Photonics in Canada:
An Outline of Current Research and Industrial Capability

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Executive Summary

This paper describes Canadian research and industrial activity in the rapidly expanding field of photonics. The aim and methodology of the document is explained in the preamble. This is followed by a short overview of the document structure, which is organized into four main sections. The first section gives a basic introduction to the science and technology of photonics. Essentially this section is a "primer" on the behaviour of light and the industrial applications of photonics. It is addressed to the needs of the layman who feels the need to acquire a basic scientific understanding of this highly technical field. The second section provides a breakdown of the current industrial capability in photonics and a description of the relevant initiatives in the training of personnel. This is followed by a description of the current organization and extent of photonics research in Canada. The final section attempts to provide some insight into opportunities for future Canadian research in this field.

The photonics industry in Canada is very broad in scope, with applications ranging from telecommunications fibre optic links to cancer treatments. The potential economic impact of photonics technologies in the next ten years is considerable, and a number of industrial organizations have predicted growth rates of up to 25% with total markets of hundreds of billions of dollars. One important aspect of the photonics component market is that it enables much larger, systems-level technologies. The OIDA estimates that, currently, a $40 billion optoelectronic industry is a key enabler of a $1.5 trillion information technology sector.

Canadian photonics companies are active in almost all areas of industrial photonics and range in size from systems companies such as Nortel Networks to small start-ups. The bulk of the industrial activity is in the telecommunications or related industries and only in this sector does Canada have a mature and comprehensive photonics industry. Nonetheless, in other sectors, such as biophotonics and industrial lasers, individual Canadian companies have managed to establish a presence in the global market.

An outstanding feature of the photonics industry in Canada is the formation of geographical clusters of activity. Clusters have formed in Ottawa, the Lower Mainland of British Columbia, Toronto, Montreal and Quebec City. These clusters represent regional concentrations of companies, research laboratories and academic institutions. The scientific and industrial activity of these organizations has tended to attract similar enterprises and produce large numbers of skilled personnel. Clusters are also characterized by the spawning of new companies from established companies and institutions. As clusters grow in size they become remarkable generators of new ideas, companies and initiatives. Government and industrial consortia are playing an important role in the promotion of these clusters.

Photonics research in Canada is extensive and very widely distributed at various institutions around the country, including the NRC, INO and the universities. University research is funded by a number of organizations, such as NSERC, NCEs and provincial granting agencies. NCEs like CIPI play an important role in providing a national network for collaboration between researchers, companies and institutes. A number of new government initiatives (for example CFI and ORDCF) have provided funds for both infrastructure and research operations and have substantially increased the amount and quality of photonics research in Canada. A significant portion of the funds provided is allocated to industrially focused work or granted as matching funds for collaborative projects with companies. Due to this industrial focus the best-supported research tends to be in optical telecommunications.

Although it is difficult to provide an exhaustive list of research opportunities in a rapidly evolving field such as photonics, a number of possibilities have been outlined. Funding for telecommunications has produced a well-established research capability in fibre optics, semiconductor optoelectronics devices, and high-speed electronics for photonics. This capability must be expanded in order to ensure Canada's continued success in the field of optical communications. One particular area of focus for future research funds is all-optical networks, local optical networks, and DWDM. Integrated optoelectronics is an area in which Canadian researchers are well-positioned to make future gains. Integrated optoelectronics is predicted to be an enabling technology for many sectors, including telecommunications, optical interconnects, sensors and biophotonics. The crossover of technology from one sector to another is likely to be important in the future, and Canadian researchers developing technology for telecommunications should be encouraged to apply their knowledge to other fields.

Biophotonics and medical applications of photonics are expected to be high growth areas in the future. These areas feature a range of technologies, from established applications like laser surgery to emergent fields such as DNA analysis. This is an area in which Canadian research shows a great deal of potential.

A number of other emerging technologies such as nanotechnology and bioengineering will co-evolve with photonics. The synergetic relationship between these technologies presents a multitude of research opportunities. Interdisciplinary work should be pursued in these areas, particularly in nano-technology/photonics, a field in which Canada can draw on its excellent scientific resources as well as its expertise in micromachining and semiconductor devices.

Finally, it should be remembered that fundamental research in the area of photonic materials and devices must be supported. New applications and technologies are usually founded on a combination of long-term basic research and subsequent industrial development. The photonics industry in Canada has a great deal of potential, but this potential can only be realized with a strong commitment to research and development.

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Preamble

Photonics is a very broad term and at least in principle describes phenomena ranging from laser light shows to photosynthesis. In its narrower sense this term refers to technologies that deal with the manipulation and application of light. This field, the photonics “industry”, has experienced explosive growth in the last ten years. The purpose of this document is to introduce the reader to the nature and extent of the photonics industry and associated research in Canada.

Due to the breadth of the field and the short time available to compile this document it will limit itself to study of the photonics component area. These components are the physical devices that enable the industry. Systems issues will not be dealt with except as they influence the components needed to build those systems.

Photonics is an area that is rapidly evolving. Some applications, such as traditional optics, are very mature, while others, such as biophotonics, are only just emerging. This has produced a rapidly changing, even chaotic industry and research environment. Information is difficult to obtain and often only relevant for a short time.

It will be observed that photonics telecommunications is the main area of focus in this paper. This is due partly to the author’s area of expertise, and partly to the Canadian industrial focus. It should be remembered that although recently telecommunications has been the highest-profile photonics market, other areas might become equally, if not more important in the future.

This document was researched using a combination of articles, interviews and web-based information. All sources are listed in the appendices. Due to the wide range of applications, technologies and research involved it is inevitable that omissions will be made. We apologize for these in advance.

Document Overview

The document begins with a definition of photonics and a brief summary of the scientific background of this discipline. The fundamental physical phenomena on which the technology is based are then discussed. This is followed by a description of the primary applications of photonics technology.

In Canada there is a great deal of activity in this field, both in the industrial and academic sectors. The main body of the document deals with past and present initiatives in photonics in Canadian industry, research organizations and universities. We begin with a discussion of photonics-related enterprise in Canadian industry, in which the activity of representative companies is delineated by area of application. The following section deals with the remarkable photonics “start-up” activity in regions such as Ottawa, Montreal and the Lower Mainland of British Columbia. A number of industrial co-operative organizations, both local and national in scale, have been involved in this endeavour. The role of these organizations in promoting industrial and academic research and development is also outlined.

Post-secondary institutions and governmental organizations have played a significant role in the development of photonics in Canada. The role of post-secondary institutes is first discussed, with a description of the initiatives in place to produce trained personnel at the college and university undergraduate level. The following section deals with industrial, government and academic research in photonics and related disciplines in Canada. The basic organizational and funding structures, both national and provincial, are outlined. Government initiatives specific to the industry have been crucial to the success of photonics in Canada, and these too are described. Current research capability in this area is a matter of great importance; this document provides a list of the key photonics centres and research groups in Canada. This guide to Canada's research capability in photonics is followed by a discussion of possible future opportunities in this field for Canadian research and industry.

1. Introduction to Photonics

This section provides an introduction to the basic physics and technical applications of photonics. It is divided into four parts.

The first part offers a definition of photonics and a description of its importance in our lives. The second section provides a basic introduction to the science of light and fundamental photonics devices. This section first discusses, in simple terms, the physics of light as both wave and particle. The fundamental characteristics of light such as wavelength, frequency and energy are then presented. Following this, a number of technologically important devices such as waveguides, lasers, interferometers and photodetectors are described.

The third section outlines the structure of the photonics industry. The size and the growth rate of the industry are discussed, as is the positioning of the Canadian photonics sector in the global market. The final section provides an outline of the primary applications of photonics. This section concentrates on areas relevant to Canadian business. It discusses photonics applications in fields such as telecommunications, memories, displays, imaging, biophotonics and sensors.

1.1 Definition and Introduction

Photonics is the study and engineering of the interaction between light and matter.

The above definition of photonics captures an extremely wide range of physical phenomena and associated technology. The word photonics is derived from "photon", the name given by physicists to an individual particle of light. The science of photonics is the study of how photons behave. The word photonics is also commonly used to describe the technology of the manipulation, generation, flow and capture of photons. This usage is very similar to the word "electronics" which is the technology used for the manipulation of electrons.

The influence of light on our world is all-pervasive. It is responsible for one of our primary biological senses – vision. Light from the sun heats our world and allows life to flourish as it carries information, energy and momentum. Fundamentally, it is a primary physical phenomena and the study of light has been a driving force in the evolution of our understanding of the world. The interaction of light and matter is primary to how the universe works, how we perceive it and how we can manipulate it.

