The Massachusetts LEAP network: Building a template for a hands-on advanced manufacturing hub in integrated photonics

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ABSTRACT

MassTech Collaborative has helped to make the Commonwealth of Massachusetts a beacon for advanced manufacturing. In partnership with the AIM Photonics manufacturing institute, MassTech has launched five Laboratories for Education and Application Prototypes (LEAPs) within academic institutions and/or companies spread across Massachusetts, to develop a skilled workforce in integrated photonics. Hands-on and in-person workshops, bootcamps and laboratory courses are offered at these LEAPs to learners from academia, industry, and the government. The MA LEAP network stands as an excellent self-sustaining model for hands-on STEM education and workforce training for the rest of the country.

Keywords: integrated photonics, photonic packaging, co-packaged optics, semiconductor workforce training, virtual reality tool simulation, blended learning bootcamp, rapid upskilling, self-sustaining education

1. INTRODUCTION

The United States is facing a severe shortage of optics technicians, amidst a global shortfall of effective workforce training programs.[1] Optics technicians in manufacturing, testing, and evaluation play vital roles for many companies making optical elements or electro-optical devices. Yet an increasing scarcity of technicians with two-year degrees in optics has forced many companies to train new hires on the job or assign tasks to engineers. To this end, the Massachusetts Institute of Technology (MIT), Bridgewater State University (BSU), Worcester Polytechnic Institute (WPI), Stonehill College, and Western New England University (WNE) have partnered as part of the MassTech Collaborative to establish a Laboratory for Education and Application Prototype (LEAP) facility on each campus. Each LEAP facility is dedicated to specializing in a different supply chain node within integrated photonics and optoelectronics manufacturing sectors as shown in Figure 1. Likewise, LEAPs are strategically located near potential technician feeder institutions including Berkshire Community College (CC), Springfield Technical CC, Mount Wachusett CC, Mass Bay CC, Quinsigamond CC, Bristol CC, Massasoit CC, and Cape Cod CC. The LEAP paradigm creates a time-share environment for training on advanced manufacturing tools relevant to local industry specialization areas. Through this intrastate lab network, the opportunistic skilling needs of a local, evolving workforce can be met. As alluded to above, these skilling needs are driven by local small-to-medium scale enterprise (SME) firms which have a competitive stake in fast-growing global market applications for photonics in datacom, wireless, sensing, and imaging sectors. In other words, these community colleges, universities, and SME firms may gain limited-time training access to costly, complex tools.

In order to optimize learning during limited-duration, on-site training, the Massachusetts LEAP network has leveraged a novel hybrid learning model through intensive, yet succinct, "bootcamp" training sessions. Within this methodology, learning ensues using a scaffolded approach where hands-on tool training, experiments, and

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lectures are complemented with targeted online training before and after the in-person aspects of the program. To facilitate this scaffolded technique, the online content deployed relies heavily on targeted massive online open courses (MOOCs) and virtual reality (VR) simulations completed by learners outside their ongoing curricular or professional commitment hours.[2] As an example of the hybrid learning model in action, the three day intensive integrated photonics bootcamp developed between the LEAPs at MIT and BSU will be described in Section 2, with a focus on year to year improvements and lessons learned.

Workforce development and education, while critical, is only half of the mission the LEAP network looks to accomplish. The second aspect is the manufacture of novel prototypes and initial proofs of concept for high volume manufacturing (HVM) applications. Included in this researcher constituency are undergraduate, graduate, or trade students or research and development arms of SMEs seeking to use this time-share environment to build, package, and test their photonic devices and accelerate industry adoption. By incorporating novel integrated photonics research alongside workforce training, iterative improvement of workforce education, device performance, and toolset selection is achieved. To illustrate this concept, an example technology being prototyped at MIT's LEAP facility - a vertical optical interconnect to enable surface mount optical devices - will be presented in Section 3 with a focus on how the LEAP facility drove device design, improved toolset quality, and improved workforce training.

