# On the Application of Demand and Price Evolution Forecasting in Road-Mapping the Optoelectronic Component Industry

## ABSTRACT

The optoelectronic component industry is a highly innovative industry with a large value chain. In order to ensure the growth of the industry much effort must be devoted to road mapping activities. In such activities demand and price evolution forecasting tools can prove quite useful in order to help in the roadmap refinement and update process. This paper attempts to provide useful guidelines in roadmapping of optical components and considers two models based on diffusion theory and the extended learning curve for demand and price evolution forecasting.

## Keywords

Optoelectronic Components, Integrated Optics, Demand Forecasting, Price Forecasting, Road-mapping

## 1. INTRODUCTION

The fiber optic channel possesses unique properties in terms of power absorption and provides large, THz bandwidth unlike any other channel [1]. In optical fiber networks there is a requirement for the efficient utilization of this large bandwidth and consequently the need for fast, reliable all-optical optoelectronic components (such as sources, detectors, amplifiers, filters). Using Wavelength Division Multiplexing (WDM) [2] the aggregate transmission capacity of a fiber optic link may exceed 1Tb/s. In spite of such achievements however, the optoelectronic component industry is still immature when compared to electronics. This is mainly because, the scale of integration for photonic components remains low and important functionalities such as optical buffering can only be implemented with bulk components.

The wide range of applications for photonic components is also another issue complicating the industry structure as requirements in one application area may not be shared by other domains. In its very early days, the optoelectronic component industry was primarily fueled by the need for higher bit rates in order to upgrade the long haul connections at the backbone network. At that time the objective was to extend the reach of optical transmission systems and increase the bit rate. As photonic components are currently trying to migrate towards the access network where much smaller bitrates are required, the issue of lowering the cost becomes extremely important.

Optical sources have also been developed for optical storage. The Compact Disc (CD) has replaced the traditional record when infrared laser diodes became very cheap. The Digital Versatile Disc (DVD) players have recently replaced the old Videocassette Recorders (VCR) because visible laser sources also achieved a very low price level. Terabyte optical discs may become available in the future.

In addition other applications [3] are being considered. The optoelectronic component industry is primarily focused on three other areas: Sensor, biophotonic and lighting/display applications. Optical sensors [4] are being used in the car industry, for surveillance and security, gas detection for environmental purposes and other applications areas. Furthermore sensor networks are of increasing importance. The rise of interest in the environment, for example, leads to many new sensor network applications, e.g. networks of sensors on the seabed or monitoring volcanoes. Biophotonics [5] is developing applications along three different paths: imaging, sensing and photodynamic therapy. Lighting and display [6] is another emerging industrial sector, related to Optoelectronic components. Lighting is achieved through organic and inorganic light emitting diodes (LED) providing high conversion efficiencies and tunability of brightness and colour.

Optoelectronics is a disruptive technology [7] and as such they possess much different characteristics than more mature (sustaining) technologies. The level of technical innovation is very high and new technologies are constantly been demonstrated in research laboratories. However, the optoelectronic component market is being considered by many as highly risky and in many cases this is due to customer resistance. Especially in the telecom arena investment decisions are mainly driven by economical reality. For example, telecom operators are not very willing to invest in optical access technologies due to the large costs associated with civil works.

The understanding of the optoelectronic market is therefore a necessary and crucial step towards the understanding of whether a given product will survive. In this paper we analyze the main attributes of the optoelectronic component industry, discuss techniques for roadmapping of an optoelectronic component and present a methodology for demand forecasting based on two different technology diffusion models: the Gompertz and the logistic models. Price evolution forecasting is also considered. Much of this work was undertaken in the framework of the Waferbonding and Active Passive Integration Technology and Implementation (WAPITI) FP6-2003-IST-004073 project.