As would be expected for such a fundamental physical phenomena the technologies associated with it are many and varied. The first applications were those of traditional optics such as lens and prisms. These applications were founded on the concept of light as an electromagnetic wave. As our understanding of light has improved the range of technologies has expanded. In the early part of the last century the birth of a new physics called quantum mechanics led to the discovery of the photon. A photon is a "packet" of light or electromagnetic energy. The discovery that light is both an electromagnetic wave and a structure of discrete photons was both revelatory and mysterious. It is our gradually improving understanding of this paradoxical concept that has led to the huge growth in light-based technology.

Primary applications of photonics have developed in remote sensing and imaging, manufacturing, communications, biomedical areas, computing and telecommunications to name just a few. Everything from the now mundane television to laser light shows is based on photonics applications. One important application is the use of photonics technologies in communications. The explosive growth of the Internet and the World Wide Web has led to a need to be able to transmit large amounts of digital information across great distances. This has proved to be a driving force for a substantial amount of industrial activity in the area of photonics telecommunications.

1.2 Scientific background

This section gives a brief outline of the physical nature of light. Two complementary models are described: 1) light as electromagnetic wave; and 2) light as particle (photon). The "wavelike" behaviour of light is described using the concepts of wavelength, frequency and velocity. The "particle" model of light is used to illustrate the phenomena of the generation and absorption of light. The relationship between the particle and wave models is then explained, leading to a discussion of the "colour" or spectral content of a light source.

The last part of this section deals with fundamental photonics devices. The wave model of light is used to explain the operation of lenses, grating, interferometers and waveguide structures such as optical fibres. The particle model of light is then used as a basis for a simplified description of the generation of light and stimulated emission. This leads to an explanation of the principles of the laser. Finally, light absorption, detection and photodetectors are discussed.

1.2.1 Light as a wave – wavelength, velocity and frequency

The pre-quantum mechanical concept of light (which is of course, still valid to a limited extent) describes this phenomenon as an electromagnetic wave travelling in a particular direction. This electromagnetic wave is understood as an oscillating set of electric and magnetic fields. In this earlier model, light is defined by a number of simple parameters (see Fig. 1). It has a frequency of oscillation – which gives it its "colour". A lightwave is also characterized by wavelength and amplitude in the same way that a wave in the ocean has height and a distance between swells. The wavelength of light is directly related to the frequency; the higher the frequency the shorter the wavelength. The frequency of the electromagnetic wave falls within a certain frequency range called the optical frequencies. A lightwave also possesses velocity. In free space this velocity is a constant and equal to 300,000 km/s. The speed of light is slower in a material such as air or glass and in this case it is characterized by an index of refraction. The higher the index of refraction the slower the light travels in a material.

Light is just a small part of larger electromagnetic spectrum including radio frequencies and microwaves. Physicists knew that waves could carry energy and that electromagnetic waves could interact with matter by moving electrons and protons. This knowledge allowed them to understand basic optical behaviour such as reflection and refraction and therefore enabled them to design lens and mirrors.

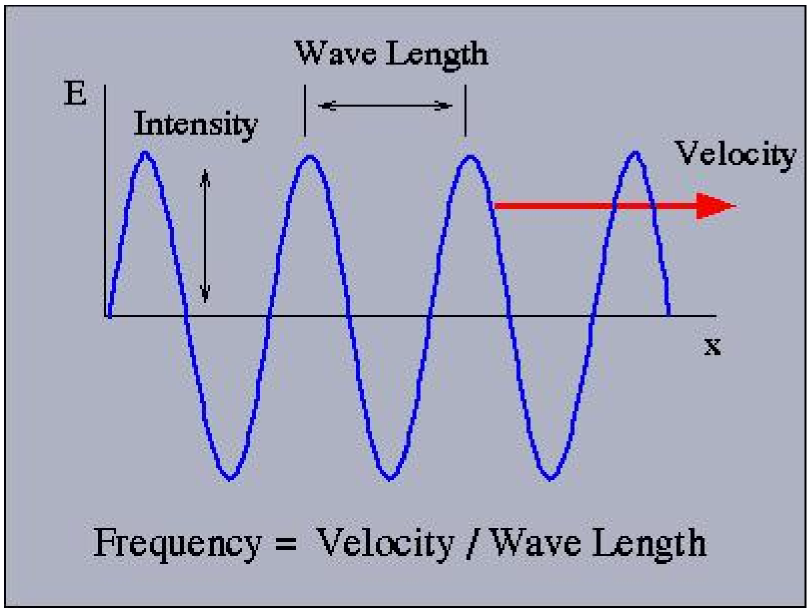

Figure 1: A figure showing the basic parameters of a light wave.

1.2.2 Light as a particle – energy and frequency

In the early part of the last century it became apparent that light not only behaved like a wave, but also featured particle-like behaviour. This particle-like phenomenon is particularly important in understanding the interaction of light and matter. To represent this behaviour the concept of a photon was used. A photon is a particle of light with a specific amount of energy. The energy of the photon is proportional to the frequency of the lightwave it represents.

A complete definition of light encompasses both its nature as an electromagnetic wave and as a group of photons. The simple relationship between the energy of a photon and its wavelength and the frequency of the associated lightwave leads scientists to use these terms interchangeably to describe the “colour” of the light or photon.

1.2.3 The colours of light – a frequency spectrum

In general, light is comprised of many colours and therefore consists of a spectrum of electromagnetic frequencies. This spectrum is very often of importance in photonics applications. For example the sun gives off light with a very specific spectral values (a prism can be used to separate out the individual colours). Sunlight therefore has colour and hue that is the sum of these spectral components. The quality of artificial light is rated according to the degree in which it matches this spectral content.

Matter reflects light in such a way that some specific colours (frequencies) are reflected more than others. This means that if white light (an even spectrum with all frequencies equally represented) is shone on a red object, primarily red frequencies will be reflected with the other colours being absorbed. Various photonics applications are designed in such as way as to take advantage of the capacity to determine the exact intensity of light at all frequencies. This information can be used to analyse the composition and structure of the object reflecting the light. Important applications are in remote sensing and material analysis.

An important concept is that of monochromatic light. Under certain conditions light can be generated at essentially a single frequency. This light is referred to as being monochromatic and can be used in a number of applications.

1.2.4 Lenses and gratings – refraction and interference

Mature optical technologies such as lens, mirrors, gratings and prisms are best described by the wave behaviour of light and the index of refraction of materials (denoted by the symbol n). A wave will propagate in a straight line when it travels through a material. If the wave travels from one material to another, for example, from air to glass, the velocity of the light changes due to a change in the index of refraction. This causes two effects to occur; reflection and refraction. Part of the incident light will be reflected at an angle equal to the incident angle while the remainder will travel into the second material, but at an angle different from the original path. The light is “bent” as it crosses the interface (see Fig. 2). Light travelling through a lens is focused to a point due to both the shape of the lens and refraction occurring at the lens surface.

A second property of waves is interference. Two waves of light will interfere with each other as they travel through the same region in space. The peaks of the waves can interfere either constructively or destructively. Constructive interference occurs when the two waves reinforce each other to produce a larger wave. Destructive interference is created when the two waves partially cancel each other out and produce a smaller wave.

One optical device that uses interference is a diffraction grating. Optical gratings are fabricated by etching many parallel grooves in a reflecting surface. A grating uses constructive and destructive interference of the reflected and scattered light to separate the incident light into different frequencies (colours). Gratings are often used to filter light and remove unwanted frequencies.

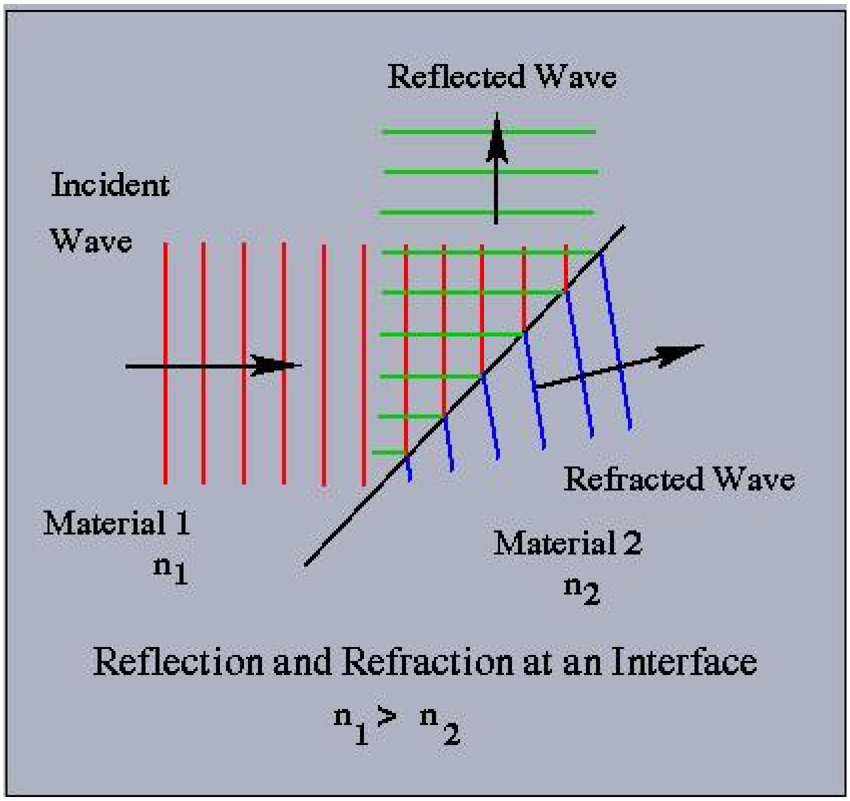

Figure 2: Light behaviour at an interface: Reflection and Refraction

1.2.5 Interferometers – beam splitting and interference

A second device that uses interference is the interferometer. An interferometer is a device in which a light beam is split into two parallel rays. Each ray then travels a fixed distance before it is rejoined to its twin in a single beam. If both the travelled distances and the indexes of refraction of the two paths are the same the rays will recombine constructively and the original beam will be recreated. If the distances are different, however, or the index of refraction in one of the paths is changed, the rays will undergo destructive interference and the new beam will display a reduced intensity.

