NNMI Comments:
A Photonics Manufacturing Institute

This document addresses a Request for Information entitled, "Proposed New Program: National Network for Manufacturing Innovation (NNMI)," dated 4 May 2012, issued by the U.S. National Institute for Standards and Technology (NIST).[1]

As outlined in the RFI, the U.S. government proposes establishing a network of Institutes for Manufacturing Innovation (IMIs) located around the U.S. to address the gap between R&D and deployment of innovations into commercial goods. The program would aim to reduce the risk of investment to scale up manufacturing (particularly for small and medium-sized businesses), and strengthen the infrastructure of key manufacturing skills and technology, among other things.

We propose that one of the IMIs address the manufacturing of photonics devices—a Photonics Institute. We answer questions in the RFI based on that example. Moreover, we believe that a successful model for an Institute should be centered on actual, substantive manufacturing. Establishing and coordinating U.S.-based foundries for manufacturing photonic integrated circuits (PICs) would provide this "center of gravity." These foundries would bring measurable value to U.S. R&D and commercial efforts, while creating a center of gravity for the broader aims of the Institute.

As a trade association centered on photonic components for over 20 years, we present here a perspective from that industry, as well as from the larger community of industry, government, and academic stakeholders that have attended our roadmapping workshops in this topic, and other efforts.

The document outline is presented in the following table.

[1] A plan was announced on March 9, 2012 by President Obama proposing $1 billion for an NNMI to catalyze up to 15 institutes for manufacturing innovation (IMIs). The public-private partnerships would serve as regional hubs of manufacturing excellence. The Advanced Manufacturing Partnership (AMP) Steering Committee called for the institutes to bridge the gap between basic research performed in universities and national laboratories, and production enterprises, particularly small and medium enterprises. The government announced its first institute, the National Additive Manufacturing Innovation Institute (NAMII), based in Ohio, in August 2012.

Section Outline	Key Points
I. A proposal for a Photonics Institute with foundry services as a center of gravity	• Foundry services serve as a substantive, manufacturing center of gravity to the Institute. • Foundry services include integrated silicon photonics, InP-based PICs, packaging, and associated electronics. • Workforce education at three levels is a key part of the Institute • Photonics industry clusters provide important local and regional connections. • An intermediary manages Institute operations, working with an Advisory Board and NNMI oversight.
II. Responses to specific questions in the RFI	This section addresses the RFI questions based on the Photonics Institute described in Section I.
III. Background on photonics, PICs, and PIC foundries	Provides some technical background and context about photonics, photonic integrated circuits (PICs), silicon and InP, and foundry services.
IV. Notable PIC fabs and foundry projects	A discussion of relevant PIC or foundry projects: • CPFC (in Canada) • JePPIX and related EuroPIC projects (in Europe) • MNX, MOSIS, and OpSIS (in the U.S.) • Japan
V. OIDA's role as trade association and foundry broker	A brief summary of OIDA's two decades of experience and history in the photonics industry, including proposals for a virtual photonics foundry, the PTAP and JOP programs, and workshop and studies.

<u>Contact information</u>

Tom Hausken, PhD
Senior Engineering and Applications Advisor

OIDA
2010 Massachusetts Ave., NW
Washington DC 20036

Direct phone: (202) 416-1937
Email: thausken@osa.org

I. A proposal for a Photonics Institute with foundry services as a center of gravity

We propose here a Photonics Institute. Some of the technical terms are mentioned here and discussed in more detail in Section III.

It is important that a Photonics Institute have a core manufacturing program—a core product—that provides the "gravity" and substance for the rest of the program. The core of a Photonics Institute would be foundry services for manufacturing photonics, providing prototypes and commercial devices for U.S. customers, while also serving as the "center of gravity" for the broader aims of the NNMI.

The foundry services would focus on photonic integrated circuits (PICs), including both silicon- and InP-based PICs, packaging, and electronics, as summarized below.

- The InP-based foundry could consist of a single qualified facility, or a set of facilties acting as a "virtual foundry." In the former case, the funding would be concentrated to the applicant considered to be the most highly qualified domestic manufacturer. This would concentrate financing to establish or maintain a production-quality operation.

  Awarding a single, "winner take all" contract for InP-based foundry services may be initially unpalatable to government agency stakeholders, or a suitable bidder may not be found. A less expensive option would be to name one or more existing fab operators to provide R&D prototyping services in a virtual foundry, rather than a single, commercial-grade service. After a set period, such as 5 years, as the foundry operations gain traction, the list of qualified foundries might be narrowed to a smaller number, or perhaps to just one, to concentrate the financing and improve the long-term success of the program.

- The silicon-based PIC foundry is better suited for the virtual foundry concept, since that leverages existing silicon fabrication facilities. The virtual foundry of the OpSIS program (see discussion in Section IV) could be that foundry, or could be included with other silicon photonics activities. Such partners might be already funded independently of the Institute (such as OpSIS) but would benefit and contribute to a more collaborative effort.

- The Photonics Institute should include not only chip fabrication, from epitaxy to wafer test, but also complete and standardized packaging. The packaging should not be viewed as a commodity service, decoupled from the device design and fabrication, but closely integrated with the foundry services.

- The Photonics Institute should also offer sets of general-purpose (silicon-based) electronics chips for driver and receiver circuits, FPGAs, and so forth. As with packaging, electronics should not be viewed as a commodity apart from the PIC design and fabrication, but as essential elements that enable and optimize the overall PIC performance. It may be necessary to coordinate electronics design (such as through MOSIS) with the PIC design, since such close marriage of photonics and electronics is critical to successful commercialization.

