circuits. The qualities needed to realize quantum photonics are low optical loss for a high throughput of entangled photon pairs, phase stability for high-quality interference in quantum devices, and reproducibility (indistinguishability) between devices. Entangled photons can be produced with $\chi^{(2)}$ nonlinearities via spontaneous parametric down conversion and with $\chi^{(3)}$ nonlinearities via degenerate four-wave mixing. Quantum light sources can be used to control atomic systems in quantum memory applications and flying qubits for quantum information transmission. Entangled photons are used as "flying qubits" to carry quantum information between systems or in all-photonic quantum computation operations. These applications each have ideal wavelength regimes; flying qubits should be optimized for telecom bands because of the availability of ultra-low-loss optical fibers in those bands. Material for quantum integrated photonic devices is also wavelength dependent and application specific. AlN could be used for quantum waveguide circuits as part of an integrated repeater node. A significant effort has gone into characterizing AlN and optimizing fabrication techniques for this specific purpose. AlN can also be used for integrated photonic circuits in the UV. Si/SiN devices can be manufactured at a foundry and are perfect candidates for frequency combs.

Frequency combs are laser sources consisting of equally spaced frequency lines. Dr Fanto presented a new quantum light source design fabricated at the AIM Photonics foundry that combines a Mach–Zehnder interferometer and an MRR to optimize both the rate and efficiency at which single photons suitable for use in quantum technologies are created.[15] Dr Fanto and collaborators are next planning to introduce fully pump-filtered, entangled NOON state, photon pair sources developed with similar fabrications techniques through AIM Photonics.

3.2.3 Technical Session 2: Nonlinear Photonics

3.2.3.1 Denys Bondar, Tulane University: Towards a Single Atom Computer

Prof Bondar presented a novel thought experiment regarding the nature of NLs in atomic and optical systems and followed with the practicalities of moving toward these ideals. Theoretically, a single-atom optical computer could exist within the framework of reservoir neuromorphic computing. The basis of these concepts stems from recent theoretical results that show it is always possible, if not practical, to determine an EM field to drive an arbitrary optical output for any given material system. Specifically, he gave examples of driving metallic and Mott insulator systems with two different input fields to achieve the same desired output field.[16] This optical mimicry depends on NLs in the Hamiltonian describing the light–matter interaction of a given system. These same NLs provide complexity sufficient to produce an output field that, when delivered through a trained output layer such as an optimized optical filter, constitutes computation of input field information. This procedure is simulated for several common ML test cases such as handwritten digit recognition and points on circle classifications. Dr Bondar concludes that this scheme could be feasibly implemented and may outperform current state-of-the-art neuromorphic reservoir computing platforms.

3.2.3.2 Alex Gaeta, Columbia University: Ubiquitous Nonlinear Photonics: Chip-Based Optical Frequency Combs

Prof Alex Gaeta presented an integrated photonics-based optical frequency comb. The compact size of integrated photonic optical frequency combs yield the possibility for efficient and portable chip-scale light sources. Optical frequency combs are coherent light whose spectrum comprises discrete, regularly spaced sharp lines. They provide a direct link between optical and microwave frequencies (as the spacing between lines is a microwave frequency). Frequency comb technology is used in a host of applications such as chemical and biological sensing, optical communications, and optical clocks, to name a few. In the specific use case of chemical and biological sensing, two frequency combs are used with a single detector to provide fast detection with no moving parts. There are multiple demonstrations of fully integrated comb and multiwavelength sources, as well as all optical clocks, amongst other examples.[17] For the purposes of this talk, Dr Gaeta discussed SiN microresonators as a source of NL, although there are many alternatives both in design and material. The advantages of Si-based microresonators are that they are complementary metal–oxide (CMOS) compatible and fully monolithic and the waveguide can be dispersion engineered and can host high-Q resonators and have relatively large NLs. Dr Gaeta already fabricated and characterized an integrated frequency comb source. This source is compact, stable, and efficient, requiring less than 100 mW of electrical power. In development is an integrated dual-comb source. One challenge has been the on-chip synchronization of the two combs. Thus far, early indications are that relative frequency will be established either through harmonic or subharmonic synchronization.

3.2.3.3 Robert Boyd, University of Rochester: Quantum Imaging

Prof Bob Boyd overviewed the possible advantages offered by quantum imaging, namely the ability to use fewer photons, achieve better spatial resolution, and achieve better signal-to-noise ratio (SNR) by exploiting quantum properties of the electromagnetic field to "beat" the classical constraints. For example, the late Jonathan Dowling introduced the idea of quantum lithography, which posits that entangled photons can be used to form an interference pattern with detail finer than the Rayleigh limit. There have been some laboratory results, but no practical implementation of this concept to date. Mankei Tsang's super-resolution procedure known as SPADE (SPAtial-mode Decomposition), whereby an image is decomposed into any complete orthogonal basis set, can lead to a factor or two increase in determining the separation of two point sources, but it is unclear if this method can be used to increase the sharpness of ordinary images comprised of many light sources. Yet another method of taking advantage of the quantum information encoded in the transverse field is quantum, nonlocal aberration correction.[18] Photons are sent down two paths, one of which is an imaging path and the other a "control" path. Quantum correlations between photons along the two paths are used to correct image aberrations. This method shows increased signal-to-noise by correcting aberrations with entangled photons. Finally, Prof Boyd presented recent experimental results involving the concept of ghost imaging. While ghost imaging is not a purely quantum mechanical process, this investigation explores the possibility of interaction-free measurement, which does depend on entangled photons. Here, images may be acquired without an object ever having interacted with a photon—a marvel of quantum mechanics. These studies are nascent, but early experimental results show promise.

3.2.3.4 Edo Waks, University of Maryland: Controlling Light with a Single Photon

Prof Waks presented a path toward single-photon all-optical switching. A key to information processing with light is photon–photon interactions. Normally photons do not interact. However, when mediated by a strongly nonlinear medium such as atoms in a cavity, photon–photon interactions are possible. In an integrated photonics platform, quantum dots can serve as artificial atoms to produce the nonlinear effects required. Demonstrations of atom–cavity systems with quantum dots have been done with PCs, microposts, and microdisks. Nanophotonics enables NL near the single-photon level. Conventional NLs cannot achieve a single-photon transistor. However, quantum states—specifically long-lived quantum states or memories—can provide the required NL. Light–matter interactions where the photon can interface with the spin of an atom and vice versa enables photon control over a spin, spin control over a photon, and photon–photon interactions. This can even be extended to photon control over a high-intensity optical field.[19] While scalability is challenging in these atom–cavity systems, new techniques enabled hybrid integration schemes where novel material systems are integrated with more conventional and scalable Si photonic technology. In the future, Prof Waks and collaborators plan to combine QOs and DNNs in an integrated nanophotonics platform.

3.2.3.5 Marco Loncar: Harvard University, Integrated LN Photonics

Prof Loncar presented recent record-breaking advances in LN photonics. The motivation for this work is to determine if there is a single material that allows integration of all of the functionalities needed for frequency comb generation and control in an integrated nanophotonics platform. LN has the advantage of being a high-refractive index (2.2) material with large diagonal $\chi^{(2)}$ NL (30 pm/V) and a wide-transparency window (0.4–5.5 µm). These properties are essential for high-quality electro-optic (EO) modulation, EO frequency comb generation, and frequency conversion. LN, however, is inert and hard to etch along with a host of other fabrication challenges. Recent advances in fabrication techniques led to record-breaking performance. Multi-octave spanning supercontinuum generation has been achieved with on the order of 100s of pJ pulse energy. Ultrahigh-Q LN cavities with Qs above 10 M have been fabricated for multiple wavelengths. Frequency combs spanning 2/3 of an octave with ultra-low pump energy have been enabled with dispersion-engineered MRRs. LN integration of frequency comb, filter, and EO modulator have been integrated on a single device.[20] Prof Loncar's group at Harvard is pushing the state of the art in energy-efficient communication systems using high-speed and low-drive voltage EO modulators driven by EO frequency combs. Applications include dual EO comb spectroscopy, EO combs as many-body physics simulators, frequency domain photonic quantum computing, and microwave to optical transducers.

3.2.4 Technical Session 3: Polaritons for Integrated Photonics

This session was motivated by the potential for polaritons to provide a compact platform for ultra-low energy-coherent integrated nanophotonics.

3.2.4.1 Ritesh Agarwal, U Penn: Generation of Helical Topological Polaritons for Integrated Photonics

Prof Agarwal discussed generation of helical topological polaritons by integrating monolayer transition metal dichalcogenides (TMD) on top of a topological PC. A polariton is a coherent combination of a photon and a particle such as an exciton in a semiconductor that acts as a single metastable particle. The PC is designed to have two topologically nontrivial domains, resulting in two topologically protected edge states at the domain boundary, analogous to edge states in quantum spin hall insulators. Strong coupling between photons in these edge states and excitons in TMDs leads to corresponding topological polariton edge states. The two edge states have opposite helicities and propagation directions; their propagation is robust against scattering by photonic defects.

The use of TMD has two advantages unavailable with other materials: first, it makes it possible to directly transcribe topological photonic states, defined by the PCs, to the polariton modes, and second, it allows topological polariton modes up to 200 K.[21] Related 2-D materials are likely to enable room-temperature operation.

Generally, topological protection provides a new pathway to reduce scattering-induced loss in integrated photonics. Topological polaritons have unique advantages in that, compared to topological photonic states, the polariton modes allow greater sensitivity to tuning by temperature and electrical and magnetic fields, and may enable nonlinear phenomena.

3.2.4.2 Dmitri Basov, Columbia University: Polaritons in van der Waals Heterostructures

Prof Basov gave a broad overview of polaritons and strong-coupling phenomena in van der Waals materials. Dr Basov emphasized two other forms of polaritons: a phonon–polariton (coupling between light and material lattice vibrations) and plasmon–polaritons (coupling between light and charge waves.) He demonstrated that phonon–polariton and plasma–polariton modes can be created and measured via near-field imaging techniques pioneered by his group.[22] As polariton modes, they exhibit interesting correlations as well as long propagation distances compared with bare phonon or charge modes. These polariton modes may form new types of building blocks of integrated photonics.

3.2.4.3 Hui Deng, University of Michigan: Nonlinear Photonics with van der Waals Heterostructures

Prof Deng discussed the potential of moiré lattice formed in van der Waals heterostructures as a new platform for ultra-low-energy photonics. When a pair of 2-D materials with a slightly different lattice constant or two layers of a single 2-D material are slightly rotated with respect to each other, a Moiré pattern is formed. Dr Deng discussed studies of the formation, identification, and characterization of moiré lattices, moiré excitons, and moiré polaritons (excitons and polaritons in moiré lattices, respectively.) She showed giant optical NL of moiré polaritons induced by the both the confinement of the potential pattern formed by the moiré lattice and strong coupling (between photons and excitons.)

A moiré lattice provides a naturally formed confinement potential on the nanometer scale. It enables creation of quantum dot arrays that in principle may be free from dot-to-dot inhomogeneity—the major challenge in quantum-dot-based quantum and OE applications.[23] With such a platform, polaritons can be formed with a small ensemble of nearly identical quantum dots. Such polaritons are free from inhomogeneity due to strong coupling, with a lifetime that is controllable via cavity Q, and at the same time possess much-greater NL than conventional quantum-well polaritons. They promise nanolasers and modulators operating at sub-fJ energy input, all integrated on SiN/Si platform.

3.2.4.4 David Snoke, University of Pittsburgh: Design Tradeoffs in Polariton Wire Networks

Prof Snoke discussed tradeoffs between gallium arsenide (GaAs) and 2-D materials for polariton networks. GaAs is one of the most mature and best understood material systems. GaAs polaritons hold the record for the longest lifetimes, coherence time, and propagation distances.[24] Many proof-of-concept demonstrations of nonlinear optical effects and operators have been demonstrated in GaAs, such as laser-controlled switches and phase modulators. However, ways to construct wire networks and to control their properties in general are limited because the quantum wells have to be embedded in nearly lattice-matched materials and protected from surfaces. Furthermore, GaAs excitons and polaritons so far only survive at cryogenic temperatures.

In contrast, 2-D materials in principle have properties unmatched by other materials, including strong Coulomb interactions that allow robust exciton and polariton effects at the room temperature, flexibility in creating heterostructures with diverse 2-D materials to drastically change their electronic and optical properties, and integration with arbitrary substrates (including Si-compound substrates) without the need for lattice-matching. However, they have been discovered quite recently, fabrication technology is still rather primitive, and many material properties are poorly understood. The possibility of putting 2-D materials in the proximity of other materials, such as electrodes and superconductors, furthermore opens up new opportunities to control their transport properties.

3.2.4.5 Feng Wang, University of California at Berkeley: Moiré Quantum Dots for Integrated Photonics

Prof Wang discussed the promise of moiré lattices for ultra-low-energy photonics. He showed scanning tunneling micrographs of moiré-confined electrons confirming strong localization of electrons in a moiré cell. When each moiré cell functions as a quantum dot, excitation of single electron or single exciton at an energy of about 0.2 aJ blocks a second excitation at the same energy, as observed via pump–probe spectroscopy. This blockade effect leads to giant EO and optical NLs, which can be used to enable attojoule photonic devices for integrated photonics.[25]

3.2.5 Technical Session 4: Materials and Devices 2: Smaller and Faster

The theme of this session was submicron-scale phenomena that can be used to push integrated photonics into higher performance: speed, sensitivity, and information density.

