Technology Roadmapping:
Mapping a Future for Integrated Photonics

Elizabeth J. Bruce and Charles H. Fine
Massachusetts Institute of Technology

Invited Tutorial

I. Introduction

Technology roadmaps are used by a growing number of organizations including corporations, government agencies and research institutes. Roadmaps are used for many purposes, in domains as varied as foreign policy, corporate strategy, and fundamental scientific research. Roadmaps can take many different forms depending on the purpose, the application, and the audience.

Roadmaps provide a framework for thinking about the future. They create a structure for strategic planning and development, for exploring potential development paths, and for ensuring that future goals are met. "Roadmapping" is the term used to describe the *process* of developing a roadmap. Practitioners often assert that the roadmapping "process" is at least as valuable, as the output, the roadmap itself.

This tutorial provides the basic concepts used in technology roadmapping, including descriptions of different types of technology roadmaps and approaches, as well as a discussion of the costs and benefits of roadmapping. A concrete example follows, discussing the challenges associated with roadmapping integrated photonics technologies in the communications industry, and efforts in this domain within MIT's Communications Technology Roadmapping (CTR) program (**http://mph-roadmap.mit.edu/**)

II. Technology Roadmapping

Background

Contemplating technology futures can be a daunting task. One must weigh many sources of uncertainty and try to comprehend how a large number of complex and dynamic factors might interrelate and influence development of a process or a technology. The challenge is to lay out a framework that takes into account the key variables that can influence the evolution of technology and relevant business development. Roadmapping provides a framework for understanding, communicating, and assessing these dynamic factors. Roadmapping is not the only tool for this type of strategic planning,[1] but it is practical and straightforward in its approach and gaining increased attention and usage.

While roadmaps have been used in a variety of fields, from medicine (the National Institutes of Health Roadmap[2]) to foreign policy (the State Department's Roadmap for Peace[3]), roadmapping has its origins in technology management [1, 2]. The processes of technology roadmapping have been developed primarily through usage in industry. Roadmapping has also received attention in the academic literature [2A-2C], with an emphasis on methodology and best practices applied to roadmapping within a business organization.

---

[1] Others include scenario planning; Delphi method [H.A. Linstone, M. Turoff, The Delphi Method: Techniques and applications, Addison-Wesley, Reading MA, 1975.]; forecasting; foresight, etc. **Need some references.**
[2] http://nihroadmap.nih.gov/
[3] http://www.state.gov/r/pa/ei/rls/22520.htm

The term "roadmap" has been used broadly, depending on the audience, participants, and purpose of the practice. Robert Galvin, former Chairman of Motorola and one of the early supporters of roadmapping, referred to the roadmapping process as the creation of a vision. He believes roadmaps can be used to create the future as well as to contemplate the future:

"*Roadmaps provide an extended look at the future of a chosen field of inquiry drawn from the collective knowledge and imagination of the groups and individuals driving change in that field. Roadmaps include statements of theories and trends, the formulation of models, identification of linkages among and within the sciences, identification of discontinuities and knowledge voids, and interpretation of investigations and experiments.*"
- Robert Galvin [3]

Roadmaps can also be used to outline a very specific set of technical requirements, for example, to map out the development of a particular product or product feature:

"Typically based on strategic plan requirements, *roadmaps incorporate product attributes and layout goals, development requirements, allocations priorities, and defined evolution plans for flagship or core products and platforms. …The output of the technology roamapping process is typically a product-specific roadmap which, in simple visual representations of hardware, software and algorithm evolution, links customer-driven features and functions to specific clusters of technologies."* - Strauss, Radnor & Peterson [4]

Within Motorola, Galvin described the use of "Emerging Technology Roadmaps," which are used to look broadly at technological possibilities, whereas Strauss et al., focus on "Product Technology Roadmaps." [ref: Motorola's Technology Roadmap Process, Willyard & McClees, 1987] which are used more narrowly, to translate a set of system specifications (or customer requirements) into specific product attributes. Product roadmaps are used to identify technology gaps and communicate resource requirements. Each of these two types of roadmaps emphasize different stages of technology development - from emerging, where the emphasis is on exploring possible future paths of a technology, to product planning, where the focus is on aligning market requirements with product development and internal resources.

While the processes and outputs of these two types of roadmapping can vary significantly, there are common elements. Roadmapping requires:

- a social and collaborative process;
- an analytical method of assessing and planning future development;
- a means of communicating using visual or graphic representations of key targets or goals as a function of time.

Although roadmapping has been deployed by many individual organizations, including Philips, Corning, British Petroleum, GM, Lockheed Martin, Intel, and Lucent Technologies, as well as Motorola, roadmapping has also proven highly effective at coordinating *groups* of organizations in collaborative contemplation of technology futures. A recent study conducted for the Dutch Ministry of Economic Affairs identified many examples of "industry roadmaps" or "sector roadmaps" (the term used in Europe), where multiple organizations from across an industry come together to collectively develop roadmaps. Examples include roadmapping at many different levels, such as:

- industrial sectors (aluminum, steel)
- economic clusters (electricity, offshore)
- sets of technologies (carbon sequestration, photovoltaics)
- cross-cutting technologies (catalysis)

- specific product areas and markets (automotive, medical imaging)
- problem areas (climate change)
- scientific sub-disciplines (computational fluid dynamics)

That study identified in April 2002 a total of 78 industry technology roadmapping projects on-going around the world. The majority of these were based in the U.S.A. (41), followed by Japan (17), Canada (12), and Europe (3). The most common industry areas include: chemical, metal, energy, electronics and semiconductors.

Roadmapping is a practical tool for strategic planning, both within organizations and across multiple organizations, and its benefits are tangible - in terms of clarifying resources or technical gaps and in improving communications within organizations and across supply chains. Still, roadmapping as a methodology is at an early stage of development, and while there are many roadmaps in existence there is no single approach to roadmapping. As roadmapping gains broader usage, many of these approaches continue to evolve as they are adapted for different purposes. The following sections provide a review of the different approaches to technology roadmapping; the benefits; key methodologies; and a discussion of the common challenges faced in launching and maintaining a roadmapping practice.

Approaches to Technology Roadmapping

The discussion above, which distinguishes between exploratory and product roadmaps and between individual and collaborative roadmaps, suggests two dimensions (technology scope and organization scope) that define four categories (shown in Figure 1) for roadmapping projects.

Technology Scope

Exploratory Mapping is used as a framework to explore emerging technologies and to examine potentially disruptive technologies. The process creates a map of the technology landscape by surveying possible future scenarios. There is not necessarily consensus on the technology or its evolution at this stage.

Target-Driven Roadmapping used to drive toward a specific technical target. The technology objective is clearly articulated and there is a level of consensus on what the targets should be. The roadmap serves to drive innovation and resources toward reaching that end goal.

Participation Scope

Single-organization roadmapping activity occurs within a firm or organization, e.g. companies; non-governmental organizations; government agencies; non-profit organizations, etc. Roadmapping projects of this sort are often led by a research lab, strategic planning team, or product development team within the organization.