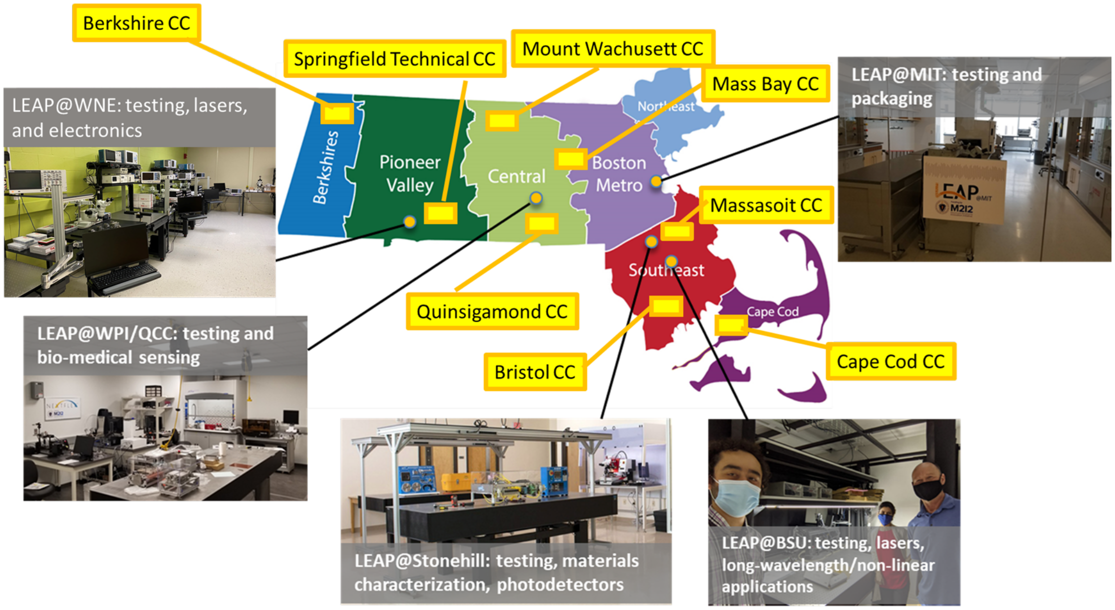
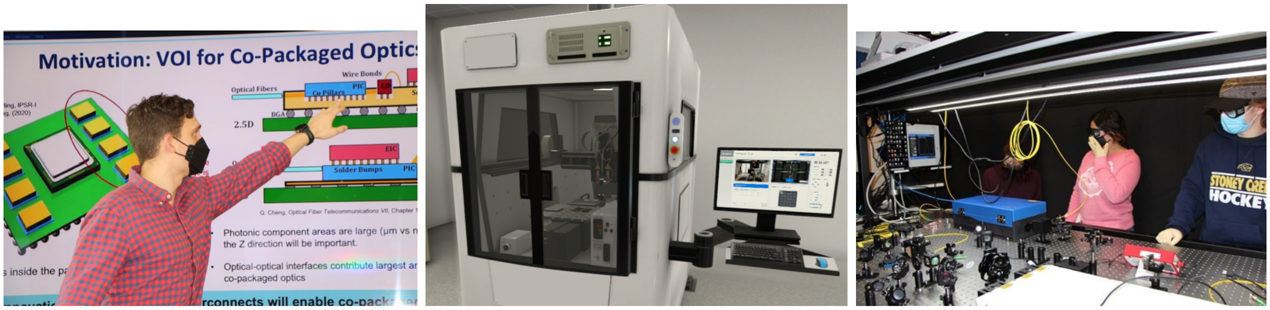


Figure 1. LEAP network in Massachusetts. The orange dots represent the different LEAP facilities with the image callouts highlighting the lab specialty. The yellow squares illustrate the close proximity to community colleges, serving as a source for future optical technicians.

