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Changing Paths: The Impact of Manufacturing Offshore on Technology Development Incentives in the Optoelectronics Industry

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This paper presents a case study of the impact of manufacturing offshore on the technological trajectory of the firm and the industry. It looks in particular at the optoelectronics industry. The paper uses a combination of simulation modeling and qualitative research methods to develop grounded theory. The results suggest that firms face an important dilemma. In the case of optoelectronic firms, they are able to reduce short-term costs by manufacturing offshore; however, manufacturing offshore creates a combination of cost and knowledge constraints which limit the firms' ability to pursue critical innovations. These results are also of interest to those concerned with trade policy. The interest here is two fold. First, the optoelectronics industry is of strategic importance in the evolution of industrial technology and thus is important to national policy. The paper's principal finding that manufacturing offshore reduces incentives for innovation raises serious questions about the appropriateness of an offshore manufacturing policy in the long run. Second, the case challenges more generally conventional theories of trade, particularly their underlying assumptions about the long term dynamic effects which work through technological change. This case raises the troublesome question of whether these effects might be generally perverse and reduce or possibly eliminate the gains from trade over the long term.

Key words: offshore, manufacturing, technology trajectory
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1. Introduction: Incentives for Technology Development

Current theories on technology development and innovation overlook the possibility that manufacturing offshore may change the technology development path of firms. Previous work on technology development has suggested the importance of technology paradigms in addition to market demand in establishing technology trajectories (Dosi 1982), has explored the influence of dominant designs in directing patterns of innovation (Utterback 1975), and has characterized technologies that disrupt the prevailing path of technological change (Christensen 1997). None of this work, however, explores the role that manufacturing location has in affecting the path of technology development.

Research on international management and information management has explored the relationship between manufacturing location and innovation, and the importance of including manufacturing location considerations in firm and national strategy. Much of this work sees nations as recipients or benefactors of technology. Vernon's product life cycle theory suggests that goods are initially manufactured in the North where product development takes place. As the good matures and becomes standardized, manufacturing is shifted to the South. (Vernon 1966) Subsequent work has explored how developing countries can assimilate, adopt, and improve imported technologies (Kim 1997, Amsden 2001), as well as how the rate of host country imitation may influence the rate of home country innovation (Krugman 1979, Grossman 1991). Other research has explored the importance of geographic proximity for innovation. Some of this work has pointed out the importance of industry clusters in encouraging innovation (Porter 2001). Other work has focused on how the type of information influences its transferability and, thus, the locus of problem solving (VonHippel 1994, Fuller 2005). A long history of work has questioned the extent to which manufacturing and innovation can be geographically separated (Vernon 1966, Cohen 1987, Fuller 2005). Still, none of this work suggests that manufacturing in a foreign nation may change the technology trajectory of the firm and the industry.

This paper uses a combination of simulation modeling and qualitative methods to develop grounded theory (Glasner 1967, Davis forthcoming). This unique pairing of methods provides insight into the combination of cost incentives and knowledge diffusion constraints that can cause manufacturing location to influence the path of technology development. Given the complex dynamics to be studied and the lack of previous work in this subject, this paper focuses on in-depth analysis of one case – emerging integrated designs in the optoelectronic industry (Glasner 1967, Eisenhardt 1989, Yin 1989).

The paper presents results based on data collected from 23 optoelectronics firms on how key process variables (yield, cycle times, downtimes, wage, materials) change with manufacturing location. The paper then explores how those factors affect the cost-preferred design. Process-based cost modeling techniques (Kirchain 2000) are used to create a model of manufacturing based on the plant-level manufacturing data collected at firms. This model is used to evaluate the cost-competitiveness of emerging versus prevailing designs, and how this cost-competitiveness changes with manufacturing location. The quantitative analysis is supplemented by information collected in semi-structured interviews. These semi-structured interviews are used to understand actual firm decisions, as compared with what the model might predict, as well as to understand the general product development environment. The paper triangulates the model and interview data with market data to provide a more holistic view of the firms' decision-making and product development environments (Jick 1979).

In the case of the optoelectronics industry, the results suggest that the static economies of offshore manufacture create patterns of factor substitution that lead to dynamic diseconomies – specifically, disincentives for innovation. Given the burst of the telecom bubble, optoelectronics firms are being forced to decide between two alternatives to remain competitive: reducing materials, labor, and packaging costs (1) by adopting emerging designs domestically or (2) by moving production to low-wage countries. Most firms are moving to mainland China, Taiwan, Malaysia, and Thailand, while few are pursuing the path of technology development and remaining in the U.S. Once in developing East Asia, a combination of non-transferable tacit knowledge in U.S. assembly line workers and implicit real-time on-the-line learning by design engineers is preventing firms from being able to cost-effectively manufacture the emerging design. Further, although the emerging design is cheaper than the prevailing design when both are manufactured in the U.S., the emerging design produced in the U.S. is not able to cost-compete with the prevailing design manufactured in developing East Asia.

The emerging designs, however, do not only reduce costs. In the short term, the emerging designs hold potential for improvements in communications network performance and speed. In the long term, the same technology found in the emerging designs may be critical to bringing the information carrying capacity of photons to computers, and to surpassing the interconnect bottleneck challenging Moore's law. Although production in developing East Asia may be reducing short-term costs, the loss of cost-incentives for integration may in the long term be slowing down technological advancement. At the extreme, U.S. optoelectronics firms may through their current actions be giving up their ability for key innovations to further Moore's Law and continue driving the information economy.

The results of this case raise troublesome questions for economic theories on gains from trade (Krugman 1994, Rodrik 1997, Baghwati 2004, Samuelson 2004). Conventional trade theory predicts that the gains of the winners from trade will be more than sufficient to compensate the losers (Samuelson 2004). Yet, technological change has come to be generally accepted in economics to contribute as strongly to economic growth as traditional factors of production.[1] If the static economies of offshore manufacture create patterns of factor substitution that encourage dynamic diseconomies – specifically, reduced innovation – gains from trade may be less than conventional trade theory predicts. This last issue can, however, of course, not be resolved through a single case study alone.

2. Background: The Optoelectronics Industry and Competitive Advantage

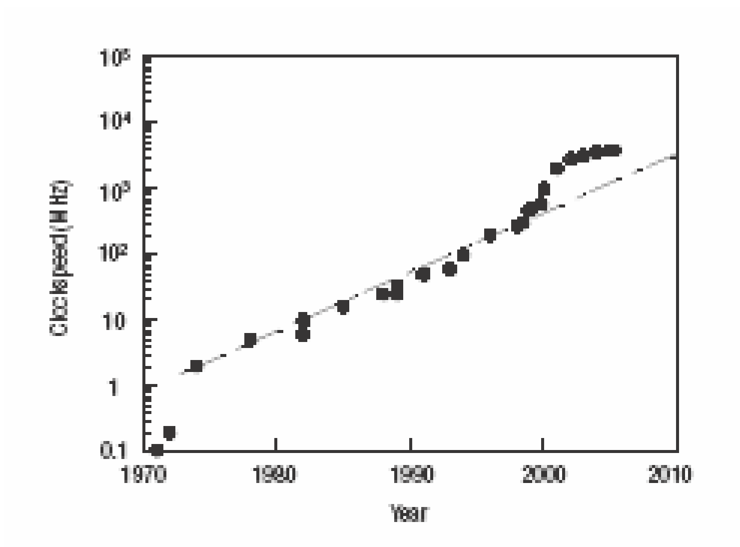
The Information Age, enabled through advances in computers, computer software, and digital transmission technologies, has revolutionized the way we do work. From the personal computer, to email, to cell phones and the Internet, our daily lives have changed irreversibly. These technological advances were originally based in electronics – which uses devices to control the flow of electrons to send, receive and process information. In the past 20 years, a new science, photonics, has begun to play a role in the sending and receiving of information. With their higher information carrying capacity, photons have been critical to meeting consumer demand in telecommunications for increased communications bandwidth (Schabel 2005). Transatlantic telephone cable using optical fibers has created virtually lossless transmission, while innovations in land area networks and fiber-to-the-home have brought Ultra-High Speed Internet, telephone, and television services to users.

In the upcoming decade, a much greater challenge faces electronics, and a much greater opportunity faces optoelectronics. Intel's ability to exponentially increase the processing speed per chip, as predicted by Moore's Law, has driven not only the chip industry. Complementing the increased processing capabilities of Intel's chips, have been innovations in innumerous other industries covering both hardware and software (Gawer 2000). The continual advance in the capabilities of Intel's

[1] Economists from Mill and Marx to Schumpeter and Solow argue for the critical contribution of technology to growth in the economy. In 1988, Robert Solow won the Nobel Prize for his famous "Solow residual" which ascribed the part of output growth that cannot be attributed to the accumulation of any input to technological progress. Solow, R. M. (1988). "Growth Theory and After." American Economic Review **78**(3): 307-317.

microprocessors plus the complementary innovations occurring in other industries have together been a key contributor to the revival and acceleration of productivity experienced since the 1990s by the U.S. economy (Feroli 2001). However, this continual advance in microprocessor speed is rapidly coming to an end. As more and more electronic transistors are squeezed on a chip, cross-talk problems arise between the wires connecting the transistors, limiting the possibility for the integration of more transistors to continue to improve performance. Photons have a higher information carrying capacity than and lack the cross-talk complications of electrons. Although copper wires and insulation have extended the lifetime of Moore's Law for electronics, if the information economy is to continue, a cure to what has come to be known in electronics as the "interconnect bottleneck" will be needed. (See Figure 1.) Optoelectronic devices, with their ability to communicate at the interface between electronics and photonics, are expected to be that cure (Kimerling 2000).