"Qualified" includes certain criteria. Foremost, the foundry must be a domestic source. It should provide the most mature and standardized process that is reasonably available. This means that it should include or integrate software modeling tools for designing a product with a high expectation that the finished device will function as expected, both the first time and from batch to batch. The emphasis here is on a "reasonable" level of sophistication for the state of the art today, because PIC fabrication for general-purpose applications is behind silicon digital electronics with regard to design rules and process integration.

The initial facilities and process development would be co-funded by U.S. government agencies and the foundry operators. The foundries could be managed as a pilot program, with periodic reviews of specific metrics, with an overall assessment of the program after 7 years.

Once the foundries are operational, contractors to government agencies, universities, and industrial customers could begin to channel projects through the foundry. In return, the foundry would charge these customers for the foundry services, as a fee-for-service or subscription.

Roadmapping, market studies, and workforce education would extend subject coverage beyond silicon- and InP-based PIC manufacturing to the commercialization and manufacturing of photonics generally. The Photonics Institute would also address manufacturing beyond silicon- and InP-based PICs to include other semiconductor photonic devices (such as GaAs-based VCSELs, GaN-based LEDs and lasers, etc.), and even other photonic devices (such as displays, solar cells, etc.). This coverage would be especially important for workforce education, roadmapping, and market studies.

Roadmapping and market studies are particularly important for the industry to have a long-term business perspective not offered through technical conferences or shorter-term market forecasts. These efforts focus on the hard problems of the industry that may require multiple stakeholders to solve.[2] OIDA currently provides a home for such roadmapping exercises, but greater support is needed.

---

[2] The roadmapping efforts would not aim for the detail of, for example, the ITRS roadmap that addresses the semiconductor industry. Rather, they would aim for a steady progress in R&D and commercialization goals that leverage the overall government and industry investments, and identify roadblocks to commercialization.

The scope of the roadmapping and market studies would also extend beyond normal business horizons, perhaps to 7-10 years or more, to help domestic companies better understand opportunities for future photonics manufacturing across an array of technologies.

Workforce education in photonics manufacturing directed at three levels. A key piece of the Photonics Institute is workforce training in technical skills and the business of photonics manufacturing. This workforce training is not focused on PhD-level training in the physics of photonics devices; those challenges are addressed directly by industry and universities, including through the foundry operations. Instead, the workforce training emphasizes the practical side of photonics manufacturing, through vocational programs and management seminars.

We suggest workforce training be directed at three levels, summarized below.

- Management-level training series on the business and management of photonics manufacturing. This program would develop case studies in the style of Harvard Business School, based on the successes and challenges faced by real photonics manufacturing companies. The program would be suited to both engineers and business executives. It would require some initial investment to establish a curriculum, possibly with a partnership through certain business schools familiar with photonics, such as Boston University,[3] among others. The training would go to both engineers and business executive, taking the seminars "on the road" to off-site seminars and/or collocated at photonics conferences. Once established, it could be self-sufficient through registration fees.

- Undergraduate and graduate-level courses for engineers on the business and management of photonics manufacturing. Similar to above, this program would be directed toward students before they leave the university. The curriculum could travel to conferences in the form of short courses, or they may be conducted at locations within the Photonics Institute, possibly away from the student's home university. The engineering management programs would also require some initial investment, but would leverage existing university programs and infrastructure as much as possible.

- Technician training in optics, aimed specifically at photonics manufacturing. This would leverage existing, emerging programs in vocational and engineering training aimed specifically at optics. The emphasis would be to leverage and

[3] In particular, the Boston University Photonics Center Incubator and Institute for Technology Entrepreneurship and Commercialization. Other relevant programs around the U.S. might also be useful.

coordinate existing efforts, such as OP-TEC,[4] rather than to create new and redundant programs.

Connections to local and regional economic development agencies through photonics clusters. The U.S. boasts many local and regional photonics "clusters," and OIDA has had long relationships with them. These clusters provide important local networking opportunities and connections to local and state governments. A Photonics Institute should include clusters as partners where there are shared interests, such as workforce education.

Formal U.S. photonics clusters include, but are not limited to, the following:

- Arizona Optics Industry Association
- Colorado Photonics Industry Association
- Florida Photonics Cluster
- M-Light—the Michigan Photonics Cluster
- New Mexico Optics Industry Association
- New York Photonics Industry Association (including the Rochester cluster)
- Rochester Regional Photonics Cluster

An intermediary would be required to navigate issues and manage the Photonics Institute operations. The foundries would require an intermediary that acts as a broker to manage legal issues, organize roadmapping and market analysis activities, create a workforce education program, conduct outreach to other Institutes, and promote the Photonics Institute's programs. This intermediary would consolidate the many operational and strategic issues of the Photonics Institute that would not fall to any single entity. This role would be best undertaken by an organization with an interest in the industry—such as OIDA—that includes connections to government agencies, customers, manufacturers, and universities.

A key early role of the intermediary might be to evaluate the interest and business model of PIC foundries, *before* additional funds are committed to an actual foundry. This evaluation would include a detailed census of available supply and actual demand, and detailed estimates of costs and financing. The intermediary would report its findings to the funding sources.

Many duties of the intermediary could be conducted in parallel with the establishment and operation of the Photonics Institute. Some of the possible duties are listed below.

- Prepare and manage legal documents addressing confidentiality (non-disclosure agreements), conflicts of interest, intellectual property, financial transactions, etc.,

[4] The National Center for Optics and Photonics Education is a consortium of two-year colleges, high schools, universities, national laboratories, industry partners, and professional societies funded by NSF's Advanced Technological Education (ATE) program. It is headquartered in Waco, Texas.

between the foundry operator, its customers, and other parties (government agencies, other contractors, etc.).