2. EDUCATION: THE HYBRID BOOTCAMP APPROACH

As alluded to in Section 1, the hybrid integrated photonics bootcamp curriculum incorporates a "three-legged stool" training methodology. As shown in Figure 2, this methodology utilizes (i) in-person lecture, (ii) scaffolded procedural and application learning through MOOCs, incorporating short video lectures followed by VR simulations on laboratory tools and photonic devices with assessment questions, and (iii) targeted hands-on experiments to facilitate in-person tool training. One of the key advantages of this approach not yet depicted is in its modularity. First, the modularity of training modes (i)-(iii) allows for extensive versatility for different audiences, for example allowing for the adaptation of the bootcamp curriculum from high school students up to leaders and experts in photonics and related fields simply by adjusting (i), (ii), or (iii) (or any combination of the three) to focus on particular learning outcomes. In addition to audience versatility, the modularity also allows



(a) (b) (c)

Figure 2. Components of the hybrid bootcamp model for education. The figures (a), (b), and (c) refer, respectively, to the in-person lectures, MOOCs and VR tool simulations, and the targeted hands-on experiments.

for the swapping of subject material within (i)-(iii) enable reinforcement of industry oriented critical concepts to integrated photonics. Finally, the modularity creates the possibility for in-person lectures to be replaced or complemented by guest lecturers who can provide insight from significant integrated photonics manufacturers in industry or SMEs in the Massachusetts area.

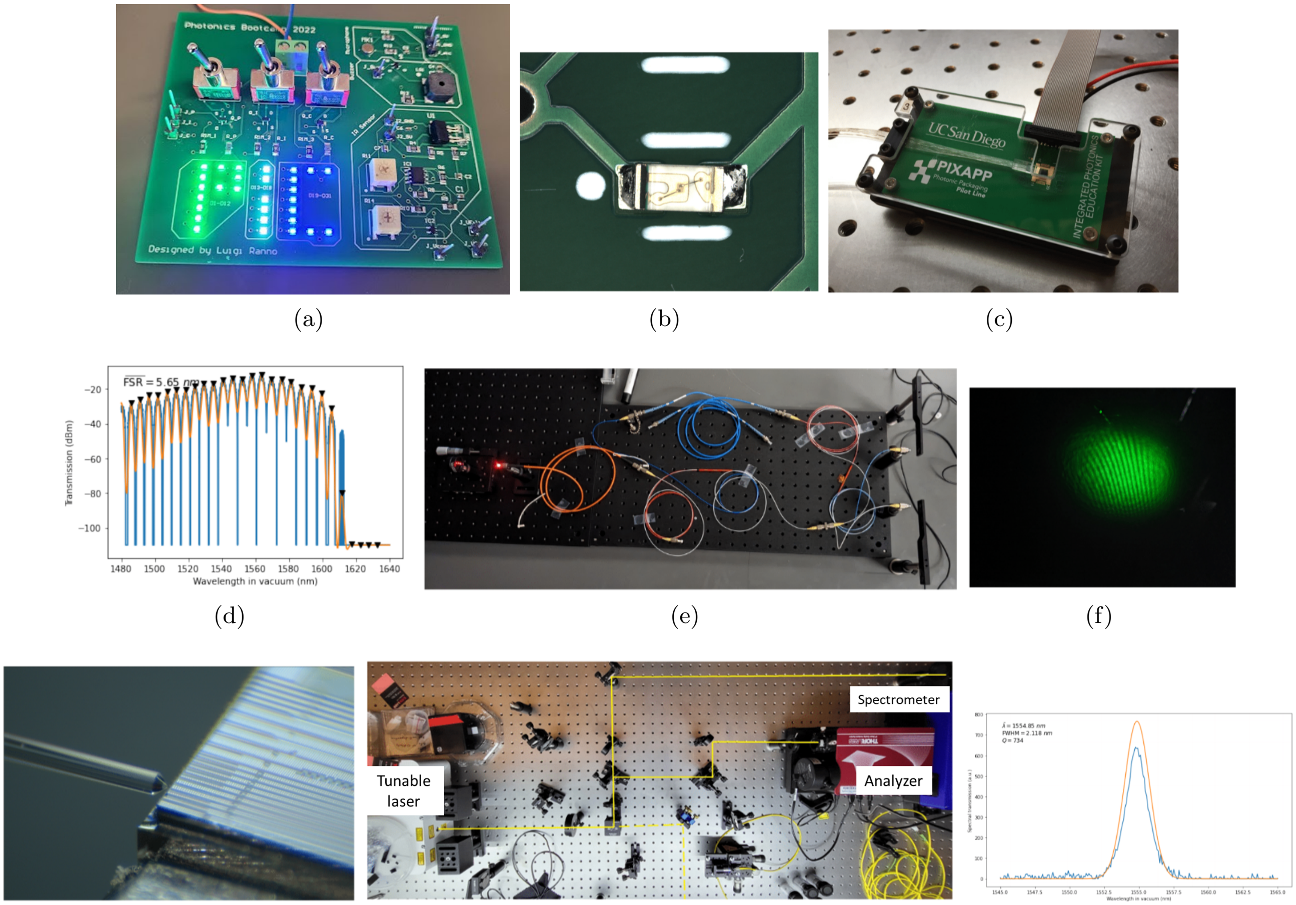
2.1 Hybrid bootcamp model example: Integrated photonics bootcamp 2023

