PSMC
Photonic Systems Manufacturing Consortium

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The Photonic System Manufacturing Consortium (PSMC)

Semi-Annual/Technical Progress Report

April 2015

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1. Project Milestones

June-October 2014: Start Up Milestones

During its first five months PSMC achieved all six of its scheduled milestones listed in Figure 1. During the first three months we established the Leadership Committee's responsibilities and the necessary infrastructure: accounting system, website, and contact data base. In August we held the first meeting of our eight-member Leadership Committee:

Robert C. Pfahl, Jr, iNEMI, Principle Investigator, PSMC

Lionel C. Kimerling, MIT, Principle Investigator, PSMC

Jim McElroy, iNEMI, Executive Director, PSMC

Bill Bottoms, Third Millennium Test Solutions, Packaging TWG Chair

Richard Otte, Promex Industries, Integration TWG Chair

John L. MacWilliams, Bishop Associates, Connectors & Substrates TWG Chair

Richard Grzybowski, MACOM, Integrated Photonic Systems Product Emulator Groups (PEGs) Chair

Randolph E. Kirchain, MIT, Emulator Modelling Co-Chair

Elsa A. Olivetti, MIT, Emulator Modelling Co-Chair

The Leadership Committee held seven meetings on a biweekly basis. The Committee's accomplishments are as follows:

- Defined Titles, Scope, Charters and Content for Website.
- Developed and distributed a survey to identify technology concerns and needs.
- Provided guidance for the process to create a quantified product emulator and acquired data from industry for emulator development.
- Identified firms and individuals to recruit.
- Planned our first workshop for November 6-7 to be held in Cambridge, MA, hosted by MIT.
- Recruited plenary, technical, manufacturing, and user speakers to present their viewpoints at the conference as background for roadmap development.
- Developed a PowerPoint template for PSMC to use at the first workshop and all subsequent presentations.
- Prepared a survey tool to use following the first workshop to gather feedback for evaluation
- Established a regular process to review progress against schedule and take necessary steps to address roadblocks.

November 2014-April 2015: Past Six Month Milestones

PSMC has achieved the first nine milestones listed in Figure 1. We are on schedule for all milestones scheduled for Stage 2 "Emulator Development." In fact we held our Spring Stakeholder Review and Roadmapping Meeting two months ahead of schedule. The eight-member Leadership Committee continues to meet on a biweekly basis.

During the last six months the Leadership Committee:

- Prepared, reviewed and submitted PSMC's 20 Year Sustainability Plan for the Integrated Photonics Integrated Manufacturing Institute (IP-IMI).
- Provided guidance for the process to create a quantified product emulator and acquired data from industry for emulator cost modelling.
- Recruited key firms and individuals to participate in the roadmapping process.
- Held two major stakeholder reviews and workshops in Cambridge, MA, hosted by MIT. The two-day meetings attracted 100 and 96 participants respectively.
- Recruited plenary, technical, manufacturing, and user speakers to present their viewpoints at the Spring Workshop as background for roadmap development.

The two Principle Investigators committed during the previous semi-annual report to establish an Executive Advisory Board (EAB). The purpose of establishing this board as discussed in the following two sections was to:

- Coalesce the integrated photonics community
- Gain executive support for establishing a jointly funded public-private partnership

The EAB has been established and its initial members are:

- Sanjay Patel, VP, IP Transport, Alcatel-Lucent
- Kal Shastri, Distinguished Engineer, Cisco
- Richard Otte, President, Promex Industries
- Terry Bowen, Fellow Corporate Technology, TE Connectivity
- Richard Grzybowski, Director of R&D, MACOM
- Bob Sankman , Intel Fellow, Intel
- Thomas Hausken, Senior Advisor, OIDA
- Katharine Schmidtke, Strategic Sourcing Manager, Facebook

An initial WebEx meeting and a face-to- face meeting at the Optical Fiber Conference (OFC) were held during this period. In addition most of the members participated in the PSMC Workshops.

Building the Integrated Photonics Community

We believe that coalescing the integrated photonics community to develop a shared vision of the future is of equal importance to the technology plan that we ultimately deliver. We plan to report on our progress on this objective in other semi-annual reports. To assist us in bringing together the diverse integrated photonics community, we scheduled a plenary session at our first workshop; Frank Gayle, Deputy Director of the Advanced Manufacturing National Program Office spoke on "National Initiatives in Advanced Manufacturing." We requested his presentation to insure that our participants understood our objective. Tom Hausken, Senior Advisor of the Optical Society of America spoke on "The State of the Industry." We requested his presentation as an important step in coalescing Integrated Photonic Systems stakeholders to focus on the technology needs for high volume, low-cost systems for commercial IT applications. Katharine Schmidtke, Facebook, spoke in the plenary session on "Expectations for the Microphotonics Supply Chain".