The rest of the paper is organized as follows: In section 2, we present some characteristics of the optoelectronic component industry relevant to the roadmapping process. In section 3 we discuss a general roadmapping methodology and exemplify it for optical ring resonators. In section 4, a diffusion model for forecasting the demand of Optoelectronic components in given based on the logistic model and the Gompetz model. In section V, a model for estimating the price evolution is given based on the extended learning curve. Some concluding remarks are given in section 6.

# 2. THE OPTOELECTRONIC INDUSTRY

As a consequence of its short history and highly innovative character the optoelectronic component industry faces many challenges in order to increase its growth rate [8].

## 2.1 Many Competing Platforms

Although the optoelectronic component industry is rather focused on III-V materials, and especially InP, there are still other competing platforms. III-V materials can generate light efficiently as well as provide a wide range of other important functionalities. InP has a high refractive index (~3.3), which allows smaller device sizes compared to Si and high index contrast waveguides for efficient light manipulation. The III-V fabrication infrastructure is quite expensive and there is a limited number of laboratories that can currently produce large scale optoelectronic chips. On the other hand, silicon materials are also attracting attention for integrated optoelectronic components. The supporters in that idea explore the possibility of replacing expensive high performance optoelectronic component elements with their silicon counterparts. This prospect will allow the extension of the massive, low-cost, mature electronic manufacturing platform into the optoelectronic component domain. Such an extension will drive the transition from electronic to optoelectronic interconnects but only if high, electronic-like yields are maintained. Silicon based optoelectronics could provide a solution for exceeding the bandwidth limits of very short range electronic based transmission of data. Organic materials also constitute a useful direction for optoelectronic integrated devices. These polymeric materials are ideal for planar processing due to the relative simplicity of fabrication.

## 2.2 Limited Component Functionality

For even the simplest telecom applications, optoelectronic components require sophisticated hybrid integration of many different materials and functionalities. Even a small 32x32 integrated add/drop multiplexer based on Arrayed Waveguide Grating (AWG) technology requires the integration of two AWGs with 32 Semiconductor Optical Amplifier (SOA) gates which poses many fabrication challenges. Unlike the electronics industry where transistors constitute the fundamental cell of electronics circuits, there is still no basic building block for optoelectronics: Optoelectronics have not yet found their “transistor” Although some nanophotonic technologies may open a path towards such a goal, there is still a need for much research and development before such technologies eventually reach the market.

Depending on the application domain, the performance requirements can be quite different and prevent the leverage of a component from one application domain to the other. For example the requirements for narrow spectral line width and wavelength stability of a telecom diode LASER are not shared in other applications.

## 2.3 Fierce Competition

There are currently, a large number of competing companies throughout the globe. Although the addressable market has been reduced by a factor of 5 from the year 2000, the number of competitors has not been reduced by the same amount. This can be seen from the number of exhibitors in the Optical Fiber Conference (OFC). In 2001, about 1000 companies were exhibiting optoelectronic products, while this number is down to about 600 in 2005 [8]. It is therefore remarkable that there are still so many companies competing over a much smaller market. The fixed costs associated with the support of an internal manufacturing infrastructure for optical components can be quite high and the large segmentation of the market prevents economy of scale.

# 3. THE NEED FOR ROADMAPPING

The development of the optoelectronic components industry affects the development of many industrial sectors creating and using this technology. These sectors are depicted in Figure 1, which describes the “Optoelectronic component value-chain” [8] which ranges from material processes right up to the end-users. It is therefore imperative to ensure the smooth development of the industry. The optoelectronic component industry is a highly innovative industry whose addressable market has reached approximately 2B $ in 2003 and 2.5B $ in 2004. Although these figures look spectacular they are much less than the addressable market size of 10B $ before the dotcom bubble in the year 2000 and are comparable to the market sizes of the late 90s.