Interferometers are extremely sensitive to changes in either the distance or the index of refraction of the two pathways. With this device changes in the distance of less than a wavelength can easily be measured. As the index of refraction of materials is sensitive to a number of parameters interferometers are widely used in applications to measure a variety of physical variables, such as displacement (distance), temperature, pressure, and strain.

1.2.6 Waveguides and Fibres – total internal reflection and “light wires”

If light strikes an interface between two materials, and the index of refraction of the first material is greater than that of second, the refracted light is bent towards the interface. At acute angles the refracted light is bent sufficiently that the light will not enter the second material. Under these conditions the light will be completely reflected and none will be refracted. This situation is called total internal reflection and is very important in a number of photonics technologies.

The waveguide is one application that uses total internal reflection of light. Optical fibre provides a typical example of the way a waveguide works. An optical fibre is a long glass wire consisting of an inner core and an outer cladding. The index of refraction of the core is higher than that of the cladding. If light is directed down into the core it will “bounce” down the fibre, undergoing total internal reflection at the core/cladding interface (see Fig. 3). The optical fibre will guide the lightwave from one end of the fibre to the other. Light generated at one end will be transferred to the other with only a very small loss of energy.

Optical fibre is frequently used as a communications link. A modulated light signal carrying information is passed along the fibre to allow for information transfer. The primary advantage of optical fibre is that it provides a significantly faster communications link than traditional metal wires.

A second commonly used waveguide structure is the planar waveguide. A planar waveguide is fabricated on a flat glass or semiconductor substrate and is usually rectangular in cross-section.

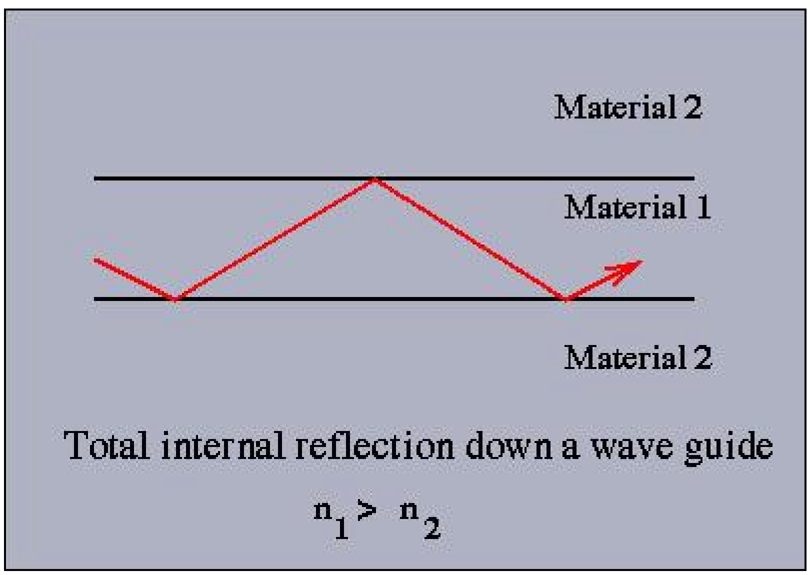

Figure 3: Light refection down a waveguide due to total internal reflection

1.2.7 Waveguide interferometers - Mach-Zender optical switches

A certain kind of interferometer incorporates two parallel waveguides. This kind of device is known as a waveguide interferometer. In this application a light beam is split into two rays. Each ray travels through a waveguide of fixed length before being rejoined to the other beam. Generally, both paths have equal indexes of refraction, so the rays are combined constructively. Therefore the full power of the beam passes through the interferometer. If the index of refraction in one of the pathways is altered, however, the output beam intensity drops due to destructive interference. The waveguide interferometer is a very useful device that can be used for a wide variety of sensing applications.

One type of waveguide interferometer that is often used for optical switching is the Mach-Zender interferometer. In this device electrodes are placed in one of the two paths. When a strong electrical potential is applied across the electrodes, the index of refraction in that path is changed. If no electrical bias is applied the beam travels through the device undisturbed. If the bias voltage is such as to cause perfect destructive interference, no output beam will appear at all. The light beam passing through the device can therefore be switched on and off by the applied electrical potential.

1.2.8 Waveguide modes – single and multimode operation

One phenomenon that occurs with the use of the waveguide is that of "mode". A "mode" is a specific physical state in the propagation of the lightwave along the fibre. Modes are associated with particular frequencies. In addition, one or many modes may be present when light is passed along a waveguide or fibre. In single mode operation only a single frequency of light is being passed along the fibre, whereas in multimode operation a number of modes and frequencies are being used. In telecommunications applications it is often desirable to use single mode operation.

1.2.9 Generation of light – emission, radiation and frequency

The generation and absorption of light by material is best understood using the concept of the photon. All matter when heated will produce photons. This is why hot material glows. In this situation the thermal energy of the material is being converted to light energy as the matter cools (i.e. loses energy) by radiation. The generation of a single photon from the material is the result of lowering the energy of the body by an amount corresponding exactly to the energy of the emitted photon. With a hot piece of material a wide frequency range of photons is emitted as the material cools, and a broad spectrum of light is produced. Other mechanisms for generating photons exist. For example, a chemical reaction may produce energy that is given off as light, as in the case of fluorescence or combustion.

1.2.10 The frequency of emitted light – quantum mechanics

Under most circumstances material will only absorb or emit energy in discrete amounts. This is because the components of matter – atoms and electrons – can only take on specific energetic states. Light will be produced when one of the components comprising the material lowers its energy from one state to another and this transition produces a photon (see Fig. 4). One example of this is the generation of light from an excited gas. If a gas such as carbon dioxide is heated by a strong electric current each gas atom will be excited and enter a higher energy state. The excited gas atoms will then release this additional energy by emitting a photon and reverting to the original energy state. The energy of the emitted photon is equal to the amount of the energy change from a higher state to a lower. If atoms are continually excited, that is, "pumped", light can be steadily generated. The light that is produced is of a single frequency determined by the energy change. This type of light generation is called spontaneous emission due to its random nature.

One device that uses this principle is the light-emitting diode (LED). An LED is an electronic component fabricated in a semiconductor such as indium phosphide. An LED can be “pumped” by an applied electric current that produces high-energy electrons. These electrons will fall to a lower energy level, producing light. The light is essentially of a single frequency or colour as it is the consequence of a fixed energy change.

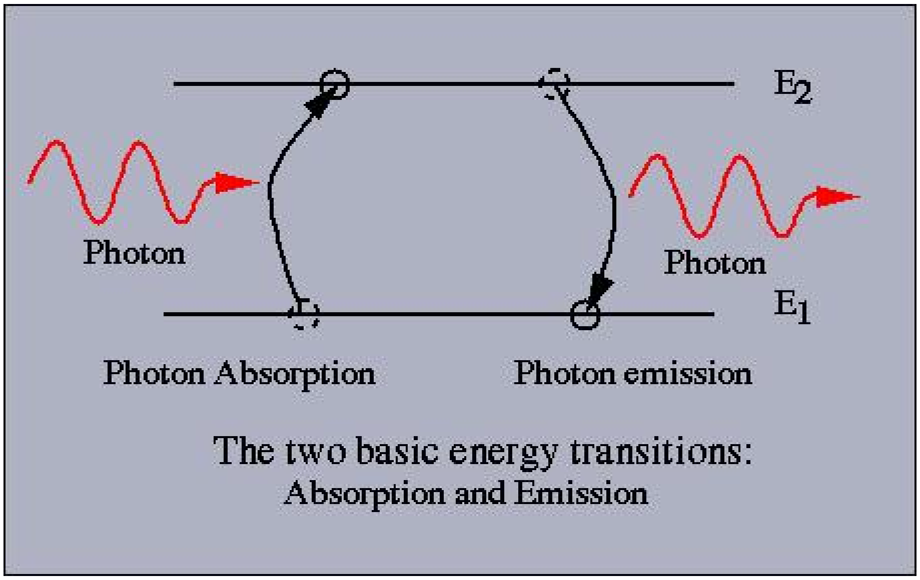

Figure 4: Two basic energy transitions – emission and absorption

1.2.11 Stimulated emission – amplification and pumping

In addition to spontaneous emission a very important phenomenon known as stimulated emission also occurs in materials. During stimulated emission an already excited atom is struck by a previously generated photon. This photon stimulates the excited atom to lower its energy and emit a second photon (see Fig. 5). It is of great significance that the second photon and the first (which still exists) have the same frequency and are in phase. This means that the second photon is added harmoniously to the lightwave and causes no disturbance, merely increasing the intensity of the wave. The action of pushing a swing provides an analogy to this. If you push “in phase” the swing goes higher and higher; if you push “out of phase” the swing motion becomes disjointed.