- Coordinating and standardizing orders and technical requirements, offering technical answers to basic questions, with deeper questions addressed by engineers at the foundry itself. The intermediary essentially does “handholding” to help the customer navigate the overall complexity: chip fab, packaging and testing, and associated electronics, including pricing and legal issues.
- Promoting the foundry service and other Photonics Institute activities to potential participants.
- Training of customers in the available design and test software, associated electronics, etc., such as through webcasts and workshops.
- Roadmapping of current and future technology needs and capabilities from the foundry, building consensus regarding key issues and trends.
- On-going estimates of PIC market demand, including a careful census of specific needs for PIC fabrication at estimated price points, etc.
- Collecting the market share data on key segments of photonics, to monitor domestic capability and future threats.
- In-depth and on-going review of interest and commitment in the photonics community to finance foundry services, either as a foundry operator, as a customer, or government partner.
- Review of the trends and success of similar PIC and PIC foundry operations around the world, their business models, and the economic impact of PICs in the industry.
- Roadmapping and market studies of other photonics manufacturing technologies where appropriate, to expand the scope of the Photonics Institute.
- Create a workforce education program that addresses multiple levels of photonic manufacturing: technicians, engineers, and managers/executives. This program would include education in the management and engineering of photonics manufacturing, technician training, and more. It would leverage as much as possible existing programs, supplementing them where necessary.
- Conducting outreach to potential partners in the Photonics Institute, such as vocational schools, business schools, manufacturers, etc.
- Building relationships with other Institutes within the NNMI to exchange information, and grow “roots” to create a true national manufacturing network.

Summary of how a Photonics Institute would address key aims of the NNMI. The RFI lists some objectives and attributes desired for each Institute. A Photonics Institute as described above is an excellent match for those aims of the NNMI. The following table summarizes the attributes listed in the RFI with a short description how a Photonics Institute might satisfy each one.

NNMI Institute Attribute	How a Photonics Institute Would Address the Attribute
Reduce cost and risk of commercializing new technologies	The barrier to entry for PIC manufacturing is high. PIC foundries lower the barrier, especially for small- and medium-size companies.
Address manufacturing challenges on a production-level scale	The PIC foundries would aim for commercial-grade, production-level scale for their own sake. That scale also provides an important center of gravity to the Photonics Institute.
Well-defined technical focus	The main technical focus of the Photonics Institute would be on silicon- and InP-based PICs, including packaging and associated electronics (drivers, receivers, and FPGAs). Other photonics technologies would be included for workforce education, roadmapping, and market studies.
Long-term partnership between industry, educational institutions, and state, regional, and local economic authorities.	The intermediary acts as executor for the Photonics Institute, consulting with an Advisory Board with representatives from these various bodies. The aim is to create self-sufficient foundries and long-lasting relationships built around the foundries and workforce training.
Flexibility to form integrated teams of experts from multiple disciplines to solve difficult problems and develop the workforce	The intermediary has the responsibility to create partnerships and teams, leveraging as much as possible existing resources, rather than creating new programs or facilities from scratch. The foundries themselves are made from "bricks and mortar" but the overall Photonics Institute would be very much "virtual."
Involvement of industry associations, professional societies, and economic development associations	OIDA has a 20-year history in roles of brokering, roadmapping, etc. for the industry, and is managed by OSA—a professional society centered on applied optics. OIDA also has strong relationships with regional photonic clusters throughout the U.S.
Analytical capability to identify critical emerging technologies that can make an impact in commercialization	A key element of the Photonics Institute would be market studies and roadmapping, directed specifically at photonics manufacturing, to closely monitor the field for new developments in manufacturing.
Ability to engage SMEs to effectively deploy technologies	Most photonics companies are small- and medium-size enterprises (SMEs), and many are OIDA members. The PIC foundry services are directed especially at SMEs, but the roadmapping and workforce training are particularly well-suited for SMEs, too.
A sustained focus on innovation with a strong reputation for quality and success	A Photonics Institute should not provide "me-too" foundry services suitable only for R&D prototypes. Such foundries offer poor manufacturing yield and do not advance the infrastructure. The foundries aim for achieving commercial-grade quality.

II. Responses to specific questions in the RFI

In this section, we address the questions listed in the RFI, using the proposed Photonics Institute as an example.

Technologies With Broad Impact

1. *What criteria should be used to select technology focus areas?*

   The best technologies are those that have substantial leverage in the economy and/or address specific national security needs. A Photonics Institute based on foundries would do both. Photonics is an enabling technology that underlies a wide range of other technologies, from displays and cameras in electronics, to auto manufacturing, to military surveillance platforms, and biomedical systems.[5]

   More important than the revenues and jobs related to photonics components alone are the products and services enabled by the photonics, and having domestic sources for those components. The domestic sources are important because the close contact helps drive innovation, and many businesses prefer to "spin-in" such sources to secure the source or leverage the vertical integration. At some point, having domestic sources is not merely convenient, but it is a national security issue of its own, insofar as having the sources helps national competitiveness.

   PICs, in particular, are now viewed as the "must-have" technology for next-generation telecom systems. Moreover, a domestic source for PICs and PIC-based telecom equipment is considered necessary to assure that the U.S. military has secure communications systems in future years. Photonics foundries would help secure a domestic source, keep U.S. communication equipment vendors more competitive, and support U.S. technology leadership generally.