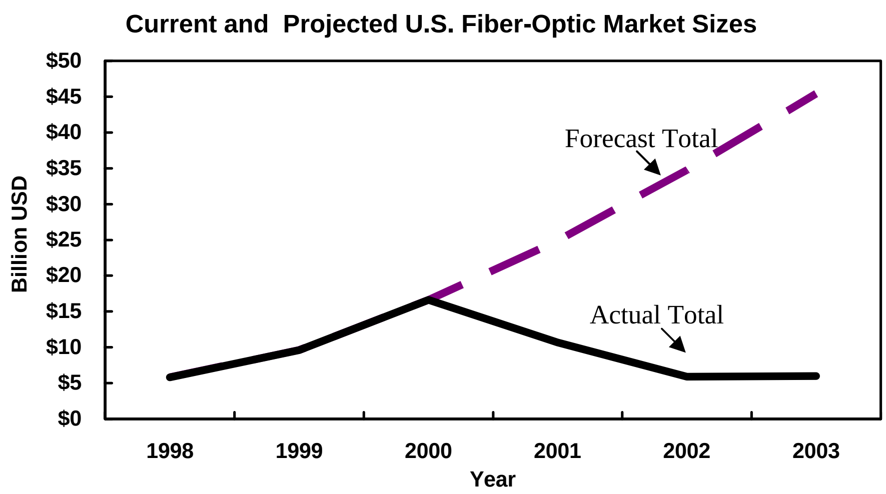
Figure 1: Will the "Interconnect Bottleneck" Challenge Moore's Law? (Source: (Muller 2005))



In order for optoelectronics to meet the demands of computer interconnects, cutting-edge researchers believe it will be necessary to develop a large-scale optoelectronic integrated circuit (Kimerling 2004, Ram 2004). This integrated circuit would consist of five critical components – a laser, modulator, waveguide, photodetector, and receiver. To bring all of these components together on a single chip, a sixth component – an isolator – will also need to be integrated. The integration[2] of components, however, is not elementary. Currently in optoelectronics, capabilities only exist for very simple integrated circuits. These circuits integrate two components – either a laser and a modulator or a detector and an amplifier.

Market forces may be getting in the way of the innovations necessary for large-scale optoelectronic integrated circuits. In the early 80s and 90s, as optoelectronics was revolutionizing telecommunications, a firm's competitiveness was dependent on being fastest at bringing the latest innovation to market. Although the telecommunications market is small, technology development for that market used to push forward the innovations in component integration necessary for the much larger computer market of the future. Since the burst of the telecommunications bubble in late 2000, however, firm survival has become a function of unit cost. (See Figure 2.)

Figure 2: Mid-2000 Optical Communications Market Forecast (Source: (Cahners Business Information 2000) versus Actual Sales (Source: (Turbini and Stafford 2003)



With costs threatening firm survival, firms may overlook innovations with long-term benefits to produce large-scale optoelectronic integrated circuits in favor of what appear to be the quick and easy cost reductions of moving manufacturing offshore. Materials, labor and packaging are the primary contributors

[2] At present there are two main approaches to integration: hybrid and monolithic. Hybrid techniques involve combining optoelectronic components in the same package or substrate using bonding techniques such as flip-chip or bump integration. Monolithic techniques involve integrating multiple component functions through sequential deposition, growth, and pattern transfer on a single substrate. The ability to integrate devices made from different materials systems may make hybrid integration an advantage in the short to medium term, but as longer serially-integrated subsystems are fabricated, the elimination of device-to-device interfacing losses is expected to favor monolithic approaches. For the rest of this paper "integration" will be used to refer to monolithic integration. Fonstad, C. G. (2005). Optoelectronic Integrated Circuits. Research Laboratory for Electronics. Cambridge, MA, Massachusetts Institute of Technology, IntensePhotonics (2005). Photonic System On Chip Solutions: What's the Recipe?.

to production costs for optoelectronic devices. The results of this work suggest that with the burst of the telecommunications bubble optoelectronic firms are being forced to choose between reducing materials, labor, and packaging costs (1) by continuing to develop integrated technologies at home or (2) by moving production to low-wage countries. Most firms are moving to developing East Asia, while a few are pursuing the path of technology development and remaining in the U.S. Although moving production to developing East Asia may in the short term reduce costs, in the long term, offshore production may have dire consequences. The results of this study suggest that moving production to developing East Asia may not only be reducing cost incentives for critical innovations toward large-scale optoelectronic integrated circuits, but also be taking away firms' very ability to make those innovations. The consequences may be disastrous for U.S. comparative advantage through the information economy.

3. Methods

This paper presents a case study from which the researchers inductively build grounded theory (Glasner 1967, Eisenhardt 1989, Yin 1989). The paper triangulates quantitative modeling data, qualitative interview data, and market data to provide a more holistic view on the drivers of technological change (Jick 1979). On the quantitative side, process-based cost modeling techniques are used to map technical design decisions to their manufacturing cost implications and thereby isolate cost incentives for technology development. The qualitative interviews and market data are used to develop a picture of the actual design and location choices being made by firms in the industry, and the short- versus long-term implications of those decisions for firms' technology development path, and ultimate competitiveness.

A long history of work has pointed out inadequacies in traditional accounting methods in supporting operations decisions (Johnson 1987, Hayes 1988, Rabino 1993, Hayes 2002). Company-based accounting methods have been shown to be particularly troublesome in supporting facility location decisions (Ghemawat 2001) and in illuminating the economics of yield-driven processes (Hampton 1996, Bohn 1999). Although not adopted widely by industry, a spattering of methods do exist in the literature to enable cost estimation during early stages of design (Ong 1995, Ou-Yang 1997, Rehman 1998, Asiedu 2000, Layer 2002). A pioneer of such methods, and today perhaps the most developed, is process-based cost modeling. Process-based cost modeling was developed as a method for analyzing the economics of emerging manufacturing processes prior to investment (Busch 1988). The application of this cost modeling has been extended to show the implications of alternative design specifications and process operating conditions on production costs, within and across manufacturing processes (Kirchain 2000).

The process-based cost model developed for this study is a spreadsheet-based tool which allows the user to forecast transmitter component production costs. The forecast is based on a detailed mathematical description of component processing including component fabrication, assembly, packaging, and all forms of testing. The model's architecture provides users with full flexibility to define the type and order of process steps as well as to set the operating conditions for each process. For the ease of the reader, a description of the model architecture is reproduced from (Fuchs 2006) in Appendix 1.
This paper extends the work in (Fuchs 2006) to address the implications of location on the relative economic advantage of technology alternatives. To achieve this goal, the authors identified a set of factors that would lead production costs for identical technologies to differ across two regions. Each factor was mapped to the set of potential model variables that would be affected. (See Table 1.) Data was collected for each region on the variables marked with an asterix in Table 1. Variable assignments, provided in parentheses, match the mathematical model. To emphasize their impact, these region-specific variables are marked in bold in Appendix 1.

4. Data Collection

4.1 Product Selection

This paper looks at the cost incentives for technology development in integration by modeling two integrated components – a laser and a modulator – and three integrated components – a laser, modulator, and isolator – against their discrete component alternatives. In Section 5.1, this study presents results on production of a 1550nm distributed feedback (DFB) laser and an electro-absorptive modulator on an InP platform. The researchers chose a product with these specifications due to the wide availability of data on its production, as well as their compatibility with the performance requirements eventually required to board-to-board and chip-to-chip computer interconnect applications. Two designs, imperfect substitutes[3] for each other in the current telecom market are compared: (1) a discrete 1550nm InP DFB laser & a discrete electro-absorptive modulator within a single package, and (2) a 1550nm InP DFB laser and an electro-absorptive modulator integrated on a single substrate.