3.2.5.1 Seth Bank, University of Texas at Austin: Staircase Avalanche Photodiodes

Prof Bank's work on high-speed/sensitivity photodetectors was highlighted. The work underpins strategic capabilities nanophotonics can provide through PICs as diverse as laser radar (LIDAR), communications, optical NNs, and quantum information processing. Advances in planar epitaxial growth have enabled nearly atomic-scale control of materials synthesis. Digital alloys—the short-period, multicomponent generalization of the superlattice—offer material properties approximating those of the corresponding random alloys, but with notable differences. $Al_xIn_{1-x}As_ySb_{1-y}$ grown as a digital alloy[26] avoids its miscibility gap, enabling sophisticated compositional grading and excellent material quality. The atomic-scale composition modulation modifies high-field carrier transport, yielding the first low-noise III-V avalanche photodiode (APD) materials family. Conventional APDs exhibit low excess noise with impact ionization (energy relaxation causing charge multiplication) ratios (k) of approximately 0.005–0.010

independent of the composition[27]—comparable with that of Si. Silicon, while an excellent low-noise APD material, is limited in both temporal bandwidth and wavelength response. AlInAsSb APDs are expected to enable significantly higher bandwidths as they are direct bandgap alloys, while spectral response can be adjusted by tuning the absorber bandgap energy using a separate absorption, charge, and multiplication structure. Indeed, high-gain-bandwidth products and access to conventional telecom (1.3–1.55 µm)[28] and emerging LIDAR (~2 µm)[29] wavelength bands have been demonstrated with digital alloy APDs. Taking advantage of their high gains and low dark currents, they have also recently performed preliminary Geiger-mode single photon counting at 300 K for quantum information processing.[30]

The same atomic-scale bandgap engineering permits fundamentally new APD architectures as well, such as the staircase APD. The staircase architecture was first proposed by Capasso and coworkers[31] to achieve very-low noise multiplication through increased spatial determinicity of impact ionization. Using a combination of compositional grading and a small applied bias, the conduction band edge is arranged into a series of steps. Unlike conventional APDs, in which avalanche multiplication occurs relatively uniformly throughout the entire multiplication region, impact ionization in the staircase APD occurs proximate to each step, which function similarly to dynodes in a photomultiplier tube. The result is a gain of approximately 2× for each electron that crosses a step.[32] Profs Bank and J Campbell (University of Virginia) have recently cascaded up to five steps. They observed significant approximately 50× lower shot noise power from 3-step staircase APDs as compared with near ideal, $k \approx 0$, conventional APDs at the same gain. Moreover, 3-step staircase APDs are predicted to produce approximately 30× lower shot noise power than an ideal photomultiplier tube at the same gain. In short, the staircase APD is the first solid-state photodetector with the potential to unseat the photomultiplier tube as the most sensitive room-temperature amplified photodetector.

3.2.5.2 Yeshaiahu Fainman, University of California at San Diego (UCSD): Nanophotonics Technology and Applications

Prof Fainman presented an overview of nanophotonics as an enabling technology that can help advance various fields such as national security (e.g., hardware security, quantum cryptography, and biometrics), environment and energy (e.g., photovoltaics and sensing), and navigation and smart cities (e.g., LIDAR and communications). For example, directing traffic in ever-expanding data centers will require on-chip optical networking, which can benefit significantly from nanophotonic advancements. With regard to nanoscale light emitters, Prof

Fainman's group demonstrated metal-clad nanolasers with high-β (i.e., the number of modes the light can spontaneously emit into is limited due to the 3-D optical confinement, causing a reduced threshold pump density to achieve lasing) that are subwavelength in all three dimensions. They also rigorously established their coherence properties via second-order correlation measurements[33,34] while also investigating coupling in a dual metallo-dielectric nanolaser system.[35] Unique tunnel-junction-assisted low-resistance nanolasers[36] were constructed as well as an investigation performed of relative intensity noise[37] and fundamental temperature fluctuation effects[38] of nanolasers. Additionally, they recently achieved the challenging task of combining the active source and modulation into one platform by directly tuning/modulating a nanolaser via an external electric field.[39] Using this technique, they were able to achieve real-time and reversible tuning of the emission wavelength up to 8.4 nm along with a demonstration of high-speed AC modulation of up to 400 MHz (can potentially reach THz regime with improved contacts). These achievements thus far have aimed to achieve the original goal of attaining field localization on the nanoscale to increase field interaction with biomolecules, nonlinear materials, quantum confined material structures, and so on. With respect to Si-photonics switching and modulation, they have explored novel modulation/switching architectures ideal for dense chip-scale integration. More specifically, they explored DC-induced Pockels effects (e.g., linear EO effect) and used the near-field interactions between surface plasmons and materials with nonlinear EO responses such as Si-rich nitride to demonstrate 2-D control of free-space optical fields at 1550 nm at GHz modulation speeds.[40] Such a plasmonic phase modulator can be useful for applications such as neuromorphic processing.

3.2.5.3 Hooman Mohseni, Northwestern University: Ultra-Low-Energy Optical Receivers Integrated on Si

Prof Mohseni discussed how ultra-low-energy photodetection impacts nanophotonic PICs' energy consumption and how this could impact emerging computation and sensing technologies, including advanced ML, large-scale quantum computing, and broadband brain–machine interface. This limitation is already evident from small-scale systems such as wearables and Internet of Things to large-scale systems such as data centers. Optical receivers with efficiencies below 20 fJ/bit and data rate densities above 1000 Tb/s/cm^2 represent breakthroughs that could address the current energy consumption limitations. Prof Mohseni has been working on nanoscale optical receivers to improve the sensitivity, efficiency, and footprint. For the first time, he theoretically demonstrated that his device's sensitivity can approach single-photon detection[41] and found that the sensitivity could be achieved by reducing the internal capacitance to nearly the fundamental quantum capacitance of $C=q^2/kT$ (q is the charge of electron, K is the Boltzmann constant, and T is the temperature in Kelvin). Using his approach, Prof Mohseni built high-speed photodetectors that outperformed the best reported devices. For example, he demonstrated the first coherent detection system that could detect single photons at room temperature without a balanced detection scheme.[42] However, the nanoscale-device size came at a cost: increased influence from the device surface. He developed effective passivation methods that could alleviate these surface effects significantly and render much-lower dark current values and hence, higher sensitivities. These lower dark current values enabled his demonstration of highly sensitive infrared detector arrays[43] (Editors' Pick and cover of *Applied Physics Letters*). He has since started a systematic evaluation of methods to enhance the gain-bandwidth product (GBP) of the detectors, since it represents one of the most important parameters of fast optical receivers. Interestingly, he discovered a method to "engineer" the GBP[41] that could be used in any high-speed phototransistor design. In parallel, he started building a new method for transferring these fast photodetectors to Si substrates for direct integration with CMOS electronics.[44] When a large number of such photodetectors are integrated onto CMOS chips, the throughput of the high-speed CMOS electronics becomes a limiting factor. To overcome this, he developed a new circuit architecture to achieve fast readout electronics.[45] Combining the new knowledge and designs, his group recently demonstrated a record sensitivity to approximately six photons in nanoscale phototransistors integrated on Si.[43] Finally, in recent unpublished work on optical receivers on Si, he achieved record data rate density above 5000 Tb/s/cm^2, at a record energy efficiency of 15 fJ/bit, and a GBP over 270 GHz. The impact on integrated photonics will be significant with 300× less energy/bit and possible efficiencies to achieve single-photon, room-temperature operation.

3.2.5.4 Bo Zhen, U Penn: Novel Nanophotonics Resonances for Photonic Integration

Prof Zhen discussed novel design approaches to integrated nanophotonic couplers based upon guided resonances. So far, most diffractive optical nanophotonic structure designs are limited to two principles: simple geometric intuitions or purely numerical optimizations. Prof Zhen has been working on a new family of "topologically enabled" photonic design paradigms, which can outperform existing devices due to their underlying design principles. His results, funded by a Presidential Early Career Award for Scientists and Engineers through ARO, include the experimental demonstration of ultrahigh-Q resonances that are robust to out-of-plane scattering losses.[46] Specifically, he improved the quality factor of guided resonances, which are defined as narrow spectral bandpass characteristics engineered into diffractive optical nanostructures (e.g., for microcavities or highly efficient coupling from one somewhat collimated, focused, or fully guided direction of propagation to another) by over an order of magnitude and showed this method can be generally applied to a family of devices.[47] Prof Zhen presented the experimental demonstration of "unidirectional guided resonances," which are topologically nontrivial optical structures that scatter light in only one direction. He demonstrated a simple grating that can send >99.8% of the power toward a single direction without the use of a mirror on the other side. His device can greatly reduce the significant energy loss produced in current data centers.

3.2.5.5 Michal Lipson, Columbia University: Next-Generation Si Photonics

Prof Lipson emphasized future directions for advances relying on Si photonics. She has pioneered low-loss waveguides, particularly in Si and SiN but also in other materials such as SiC. Her work on spatial division multiplexing within PICs, via Si waveguides, is well known.[48] By carefully etching well-designed waveguide transitions, modes can be stripped off of a larger waveguide, similar to how wavelength division multiplexing is achieved by resonant microrings. Her main future-looking emphasis was upon multiplexing with much higher numbers of modes—possibly 20 or more (this was not specified). Information bandwidth density could scale with such achievements if the transitions and control could also be made dense enough. Area is a key commodity in PIC design. Multiplanar light control, pioneered at Nokia Bell Labs by N Fontaine,[49] has shown 210 mode-multiplexing, but this is not done in a fully planar regime. Other groups are also considering such things for micro-optical systems, as communications bandwidths are key to many systems. Fully harnessing the advantages of photonics means maximizing multiplexing. As Lipson is also a pioneer, along with Alex Gaeta, of microresonator-based frequency combs, the bidimensional capabilities of both space and frequency multiplexing are certainly areas of potential advance.[50] How the most bandwidth density and energy consumption efficiency can be achieved still remains to be seen.

3.2.5.6 Zubin Jacob, Purdue University: On-Chip Spin Quantum Electrodynamics

Prof Jacob discussed the pathway toward realizing spin quantum electrodynamics in an integrated package. First, he discussed several recent experimental and theoretical results that illuminate the intrinsic relationship between spin and momentum in evanescent waves.[51] These concepts are universal to all evanescent waves and can be used to better understand topological photonics. In topological electronic systems, intrinsic spin-momentum locking phenomena leads to the propagation of unidirectional edge states with viscous type effects. The theory, in the semiclassical picture, supports the existence of topological, subwavelength structures for signal routing in OE devices. A fully quantum theory would require a photon spin operator, which would resolve a long-standing conflict between laser optics and particle physics and have broad impact for QOs, topological photonics, and nanophotonics. Prof Jacob discussed his group's recent work on this topic and their potential discovery of a photon spin operator.[52] The talk concludes by making the point that photon spin is always present and often unexploited. New nanophotonic components, specifically photon spin detectors, could provide additional capabilities for integrated nanophotonic devices.

3.3 Army Panel

The Army panel consisted of representatives of the US Army Combat Capabilities Development Command Army Research Laboratory (ARO, Sensors and Electron Devices Directorate [SEDD], and Advanced Concepts Office) centers and the Army Futures Command (AFC) Futures and Concepts Center. Other Army scientists provided input as well including DEVCOM Armaments Center and the Army Optics ST (stationed at DEVCOM Aviation and Missile Center). Many of these people were also instrumental to the AFC Deep Dive in Optoelectronics where similar discussions are provided in the written report based on the August 2020 Deep Dive.

First, Dr Gerhold, PM of ARO Optoelectronics, gave an overview of his program's Army relevance and integrated nanophotonics interests. Second, Drs Paul Pellegrino and Justin Bickford spoke generally about DEVCOM Army Research Laboratory's role in providing guidance and using the capabilities of DOD AIM Photonics (www.aimphotonics.com), which uses CMOS foundry-level processes for integrated photonics, primarily Si photonics through the SUNY-Polytechnic nanofabrication facility. Dr Fred Long of Army DEVCOM Armaments Center related some of their interests in neuromorphic PIC capabilities for imaging, target recognition, and LIDAR. They are especially interested in single-photon LIDAR to achieve high-sensitivity targeting and surveillance. Finally, a panel discussion from many of the Team Ignite members—Mark Fisher, Major Minou Pak, Major Jake Spangler, and a few others—described their interests in AI/ML, relevant to neuromorphic processing, to make and disseminate decisions faster. For this Army-relevant discussion, certain aspects of ARO OE as well as the new Quantum Optics programs will be highlighted (that were not already discussed in Section 3.1), along with some of the interests of ARL SEDD's integrated photonics group.

ARO OE opportunities related to integrated nanophotonics for Army relevance include nanolasers (or microlasers with significant nanoscale design features) at various wavelengths. For example, ultra-narrow-linewidth lasers have been developed with single optical mode characteristics (both transverse and longitudinal) with microcavity designs that use very-high precision nanolithography. Some of the Army-related needs for improved surveillance and autonomous navigation via high-resolution LIDAR are enabled by these lasers. Other Army relevance is seen in needs for high-speed data processing, particularly from sensors. Cryogenic optical interconnects are one direction ARO is investing in for high-speed surveillance, with high-sensitivity focal-plane imaging. Finally, nanopatterning is an important consideration for UV- and VIS-oriented regimes where low-dimensional active regions, such as nanowires, are showing promise. Applications of such devices include water purification, surface sterilization, and biomolecule/chemical agent sensing. Other reasons to pursue shorter wavelength photonics is the ability to make denser PICs in terms of device count. The wide-bandgap semiconductor materials, particularly III-Nitrides, have direct bandgaps and progress is showing opportunities for PICs.

ARO's QOs program recognizes that integrated nanophotonic devices serve as key enablers for QOs experiments and will continue to do so. It is clear the robustness, precision, and control afforded by integrated photonic light sources will be a key element for quantum technologies sensitive to environmentally induced decoherence. Traditional optical elements are heavy, bulky, and prone to misalignment due to temperature variation and vibration while quantum technologies require optical sources with extreme accuracy and precision. Fieldable quantum technologies for position, navigation, and timing (PNT) or quantum secure communications are two examples of Army-relevant applications that will depend upon integrated nanophotonic components to meet these stringent requirements. Further, decades-old scientific discovery in such fields as NLOs like spontaneous parametric down conversion, ultrafast laser physics, and optical frequency combs have combined with advancements in our understanding of optical materials and fabrication techniques to produce the state of the art in integrated nanophotonics. It is the position of the Quantum Optics program that new discovery and understandings in such burgeoning fields as topological photonics and non-Hermitian physics and PT symmetry in optics[53] will similarly contribute to next-generation integrated photonic devices.

ARL SEDD discussed its view of integrated photonics through its technical leadership role in AIM Photonics. Dr Paul Pellegrino leads the branch where this work is pursued and its chief technical liaison is Dr Justin Bickford. Dr Weimin Zhou leads another team within this effort as well. Dr Bickford's interests are somewhat broad and he is the lead Army representative to AIM Photonics. One of the areas he works on with AIM, both as a technical oversight leader for the government as well as on individual PIC designs, includes RF photonics; that is, phased-array beam steering PICs and medical and chemical or biomolecule sensors.