To avoid such downturns, specific roadmapping processes are needed, aiming to support its commercialization activities. By definition, technology roadmapping is “a need-driven technology planning process to help identify, select and develop technology alternatives to satisfy a set of product needs. It brings together a team of experts to develop a framework for organizing and presenting the critical technology-planning information to make the appropriate technology investment decisions and to leverage those investments” [9]. The challenge to the roadmapping process today lies in the ability of academics and professionals to take advantage of a strategic process that has proved so successful when addressing sustaining technologies by adapting the process to the needs of a disruptive technology stream. Techniques that are used by roadmapping professionals that show promise to roadmapping disruptive technology include complexity theory and the Delphi method [10][11]. The utility of the roadmapping process via an industrial case study and a model based on an international effort aimed at providing a practical approach for an international industry-wide effort to roadmap a disruptive technology is presented in Figure 2 [10].

Figure 3 exemplifies a preliminary visual output of the technology roadmap for ring resonators [12] designed for telecom and information applications. These devices can perform many optical functionalities including optical filtering, optical gating, wavelength conversion and signal processing and may therefore constitute a basic building block in future integrated optical components. In an attempt to demonstrate the possible time evolution of these components, the functionalities are depicted from right to left sorted according to their complexity. For example, Coupled Resonator Optical Waveguides (CROWs) [13] which are arrays of coupled ring resonators are seen to evolve from the simpler, ring resonator technology. Such diagrams present an initial phase of the roadmap, as the opinions of many experts, from a variety of disciplines must be gathered in order to refocus and refine the roadmapping effort.

Table 1: The three phases in the technology roadmapping process [10]

| Phase | Phase description | Tasks |
|---|---|---|
| 1 | Preliminary Activity | Satisfy essential conditions |
| | | Provide leadership/sponsorship |
| | | Define the scope and the boundaries |
| 2 | Development of the technology roadmap | Identify the “product” which is the focus of the roadmap |
| | | Identify critical system requirements and targets |
| | | Specify main technology areas |
| | | Specify technology drivers and their targets |
| | | Identify technology alternatives and time lines |
| | | Study technology alternatives |
| | | Create technology roadmap report |
| 3 | Follow up activity | Critique and validate the technology roadmap |
| | | Develop an implementation plan |
| | | Review and update |

Given the uncertainties involved in roadmapping a disruptive technology and in an attempt to quantify the business aspects of various technology alternatives, the roadmap can benefit from forecasting tools. Based on historical data, one may apply diffusion models in order to perform long term forecasting of various economic aspects of the optoelectronic components industry such as the demand and the price evolution discussed in the next sections.

## 4. DEMAND FORECASTING

Diffusion models are mathematical functions of time, used to estimate the parameters of the diffusion process of a product’s life cycle at an aggregate level, without taking in consideration the underlying specific parameters that drive the process. Such models are particularly useful if not much information is known because the component is new or not even introduced in the market. The obtained curves have the needed generality form most type of processes.

The two formulations of the Gompertz model been met in literature (for simplicity reason we call them Gompertz model I and Gompertz model II, respectively)[14] are used in this testing. The corresponding formulations are given below.

The first model is described by the following equation:

$$Y(t) = Se^{-a-bt} \tag{1}$$

where Y=Y(t) is the is the estimated diffusion level at time t, b>0 and the parameter S is referred to as the saturation level. The three parameters that determine the model are S, a, b. The following function describes the second instance of the Gompertz model:

$$Y(t) = S\exp\left(-a\exp\left(-bt\right)\right) \tag{2}$$

The parameters of the model are similar to the ones of the first variation. In both formulations, parameter a is related to the year that diffusion reaches 37% of its upper level, and parameter b measures the diffusion speed, or how fast the adoption progresses.

As far as the logistic models are concerned [14] their general form is given by:

$$Y(t) = \frac{S}{1+e^{f(t)}} \tag{3}$$

where Y(t) is again the estimated diffusion level and S the saturation level. The function *f*(*t*) is given by the following formula:

$$f(t) = -a - bT(t) \tag{4}$$

where *T*(*t*) is a linear or non-linear function of time and is determined by the model’s construction. The linear instance of the model is given by:

$$T(t) = t \tag{5}$$

The linear logistic model is also known as Fisher - Pry model. The linear logistic model, as well as the Gompertz is described by functions that are monotonically increasing between bounds of zero and *S*. The linear logistic model is graphically depicted by a symmetric S-curve and has an inflection point that occurs when $Y(t)=S/2$. This means that the maximum growth rate is met when *Y* reaches half of its saturation level. On the other hand, the Gompertz model is asymmetric, with a point of inflection occurring at $Y(t)=S/e$ which means that it is achieved when y reaches 37% of its upper bound.