Multi-organization roadmapping incorporates more than one organization, and can focus on an entire industry or sub-sector of the industry. Participants may include corporations, academic institutions, government agencies, etc. Roadmapping projects of this sort are often led by a government agency, consortium or industry trade association.

Exploratory Mapping vs. Target-Driven Roadmapping

Technological progress cannot be expected to follow a linear and predictable trajectory. Therefore, to be effective, roadmapping must include some way of identifying and incorporating potentially disruptive innovations. Exploratory mapping includes the process of surveying an uncertain technology landscape, while target-driven roadmapping focuses on processes for incremental development along an established trajectory, with a known set of technology objectives. The difference between these two activities is significant; however, technology roadmapping can provide a useful framework for managing either.

In exploratory mapping, the emphasis is not on driving consensus, but on identifying possible paths and scenarios that might obsolete existing solutions. Many technology alternatives may be considered, including both incremental and potentially disruptive technologies. This process should also consider non-technological disruptive innovations, such as new business models, cost structures, or manufacturing processes that might also impact the technology landscape.

Within a company, exploratory mapping may be used, for example, when a new technology is developed or acquired and a company needs to assess its capabilities; forecast the possible future development paths of the new technology; explore its application in existing or future products; assess competing technologies, or determine what new market opportunities may exist. As a multi-organization activity, this process is done collectively and collaboratively.

When a technology goal is well-specified, the technology roadmapping process is used to allocate resources and drive progress, articulating a path to get from Point A (current state) to Point B (desired state). The roadmapping process is focused on technical targets and on driving consensus around how to meet those targets. Unlike the exploratory mapping stage, Point B is typically well-defined and progress moves incrementally from Point A to Point B. Progress is tracked by a set of performance metrics and key targets are translated down the value chain, from systems to components to devices to manufacturing requirements to materials and processes.

Roadmapping is more straightforward in the case of target-driven roadmapping, as the evolutionary path of a technology will be better understood and more easily identified. It is easier to anticipate incremental and linear advances in technology development.,

"Although roadmapping incorporates technology trajectories and competitive environment inputs, as typically implemented, it generally assumes a straight line, incremental assumption set" - Kappel, Radnor and Peterson [8]

Exploratory mapping is more difficult; it focuses on assessing alternate future scenarios and challenges participants to consider non-incremental possibilities.

Technology S-curves are often used to describe the technology life-cycle [9]. As a technology matures, its performance goes through a period of steady improvements over time until it eventually flattens out. In terms of roadmapping, at the early stages of the S-curve the emphasis is on exploratory mapping. As a technology matures and the focus shifts to improving key performance metrics, there is more emphasis on target-driven roadmapping. During this stage, target-driven roadmapping can improve the slope of the S-curve, by accelerating technology development. (see Figure 2)[4]

[4] S-curves are also be used to describe the product lifecycle or market penetration of a product over time [10]. The diagrams look the same, but our focus here is on improvement of technological performance over time, not on product volumes.

In practice the dividing line between target-driven roadmapping and exploratory mapping is not rigid, instead the transition between one and the other is continuous. In any roadmapping practice, the emphasis will change over time as an industry and its technologies mature and as new technologies emerge. If a target-driven roadmap exists, then exploratory mapping is used to look "off-the-roadmap". Exploratory mapping can lead to development of one or more target-driven roadmaps to support critical sustaining technologies. The percentage of time spent on each will change over time during the different stages of technology maturity.

"Target-driven roadmapping" refers to a defined set of technical or product targets. All organizations have business and policy objectives to consider as well. These targets may be clearly articulated and roadmapping can be used to drive progress toward these objectives as well. Business targets, for example, often translate to profitability metrics, such as a 10% cost reduction over the next 3 quarters. Policy targets are often social objectives driven by governments, regulatory agencies or industries collectively. Translating these objectives to technology development can still be a significant challenge. Defining a policy initiative, such as high-speed internet connectivity at "100Mb/sec to 100 million homes by 2010", is a clear target, but it does not directly translate to a broadband technology roadmap. Despite clear business and policy targets, exploratory mapping may still be a critical part of the technology roadmapping process.

Single vs. Multi-Organization Roadmapping

Exploratory mapping and target-driven roadmapping describe two different approaches to the technology scope of the roadmapping process, with a shift in emphasis from laying out the technology landscape to mapping a direct route. The type of roadmapping participation will also shift the emphasis of a roadmap, from internallyfocused projects conducted by a single organizarion to cross-industry projects conducted across multiple organizations.

Single-Organization Roadmapping

Adoption of roadmapping within firms varies widely, from a one-time planning process to an on-going part of business planning and strategy. In a corporation, one primary need for roadmapping is at the product-line level. Roadmapping is used to align product development with customer demand and product features with customer preferences. Roadmapping can be used to map out the key organizational resources needed and to identify gaps where the organization may need to outsource, partner or acquire a technology or some other resource.

Participation can span different roles within an organization, from researchers, applications & development engineers to marketing and sales team members. Depending on how roadmapping is incorporated, a firm may re-visit the roadmaps once a year during an annual strategy planning process or several times a week when roadmapping is an integral part of business planning or during periods of rapid change. Versions of product roadmaps are often used for communicating externally, with suppliers, customers, investors, etc.

A number of researchers have explored the use of technology roadmapping within corporations and several case studies on this topic have been presented [11-13A].

Multi-Organization Roadmapping

Academic-industry consortia, government organizations, and industry trade associations have a unique role in roadmapping since they can bring together representatives from across

an entire industry or value-chain. Since there are strong inter-dependencies among different parts of a value-chain, these linkages must be considered in any roadmapping process. Depending on the scope and objectives of the roadmapping activity, participants may choose to focus on a segment of the value-chain or they may choose to address the entire value-chain. Figure 3 shows a value-chain for optical communications. A roadmapping effort might focus specifically on the optical components portion of the supply chain or it may encompass the entire value-chain.
Industry roadmapping can accelerate progress of an entire industry and provide a forum for learning that benefits of all the stakeholders. The roadmapping process facilitates the discussion and exchange of information and ideas. It challenges an industry to ask difficult questions and consider alternative futures and/or disruptive innovations. Industry roadmaps can address issues that may be difficult for just one organization or company to manage alone, instead cross-industry collaboration and planning may be required in order to make progress.

Industry roadmaps can be used to coordinate efforts aimed at assuring long term health of an entire industry and its supply chain by reinforcing critical components of the industry's infrastructure and reducing duplication of costly commonly needed research resources. Roadmaps can be used to advise and guide government funding of fundamental scientific research needed to sustain an industry in the long term. Development of necessary enabling technologies can be accomplished without violating the intellectual property rights or trade secrets of the participating companies.