2. *What technology focus areas that meet these criteria would you be willing to invest in?*

   There are industrial partners in our community that might co-fund capital equipment and process development for PIC foundry services, although many details are not resolved. Some have already committed funding independent of the NNMI; the Photonics Institute

[5] OIDA estimates that photonics components companies located in the U.S. generate approximately $19 billion, and the systems based on those components bring much more. The jobs related to the photonics components alone may amount to as many as 100,000. A recent European study estimated 300,000 jobs exist in Europe due to photonics and the systems that photonics closely enables.

might bring such partners together as part of a larger team. In this way, much of the effort would be a matter of coordinating and "joining forces."

3. *What measures could demonstrate that Institute technology activities assist U.S. manufacturing?*

   The advantage of having the core program centered on PIC manufacturing foundry services is that there is already a specific need for PIC foundry services and product development, and it offers other opportunities for unforeseen spinoffs. The PIC foundry services thus bring a value of their own, as well as provide a center of gravity to the Photonics Institute. This value can be measured in terms of revenue versus expenses, and the "downstream" impact, as well as in other, less monetary benefits.

4. *What measures could assess the performance and impact of Institutes?*

   A key measure would be if the Institute becomes self-sustaining through public and private funding, and/or as a not-of-profit business. The foundry services of a Photonics Institute should aim to be financially break-even in 5-7 years.

Institute Structure and Governance

5. *What business models would be effective for the Institutes to manage business decisions?*

   A Photonics Institute would have at its core the PIC foundry services, which would have a specific business model based on delivering services. At first, the government and foundry operators would co-fund the capital equipment, process development, and operating expenses. Over time, as more customers use the services, the user fees would increasingly offset the operating expenses. The aim is that eventually the user fees fully offset expenses.

   The two foundries—silicon photonics and InP-based—have very different capital and operating costs, but the basic business strategy is the same for each.

   The other activities of the Photonics Institute (workforce training, roadmapping, market studies, etc.) would operate in parallel to the core foundry services. Some efforts would require initial funding from the NNMI to get started, such as for creating a curriculum in workforce training. Eventually, most activities would be paid as much as possible through user and registration fees. Government funding is nonetheless important to maintain momentum for activities that have benefits to government (such as those related to national security issues, or identifying trends for funding R&D or metrology).

6. *What governance models would be effective for the Institutes to manage business decisions?*

   We strongly support the use of an intermediary—such as OIDA—as the executor of the Photonics Institute. NIST and other NNMI agency partners would provide oversight of NNMI funding of the intermediary and of the overall program.

   The intermediary would also consult with an Advisory Board consisting of representatives from key partners and participating companies. Advisory Board members might include representatives from the following:

   - NIST and other NNMI funding agencies
   - Foundry operators
   - Key foundry customers and/or co-funding partners
   - Small- and medium-businesses
   - Educational institutions (such as OP-TEC) as partners in workforce education
   - Selected university centers that specialize in aspects of photonics manufacturing
   - The intermediary

7. *What membership and participation structure would be effective for the Institutes, such as financial and intellectual property obligations, access and licensing?*

   The legal and financial issues for foundry services are complex, but the services in a Photonics Institute would be based on similar models already in place (such as OpSIS, MOSIS, NMX, CPFC, and EuroPIC—see discussion in the Section IV). The services are best managed through an intermediary that also manages the other activities of the Institute (such as training, roadmapping, market studies, etc.). In short, foundry operators are selected, customers subscribe or pay for the services, and the intermediary manages the Institute.

8. *How should a network of Institutes optimally operate?*

   Each Institute would address its own core technology, material, process, or industry, and each may include an intermediary as executor, such as we propose here. These executors could form a consortium of their own—the Network of Institutes—for sharing ideas.

Over time, this consortium might grow its own roots, creating new relationships with industry, government, and universities apart from the relationships with their constituent members.

9. *What measures could assess effectiveness of Network structure and governance?*

   It is important that some metrics be established that demonstrate that the Network is greater than the sum of its parts, rather than a Network in name only. This could count substantive outcomes, such as Network-level funding (independent of the constituent Institutes) or unique Network-level activities (other than periodic meetings of Institute executors).

Strategies for Sustainable Institute Operations

10. *How should initial funding co-investments of the Federal government and others be organized by types and proportions?*

    We are continuing to evaluate the specific costs and potential demand for the foundry services that would form the core of a Photonics Institute. The exact proportions would be different for the two types of foundry services: silicon photonics and InP. Some activities might be funded independently of the NNMI program. The operations of the intermediary and subcontractors would be funded from the Federal government, but many costs would be recovered through user fees and registration fees.

11. *What arrangements for co-investment proportions and types could help an Institute become self-sustaining?*

    The funding from the Federal government would be directed mainly at initial capital equipment, process development, and early operating costs. Over time, the foundries would be expected to gain users. The aim is to offset the operating costs with user fees. Likewise, some funding would be used to develop training, roadmapping, etc. The aim is to make these activities nearly self-sufficient.

12. *What measures could assess progress of an Institute towards being self-sustaining?*

    The foundry services that would form the core of the Photonics Institute would begin with an explicit business plan and financial forecast. The plan would be evaluated periodically by the Advisory Board and the NNMI oversight.

13. What actions or conditions could improve how Institute operations support domestic manufacturing facilities while maintaining consistency with our international obligations?

The foundry operations themselves would be located in the U.S., but the services might be made available to international customers, on a case by case basis, to help achieve self-sufficiency. The policy for use would require approval by the Advisory Council and NNMI oversight.

Workforce education, roadmapping activities, and market studies might be restricted through policies established by the Advisory Council and NNMI oversight.