Dr Zhou's team primarily focuses upon RF photonics. A main reason that AIM Photonics was formed, according to some participants, is low-volume production. Many PICs will likely not exceed around a thousand devices even at their peak of being incorporated into new systems. Such low-volume runs require access to multiproject wafer (MPW) capabilities, which Si CMOS foundries generally provide. However, the real challenge lies in the high-performance specifications needed for the RF PIC approaches to outperform current fully RF approaches. Other points were raised about Army relevance of the various PICs being pursued, which are again discussed in other places. How this relates to integrated nanophotonics per se (and not just PIC technology in general) may have been a bit lost in the mix, but a few points can be made. One is that a lot of the Army relevance has to do with achieving a specified, high level of performance, which requires high-precision etching that is made available through nanolithography and precision-etching tools. CMOS foundries for integrated photonics provide essential high-performance tools, namely photolithography and etching tools, a known process design kit (PDK) and numerous ancillary capabilities for testing, assembly, and packaging (TAP). Both PDK and TAP capabilities related to integrated photonics require significant engineering, updating for latest R&D advances, and specialized tools—many specialized for interfacing with various ancillary electronics and fiber optic interfaces. In this context, PICs can be designed at a "one-stop shop" and thought about in terms of new capabilities from a holistic point of view. How this relates to nanophotonics for the Army is more complicated. Some of the salient points will be relayed in the Findings (Section 4) of the report.

3.4 Breakout Sessions: Topics and Discussion Summaries

3.4.1 Topic 1: Neuromorphic Processing with Photonic Integrated Circuits (Profs Volker Sorger, George Washington University [GWU] and Yeshaiahu Fainman, University of California at San Diego [UCSD])

Neuromorphic information processing with photonics has been shown to have exciting prospects in terms of physical system size, energy consumption, computational performance, and cost. Processing paradigms for learning, and possibly even deep learning, have been shown and postulated. However, many aspects of this problem need to be understood separately for progress to be made: photonic architectures for scaling, needs for integration of electronics to access data and interface with outside systems, device metrics for adequately precise outputs including at learning, and final output stages. Also, a consideration of the types of problems envisioned for pursuit in the short, mid, and long term was sought.

The goal of the neuromorphic PICs session is to envision needed research goals and prospects of neuromorphic photonics over the next two decades or so from device, architecture, and systems' perspectives.

Focus areas and questions that were considered:

- Architectural goals: How can cascading and scaling to real-world problems N = 1000 or larger be accomplished?
- Electronic integration issues: How can electronic functions for memory or nonlinear activation be integrated?
- Precision of outputs: Can the outputs be adequate for multiply and accumulates (MACs), nonlinear activation functions (NLAFs), and data resolution?
- Types of problems to be considered such as 1) matrix operations–multiplies, 2) learning, 3) deep learning, and 4) other complex computational regimes.
- Can neuromorphic PICs outperform von Neumann and nonphotonic neuromorphic systems and, if so, by how much? What problems should be focused upon?

3.4.1.1 Summary of Topic 1: Neuromorphic Processing with Photonic Integrated Circuits

Guiding principle discussed:

> *"Let optics do what it is naturally good at; don't chase (mimic) electronic approaches."*

3.4.1.1.1 Subtopic a: (Linear) Vector Matrix Multiplication (VMM) Operations. Bit resolution is less important during inference than in training.
What bit resolution is required? The computer science community has established that 4–8 bits are sufficient for performing inference adequately. Even 1-bit (two states) has provided a decent accuracy, but only for simple data sets, such as the 1-bit (black–white) MNIST data set. For more complex data, such as the 8-bit RGB CIFAR-10 data set, 4–8 bits are required and provide satisfactory performance.

Experimental VMM options discussed in the workshop (talks and breakouts) included interferometer-based networks (MIT), GHz-fast spatial light modulator (SLM) (UCSD), tensor core approaches (GWU), topological edge-state router networks (U Penn), and MRR weight-banks (Princeton).

What bit resolution can we achieve experimentally in PICs? The answer is in two parts. Given that photonic and optical weights are analog in nature, the precision could be, mathematically speaking, infinite. Realistically, however, noise will limit distinguishable states. Also, if such programmability requires digital-to-analog converters (DACs), then the DAC resolution (and its associated overhead on power/speed/footprint) needs to be considered. Also, while having a high-bit precision may be possible (e.g., programming an MZI network), its operational stability and hence overhead may be unrealistically high. Such hardware/device-to-performance mapping is yet to be completed in a rigorous way and future funding programs in photonic NNs should include such a mapping, certainly, for foundry PIC-based approaches. It would be interesting to ask—given an established PDK from, say, AIM Photonics—what VMM performance and with what reliability one can obtain? For example, the Princeton group demonstrated 6-bit precision of MRR weights, but only using MHz-modulated signals. More generally speaking, a discussion of bit resolution should be viewed not only from the OE device point of view, but from a link point of view. That is, downstream in the NN (at least at the end of one node), then the weighted signal (i.e., the signal's extinction ratio; for example, 1 dB) must be detectable at the data speed by, for example, the detector, if the device is used for MAC summation. Hence, if the bit precision only delivers, for example, 0.1 dB of signal extinction corresponding to a total signal range of 0.1 dB * 64 = 6.4 dB (e.g., for 6-bits), which is actually controllable, distinguishing such 0.1 dB differences at 50 GHz is likely not possible. Thus, speed-bit precision mapping in conjunction with PIC control and repeatability should be investigated.

3.4.1.1.2 Subtopic b: Nonlinearity (NL). While electronic VMM engines are actually decent, optics solutions could yet improve them by a factor of 10–100 with respect to throughput, and 10–1000 with respect to operational efficiency. In addition, optics offers a (relatively) strong NL, which has high relevance for NNs (the exact performance impact needs to be investigated). The required NL does change with layer position of a NN. For instance, upstream of a simple rectified linear unit, for example, a piecewise linear function that will output the input directly if it is positive, otherwise it will output zero (or squared NL), is sufficient, while further downstream (and certainly at the final layer that is fully connected) a "decision" must be made; hence, the final layer's NL must be a function exhibiting saturation (e.g., sigmoidal, tanh, and so on).

Three types of NL were discussed: 1) EO; 2) all-optic (AO); and 3) O-to-E-conversion (basically an EO, but with a squared NL shape).

1) EO options offer the freedom to engineer the NL using the transfer function of a modulator, for example. Performance wise (i.e., speed and power), EO NL is governed by modulator physics; hence, we can expect 10s of ps (i.e., 50 GHz) response times of such NL and energy consumption on the order of fJ/operation. However, such a solution requires an additional laser

source, which is costly, yet this source could be shared (fanned out) with many nodes.

2) AO solutions are probably the most interesting value proposition since much work has been done. Such a scheme would, essentially, require a pump–probe scheme on the PIC. Given the weak AO NL, however, the required pump energy may be exceedingly high. Nonetheless, the main advantage for AO NN approaches would be the short temporal response of approximately 1 ps. However, 1 ps correlates to 1 THz and the corresponding optical signals need to eventually be converted into electronic signals, which would be challenging (i.e., a very fast photodetector). However, high-electron mobility transistors are known to switch at approximately THz and a photo-transistor could be used for the O-to-E transduction. A discussion on resonant nonlinear effects, which are usually stronger than those discussed previously, have also been considered in conjunction with their response time. It may have an important implication on all-optical NLs provided the response time can be either tolerated by the system or engineered to meet the system requirements. There were some recent demonstrations with such NL switching at energies of about 1 pJ/bit employing engineered semiconductor heterostructures. These will need to be integrated with PICs, which may be a challenge.

3) The naturally occurring O-to-E conversion at photodetectors offers an elegant form of EO NL; its square shape may not be suitable for all required shapes of NL, but is sufficient for upstream nodes in a NN.

Options in optics are many, in general. However, PIC-integration options of NL are yet rare and need to be explored. Also, the level of required optical power in such a pump–probe scheme needs to be carefully evaluated. It is likely not going to be competitive, unless high-speed signals (10s of GHz) are being processed to help amortize the high power; that is, lower energy/operation. This lack of AO NL on PICs should be addressed in future programs.

While it is generally understood that NL is required for decision making—"latching" to a case (e.g., making a decision whether an image is a cat or a dog)—deep optical NNs consisting of trained weighting layers have shown respective performance without using NL at each node (see work from the Ozcan Group[54]). This raises the question: What NL is actually required? What NN depth (number of layers) results into what accuracy performance, given a certain task?

3.4.1.1.3 Subtopic c: Training. Can we train photonic NNs on hardware rather than in a digital computer? If so, it would be extremely powerful. Training an actual analog photonic system results in the highest achievable accuracy performance as compared to training it electronically and then uploading the weights into the photonic processor afterward. Before providing an answer, what is required for such a case is to send information backward through the system and update the weights at each node and layer. The common approach is to use a gradient-descent approach where a cost-function is iteratively minimized. The nonreciprocity of NN systems, such as when intermittent OE components are used that ignore phase information, for example, render direct training challenging. However, AO NNs might allow for such possibilities for enhanced training speeds and performance.

3.4.1.1.4 Subtopic d: Architectural Considerations. What are the natural strengths of optics? With optical NN offering numerous DoFs for parallelization (i.e., space, time, wavelength, polarization, beam-structure, and so on), such "real estate" lends itself especially to NNs that are wide, but possibly not very deep (i.e., number of layers—see previous comments on NL). That is, NN depth demands an efficient NL.

Also, use of spatial DoFs should be included when discussing optical NN solutions. That both the information interconnectivity (such as required in a NN) and the information flow are currently required to be present in the same dimensional space (e.g., 2-D) is fundamentally limiting. This "routing problem" is well known in the electronic integrated circuit (IC) community and has been a main field of research in electronic design automation for decades. Hence, 3-D approaches in optics should be explored in future programs. One direction is also to explore hybrid design consisting of both free-space optics and PICs. For instance, the massive parallelism offered by display technologies such as SLMs or digital micromirror devices, providing 10^6 individually programmable "channels" (i.e., pixels), could be combined in future programs with Gb/s reconfigurability enabled by OE components. Such a utopian future system would offer a throughput of (1000 × 1000) pixels * 1 GHz reconfigurability at 1-bit = 1 Peta-OPS (operations per second), which is about 5–10× faster than today's electronics. If extended to, say, 4-bit resolution, 4-k pixels resolution, and 10 GHz, the throughput would be (4000*4000) pixels * 2^4 bit * 10 GHz—in excess of 1 Exa-OPS. This is a very attainable goal in the next decade and the Army could lead an initiative to enable such high-end technology. One approach to this free-space–PIC cross-integration for hybrid AI systems is to involve near-field metasurfaces for the interface.

Approaches to reservoir computing have been also discussed. Here the optical connectivity can be exploited to achieve the necessary increase of the dimensionality/scalability of the NN reservoir with required memory. The memory may be realized employing resonant phenomena and "slow light" integrated with optical NLs. Some of the topological optics and PT symmetry approaches could also be explored.

3.4.1.1.5 Subtopic e: Reconfigurability. With systems being trained for a particular purpose, typically a NN and AI system cannot recover once it has lost its dedicated training parameters. Such an "event" can render the entire AI system (e.g., autonomous vehicle) useless. Thus, in the future we need to think about systems that are 1) very robust, 2) reprogrammable, or 3) retrainable. First, an AI system can be made more robust by training with noisy data. The system can "learn" to effectively operate in noisy environments. Typically, this requires a higher bit fidelity, however, and such "sensitivity" should be investigated in future programs. Typically, the absolute accuracy drops by a few percent in systems trained with noisy data (data-set dependent), but the system robustness improves by orders of magnitude. Second, reprogrammability is certainly within the possibilities of PICs due to EOs such as used in PIC VMMs. During the writing of this report, an 8-bit reconfigurable integrated photonic quantum information processor was reported in *Nature* magazine, demonstrating the veracity of this approach. Even in the broader context of NN, the efficiency and speed are yet to be tested and explored. And finally, the matter of training a photonic NN has been discussed in the previous Training section.

3.4.1.2.6 Subtopic f: State Retention and Memory. Many photonic (and optical) NN approaches today rely on EO element-wise programmability, which requires a constant (permanent) voltage control. This not only costs energy, but also may lead to bit precision challenges; that is, if an EO element is switchable at high speed, then it will likely not be very stable over time and vice versa. Paradigms like this motivate the exploration of nonvolatile OE elements. Indeed, from an NN point of view, retention-of-state (memory) is highly desired, since the NN is usually only trained once, or if retrained, seldom (e.g., days, weeks, and months). This is either because training requires this amount of time or because no new data sets are available to redo the training.

All-optical memory is out of the question, at least if nonvolatility (e.g., time scales of days to weeks) is considered, and hence any truly nonvolatile photonic memory solution will have to include a light–matter interaction. Phase-change materials are a promising candidate for state retention, since their "threshold" allows one to latch onto one of two states (crystalline vs. amorphous). They are programmable as well using electro-thermal pulses. However, the most prominent candidate today (GeSbTe, i.e., GST) has prohibitively high losses (imaginary part of index between 0.2 and 1.5 for both states in the VIS and near-infrared [NIR] spectral range). Thus, alloys of GST and other phase change materials should be investigated as low-loss alternatives, with NL figure of merits (FOMs) exceeding 5 (i.e., $\Delta n/\Delta\kappa\Delta > 5$). Other approaches to nonvolatility should also be considered. Note that this also invokes another level of complexity that must be considered: PIC integration, programmability, power-efficiency, and other FOMs.

3.4.2 Topic 2: What's Next through Novel Physics for Integrated Nanophotonics? (Prof Ritesh Agarwal, U Penn)

Photonics is the key enabling technology for the ongoing fourth industrial revolution that requires massively increasing the information-handling capacity of all our devices and communications networks. Integrated nanophotonics can provide solutions for these challenges. These solutions include using the many other DoFs of light to encode, transmit, and decrypt information; for example, using symmetry engineering at the nanoscale to transmit information with no losses and backscattering and performing computation at the nanoscale while simultaneously minimizing energy losses for all optical or hybrid OE platforms. Future quantum technologies will also make use of integrated nanophotonics to encode and transmit quantum information. New physics and design methodologies are needed for quantum signal control and networking.