An example of how the hybrid model's modularity can be optimized for effective training can be visualized by the use of the Mach Zehnder Interferometer or Mach Zehnder Modulator (MZI or MZM, respectively) device in the integrated photonics bootcamp 2023. On the first day, an in-person lecture consisted of a description of photonic device fundamentals with a focus on the theory of MZI/MZM devices. Later that same day, the lecture was reinforced by allotting time for VR simulations focused on photonics fundamentals, among which was a MZI and MZM simulation with targeted assessment questions. Immediately following the VR simulations was then a workshop from Synopsis on how to design, simulate, and validate an integrated MZI/MZM device. Finally, understanding of the MZI/MZM system was reinforced by implementing hands-on experiments at BSU on Day 3 involving integrated MZIs, free space MZIs, and fibered MZIs. Similarly, learning experiences were developed using the three-legged stool hybrid approach for 1) fiber-to-chip coupling using edge couplers , 2) electronic-photonic packaging and assembly using high speed pick and place tools, and 3) non-mechanical beam steering using optical phased arrays (OPAs). A selection of images from experiments related to the MZI/MZM, fiber-to-chip coupling, optoelectronic packaging and assembly, and use of OPAs can be found in Figure 3.

The design of the 2023 integrated photonics bootcamp also demonstrates a point noted in Section 2 - the curriculum can be tailored to the audience due to modularity in the hybrid model. In terms of participant background, the 2023 integrated photonics bootcamp had 10 attendees which had predominately industry oriented pedigrees. This is in stark contrast to the 2022 integrated photonics bootcamp which had 22 attendees nearly entirely composed of undergraduate or graudate students or postdoctoral research associates. For the 2022 integrated photonics bootcamp, content was oriented more towards fundamentals and giving participates a well rounded background in integrated photonics packaging, assembly, and testing; therefore, depth was traded off for breadth in several areas. On the other hand, the 2023 integrated photonics bootcamp was significantly more oriented towards immediate skills required by technicians in industry, for example opting for the in depth workshop on electronic-photonic design automation (EPDA) tools for foundry tapeout as well as looking at the standard integrated photonics building blocks (i.e. the MZI, fiber-to-chip coupling, etc.) thoroughly with multiple experiments across both LEAP facilities. This style of targeted instruction is critical to ensure the workforce that is being trained is not being taught efficiently, but they are ready to join and contribute immediately to integrated photonics markets.