In the plenary session of our Spring workshop Mr. James Kisner, Senior Vice President, Jefferies LLC spoke on "Silicon Photonics: The Final Countdown." His presentation emphasized that consolidation and vertical integration of firms was necessary and already had begun in silicon photonics and provided several examples. He and Dr. Kal Shastri of Cisco stated that the silicon photonics hardware would be commoditized. All of these issues are necessary steps to build the integrated silicon photonics community from today's competitive market of small vendors.

Sustainability Plan

In January 2015 PSMC submitted its "Sustainability Plan for the Integrated Photonics Integrated Manufacturing Institute (IP-IMI) as required by our NIST AMTech award. This sixteen page document is attached as Appendix A to this document. This report defined our vision of the:

- Efficient 'stand up' and operation of the Integrated Photonics Institute for Manufacturing Innovation (IP-IMI) funded by a five-year grant from the U.S. Government (DoD-AFRL) and matching contributions from industry, states, universities and research institutes.

- Support of Advanced Manufacturing Partnership (AMP) 2.0 goals by establishment of a new public-private manufacturing research and development infrastructure to support the innovation pipeline, that complements Manufacturing Innovation Institutes at earlier and later technology maturation stages, through the creation of manufacturing centers of excellence (MCEs) and manufacturing technology testbeds (MTTs) to provide a framework that supports manufacturing innovation at different stages of maturity and allows small and medium-sized enterprises to benefit from these investments.

The PSMC Principle Investigators have communicated with the three contenders for the IP-IMI DoD Award. The PSMC Principle Investigators committed to play a major role in the Administration's Institutes for Manufacturing Innovation and subsequent entities under AMP 2.0. PSMC will cooperate and support all AMP entities in the development of a strong US integrated photonics manufacturing base. In Phase 2 we will offer our experience in establishing an organization dedicated to manufacturing innovation; we will provide data and analyses based on our industry-wide strategic Technical Working

Groups; and we will actively compete to partner or lead AMP 2.0 MCEs and MTTs. The PSMC Technology Roadmap and supply chain coordination are critical elements for the IP-IMI core missions of manufacturing technology implementation and job creation. Definition of technology roadblocks and potential solutions will help structure the IP-IMI project requirements; and technology timelines and cost analyses will help forecast the pace and content of the Education and Work Force Development in support of job creation. The PSMC technology targets, production and market data, and gap analyses will give continuous guidance to the IP-IMI strategic objectives. For further details see Appendix A.

2. Technical Progress

Introduction

The Technical Progress section of this report presents PSMC's technical progress in terms of accomplishments of the major functional groups of PSMC:

- PSMC Technology Working Groups
- PSMC Product Emulator Groups and Cost Modelling
- Workshops and Stakeholder Reviews

PSMC Technology Working Groups (TWGs)

During Phase 1 we have integrated the roadmapping efforts of iNEMI and the MIT Photonics Center to address both the systems needs and the manufacturing needs of integrated photonics The five Photonic Systems Manufacturing Consortium (PSMC) Technology Working Groups (TWGs) have been established and are developing the roadmap. They are similar to existing iNEMI and Microphotonics Center TWGs, but they differ in scope. PSMC has been added to all TWG titles to make this distinction in scope. The PSMC TWGs include many members from existing iNEMI-MIT groups, but their charters are More detailed and cover a longer period of time.

Since August the TWG leaders have been recruiting additional members and working with their TWGs. The titles of several of the TWGs have changed from the previous report to reflect more accurately their focus and the needs identified by the participants in the TWGs. The four PSMC Technology Working Groups (TWGs) and their leaders are:

- PSMC Monolithic Integration TWG: Lionel Kimerling, MIT
    - Chips: silicon photonics, InP
    - Tradeoffs for cost, bandwidth density, power efficiency, and functional latency
- PSMC Packaging TWG: Bill Bottoms, Third Millennium Test Solutions:
    - Cost, materials, heat, footprint, port count, bandwidth, integration, functionality
- PSMC Connector & Substrate TWG: John MacWilliams, Bishop Associates
    - Connectors includes: all separable interfaces within the system scope
- PSMC Assembly and Test TWG: Dick Otte, Promex Industries
    - Design for Manufacturing
    - Assembly and Test
    - Supply Chain Trade Offs