This session brainstormed on what basic research can be done now to provide novel functionalities to the photonics toolkit.

Focus areas and questions that were considered:

- Topological photonics including higher-order topological insulators. Can we think beyond borrowing ideas from condensed matter physics and solve unique problems in photonic topological physics?
- Can topological photonics extend their functionality from passive to actively tunable devices, perhaps through topological exciton–polaritons and plasmon–polaritons? What are the fundamental science challenges?
- Non-Hermitian, PT symmetric and supersymmetry concepts in photonics have delivered new functionality at a single-device level that cannot be easily accessible in electronic systems. Can they enable active signal control for large-scale networks, such as new routing and switching principles? Can they enable large-area high-power lasers? What else is possible?
- Plasmonic devices have intrinsic physical limitations such as high losses. Is this fundamental? Can topological physics help? Coupling to gain and nonlinear media has been discussed; what is limiting the progress?
- Using additional DoFs of light such as spin and OAM may increase the capacity of optical networks. How can one generate, transmit, and detect light with these additional DoFs on microchip?

- What new materials do we need to enable everything?

3.4.2.1 Summary of Topic 2: What's next through Novel Physics for Integrated Nanophotonics?

In this breakout session, attendees were encouraged to address areas where new physics discoveries were being made that may impact integrated nanophotonics. The discussion was wide ranging. The following is from a collection of notes taken during the discussion organized by a subject-matter expert (SME).

3.4.2.1.1 Subtopic a: Polaritons. One area of discussion focused on the recent investigations of polaritons, especially studies of the collective behavior of coupled exciton–polariton systems. Exciton–polariton systems can form a Bose–Einstein condensate (BEC), a state of matter that exhibits long-lived quantum coherences and superfluidity. For the past few decades, exciton–polaritons have been a candidate system for producing BECs with large critical temperatures, potentially approaching room temperature. Polaritonic BECs can be experimentally realized at cryogenic temperatures by coupling charge carriers in quantum wells to optical cavities and then pumping the optical cavities to produce excitons–polaritons.

Coherence is a defining feature of BECs. However, on resonance, short condensate lifetimes limit propagation distance to a few microns, which becomes a real problem for using polaritons in integrated photonics. A similar problem existed for plasmonic systems as well. The plasmon community spent a decade working on solving the propagation problem with no resolution. These are outstanding challenges for the propagation of polaritons that need to be addressed before they can be considered a candidate system for quantum integrated photonics.

One possible path forward is because stronger exciton–polariton coupling increases the lifetime of the polaritons, perhaps providing sufficient time to propagate information over sufficiently long distances. For example, it is conceivable that quantum information could be sent a long distance via excitonic resonances. The trade-off between the photonic part and excitonic part of an exciton–polariton requires balancing lifetime (excitonic) versus coherence (photonic).

It is worth noting a caveat regarding the limitation of not having a single-particle picture in a BEC. There are advantages to having a collective system. For example, it has coherence (a laser's coherence is due to the same sort of condensate behavior) and can exhibit quantum mechanical properties such as interference and, if properly engineered, entanglement. A condensate is also more robust against material defects and environmental factors. Additionally, depending upon how an experiment or device is designed, the properties can be controlled both optically and electronically.

3.4.2.1.2 Subtopic b: DoFs. Another area of focus was on the utilization of other DoFs of light in integrated nanophotonics. Much of the discussion centered on the difference between OAM and spatial modes and their utility in integrated photonics applications for either quantum or classical applications. OAM in free space can transmit, via a family of orthogonal modes, densely encoded information. Hyper-entanglement—meaning higher order encoding of quantum information— has been demonstrated using OAM modes as well. Dense coding and hyper-entanglement could be beneficial for efficient transmission of classical and quantum information.

The question here remains, however, *Is OAM fundamentally beneficial?* It has been suggested OAM modes may be exploited for multiplexing and may enable an end-run around constraints inherent in other modal schemes. Much progress has been made for free-space OAM, but spatial modes may, for example, be a more natural configuration in an integrated nanophotonic platform due to their geometry. The advantages of different schemes should be compared. Other avenues are also evident. For example, OAM modes may enable hybrid free-space–PIC concept devices. Metasurfaces could serve to launch OAM beams in free space. Also, if different modes (i.e., OAM and spatial) can be placed on equal footing within an integrated nanophotonic platform, it provides access to an increased mode volume for higher dimensionality within an ONN.

3.4.2.1.3 Subtopic c: Symmetry and Topology. Concepts regarding symmetry and topology were touched on throughout the session. It was generally agreed that using symmetry and topology to build a next-generation detector is incredibly appealing. Added topological protection can only help. Some general questions arose here: *Can one combine the topology of light and the topology of materials? How do these two systems work together?* Ideas originating from metamaterials came from photonics and are now being exploited in condensed matter systems. Geometry is the key unifying idea; it is a different way of thinking about condensed matter and light–matter interaction.

3.4.2.1.4 Subtopic d: Odds and Ends. And finally, over the course of discussion when the idea of priority investments was broached, there were several suggestions that either did not fall within any category or could be applied to several:

- Investments should be made in direct AO approaches for interacting with spins in materials; that is, without frequency conversion to/from optical-to-microwave frequencies.
- Strong and ultra-strong coupling between light and matter was generally well accepted as being a fertile bed for discovery that would contribute to integrated nanophotonics. Strong and ultra-strong coupling is a way to change the properties of a system through cavity light–matter interaction.

- Physicists are still making their own tools (i.e., special-use spectroscopic setups). Is funding available for these types of investigations?
- New materials and new tools (such as at the extreme of spatial and temporal resolution) are the key enablers.
- Materials aspects are sometimes ignored. There are new revolutionary tools to investigate materials.
- Never discount the people who are doing these things on the side; one never knows what could happen.
- Do not be afraid of oddball ideas and a willingness to invest in high-risk efforts. But, invest in the cutting edge, not just the hype.

3.4.3 Topic 3: Nanophotonic Architectures and Design Principles (Profs Hooman Mohseni, Northwestern University, and Bo Zhen, U Penn)

Integrated photonics is commonly thought of in terms of either Si photonics (SiPh) or indium phosphide (InP) photonics. However, new paradigms are enabled by techniques that incorporate other materials. Even 2-D materials such as graphene (IMEC, Belgium) are being pursued now. A second consideration for new architectures and goals for future nanophotonics is how to enable efficient coupling into and out of PICs. Edge and surface coupling needs to be vastly improved and manufacturable.

The goal of the nanophotonic architectures and design principles' session is to consider developing new techniques and design methods for high-performance systems.

Focus areas and questions that were considered:

- What are unique approaches to efficient coupling in and out of layers and devices?
- Complexity—how can higher device density be achieved, considering in-plane cascading and networking?
- Complexity II—3-D integrated nanophotonics: using diffractive and orthogonal properties of light.
- How can disparate materials with desirable properties be incorporated a) in-plane and b) by stacking or in volumetric architectures?

- What are the performance needs of systems or parts of systems to enable processing of signals at different power levels, spectral bands, and angular tolerances or distributions?

3.4.3.1 Summary of Topic 3: Nanophotonic Architectures and Design Principles

3.4.3.1.1 Subtopic a: Couplers. Optical coupling needs to be done with high efficiency and from both the edges and surfaces of PICs. Broad bandwidth is also desired to make use of wavelength division multiplexing. Controllable mode profiles and sizes are needed. High power levels are desired for future directed-energy-related PICs. Couplers need to access regimes with varying material platforms and wavelengths.

Challenges were identified that relate coupler designs to the applications. For example, optical phased arrays (OPAs) require a certain level of directionality and side-lobe suppression. The design criteria to meet the system specifications fall into coupler design. Imaging is an area that needs very-high efficiency coupling, which also may need to be broadband. However, coherent LIDAR (active imaging) may be narrow linewidth and high efficiency and thus a more reasonable starting place for PIC opportunities.

Short-distance optical coupling may be more straightforward when it comes to coupler design, but it still has important challenges. Vertical-cavity surface-emitting lasers (VCSELs) or photonic-crystal surface-emitting lasers (PCSELs) have not been widely considered as light sources for PICs but, nevertheless, could be transformative. They are small and can be made of narrow linewidth (MHz, or possibly less), but they require high-efficiency coupling. Edge-emitting lasers have been the more obvious choice for PIC light sources and in-plane waveguides. However, VCSELs can be made at low cost, high efficiency, and tailorable wavelengths for wavelength-division multiplexing (WDM) (coarse WDM, if not dense.) Coupler design needs to consider the coupling distance in terms of the laser-mode profile and divergence. Specific couplers can be made for mm-scale distance where parallel boards or PICs are being interfaced, as well as longer distances that interface to other chips, racks, or lines for free-space interfacing across platforms (or data centers).

3.4.3.1.2 Subtopic b: Complex 2-D Photonic Circuits. Highly complex PICs require cascading a large number of devices and thus point to the need for low-insertion-loss devices. Losses in general, particularly from any waveguide, need reduced. Compact and efficient transducers are needed at the front and back ends of any PIC; for example, for RF photonics systems. Coherent transducers may also be needed, for example, for superconducting RF cavities to C-band photons. Part of the complexity issue is related to the need for nonlinear photonic circuits. In the nonlinear, complex regime, low-energy nonlinear processes are desirable. This returns to the need for low loss and high Q. Numerical tools to simulate time-dependent and nonlinear large systems are part of what is required to increase complexity.

When it comes to complexity in the plane, two major issues were raised. The first is loss. Currently, state-of-the-art waveguide losses, for example, SiN, have achieved gains down to 100 to 1000 times above the fundamental Rayleigh scattering limit. These results came from intense research on optimization and interface studies with etching and patterning down to the atomic level. Reducing it further, another order of magnitude, could have remarkable implications for various needs such as longer delay lines for optical memory and buffering, narrower linewidth regimes based on ultrahigh-Q resonators, and low-energy NLO devices, to name a few. Discussion here centered on why loss has not been identified as a key research challenge. The participants pointed to the need for industry or institutes such as AIM Photonics to focus engineering resources on loss. Corning achieved its 0.2-dB/km C-band optical-fiber losses through years of significant research and investigation. How such research can take place for integrated photonics needs to be considered. Atomically smooth surfaces for waveguides also need to be developed to enable lower levels of loss. Such studies are needed across the spectrum. Research at VIS wavelengths is now being pursued through the DARPA Lasers for Universal Microscale Optical Systems (LUMOS) program. Investments are needed to enable shorter wavelength regimes along with much-longer mid-infrared wavelengths.

A second major discussion point related to complex 2-D circuits points to research and design methods that are dependent upon multiple devices and components. A focus purely on individual devices does not automatically enable successful PIC-based technologies. Due to the coherence and diffraction of light waves, their propagation, reflections, and refraction are governed by wave equations such that a PIC operates more as a collective unit than as a cascade of individual devices. In comparison, digital electronics operate in very-controlled block structures that are easily cascaded and scaled into higher-precision state machines without interactions finagling with the fundamental behavior of each block. Analog electronics are more similar to photonics and can suffer from nonlinear harmonics and reflections due to wave-like phenomena. However, coherence and wavelength dispersion considerations apropos to photonics are not generally in play. Photonics design software and PIC limitations must consider these more complex and challenging effects. Of particular note was dispersion control for issues in nonlinear PICs and lengthy delay lines. Elements that allow arbitrary dispersion control can be helpful. Investments in how delay can be accomplished in the presence of dispersion and loss are needed. An example of an investment area for this is "slow-light" research. This may also benefit complexity in 3-D photonic circuits, which are discussed in the next section. Light sources likewise must be studied in the context of coupling into PICs. Power scaling and multiplexing could be improved by couplers that work with arrays of lasers. Comb sources are an example of broadband coherent light sources that need special coupler design considerations.

3.4.3.1.3 Subtopic c: Complex 3-D Devices and Systems. Photonics has the greatest potential to exceed electronics capabilities by pursuing 3-D paradigms. Three-dimensional optical and electrical interconnects may be required for this. New design methods, for example, inverse design, are necessary for optimal components, especially nonlinear optical devices. Advances are being pursued with CMOS electronics toward 3-D stacking, but interfacing CMOS with 3-D photonics may bring significant new challenges.

From the very early days of research in 3-D electronic ICs, it was recognized that many advantages of 3-D integration could be realized using 2.5-D integration, that is, by placing bare dies side by side on an interposer instead of stacking them vertically. It turns out, furthermore, that 2.5-D integration is actually more than just "halfway to 3-D" because

- An interposer can support heterogeneous integration (HI) of dies of different pitch, size, material, and process node.
- Placing dies side by side instead of stacking them vertically reduces heat buildup.

Extension of PICs to 3-D is also expected to bring scalability and energy efficiency for photonic signal processing. However, 3-D photonic integration cannot be implemented using the same or similar approaches as for 3-D and 2.5-D electronic ICs. The main reason is that each interconnect for electron transport supports a single DoF from an information-theoretic perspective, whereas a photon possesses many DoFs that cannot be utilized fully with single-mode waveguides (akin to 1-D, or limited dimensionality) interconnects.

We can start by enlarging the in-plane dimension of optical waveguides, which has already begun in the research community, to increase the DoFs of optical waveguides/interconnects. However, the information density or DoF density per unit in-plane width cannot increase significantly because the DoFs of optical waveguides scale linearly with the in-plane width. A further step would be to also increase the vertical dimension to form 2-D optical waveguides. This approach would provide multiplicative increase in the information/DoF density per unit in-plane width. However, the multiplicative factor will be limited to the finite height of the optical waveguide that can be reliably fabricated. In addition to the limited scalability, optical waveguides cannot cross each other without incurring loss and crosstalk, thus limiting physical and logic paths of optical interconnects, unlike in free space in which light can cross each other without any interaction. It should also be noted that 2.5-D photonic integration using optical waveguides as interconnects cannot reap the benefits of all the DoFs of photons due to the limited DoFs of the interconnects. Therefore, to realize the ultimate potential of photonic integration, long-term investment is needed to develop the scientific knowledge and technological tools for transforming 3-D bulk optics into lithographically defined 2.5-D and 3-D PICs, providing the benefits of integration (SWaP consumption as well as cost and reliability) without sacrificing information capacity.