Table 1: Region-Specific Factor Inputs Affecting Process-Based Cost Model Variables

Region-Specific Factor Inputs	**Potential Affected Model Variables**
Labor	
Wage	**Wage* (P^l)
Skill	**Downtime (UD), *yield (Y), scrap, *cycle time* ($cycT_i$+suT_i)
Experience	*Initial investment, labor availability*
Absenteeism	*Fixed versus variable labor costs, "buffer labor" factor = number of laborers multiplied by (1 - absentee rate)*
Raw Materials	
Price	**Buying price (P^m), cost of transport, tariffs/fees*
Quality	**Yield* (Y)*, scrap, line rate, design change requirements (thicker, etc.)*
Reliability	*Inventory, back-up supplier, *yield* (Y)
Electricity	
Price	**Price per kWhr* (P^e)
Reliability/availability	**Downtime* (UD)*, capital (industrial boiler, etc.)*
Real Estate	
Price	**Price per sq. m* ($R_{Building}$)
Components (Source)	
Imported from supplier	*Transportation cost*
Imported from OEM's production Facilities	*Transportation cost*
Produced by local firm w/ OEM oversight (or) Produced locally by an OEM.	*Transportation cost, investment for oversight functions, *yield* (Y)*, scrap, line rate, product and process design changes*
Capital (Source)	
Discount rate	**Discount rate* (d)
Imported from supplier	*Transportation costs*
Produced by local firm w/ OEM Oversight	*Transportation costs, investment for oversight functions, *yield* (Y)*, scrap, *downtime* (PD+UD)*, product and process design changes*

Laser-modulator devices such as studied in this paper are assembled into optoelectronic transmitters. Transmitters perform the role of transmitting and receiving data signals in applications ranging from telecommunications networks to sensors to computer interconnects. A SONET telecommunications network transmitter, such as would hold the 1550nm DFB laser and an electro-absorptive modulator, is made up of two components in addition to the laser and modulator – an isolator and a thermoelectric cooler. These components are brought together during the back-end production processes known as optical subassembly. The ability to integrate an isolator may be critical to enabling

[3] In today's market, discretely packaged lasers and modulators, discrete lasers and modulators in a single package, and integrated laser and modulator designs compete for the same market. In reality, the integrated design is smaller than the discrete design, and may already provide some additional reliability. These improved performance characteristics, although beneficial in future applications both in telecommunications networks and computing, are not yet required for today's applications.

large-scale optoelectronic integrated circuits for board-to-board and chip-to-chip computer interconnects (Ram 2004). Integrated isolators are not currently available on the market. Integrating the isolator onto the same substrate as the laser and modulator should, however, reduce both size and cost by eliminating the need to assemble yet another component during backend optical subassembly. In its second section (see results in Section 5.2), this study looks at whether extending integration to not only the laser and modulator but also the isolator provides diminishing or increasing savings in production costs. Two designs, imperfect substitutes[4] for each other in the current market place, are compared: a 10G long wavelength XFP transmitter (1) with an integrated laser and modulator, but discrete isolator, and (2) with an integrated laser, modulator and isolator[5].

4.2 Company Participation

In carrying out this study, the researchers were engaged with over 23 companies up and down the supply chain in the industry. Sixteen of the 23 companies involved in the study were optoelectronic component manufacturers. Together these 16 component companies held over half of the total optoelectronic component market in 2005, and included five of the seven companies which together held the majority share of the component market (Schabel 2005).[6] This study also involves several companies with a smaller market share but potentially critical insights to the future of the industry. These companies include Intel, Infinera (a start-up company with new integration technology), Flextronics (a U.S.-owned contract manufacturer, traditionally in electronics but moving into the optoelectronics space), and two developing East Asia contract manufacturers used by a large cross-section of the industry. Participants from these companies were interviewed, totaling over 100 interviews. The authors were able to receive

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[4] Extrapolating from the laser-modulator designs studied in Case I, we assume in Case II that the transmitter with the discrete isolator and the transmitter with the integrated isolator would initially compete for the same market. Similar to the laser-modulators in Case I, the integrated laser, modulator, and isolator design would be smaller than the discrete design, and would have the potential to provide additional reliability.

[5] Transmitters are classified according to their transmission speed (Gigbits per second, or G), instead of the wavelength of their lasers. A 1550nm InP DFB laser is one type of laser which could be found in a 10G transmitter. Due to rapid changes in packaging (Schabel, M. J. (2005). Current State of the Photonics Industry. Microphotonics: Hardware for the Information Age. L. Kimerling. Cambridge, MA, M.I.T. Microphotonics Center.), this study looks at optical subassembly of a transmitter with an (uncooled) 1350nm DFB laser for SONET applications instead of a (cooled) 1550nm DFB laser for SONET applications. The 1350nm laser, by not requiring cooling, can be packaged in what is known in the industry as a “TO-can.” TO-cans are rapidly becoming the packing standard for optoelectronic transmitters. Currently 1550nm DFB lasers are packaged in larger, butterfly packages, which are required to provide the extra space for a thermo-electric cooler. Advancements in cooling technologies (monolithic integration of thermoelectric coolers being one potential solution), may eventually enable all transmitter technologies to fit into the smaller TO-can-like packages.

[6] Of the seven component companies – Agilent Technologies, JDSUniphase, Bookham, Finisar, Infineon, Mitsubishi, and Sumitomo Electric/ExceLight -- which together held the majority share (65%) of the market in 2005, this study does not include the two Japanese-owned companies – Mitsubishi, and Sumitomo Electric/ExceLight.

additional company insights and feedback through participation in three industry consortiums, namely, the MIT Microphotonics Roadmapping Consortium, the MIT Center for Integrated Photonics Colloqium, and the MIT Communications Futures Program.

4.3 Model-Building and Data Collection: Process-Based Cost Model

Process-based cost modeling methods provide a means to compare technologies outside of an individual firm's processing decisions. Different companies were willing to contribute different types of information, and different levels of detail on their production. In all cases, the researchers' data collection efforts were to two main ends (1) to have sufficient data to obscure individual company production information, and (2) to have model results representative of the industry as a whole, despite the range of design and production strategies followed by individual firms. Although different component manufacturers contributed to the "front-end" device manufacturing data and the "back-end" optical subassembly data, all nine of the component manufacturers providing direct production data had both front-end and back-end production capabilities internal to the company. Details on the data collection approach and company contributions to different aspects of the study are provided below.

Data for the process-based cost model of front-end device fabrication (the results for which are presented in Section 5.1) were collected from 10 firms across the optoelectronics supply chain. These firms included three end-users of laser-modulator devices, three device manufacturers, and four manufacturers of production-line equipment. The three device manufacturers were chosen to represent the different production approaches in the industry: high-volume automated manufacture, low-volume labor-dominated manufacture, and a middle-of-the-road approach. Discussions with device end-users and with equipment manufacturers were used to bolster and cross-check data from the device manufacturers.

Data for the process-based cost model of the back-end assembly of the transmitter (the results for which are presented in Section 5.2) were collected from six firms. Again, these firms were chosen to represent a cross-section of the industry – including a large firm with highly automated production facilities, three mid-sized U.S.-based firms with production sites in developing East Asia, and two developing East Asia contract manufacturers focused on providing rock-bottom costs.

At each firm, data collection was focused in three main areas: (1) design: (a) current design (material, process, and geometry) and (b) emerging design alternatives; (2) production: (a) production data for current manufacturing technology and (b) new production requirements for emerging design alternatives; and (3) location: differences in production variables between the U.S. and the offshore manufacturing location. The model was validated with each firm using the data from that firm. The data was then aggregated across firms to create a generic production scenario representative of the industry.

4.3.1. Design

For the laser-modulator device, the authors chose to study a SONET-compatible[7] 1550nm InP system 10Gb/s distributed feedback (DFB) laser and electro-absorptive modulator (EA). The first author collected specification sheets and product information, as available publicly, from each of the three device manufacturers on an integrated laser and modulator and a discrete laser and discrete modulator in a single package being manufactured to the above-described specifications. The first author was also able to obtain from one device manufacturer electronic copies of in-house design diagrams.

For the transmitter, the authors chose to study a SONET-compatible 10G long wavelength XFP small form factor (SFF) multi-source agreement compliant transmitter design with an uncooled, 1350nm isolated DFB laser. Again, the first author collected specification sheets and product information, as available publicly, at each firm. In the case of four of the six firms, the first author was able to collect diagrams of the firm's particular design on-site. Design options for an integrated isolator were discussed with M.I.T. Professor Rajeev Ram based ongoing research projects within the Research Laboratory for Electronics (RLE). To avoid current debates over the design necessary to integrate an isolator with a laser and modulator this study sets the cost of integrating the isolator to its theoretical minimum – $0.

4.3.2. Process

Three types of data were collected at each company to create the "virtual fab" in the model. First, a process flow for each product was created with a representative engineer. Internal cost models, bill of

[7] Industry-wide component design standards do not yet exist for the optoelectronics industry. Roadmaps and workmanship guidelines have evolved in place of standards through industry associations such as NEMI, IPC, NIST, and IMAPS. Standards, called SONET and SDH, do exist to regulate data transmission rates over fiber optical networks. Suppliers also develop *de facto* standards through cooperative multi-source agreements (MSA), where component form factors, pin-outs, and control features are established as common features. (Schabel 2005).

materials and material handling sheets, equipment investment files, and operations documents were then collected to fill in the 26 inputs necessary for each process step (see Table 3). Notes were taken during a tour of the production facilities, and cross-checked to identify overlooked process steps, scrap and yield sources, downtimes, and cycle times. In the two cases where facility visits (one front-end fabrication facility, and one optical subassembly facility) were not allowed, experiences at other firms were used to cross-check the process flow and other data for inconsistencies or missing items. The process flow and data were then aggregated into a table showing the data for each process step, and confirmed with the engineering team.