14. How should Institutes engage other manufacturing related programs and networks?

The Photonics Institute would include both foundry services as well as packaging and associated electronics (such as drivers, receivers, and FPGAs) as integral parts of the program.

The Photonics Institute would also aim to examine the manufacturing of all types of photonics products, beyond just PICs, for its activities in roadmapping, market studies, and workforce education. Such products include diode lasers, LEDs, solar cells, image sensors, fiber lasers, and displays, to name a few.

The Institutes would also engage each other at the level of the Network of Institutes.

15. How should Institutes interact with state and local economic development authorities?

Useful channels for addressing state and local authorities are through local and regional photonics clusters, of which there are many across the U.S. OIDA has had long and close relationships with these clusters. For example, OIDA submitted a response to an earlier RFI on the proposed AMTech program[6] with the Florida Photonics Cluster. These clusters provide important "on the ground" relationships and energy in addition to the industry-wide relationships of an industry association, such as OIDA.

[6] "NIST Seeks Comments on Structure for Proposed Advanced Manufacturing Technology Consortia (AMTech) Program," 22 July 2011. OIDA comments were submitted 15 September 2011.

16. *What measures could assess Institute contributions to long term national security and competitiveness?*

One reason for using PIC foundries as the focus of a Photonics Institute is to assure a domestic manufacturing capability for this technology for future communications systems, including those procured for military applications. PICs might also be critical for future systems using RF photonics that are used in military over-the-air communications.

The U.S. military has place greater attention on securing a domestic source for key communications components and systems, including PICs for future systems.

Education and Workforce Development

17. *How could Institutes support advanced manufacturing workforce development at all educational levels?*

We propose that the workforce education program in photonics manufacturing that addresses all types of photonics devices, because of the broad impact those technologies have in the U.S. economy. Until now, there has not been a program addressing the business and manufacturing of photonics. As noted in the description above, the proposed program address three levels (see discussion in Section I):

- Management-level training series on the business and management of photonics manufacturing.
- Undergraduate and graduate-level courses for engineers on the business and management of photonics manufacturing.
- Technician training in optics and photonics manufacturing.

We emphasize that in some cases, the courses would have to be developed with relatively little initial funding, but the emphasis would be to leverage existing resources as much as possible, such as programs at optics departments at universities and OP-TEC (see earlier footnote).

18. *How could Institutes ensure that advanced manufacturing workforce development activities address industry needs?*

The program would be assembled by the intermediary by subcontracting resources from business schools and industry. The emphasis is on practical workforce training (such as in process control, financing, and intellectual property) rather than on specific manufacturing innovations (such as R&D in new packaging technologies).

19. *How could Institutes and the NNMI leverage and complement other education and workforce development programs?*

It is important that the U.S. address workforce training issues that are specific to photonics manufacturing, such as in the use of business case studies from that industry and technical training in optics for technicians. However, many aspects of the training can draw from resources used in other NNMI Institutes. For example, fabrication for silicon electronics offers many useful parallels/contrasts with semiconductor-based photonics manufacturing. Solar cell and panel manufacturing is itself a photonics technology.

Likewise, a strong education program developed for a Photonics Institute might also serve as a model for other Institutes.

20. *What measures could assess Institute performance and impact on education and workforce development?*

There have been no programs—up to now—dedicated to photonics manufacturing. Business schools now generally focus on companies providing software or services, not manufacturing, and certainly not photonics manufacturing. Moreover, the photonics industry has long complained that graduates must be retrained to work in the real world, leaving a wide gap between the training in universities and what is needed in industry. Finally, there are few programs in the U.S. dedicated to optics, particularly at the undergraduate level or below. Simply establishing, coordinating, and promoting such programs to become self-sustaining as a networks would be a significant achievement.

21. *How might institutes integrate R&D activities and education to best prepare the current and future workforce?*

One advantage of using the PIC foundries as the focus of a Photonics Institute is that it is a worthwhile end in itself, not an R&D project or proof-of-principle. Some of the R&D of photonics manufacturing will be integrated into the foundries by necessity.

It is important to emphasize that the greatest value of a Photonics Institute would not be the accumulation and transfer of manufacturing R&D per se.[7] Rather, it would lower the barriers to innovation and commercialization, particularly for small- and medium-size enterprises (SMEs). It would also open channels of communication between industry and universities, directing universities toward more valuable directions, and better preparing students for real-world jobs. Workforce education would emphasize the practical and business aspects of photonics manufacturing, rather than deep R&D.

[7] The chip design and process development performed within the PIC foundries do accumulate substantial R&D value, which is important for its own sake as well as to the overall Photonics Institute. The point is that that the specific R&D achievement developments do not define the overall Institute, but rather provide a real and substantive "center of gravity" to the Institute, which includes other, more broad and important efforts in workforce education.

III. Background on photonics, PICs, and PIC foundries

"Photonics" is like electronics, but using photons—i.e., light—usually in addition to electrons. Photonics products include lasers, LEDs, optical fiber, liquid crystal displays, solar cells, image sensors in cameras, and much more. They are often the enabling technology in other products, such as laser welders for auto manufacturing, communication networks, solid-state lighting, military surveillance equipment, biomedical diagnostic systems, and more.

Most semiconductor-based photonic devices have been manufactured as discrete devices or subsystems, until recently. This means that diode lasers and LEDs are fabricated on wafers, the wafer is diced into chips, and the chips are packaged individually.[8] The wide diversity of photonics technologies and products means that there has been little uniformity or sharing of knowledge in manufacturing.