The International Technology Roadmap for Semiconductors (ITRS) is one of the most well-recognized multi-organization technology roadmapping efforts [14]. Roadmapping in the semiconductor industry began in the United States in the early 1990s with Micro Tech 2000 - a workshop organized to chart the technology strategy for semiconductors over the coming decade with the end goal of achieving a significant technical target by the year 2000 [27]. ITRS participation has now expanded to include over 900 people from the U.S., Japan, Europe, Korea, Taiwan, China and other regions. The objective of the roadmap over the past decade has been to sustain historical industrial productivity (or "Moore's Law").

ITRS is target-driven with 'device minimum feature size' representing the principal metric for scaling. ITRS has lead the way in defining multi-organization roadmapping processes and is often the activity against which other roadmapping efforts are compared. Additional examples of industry roadmaps include: National Electronics Manufacturing Initiative Roadmap (NEMI), Lighting Technology Roadmap (DOE); Photovoltaics TRM (Photovoltaics Industry); MEMS Industry Group Developing Industry Roadmap (MEMS Industry Group); European commission (RACE, Espirit). [Ref.]

Benefits of Roadmapping

The benefits of roadmapping are often derived directly from participating in the roadmapping process itself, rather than merely consuming a roadmap document produced as a final report. Examples of some of the benefits derived from the roadmapping process include:

1. Establish a vision for the future. Roadmaps create a common framework for thinking about the future and create a platform from which to discuss and debate the key issues.
2. Encourage systems-thinking. A comprehensive roadmapping framework forces the roadmap participants to think about technology development within the context of a larger system and aids better understanding of the linkages among technology, policy, and industry dynamics.

3. Planning and coordination tool. Roadmaps align technologies and products with market demand by representing the co-evolution of technology and markets. Roadmaps can help in uncovering common technology needs within an organization, enabling the sharing and consolidation of R&D, supply-line and other common resources [15]
4. Accelerate innovation. Roadmapping provides a better understanding of the potential paths for innovation, helping to visualize new opportunities for future generations of product developments.
5. Communications. Within corporations, roadmaps can provide a crucial link between management teams, marketing, engineering and R&D - improving communications and providing a clear sense of near term and long term targets. Visual representations of technology development and technology gaps can help executive management clearly understand the factors that go into making strategic decisions. Industry roadmaps can aid communications with customers and across the value-chain.

In addition, multi-organization roadmapping can:

6. Enhance prospects for economic growth for an entire industry sector through collaborative efforts at innovation and technological development.
7. Justify investment opportunities and lower investment risk. Industry roadmaps can provide a means for reducing investment risk by aligning and developing a common set of resources or tools. A roadmap can be used to optimize resources across a value-chain, for example, to ensure that key technologies and manufacturing tools required to develop them are available within the necessary time frame. Knowing what is required and when can reduce investment risk, improve the probability of success, and speed timeframes for development, ensuring that technology development and innovation continue.
8. Guide fundamental scientific research and government funding. Roadmaps can be used to convince those in government regarding support of fundamental scientific research that will address long term technology barriers. [15A]

Technology Roadmapping Process

Launching a Roadmapping Process

Initiating a technology roadmapping process can be one of the most challenging obstacles in the entire process. There must be a strong commitment from those involved to make the process successful. Getting the process started requires a significant amount of effort, especially in the early planning stages where the objectives, scope, process and framework are defined and tailored for the specific application. Research by Kappel, et al. reveals that "…the most influential roadmaps originate as responses to perceived threats and link the technical storyline to organizational and personal concerns," suggesting that that fear works best to motivate roadmapping, rather than just "seeking opportunities to get ahead." [16]

Building a Framework for Analysis

A complete roadmap framework should consider the interplay among the dynamics of technology development, business environment changes, and public policy enactment. These factors can all play significant roles in shaping the future of a technology-based industry and should therefore be integral to the roadmapping process Figure 4 (the Gear Model), suggests that business environment dynamics include business cycle dynamics; industry structure dynamics; corporate strategy dynamics; customer preference dynamics; and capital market dynamics. Availability of resources for investing in new technologies is highly dependent on business cycles and availability of capital. Changes in industry

structure, from horizontal integration to vertical disintegration [17], can significantly impact supply chains and manufacturing. Shifting customer preferences can change market opportunities and impact product features.
Policy dynamics include changes in different regulatory environments, at a local, national and international level, that can directly impact, for example, the rate of technology investment and/or adoption. Regulatory issues can play a critical role in defining the roll-out of new products and technologies in certain markets. For example, in the broadband FTTH (Fiber To The Home) market, rulings of the FCC (Federal Communications Commission) regarding competitive regulation of the incumbent service providers, has significant impact on the business decisions of many telecommunications companies [18]. Decisions on regulated prices for service can impact technology choices and the rate of deployment of communications equipment. Understanding regulatory and policy dynamics can be critical in roadmapping certain technology areas-- for instance communications, commercial aircraft, pharmaceuticals - areas that are heavily regulated by the federal government.

The degree to which each of these dynamic processes impacts a technology roadmap will vary. In some cases policy dynamics may be largely irrelevant; in other cases in may be a critical gating factor to deployment. Understanding which of these dynamic forces are key, and how to incorporate them in an overall roadmapping framework, is an essential part of the planning process.

Roadmapping Methodologies

No single formalized methodology for technology roadmapping exists because roadmapping frameworks and processes are tailored depending on the application. However, there are a set of common steps useful in many roadmapping processes (see Figure 5):

Phase I. Planning. The planning stage frames the roadmapping process based on the objectives and scope of the particular application. During the planning process, the boundaries of the activity are defined; the resources for the activity are secured; and buy-in from the participants and contributors is established.

Phase II. Input & Analysis.
<u>Expert-Based Input.</u> Workshops and/or working groups are a primary mechanism for roadmap development. Workshops are typically a series of meetings that bring together the appropriate people to voice opinions and provide expert testimony as required. Identifying the right group of participants is critical.

<u>Analysis.</u> The analytical work that supports roadmap development may include predictive modeling tools, computer simulations, and/or case studies.

Phase III. Roadmap Output. Visualization is an important part of communicating the roadmapping findings. Forms of displaying the information may differ depending on audience, e.g. upper management, decision makers, cross-industry, suppliers, etc.

A basic technology roadmap format includes different layers representing market drivers ("why"); products or systems ("what"); and technology ("how") [15], [19] (see Figure 6). These key areas are mapped out as a function of time. The roadmap can also be used to illustrate the linkages between these domains translating the overall roadmapping framework into a straightforward visual representation. Roadmap formats are adapted to reflect the application, often leading to additional layers in the roadmap. These layers might include, for example:

- "Why": Market drivers; customer requirements; competitors; environment; industry trends; industry structure; business objectives; strategic objectives; policy goals.
- "What": Products; systems; services; applications; capabilities; performance; features; components; processes; platforms.
- "How": Technology; competencies; knowledge; skills; facilities; infrastructure; standards; science; finance; R&D projects. [19], [20].

Since roadmapping can be used for such a wide variety of applications, both the process and the framework require customization to be effective.