Because of the fact that the point of inflection is predetermined, either in a symmetric (Linear logistic), or asymmetric (Gompertz) diffusion model there is a strong need to use both models in order to ensure the accuracy of the predictions given the fact that the data-determined point of inflection and the degree of symmetry for optoelectronics diffusion are not known. Using the above described models, an estimation of potential market for optoelectronics and subsequently for iptoelectronic component products has been performed and presented in figures 4,5,6. The estimated market in 2010 varies between 30-35 MUnits for telecom optoelectronics, 5000-6500 MUnits for optical storage optoelectronics while the potential market for medical optoelectronics is 8-10 MUnits.

While the increase in the demand for optical storage optoelectronic components is rather expected, the increase in demand for telecom and medical applications should be justified. The increase in demand for telecom optoelectronic components is consistent with current market trends [8]. The expansion of telecommunication networks in the near and longer terms is still important, as traffic continues to grow at 100% per annum. Additionally, the ever increasing importance of secure data storage (2 Exabytes of new data are created every year) leads to the expanding application area of storage area networks (SANs), which require the ability to move huge data files over a regional area to storage farms. Data networking [3] is also expanding and application networks overlaying regional and backbone networks are being considered. Grid networks are currently a major area of expansion. Computing Grids, for example, require networks which will support very high capacity demands on a short time scale. Grid infrastructures place stringent demands on the underlying technology. This continuous increase in the need for transmission bandwidth, at a competitive price, is one of the drivers for the research and development in optical telecommunication networks, systems and components. On the components side the rapid development has led to a huge number of new devices, technologies and materials and the scope is far too wide to be covered here. In line with this many results originally obtained in the telecommunication field can be transferred to other related areas like biophotonics or sensing technologies. Examples include quantum cascade lasers that can be used to reach new frequencies suited for free-space communication as well as for imaging and diagnostics in medicine. Another example is fibre technology where micro structuring of fibres, both so-called holey or crystal fibres and fibre Bragg gratings, find use both in communication and sensor applications.

As far as medical applications are concerned the increase in demand should be attributed to the increase development in the area of Biophotonics [5] which is developing applications along three different paths: imaging, sensing and photodynamic therapy. In the area of imaging the field of biophotonics seeks to improve the effectiveness of medical diagnosis and treatment using optical technologies to process the information content in a video image, or to create more information content in an image through addition of spectral signatures. There is special emphasis on being able to “see into” the body, thus providing an optical replacement for X-ray exposures or expensive CAT imaging scanners. In sensing applications, the major objective is to create a micro analysis laboratory that can perform real-time chemical analysis on picolitres of body fluids. Due to the large field of potential applications an all-embracing view on optoelectronic technologies and applications is missing so far. For a further boost of the optoelectronic technologies it is necessary to bundle the driving forces. This has to include users as well as developers.

# 5. PRICE EVOLUTION

The analysis of price evolution especially for the network components is of paramount importance for the telecom operators. In the past, a prediction of cost trends could be based on information and statistical data referring to previous years. Today, rapid technical innovation, and consequent insufficient historical data, makes predictions extremely difficult.