2.2 Use of VR die bonder tool simulation

Of the three hybrid model elements, the use of VR tool simulations will be elaborated on further because 1) the 2022 and 2023 integrated photonics bootcamp deployed a novel VR die bonder simulation and 2) new survey data



(a) (b) (c)

(d) (e) (f)

(g) (h) (i)

Figure 3. A sample of the experiments conducted at the 2022 and 2023 integrated photonics bootcamp between the LEAP facilities at MIT and BSU. In (a) an image of a fully assembled PCB, which students learned how to program in Arduino, is shown, while in (b) a microscope image of an LED folling solder paste reflow is shown. In (c) the educational photonic package used to test integrated MZI performance is shown, with an example transmission spectrum shown in (d). In (e) a top view of an optical fiber MZI experiment is shown, with an example interference pattern measured at BSU shown in (f). The microscope image shown in (g) illustrates the tapered fiber edge coupling experiment on a MapleLeaf system using chips fabricated by AIM Photonics. In (h) a top view of a tunable laser characterization experiment is shown with labels for the source, analyzer, and spectrometer. Lastly, a fitted transmission spectrum (transmission vs wavelength) is shown in (i) for the tunable laser characterization setup where the blue curve is the measured data and the orange curve is the fitted data.

demonstrates how instructor planning can be improved before in-person experiments using these simulations. Generally spekaing, educational VR has been rapidly expanding in recent years due to technology advancements and the capacity to improve learning outcomes. In particular, digital simulations provide a safe environment to make mistakes, recognize equipment limits and failure states, and can be tailored to the student to improve learning experiences. Moreover, studies have shown that retention, concentration, and enthusiasm have been positively linked to active learning models particularly for VR training simulations.[3–5] To address the need for skilled technicians in advanced packaging and assembly techniques, a desktop VR simulation was developed to train students in operating a high speed, high accuracy pick and place die bonder, which was deployed during the 2022 and 2023 integrated photonics bootcamp. The VR simulation allows the learner to pick and place die onto substrates multiple times in a safe virtual environment at minimal cost while allowing them to gain familiarity with tools and equipment used in the process. Images of the real die bonder equipment and user interface alongside the VR simulation are shown in Figure 4. Typical training on this tool, based on users in MIT's LEAP facility, requires several days of in-person tool time with oversight, equating to roughly 9-12 hours of time. This time needs to be logged even before advanced features such as flip chip bonding, epoxy or solder dispense, or use of the eutectic stage can be taught, and before the learner can undergo a "driver's test" to fully operate the machinery independently. Through the use of the VR die bonder simulation in the hybrid model, attendees were able to complete this typical 9-12 hour training regiment with only 2 hours of in-person training (note that learners were still not fully qualified as the bootcamp did not include the driver's test for independent operation).