Materials Integration

New methods for material integration with both 2-D materials and 3-D structures need to be explored to increase integrated nanophotonics opportunities. Additive 3-D integration techniques are of interest, but they need to be assessed for nanoscale precision. As stated in previous sections, loss is related to atomic level smoothness, which will need to be achieved along with high precision. The 2-D materials hold promise for improved physics, such as high-operating temperatures, due to increased exciton binding energy. However, they are currently of very limited area and may be damaged by microtransfer processes. Advances have been made in both of these materials' integration areas. For 3-D structures, stereolithography tools are enabling waveguide bends with special design features. 2-D material integration is being pursued at Ghent University in Belgium with IMEC. Special focus is currently being pursued on graphene that may have implications for TMD-based 2-D nanosheets. However, neither of these (2-D materials and additive manufacturing) yet have a known path to manufacturability at reasonable volumes where III-V and Si nanofabrication processes shine.

3.4.4 Topic 4: At the Forefront of Device Design: Immediate Challenges (Prof Michal Lipson, Columbia University)

Current foundry PDKs need to be improved to include novel design approaches, new materials, and creative architectures to increase fundamental robustness. Focusing upon device paradigms, there are many opportunities for creative advances in photonics. New ideas that promote faster switching of signals are of interest, whether within a single channel or between orthogonal modes in that channel, between spatially separated channels, or nonlinear processes to transduce signals between wavelengths or at different intensities. Discussions about the current integrated photonic landscape and what advances should be pursued to enable breakthroughs in PIC performance for sensing, beam steering, routing, and high-speed networking are also of interest.

This session on forefront device design brainstormed on *immediate challenges* that need to be addressed to enable high-performance, photonic functionality (regardless of heterogeneous challenges for full-scale PICs).

Focus areas and questions that were considered:

- How can sensitivities on the order of a few nm material thickness be overcome to avoid thermal tuning of individual devices? Can fundamental approaches prevent this a priori?
- What are some novel approaches for large phase tuning with low loss?
- What are fundamental issues for designing modulators with high-efficiency in-and-out coupling?
- How can the efficiency of nonlinear processes be improved (i.e., frequency combs, wavelength switching, and so on)?
- What are untapped opportunities for harmonic generation and difference frequency generation (i.e., interactions with RF, UV, THz or another spectral window of interest)?
- What are the opportunities involving photonic polariton modes such as surface phonon–polariton, exciton–polaritons, and plasmon–polariton-based devices?

3.4.4.1 Summary of Topic 4: At the Forefront of Device Design: Immediate Challenges

Resulting from decreased loss in SiN waveguides, many advances are now forthcoming. The low loss leads to potentially high-Q factor microcavities that can impact device design. Three key areas were highlighted in the panel's discussions. Each will be summarized in the following.

3.4.4.1.1 Subtopic a: Narrow Linewidth Lasers. Sufficiently high-power, narrow-linewidth lasers are not available. Microresonator-based frequency combs provide for a compact source of controllably, dense optical channels; however, attaining narrow linewidth at high powers is not easy. For example, work funded by ARO (Prof Amnon Yariv, California Institute of Technology) has achieved rather compact 1- to 10-mW lasers. They are based upon high-Q ridge waveguide designs. Linewidths of around 5 kHz were achieved with reasonable yield; however, hero results of 1 kHz or less were not highly reproducible. Nonetheless, that work was a significant breakthrough and surpasses previous distributed feedback laser designs, where 150 kHz or more is typical. The VCSELs also have single-mode capability and fairly narrow linewidths (MHz), but work on reducing the linewidth to 100 kHz or below would require complex cavity modification, likely untenable. However, variations on PCSELs are poised for such designs. An important question is how compact and power scalable one could make them. PCSELs have been made up to 10 W of single-lobed power, so incorporating higher Q designs may be possible. The staff of DARPA LUMOS is investigating some approaches to this problem via edge emitters in the VIS wavelength regime (400–900 nm) for atomic-clock applications. High-power, narrow-linewidth 1.5-micron "eye-safer" lasers are needed for LIDAR and other optical communications and optical phased-array PICs. Companies like Analog Photonics are pursuing some DOD efforts in this area; however, more basic research on the laser approach is needed. NLO comb generation would benefit from a high-power, narrow-linewidth pump source as well, although the relationship between the pump and comb channel linewidths may need significant studies. Linewidths are sensitive to several environmental factors too and variation to nanofabrication processes is a big concern.

3.4.4.1.2 Subtopic b: NL at Low Power. SiN has already been used for significant NLO conversions with only 100 μWs. Microcavities are used for these effects and some approaches show NL down to the single-photon level. Exciton–polariton provides another opportunity where increased NLO properties can be harnessed. The panel said that it can depend upon the FOM; for example, interaction strength multiplied by the interaction length. Length also depends on loss. For an example, in GaAs, where exciton–polariton physics is well known, the interaction is not very strong but the propagation length can be significant. Exciton–polariton systems are interesting because NL comes from strong light–matter interactions; that is, how exciton–polaritons are formed such as in a microcavity. Increasing light–matter coupling means going toward the strong coupling regime. It is well established that exciton–polariton systems have much stronger NLs than nonpolariton systems. The challenge can be rephrased as how to move toward stronger coupling without getting overwhelmed by loss. There may not be obvious answers, and the fundamental and practical tradeoffs between ultrahigh optical quality and strong NL is an open frontier. This is an area that has been studied for decades in many different contexts. One potentially very rewarding new direction is the possibility to integrate ultrahigh-Q optical structures (that has been developed relatively recently) with newer materials (e.g., 2-D materials, hexagonal boron nitride, AlN, and some organic crystals). However, access to high-Q SiN microcavities may be difficult, requiring collaboration with expensive foundries (issues discussed in Section 3.4.6, Topic 6).

3.4.4.1.3 Subtopic c: Phase Change, 2-D, and Wide-Bandgap Materials. There are a number of promising emerging materials that can be considered for integrated nanophotonics. NL materials were covered in Topic 2, but three other classes of materials were discussed here: phase-change materials (PCMs), 2-D monolayers and nanosheets (multilayer), and wide-bandgap (UV–VIS bandgap). Some of the issues with these three classes were discussed.

PCMs that have made the most progress include GST and GSST (i.e., Prof J J Hu, MIT) through ARO and the DARPA Young Faculty Award program. The panel discussed how the large refractive index change ($\Delta n > 1$) of PCM materials is good, but the wavelength where this property is exhibited is not at C-band (near 1.5 microns) where most PICs are developed. The PCM Sb_2S_3 does have large Δn with reasonably low losses at 1.55 microns, but its phase change is too slow for ultrafast devices. They are good for reconfigurable waveguide switching (or routing) but are limited to nanoseconds (at best, and generally microseconds). In a bid to overcome this speed limit, ARO is now investing through an early career award (Prof Tingyi Gu, University of Delaware) in the exploration of InSe PCMs. This material family may be able to reach sub-ns switching times when embedded in optical microcavities.[55] Computing, communications, and LIDAR applications can likely make use of these, with some improvement over the state of the art; however, NL materials are seen as the ultimate platform for subnanosecond to picosecond switching and routing through use of ultrafast EO effects. However, this benefit comes at the cost of greatly reduced Δn. The use of non-Hermitian and topological photonics regimes may be combined therein to advance the performance.

Monolayer 2-D materials such as graphene or TMDs (e.g., WSe_2, MoS_2, and so on) have extraordinary properties from strong reflection to high absorption to high exciton binding energies. Integration of 2-D materials with integrated nanophotonics is being pursued in academic settings. At European photonics foundries, graphene incorporation is being pursued for manufacturable nanofabrication processes. However, TMDs, the most sought after 2-D materials for photonics, still suffer from material defects and small size samples. The panel discussed how 2-D materials can be pursued for integration into device active regions since their monolayer thickness limits the interaction with the optical mode. Currently, this is often seen to be of limited use in terms of performance advances of standard regimes (lasers, photodetectors, and modulators); however, microcavity-based devices show promise. The use of PC and high-Q microcavities is especially needed for exciton–polariton systems (i.e., as being explored in an ARO MURI, *Toward Room Temperature Exciton–Polaritonics*). The panel liked thoughts presented by Prof Lipson (Columbia University) on integration of 2-D materials with back-gated Si waveguides, and so on, as a launching pad for a variety of device concepts. Thicker nanosheet, 2-D related materials such as phophorene (or other TMDs as well) often have interesting properties that can be exploited. For example, bandgaps across the difficult VIS region (500–600 nm) are commonly attainable with TMDs and phosphorene can reach into the mid-infrared. Placing them onto device postfoundry fabrication could solve any Si CMOS process compatibility issues. Some on the panel believe that Si CMOS photonic foundries can be (and have demonstrated) more flexible for incorporating heterogeneous materials than typical Si CMOS electronic IC foundries. While 2-D materials may be possible to incorporate into integrated photonics foundry processes, that would require improvement in the quality of large area 2-D nanosheets. Currently, most 2-D materials of very-high quality are still small and possibly very fragile. It remains to be seen whether they can become as useful as monolithic III-V devices that are incorporated via microtransfer printing for robust PICs.

Finally, wide-bandgap or ultra-wide-bandgap semiconductors are important materials for future nanophotonics. Advances in both nanowires and epilayers are still being made for bandgaps in the VIS/NIR (400–900 nm), important for sensing and atomic clocks, as well as in the UV (200–400 nm) for numerous sensing, communication, and data processing applications. Material quality advances are needed for these semiconductors to make efficient and reliable lasers in many spectral bands; for example, 480–800 and 200–360 nm. A clear motivation for this is not only the variety of applications, but shorter wavelength implies higher device density, which is especially important for neuromorphic processing.

3.4.4.1.4 Subtopic c: Overall Concerns. Finally, a significant concern was process variations; that is, not receiving the specifications on the resulting device as it was designed. This requires one to place multiple variations of the design on a mask to meet a given specification. And, for cascaded devices, variations across a wafer may not be controlled to the point that PICs are tenable for some applications. This can be partially overcome with thermal tuning (heaters), but they often require over-burdensome power consumption. Another factor is the desire for broadband designs for many applications. For example, one would like to use frequency combs for WDM to increase the total bandwidth of information processing. Heaters are also needed to align the combs with the given bandwidth of a PIC; for example, Prof Dirk Englund's neuromorphic PIC was cited as having 20-GHz optical bandwidth, although use of combs was not explicitly stated. Potentially, the computing architecture of neuromorphic PICs may enable them to be trained to be robust against variations, making the fabrication tolerance issue possibly moot or somewhat alleviated. A panel member stated that process errors are not necessarily always solvable through thermal tuning. Process variations have some statistical distribution that may not be solved by simply thermal tuning. An NN type of training may be needed to tune a large number of heaters for all the devices across a PIC, so the tuning would take significant power and relate to challenges for increased PIC device density.

3.4.5 Topic 5: Quantum Devices: Fundamental and Practical Limits (Prof Zubin Jacob, Purdue University)

The entire gamut of quantum devices on-chip can be re-envisioned for the next decade including nonclassical light sources, single-photon detectors, and a large array of sensors, on-chip memories, and qubit–photon interfaces, among others. One pathway is to use the large scalability of integrated photonics to aid future quantum computing endeavors while another lies in building new nodes for quantum networking and quantum sensing. Practical challenges that need to be overcome to achieve fundamental limits of quantum device performance were discussed. In addition, this brainstorming session aimed to identify new game-changing advances that significantly expand the photonics toolkit for new quantum systems.

The goal of this breakout session was to unlock what the future holds for quantum devices on an integrated photonics platform.

Focus areas and questions that were considered:

- Which quantum devices lend themselves to an integrated platform, and conversely, which would prove more challenging?
- How would an integrated platform affect decoherence? Entanglement?
- Can we envision integrated devices with multifunctionality? What would be the challenges associated with such a system?
- What would a quantum network node look like in an integrated package?
- Which quantum device metrics clearly delineate the integrated photonics advantage?
- What advances in design, fabrication, and materials are necessary to integrate sensors, memories, sources, and detectors on-chip?
- What are new quantum devices that can be implemented on-chip combining photons with spintronics/magnonics/acoustics?

3.4.5.1 Summary of Topic 5: Quantum Devices: Fundamental and Practical Limits

The breakout session on quantum devices was speculative. Much of the time was spent discussing the role QOs plays in integrated devices. Any physical device will be a hybrid device containing both classical and quantum components and integrated photonics can contribute to either. The group asked the following question as a thread that can be traced throughout: *Where can quantum integrated photonics play a disruptive role?* The following is from a collection of notes taken during the discussion and organized by subject matter.

3.4.5.1.1 Subtopic a: Integrated Photonics as an Enabler. Devices based on the quantum state of atomic and material systems require optical sources to prepare and manipulate quantum states, perform entangling operations, and read out and transmit quantum information. Some of these quantum processes can be carried out by classical light: microwave pulses in superconducting circuits or optical control fields in trapped ion systems, for example. Even if these integrated photonics solutions fall under the strict definition of classical light, they are still part of a classical-quantum hybrid system.

If atoms are used, there are a lot of things that photonics can do to accelerate device manufacturing. Integrated photonics is an enabler. One can envisage thousands of light sources on a chip with exotic control such as many foci and spin DoFs. It is not necessary to conduct quantum operations on chips with light. Integrated photonics will be essential for the development of non-PIC and nonoptical quantum technology. Because nearly all quantum technologies and studies involve optical elements, nonquantum integrated photonics will likely be a key component.

Currently there is a demand for and rapid development of traditionally classical components such as the interferometers and sensors, the best of which use nonclassical squeezed light. Both nonclassical and quantum integrated light sources of many different wavelengths, especially shorter wavelengths, will be an important supporting technology. The degree of needed control is ever increasing.

Having dense and functionalized detectors is another area of importance. In some cases, only one laser is necessary but many detectors are required. *Can a way be found to push arrays of single-photon detectors to room-temperature operation?* A big part of sensing requires the incorporation of a frequency standard on chips. *Can this be done artificially?* Though current concepts rely on atomic systems, perhaps solid-state approaches are possible. For example, developing technology based on the thorium nuclear transition (a near-UV wavelength) would go a long way to meet these needs. Quantum memories based on color centers in diamond are another area that is being looked at closely for room-temperature quantum memories.