"…roadmapping can support a range of different business aims, including product planning, exploration of new opportunities, resource allocation and management, and improved business strategy and planning. In addition, each organization is different in terms of its particular business context, organizational culture, business processes, available resources, technology types, etc. For these reasons, if the full benefits of roadmapping are to be gained, then it should be expected that the approach will need to be customized to suit the particular application." [20]

Figure 7 illustrates many of the different uses for technology roadmaps. While some roadmaps may focus on one of these particular areas, often they incorporate different elements from several of these areas to serve the specific requirements of a group. Determining how to tailor the roadmapping process to a particular use is a critical part of the planning process. For further reading on customizing the roadmapping process see [19] [19A]. [20].

Techniques for Target-Driven Roadmapping

The following process for development of a product technology roadmap illustrates the general approach to target-driven roadmapping (adopted from Strauss, Radnor & Peterson, [4]:

1. Identify the product. Participants select the product to focus on and agree on the set of customer needs driving the features and functionality.
2. Specify the critical system requirements and their targets. Requirements should focus on meeting customer needs. There may be multiple sub-systems and components that need to be defined. Identify major technology clusters (e.g. software; physical interfaces; displays; quality and reliability). These groups should represent the key enabling technologies and components.
3. Translate system requirements into technology requirements. These requirements will determine which technology is required to deliver necessary system or product performance. Assess current capabilities with respect to the enabling technologies and performance targets.
4. Creation of roadmap visuals. Translate technology mapping to customer drivers, show where commitments have been made and where near term funding decisions are required.

During this process, exploratory mapping of different technology alternatives may prove valuable. Different analytical and modeling tools might be used to help assess which technology alternatives to pursue.

Techniques for Exploratory Mapping

Exploratory roadmapping can be significantly more challenging than target-driven roadmapping since there are a number of possible paths to explore and setting the boundaries, without immediately ruling out possible scenarios, can be difficult and time consuming. Several approaches and tools for exploratory mapping (or "disruptive roadmapping") have been suggested in the roadmapping literature:

- Multi-Scenario Mapping combines both scenario mapping and roadmapping as a process for considering alternative paths within a roadmapping framework. Scenario mapping is the process of developing detailed pictures of alternative futures. Scenarios are derived from a future perspective rather than projecting from present situations, allowing the consideration of systemic change. [21]
- Text-mining and literature-based discovery are used to identify all technology alternatives. Clustering techniques are used to identify main technology categories and key researchers/organizations in these areas. Representatives from these areas are brought together to participate in the roadmapping process (through workshops) to identify the most promising (technology based and non-technology based) solutions. [22].
- The SAILS methodology is a heuristic approach for exploring disruptive technologies that includes a systematic assessment of Standards; Architecture; Integration; Linkages; and Substitutions. [23]
- Knowledge mapping and free-form simulation games can be used map out technology futures. Knowledge mapping is a visualization tool for mapping large datasets, such as the Science Citation Index. Simulation games provide an interactive forum for exploring different potential scenarios in a group and considering the complex relationships and problems that can arise. [25]

Technology roadmapping can be used to explore emerging technologies, both within firms and at the industry level. At the industry level for example, the international Micro and Nano-technology Commercialization Education Foundation has used technology roadmapping to explore the potential futures for MEMS (Micro Electro-Mechanical Systems). A case study, by S. Walsh, provides an overview of how they applied the roadmapping process and how they were able to adopt and tailor certain techniques from target-driven roadmapping processes [23A]

Tools for Roadmapping Development

Software based tools have been developed for managing roadmaps electronically. Software tools can incorporate large databases, electronic surveys, graphics tools, and project management tools. These tools can be used to continuously update and maintain roadmaps and provide a systematic method for linking multiple roadmaps. Strateva's 'Vision Strategist' is a software tool designed specifically for roadmapping [24]. Motorola has incorporated this software in their organization to manage all of their on-going corporate roadmapping activities, which now include over 1400 users and 1100 roadmaps. [6]. Purdue University Centre for Technology Roadmapping also utilizes the Vision Strategist software to maintain a large database of industry roadmaps [24A].

Incorporating software based roadmapping tools can be challenging at the early stages of the process, practitioners have found software tools most useful once a roadmapping process has been established and participants are familiar with the techniques[5]. While software tools may provide significant value to the roadmapping process they should not become a replacement for the social aspect of roadmapping. Face-to-face workshops, meetings, and on-going interactions are a central part of the roadmapping process.

[5] Telephone interview with Bruce Kirk at Corning, Inc., June 2004

Social Aspects of Roadmapping

Roadmapping is a collective activity; the social and interactive aspects should not be underestimated. Roadmaps result from a collection of people working collaboratively. Roadmapping workshops and working groups provide a forum for interaction across different industry segments and organizations, and provide a unique meeting place for people that may not normally come together. Roadmapping workshops purposely create time to 'think' about the future, to step out of one's day-to-day mind set, and to challenge conventional ways of thinking. During these workshops, open interaction is important and techniques for incorporating contributions from all of the participants should be used to capture differing and "minority" viewpoints.

Roadmaps will be subject to the biased frames of their authors. How a person views a technology, the product requirements, or market demand - is a function of their background, experiences, and personal agenda. It is important to consider the different influencing factors dominating individual perspectives. A successful roadmapping process must consider this by seeking input from people with different backgrounds and experiences. [26]

Another critical component for industry roadmapping is trust.[6] There must be a willingness and openness to share information publicly. Semiconductor companies involved in the ITRS have tried to focus on "pre-competitive" information, meaning information that provides technology infrastructure to the industry, rather than on technology specific to any particular semiconductor product(s). Over the history of the ITRS roadmap, the proportion of total knowledge denoted pre-competitive has grown over time, …"successive roadmaps have become more complete (increased specificity and granularity of technology requirements)." Members of the semiconductor community became more comfortable sharing information as trust was established and the roadmap became more widely accepted. [27].

Roadmap ownership

As a roadmapping process shifts from exploratory mapping to target-driven, there is also a shift in participation and leadership (see Figure 8). For single-organization roadmapping, exploratory mapping may be driven by research and development labs or by a corporate strategy team. As roadmapping becomes increasingly target-driven, it will likely be led by the actual product development team engaged in creating a product for an end customer. In the case of multi-organization roadmapping, academic-industry consortia and government agencies may lead exploratory mapping. Target-driven roadmapping, especially where there is a shift toward driving industry standards or coordination of the supply chain, is best lead by industry (typically an industry or trade association), rather than academia or government.

Roadmapping Success Factors

There are many factors that go into establishing a successful roadmapping process. Above all, roadmapping:

- should be an iterative process;
- requires commitment from the participants, in terms of both time and resources;
- depends on the competence of roadmap participants; .
- should be led by the stake-holders.

[6] Telephone interview with Herbert Bennett, Semiconductor Electronics Division, NIST, July 2004.