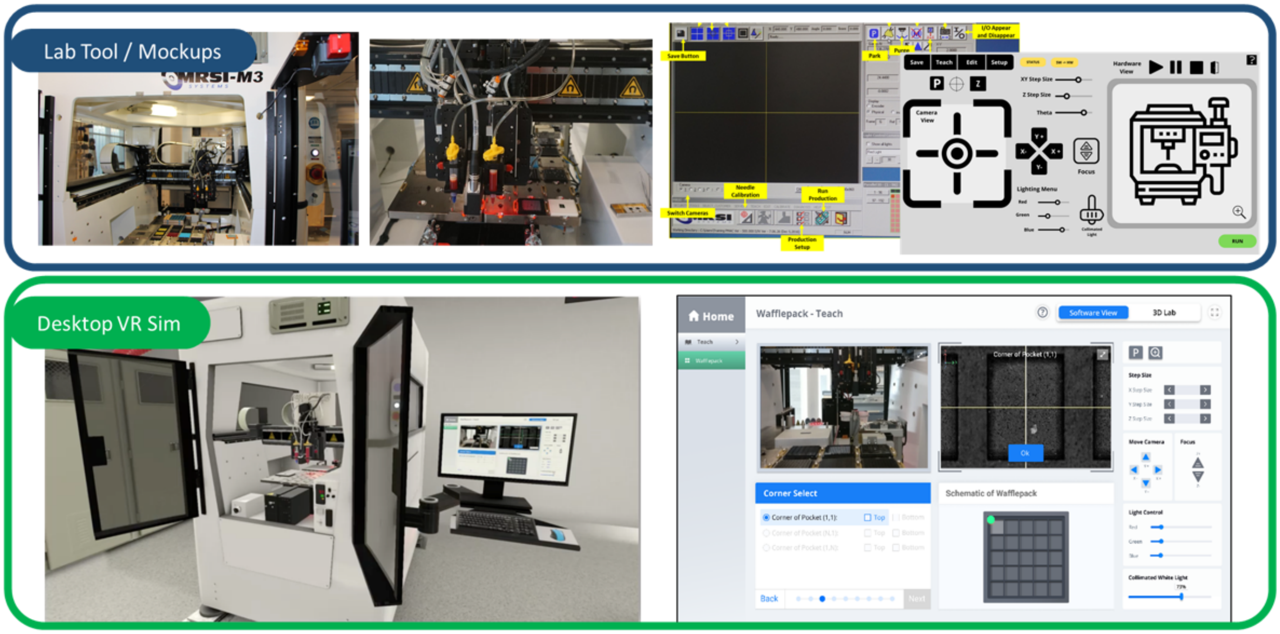
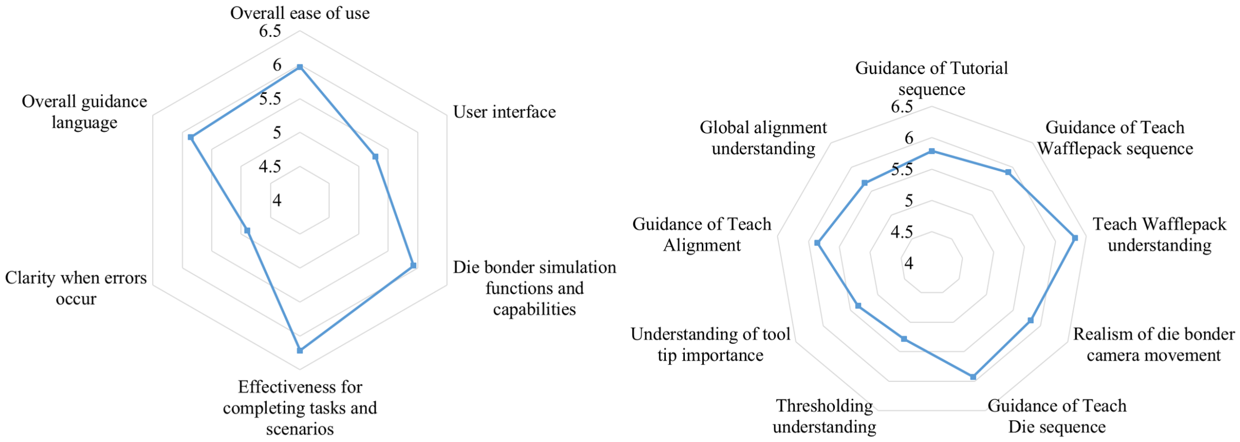


Figure 4. An example of a desktop VR simulation for workforce training on advanced manufacturing tools. From upper left, real images of the MRSI-M3 die bonder with the actual user interface (third from left) are shown. The fourth image from left in the top row shows the initial VR mockup and rough design schematic which served as a blueprint for building the simulation. From lower left, the final 3D VR simulation of the die bonder is shown, with the final VR user interface shown on the lower right.