Are there opportunities for quantum imaging in integrated photonics? The question that needs to be addressed is whether imaging is inherently free space or not. Imaging could be done with a mode sorter on chip. However, for a 2-D image, stacking the data stream would be an immense task. Two-color ghost imaging is also possible in which a target is illuminated with one wavelength and detected with a different wavelength. Photon counting with an optimal receiver can detect quantum correlations providing additional information in specialized cases. For general imaging tasks, however, excessive noise will always make finding a quantum advantage in imaging difficult. A related question worth considering is this: *Can ghost imaging be used to transfer quantum information distinct from quantum teleportation?* This remains an open question worth exploring.

3.4.5.1.2 Subtopic b: New qubits. In solid-state devices, quantum memories are based on electron spin. In general, one can explore different types of coherences beyond spins, such as vibration, electronic, or highly nonlinear optical processes. Superconducting qubits are a condensate of Cooper pairs that distill into a quantized coherent state. In a polariton condensate there is something completely analogous. Circulating polaritons also distill into a coherent state. As evidence, vortices have been observed in polariton condensates just as they have been in superconductors. A polariton condensate could be robust by constantly pumping them in a quasi-equilibrium. There is a danger of this being oversold. This would require a way to couple to a single particle transition, which does not exist at the moment.

Photonic losses are a major impediment to photonic quantum computing. It is possible that topological photonics may provide a route to alleviate loss. It is important to continue working on the quality of these materials to get to fundamental limits. Such improvements are difficult because efforts to do so are not as flashy and garner less attention, which slows technological advancement in these important areas.

3.4.5.1.3 Subtopic c: Quantum NL. Quantum NL is NL at the one or few-photon level. In bulk nonlinear crystals, NLs are too small to go beyond the regime of linear optics and enable quantum computing. Integrated quantum photonics suffers from photons not interacting strongly enough, but quantum nonlinear operations are a key component of any manipulation of quantum information. *Is it possible to leverage quantum NL to devise single-photon switches?* This is an area where integrated photonics may truly shine. There are multiple pathways for single-photon switching. Currently, low NLs are limiting the community. Polariton condensates are likely candidate systems but a lifetime of the condensate remains an issue. Significant progress has been made looking at PPLN to demonstrate single-photon NL.

3.4.5.1.4 Subtopic d: Nondemolition experiment. An important capability in quantum information is the ability to extract information in a system with as little impact on the system as possible (because to measure is to disturb). *Is there a new type of a nondemolition experiment?* A quantum nondemolition measurement is a measurement that does not strongly modify the particle's state or increase the uncertainty of the measured observable. For example, in an optical waveguide, a resonance region such as an MRR provides interactions with a material without the requirement that a photon is absorbed. It is a situation in which a photon arrives, interacts, and just moves on, so to speak. By turning on and off interactions, the impact on the photon's quantum state is minimized, yet information can be gleaned from the interaction. This has been demonstrated by observing back-action effects of microwave pulse trains interacting with superconducting qubits. Accurate monitoring of a qubit state is required for feedback control of quantum systems and new nondemolition measurements could provide this capability.

3.4.6 Topic 6: The Photonic Enterprise Ecology and Technology Transfer (Dr Michael Gerhold, ARO, and Prof Weidong Zhou, University of Texas at Arlington)

Current foundries have limited PDK functionality due to a lack of HI techniques. Integration with electronic systems and other available microsensor components and systems also requires a high degree of integration flexibility. How the overall enterprise of integrated nanophotonics can be restructured to enable effective advances from the university or other basic research communities needs careful thought. Can basic research advances in devices and techniques make their way into foundry processes? What barriers are there now that may be overcome by some community-wide endeavor?

The photonic enterprise session focused on big-picture issues related to improving the R&D ecology and technology transfer.

Focus areas and questions that were considered:

- How can government, academia, and industry work together? How can the high cost of entry be addressed?
- Photonic packaging—why has the Tyndall National Institute been successful and can the United States start something similar?
- What photonic device integration issues need to be solved for III-V and 2-D integration?
- How does one best incorporate electronics with photonics? In-plane or hybrid layers?

- What are the spectroscopic, imaging, and fluidic considerations for chemical/biological multidisciplinary device integration?
- Fiber optic attachment issues—quantum/classical from surface or edge? Arrays, VCSEL/microlaser coupling?
- What technology transfer pathways can be sought or encouraged for university/basic device research incorporation: AIM Photonics (DOD), IMEC (Belgium/USA), BRIDG (Orlando), and Tower Semi, Global Foundries (NY/IBM)?
- How can integrated nanophotonics become financially successful and incorporate SME/university MPW runs? Have Intel's commercial SiPh 100-G transceivers been a true success or is the validity of integrated photonics as a profit-making business still unproven?

3.4.6.1 Summary of Topic 6: The Photonic Enterprise Ecology and Technology Transfer

The integrated photonics enterprise is a highly complex ecosystem. It needs to engage R&D communities involving both basic research and more applied engineering. The reason for this is clearly to garner advances from physics and employ them for new device paradigms, for example, non-Hermitian and topological physics, ways to capture bosonic DoFs, and so on, and bring them into a usable PDK. Engineering is needed for a number of aspects that include challenges in test, assembly, and packaging, HI—both in single plane PICs, as well as 2.5- and 3-D integration, device, and full PIC simulation, and so on. Some of the needs for this to work together will be described in more detail in the following. Overall, though, the panel thought the United States should follow the European Union (EU) model and establish consortiums across the nations, including large clusters of members, for resource sharing, stronger collaborations, and faster progress. Different consortiums can focus on different concentrated areas/issues such as microtransfer printing and HI. The need for government involvement to facilitate this is clear; limited funding can be made more efficient by reducing extensive duplication of expensive facilities.

3.4.6.2.1 Subtopic a: Simulation Tools. Although commercial software tools are helpful, their interfacing with foundry PDKs is limited. Large PIC simulation environments are needed to optimize performance. This is something that often needs to be done with complex electronic circuits and systems, but it is even more critical with photonics. This is due to the nature of bosons (i.e., photons) and the current availability of only very-short-term optical memory (such as from delay lines) as well as multiplexing and the wave nature of bosons versus electrons. State machines such as seen in digital electronics, where cascading and highly scalable circuit layouts are made, have no duplication with PIC technologies. However, the electromagnetic wave nature of photonics, including wavelength dispersive properties of devices, waveguides, and circuits, needs full simulation. The panel discussed simulation tool sharing, suggesting potentially free access of PDK tools from AIM Photonics to facilitate thorough PIC simulation capabilities. Such detailed PDK simulation availability would potentially be made ready for "plug-and-play" into commercial simulation software; for example, Synopsys, Lumerical, and similar tools, including academic-related software found on free-access websites. GitHub, for example, is a free resource where inverse design software is available from Stanford University (Prof J Vuckovic's group). Working groups need to facilitate this for PC utilization, including access to process parameters including statistical variation in etching of PC holes. Prototyping design fabrication runs can use the more accurate simulation tools, based upon foundry processes to develop realistic prototypes within nonfoundry or university fabrication facilities. Capabilities to simulate hybrid electronic ICs and PICs as one circuit would enable quick development of new optical networking and computing microsystems. Why is this needed for "integrated nanophotonics"? Because of the highly complex nature of device research with nanoscale features (see Findings in Section 4 for further discussion).

3.4.6.2.2 Subtopic b: MPW runs in CMOS foundries. As mentioned, the EU has multiple institutes and foundries related to integrated photonics and they are ahead of the United States due to these consortia and stable funding. Currently, the US DOD is funding AIM Photonics (see www.aimphotonics.com) to pursue increased manufacturing-readiness-level integrated photonics capabilities, primarily at SUNY Polytechnic via Si CMOS foundry runs. The 12-inch Si wafers are diced into roughly square-centimeter MPW PICs. This enables many different groups to use a small fraction of the reticles for their work. The masks for such processes are quite expensive, costing up to a million dollars for a single MPW run (depending on the tools used, the number of masks, etc.). Such expenses have raised multiple logistic, cost, and access issues due to intellectual property (IP), membership access fees, and so on. PDK-related IP has limited access to member-only access agreements. A more open access MPW design process is needed. Access to DOD-funded grantees and contractors would enable integrated nanophotonics researchers to develop devices useful for CMOS foundries and PICs. The panel feels it would be the best if the barrier to AIM MPW runs can be lowered either by cost sharing from DOD/National Science Foundation (NSF) or even free runs on unused wafer segments during MPW runs. The panel also feels that AIM Photonics can be a little more accommodating and flexible to support new device structures. For example, the standard SiN thickness AIM supports is 300 nm, which is much thinner than the 600–700-nm SiN thickness needed for nonlinear integrated photonics.

3.4.6.2.3 Subtopic c: Heterogeneous Integration (HI). Si photonics is based on CMOS foundry processes because of the high-quality/highly refined etching processes available to make wafer-scale, low-loss waveguides and devices. However, Si is an indirect bandgap semiconductor and thus an inefficient light emitter. Direct bandgap (most commonly, group III-V compound semiconductor) devices are needed for light-emitting purposes. The methods pursued to meet this challenge are 1) laser coupling to SiPh PICs, from off-chip; 2) direct epitaxy on Si; and 3) microtransfer printing of III-V epilayer devices. The first is hindered by inefficient coupling and distribution of light. However, more efficient coupling may still be possible, even potentially enabling high-power PICs. Secondly, direct epitaxy on Si is showing great promise. Longevity of lasers has been shown to be substantial and wall-plug efficiencies are improving. However, lattice-mismatched lasers will have to endure inherent weaknesses in coefficient of thermal expansion (CTE) mismatch for many DOD applications which, like commercial applications, require regular thermal cycling. The reliability of III-V lasers on Si under realistic thermal environments is being ignored and it will hinder use for widespread commercial applications. Accordingly, microtransfer printing may hold the key. III-V epilayers can be lifted off and bonded to SiPh PIC surfaces. The interface for this bonding is not constrained and may withstand large CTE mismatch. Currently, the problem needing addressed in the transfer of devices is the precision of alignment. Half-micron or better precision is needed to ensure a high degree of light coupling via waveguide tapers. The Tyndall National Institute at University College Cork, Ireland (the group of Dr Peter O'Brien), developed the technique and X-celeprint, Inc, started making industrial microtransfer printers (located in Durham, North Carolina). The precision of their process is 1.5 microns, suitable of micro-LED displays, but not coherent photonics. Therefore, further development of this technique is necessary.

3.4.6.2.4 Subtopic d: TAP Facilities. Test, assembly, and packaging requires substantial investment for developing new PICs. The needs relate to hybrid ICs—both electronic and photonics, as well as alignment tolerance issues that require precision to subwavelength scales (~0.5 microns). Increased coupling efficiency has been discussed before (see Materials and Devices 2 session, Section 3.2.5.4; Prof Bo Zhen, U Penn) but implementation of such new designs has yet to occur. The slanted, vertical couplers devised by Prof Zhen could facilitate much-higher coupling efficiencies than the usual grating couplers (3-dB loss). For edge coupling, in-plane to a PIC, machines have been developed that use laser-written polymers to create aligned interconnect waveguides. The written waveguides use active image-based alignment to ensure reduced loss. Such approaches are being pursued both at academic institutions and some foundries. However, higher-efficiency edge coupling to PICs is possible and necessary for many high-performance applications.

Assembly is related to placing various dies or chips onto the same carrier. Placement tolerances of 0.5 microns may also be necessary and the techniques needed may be similar to microtransfer printing, as described previously. However, assembly is more generally describing the microsystem of both electronic, photonic, and other thermal or packaging-related processes. Metallization, wire bonding, die attach, flip-chip bonding, and so on, are part of this. AIM Photonics has a TAP facility that is leveraging electronics-industry techniques to get up and running.

Finally, testing is required based on high-speed characterization equipment needed for optical communications. Adaptable characterization platforms such as those made by ficonTEC (Germany) may be needed to interface with PICs. C-band and L-band (~1.5- and ~1.3-micron wavelengths, respectively) are most clearly accessible in terms of high-speed testing, but other wavelengths will be needed, especially as advances make VIS and UV PICs possible. Bit-error-rate testing and use of arbitrary waveform generators are needed and the equipment is quite expensive, again leading to the need for shared facilities.

3.4.6.2.5 Subtopic e: Multidisciplinary Efforts. One can learn from the success of organic electronics to address some of the challenging issues in materials by pursuing interdisciplinary collaborations in chemical engineering, physics, materials, electrical engineering, and so on. Of particular interest is the interface with chemical and biomolecule delivery, such as through micro- and nano-fluidics. Environmental sensing is another challenge. Other means of interfacing with the immediate PIC environment require leveraging decades of expertise from chemistry and biology investigation and research. Low-temperature environments pose challenges for important areas of research—from 77 K (liquid nitrogen) temperature used to interface high-sensitivity focal planes to 4 K or below for superconducting quantum computing applications. These multidisciplinary needs add to the TAP and HI challenges.

3.4.6.2.6 Subtopic f: Entrepreneurship Ecology. The Army is looking at taking the most advantage possible from scientific advances. Most of those advances in the last decade or two come from academic research. Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) programs are vehicles used to spin off companies. Successful ventures in this regard depend on multiple key aspects. The panel discussed some of these including the need for continuous funding of postdoctoral entrepreneurs whose funding for employment and continued scientific and engineering advances relies on "soft" money. The gap often experienced between a 6-month Phase I SBIR/STTR and the 2-year Phase II is often too much of a financial setback to maintain highly motivated and equipped postdocs. The DOD is exploring solutions to this gap with so-called "direct to Phase II" or intermediary Phase I option funding approaches. Entrepreneurial fellowships were encouraged by the panel. When the spinoff is faced with a downturn in funding, the commercial sector often lures them away with significant opportunities stalling higher-risk, higher-payoff opportunities.

Collaborations between DOD, industry, and academia can also accelerate advances. For example, significant interactions and collaborations can take place during the SBIR/STTR programs to leverage complementary expertise of DOD personnel and contractors. Prime contractors such as Lockheed Martin have annual meetings to encourage such things; however, the DOD often has rather limited participation. Strong encouragement from upper management may boost interactions and accelerate advances for the military. Additionally, program executive officers may be able to boost technology development by working with DEVCOM scientists and engineers who are thoroughly aware of the most recent technology advances, particularly those just forthcoming from academic research.