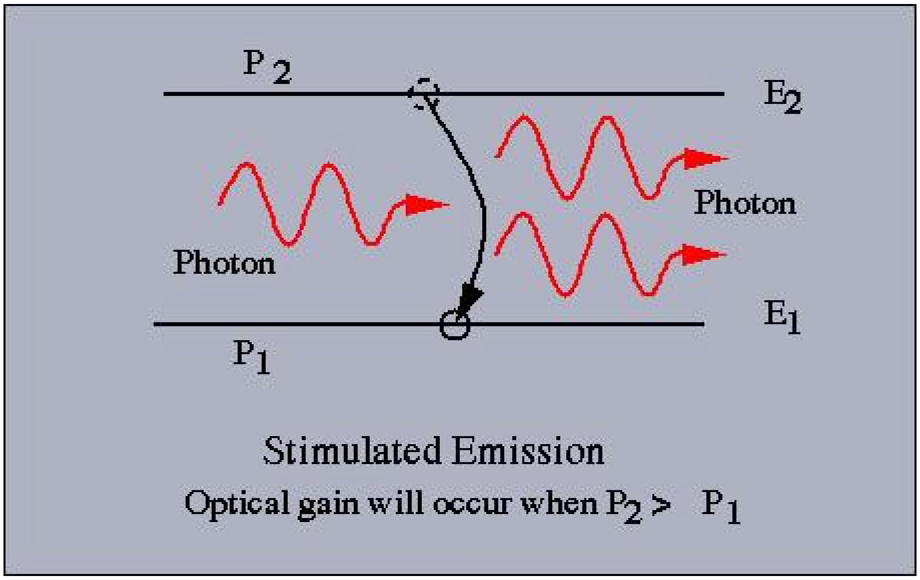

Figure 5: Stimulated emission of a second photon. The second photon is in phase and of the same frequency as the first. If the number of filled states at the energy E_2 is greater than that of E_1 optical gain is possible.

The application of stimulated emission is very important, as it is a means of amplifying an already existing lightwave. A lightwave passed through a medium that has been “pumped” or excited will be amplified by stimulated emission. In order to produce amplification a method of pumping the material must be available. Typically, this is done either optically or electrically. In an optical pumping system a strong source of light is used to excite the medium and provide a pumping mechanism. The source of light could, for example, be an electrically driven lamp. In some situations pumping can be achieved directly using an electric current. In a gas the applied current excites the atoms, while in a solid material it provides energetic electrons that can themselves produce stimulated emission.

1.2.12 Lasers – waveguiding, amplification and mirrors

Perhaps the most important technology that has been produced using photonics is the laser (Light Amplification by Stimulated Emission of Radiation). A laser is fabricated using a waveguide made out of an amplifying medium (often referred to as a lasing medium.) Photons trapped in the waveguide are multiplied by stimulated emission as they travel down the laser and the intensity of the lightwave increases. A mirror is placed at each end of the laser reflecting the photons back down the waveguide where they undergo more amplification. One of the mirrors is semi-reflecting, allowing for a portion of photons travelling up and down the laser to pass out through the end (see Fig. 4).

The net result of this configuration is that the light leaving a laser has three very important properties:

- the light is monochromatic and essentially at a single frequency

• the light is coherent – which means all the light leaving the laser is in phase

• the light is well collimated.

The light is monochromatic and coherent as it results from stimulated emission from a particular energy transition. The light leaving the laser is collimated into a beam because only photons travelling between the two mirrors are efficiently multiplied. The power of the laser can be adjusted by changing the rate of pumping of the "lasing" medium.

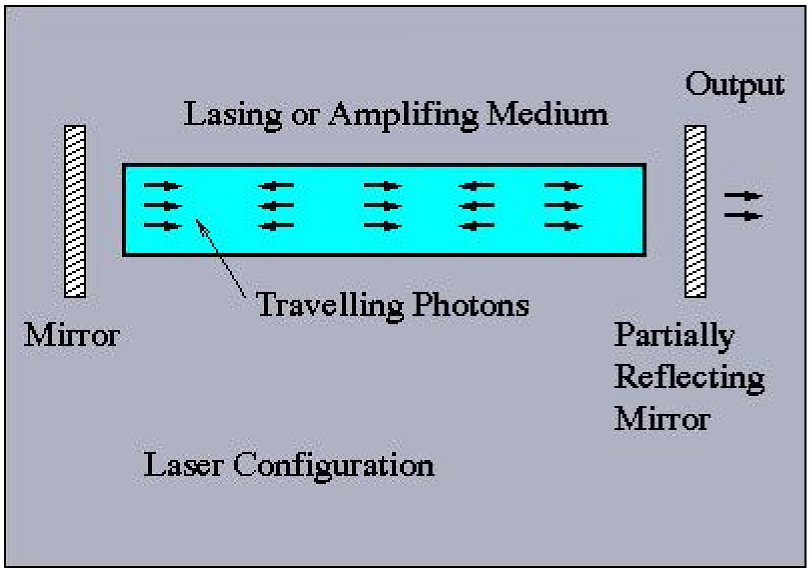

Fig 6: Laser geometry

A beam of light with these characteristics has a great number of applications, some of which are due to the monochromatic and coherent nature of the beam. Other applications take advantage of the ability of the laser to supply a large amount of optical power to a very small and precise area. Lasers can be used in either a pulsed or continuous manner. It is also possible to have a laser produce very short intense pulses of optical energy. These pulses have unique properties that can be exploited for laser machining and material analysis. It is also common to modulate the intensity of the light produced by the laser and use the laser to carry information.

Lasers come in three basic types:

Gas Lasers These lasers consist of a chamber filled with a gas such as CO_2. The gas is used as a lasing medium and provides light amplification when excited. The pumping of these lasers is typically effected by an electric discharge or a strong optical pulse.

Solid State Lasers Solid state lasers are made of a solid material such as glass doped with an impurity like neodymium. These impurities act as a site for excitation and provide a means of producing stimulated emission. The pumping mechanism for these lasers is typically optical, i.e., a strong lamp or another laser.

Semiconductor Lasers Semiconductor lasers are manufactured using flat substrates (known as chips) that are made of materials such as GaAs and InP. A waveguide is fabricated on the surface of the chip with a mirror at each end. An electrical current is then passed through the device. This electrical current will provide high-energy electrons that will undergo stimulated emission and drop to a lower energy state. The energy separation between these two electron energy levels is known as the "band gap". The size of the "band gap" determines the operating frequency of the laser. Semiconductor lasers have become a mainstay of the industry for low power applications.

1.2.13 Light absorption – heat and detection

A material can absorb light. When a photon strikes the material, increasing the energy of a component of the material (either an atom or electron) and destroying itself in the process. The excited component will then release the additional energy as heat or for some materials emit a second photon. The amount of absorption is dependent on the type of material. Using a laser it is possible to deliver large amounts of highly concentrated light energy. If the frequency of the light is chosen so as to be well absorbed by the material the laser can be used as a tool for cutting, drilling and heating. At lower energies the laser can achieve more subtle effects including marking, annealing and activating chemical reactions.

In many applications it is important to be able to detect light or photons. There are many methods of achieving this, both chemical (photographic film is an example) and electronic. One of the most important is the semiconductor photo-detector or photodiode. Using devices similar to the semiconductor laser light energy can be transformed into an electrical signal. This signal can be used as an input to electronics circuitry where it can be processed and manipulated. A solar power cell is essentially a very large photodetector in which light energy is directly changed into electrical potential and used as a power source.