4.3.3. Location

All three of the firms which provided front-end fabrication data produced their laser and modulator components in the U.S. or in Europe. This trend to do front-end fabrication in the home country is currently true for all U.S. and European firms in the optoelectronics industry with the exception of Agilent, which moved its front-end manufacturing to Singapore in 1988 (Yao 2003).[8,9] Contract manufacturers and Japanese-owned firms may be doing front-end fabrication in developing East Asia; however, it is unlikely that at this time any of this fabrication is of high-end laser-modulators such as the one modeled in this study. Actual plant data was therefore not available to the researchers on front-end production differences between the U.S. and developing East Asia at the time of the study. Future manufacturing location trends for front-end optoelectronic device fabrication are difficult to postulate, and it is likely that at least some of front-end fabrication will move to developing East Asia, even if not through U.S.- or European-owned firms. This study therefore explores the cost-implications of laser-modulator fabrication in a developing East Asian production environment. Initial estimates for laser-

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[8] Agilent's operations in Singapore go back to when Hewlett-Packard established its first assembly and test facility in Singapore in 1971.Yao, G. (2003). Mr. George Yao, Minister for Trade and Industry, at the Opening of Agilent Technologies Singapore New Building at Yishun on 25 February 2003, Singapore Ministry of Trade and Industry.

[9] Although Singapore can have lower wages than the U.S., Europe, or Japan, it is not considered in this paper to be in the same category as low-wage countries such as China, Thailand, and Malaysia. Singapore is listed as one of 29 "advanced economies" by the IMF and as one of 55 "high-income economies" by the World Bank Group. Singapore is not listed as one of 42 "Developed Regions" by the United Nations. http://www.imf.org/external/pubs/ft/weo/2005/01/data/groups.htm#1, http://www.worldbank.org/data/countryclass/classgroups.htm#High_income, http://unstats.un.org/unsd/mi/developed_new.htm.

modulator production differences between the U.S. and developing East Asia are based on production differences between the two regions observed for the back-end optical subassembly.

Of the six firms contributing to optical subassembly production data for the study, all six were either in the process of moving or were already performing optical subassembly operations in developing East Asia. Based on the variable mapping shown in Table 4, the authors chose seven variables for initial focus when working with firms to identify U.S. and European versus developing East Asia production differences. These seven variables, starred in Table 4, are wage, yield, downtime, cycle time, price of building space, price of electricity, and discount rate. Data collected on the process (see (2)) were used to document values for these variables in each location during visits with the six firms contributing to back-end optical subassembly data. Discussions with engineers were used to gain insights on the source of the observed production differences. The authors did not, however, attempt to quantify the magnitudes of the different sources' contributions.

The data collected by the researchers show the impact of production in mainland China, Taiwan, Thailand, or Malaysia on transceiver subassembly production parameters to vary by firm. Although it took one firm six months to re-qualify its product after transfer from the U.S. to its plant in developing East Asia, the firm was eventually able to achieve equal or better cycle times and yields for each process step. Some firms expressed similar experiences with transfer times and improved assembly yields; however, other firms experienced worse yields in developing East Asia. Downtimes were longer in the developing country production environment for all firms due to a lack of local equipment expertise. With capital equipment developers and manufacturers still in the U.S. or Japan, time differences and lack of local expertise could often cause a machine to remain out of order for 1-3 days. Worker schedules also tended to be different in developing East Asia for all firms interviewed.

A more accurate portrayal of the impact of changing manufacturing location will require further data collection. A set of preliminary assumptions regarding differences in variables between a developed country and a developing country manufacturing facility therefore are used here. These preliminary variables chosen to represent the U.S. and developing country production are based on differences seen in all of the firms interviewed (see Table 2). These country-dependent variables are used to demonstrate the potential of process-based cost modeling methods for assessing the impact of manufacturing location on the relative economic position of technology alternatives. These preliminary production differences are also used as a base-point for exploring the sensitivity of results to these location-specific variables.

Table 2: Production Factor Differences for Initial U.S. vs. Developing East Asia Scenarios

	Model Variable	**U.S.**	**Developing East Asia**
Working Days per Year	DPY	240	360
Number of Shifts	NS	3 x 8-hour shifts	2 x 12 hour shifts
Wage Incl. Benefits	P^l, l = skilled	$15 / hour	$2.60 / hour **
Discount Rate	*D*	10%	16%
Worker Unpaid Breaks	UB	1 hour / day	1.5 hours / day
Downtime (Paid Breaks)	PB	1.2 hours / day (5%)	1.8 hours / day (7.5%)

** The $2.60 hourly wage used for "developing East Asia" is an average of observed wages. While wages observed in mainland China were around $0.57 per hour with benefits, wages in Taiwan were on average $4.51 per hour with benefits.

4.3.4. Model Validation

Data were collected under non-disclosure agreements to encourage companies to provide the maximum amount of information. To increase incentives for participation and honesty, companies were encouraged to add products of interest to their individual company to the analyses. Analyses and recommendations were given back to each company based on the products and information they provided. Since production costs for an accurate comparison of two technologies are not necessarily calculated with the same goals as production costs as calculated for accounting purposes, unit costs were not considered a good check of model validity. The authors instead validated the model results by cross-checking that the production facilities generated by the model for a production volume equivalent to the maximum capacity of the participating firm, were the same as the production facilities of the firm. With respect to production facilities, the authors cross-checked that equipment count, total building space, total direct labor count, total capital investment and annual material flows in the model were equivalent to those found within the actual firm. The authors did confirm with each company that unit cost outputs for that company were within an order of magnitude of what would be expected to be the equivalent cost calculations within the firm.

4.3.5. Development of a Generic Production Scenario

Drawing from the individual firms data, the authors then developed a public, "generic production scenario" to represent common, industry-wide practice. For all companies, participants were asked to identify what of their processes they felt were non-generic. These confidential practices were excluded from the generic process flow. Mean values across the represented firms were then calculated for the 25 inputs for each process step used in the generic process flow. Unit cost results for the generic process flow were cross-checked with unit cost results of individual companies to ensure the generic process flow results were representative.

4.4. Qualitative Data Collection: On-Site Interviews

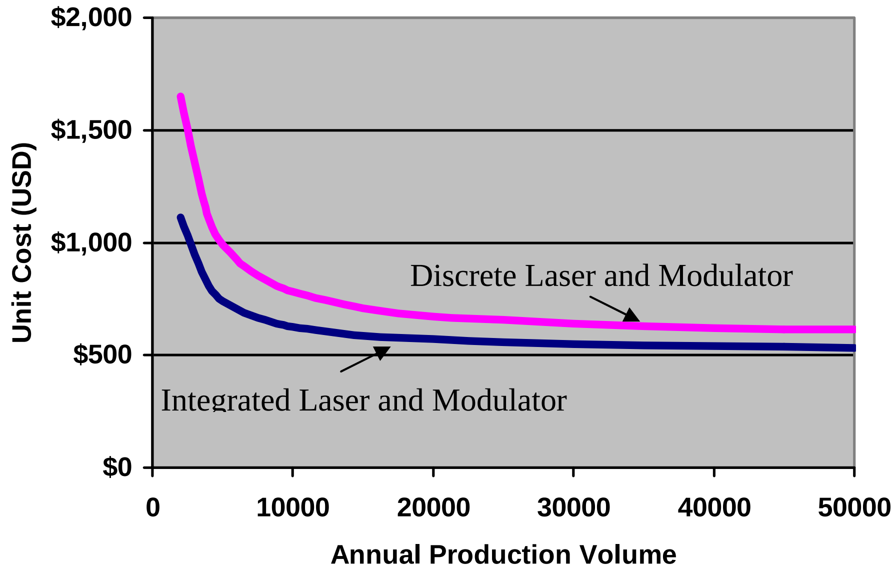
A combination of semi-structured interviews and market reports were used to develop a picture of company decisions. The interviews focused on both (a) design (material, process, and geometry) decisions in the home-country versus the offshore manufacturing location, and (b) company explanations or logic behind those decisions. The interviews were primarily informal, occurring naturally during the process of product and process data collection. In four cases, when dealing with higher levels of management, actual times for interviews were arranged. All interviews were semi-structured, allowing interviewees to bring-out the most important points in their individual experience. Notes were taken throughout company visits during data collection, discussions, and interviews, and transcribed within 24 hours.

5. Results and Discussion: Changes in Cost Incentives with Location

5.1 Integration of Two Components

A SONET-compatible integrated InP 1550nm DFB laser and electro-absorptive modulator is available from many firms today for telecommunications applications. The emerging integrated design competes with prevailing discrete designs which provide the same functionality. Researchers have for a long time argued that integration will provide the same unparalleled gains in functionality and reductions in cost for optoelectronics that it did for electronics. Agreement is lacking in the industry on whether the current integrated optoelectronic designs, given their lower yields, are actually more cost effective. Since both the integrated and discrete designs are available on the market, the authors were able to provide results based on real, plant-level production data – including material costs, downtimes, cycle times and yields. The competitiveness, based on the U.S. manufacturing data collected for this study, of an InP 1550nm DFB laser integrated with a electro-absorptive modulator against the discrete alternative is reproduced from (Fuchs 2006) in Figure 3 below.