4. Findings

4.1 Technical Sessions: Future Research Directions

4.1.1 Plenary Session: Neuromorphic Photonic Computing

The subject of neuromorphic computing was explored in four plenary talks. Two of the talks were related to what is known as "reservoir computing" and the other two were related to NN approaches. The former is a means of finding optimal points (maxima or minima) in a manifold. It occurs via interrelated mesh of polaritons, for example, to come to a solution, and in the case of photonics, very rapidly.

Reservoir computing for target recognition. BECs of either gas-state atoms or solid-state exciton–polaritons hold promise for faster computing regimes. High-speed optimization involving pattern matching, such as target recognition, can be pursued via steepest descent dynamics available with BEC manifolds. What clearly needs investment is the solid-state regime where computing may be able to proceed effectively, that is, microcavity exciton–polaritons. The Stanford University work of Benjamin Lev has shown promise, yet the systems may likely be difficult to miniaturize, mass produce, or make rugged for mobile Army platforms.

Semiconductor-based microcavity polaritons could do all of these and be low cost but might require cryogenic temperatures. Using wide-bandgap semiconductors may enable MIL-SPEC temperature operations.

End-to-end designs for vision systems. Significant advances have been made in the area of metasurfaces for enabling novel microns-thick lenses. However, ultimately, powerful vision systems would be a combination of metasurface optical processing with appropriate computational algorithms and electronic processing. The absolute optimal system cannot be accomplished by optimizing the photonics part (metalens) alone. Instead, there must be unified, disruptive, and simultaneous co-optimization of the *entire system together, end-to-end*: metasurface optics, algorithms, electronic processing, and their integration.

ONNs based on coherent detection. DNNs running on traditional electronic architectures face many challenges, including high power consumption and slow speed. Therefore, they have a large carbon footprint and limited computing power, which precludes certain applications, especially for the Army. This has motivated the development of specialized hardware accelerators. Of particular promise are ONN architectures based on time multiplexing and coherent detection that could drastically improve energy consumption and speed of NN computations. ONN devices should also be adaptable to solving combinatorial optimization problems such as maximum independent sets, MAX-CUT, and Ising problems.

Novel photonic architectures for optimization, probabilistic computing, and ML. Many exciting opportunities were presented during this session including the MIT work[56] on nanophotonic Ising solvers, which solves a set of nondeterministic polynomial-(NP)-hard problems that can be mapped onto the Ising model that can be implemented in a nanophotonic device. There are opportunities to develop optimal algorithms for implementation on photonic architectures to solve NP-hard problems, including Ising problems and beyond. Efforts are needed to investigate optimal novel photonic architectures to solve NP-hard problems beyond Ising problems. Next, in contrast to almost all other computational paradigms that aim to enhance SNR ratio to minimize (ideally eliminate) the impact of noise on the calculations, one concept was presented[57] that uses noise as a resource. There are indications that our brains also use noise as a resource for some calculations. Thus, it is exciting and important to investigate physical computing architectures for probabilistic/stochastic computing that rely on natural sources of noise. Intimately connected with this is the prospect of implementing Bayesian neural networks (BNNs) in photonics. There is a lot of excitement in the AI research community about BNNs, but their inherently probabilistic nature makes them very cumbersome (and thus very slow) to implement on conventional hardware. Using noise as a resource could thus enable a dramatically faster hardware approach for BNNs.

Finally, connected to probabilistic computing, consideration should be given to devise novel analog computing platforms based on effects that do not have a counterpart in the digital world (for instance, spontaneous symmetry breaking).

4.1.2 Technical Session 1: Materials and Devices 1: New Capabilities

It is clear that rapid advances are pushing the state of the art in integrated nanophotonics. Materials characterization and development of novel fabrication techniques are two of the key enablers of these advances. LN, traditionally difficult to fabricate, has outstanding optical properties and has been used in several record-breaking demonstrations. AlN has enabled integrated nanophotonic devices that operate at UV wavelengths. Si/SiN devices can now be manufactured by foundries offering precision and repeatability of device performance. In addition to materials and fabrication, advances in our understanding of physical systems are leading to new design paradigms. Novel device capabilities are enabled by non-Hermitian photonics based on PT symmetry (and going further, by implementing supersymmetry in device design) and by 2-D topological photonics. Using these concepts, regions of gain and loss created by external fields have been used in all-to-all optical routing demonstrations. The state of the art in nanophotonics device optimization uses inverse design techniques that are now commercially available and in collaboration with foundry fabrication facilities. Each of these key enablers were presented in this technical session and provide insight into the current state of the art in integrated nanophotonic device development.

4.1.3 Technical Session 2: Nonlinear Photonics

Exploitation of optical NLs has resulted in some of the most important advances in optical physics, enabling quantum light sources, high-speed optical modulation for information routing and manipulation, optical storage, advanced metrology, and many noveler capabilities. In this session, principal investigators presented on the state of the art in NLOs in the context of integrated nanophotonics. Some topics envisioned capabilities not yet mature or even realized, ranging from single-photon optical switches to the utilization of intrinsic NL in a single atom for information processing. Presentations of the state of the art in nonlinear photonics for integrated nanophotonics included the development of chip optical comb sources in SiN devices and record-breaking advances in LN-integrated nanophotonic EO devices. Clearly, there is a significant body of research in nonlinear photonics that could not be covered sufficiently in this workshop. It is evident that advances in nonlinear optical materials characterization as well as fabrication techniques and a deep understanding of the underlying physics has informed the current generation of integrated nanophotonic devices and will likely do so for future devices as well.

Therefore, continued investment in NLOs with a particular emphasis on its relation to integrated nanophotonics is necessary.

4.1.4 Technical Session 3: Polaritons for Integrated Photonics

Polaritons are light–matter interactions that are of high interest for lower-energy photonics. BECs can form at very low intensities, even at room temperature in strong enough exciton binding-energy materials; for example, 2-D nanosheets. An ARO MURI, now in its fourth year, is still aiming to assess the potential for exciton–polaritons in future integrated nanophotonics. The impact of exciton–polaritons on integrated nanophotonics depends on advancing the 2-D materials quality over increasingly large areas and investments should be made accordingly. Quantification of some of the metrics takes careful measurements, as have been made in GaAs at low temperatures. Progress may be quite slow, taking a decade or more to truly enable consideration of viable 2-D material-based integrated nanophotonic circuits. However, two promising directions, among others, can be noted. First, the promise of monolayer gallium nitride (GaN) can be explored. Its exciton binding energy is significantly higher than bulk GaN, on the same order of magnitude as TMDs. Its promise lies in established processes enabling monolithic incorporation onto the whole surface of the PIC through MBE. Ultra-wide-bandgap semiconductors such as boron nitride and AlN can do potentially similar things, with even greater possibilities due to stronger light–matter interactions. A second opportunity is the recent demonstration of topological control of polaritons near 200 K. Reductions in scattering induced loss and materials improvements may make such phenomena observable (and thus exploitable for technology) at room temperature and provide improved coherence for polariton-based PICs.

4.1.5 Technical Session 4: Materials and Devices 2: Smaller and Faster

Certainly, many opportunities exist to improve integrated nanophotonics for lower-energy consumption, much-higher speeds, and lower noise. Applications to higher bandwidth communications and processing systems due to higher device densities (smaller device dimensions) and higher device speeds will naturally follow such advances. Two applications noted in the session were on photodetectors, both of which include built-in amplification of the photo-generated signals. First, a breakthrough in staircase APDs showed a clear need for further basic research into optimal and improved staircase designs, both in terms of the number of steps and in the filtering of noise-producing photo-generated carriers. Another approach may also achieve room temperature, single-photon sensitivity and very high speed. It is based upon internal photocurrent control with electrically tunable electron barriers. The prediction of higher sensitivity and speed with smaller-dimension nanopillars (of 500 nm or less diameter) are key. Success will depend upon sufficient nanoscale process refinement. On the source and modulation side of integrated nanophotonics, progress is still forthcoming. Ultra-low thresholds can be obtained by controlling the spontaneous emission efficiency spatially, through Purcell effect enhancements. Recent ARO investments have also led to demonstrations of high-speed wavelength tuning with nanocavities. The direct modulation of very small micro- and nanolasers shows promise to achieve sub-fJ/bit efficiency. Such achievements warrant investment based on work described in the keynote talk by Hamerly et al.[56] Other PIC regimes, such as the DARPA Photonics in the Package for Extreme Scalability (PIPES) regime, of co-integration of photonic interconnects with electronic circuits also motivates nanolasers and LEDs. On-chip spin-based QED also may bring forth other low-energy intra-chip communications regimes.

4.2 Army Panel highlights

4.2.1 R&D Ecosystem

The long-term success of integrated nanophotonics research will depend upon a functional R&D ecosystem in photonics. Basic physical device research alone on integrated nanophotonics cannot succeed without motivation from photonic circuits or without studying device functionality within an integrated platform. Furthermore, in addition to enhanced device performance metrics based upon advances in physics at the nanoscale, the technology pull of how those improvements can be used within microsystems and their circuits needs to be considered. This is currently challenged by the limited resources for integrated nanophotonics research. Full consideration of the potential of a particular device architecture can take 5–10 years for well-refined foundry capabilities, such as those based upon III-V epitaxial materials. However, with new materials and regimes that require innovative techniques to incorporate them, for example, microtransfer printing for 2-D or heterogeneous III-V materials, several decades are needed to assess whether the materials can be made of sufficient size (area or volume) with low enough nonradiative defects, and whether they can be used in manufacturable nanoscale processes. New device architectures can use a number of high-sensitivity process variables that take extensive optimization. The work takes time and resources that do not get evaluated sufficiently for further circuit design consideration without proper motivation. For example, ARO managed a 6.1-funded DARPA nanolaser program (NACHOS, 2009–2012) that helped make strides in achieving full 3-D subwavelength-scale lasers. The best of these lasers operated under electrical injection at room temperature. However, until 2019, with the advent of the DARPA PIPES vision for integration of optical interconnects with complex and powerful microscale electronics, the motivation for continued nanolaser advances was absent. Factors for larger-scale program investments such as PIPES ($60 million, 6.2 and 6.3 funding) with pressure to transition to foundries by 2028, did not motivate further nanolaser investment due to substantial risk in basic device physics research. Future PIC research advances therefore optimally require collaborative research goals that include 6.1 tasks, alongside the 6.2 and 6.3 goals to overcome intermediate-scale "valleys of death" that keep groundbreaking integrated nanophotonics research results on the shelf and instead lead to more transformative performance gains (a second story related to this point will be given in the Conclusions section). In so doing, the photonics R&D ecosystem will be optimized and, in concert with Army labs and centers, operationalized for transformational overmatch more rapidly.

4.2.2 Multidomain Battlefield

A second overall finding about integrated nanophotonics basic research is the large scope of PIC applications available to reach a broad range of enhanced Army microsystem performance goals. Accordingly, Army DEVCOM Centers are pursuing a broad scope of general PIC types with wide-ranging systems applications. The "Multidomain Battlefield" can make use of the outcomes of nanophotonics advances for various purposes, namely sensors, communications, processing, and computing. The DOD AIM Photonics, integrated photonics "manufacturing" research institute (see aimphotonics.com), has four key technology manufacturing areas (KTMAs): 1) very-high-speed digital data, 2) RF/analog photonics, 3) phased array/LIDAR, and 4) chemical/biomolecule sensing. These, established in 2015, encompass the major modalities of PICs. However, at the time, the neuromorphic photonic processing and computing opportunity was not well established. It is now understood that neuromorphic photonics can address KTMAs 1 and 2 and combinations thereof more effectively than previously envisioned.

What are some of those applications? For example, KTMA 1 is related to high-speed electronic and photonic systems akin to telecommunications systems, high-performance data centers, and application-specific (or sensor-specific) data analysis. As such, this KTMA impacts a wide span of C5ISR goals. KTMA 2 relates more directly to RF signal processing for communications and radar. Integrated photonics represents a fantastic opportunity for this. KTMA 3 focuses on the transformative capability of OPAs to be made on microscales. Such OPAs can achieve rapid electronically controlled beam steering for 3-D imaging and surveillance, including active EO sensing. KTMA 4 is aimed at sensing various chemical and biomolecule analytes—generally, at point-sensing locations, not standoff distances of more than a few meters. (Note: A more in-depth discussion of advances being made in integrated photonics can likely be found in conjunction with AIM Photonics as well as numerous technical publications; of particular note would be *IEEE Journal of Selected Topics in Quantum Electronics* and the IEEE Conference on Lasers and Electro-Optics. One could find an amazing growth of research that began just subsequent to AIM Photonics [2015] that especially became noticeable in 2018.)

4.3 Topical Area Findings

Key findings from the six breakout roundtable sessions are provided here.

4.3.1 Topic 1: Neuromorphic Photonic Processing

The vast complexity and scope of opportunities in neuromorphic photonic processing lies before us. The roundtable concluded that several of the integrated nanophotonics concepts suggested during the workshop could be advanced within a MURI or with MURI-like interdisciplinary investments. The interdependent relationship among materials advancement, device concept science, and integration challenges indicate a coherent effort involving each of these is essential to achieve meaningful advances. Furthermore, computer architecture and mathematical algorithmic considerations would be useful to guide investigation of tenable paradigms for near-term success that could lay the foundation for long-term investigation, as seen in general terms with electronic ICs and CPUs, though in the context of non-Von Neumann processes.

4.3.2 Topic 2: What's Next through Novel Physics for Integrated Nanophotonics?

In this breakout session, the discussion centered on recent studies of fundamental physics most likely to provide breakthrough discoveries that would determine the next generation of integrated nanophotonics advances. A major topic of discussion was on the study of polaritons and BECs of exciton–polaritons. Both advantages and fundamental limitations were discussed, and continued investment is required to determine if the promise of these systems can be realized in the context of integrated nanophotonic devices. Another major area of discussion centered on the utility of OAM for all-optical information processing and, by extension, into integrated photonics platforms. It is demonstrated as possible and beneficial to produce and sense free-space light-containing higher-order OAM light in an integrated photonics package. Also, many of the advantages of OAM modes such as infinite orthogonal modes for large channel capacity can be realized with Hermite-Gaussian modes that are perhaps more amenable to integrated photonics device geometries. For these high capacities to be realized, investments to devise and develop more efficient mode sorters are also required. Integrated nanophotonics platforms are ideal for studying strong and ultra-strong coupling between light and matter. The increased interaction strength of cavity QED systems affords a greater degree of control and capability and provides a means by which photon–photon interactions are possible. More esoteric studies in topological-based, PT-symmetry-based, and non-Hermitian Hamiltonian systems have also provided demonstrations of novel capabilities and benefits. Demonstration of all-optical routing and switching and more powerful and efficient lasers are just two recent discoveries from studies of fundamental physics that will provide transformative capabilities in integrated nanophotonics. These investigations should be monitored and transitioned when it is deemed likely to beat out currently equivalent technology or when novel capability is required for integrated device functionality.