1.2.14 Momentum and force – moving material

Most of the effects described above have dealt with the wave-like or energetic behaviour of light. Photons also carry momentum, however. This momentum causes a force to be exerted on a material when a photon is reflected. This force can be used to move material. There are a number of applications that use lasers to manipulate very tiny pieces of material such as large molecules or small particles. Applications featuring this principle are emerging in medicine, biophotonics and nano-technologies.

In addition to direct momentum transfer from the photon to the object, a second form of momentum transfer called photophoresis can occur. In this situation light is used to heat a surface and molecules bouncing off the surface gain momentum due to the higher temperature of the surface. The net result is a propulsive force that is applied to the object.

1.2.15 Optoelectronics – electronics and light

The development of electrical technologies such as the LED, the semiconductor laser, photodiodes and Mach-Zender interferometers have produced some of the most remarkable photonics applications. The term “optoelectronic” is used for devices that use electrical fields or currents to directly generate, manipulate or detect light. The use of optoelectronic components is an amazingly powerful enabling technology, not only reducing costs, but also opening up entirely new photonics applications. In telecommunications the introduction of optoelectronics has produced the recent dramatic growth in optical data transmission technologies. Two other terms that are used interchangeably for optoelectronics are “electro-optics” and “optronics”.

1.2.16 Photonics components – “Active” versus “passive”

Photonics devices are often characterized as either “active” or “passive”. Active components are devices that are electrically activated using a current or a voltage. Examples of active components are lasers, amplifiers, modulators and photodetectors. Passive components rely on simple material properties to perform their function. Examples of passive devices are lens, gratings and waveguides.

1.3 Industrial Structure

The following section provides an outline of the photonics industry and describes its importance as an industrial sector. It reports expected growth rates and provides a perspective on the integration of the photonics sector into the larger economy.

The rapid growth of the electronics industry in the last part of the previous century offers an example of the way in which a new technology can transform the way in which we live. The advent of the integrated circuit, which dramatically reduced costs, paved the way for the creation of entirely new electronics industries. The early part of this century may be dominated in a similar way by the growth and expansion of photonics technologies. The application of photonics technologies in the areas of telecommunications, displays, and imaging has already made large impacts and this may be only the leading edge of the changes to come. Emerging technologies such as optical computing and biophotonics can be expected to have equally dramatic consequences. Completely unforeseen applications may well be of greater industrial importance than anything so far contemplated.

A key driving force for current photonics activity has been the telecommunication and information technology industries. An explosive increase in the need for bandwidth (a measure of how much information can be carried on a transmission system) has led telecommunication companies to install photonics-based communication links. Although telecommunications has been the high-profile photonics success of the last 5 years growth in other photonics areas such as imaging, displays and biophotonics has also been impressive.

The photonics industry is volatile, which makes it difficult to predict its future rate of growth. It is possible to foresee some trends, however, based on current market values. The Optoelectronics Industry Development Association (OIDA) reported in 1997 that the value of the US photonics industry was $147 billion, a figure that is expected to double every four years (in fact, the US photonics industry was believed to be worth $188 billion in 1998). The Japanese photonics market was estimated to attain a value of $69.6 billion in 2000.

Industrial capability in photonics is found in almost all developed nations, with strong concentrations in the US, Japan and Europe. The Canadian presence is particularly significant, however. Companies such Nortel Networks, JDS-Uniphase and Lumonics are leaders in their fields.

It is important to understand the nature of the photonics industry. Photonics capability is founded on basic physics and material science. Research in photonics and the related fabrication and material-processing technology leads to component development. Components are the specific photonics devices used to supply, transmit, manipulate and detect light. Suppliers such as JDS-Uniphase manufacture these components. Components are integrated into large systems typically containing photonics, electronics and mechanical components. These systems provide solutions to complete problems. An example of this is a laser system for performing surgery. Some companies such as Nortel Networks manufacture both components and systems.

The role of photonics as an enabling technology is of supreme economic importance. OIDA estimates that a $40 billion photonics component market enables a $110 billion optoelectronic equipment market that in turn is used in a $1.5 trillion information services market. Photonics is now making possible entirely new industries and reducing overheads in old ones. These developments are likely to produce profound changes in the way in which we live, do business and entertain ourselves.

1.4 Primary Applications

Photonics has a very wide range of application across many industrial sectors. In this section we will attempt to outline the applications found in a number of key areas. The areas discussed are telecommunications; optical computing; displays; imaging; solar energy; biophotonics and medical applications; manufacturing; and sensing. This does not represent an exhaustive list of all photonics applications.

1.4.1 Telecommunications

In the late 1970s and early 1980s optical fibre and associated optoelectronic components began to be used for long-haul large capacity networks between cities. By the mid 1980s fibre optic transmission systems were clearly more cost-effective than traditional copper-wire and microwave systems. In the former type of system the high cost of the optoelectronic components is shared by a large number of users.

In fibre optic transmission systems the basic communications link features a light source (laser), a single or multimode fibre and a detector (photodiode). A light signal at a single-carrier frequency is generated by the source, passed along the fibre and finally converted back to an electrical signal by the detector. In such a system a number of lower-frequency electrical data streams are multiplexed (interwoven) in time to produce a single high frequency signal. This signal is then used to modulate the optical light from the laser source. At the end of the fibre link the optical signal is demultiplexed (un-woven) and the electrical signals are recovered. The term Time Division Multiplexing (TDM), which refers to multiplexing lower-speed electrical signals in time, is frequently used to refer to this type of system.

Wave Division Multiplexing – The recent dramatic increase in the amount of data traffic on the Internet has lead to a need for larger bandwidth optical communication links. A simple system based on Time Division Multiplexing of a single optical carrier is inadequate. One solution to this problem is Wavelength Division Multiplexing (WDM). WDM technology uses the same type of fibre-based communication link as TDM technology. The difference is that WDM uses more than one channel of information on a single fibre. In addition, each information channel is carried at a different optical frequency.

The use of WDM requires more sophisticated light sources and detectors, but allows for a significant expansion of data-carrying capacity on an existing fibre. An important part of a WDM system is optical gratings that allow for the mixing and separation of the optical channels by frequency. The gratings multiplex (i.e., mix) large numbers of signals at different frequencies onto a single fibre and then demultiplex (un-mix) these signals at the end of the fibre. Current WDM technology allows for up to 40-80 data channels on one fibre. As the number of channels has increased, WDM has come to be referred to as Dense Wave Division Multiplexing (DWDM). There are ongoing efforts to increase the bandwidth of long-haul data links that will multiply both the number of channels and the TDM data rate of each channel.

Fibre amplifiers – A key factor in the success of WDM technology was the development of the fibre-based optical amplifier. The amplifier is a specially modified length of fibre that uses stimulated emission to produced amplification of an optical signal. Optical power from a pump laser is used to amplify all the channels passing through a WDM system. This allows for the compensation of optical loss in WDM systems arising from filters, switches and attenuation. It also reduces the cost of WDM systems by decreasing the number of electronic repeaters used in an optical communication link.

Local optical networks – Although in the past fibre has been used primarily for long-haul systems, there is a growing need to move the optical network closer to the end user. The merging of voice, data and video technologies have produced a demand for high capacity communications links to the home and office. The cost of the optical electronics components is the chief limitation on the provision of optical connections to end-users. The use of optical links for local area networks and PC-to-PC applications will require a substantial lowering of component costs. This cost reduction will have to be achieved in a number of ways including optical integration and the development of new technologies. Integrated electronics obtained incredible cost reductions by fabricating a large number of electrical devices on a single chip. Integrated optoelectronics is attempting to achieve the same cost reductions with optical components such as lasers, detectors, waveguides, switches and multiplexers. These components would be integrated onto a single optical semiconductor chip.

The development of practical silicon LEDs and laser diodes will represent a significant technological advance. Silicon components offer many advantages with regards to integration, but at present they have only been demonstrated under laboratory conditions.

All-optical networks – One major limitation of current optical communication systems is the need to revert back to an electronic signal to handle switching and routing. Switching and routing are used to send the data streams to the correct network nodes or addresses. This routing is achieved by having each data packet carry information about its destination. Electronic switches use this information to route the packet. All-optical switches and routers have the potential to function considerably faster than electronically based devices. The development of all-optical switches and networks poses a significant challenge, however; initially it will involve data streams being routed from one network node to another. It is expected that eventually individual data packets will be routed and delivered using only optical devices.

1.4.2 Optical computing and memories

Optical storage – The simplest form of optical memory - CD and DVD discs - has become commonplace. With the advent of read/writable optical disc media and decreasing access times optical disc drives are now a significant consumer product. They support large amounts of data storage and are the media of choice for the distribution of data. Optical disc storage for electronics data is an $8 billion market. A great deal of research effort is being directed towards expanding the capabilities of optical disc technologies.