A photonic integrated circuit (PIC) is essentially the photonic analog of the electronic integrated circuit. Nearly all photonic devices made from semiconductor wafers (mainly diode lasers, LEDs, and detectors) are packaged as discrete devices, like many discrete transistors and resistors are packaged for electronics. Now the technology is available to integrate multiple photonic devices onto the same chip, and assemble the chip into a single package. This reduces the overall circuit size; it also reduces the cost of packaging and improves the reliability. However, it increases the complexity and cost of chip fabrication, raising the barrier to commercial manufacturing. The barrier is so high, that achieving commercial-grade PIC manufacturing at a large scale of circuit integration has been unattainable until the last few years.

Others have made this case, in the U.S. and abroad, most recently in the new National Research Council report released in autumn 2012.[9] The report includes two grand challenges and several recommendations toward U.S. leadership in communications. One of the key recommendations offers a path toward those goals: "The U.S. government, and specifically the Department of Defense, should strive toward harmonizing optics with silicon-based electronics to provide a new, readily accessible and usable, integrated electronics and optics platform." The report goes on to suggest that, "Government funding agencies, the DOD, and possibly a consortium of companies requiring these technologies should work together to implement this recommendation."

Several terms are also sometimes used in the industry, other than "PIC." The first term in wide use that referred to wafer-based integration of optical and electronic devices was the "OEIC" (Optoelectronic Integrated Circuit), which dates to the 1980s. Planar lightwave circuits

---

[8] CMOS image sensors are a notable exception. They commonly integrate electronic input-output and image processing circuits on the same chip with the sensor array, all fabricated on silicon wafers.

[9] *Optics and Photonics: Essential Technologies for Our Nation*, National Research Council (National Academy Press, 2012).

(PLCs) was a term commonly used by Japanese firms in the 1990s for OEIC products aimed at commercial fiber-to-the-home networks. Photonic ASICs extends the concept of the semi-custom application-specific integrated circuit to a concept equivalent to the PIC.[10] European programs also refer to ASPICs: application-specific PICs.

PICs have been a subject of research for many years, but there is renewed and increased attention on PICs, for the following reasons.

- Manufacturing technology has more recently advanced to the point that larger-scale integration can be cost-effective, on a scale not possible even 10 years ago. This achievement arises from heavy investments in the process over a long period. The investment is not only in the PIC chip, but also in the overall packaging and the associated electronics (i.e., drivers, receivers, and FPGAs) that enable a fully commercial product.

- Communications equipment designers are turning to more sophisticated coding (i.e., coherent techniques) to achieve greater serial data rates, and the number of photonic circuit elements required for coherent communications is much greater than techniques that use simple “on/off” coding. While simpler solutions were sufficient for generations of equipment up to now, PICs are considered to be the superior technology in which to implement these techniques, since many elements can be integrated into one chip. PICs represent the next frontier for communications components: more compact, higher performance, more reliable, and more cost-effective solutions.

PICs are now recognized for their value in coherent techniques[11] for long-haul telecommunications. But they are also well suited for equipment employing RF photonics[12]: the use of light to carry radio frequency or microwave signals. What distinguishes RF photonics components are the applications and the architectures to support them, particularly wherever there is high frequency “over-the-air” communications. RF photonics is particularly prominent in over-the-air communications, as well as in other applications that use RF and microwaves: radar systems, cellular and wireless systems, satellite and radio astronomy, cable television networks, and optical signal processing.

---

[10] Bookham Technology (now Oclaro) named its process for making OEICs ASOC, for application-specific optical circuit.

[11] Most simply, coherent techniques mix waves to send and receive signals, as in over-the-air radio and television transmission and most coaxial cable television transmission. Conventional optical communications uses basic “on-off” signaling.

[12] Also known as microwave photonics.

RF photonics is particularly important for military applications, because of the wide use of over-the-air communications and radar, and the need for equipment with low size, weight, and power consumption.

PICs may also have great value in other, as yet unforeseen, applications. Indeed, much of the value of a PIC foundry is this capacity to drive new applications, which reinforce and finance the original application. An established, commercial-grade foundry would especially help provide investors in small companies a lower-risk path around the "Valley of Death" from idea conception to prototyping and low-volume production.

InP- and silicon-based PICs. We apply the term PIC to all photonic integration—both InP and silicon based. OIDA supports both silicon photonics and InP-based PIC foundry services as R&D goals, and we suggest that the both be funded and evaluated as much as possible as a single, coherent program in a Photonics Institute.

InP refers to the wafer material, analogous to silicon-based wafers used for most electronics fabrication. Indium (In) and phosphorus (P) are group III and V elements in the periodic table, respectively, so InP is a III-V semiconductor (silicon is a group IV semiconductor, and forms a simpler crystal). During the chip fabrication, other materials are grown on top of the wafer, etched, redeposited, and so on, as in electronics fabrication.

Discrete InP devices are relatively mature, but large-scale integration onto one chip is not. The wafers are small (usually 3- or 4-inches diameter, or less) and brittle. The epitaxial materials deposited on top of the wafer can form crystalline layers from as many as four elements, making crystal growth mysterious and difficult. Circuit elements behave best when fabricated with a specific process, and do not function well when compromises in the process are used to integrate dissimilar devices. And while many labs can demonstrate a single, successful prototype, it remains a formidable challenge to design and fabricate PICs as a predictable, profit-making business.

We refer here to "silicon photonics" as PICs based on silicon wafers (as opposed to InP wafers) in its many forms. Silicon is a more mature material in many respects, and in particular, electronic circuits can be fabricated monolithically on the same chip. Silicon has been used for decades for detectors, such as in CCDs and CMOS image sensors. But it is difficult to design efficient sources (such as lasers) in silicon, without combining it with more exotic materials such as InP chips or wafers (known as heterogeneous integration).