What are the metrics of success? Roadmapping success is not necessarily dictated by how accurately the roadmap predicts technology targets. Success factors include:

- longevity of the effort (people only stay engaged of they are learning something of value);
- scope of impact (*i.e.,* degree to which it is referenced in industry, conferences, publications, *etc.*);
- rate of improvement in technology development and profitability;
- amount of influence and impact on decision-making.

Roadmapping Challenges

Practitioners can face many challenges in attempting to launch and maintain a roadmapping process. As an on-going activity, roadmapping consumes time and resources, especially as a multi-organization activity where effort may require input from a vast number of people from different organizations and countries (ITRS has over 900 people participating). Maintaining the roadmap and the process becomes partly an issue of project management.

As a one-time process, the output and benefits of roadmapping may be short-lived, particularly in "high-clockspeed" industries where technology and customer/consumer demand can change rapidly and the complex dynamic forces that shape the industry are constantly evolving. Therefore, successful roadmapping should be adopted as a part of an on-going strategic and planning process.

Additional challenges include defining in a useful way a format for the output and visualization of an exploratory mapping activity, as well as developing a common "vocabulary" for people who come to a roadmap project from a wide range of organiazations and backgrounds.

III. Photonics Industry Roadmapping as a Case Study

Need for a Roadmap

The photonics industry, whose contributions include the core technologies for fiber optic communication systems, faces many challenges in the aftermath of the dot-com/telecom boom and bust. Still recovering from the dramatic industry-wide downturn, many companies are struggling to become profitable and survive. The photonics industry provides an interesting domain to consider roadmapping because it shares many features with the semiconductor industry, but is smaller and less mature. Photonics industry challenges include:

- Increased component pricing pressure.
- Limited set of common standards or platforms. At the component and sub-component level there are few standards or platforms that address multiple applications and/or markets.
- Proliferation of products and manufacturing processes.
- Limited resources for investment.
- Limited tools available specifically for manufacturing and testing photonic devices, including process equipment; software design tools; and metrology tools.
- Lack of a successful foundry model for photonic devices.

Over the next decade the number of applications for photonics will grow, further adding to the challenges listed above. Markets for integrated photonics are diverse including: telecommunications (long haul, metro, submarine), datacom, storage area networks, optical backplanes, automotive, consumer electronics, interconnects (board-to-board, chip-to-chip), broadband Internet connectivity, and more.

Optical transceivers provide an example of product proliferation in the photonics industry. Transceivers have been designed to address a variety of applications and products vary in terms of bit rates; wavelengths; form factors; and reach (see Figure 9). As a result there is a huge variety of transceiver products commercially available (a recent survey of commercial transceiver products reveals over 500 different transceiver products [28.] As new markets emerge for photonics, this proliferation is likely to continue. With a limited set of common standards and platforms across these different markets, the challenges of reducing component costs; developing common manufacturing processes and tools; and increasing volume production will persist.

How might a roadmap contribute to the photonics industry?

- Educate suppliers on critical technical, industry, and policy barriers and create a forum for discussing potential solutions or alternatives.
- Drive process development.
- Establish a common platform to drive higher scale in manufacturing.
- Encourage development of new tools specialized for photonics.
- Recommend the adoption of new standards.
- Ensure a sustainable supply-chain for optical communications.
- Focus limited investment resources on critical problems.
- Develop and promote a successful foundry model for photonics.

Challenges in Roadmapping Photonics

Despite the incentives, roadmapping in the photonics industry has been sporadic and has met with limited success. An Internet search for “photonic roadmap” reveals about 6,000 sites, by comparison an Internet search for “semiconductor roadmap” finds over 70,000 sites. While there are many analogies between the semiconductor industry and the photonics industry, there are also some unique differences. In the following section we describe some of the challenges in roadmapping photonics.

Integrated photonics is at the early stages of maturity. Roadmapping during this stage is more challenging and should focus primarily on exploratory mapping. In contrast, the semiconductor industry has been developing target-driven roadmaps consistently since the early 1990s. Figure 10 compares the stages of technology maturity on the technology S-curve. The performance of integrated circuits has been continually improving over the last decade, driven by Moore’s Law. The ITRS roadmap focuses on particular target metrics, device minimum feature size, and guides progress and development along with scaling of these targets over time. The equivalent scaling metrics and scale of market demand do not exist in the photonics industry.

Rapidly changing industry and policy dynamics mean Roadmaps are quickly outdated.. The global market for optical components reached a peak in 2000 at $6.8 billion, falling to $2.2 billion in 2002 [source: RHK]. During this period Venture Capital funding for communications significantly dropped: telecom-related startups raised $2.9 billion in 2002, compared to $6.4 billion in 2001. The industry structure has shifted as major systems companies sold off their component divisions (Nortel, Lucent, Alcatel) and several suppliers have exited the industry (Agere, Marconi, ADC). In addition, the regulatory environment remains uncertain for broadband deployment (recent FCC rulings, Feb 2003). All of these dynamics heavily influence technology development and planning. Roadmapping can be especially challenging during periods of rapid change and roadmaps quickly become irrelevant. The benefits of roadmapping during periods of rapid change, are derived at least as much from the process of weighing scenarios as from the reported output.

Diverse set of materials and processes makes it difficult to focus on a common platform and set of standard processes. Photonic devices are manufactured from a range of materials, including silicon, III-Vs, organics, silica, ceramics, and lithium niobate. Further, each material platform has a diverse set of process technologies for manufacturing. Engineers in electronics and photonics have expertise in very different fabrication processes, increasing the challenges of integrating both electronic and photonic functions on the same chip. Semiconductors and the processes addressed in the ITRS roadmap, on the other hand, are focused on silicon. There are common process technologies and equipment, established device and test standards, and high levels of integration. The diversity of materials and processes in the photonics industry significantly increases the challenges in developing a target-driven industry roadmap.

Limited history of collaboration across the photonics industry means it will take time to establish trust. It can be more difficult to initiate technology roadmapping in industry sectors that do not have a history of collaboration or do not have some network structure in place. This may be one of the challenges with initiating a collective roadmapping activity in photonics industry since there is little history of open collaboration or sharing of information in the past. For the semiconductor industry SEMATECH and Microtech 2000, established social networks and a precedent for sharing information and collective action [27].

In summary, roadmapping in the photonics industry is at a very different stage than the semiconductor industry (see Figure 11). ITRS has historically focused on target-driven roadmapping, although there is now a shift to incorporate exploratory mapping. For the first time in 2003, the ITRS included a chapter on "emerging technologies" the semiconductor industry is no longer scaling at its historical rate as industry seemingly approaches the end of improvement rates aligned with the predictions of Moore's Law. The photonics industry is at initial stages of exploratory mapping, with a focus on surveying the technology landscape and assessing different technology alternatives. We should not expect the output to look like an ITRS roadmap at this stage.

Overview of Photonic Industry Roadmaps

The following section provides a brief overview of past and present roadmapping efforts in photonics at the industry (multi-organization) level.