A significant limitation of disc storage systems is the necessary use of sequential access and associated mechanical delays. One technological response to this problem is optical random access memory (RAM), which is currently under development. Optical RAM promises to deliver enormous potential increases in both storage densities and access times compared to what is possible with electronic RAM. Optical RAM also offers the possible advantage of parallel access to the stored data; it is feasible that megabits could be read simultaneously. A number of optical RAM technologies such as holographic systems are under development.

Optical interconnects – In optical computing applications the most immediately promising areas are found in local data interconnections. High-speed electronics is currently limited in speed by the inherent delays of the electrical interconnects and the crosstalk or interference between adjacent interconnects. Optical interconnects are fundamentally faster than electrical ones and do not suffer from cross-talk problems.

It can be expected that optical interconnects will first be applied to data bottlenecks at the board and backplane levels. Optical interconnection systems are likely to come in two forms: guided optical interconnects and free-space interconnects. In a guided system fibres and waveguides will function as the “wires” for data transfer. In order to make this solution cost-effective a large amount of optical integration would need to be achieved.

A drawback to the use of guided interconnects is the need to fabricate complicated and costly waveguide structures. A possible solution is to use an array of laser sources and detectors and use free-space interconnects. In such a system no waveguide would be used; instead, the natural collimation of the laser would be applied to direct light at an appropriate detector and make an optical connection. A beam-steering element would be needed to control the interconnection. This method of interconnection has many possible advantages, including re-configurability, high data rates and simple fabrication.

All-optical computing – The development of purely optical computing lies in the distant future. The most powerful incentive for further investigation in this area is the manifest physical limitations of the electronic computer. These limitations have motivated research groups to work on creating optical switches and logic devices that could be integrated into an all-optical computer that is potentially much faster than traditional electronic computers.

1.4.3 LED technologies

The light-emitting diode was one of the first optoelectronics devices. When an electrical current is passed through an LED light is produced by spontaneous emission. The light that is produced is of a single frequency or colour. Early LEDs could only be made to produce light of a very restricted number of colours. Recent advances in materials and devices have made possible the creation of LEDs that can produce light of almost any colour. Blue LEDs have proven to be the most difficult to create, and have only recently been fabricated. It should be noted that a blue LED could more than double the memory capacity of a CD.

LEDs were initially used for a restricted number of applications such as simple displays, barcode readers and some optical communication links. LEDs are inherently more efficient than traditional lighting sources, however, as they are very rugged and reliable. As more colours have become available, including infrared, LEDs have become a commonly used photonics device. Recent LED research has lead to a wealth of possible applications include general lighting, medical applications, short-haul communication links and flat panel displays. LEDs are already being used in traffic lights because of their low maintenance costs compared to incandescent lamps.

1.4.4 Display Technology

The worldwide display market is very large. The potential flat panel TV market is estimated at $80 billion, but the computer monitor market is also very substantial and specialized applications for medical and military equipment represent significant demand.

This market is in some ways very mature with the cathode ray tube (CRT) being the dominant display technology for moderate-sized displays. The CRT's disadvantages - size, weight and power consumption - are producing a strong incentive for the development of flat panel displays. In the past, due to cost and technical limitations, flat panel displays were only introduced in specialized applications such as laptop computers, where portability is the key. As the price decreases, Liquid Crystal Displays (LCDs) are becoming competitive with CRTs and their introduction into other market segments is inevitable.

Liquid Crystal Displays – The challenge for flat panel display technology is to match the resolution, brightness, contrast, colour performance and viewing angle of CRTs. A significant challenge is to match these criteria for a large screen display providing video performance. Traditional flat panel displays have used liquid crystal technology. A liquid crystal is an organic material that can be used as an electrically controlled optical switch. A rectangular array of a large number of LCD switches can then be used to form a display. In the last ten years a series of improvements in LCD technology has produced near-CRT quality for moderate-sized displays. Large LCD displays are difficult to fabricate, however; at present they are not cost-competitive with CRTs. Research and development is being aggressively pursued in this field.

Other flat panel technologies – Many other flat panel display technologies are being investigated. These include: field emission displays, plasma displays and luminescent displays. Field emission displays are similar in principle to a CRT. Using micromachining techniques a flat array of very small sharp tips is created. These tips can be used to control the electron flow to a phosphor-covered screen placed above the array of tips. The phosphor screen then produces an image.

A plasma display panel (PDP) is essentially an array of tiny fluorescent tubes that are controlled by electronic devices, producing an image. Some advantages of PDPs are; easy scaling to very large sizes, relatively low weight and a thickness of about three to four inches. Large size PDPs (e.g. 50 inchs) are already on the market today. Currently PDPs are more expensive than comparable CRTs.

Luminescent displays use electrically activated phosphors and arrays of electrical contacts to produce an image. The chief advantages are scalability and low fabrication costs. The primary problems are in the areas of brightness and contrast.

1.4.5 Imaging technology

One example of a simple photonic imaging device is photographic film. Recently, photonics imaging devices based on semiconductor technology have become a significant market. The development of document scanning, digital video technologies and digital image processing have all been made possible by photonic imaging technologies. These technologies create an “electronic film” that allows for the direct capture of an image as electrical data

CCD imagers – The most common technology is the charge-coupled device (CCD). Charge-coupled device technology was first demonstrated in 1969 at the Bell Laboratories. It was first developed for specialized remote sensing applications in 1974, under the sponsorship of NASA. A CCD image sensor is a small silicon chip on which is placed an array of light-sensitive CCD devices. When photons strike a CCD they are absorbed and an electronic charge is generated. The magnitude of this charge is proportional to the intensity of the impinging light. The lowering of the cost of CCD technology, due to the application of microelectronics fabrication methods, has revolutionized both home and studio video recording. CCD imaging sensors are routinely used in video and still cameras and in fact are used as an “electronic eye” in a great many applications.

CMOS imagers – A recent alternative to CCD devices are CMOS imagers. As with the CCD an array of light-sensitive devices are fabricated. These devices are built in a standard microelectronic fabrication process rather than with specialized, higher cost CCD technology. A major advantage of CMOS imagers is the ability to integrate the imaging array with processing electronics, thereby improving performance and further lowering costs. Current research challenges include the improvement of resolution and sensitivity. .

An important application of these technologies is infrared imaging. Using a variety of devices sensitive to short wavelength applications such as night vision and remote sensing have been developed.

1.4.6 Solar Energy

The generation of energy from sunlight is an attractive alternative for power generation. The primary requirement is a photonics device that efficiently converts light to electrical power. This power can then charge a battery for future consumption. The device used to convert the light to electrical power is a solar cell. A solar cell is typically a very large version of the photodiode used to detect light in a telecommunications fibre link. The specifications for the device are very different, however. The solar cell must be very inexpensive, reliable and it must be possible to manufacture large devices to capture significant amounts of sunlight. Typically, solar cells are fabricated using silicon due to its low manufacturing costs. The economics of solar energy are currently such that it is only used in special circumstances where the regular power grid is unavailable. Research is ongoing into reducing the costs, and as the price decreases the solar cell will make inroads into mainstream applications.

1.4.7 Biophotonics and Medical applications

Biophotonics is the study and application of the interaction of light and biological systems. Biophotonics is a very extensive field that encompasses a wide variety of scientific disciplines and applications; it could be said to take in everything from photosynthesis in plants to laser surgery. The following is a brief list of some biophotonic applications.

Laser Surgery – Lasers were first developed in 1964 for industrial uses, such as the precise cutting of metals and plastics. These lasers emitted continuous beams of light. During the following twenty years all laser medical treatments were performed using industrial lasers that had been adapted for medical use. In the early 1980s a better understanding of the effect of lasers on tissue led to the use of lasers that produce short pulses of light and laser surgery became much more precise and effective. Lasers have now become a generally used tool for surgery of many types.

Laser Therapies – Other examples of laser therapies include the clearing of blocked arteries, dermatology and dental repair. Non-intrusive, photonics-based cancer therapies are possible using photodynamic therapies that work by injecting a photosensitive chemical into a patient**.** This chemical accumulates in a tumour. The tumour is then irradiated by a laser, which activates a photochemical reaction that kills the malignancy.

Lower levels of laser light have been found to be useful in many medical applications. For example, lasers are in widespread use for the treatment of a range of musculoskeletal problems and are often used for the relief of acute or chronic pain. Specific uses include the treatment of conditions such as rheumatoid arthritis and osteoarthritis, and in sports medicine.

Medical imaging – Until recently X-ray imaging has been the dominant light-based medical imaging technique. Photonic semiconductor imagers are now starting to be introduced, though these devices are primarily based on photographic film technology. Use of photonic semiconductor imagers can be expected to grow.

Laser Scanning Confocal Microscopy (LSCM - also referred to as CSLM), is now established as a valuable tool for obtaining high-resolution images and 3-D reconstructions of a variety of biological specimens. LSCM uses a laser to irradiate a biological sample dyed with a fluorescent chemical. An optical system using lenses, a pinhole device and a photo-detector can then be used to obtain 3-D images of the structure of the biological sample.