PIC foundries. Establishing a PIC foundry in the U.S. is a way to maintain U.S. leadership in PIC technology. Many stakeholders in government and industry have called for a U.S. PIC foundry, including OIDA (see discussion in Section V). Until recently, however, there was a lack of cohesion or a strong champion among the many government agencies and companies that might be potential partners in such a foundry. The national security consequences may not have been as widely appreciated as they are today. And the financial barrier toward a sustainable foundry business has been difficult to understand and overcome.

Many photonic and electronic components can be considered critical to national security. Such components range from general-purpose microprocessors to custom electronics, and from mid-infrared semiconductor lasers and imagers to high-power pump lasers. Some of these technologies may be already considered secure as commercial products (such as microprocessors) or have been made secure through dedicated military R&D or procurement (such as mid-infrared devices).

Some products—including many existing or future PICs—are neither secure through the market nor through dedicated funding. As evidence, some domestic photonics designers have used foreign foundry services because there were no U.S. foundries willing or able to fabricate their designs.

A foundry for fabricating PICs should be a cornerstone of any effort to secure hardware for future communications networks, as well as to maintain U.S. competitiveness in communications technology and photonics more broadly. The barrier to entry to make large-scale, commercial PIC fabrication is substantial, and few players will be able to manufacture devices in the future. U.S. leadership is not assured.[13] This raises the stakes to maintain manufacturing leadership in this critical component while there is still time.

There is an effort underway in the U.S. to develop silicon photonics foundry services (see discussion in Section IV regarding OpSIS), but there is not yet a commercial-grade U.S. InP-based foundry.

[13] For example, Europe has been strong in PIC R&D for decades. Section IV discusses the current European PIC foundry programs.

IV. Notable PIC fabs and foundry projects

Canada. The National Research Council of Canada (NRC-Canada) established the Canadian Photonics Fabrication Center (CPFC) in 2002. It considers itself the only pure-play, specialized independent III-V foundry in North America. It aims to fill a pre-commercial gap between universities and organizations (such as NRC-Canada) on one side, and industry and investors on the other (in contrast to a full production-grade facility). The center is a foundry based on facilities formerly used by Nortel. The foundry contains equipment with an initial capital value over $150 million CAD (as much as $230 million USD at the 2002 exchange rate), but it was acquired from Nortel at a small fraction of that value. The center was supported by federal and provincial investment exceeding $80 CAD over 10 years since its founding. It offers its services for a fee.

The CPFC complements the Solid State Optoelectronics Consortium (SSOC), established by the NRC-Canada in 1988. The SSOC began with an initial investment of approximately $25 million CAD, and was created through a public-private partnership.

Europe. Europe has a program for photonic integration, EuroPIC, aimed in part at small enterprises that lack a suitable photonic fabrication facility. There are three officially-sanctioned foundry efforts using standardized processes for photonics fabrication. The foundries have been funded through European project funds, national funding, industry matching funds, and user fees. The program has also considered adding a standardized packaging facility to address packaging needs. The foundries are summarized below.

- ***JePPIX*** (Joint European Platform for InP-based Photonic Integration of Components and Circuits) was founded in 2007 under the ePIXnet program. JePPIX is working with Oclaro (UK) and the Heinrich Hertz Institute (Germany) to help move InP technology into its foundry operation and European industry. JePPIX is coordinated by the COBRA institute at the Technical University of Eindhoven. After the expiration of ePIXnet in 2009, JePPIX continued without external funding at a reduced level. The European project PARADIGM (Photonic Advanced Manufacturing Platform for Photonic Integrated Circuits) also supports PIC development, at about €20-30 million spread over about 25 companies.

- ***ePIXfab*** (previously called ePIXnet, the European Network in Photonic Integration of Components and Circuits) has offered foundry services for silicon photonics since 2004 though IMEC, and later through collaboration with CEA-LETI, two European institutes, the University of Gent. It has continued under different European programs, most recently PhotonFAB, aiming at reducing barriers to access (including price, available technology, design ease, and need for training). ePIXnet formally expired in 2009, but European project funding continues to cover operational costs for European customers; direct material costs are covered by the customers. Non-European customers pay the full costs. ePIXfab collaborates with Europractice, a European Commission cluster of (silicon electronics) ASIC services, and sufficiently mature ePIXfab technology is fabricated through the Europractice foundries. The European projects HELIOS and WADIMOS also direct funds to development of silicon photonics.

- ***TriPleX*** provides access to dielectric (glass) waveguide technology (called TriPlex) by Dutch company Lionix and the University of Twente. It is operating as an established foundry within the EuroPIC umbrella.

Europe is considered to have been in the lead in photonic integration in the 1990s, and EuroPIC backers claim that it remains in the lead in offering a standardized foundry process, what they call a "generic" foundry. They point to U.S.-based Infinera as having a strong technology, but Infinera is not currently available to others as JePPIX is. The EuroPIC backers point to the closely cooperating consortium and "substantial supporting funding" as reasons for its success so far.[14]

Detractors argue that JePPIX is merely an R&D prototyping foundry: the kind that allows devices to be selected from a batch to demonstrate new levels of performance, but which cannot be manufactured reliably from run to run, or cost-effectively.

More broadly, the European Commission has identified photonics as one of five official enabling technologies that it will support in coming programs. The Photonics21 organization represents stakeholders in addressing the Commission's programs. Photonics21 membership is open to non-Europeans and is free. Photonics21 claims that the European Commission currently funds over €500 million for photonic R&D (amounting to about $130 million per year at the current exchange rate), comprising more than 100 projects.