In addition to efficiency, quantitative feedback from learners who used the VR tool simulations demonstrates the opportunity to use VR tool simulations to help instructors tailor curriculum to student needs. In Figure 5, survey results from participants on the general satisfaction of the die bonder simulation (Figure 5(a)) and on satisfaction of particular critical learning outcomes (Figure 5(b)) are shown. The 30 total participants from the 2022 and 2023 integrated photonics bootcamp (note that 2 participants from the 2022 integrated photonics bootcamp did not answer the survey) were asked to rate their satisfaction in these areas on a scale of 0 to 7 ; then, scores for each area were averaged to create the plots shown in this report. Data clearly indicates that participants struggled the most with understanding the importance of selecting the correct tool tip, how the concept of thresholding works, and the difference in camera movement from the simulation versus the actual tool. This type of information is crucial when planning future bootcamp experiences, allowing for instructors to leave more time for challenging aspects during in-person training versus concepts clearly understood using the simulation. In essence, the use of VR simulations for lab equipment provides a teaching tool which can simultaneously improve efficiency as well as teaching effectiveness.

3. PROTOTYPING EXAMPLE: VERTICAL OPTICAL INTERCONNECTS

In addition to the education aspects highlighted above, developing prototypes for novel photonic solutions is a crucial aspect of the LEAP network methodology. As an example, the vertical optical interconnect (VOI)



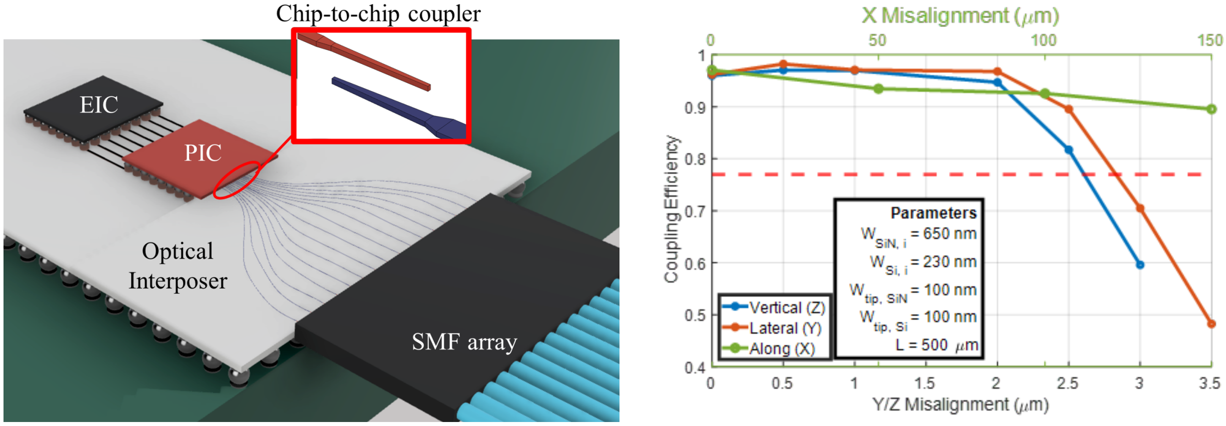
(a) (b)

Figure 5. Survey results completed by bootcamp participants following the 2023 and 2022 integrated photonics bootcamp assessing their satisfaction and the effectiveness of a desktop VR simulation for learning to operate high speed, pick and place tools. In (a), a plot shows the average score on a scale of 0 to 7 given by the 20 participants in the 2022 integrated photonics bootcamp and 10 participants in the 2023 integrated photonics bootcamp to general characteristics of the die bonder simulation. In (b), the average scores on a scale of 0 to 7 are shown for specific topics covered throughout the duration of the simulation.