Figure 3: Laser-Modulator Device Cost Sensitivity to Annual Production Volume (APV)



As can be seen in Figure 3, according to the data collected in this study, the integrated design is cheaper than the discrete alternative regardless of production volume. (Fuchs 2006) shows the robustness of this result across the range of yields expected in industry. At production volumes of 30,000 units annually, the integrated DFB laser and electro-adsorptive modulator device saves $92 per unit over the discrete laser and modulator, a 14% cost reduction. These savings are brought about by the streamlining of backend packaging, assembly, and testing allowed by integration. The cost savings occur despite a 41% and 71% decrease in yield (i.e., from 3.9% and 7.9% for the discrete laser and modulator, respectively, to 2.3% for the integrated laser-modulator). Of the integration cost savings, 17% are due to reduction in labor requirements. (Labor costs drop by $66, or 42%.) Of the integration cost savings, 28% are through reduction in material requirements. The remaining cost savings are through the reduction of backend equipment and their associated requirements (i.e. electricity, maintenance, and overhead).

Notably, moving production to developing East Asia is attributed to providing cost savings in exactly the same areas – namely labor and material costs – as integration.

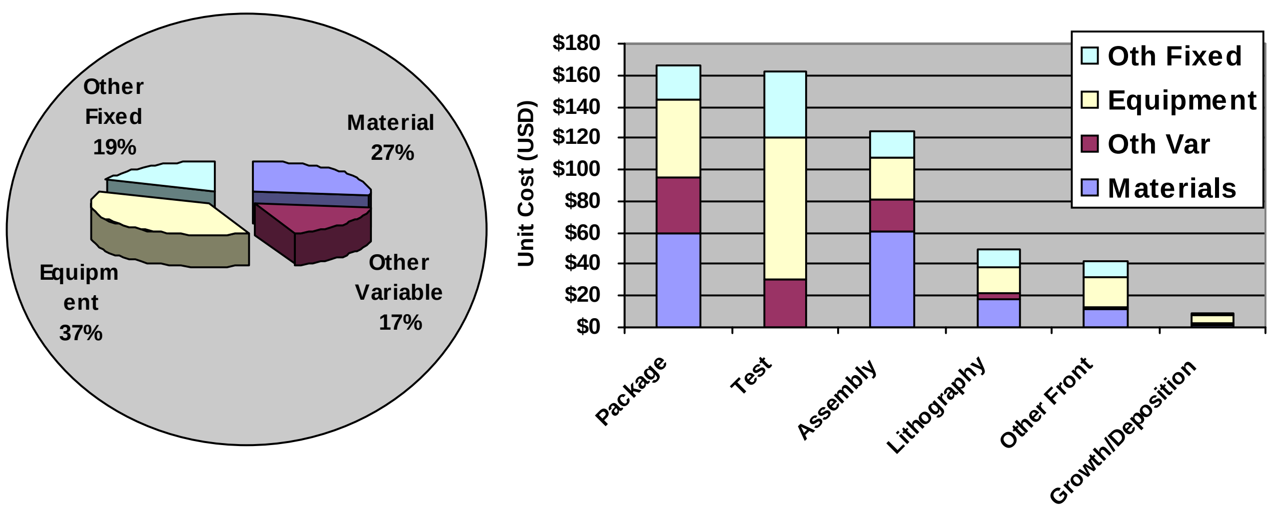
Second, as can be seen in Figure 3, economies of scale are achieved at 30,000 units annually for both the integrated and the discrete design.[10] This annual production volume was equal to the entire market for the SONET-compatible InP 1550nm DFB laser and modulator devices as of 2001(Schabel 2005). Although firms are able to do some platform sharing across products, they are unable to achieve production costs lower than revenues with more than one production facility. Further discussion of the limits of raising production volumes in reducing costs as well as of current and future estimates of the optoelectronics market can be found in (Fuchs 2006) and (Schabel 2005), respectively. The importance of a constrained market to this case is discussed later in the document.

Figure 4 provides a breakdown of the major contributors to the production costs of the emerging integrated design. The left-hand side of Figure 4 shows the contribution of fixed versus variable costs to the total unit cost of manufacturing the integrated design. "Other variable" costs in the figure below include both labor and energy, but labor, at $88, represents 90% of this category. "Other fixed" costs include maintenance, tooling, building space, and overhead. Given that materials and labor contribute to 43% of the total unit cost of producing the integrated design, incentives seem to still exist, to produce the integrated design in developing East Asia. As can be seen on the right hand side of Figure 4, production costs of the integrated laser-modulator are still, like the conventional discrete design, dominated by backend costs for packaging, assembly, and testing. The processes which fall under backend packaging, assembly, and testing can be seen under the model description in the methods section in Appendix 1. The dominant nature of the backend costs suggest that there may be cost advantages (or cost incentives) for further integration.

[10] The term "economies of scale" is more correctly used to describe the economic phenomenon where cost per unit reduces with increased production. Here, the term "economies of scale" is used more loosely to describe the area of the production curve where further increases in production volume no longer lead to dramatic reductions in cost. In Figure 2, the unit cost of the integrated laser and modulator drops 15% between 10,000 and 30,000 annual units, whereas it drops only 2% between 30,000 and 50,000 annual units, and similarly only 1% between 50,000 and 70,000 annual units.)

Although data was not available at the time of the study on production of an InP 1550nm DFB laser and electro-absorptive modulator in developing East Asia, several firms are exploring this option. The inputs in Table 2, showing the labor, plant operation, and downtime differences observed for the U.S. versus developing East Asia optical subassembly facilities, are used as an initial estimate of U.S. versus developing East Asia differences for laser-modulator manufacture. As can be seen in Figure 5, placing laser-modulator device fabrication in the low-wage environment depicted in Table 2 enables a significant cost reduction for both designs. At 30,000 units per year, the discrete laser and discrete modulator in a single package is $193 cheaper in the developing East Asia than in the U.S. production environment. According to these results, a firm can be more cost-competitive by producing the prevailing discrete design in a developing East Asian environment than producing the emerging integrated technology in the U.S.

Figure 4: Integrated Device Cost Breakdown by Process (30,000 APV)

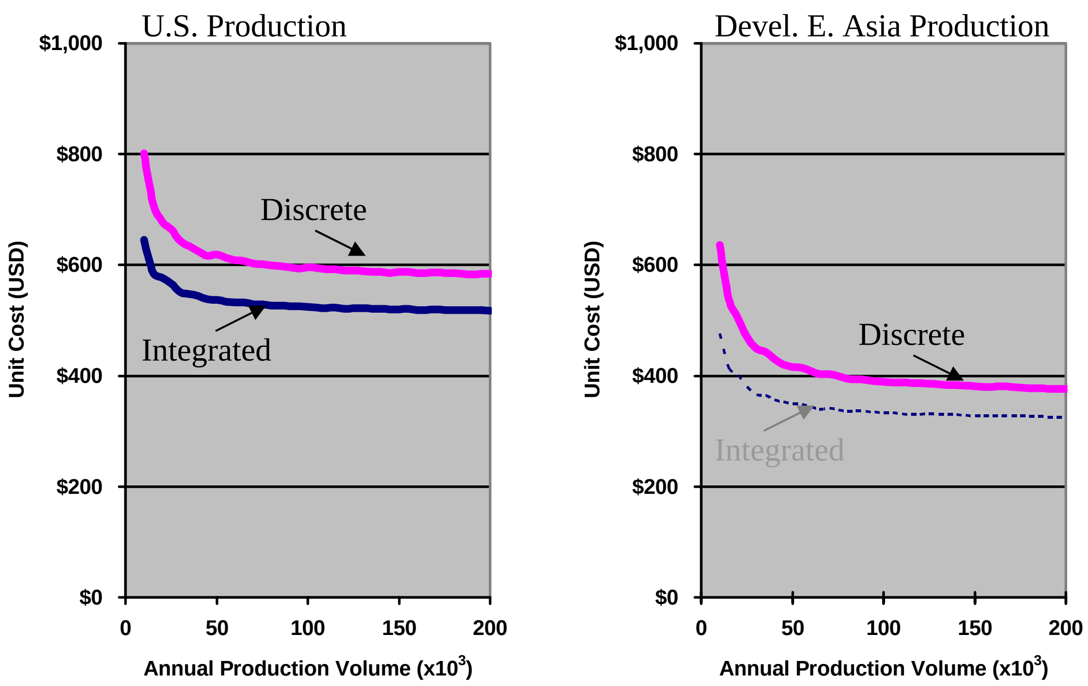


The integrated design's cost curve is shown as a dotted line since interviews with firms suggest that this technology could not currently be produced in developing East Asia. Production engineers expect that the extremely low yields (2.3% and lower) experienced during the production of the integrated design in the U.S. would drop even lower in developing East Asia, and without engineers in the vicinity to solve production line crises, output would grind to a halt. The ability to produce new designs in developing East Asia is discussed in greater detail in the section on "Difficulties Manufacturing High-

Performance Optoelectronics in Developing East Asia" below. If the integrated design could be produced in developing East Asia (as defined in Table 2) at the same yields as it is produced in the U.S., the integrated design's unit cost curve would be equivalent to the dotted line shown in Figure 5.