Japan. Japan does not currently have an explicit project for an open foundry for photonic integration, but the national government has funded programs dating to the 1980s aimed at PICs in its various forms and nomenclature. Over the years, Japan's emphasis on optical communications has taken a lower priority compared to other national interests, but it continues to have strong funding from the national government.

A notable new effort is managed by PETRA, the Photonics and Electronics convergence Technology Research Association. It was incorporated in 2009 to manage a research project for METI, the Ministry of Economy, Trade and Industry. METI has allocated about $400 million over 10 years for the project, about $40 million per year. PETRA manages the government-

---

[14] "Europe backs a foundry for photonic integrated circuits," Compound Semiconductor, 9 November 2010.

industry partnership, and will dissolve when the project ends, in 2021. Many projects are aimed at energy efficient networks, and include projects in photonic integration.

MEMS and Nanotechnology Exchange (MNX). The Corporation for National Research Initiatives (CNRI) manages an exchange, which is a broker between a network of fabrication facilities making MEMS devices, and its customers. The exchange was established at CNRI with support from DARPA, and became operational in 1999. It began entirely as a broker of foundry services provided by commercial and academic facilities in the U.S. Today, the MNX mostly uses its own facilities for prototyping and low- to medium-volume production. MNX contracts with commercial foundries to transition customers to high-volume production.

MOSIS. MOSIS was launched by DARPA in 1981 and became self-sufficient as a low-volume foundry for university and other researchers. MOSIS takes the foundry model further by consolidating chip designs from different customers and arranging them onto the same wafer. (The conventional foundry fabricates chips from different customers, but in batches of wafers, therefore still requiring a significant cost just to fabricate a few wafers.) By spreading the fabrication cost of a batch of wafers over many users, many researchers can receive custom chips at an affordable price.

While instructive, the MOSIS approach is not necessarily a good model for a photonics foundry concept, or at least for one based on InP. The manufacturing volumes and wafer sizes for electronic circuits are much greater than those required for integrated photonics. While many electronic circuits may fit on a photomask for a 6-inch or 8-inch silicon wafer, only one or a few may fit on a 3- or 4-inch InP wafer. Moreover, the separation of design and fabrication in silicon electronics is well-established, and the commercial silicon foundries are financially sound; MOSIS merely addresses the problem of obtaining small volumes. In contrast, the production-grade photonic foundry is still relatively new.

OpSIS. The Optoelectronics Systems Integration in Silicon (OpSIS) foundry was established in 2011 on a multi-project model much like MOSIS, but exclusively for silicon photonics. It has received initial funding from the Air Force and Intel. It offers device designs from Luxtera, and fabrication services from BAE Systems (in Virginia) and IME (in Singapore). It eventually expects to offer 3 runs per year, accommodating 30-40 users per run, and is completing its first run in fall 2012. It uses 8-inch diameter wafers with 90-nm minimum feature sizes. It is managed from the University of Delaware. Intel, IBM, HP, STM, and other companies are also financing silicon photonics development on their own.

V. OIDA's role as a trade association and foundry broker

OIDA was established in 1991 in response to the sentiment at that time that the U.S. was losing key optoelectronics technology to other countries, primarily Japan. During the 1980s, Japan supported national projects to gain leadership in optoelectronics, including efforts in OEICs. The first report from the National Research Council on photonics,[15] in 1988, highlighted the issue and called for a North American trade association to represent U.S. interests, much as the Optoelectronics Industry and Technology Development Association (OITDA) did in Japan. Since the 1990s, OIDA has managed roadmapping workshops, market studies, and acted as a technology broker, funded in part by the U.S. government agencies DARPA, NSF, and NIST.

OIDA continues to concentrate on optical communication components, particularly those that address pre-commercial development for next-generation equipment, such as PICs. Since 2011, OSA—the Optical Society—has managed OIDA as a division, following an asset-transfer. OSA is a technical society established in 1916, with over 17,000 individual members and over 200 corporate members. OSA's solid management assures financial and operational stability for OIDA, while OIDA maintains its unique industry role.

The following summarizes selected activities that OIDA has managed that are relevant to a foundry intermediary.

- In 2008, OIDA offered a proposal to manage a "Virtual Photonics Foundry" (ViPF) that included CNRI as a partner to provide administrative services while OIDA provided managerial and technical services. Among other things, that proposal emphasized the use of a virtual network of existing commercial photonics facilities to fabricate photonic devices for military system developers and university researchers. The initial focus was to be on lasers, modulators, and detectors for integration, and included silicon photonics. The proposal was presented to the DARPA Microsystems Technology Office. The ViPF was a modification on an earlier proposal for a multi-project foundry service, in 2006, called the Virtual Photonics Research Foundry System (VIPERS).

- OIDA managed the PTAP (Photonics Technology Access Program) from 2002 to 2010, with funding from DARPA and NSF. The program was an exchange that provided university researchers with pre-commercial devices from industry, speeding university innovation and improving connections between academia and industry. OIDA managed operational, legal, and financial aspects of the transactions. The program built on an earlier program with Japan, the U.S.-Japan

---

[15] *Photonics: Maintaining Competitiveness in the Information Era*, National Research Council (National Academy Press, 1988).

Joint Optoelectronics Project (JOP), which operated from 1995 to 2001, funded and overseen by NIST, NSF, and DARPA.

- OIDA has also led numerous roadmapping workshops and published roadmapping and market reports on various topics in the photonics industry, since its founding in 1991. The topics planned for workshops in 2013 include photonic integration, and metrics for photonics in data centers.

OIDA is well placed to continue in this role as an industry intermediary, if appropriate.