currently under development at MIT's LEAP facility can be utilized.[6,7] The coupler design enables surface mount assembly of PICs by using an evanescent coupler with low insertion loss, high translational and rotational alignment tolerance, CMOS process flow compatibility, and fine lateral pitch. A diagram of how this connector can be used in a co-packaged optics module is shown in Figure 6(a). The diagram shows a SiO$_2$ optical interposer providing optical fanout from the PIC to an array of single mode fibers. The importance of optical fanout is that it allows for a higher density of optical I/O along the available shoreline of the PIC because the the waveguides on the PIC are limited only by the mode size of a single mode waveguide while the waveguides at the edge of the interposer are limited by the fiber pitch whose standard value is either 127 or 250 μm. Additionally, the use of an optical interposer allows for high speed pick and place tools to be used for passive assembly of PICs instead of relying on flyover fiber attachment to each PIC individually.[8] Through surface mount passive assembly, the need for active alignment of optical components can be significantly reduced or eliminated - a factor which accounts for over 80% of the total expense for photonic packages.[9]

In the context of this report, it is important to emphasize the potential for cyclical improvement between device design, tool upgrade and selection, and quality of education which can be achieved by including prototyping in the LEAP's mission. In order to design the VOI for integration with LEAP toolsets, the 1 dB lateral alignment tolerance of the VOI needed to be roughly 3 μm. This is because the MIT LEAP houses an MRSI-M3 die bonder - a standard pick and place tool found in microelectronic packaging process flows - which has a 3 σ alignment tolerance of $\pm$ 3 μm and a 1 σ tolerance of $\pm$ 1 μm. Note that typical evanescent couplers in silicon photonics have lateral and vertical alignment tolerances on the order of hundreds of nanometers;[10–18] thus, VOI design was driven towards higher performance due to the intention to assemble using the toolset found in the LEAP. The final alignment tolerances of the coupler following optimization with FDTD simulations can be found in Figure 6(b), showing tolerances within 400 nm of 3 μm laterally and vertically.

Furthermore, the use of the MRSI-M3 for assembly of novel photonic coupling devices drove tool upgrades such as improved tool tips to facilitate higher applied forces during bonding and the installation of in situ UV lamps for epoxy curing - a necessity for achieving the fine epoxy thicknesses necessary for optical coupling without sacrificing lateral alignment by needing to move die to a separate curing tool. In turn, the upgrading of toolsets assists workforce development by 1) creating new possibilities for experiments to be employed in future hybrid learning programs and 2) allowing technicians to gain experience and understanding of future technology nodes in integrated photonics. Thus, as a result of the prototyping process being conducted side by side with workforce training programs, future technicians can gain a deeper understanding and heightened preparedness for when industry integration of these technologies occurs over the course of the next 5-10 years.



(a) (b)

Figure 6. A schematic of the proposed co-packaged design, which uses high density vertical optical interconnects to enable optical fanout to an array of SMFs, is shown in (a). The design is composed of an EIC shown in black and a silicon PIC shown in red, both of which sit on top of the SiO_2 optical interposer shown in white, which are assembled using pick and place technology. Note that while only one PIC was shown in this diagram, the package is intended to hold a large number of chips, and that the diagram is not to scale in terms of electronic or photonic chip sizes. In (b) the lateral, vertical, and longitudinal alignment tolerances of the evanescent coupler are shown along with a 1 dB additional loss line to guide the eyes.

4. CONCLUSION

To address the technology and workforce needs of the optics and photonics manufacturing industry, the Massachusetts LEAP network is striving to create highly specialized training centers. Preliminary efforts have shown promising results for all three aspects of the hybrid education model: in-person lectures, MOOC content and desktop VR tool simulations, and targeted hands-on experiments. In tandem with educational training programs are efforts to build innovative technologies in LEAP facilities across Massachusetts. Novel solutions, such as vertical optical interconnects for passive assembly, can simultaneously drive technological innovation while improving workforce preparedness. By preparing a 21st century integrated photonics manufacturing workforce and developing needed, industry oriented innovations, U.S. manufacturing can adapt to the rapid evolution of modern industry and regain its competitive advantage on the international stage.

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