North America: Optoelectronics Industry Development Association (OIDA) [30].
OIDA is an industry association representing optoelectronic systems and components suppliers. OIDA has developed optoelectronics technology roadmaps in a number of areas including - sensors, multimedia, parallel optical interconnects, military and aerospace. They have recently focused on roadmapping LEDs[7] and photonics manufacturing. OIDA's roadmap for optical communications was published in Sept,1999 (see Figure 12. [Need Permission to Reprint from OIDA]). OIDA did not continue roadmapping optical communications beyond 2000. The roadmap was generated from the output of a series of workshops and projected technology targets (including bit rate; number of WDM channels; and level of integration) out to 2010.

North America: National Electronics Manufacturing Initiative (NEMI) [31]

[7] (Ref: "Light Emitting Diodes for General Illumination: An OIDA Technology Roadmap Update 2002")

NEMI is an industry led consortium, representing manufacturers and suppliers from across the electronics manufacturing supply chain. NEMI roadmaps incorporate input from other industry roadmaps including: Magnetic & Optical Storage Roadmap; the OIDA roadmap; the IPC Interconnection Substrates Roadmap; the Semiconductor SIA roadmap; and the USDC display roadmap. NEMI incorporates a chapter on "Optoelectronics" in their roadmap document (one of nineteen total roadmaps published by NEMI). NEMI maintains an Optoelectronic Technology Working Group (TWG) - responsible for writing the roadmap chapter - and an Optoelectronic Assembly Technical Interest Group (TIG). NEMI's roadmap focuses on the manufacturing and assembly technologies of opto-electronic components, emphasizing optical backplane/interconnects applications. Figure 13. [Need Permission to Reprint from NEMI] shows a roadmap chart for OE data communication technology at the product or board level. NEMI's roadmapping process involves identifying a "product emulator", a representative product used for roadmapping technology targets.

North America: IPC and PMAC (Photonics Manufacturers Association) [32]
IPC, the Association Connecting Electronics Industries, is a global industry association for printed circuit board and electronics manufacturing services companies, their customers and suppliers. The PMA is a group within IPC with a specific focus on photonics, roadmapping and standards activities. PMA has a subcommittee that distills existing industry roadmaps (from NEMI, OIDA, IPC, and SIA) specifically focusing on the assembly, test, and standardization of OE devices and modules. PMA uses the roadmapping process to identify areas requiring standards and prioritizes key standards generation efforts.

In Nov 2002, IPC generated a Roadmap for Optoelectronic Standards [Ref. IPC-0040 "Optoelectronics Assembly and Packaging Technology"] document - this document identifies 23 key areas requiring standards development (see Figure 14) [Need permission from IPC to reproduce]. The work emphasizes that although some standards do exist, they are not aligned, some are only partly relevant, and they don't necessarily address the right set of issues. Work has since begun in defining standards in some of these areas.

Canada: Canadian Photonics Consortium (CPC)
The CPC is a consortium formed of Canada's photonics-related organizations and institutions. The CPC initially launched a photonics roadmapping activity in 2000 that included a series of workshops with industry and government participants from across-Canada representing different photonic areas. Focus of the roadmapping activity was on identifying and prioritizing the high-level technology issues and areas of required research development. CPC's photonics roadmapping activities have not continued beyond 2000. [Ref. CPC roadmap report]

Global: International Technology Roadmap for Semiconductors (ITRS) [14]
The ITRS does not include a photonics industry roadmap. However, for the first time, in 2003 ITRS document includes a III-V compound semiconductor roadmap. The III-V roadmap is embedded in the Chapter on RF and Analog-Mixed Signal Technologies (for wireless communications). [29] In addition, as delays become increasingly problematic with conventional copper interconnects, alternative technologies must be explored - including the possible use of optical interconnects. Optical clock distribution on silicon ICs may also become a possibility in the long term (beyond 10 years). The question is how and when do photonics become integrated with CMOS circuits and will ITRS take a lead on roadmapping this convergence?

Europe: Information Society Technologies (IST) OPTIMIST Programme [34]
The European IST Optimist program (funded by the EU) lasted four years, ending June 2004. The focus of this group was on roadmapping photonics, from a technology-push or

bottoms-up perspective. The program involved government, companies and universities from across Europe. The roadmapping activity included a series of brainstorming and planning workshops and several roadmap documents were generated (available for download from their site). Late 2003, the European Photonics Industry Consortium (EPIC) was founded to continue on the work started by the OPTIMIST program. EPIC plans to develop and maintain the technology roadmap for photonic technologies in Europe (http://www.epic-assoc.com/). The EU sponsored BREAD (Broadband in Europe for All: a multi-Disciplinary approach) program will also continue the work in mapping photonics under a much broader framework examining broadband.

Japan: Optical Industry and Technology Development Association (OITDA) [35]
OITDA is Japan's optoelectronics industry association, representing 170 companies. According to a recent survey of industry roadmaps from across the globe, the 1996 Photonics Technology Roadmapping published by the OITDA was the first multi-organization technology roadmapping report to emerge from Japan.[7] OITDA has since updated the optical communications roadmap in 1999 and again in 2001. The roadmap sets high-level technology targets including WDM channels; fiber transmission capacity; fiber amplifier bandwidth (see Figure 15., need permission from OITDA).

Singapore: Infocomm Development Authority of Singapore (IDA Singapore) [36]
The IDA of Singapore developed a roadmap report on optical networks and photonics in 2002. [Ref. "Next Gen Optical Networks and Photonics Technology Roadmap Report.", available for download from website] The report highlights the enabling photonic technologies required for future optical communications systems. Included is a survey of key technology alternatives, trends, issues and challenges.

In summary, a survey of photonic technology roadmaps reveals a broad interpretation of roadmapping. Each of the roadmaps varied in terms of approach, level of analysis and framework. Roadmap output typically consisted of a report summarizing a series of workshops, primarily relying on expert testimony... None of the roadmaps provided a significant amount of in-depth or detailed technical or economic analysis. None of the roadmaps have depth in terms of materials processing. Roadmapping efforts focus on high-level industry and technology trends, including surveys of technology alternatives and market assessments.

Few of the photonics industry roadmapping activities have been established as an on-going process maintained over any extended period of time Several roadmapping activities were initiated during the industry bubble by industry funded consortiums, but ended when the downturn hit the industry. – This is representative of the challenges in maintaining roadmaps in resource constrained environment, despite the fact that the need for a roadmap may be greater during this period.