PSMC Monolithic Integration TWG

This PSMC TWG addresses chip-level integration on the Si and InP platforms, design for manufacturing, and tradeoffs for cost, bandwidth density, power efficiency, and functional latency. The long term view will include identifying functional optical components such as optical switching. The chair of this TWG is Lionel Kimerling: lckim@MIT.EDU

PSMC Packaging of Electronic Photonic Systems TWG

This PSMC TWG focuses on the Packaging Technology and cost objectives needed to meet market requirements for low cost high volume photonic components and sub-systems for integration into the global network. Cost and performance objectives for system level, board level, package level and where it is practical chip level integration of photonics are the initial step. Members will develop the needs for cost, materials, thermal, footprint, port count, and bandwidth. The chair of this PSMC TWG is: Bill Bottoms: bill_bottoms@3mts.com

PSMC Circuit boards, Backplanes and Connectors TWG

This PSMC TWG covers the intra-system connector and circuit board technology that will be needed for integrated photonic systems. Connectors include all separable interfaces within the system scope. Substrates include all circuit board and backplane components. The chair of this PSMC TWG is John MacWilliams: jmacwilliams@bishopinc.com

PSMC Assembly and Test TWG

This PSMC TWG addresses the development of manufacturing processes, materials and equipment to produce integrated photonic systems with ever decreasing cost and increasing volume. The PSMC TWG covers the needs for cost, integration, assembly, test, functionality, and tools. The chair of this PSMC TWG is Dick Otte: otte@promex-ind.com

PSMC Product Emulator Groups (PEGs) and Cost Modelling

Introduction

Two Product Emulators have been defined utilizing input from the MIT Microphotonics Open Architecture System Optimization (OASO), the Leadership Committee, and the EAB. The emulators define the application needs and system performance targets, based upon an understanding of the consequences of parallelism, virtualization, and software defined networks. Each PEG report will be divided into near term (10 years) and long term (30 years) sections. The near term will look more like a traditional iNEMI Product Emulator Group (PEG) structure with well-defined attributes evolving over specific time intervals (application needs). The long term will be more speculative with less specificity on attributes (system targets). The chair of these activities is Rich Grzybowski: grzybowski@macom.com

PSMC Data Center PEG

Data centers are a critical node of network architecture that is driving higher bandwidth from the core network to ever shorter distances. As single channel data rates exceed 10Gb/s, copper transmission lines introduce excessive loss, necessitating a transition to photonic interconnects. The pervasive use of photonic interconnects at short distances means that photonic transport becomes a higher fraction of system data movement, requiring system design, architecture, software and hardware to be reconsidered. The Grand Challenges for information hardware are i) photonic integration for bandwidth density and ii) high volume manufacturing to meet the system demand.

Requirements for these applications focus on:

- High bandwidth (single mode/Wave Division Multiplex)
- Low latency
- Low power consumption
- Continuous duty at full speed
- Thermal stability for photonic components
- Heterogeneous integration
- Variable frequency for power reduction
- Redundancy or other means to insure no failures
- Optical to Electronic and Electronic to Optical (O to E and E to O) located in PWB mounted SiP (System in Package)
- Low cost with path to continuous cost improvement

PSMC Internet of Things (IoT) PEG

Chip-scale integrated photonic sensing systems are emerging as diagnostic sensors for medical, environmental and security applications, structural health monitoring, military sensing, and wireless sensor networks – the entire Internet of Things (IoT) space. The field is advancing rapidly, with fabrication technologies that leverage standard microfabrication infrastructure and enable the co-integration of sensors, photonics, electronics, and microfluidic sample preparation systems. Requirements for these applications focus on:

- Very Low cost with path for continuous cost reduction
- Store and forward capability for sensor data
- Very Low power consumption
- Intermittent duty, standby/sleep mode
- Standard photonic parts for all applications
- Heterogeneous integration with standard and customized parts integrated into a single SiP

PSMC Emulator Cost Model Development

PSMC is developing technology-based models for the cost, energy, and environmental implications of various component and architecture alternatives for the two emulators under consideration. These process-based cost models (PBCM) will enable the modeling team to characterize how technologies will perform as photonics are integrated further into electronic systems. These tools will also serve to answer economic and energy use questions surrounding system architecture - enabling reliability and redundancy. Randolph Kirchain and Elsa Olivetti have started developing the PSMC cost emulator. They have had several discussions between themselves and with other members of the Leadership Committee on process, content and data acquisition. This effort will develop a process-based cost model to guide engineering decisions to select options in design and manufacturing. The models will be constructed using actual cost data from participating companies. The data will be accurate for application and anonymized to protect sensitive source value points.