A prediction model for price evolution can be based on Crawford’s interpretation of Wright’s empirical law [13] for the decrease in production time of a product as a function of the number of the produced units. Let $T_n$ denote the time taken to complete the $n^{\text{th}}$ unit of a product. Then $T_n$ is related to the time, $T_0$, taken to complete the first unit by

$$T_n = n^{-a} T_0 \tag{6}$$

where $a>0$ is a positive quantity. Assuming that the price $P_n$ of the product is proportional to its production time $T_n$ and defining the constant $K$ as $K=P_{2n}/P_n=2^{-a}$, one can easily show that the price $P(t)$ of a product at time $t$ is related to its initial price by

$$P(t) = P(0)\left(n_r(t)/n_r(0)\right)^{\log_2 K} \tag{7}$$

where $n_r(t)=n(t)/\max\{n(t)\}$ and $n(t)$ are the normalized and the actual accumulated production volume of the product at time $t$ respectively. To express $n_r(t)$ as an explicit function of $t$, the logistic model is used:

$$n_r(t) = \left[1+e^{c+d\cdot t}\right]^{-1} \tag{8}$$

where $c$ and $d$ are the parameters of the logistic model. Instead of $c$ and $d$ one may alternatively use $n_r(0)$ and the growth period $\Delta T$ to specify the logistic model. The growth period is defined as the time taken for the total production volume to reach from 10% to 90% of its maximum value. It can be easily shown that $d=(-2\ln 9)/\Delta T$ and combining (7) and (8) the following expression for $P(t)$ is obtained:

$$P(t) = P(0)\left[n_r(0)^{-1}\left\{1+e^{\ln\left[n_r(0)^{-1}-1\right]-\frac{2\ln 9}{\Delta T}t}\right\}^{-1}\right]^{\log_2 K} \tag{9}$$

The value of $n_r(0)$ reflects the relative accumulative production volume and is equal to 0.5, for components that exist in the market and their price is expected to be further reduced due to aging rather than due to an increase in production volume (i.e. very old products that are many years in the market). From estimations on industrial telecommunication network components, nr(0) could be 0.1 for mature products and 0.01 for new components in the market. P(0) is the price in the reference year 0, $\Delta T$ is the time required for the accumulated production volume to grow from 10 % to 90 %, and K is the learning curve coefficient. The coefficient K reflects the reduction in price when the production volume is doubled and can be obtained from data provided by the production industry, mainly the suppliers. For a component (with constant $n_r(0)=0.1$) for which $\Delta T$ is equal to 10 years and K is equal to 0.98, Eq. (1) gives about 2% of reduction in the component price per year for the first 10 years. If $\Delta T$ is 5 years, this reduction is almost 4% per year for the first 5 years. All the above-described values have been extensively used for the evaluation of telecommunications investment projects [17],[18],[19],[20]. The above described methodology was employed in order to estimate the price evolution of optoelectronics taking into account the price trends of emerging/new technologies (such as optoelectronics) as well as experiences from other more mature components. Further, civil works such as fiber pulling, digging and laying tubes may be very costly, but these costs are well known to planners beforehand and therefore have little or no uncertainty. In order to model the effects of optical component technology, $\Delta T$ have been chosen as an uncertainty variable. The expected value for $\Delta T$ (used in the database) is 10 years. With 90% probability, the reduction in equipment price in 2010 will be between 55.5% and 77% of the price in 2001.

Figure 7 depicts the price evolution of the average telecom optoelectronic components as a function of time. Note that care must be exercised in defining the reference year. Given the values obtained in figures 4 and 7 one may predict a demand of 30-35Munits by 2010 and a price of 100$ to 300$ corresponding to a market size of at least 3B $.

## 6. CONCLUSIONS

The optoelectronic component industry is a rapidly developing sector where innovation can play an important role. As in any disruptive technology, much effort must be devoted to ensure smooth industry growth through careful roadmapping. The roadmapping process can benefit from various forecasting models for either the demand or the price evolution. This paper presented two such forecasting tools based on diffusion theory and the extended learning curve in order to calculate the future demand and the price evolution for optoelectronic components.

## REFERENCES

[1] G. Einarsson, *Principles of Lightwave Communications* New York: Wiley 1995

[2] C. A. Brackett "Dense Wavelength Division Multiplexing Networks: Principles and Applications", *IEEE J. Select. Areas in Communications*, Vol. 8, No. 6, August 1990, pp. 948-963.