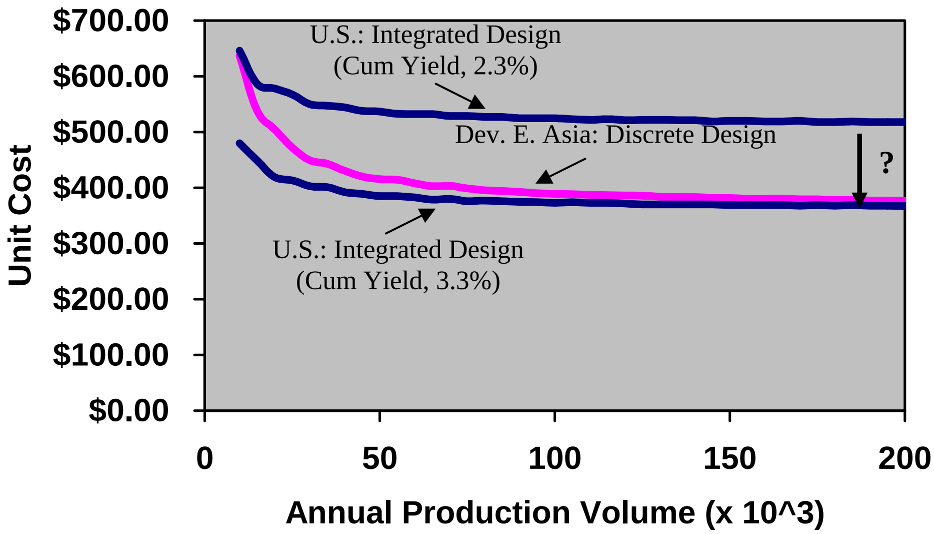
Notably, even if the integrated design could be produced at similar (or even better yields) in developing East Asia, the incentives to integrate are less in the developing East Asia than in the U.S. While integration saves $92 over the prevailing discrete design in the U.S., it only would save $83 in the low-wage country environment.

Figure 5: Cost-Competitiveness of U.S. Produced Integrated Laser Modulator Versus Developing East Asia Produced Discrete Laser and Modulator Design



Inevitably, a company which chooses to pursue the integrated device may be able, through learning, to achieve improved yields over time. Figure 6 shows the yield improvements necessary for the integrated design manufactured in a U.S. production environment to be cheaper than a discrete design manufactured in the developing East Asia with the yields found in this study.

Figure 6: Yield improvements necessary for an integrated laser modulator produced in the U.S. to be more cost competitive than a discrete laser and modulator produced in developing East Asia.



To be cheaper than the discrete design at all production volumes, a company must improve its cumulative yield above the base case by 43%. This large an improvement in cumulative yield would require significant yield improvements throughout production process. Although such dramatic improvements are not inconceivable, the time and monetary investments required create significant disincentives for firms to pursue the integrated design over the seemingly immediately cost reductions of moving manufacturing of the discrete design offshore.

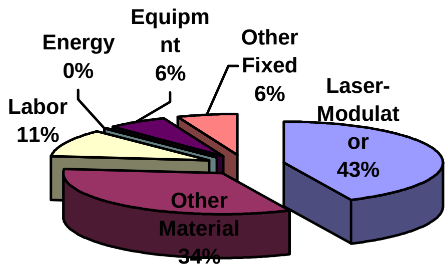
5.2. Integration of Three Components

Research and development efforts for further integration and other technological advancements to reduce packaging costs pervade the optoelectronics industry. These research efforts have two items in common. They are all located in developed countries (specifically, the U.S., Europe, and Japan) and they all act to reduce the major cost driver in U.S.-located optoelectronics production – back-end packaging and assembly. Unlike laser-modulator fabrication, optical subassembly currently occurs in both developed countries and the developing world. With increased cost pressures in the industry, many producers are making moves to perform all optical subassembly in developing East Asia. This relocation may reduce the relevancy of current packaging-focused efforts, and remove the cost-pressure for the developments in integration critical to overcoming the interconnect bottleneck.

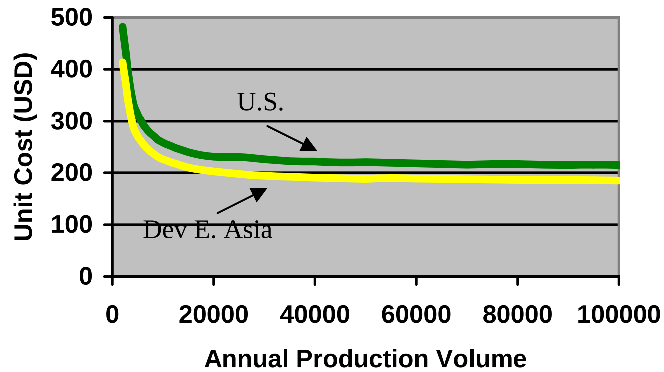
This second part explores whether an integrated laser and modulator with a discrete isolator produced in developing East Asia is cheaper than an integrated laser, modulator, and isolator produced in the U.S. The capability to integrate the isolator is a critical step towards being able to integrate the other components necessary for large-scale optoelectronics integrated circuits for computer interconnects. Two designs, imperfect substitutes for each other in the current market place, are compared: a 10G long wavelength XFP transmitter (1) with an integrated laser and modulator, but discrete isolator, versus (2) with an integrated laser, modulator and isolator. Assembly of a 10G long wavelength small form factor XFP transmitter occurs in two phases. In the first phase the laser and modulator are mounted onto submounts and then assembled into a package known as the TO-can. In the second phase this TO-can is aligned and laser-welded to a housing. This housing contains the isolator, a focusing lens, and a fiber receptacle. This second phase is called the transmitter optical subassembly (TOSA).

Figure 7 below shows the unit cost for the 10G DFB laser TO-Can build and TOSA in the U.S. versus developing East Asia. As can be seen in Figure 6, 19% of the US-produced transmitter costs (not including the costs of the laser-modulator) are labor costs. Given the labor, plant schedule, and downtime production characteristics shown in Table 2, companies are able to save $31 per unit by moving production to developing East Asia. Although not represented in Table 2, production engineers within companies repeatedly expressed expectations in the near term to begin to source materials (other than the laser-modulator) cheaper in developing East Asia. With labor (19%) and materials (59%) together 78% of total transmitter unit costs (not including the laser-modulator), it is easy to see the strong push for companies to move these operations to developing East Asia where labor and material costs are reduced.

Figure 7: 10G TO-Can Build and Transmitter Optical Subassembly in the U.S. vs. Developing East Asia

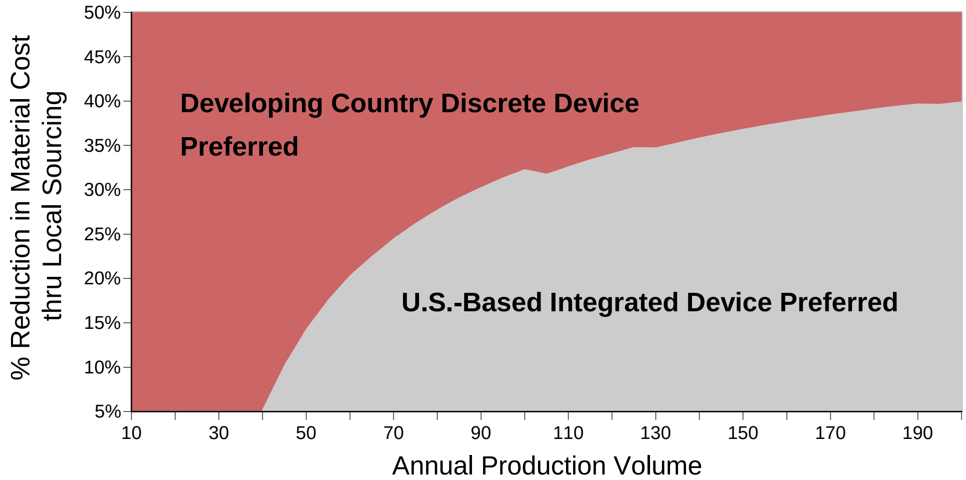


U.S. Cost Breakdown
@ 30K Annual Units



Of the $21.31 it costs to put together the isolator subassembly in the U.S., $20.55, or 96%, is the price of the isolator part itself. Similarly, for the low-wage TOSA production, of the $20.88 it costs to put together the isolator, $20.55, or 98%, is the cost of the isolator itself. In the interviews to-date, the isolator is included in the parts that companies plan to source cheaper in developing East Asia. Figure 8 shows the cost boundary at which an integrated isolator ceases to be cost-competitive against a product assembled with cheaper parts within the developing country. Given the lack of a completed model of integrated isolator production, U.S. integrated isolator production costs are set to $0 – the optimistic limit in possible cost savings through integration. With this assumption, at production volumes of 100,000 annually, local sourcing needs to save 35% in material costs to make it impossible for a U.S.- produced transmitter with an integrated isolator to compete on cost. The two interviewees (from different firms) who believed that they could achieve material cost savings by sourcing locally in developing East Asia, when asked, both believed it was not unreasonable to achieve materials cost-savings of this magnitude.

Figure 8: Discrete Isolator Transmitter Production in Developing East Asia – Cost Savings Over Integrated Isolator Transmitter Production in the U.S.