Workshops

During the past six months PSMC held two stakeholder reviews and roadmap workshops. The following summarizes the results of the two workshops:

Fall 2014 Stakeholders Review and Roadmap Workshop

Appendix A provides the agenda and speakers for the Fall 2014 Workshop that was held on November 6-7. One Hundred people participated in the program. Following are three areas of key learning points from the meeting:

- Packaging TWG
  - Major Challenges
    - Power
    - Latency
    - Thermal management
    - Bandwidth density
    - Cost
  - We must move things closer together
- Hybrid Integration TWG (Renamed the Assembly and Test TWG)
    - Implement Panel Processing
    - Implement a Flexible Architecture to serve changing, evolving needs
    - Accurate Assembly Equipment
    - US Integrated Photonic Systems Foundry
    - Optical Test Functions
    - Suggested list of classic functions needed in an integrated photonic system
- Monolithic Integration TWG
    - Light Source
    - Process Tools (193nm litho, 65nm CMOS)
    - Universal E-P CAD for photonic integration
    - E-P process integration
    - Power distribution
    - Athermal devices
    - Wafer-level inspection and test
    - Scalable (single mode, E-P) packaging solution

Spring 2015 Stakeholders Review and Roadmap Workshop

Appendix C provides the agenda and speakers for the Spring 2015 Workshop that was held on April 23-24. Ninety-six people participated in the program. This stakeholder meeting demonstrated that consensus was developing on a number of key requirements for establishing a low-cost high-volume silicon photonics manufacturing supply-chain. In particular the Assembly and Test TWG reached consensus on a number of issues.

Following is a summary of Key learning points from the meeting:

- Importance of high volume, low cost
  - Need for consolidation in supply chain
  - Reducing Cycle Time is central to cost reduction
    - Improved materials (epoxies) are needed
  - Equipment for low volume processing from electronic packaging industry is available
    - Unique equipment will be needed for high volume
- Use Two emulators: Data Center & IoT
- Single Mode fiber is the focus & is not a packaging Challenge
  - Use Self Alignment similar to Silicon Optical Bench-No active alignment
- InP mounted on silicon photonics substrate will be the initial approach to Monolithic Integration
- Importance of Technology Training
  - DfX (Manufacturing & Testing) training for designers
  - Training for manufacturing engineers on impact of going from multimode to single mode on accuracy requirements
- Leading OEMs are now working with test and equipment vendors. This activity may stimulate the development of necessary infrastructure and tools.

In addition the stakeholders identified a number of issues and questions where more information is needed to reach a consensus opinion. Those issues were then assigned to members of the Leadership Committee for resolution:

- Monolithic Integration
  - Will a foundry model (Global Foundries, TMSC, Infinera) or OEM (Intel, STMicro. Freescale) Prevail?
  - How will design IP be addressed? Synopsys?
  - What will be the technology for InP Mounting?
    - Bonding
    - Monolithic Deposition oxide to oxide
    - Solder Bumps
- What is the definition of a Standard Platform?
- Two emulators: Data Center & IoT
  - What is the market size for each and how will they grow (Sources of Info: Yole, IHS, Prismark, Light Counting,
  - What application will need a million devices?
- How do we continue the supply-chain dialogue established in the Assembly & Test TWG at Workshop?

Building the Integrated Photonics Community

We believe that coalescing the integrated photonics community to develop a shared vision of the future is of equal importance to the technology plan that PSMC ultimately delivers. The Principle Investigators believe that the success of PSMC and the IP-IMI depend on the degree to which the microphotonics

stakeholders can develop a shared vision and work together to develop the tools, materials, and processes in a public-private partnership which results in manufacturing silicon photonics in high-volume and at low-cost. Achieving this shared vision is a greater challenge than producing a roadmap and a technical plan for implementation.

We were greatly encouraged at our Spring Workshop to see that a core group of stakeholders now:

- Recognize the need for consolidation in the industry
- Agree on certain technology choices
- Agree on the need for Technical Training in the new technology particularly for the designers

In particular this workshop highlighted three keys issues related to reducing cost and implementing the IP IMI.