Standard LSCM systems are limited to small samples. Because of this, non-X-ray light-based imaging techniques using optical or infrared frequencies and laser light sources are being developed to image larger structures such as organs. These techniques are based on the concept of photon scattering in human tissue, which is an area of intense investigation. As these techniques improve they can be expected produce photonics-based diagnostic devices.

Endoscopes – The optical fibre is also used in medical applications to allow for minimally intrusive viewing and surgery of internal structures. An endoscope consists of a lens and a light source at the end of an optical fibre. The fibre is passed into the body and a view of the internal structure of the body is obtained. This allows a diagnosis to be made without intrusive surgery. An optical fibre can also be used to deliver high intensity laser light to an internal region in the body, for example, to remove tumours.

1.4.8 Manufacturing

Photonics devices such as the laser have a wide variety of applications in manufacturing. The following outlines a number of the more important technologies.

Machining – When the laser was first invented, it was used primarily for cutting, welding and drilling materials, applications that can be covered by the general term “laser machining”. Laser machining harnesses the laser’s ability to apply large amounts of power over very small areas. Also included among laser machining applications are surface hardening and local annealing using lasers at a power low enough to alter the properties of the material in a controlled manner. Laser machining offers potential advantages such as a reduction in the number of steps in processing and a higher product quality. Lasers are also very suitable for automated production.

Industrial interest in lasers is on the rise due to the increasing use of innovative materials such as superalloys, composites and ceramics. Laser processes can machine components from these sophisticated materials, and in fact often represent the only possible choice for working with them. Modern lasers are designed so that the pulse rate of the laser and the operating frequency are optimized for particular tasks. Lasers can also be designed to machine materials from steel to polymers to semiconductors. High power industrial lasers are used for cutting everything from steel to cloth and also can be used for large-scale welding applications.

Rapid Prototyping – Lasers are also used extensively in the field of rapid prototyping. Rapid prototyping is the creation of a three-dimensional part from a computer representation. Generally, in rapid prototyping a part is gradually built up using deposition of material in a controlled manner to create the part layer by layer. In laser-based technologies photosensitive polymers, powders or liquids are solidified using a laser. A computer-controlled laser is used to create the 3-D model.

Marking and labelling – At lower power levels the laser is ideally suited for marking and engraving materials. It is widely used to mark almost all solid materials. Laser marking is a non-contact process with the ability to mark or label anything from computer chips to lumber. The chief advantages of laser marking are speed, absence of contamination, and the ability to produce high quality complex markings at a wide variety of scale lengths. Lasers are also used with photodetectors to read barcodes and other labels.

Microelectronics processing – Lasers are making significant inroads into the microelectronic fabrication industry. They are widely used for trimming both thick and thin film resistors, for drilling holes in boards and substrates, for the welding of hermetically sealed packages, and for stripping insulation from wires. The marking of silicon wafers with identification numbers has also become well established. The application of lasers in microelectronic fabrication has become accepted on a routine production basis because it offers economic advantages in many cases.

A related use of lasers is in micromachining. Micromachining is the creation of very small structures using the fabrication techniques of integrated electronics. Direct machining of such structures is possible using lasers.

One application of photonics that offers significant promise for microelectronics is photonic verification of circuit and process functionality. At present, however, testing cannot be effected with conventional metal probes because of their comparatively large size and poor frequency response. Photonic testing of integrated circuits is yet to be realized, but it does offer the possibility of non-contact circuit testing at the wafer-stage using many photonic test points (i.e. light sources and photodetectors). This capability would improve the reliability of integrated systems and also reduce production costs.

Control and Monitoring – Lasers are also used in manufacturing lines for monitoring material dimensions, aligning machinery and other sensing applications. A fibre-based photonics application is the control of machinery using optical communication systems. Due its immunity to electromagnetic interference optical fibre is a good choice for machine control and electronic communication in an electrically noisy environment. The photonics components used for this application are essentially the same as those used for short-link telecommunication applications.

Semiconductor photolithography – Photolithography is a basic operation in semiconductor microelectronic manufacturing. It can be defined as the process of transferring geometric shapes from a mask to the surface of a semiconductor wafer. The patterns produced are then used to manufacture the very small devices that make up the electronic circuit. The process is very similar to that of photography. An image is projected onto the wafer using a machine called a stepper. This image illuminates a light-sensitive film that has been coated onto the wafer surface. The primary challenge in the photolithographic process is producing very small feature sizes.

Currently photolithography is a $1 billion industry; it is also key to further performance increases in microelectronics. A number of initiatives have been made to produce steppers operating at shorter wavelengths; this is due to the fact that the wavelength of the light used for producing the image determines the minimum feature size. Unfortunately, optical lithography is suboptimal at feature sizes less than 0.2 microns. A considerable amount of research is being pursued to develop sub 0.1-micron lithography. X-ray technologies are among those being considered for this purpose.

1.4.9 Sensors

Photonics devices can be used to measure a wide variety of physical, material, structural and chemical properties. For example, an optical fibre can be made sensitive to a large number of factors in the environment in which it is placed. Mechanical stresses, spatial displacement, temperature, pressure and deformation all cause changes in a fibre's propagation properties. To use an optical fibre as a sensor a light signal is passed along the fibre. Characteristics of the light passed through the fibre (i.e., phase and intensity) are monitored and changes in these quantities can be used to measure a particular quality such as temperature. Fibre optic sensors have the potential to be very accurate and have numerous other advantages such as minimal weight. They can also be embedded in materials and structures such as buildings and bridges, providing information on loading, wear and displacements. Fibre optic sensors have been applied in many fields including chemical manufacturing, biological/medical technologies and automotives.

2. Canadian industry and research capability

This section provides a brief overview of the history of photonics in Canada, followed by a description of current national capability in this area. The discussion of current national capability is divided into three parts; the first gives an overview of industrial activity; the second provides a list of organizations that facilitate the growth of the photonics industry in Canada, and the third reviews the post-secondary education system in Canada, with specific reference to the production of personnel with expertise in the area of photonics.

The discussion of industrial activity (which is limited by space considerations) involves both established companies and smaller "start-up" firms. The list of collaborative industrial organizations provides a brief description and history of each organization along with its mandate. This is followed by an analysis of the striking Canadian phenomenon of small start-up companies being generated by research originating in established laboratories.

The discussion of the post-secondary education system provides an overview of the training of skilled personnel for the photonics industry by Canadian colleges and universities. A number of government, university and college initiatives to increase the number of trained personnel are described.

In Canada, researchers have been involved in photonics for a considerable length of time. A number of Canadian academics have made significant contributions to photonics and related fields. One such academic was G. Herzberg, who was based at the University of Saskatchewan (1935) and then the National Research Council (1948). His research, which won him the Nobel Prize in 1971, was in the fields of chemistry and spectroscopy. In the 1950s, the University of Toronto and Université Laval became known for their work in optics. During the last 20 years optical, laser and photonics research has been undertaken at most Canadian universities, often leading to outstanding work. One of the best-known researchers in the field is of course J. Polanyi of the University of Toronto. Polanyi's work, which involved the use of photonics techniques in chemical reaction dynamics, was recognised with a Nobel Prize in Chemistry in 1986.

The Communications Research Centre (CRC) in Ottawa is one of the pioneering Canadian research and development institutions in the field of optical communications. The program was established in 1969 in response to the announcement by Corning Glass Works of new low loss fibre optic waveguide. CRC went on to produce and patent many inventions, notably the biconical fused-taper coupler and the Bragg-grating fibre filter/reflector.

Research undertaken by Canadian Armament Research and Development Establishment (CARDE) in Valcartier, Quebec was also important in the development of photonics in Canada. Initially, researchers at CARDE studied laser propagation in the atmosphere and in 1965 CARDE scientists developed the first solid-state laser range finder and demonstrated for the first time the feasibility of CO2 Transversely Excited Atmospheric (TEA) lasers. In the following 2 years, the team patented 25 inventions in 15 countries.

In the industrial sector Canadian companies have established a presence in several areas of photonics. Bell-Northern Research was established in the late 1960s, as was the Optical Communications Group, which became a key factor in the development of the photonics telecommunication industry. Lumonics Inc. was established in the 1970s to exploit laser technology developed by CARDE and is now one of the largest manufacturers of industrial lasers in the world. It is in telecommunications, however, that Canada has the most established capacity. Nortel Networks is one of the world's leading optical networking companies. Its current pre-eminent position is largely due to its strong research base, the foundations of which were laid by Bell Northern Research and the National Research Council in the 1970s and 1980s.