[3] A. M. Rodriguez, O. Bonenfant, S. Baroni and R. Wu "Optical Data Networking: Protocols, Technologies and Architectures for Next Generation Optical Networks and Optical Internetworks", *IEEE J. Select Areas in Communications* Vol. 18, No 10, October 2000, pp. 1855-1871.

[4] V. Ramamurthy, K. S. Schanze, *Optical Sensors and Switches*, Marcel Dekker, 2001

[5] X. Shen and R. V. Wijk, Biophotonics: *Optical Science and Engineering for the 21st Century*, Springer 2006.

[6] A. Zukauskas, M. S. Shur, R. Gaska, *Introduction to Solid-State Lighting*, Wiley-Interscience 2002

[7] S. Walsh and J. Linton, "Infrastructure for emerging markets based on discontinuous innovations", *J. Engineering Management*, Vol. 12, No. 2 pp. 23-31 (2000).

[8] CTR, MIT Microphotonics Center, "Microphotonics: Hardware for the Information Age, Current State of the Industry", Communications Technology Roadmapping, 2005. http://mph-roadmap.mit.edu/about_ctr/report2005/

[9] Sandia National Laboratories: Fundamentals of technology Roadmapping, http://www.sandia.gov

[10] S. T. Walsh, "Roadmapping a disruptive technology: A case study - The emerging microsystems and top-down nanosystems industry", *Technological Forecasting and Social Change*, vol. 71, pp. 161-185, 2004.

[11] S. T. Walsh, et al., "The semiconductor silicon industry roadmap: Epochs driven by the dynamics between disruptive technologies and core competencies", *Technological Forecasting and Social Change*, vol. 72, pp. 213-236, 2005

[12] M. Hamacher, et al., "Optically Amplifying Microring Resonator Components Based on GaInAsP/InP: Challenges and Perspectives", presented at CAS 2004, 2004.

[13] A. Yariv, Y. Xu, R.K. Lee and A. Scherer, "Coupled-resonator optical waveguide: a proposal and analysis", *OSA Optics Letters*, Vol. 24, pp. 711-713, 1999.

[14] R. Fildes, "Telecommunications demand forecasting - a review" *International Journal of Forecasting*, vol. 19, pp. 337-337, 2003.

[15] B. T. Olsen and K. Stordahl, "Models for forecasting cost evolution of components and technologies", *Telektronikk*, 4, pp. 138-148.

[16] IST-TONIC, EU "Techno-economics of IP Optimised Networks and Services", IST-2000-25172. Available at http://www-nrc.nokia.com/tonic/

[17] B. T. Olsen, et al., "Techno-economic evaluation of narrowband and broadband access network alternatives and evolution scenario assessment", *IEEE JSAC*, vol. 14, pp. 1203, 1996.

[18] T. Monath, et al., "Economics of fixed broadband access network strategies", *IEEE Commun. Mag.*, vol. 41, pp. 132-139, 2003.

[19] D. Varoutas, et al., "Business opportunities through UMTS-WLAN networks", *Ann. Telecommun.*, vol. 58, pp. 553-575, 2003.

[20] D. Katsianis, et al., "The financial perspective of the mobile networks in Europe", *IEEE Pers. Commun.*, vol. 8, pp. 58-64, 2001.

## CAPTIONS

Figure 1: Industrial Sectors using and generating technology in Optoelectronic components

Figure 2: A multitiered visual output of a technology roadmap [10].

Figure 3: A preliminary version of the output of a technology roadmap for ring resonators.

Figure 4: Long term demand forecasts for telecommunication optoelectronics

Figure 5: Long term demand forecasts for optical storage optoelectronics

Figure6: Long term demand forecasts for medical optoelectronics

Figure 7: Price evolution estimations for telecom optoelectronics, using reference value from different years