- While many current optical communication products are built today utilizing multi-mode technology that requires assembly tolerances of +/- 5 microns, the future for optical communications is single mode due to the greater bandwidth, reach and data density single mode offers. Hence, assembly technology development must focus on methods suitable for single mode photonic devices.
- The assembly technologies used in electronics are the starting point for photonic assembly. These technologies are solder and epoxy based methods that typically utilize bond lines that are 25 to 75 microns thick on substrate pads that have X and Y tolerances of +/- 25 microns. The resulting uncertainty in X, Y and Z locations are far greater than the < 1 micron tolerance required for single mode optical assembly. Hence high accuracy, thinner bond line processes, including attachment materials, placement tools and control of part dimensions, all need to be developed for low cost photonics.
- In recent years, approximately 250 million transceivers are sold each year. That number contrasts with the approximately 250 billion integrated circuits sold each year. That 1000:1 ratio highlights the size of the infrastructure and industrial activity supporting the two industries. Photonics can adopt a lot from the integrated circuit industry, but eventually an infrastructure specifically adopted for photonics needs to be developed. A major effort during the next semi-annual period will continue to be on developing and expanding this shared vision for PSMC and the IP-IMI.

Supporting the IP-IMI

During the current six month period the PSMC Principle Investigators have communicated with the three contenders for the IP-IMI DoD Award and committed to play a major role in the continuing role out of the Administration's Institutes for Manufacturing Innovation and subsequent entities under AMP 2.0. PSMC will cooperate and support all AMP entities in the development of a strong US integrated photonics manufacturing base. In Phase 2 we will offer our experience in establishing an organization dedicated to manufacturing innovation; we will provide data and analyses based on our industry-wide strategic Technical Working Groups; and we will actively compete to partner or lead AMP 2.0 MCEs and MTTs. The PSMC Technology Roadmap and supply chain coordination are critical elements of the IP-IMI core missions of manufacturing technology implementation and job creation. Definition of technology

roadblocks and potential solutions will help structure the IP-IMI project requirements; and technology timelines and cost analyses will help forecast the pace and content of the Education and Work Force Development in support of job creation. The PSMC technology targets, production and market data, and gap analyses will give continuous guidance to the IP-IMI strategic objectives.

3. Summary of Project Changes

In September the Leadership Committee identified that PSMC needed to hold a brainstorming session with leading industry thinkers to get their views on long term needs to implement Photonic Integrated Systems and develop the required technical solutions. The two-hour meeting of six leaders was held in Santa Clara, CA, and was led by Dick Otte and Bill Bottoms of the Steering Committee. This meeting that had not been anticipated has been valuable in establishing a strawman vision that led to the definition of the two product emulators. During the current period we modified the definition of the Assembly and Test TWG to attract key stakeholders to participate in defining key manufacturing roadblocks.

4. Problems and Opportunities

Integrated photonics manufacturing is at a critical launch point for high volume applications and production. The firms in this industry are extremely busy in building customer bases and in evaluating technological directions. The PSMC will have to present necessary value in every activity to attract a constituency of technology leaders and to meet its Phase 1 goals of i) building mutual trust and cooperation among the supply chain stakeholders to establish a common vision for high volume photonic system manufacturing system and for the technology gaps that need to be closed, and ii) development of a cohesive roadmap for integrated photonic system design. As previously stated in Section 3 of this report, we have used our first workshop to help coalesce the integrated photonics community. We selected our plenary speakers with that opportunity in mind: Frank Gayle, Deputy Director of the Advanced Manufacturing National Program Office spoke on “National Initiatives in Advanced Manufacturing,” to insure that our participants understood our objective. Tom Hausken, Senior Advisor of the Optical Society of America spoke on “The State of the Industry,” as an important step in coalescing Integrated Photonic Systems stakeholders to focus on the technology needs for high volume, low-cost systems for commercial IT applications.

We used our second workshop to further contribute to ownership of the project by stakeholder. Key note presentations by James Kisner of Jefferies and Kal Shastri of Cisco predicted that silicon photonics hardware would be commoditized. Acceptance of this prediction is a necessary step to build the integrated silicon photonics community from today’s competitive market of small vendors.

5. Organizational Issues

Because the entire Leadership Committee and many of the TWG members have worked together over many years, we have not encountered any organizational issues. We have integrated a number of new participants and firms into our Roadmapping and Technology Planning through the Fall and Spring Stakeholder Meetings. We are encouraged that additional firms and IP-IMI candidates now recognize the need for a roadmap which drives technology consolidation to achieve high-volume, low cost integrated photonics manufacturing in the United States.