IV. Experiences Roadmapping in Academia

Roadmapping in Academic-Industry Consortium

Industry roadmaps can be led by various organizations, including government, industry, or academia. Traditionally industry roadmaps are often funded and driven by government or industry associations/consortiums. Based on experiences at MIT, we have found that academic-industry consortium can be successful at driving industry roadmapping. We found that this forum works best for exploratory mapping. Benefits of academic-industry roadmapping include:

- Universities are generally neutral ground for exploring and debating technology alternatives.
- Roadmapping process provides guidance to University researchers on the fundamental technical barriers and the interesting problems that are relevant to work on. Researchers can align their research priorities with long-term industry requirements.
- Universities can draw on expertise from faculty and students from across an industry value-chain - materials, physics, chemistry, engineering, economics, business schools, policy departments, etc. - to participate in the roadmapping process.
- Universities have expertise for providing in-depth analysis required to support roadmapping. Analytical modeling tools (e.g. technical device models, economic models, cost models, etc) can be developed to help better understand possible future development paths and explore technology alternatives.
- University researchers can provide a perspective outside of the corporate mindset and can challenge conventional thinking. University researchers can bring a longer-term view (whereas many companies are focused heavily on the next few quarters or years).
- With corporations relying more heavily on university research (rather than corporate R&D labs) roadmapping can provide industry with insights into emerging technologies and their development timeframes.

Roadmapping Photonics: Communications Technology Roadmapping (CTR)

The MIT Communications Technology Roadmapping (CTR) program focuses on the future of enabling photonic technologies for next-generation communications systems. CTR was initiated in 2000 and is funded by the MIT Microphotonics Center Industry Consortium. CTR is a multi-organization roadmapping program, involving participation from over 40 organizations (companies and universities). CTR incorporates both expert-based working groups and analytical tools as input to the roadmapping process (see Figure 16.).

Industry Working Groups

CTR decided to focus initially on optical transceivers for communications. Current Working Groups (WGs) are based on three layers: Applications/Market Drivers (market-pull); Modules/Systems; and Technologies (technology-push). Each WG is comprised of experts in each particular area, and focuses on addressing a different set of issues. The linkages between the WGs are critical in translating industry drivers, to system requirements, to enabling technologies.

Initial work within CTR included an assessment of the current state of integrated photonic technologies. Figure 17, for example, summarizes the development of different integrated photonic functions based on material platform. Working Group meetings were used to then assess different integration scenarios in each of the material platforms. Output from one of the III-V WG meetings is summarized below. The meeting was used to identify the drivers, barriers, and actions associated with monolithic opto-electronic integration in III-Vs.

DRIVERS – Opto-Electronic Integration in III-V's

▪ **Ease of Use**
    ▪ Simplify interface requirements for the customer
▪ **Lower Manufacturing Costs**
    ▪ Reduced fiber splices and handling
    ▪ Reduced number of hermetically sealed packages
▪ **Lower Operating Costs**
    ▪ Reduce real estate
    ▪ Improve energy efficiency
▪ **Increase Volume Manufacturing Potential**

- Design based on a small number of scalable building blocks

BARRIERS – Opto-Electronic Integration in III-V's

- **Integration means sacrificing customization and performance**
  - Compromises in design can limit performance, e.g. cross-talk from digital circuits at input to TIA.
  - Perception that integration limits innovation and flexibility
- **Yield Impact**
  - Yield decreases with increasing number of components, especially for low volume processes
- **Lack of standards**
  - Diversity leads to low volumes for manufacturing
  - Lack of consensus on accepted performance specifications for individual functions
  - Need for standard optical interface, ideally matched to fiber (mode tapers)
- **Power dissipation and thermal management**
  - Higher power density
  - Diverse thermal requirements for active and passive components
- **Lack of simulation tools**
  - Simulation tools for developing and modeling opto-electronic integrated circuits are not available. Lack of tools means that design cycle for integrated devices is significantly longer than discrete devices
- **Difficult to gather breadth of capability and resources in one place**
  - Requires engineers with expertise from a broad range of fields
  - Large scale integration is very capital intensive
  - Legal issues with intellectual property of integrated functions
- **Noise Interference**
  - Sensitivity may be severely impacted by noise interference when high sensitivity devices are integrated with digital or high output devices

ACTIONS – Opto-Electronic Integration in III-V's

- **Develop practical tools for local thermal management**
  - Novel techniques for managing power dissipation on a localized level will vastly improve the efficiency of circuit design
- **Introduce a "layer of abstraction" in the module or sub-system architecture**
  - Meaning component performance and device physics become irrelevant to the systems engineer
  - Increased levels of flexibility at the sub-system layer in how functions are integrated and where performance trade-off's are incorporated
- **Design for Integration**
  - Develop a set of functional building blocks and design rules that allow consistency within a set of integrated functions
  - Design rules should incorporate an understanding of performance issues and trade-offs
- **Develop modeling and simulation tools for OEICs**
  - Simplify the design process and shorten the development time
- **Standards that incorporate both telecom and datacom**
  - Develop components that can address both markets and target high volumes, e.g. a 10 Gb/sec transponder that meets requirements of both telecom and datacom

Analytical Tools

Complementing the WGs, CTR has engaged in the development of various analytical modeling tools to support the roadmapping process and provide further in-depth analysis when needed. These models include, for example: device models, process-based cost models, and system dynamics models.

Device models serve to delineate that which is physically possible. These models can be used to project technologies from other areas (e.g. microprocessors) to better understand how their development will impact optical transceivers. A set of predictive models for transceiver performance was developed to assess power dissipation of key components, including the multiplexer, thermoelectric cooler and the driver amplifier [37].

Technical cost models provide an essential tool for determining the costs associated with technical design decisions; they provide a link between physical manufacturing processes, performance, and device cost. A series of process-based cost models is currently under development for two design cases: 1.) InP based laser and modulator and 2.) 10Gb/sec optical transceiver platform. [38]

System dynamics models provide a quantitative framework for modeling the influence of policy decisions and technology choice on evolving markets [39]. CTR has developed several system dynamic based models, to assess the impact of industry and policy dynamics on technology deployment. One model focuses on the adoption of broadband technology in the FTTH market and the impact of different regulatory policies [40]. The second model examines the dynamics of the transceiver industry, and the trade-offs between product proliferation and standardization. [41].

V. Conclusions

As a business process, technology roadmapping has one smashing success under its belt (the ITRS), and many small wins in a wide range of companies and consortia. Roadmapping has no widely accepted standard tools, but does have a large and growing population of experiments, as we have described. Although one should not go into roadmapping expecting a "crystal ball" answer, a great deal of understanding about future scenarios can be developed using the roadmapping approach.

In the photonics industry, roadmapping has the potential to provide a mechanism for driving growth and sorting through the wide diversity of technical choices. Roadmapping can play a role to define the future and focus investment decisions for the benefit of the industry. however, there are also fundamental technical barriers to integrated photonics that need to be solved to advance the industry.