5.3. Difficulties Manufacturing High-Performance Optoelectronics In Developing East Asia

Sections 5.1 and 5.2 compare manufacturing an integrated design in the U.S. with manufacturing a conventional, discrete design in developing East Asia. Production characteristics specific to the optoelectronics industry make it difficult to produce high-performance designs in a developing country environment.

Front-end fabrication techniques are necessary for integration and are dominant in laser-modulator production such as for the designs studied in Section 5.1. Front-end fabrication techniques are currently almost exclusively implemented close to their research and development centers in developed country environments (primarily the U.S., U.K., Canada, and Japan). There are many indications as to why front-end optoelectronic device fabrication is still located close to research and development. For front-end fabrication, yields can fall below 10%, ranging as low as 1-3% for high-performance integrated devices. For a high-performance device such as the 1550nm InP laser-modulator, days can go by without yielding a single good device. Production, design, and test engineers are needed on the shop floor multiple times a day. With significant aspects of product functionality only testable after final product assembly, sources of yield problems within the process are left largely unknown. Solving yield difficulties thus requires an intimate connection between the design engineers, the production engineers, and the production process itself. With product lifetimes of only 3 years, new designs often replace old ones before yields have stabilized.

The need to locate front-end device fabrication near research and development may change over time. Despite the short product life of optoelectronic devices, the technology as a whole may mature, raising yields. Codification of currently non-standardized production techniques may also be expected to raise yields. Also, optoelectronics technology knowledge in mainland China, Malaysia, Thailand, and Taiwan, may increase, possibly allowing research and development to be located in these countries along with manufacturing. If optoelectronics production processes could mature and technical skills in optoelectronic factories could improve in the short term while wages, interest rates, and downtimes were to remain typical of a developing country environment, there could be cost-advantages to producing all optoelectronic designs in developing East Asia. Assuming this hypothetical case in which the same yields currently achieved in the U.S. could be achieved in developing East Asia, production costs would be similar to the dotted unit cost curve representing the integrated design in Figure 4.

Although firms are in the process of trying to move all backend assembly (such as the TO-Can build and transmitter optical assembly studied in Section 5.2) to developing East Asia, many problems, again, are arising with high-performance designs. Multiple reasons are cited for the difficulty of transferring production to an alternative location, and for the location of high-end production facilities in developed country environments. Optoelectronic assembly continues to be non-standardized rather than designed for high-volume manufacture. Alignment of lasers with lenses and other devices, although machine-aided, is done manually. The more high-power a laser is, the more challenging its alignment requirements. Like for laser-modulator production, production, design, and test engineers are on the phone with the shop floor multiple times per day, and suit up to go into the clean room at least once a day. In the case of high-performance alignments, however, the craft-like skills of the direct laborers in the U.S. seem to be difficult to transfer to developing East Asia. Most firms sent one or two workers for several days to several weeks to pass along their skills. One firm sent an entire team of direct laborers for the backend processes over to developing East Asia for two weeks to teach their techniques to the workers at the new Asian facility, but with no success. At the time of study, the six researched firms were still primarily producing low-performance products in developing East Asia. The one firm with a slightly more advanced product – a 10G FP transmitter – being produced in developing East Asia expressed significant concern about being able to meet specifications three months after the product's introduction, and was considering bringing the product back to production in the U.S.

The requirements for interaction with engineering and the difficulty of transferring the tacit assembly knowledge suggest that firms will, in the short term, be forced to choose between designing advanced technology alternatives for production in the U.S., and designing low-technology alternatives for production in the developing world. This research suggests that by moving production to developing East Asia, the U.S. firms in this industry may be removing not only their incentives but also their ability to make the innovations necessary to continue to survive in optoelectronics, once the demands from the computer interconnect market become critical.

6. Conclusions

Current theories on technology trajectories and gains from trade overlook the possibility that manufacturing offshore changes firms' technology development paths. This paper provides in-depth analysis of a single case – emerging integrated designs in the optoelectronics industry. Photonics has been and is expected to continue replacing electronic applications – moving from transcontinental fiber-optic cables, to local land-area-networks, eventually into intra-computer applications. As the photonic-electronic interface moves nearer to the computer's core, the demand for optoelectronic devices – the devices that act at this photonic-electronic interface – grows. In the 80's and 90's, the most competitive optoelectronics firms were those quickest at bringing the latest innovation to market. A primary direction of these innovations was the integration of multiple devices on a single chip. In the short term, integrated devices are expected to increase network speed, improve network performance, reduce device size, and reduce device and network costs in telecommunications. In the long term, integrated designs are considered key to solving the interconnect bottleneck which threatens to prevent the advancement of Moore's Law, and for optoelectronics to access the much larger computer market.

However, since the burst of the telecom bubble in early 2000, competitiveness in the optoelectronics industry has become a function of cost. As a result, firms have been forced to choose between two options to reduce material, labor, and packaging costs – (1) to continue to develop new technologies at home (specifically, integrated designs) or (2) to move production to low-wage countries. Several factors constrain firms to the above two options: First, firms are currently unable produce integrated designs in their offshore production facilities due to a lack of local highly skilled design engineers and to problems transferring tacit backend assembly skills. Further, the constant attention of design engineers required on the production line makes it difficult to geographically separate design activities and production. Second, the size of the current telecommunications market does not support multiple production sites. As shown in the cost-results in this paper and supported by interviews, component manufacturers are unable to support two facilities (one in the U.S. producing the emerging technology and one in developing East Asia producing low-cost products with the prevailing technology) without pricing under cost.

The cost results of this work show that although the emerging integrated design is cheaper than the prevailing design when both are manufactured in the U.S., the emerging design produced in the U.S. is not able to cost-compete with the prevailing design manufactured in developing East Asia. Almost all of the firms studied have chosen the path of relocating manufacturing offshore and continuing to produce the prevailing technology. Although in the short-term these firms are reducing production costs, they are also reducing cost incentives for research agendas in the U.S. focused on integration. The advance of integrated designs in the optoelectronics industry may be critical to continuing Moore's Law and driving the information economy. If shifting production to developing East Asia slows this advance, the negative effects are significant. Either no firms will advance Moore's Law and the information economy will slow globally, or U.S. firms will fall behind and lose the technological rents associated with driving the information economy. Such negative effects may more than offset any gains from lower labor and material costs.

This paper's principal finding that manufacturing offshore reduces incentives for innovation challenges conventional theories of trade, in particular their underlying assumptions about the long term dynamic effects which work through technological change. Although only one case, the optoelectronics case raises the troublesome question about whether these effects might be generally perverse and reduce or possibly eliminate the gains from trade over the long term.

7. Future Work

This paper demonstrates the potential of process-based cost modeling methods to show shifts in the relative economic position of emerging technologies due to manufacturing location. As research on these shifts develops, it will be important to assess implications for firm strategy. Important for the optoelectronics industry will be whether firms should be producing low-tech optoelectronic solutions in developing East Asia, pushing forward technology solutions in a developed country environment such as the U.S., or hedging bets by keeping manufacturing in both locations. Although firms pushing for high-tech solutions in the developed world could come out ahead, cost pressures could also put them out of business before technology can come to the rescue. Markets, technologies, and national comparative advantage (in the form of different wages, skills, material costs, etc.), however, all change over time. The relative rates of change of these variables could make the difference between a cost-effective versus a failed investment. For example, if the optoelectronics engineering knowledge in developing East Asia would develop to the point of being able to design and manufacture integrated devices in time to meet the demand for these emerging designs in the computer market, would investment in manufacturing facilities in developing East Asia still be a poor investment decision? Likewise, if optoelectronics production technology would standardize to the point that engineers were no longer required on the line to produce emerging integrated designs, would investment in manufacturing facilities in developing East Asia then not be a poor investment? Future work should include model development to illuminate how investment risks are affected by relative rates of change in markets, technologies, and national comparative advantage.

As shown in this paper, production and investment costs are not the whole story. Future work should continue to follow the story of the optoelectronics industry for insights on the impact of manufacturing offshore on technology advancement, firm competitive advantage, and economic competitiveness in the U.S. The lack of wide-spread product or process standards as well as the existence of primary competitors to the firms studied in this paper in a different country (Japan) under a very different industry and regulatory structure, makes the optoelectronics industry particularly interesting for further study. In terms of technology advancement, with industry standards in the early stages of development, one can imagine short-term cost pressures leading to standards that lock the industry in to a set of inferior technology solutions. In terms of the impact of manufacturing offshore on technology development paths, national competitiveness, and innovation, Japan is an important next case. In contrast to the U.S., Japan has long-term oriented firm structures, legislative incentives to manufacture onshore, and government initiatives aimed at providing critical financial support for optoelectronics R&D. Early discussions with U.S. firms suggest that their Japanese competitors may be significantly ahead in developing critical integrated design technology.

Although in-depth study of a single case provides critical insights not possible in broader studies, additional research will be required to understand the wider implications and applicability of the optoelectronics industry case. Given the lack of prior study on the impact of manufacturing offshore on the product development decisions of firms, future work should in the short term continue to be case-study based. Two aspects of the optoelectronics case stand out as particularly relevant to influencing the firms' paths of technology development: (1) lack of standardization in the front- and back-end processes, and (2) that market size constrained the firms to having only one manufacturing facility. Future work should explore the impact of manufacturing offshore on technology trajectories of firms in other industries where these characteristics are not the case. A particularly interesting next case would be an industry with standardized production processes where the companies are able to have multiple manufacturing facilities.