4.3.3 Topic 3: Nanophotonic Architectures and Design Principles

Investments should be made to improve coupling into and out of PICs and reduced loss across PICs for both waveguides and devices. PDKs should be advanced to include both electronic and photonic elements (whether they are available in the same layer or not) as well as multiple packaging and assembly considerations, such as thermal management. Finally, novel material integration techniques for novel materials such as 2-D nanosheets and custom 3-D structures should be advanced.

4.3.4 Topic 4: At the Forefront of Device Design: Immediate Challenges

The near-term device design challenges worthy of investment were described as the following four areas: first, narrow-linewidth lasers that operate at higher power levels and with sufficient compactness to make use of PIC real estate efficiently; second, NL at low power. This is expected to be made possible by further advances in microresonator-based frequency combs and development of exciton–polariton-based microcavity regimes. Third, further substantial investment in novel materials, specifically 2-D, phase-change, and wide-bandgap materials is warranted. Optical memory and lower-power PICs could result. Finally, investments need to encourage device development within the integrated environment. The overall concern revolved around the R&D ecosystem where photonic-device utilization and potential cannot be effectively reached and exploited apart from full PIC simulation and design constraints. The PIC functionality and performance not only depends on individual device metrics but how the devices interact (reflections and dispersion properties) and process variations across the wafer, which are related to requirements for high-end foundry uniformity.

4.3.5 Topic 5: Quantum Devices: Fundamental and Practical Limits

Four main areas exist for quantum technology: quantum computing, quantum simulation, quantum metrology, and quantum networking and communications. The discussion touched on each of these areas to a greater or lesser degree. First, it is apparent that integrated photonics could be an enabler in the near term for quantum technology by providing both quantum and classical light sources for either atomic or solid-state systems. This aligns with the goals of the DARPA LUMOS program. Further funding of integrated photonics to produces narrow linewidth lasers at multiple wavelength, squeezed light, single-photon switches, and sources of entangled photons is recommended. Quantum metrology device applications like quantum PNT also benefits from access to robust integrated photonic light sources like optical combs and precision clocks. Additionally, fundamental studies to improve single-photon detectors or develop novel nondemolition probes are recommended. In the medium term, it is essential to deal with a major roadblock for all-optical devices, namely photon loss and quantum state decoherence. Realizations of all-optical quantum computing will have to deal with these fundamental issues. The issue of loss and decoherence is not only an issue for quantum processing, but for any quantum device. It would therefore make sense to invest in developing low-loss quantum materials, investigating and understanding sources of decoherence, and developing ways to combat decoherence such as control schemes based on adaptive ML algorithms. In the far term, interesting ideas exist to develop new qubits from hybrid electronic, material, and photonic systems that would be more robust to photonic loss. These ideas are nascent and require substantial 6.1 investments before it is possible to know whether or not they would provide a practical advantage beyond leading quantum computing architectures. Fundamental studies of light–matter interaction geared toward control of the entire optical field are also warranted. These include efforts in nonlinear photonics, topological photonics, ultrafast lasers, and subwavelength effects. A rich and variegated basic research ecosystem is required for transformative scientific breakthroughs of this nature.

4.3.6 Topic 6: The Photonic Enterprise Ecology and Technology Transfer

The overall finding was that faster PIC R&D can take place by considering device research as a coherent part of the larger ecosystem. Whereas PIC development takes significant engineering costs, and it is often done apart from novel device physics, there needs to be an overarching strategic viewpoint and leadership from the Army/DOD to facilitate academic–DOD lab–industry interaction. AIM Photonics has made slow progress and high-level, long-term support of it from the DOD can benefit from more-thorough justification. To foster device research within the larger ecosystem, simulation tools that can be incorporated into PDK photonic design software should be a priority. Academic research access to MPW runs needs programmatic emphasis. Advances from topological photonics, PC approaches, and other subwavelength, integrated nanophotonics need a way to join into more extensive PIC simulation so they can be included in MPW runs. PDK advances need to be prioritized and pursued from an institute level. Advances in nanolasers, sub-10-micron-length modulators, and subwavelength-featured inverse-designed (or topological photonics influenced design) couplers and devices, among others, need to be advanced not just individually but studied and advanced within PICs. The ecosystem issues include HI as well as packaging. Such capabilities that can incorporate new materials and high-performance III-V or other devices are critical to high-performance military needs. Leveraging of NSF National Nanotechnology Infrastructure Network facilities should be made. Possible SBIR topics may also be helpful to address some of the challenges; for example, high-alignment accuracy for HI, via microtransfer printing, and so on. Multiple material platform co-integration 3-D or 2.5-D integration architecture should also be explored including considerations for energy efficiency, integration density, and novel functionality. Challenges on quality of materials and fabrication processes toward multilayer material platforms, including Si, III-V, SiN, AlN, LNOI (thin-film LN on insulator), and so on, must also be included. The high cost of LNOI is also a major concern and investments may discover ways to bring this down.

Another concern to highlight here is the technology-transfer ecology. Due to the rapidly advancing integrated photonics field, continual interactions across the Army and DOD are critical. The Army acquisitions community (project executive offices [PEOs] and similar offices) may not be following rapidly moving scientific advances and nanofabrication techniques. Therefore, it is critical to provide ways for S&Es (across AFC) to interface with PEOs for acquisitions advances. SBIR and RIF (larger SBIR type programs) are needed to provide means to prototype PICs, but this starts with technical interactions that lead to funding opportunity announcements that specify the appropriate requirements (i.e. based on the latest advances in the technical community, as per publications and conferences), that goes beyond what PEOs and major defense enterprise may be aware of (i.e. the mission of ARL and the DEVCOM centers). The Army Futures Command with the intentional interactions between Concepts and DEVCOM scientists and engineers is an approach aimed at addressing this ecology. It has a strong potential to provide the means to achieve these goals.

5. Overall Conclusions/High-Level Recommendations

This ASPSM workshop revealed a critical need for integrated nanophotonics research to be conducted in context of the larger integrated photonics enterprise. As mentioned previously in the Topic 6 findings, integrated nanophotonics cannot effectively be pursued apart from the PIC (that is, foundry) context. Regrettably, the ability for academic researchers to interface with MPW PIC development has been nearly excluded due to cost, limiting the most effective academic to SBIR Phase II or DARPA-sized efforts; that is, \$1.1–\$8 million over 2 years or more. A better-rounded photonics R&D ecosystem is critical for advancing the research and capabilities that integrated nanophotonics can provide to foster high-risk investigation and pursuit of novel device physics within the context of some larger PIC functionality. A device often functions with some kind of transfer function and each part of the PIC affects the rest of it. While some advances can be made relying on well-established and less-expensive Si foundries, integrated nanophotonics is showing a clear need for direct bandgap, non-Si-based materials such as III-V compound semiconductors, 2-D nanosheets, and even organic and other exotic phase-change materials. Incorporation of those materials repeatedly and reliably to get expected design criteria metrics for PIC functionality is a new world. Coupling efficiency from HI devices, their thermal performance, and reliability or effects on each other optically are all driving motivation for including integrated nanophotonics as part of the larger integrated photonics enterprise.

An example of this is warranted and keys off the plenary session on neuromorphic photonic computing from this ASPSM workshop. Notably, AFOSR awarded two integrated nanophotonics MURIs in mid-2017. Its emphasis was clearly aimed at device science: achieving integrated nanophotonic devices with sub-fJ (i.e., aJ) levels of energy/bit efficiency. The third-year review of these teams revealed a PIC-level initiative across the board. Almost all of the groups involved are working on neuromorphic photonics, many times leveraging other collaborations (through DARPA, ARO/National Security Agency efforts, etc.) demonstrating that a device-level advance requires a PIC-level context and effort. The teams are pushing the edge of foundry-integrated photonic PDKs (which admittedly appears 6.2 or 6.3 in nature) to answer fundamental questions regarding PIC architectures. When the architectures point to clear needs for focused work on materials and devices, the needed advances in integrated nanophotonic concepts come to light. Without proactively seeking motivation for integrated nanophotonics research to enable this sort of holistic approach, progress will be quite slow.

One means to promulgate this type of ecosystem is to form new research initiatives that combine high-risk 6.1 research endeavors alongside lower-risk 6.2 and 6.3 PIC development plans. For example, DARPA PIPES, a 6.2/6.3 program, funds little if any integrated-nanophotonics-related projects (similar to LUMOS, a 6.2 program) due to what they see as significant risk. Perhaps in the current ecosystem, combined 6.1 MURI-like initiatives working alongside 6.2/6.3 DARPA could be particularly powerful. Future advancements will be accelerated by intentionally overcoming this integrated nanophotonics 6.1 to 6.2 “valley of death”.

Finally, the recommendation to solve this problem involves agency-wide communication and cooperation. The whole microelectronics industry historically benefited dramatically through large-scale investment from DARPA and DOD. Perhaps a similar cooperative investment can repeat this in the more heterogeneous (materials and device-wise) and scientifically complex integrated nanophotonics regime. Strategic coordination and pursuits is a key approach to operationalizing the scientific and engineering advancement of this field for technological overmatch. International investments are concerning. The last decade saw the European integrated photonic institutes take the lead. Further, based on observations at IEEE Conference on Lasers and Electro-Optics (CLEO), the Chinese are seeking to dominate this R&D realm as well. Chinese participation in 2018–2020 in CLEO (held in San Jose, California, each year) showed a dramatic increase. Asian-based foundries are being leveraged (Advanced Micro Foundary-Singapore and Taiwan Semiconductor Manufacturing Company-Taiwan, alongside the huge academic investments) to bolster progress. The DARPA Electronics Resurgence Initiative (2017–2022), however, has re-energized the US microelectronics capabilities and is now beginning to impact integrated photonics. Further incorporation of 6.1 investment can ensure US dominance. Integrated nanophotonics requires multidisciplinary and vast scientific consideration across physics, materials, and electrical engineering subdisciplines as well as engaging other scientific fields (i.e., computer and information sciences).

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List of Symbols, Abbreviations, and Acronyms

1-D	one-dimensional
2-D	two-dimensional
2.5-D	two-and-a-half-dimensional
3-D	three-dimensional
AC	alternating current
AFC	Army Futures Command
AFOSR	Air Force Office of Scientific Research
AI	artificial intelligence
aka	also known as
AlN	aluminum nitride
AO	all-optic
APD	avalanche photodiode
ARL	Army Research Laboratory
ARO	Army Research Office
ASPSM	Army Science Planning and Strategy Meeting
BAA	Broad Agency Announcement
BEC	Bose–Einstein condensate
BNN	Bayesian neural network
CLEO	Conference on Lasers and Electro-Optics
CMOS	complementary metal–oxide
CPU	central processing unit
CTE	coefficient of thermal expansion
DAC	digital-to-analog converter
DARPA	Defense Advanced Research Projects Agency
DC	direct current
DEVCOM	US Army Combat Capabilities Development Command

DNN	deep neural network
DOD	Department of Defense
DoF	degree of freedom
EM	electromagnetic
EO	electro-optic
EU	European Union
FOM	figure of merit
GaAs	gallium arsenide
GaN	gallium nitride
GBP	gain-bandwidth product
Ge	germanium
GST	Ge–Sb–Te
GSST	Ge–Sb–Se–Te
GWU	George Washington University
HI	heterogeneous integration
IC	integrated circuit
IEEE	Institute of Electrical and Electronics Engineers
InGaAsP	indium gallium arsenide phosphide
InP	indium phosphide
IP	intellectual property
KTMA	key technology manufacturing area
LED	light-emitting diode
LIDAR	laser radar
LN	lithium niobate
LNOI	lithium niobate on insulator
LUMOS	Lasers for Universal Microscale Optical Systems
MAC	multiply and accumulate

MBE	molecular-beam epitaxy
MIT	Massachusetts Institute of Technology
ML	machine learning
MPW	multiproject wafer
MRR	microring resonator
MURI	Multidisciplinary University Research Initiative
MZI	Mach Zehnder Interferometer
NACHOS	Nanoscale Coherent Hyperopic Sources
NIR	near infrared
NL	nonlinearity
NLAF	nonlinear activation function
NLO	nonlinear optic
NN	neural network
NP	nondeterministic polynomial
NSF	National Science Foundation
OAM	orbital angular momentum
OE	optoelectronics
ONN	optical neural network
OPA	optical phased array
OPS	operations per second
PC	photonic crystal
PCM	phase-change material
PCSEL	photonic-crystal surface-emitting laser
PDK	process design kit
PEO	project executive office
PIC	photonic integrated circuit
PIPES	Photonics in the Package for Extreme Scalability

PM	Project Manager
PNT	position, navigation, and timing
PPLN	periodically poled lithium niobate
Prof	professor
PT	parity-time
Q	quality
QED	quantum electrodynamics
QO	quantum optics
R&D	research and development
RF	radio frequency
S&E	scientist and engineer
SBIR	Small Business Innovation Research
SEDD	Sensors and Electron Devices Directorate
Si	silicon
SiC	silicon carbide
SiN	silicon nitride
SiPh	silicon photonics
SLM	spatial light modulator
SME	subject-matter expert
SNR	signal-to-noise ratio
SPADE	SPAtial-mode Decomposition
STTR	Small Business Technology Transfer
SWaP-C	size, weight, power, and cost
TAP	testing, assembly, and packaging
TMD	transition metal dichalcogenides
UCSD	University of California at San Diego
U Penn	University of Pennsylvania

UV	ultraviolet
VCSEL	vertical-cavity surface-emitting laser
VIS	visible
VMM	vector matrix multiplication
WDM	wavelength-division multiplexing

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