Acknowledgements

[to be added]

References

[1] Willyard, C.H. and McClees, C.W. (1987), "Motorola's technology roadmap process", *Research Management*, Sept-Oct, pp. 13-19.
[2] Sandia National Laboratories, Fundamentals of Technology Roadmapping, [http://www.sandia.gov/Roadmap/]
[2A] "Technology Roadmapping in Industry: A Special Report." Research Technology Management, pp. 26-59, Mar-Apr 2003.
[2B] Technological Forecasting and Social Change, vol. 71, 2004.
[2C] D. Probert, N. Shehabuddeen, "Technology Roadmapping: the issues of managing technology change", International Journal of Technology Management, Vol 17, No 6, 1999.
[3] R. Galvin, "Roadmapping - a practioner's update," *Technological Forecasting and Social Change*, vol. 71, pp. 101-103, 2004.
[4] Strauss, J. D., Radnor, M. and Peterson, J.W. (1998), "Plotting and Navigating a Non-Linear Roadmap: Knowledge-Based Roadmappping for Emerging and Dynamic Environments", *Knowledge Creation Management in Asia Conference*, Singapore, March, 1998.
[6] M. Grinnel; J. Richey; E. McQueen, "Motorola Case Study: Innovation Roadmapping Using Enterprise Automation Software," Motorola publication, pp. 1-7, June 2002.
[7] De Laat, B. and McKibbin, S. (2003), 'The effectiveness of technology road mapping - building a strategic vision', Dutch Ministry of Economic Affairs. [http://www.ez.nl]
[8] Kappel, Radnor and Peterson, "Management of Technology through roadmapping tools," Product Strategy Summit '97, Management Roundtable. Waltham, MA, 1997.
[9] NEED REFERENCE on technology s-curve - ??? Richard N. Foster (1986), *Innovation: The Attacker's Advantage*, NY: Summit Books.

[10] CONFIRM REFERENCE. Mahajan, V., Muller, E., and Bass, F.M. New product diffusion models in marketing: A review and directions for research. *Journal of Marketing* **54**, 1 (January 1990), 1-26. OR Bass, F.M., "A new product growth model for consumer durables," Management Science 15, pp. 215-227.
[11] R. E. Albright, T. A. Kappel, "Roadmapping in the Corporation", Research Technology Management, 42 (2), pp. 31-40, 2003.
[12] D. S. Grossman, "Putting Technology on the Road", Research Technology Management, 47 (2), pp. 41-46, Mar/Apr 2004.
[13] D. 4]H.A., D. Smith, "Technology Foresight Using Roadmaps," Vol. 28, No. 2, pp. 21-28, 1995.
[13A] Groenveld, P. "Roadmapping Integrates Business and Technology," Research Technology Management 40 (5), pp.48-55, 1997.
[13B] I. Petrick, A. Echols, "Technology roadmapping in review: a tool for making sustainable new product development decisions," *Technological Forecasting and Social Change*, vol. 71, pp. 81-100, 2004.
[14] International Technology Roadmap for Semiconductors (ITRS), published by International SEMATECH, Austin, TX. http:/public.itrs.net
[15] R. N. Kostoff and R. R. Schaller (2001), "Science and Technology Roadmaps", IEEE Transactions on Engineering Management, Vol 48, No 2.
[16] Kappel, "Perspectives on roadmaps: how organizations talk about the future," J. of Product Innovation Management, Aug 2000.
[17] C. Fine, NEED REFERENCE.
[18] Gartner report, "G. Broadband Regulatory Environment and Recommendations," published by CENIC, Corporation for Education Network Initiatives in California, 2003.
[19] R. Phaal, C. Farrukh, D. Probert, "Customizing Roadmapping," Research Technology Management, 47 (2), pp. 26-37, Mar/Apr 2004.
[19A] R. Phaal, C. Farrukh, C. Mills, D. Probert, "Customizing the technology roadmapping approach," Proceedings of Portland International Conference on Management of Engineering and Technology (PICMET), Portland, 20-24th July.
[20] R. Phaal, C. Farrukh, D. Probert, "Technology Roadmapping - a planning framework for evolution and revolution," *Technological Forecasting and Social Change*, vol. 71, pp. 5-26, 2004.
[21] J. Strauss, M. Radnor, "Roadmapping for dynamic and uncertain times", Research Technology Management, 47 (2), pp. 51-57.
[22] R. Kostoff, R. Boylan, G. Simons, "Disruptive technology roadmaps," *Technological Forecasting and Social Change*, vol. 71, pp. 141-159, 2004.
[23] B. Vojak, F. Chambers, "Roadmapping disruptive technical threats and opportunities in complex, technology-based sub-systems: The SAILS methodology," *Technological Forecasting and Social Change*, vol. 71, pp. 121-139, 2004.
[24] Geneva Vision Strategist, company based in California [www.strateva.com]
[24A] Purdue University Centre for Technology Roadmapping, [http://roadmap.ecn.purdue.edu/CTR/default.htm]
[25] D. Beck, K. Boyack, O. Bray, W. Siemens, "Bringing the Fuzzy Front End into Focus," submitted to Chemtech, Sandia National Laboratories, SAND99-0532J, 1999.
[26] S. Kaplan, "Cognitive frames and strategic choice: examining communications technology firm response to the fiber-optic revolution," MIT Communications Technology Roadmapping White Paper, June 2004.
[27] R. Schaller, "Technological Innovation in the Semiconductor Industry: A Case Study of the International Technology Roadmap for Semiconductors (ITRS), " PhD Dissertation, George Mason University, 2004.
[28] Based on study by M. Speerschneider for the MIT Communications Technology Roadmapping program - including transceivers commercially available from Finisar, JDSU, Infineon, Excelight, Agilent and Intel, May, 2004.
[29] Herb Bennett, NIST, "Compound Semiconductor Roadmap Embedded in the 2003 International Technology Roadmap for Semiconductors", EDS Newsletter, March 2004.
[30] Optoelectronics Industry Development Association (OIDA).
http://www.oida.org/
[31] North America: National Electronics Manufacturing Initiative (NEMI)
http://www.nemi.org/
[32] North America: IPC and PMAC (Photonics Manufacturers Association)
http://www.ipc.org/ and http://pmac.ipc.org/
[33] Canada - Canadian Photonics Consortium (CPC)
http://www.photonics.ca/
[34] Europe: Information Society Technologies (IST) OPTIMIST Programme
http://www.ist-optimist.org/tech.asp
[35] Japan: Optical Industry and Technology Development Association (OITDA)
http://www.oitda.or.jp/
[36] Singapore: Infocomm Development Authority of Singapore (IDA Singapore)
http://www.ida.gov.sg/

[37] K. Butler, "Predictive Models for Power Dissipation in Optical Transceivers" Masters of Engineering Degree, MIT, May 2004.
[38] E. Fuchs, R. Kirchain, "Understanding the Economics of Integration: Process-Based Cost Modeling of Opto-Electronics Production", MIT CTR White Paper, Nov 2003.
[39] J. Sterman, "Business Dynamics: Systems Thinking and Modeling for a Complex World", Irwin McGraw-Hill, 2000.
[40] A. Kelic, "Networking Technology Adoption: System Dynamics Modeling of FTTH. Technology, Standards, and Economies of Scale," MIT CTR White Paper, Nov 2003.
[41] M. Speerschneider, "…." MIT Masters thesis TBP.