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Appendix 1

1. Model Architecture

The cost per good device is developed in Equations 1 -17. Aggregate costs are calculated as follows:

$$C_{Tot} = C_{Material} + C_{Labor} + C_{Energy} + C_{Equipment} + C_{Tooling} + C_{Building} + C_{Overhead} \quad \text{Equation 1}$$

$$C_{El} = {AC_{El}}/{PV} \quad \text{Equation 2}$$

where C = unit cost ($ per good unit), AC = annual cost ($ per year), PV = good devices per year, and El= cost element (Materials, Labor, Energy, Equipment, Tooling, Maintenance, Overhead).

Currently, the model includes 57 sub-modules each covering a different process. Each sub-module, consists of 25 variable inputs which provide a description of the materials, actions, and operating conditions necessary to execute a given process step. A full list of the 57 processes covered in the model as well as the 25 variable inputs used to describe each process can be found in (Fuchs 2006.)

1.1 Materials, Labor, and Energy Costs

Ultimately, material costs are directly driven by the effective production volume for each step ($effPV_i$), defined as the gross number of units processed at step i to achieve the desired number of good units (PV) after step n. The calculations for effective production volume and material costs are shown in Equations 3 – 6 below:

$$effPV_n = PV / \boldsymbol{Y_n} \quad \text{Equation 3}$$

$$effPV_i = effPV_{i+1} / \boldsymbol{Y_i} \; , \; \forall \; i \in [1, \ldots, n-1] \quad \text{Equation 4}$$

$$effAB_i = effPV_i / Batch_i \quad \text{Equation 5}$$

$$AC_{Material} = \sum_{i,m} U_i^m \cdot effAB_i \cdot \boldsymbol{P^m} \quad \text{Equation 6}$$

where i = process step number, n= total number process steps, Y_i= yield at step i, $effAB_i$ = gross annual batches processed at i, $Batch_i$ = mean batch size for i, m = material type, AU = annual usage of material m in step i, P^m = unit price of material m, U_i^m = unit usage of material m per $Batch_i$.

Energy costs are based on user-specified energy consumption rates for each machine. Energy consumption values are estimated for each process according to equipment requirements, leading to annual energy costs calculated as:

$$AC_{Energy} = \sum_{i} reqLT_i \cdot EI_i \cdot \boldsymbol{P^e} \quad \text{Equation 7}$$

where EI_i = Energy intensity of step i in kiloWatts (kW) and $reqLT_i$ = the line time required to produce $effPV_i$.

Users may specify direct labor requirements in four separate classifications – higher education labor, technicians, skilled labor, and unskilled labor. The annual cost of these laborers is computed as described below in Equation 8:

$$AC_{Labor} = \sum_{i,l} APT_i^l \cdot \boldsymbol{P^l} \quad \text{Equation 8}$$

where l = labor type (PhD, Technician, Skilled, Unskilled), APT_i^l = annual paid labor time for labor type l for step i.

1.2 Capital Costs

In the model, costs are assumed to be distributed evenly in time over the usable lifetime of a resource for those cash flows with periodicity longer than one year (e.g., equipment investments). The opportunity cost associated with tying up these funds in this long-term investment is incorporated using a standard capital recovery factor (see Equation 9).

$$R_{El} = I_{El} \frac{[\boldsymbol{d}(1+\boldsymbol{d})^{s_{El}}]}{[(1+\boldsymbol{d})^{s_{El}} - 1]}, \forall\ El \in \mathbb{Z} \qquad \text{Equation 9}$$

where $\mathbb{Z}$ ={*Tool*, *Equipment*, *Building*}, R = the allocated cost for a defined period (here, one year), I = the non-periodic investment to be allocated, d = the periodic discount rate (here, d=10%), s = the number of periods over which is investment is distributed (here, s_{Tool} = 3, $s_{Equipment}$=10, and $s_{Building}$ = 25).

Along with each machine's direct cost, an input is provided to establish whether the machine is a) dedicated to the production of the product being analyzed or b) shared across other products. In the latter case, following the approach of time-based allocation, investment expense is apportioned according to the fraction of equipment available time which is dedicated to the manufacture of the component of interest. The details of this forecast are described in the section on operating time. For the purposes of the case presented in this paper, the model was configured based on an assumption that even if a production line is dedicated to a single product, processes which require the same equipment in that production line will choose, when possible, to run on the same machine. This approach was based on observation of industry practice and recognition of the exceptionally low utilization that would result otherwise for low production volume, high performance products. Based on this approach, fixed costs are calculated as shown in Equations 10-12.

$$AC_{El} = AC_{El,ded} + AC_{El,nonded}, \forall\ El \in \mathbb{Z} \qquad \text{Equation 10}$$

$$AC_{El,nonded} = \sum_i (R_{El,i} * LR_i), \forall\ i \in \{\text{non-dedicated}\} \qquad \text{Equation 11}$$

$$AC_{El,ded} = \sum_j R_{El,j} \cdot \left(\left\lceil \sum_i \left(LR_{ij} - \lfloor LR_{ij} \rfloor \right) \right\rceil + \sum_i \lfloor LR_{ij} \rfloor \right), \ \forall i \in \{\text{dedicated}\} \text{ and } \forall j \in [1,...,J] \qquad \text{Equation 12}$$

Where {non-dedicated} = the set of all steps which have non-dedicated processes, {dedicated} = the set of all steps which have dedicated processes, j = process type, J is the total number of process types, and LR_i is the ratio of required operating time to effective available operating time at step i, as shown in the next section.

1.3 Operating Time

The time required for a given process step is a key determinant of many process costs, including labor, energy, and capital requirements. Three quantities of time are tracked within any PBCM: 1) the amount of time that a particular resource (machine, labor, etc.) is required – *required operating time*, 2) the amount of time that a unit of that resource is available in a given year – *available operating time* and 3) the amount of time that a laborer would be paid for a full year, *annual paid labor time*.

Annual paid labor time, lines required, required operating time, and available operating time are calculated as follows:

$$APT_i^l = \boldsymbol{DPY} \cdot (24 - \boldsymbol{NS} - \boldsymbol{UB}) \cdot WPL_i^l \cdot LR_i \qquad \text{Equation 13}$$

$$LR_i = {reqLT_i}/{availLT} \qquad \text{Equation 14}$$

$$reqLT_i = effAB_i \cdot (cycT_i + suT_i) \qquad \text{Equation 15}$$

$$availLT = \boldsymbol{DPY} \cdot (24 - \boldsymbol{NS} - \boldsymbol{UB} - \boldsymbol{PB} - \boldsymbol{UD}) \qquad \text{Equation 16}$$

where *DPY*=operating days per year, *NS* = no operations (hr/day the plant is closed), *UB* = unpaid breaks (hr/day), WPL_i^l = Fractional labor type *l* assigned to step *i*, $cycT_i$ = operating cycle time of i per batch, suT_i = setup time of process i per batch, *PB* = paid breaks (hr/day), and *UD* = Unplanned downtime (hr/day).

1.4 Yield

The unit costs (C_{Tot}) reported in this paper represent what is often known in the industry as "yielded costs," in other words the effective cost per good non-defective device. Unlike classic industry models, two yield numbers are assigned to each step in the process flow – an incidental yield and an embedded yield. Both of these yield values are inputs provided for each step by the user. The incidental yield represents the yield hit taken immediately at a given step due to obvious problems which can be identified without testing (e.g., occasional wafer breakage). The embedded yield represents defects caused within a process step, but not discarded from the production line until later when identified as defective during testing. Thus, embedded yields accumulate during production until they are identified and removed during a testing step. Although only process steps that are not test steps can have embedded yields, test steps may have their own incidental yield. Equation 17 shows how yield (Y_i) would be calculated for some step, i=k, where $k \in [0, \ldots, n]$:

$$Y_{i=k} = \begin{cases} \boldsymbol{incY_k} \cdot \prod_{x=(t^*+1)}^{k} \boldsymbol{embY_x}, & k = test \\ \boldsymbol{incY_k} , & k \neq test \end{cases} \qquad \text{Equation 17}$$

where $\boldsymbol{t^*} = \max \Im, \forall \boldsymbol{i} \in \{\boldsymbol{test}\}$, where $\Im = \{\boldsymbol{i}\}_{\boldsymbol{i}=1}^{\boldsymbol{k}-1}$ and {test} = the set of steps which are test steps. In words, t* is the most recent step prior to k that was a test. The user inputs incidental yield (*inc*Y_i) and embedded yield (*emb*Y_i) for all i. Assuming a total of n steps in the process flow, the cumulative yield, $Y_{Cumulative}$, can be calculated as :

$$Y_{Cumulative} = \prod_{i=1}^{n} Y_i \qquad \text{Equation 18}$$

The yields (Yi) used for the analysis presented in this paper are based on the yields the studied firms were able to achieve post-rework. Future modeling efforts to integrate the direct cost of rework would be a useful extension of this analysis.