One factor that led to Canadian pre-eminence in the use of the use of fibre optic transmission systems for long distances was the decision by Trans-Canada Telephone Association during the early 1970s to move towards digital data transmission for the Trans-Canada Telephone System (TCTS). By 1979 the TCTS was fully digital. Because of this decision the upgrading of the TCTS to optical fibre was a relatively simple operation, and by 1993, fibre optic transmission systems were used coast-to-coast. Other initiatives in fibre optic-based communications followed. In 1980, SaskTel decided to construct a fibre optic network linking all cities, towns and villages with more than 500 homes. This came to be the first commercial application of fibre optic transmission systems in the world. By the late 1980s, more than 3,200 km of fibre optic cable had been laid in the province. In the mid 1980s, Manitoba Telephone (in partnership with Northern Telecom) carried out the Elie Fibre Optic Subscriber Loop Trials whereby telephone, cable TV and farm data information services were provided to 250 homes from a specially constructed central office. All of this activity produced a receptive environment for photonics component development.

The Canadian photonics industry has been supported by a number of government initiatives. The Solid State Optoelectronics Consortium (SSOC) is an historical example of a significant government industrial collaboration. SSOC was founded in 1988 under the guidance of the National Research Council. Its mandate was to establish a Canadian capability in photonics. SSOC directed a large portion of its energies towards the development of integrated photonics devices for WDM on a single chip. There have been many other SSOC successes however; one notable achievement was the development of several types of lasers for telecommunications applications. SSOC was a crucial factor in creating a Canadian photonics infrastructure and in promoting coordination between industry and research institutions.

The growth of the Canadian optical telecommunications industry in the late 1990s has been astonishing. One of the most dramatic examples is JDS-Uniphase, a company that grew from 180 employees in 1993 to over 17,000 in 2001. Very recently, a large number of small, innovative start-up companies have been spawned from larger, established companies, universities and government institutions. In Ottawa alone, over one hundred photonics-related start-ups have appeared in the last two years.

It is important to realise that the photonics industry provides components for other industries. The introduction of WDM by Nortel Networks is an example of how fundamental materials and device research can be crucial in making possible new system-level solutions. Nortel was able to see the advantages of a WDM communications link because of its expertise at both the component and the system level. The company was able to provide a complete solution to a problem by firstly, developing new photonics devices for WDM systems, and secondly, using these devices to produce optical communications systems. This shows that while photonics component work is important for new application development, the presence of a system-level receptor company capable of recognising the implications of the technology and implementing the solution is equally crucial.

The structure of the photonics industry can be modelled as a vertical progression from material production, through component supply, to the marketing of fully integrated systems. At each stage of integration the economic impact is increased. It can be seen from this that much greater benefits accrue to the Canadian economy if the system company is Canadian.

2.1 Current industry position

This section provides an outline of the current status of the Canadian photonics industry. Companies currently active in the photonics area are listed; these are grouped according to particular company focus, that is, the photonics application that the company specializes in. Each company's photonics-related activity is briefly described; it should be noted that due to the large number of companies involved in this area, only selected examples are presented. At the end of the section a short description of photonics start-up activity is given.

In 1993 there were approximately ninety companies involved in photonics-related work in Canada. Today there are over 700 in Ontario alone. These companies run the gamut from large-systems integration companies to small research and development shops. It is estimated that in Canada, photonics is a US$6 billion industry that employs 24,000 people. It is further estimated that this industry is growing at a rate of 50% per year.

High-technology industry tends to organize itself into "clusters" of activity. A cluster is an identifiable local grouping of industrial activity, academic research and post-secondary training in a particular industrial sector such as photonics. Clusters are seen as being important factors in spurring economic activity. At present there are five clusters of photonics activity in Canada: Vancouver, Ottawa, Toronto, Montreal and Quebec City.

The following is a list of some of the key photonics-related companies in Canada. The list focuses on companies that manufacture photonics components. The aim is to give the reader an idea of the scope of Canadian industrial photonics capability. A more complete list is available from Industry Canada (see the "Canadian Photonics Capability Guide").

2.1.1 Telecommunications

Nortel Networks – Nortel Networks is a global Internet and communications leader with capabilities spanning Optical Internet, Wireless Internet, Local Internet, eBusiness, and Personal Internet. Nortel had revenues of US $30.3 billion in the year 2000, and it employed 94,500 people. It is one of the world's leading telecommunication companies with a strong optical systems capability. It is estimated that 75 percent of the Internet traffic in North America and 50 percent in Europe is carried on Nortel products. A significant move into WDM technology pushed Nortel to the front of the optical network market. A strong effort in photonics research and development with a major centre at Ottawa is expected to keep Nortel growing in the future. Currently Nortel is developing the next generation of optoelectronic components for optical interconnects. Research is ongoing in areas such as: lasers, passive waveguides, optical switches, DWDM and optoelectronic integration.

JDS-Uniphase – JDS Uniphase is a leader in the design, development, manufacture, and distribution of advanced fibre optic products for telecommunications and cable television. JDS-Uniphase has been remarkably successful. In 1993 it employed 230 people and generated revenues of $20 million. By the year 2000 its revenue was $1.43 billion and it employed over 17,000 people. The company began by supplying components for the rapidly expanding optical telecommunications market for systems builders such as Nortel. It grew by acquiring or merging with companies such Uniphase and SDL. The company now supplies a whole range of passive and active optical components.

OZ Optics – OZ Optics is a fibre optic component supplier founded in 1985 to provide components for interferometric sensors and the telecommunications field. It now produces photonics components for telecommunications and cable television, as well as the computer, industrial, military, medical, sensors, and educational fields. OZ Optics is expanding rapidly. It has grown from 65 employees to over 300 in eight months.

Mitel Semiconductor – Mitel Semiconductor is a semiconductor and optical component company centred on telecommunications applications. Mitel Semiconductor recently sold off its systems operations, becoming solely a semiconductor company that delivers broadband connectivity solutions targeted to the wireless and optical markets. It employs 2500 people and generates annual revenues of $600 million. Mitel Semiconductor has both research and development and manufacturing centres in Ontario and Quebec as well as overseas. Photonics products and research are in CCD devices, integrated waveguide technologies, lasers, LED, and photodiode products.

MPB Technologies – MPB is an example of a medium-sized, research-intensive company. Based in Quebec, it employs 200 people. Its areas of expertise include telecommunications, laser cutting and tuneable lasers.

EXFO – EXFO is a Quebec-based company involved in the design, manufacturing, and marketing of fibre optic test, measurement, and monitoring instruments for the telecommunications industry. With 950 employees and sales of $28.5 million per quarter EXFO is a significant supplier of test equipment to the world

Alcatel – Alcatel brought a significant international presence to Canada when it bought Newbridge Networks of Ottawa in 2000. Alcatel is a major systems and component supplier in the telecommunications and Internet markets. It is a very large company with 130,000 employees worldwide. In the year 2000 it generated sales of EURO$31 billion. Alcatel has a strong commitment to research in photonics, especially the areas of semiconductor optical amplifiers and WDM technology. On 5 July 2000 Alcatel announced the acquisition of Innovative Fibres, a Gatineau, Quebec based company that was founded in 1995. Innovative Fibres now employs approximately 220 people working in DWDM optical filters (Fibre Bragg Grating technology).

STMicroelectronics – In May of 2000 STMicroelectronics announced the purchase of Nortel Networks' silicon semiconductor production operations located in Ottawa.. STM is the world's seventh largest semiconductor company with 40,000 employees and US$8 billion of revenues in 2000. This research-intensive company spent US$836 million (16.5% of revenues) on research and development in 1999. Although STMicroelectronics is primarily an electronics company it is well-positioned to move into the photonics area.

2.1.2 Industrial

GSI Lumonics Inc – GSI Lumonics is a broadly based photonics company whose main office is in Ottawa. Lumonics produces a greater assortment of laser-based systems, components, and services than any other company. It provides products and services to the semiconductor, electronics, automotive and telecommunications precision optics markets. It also supplies products and services to general manufacturing. For the 12-month period that ended December 31, 1999 the company generated sales of US$274.6 million. GSI Lumonics produces lasers for general machining and inspection purposes, components for telecommunication systems and scanning and printing technologies.

LMI Inc. – Laser Measurement International, Inc. was created in 1998 with the amalgamation of five innovative companies in industrial non-contact laser-based measurement and control sensors. LMI products and systems are used in a variety of industries, from foundries, wood and rubber to building, road, welding and automobile manufacturing. LMI is based in Vancouver, British Columbia, and maintains research and development, manufacturing and sales facilities in four other locations in the US, Canada, Sweden and the Netherlands.

EFOS Corporation – EFOS Corporation opened its doors in 1982 with a mandate to research, develop and manufacture systems and equipment that make innovative use of light energy. EFOS develops a wide range of photonics equipment based on lamps that deliver specific wavelengths and intensities of light. The EFOS Manufacturing Assembly Division designs and manufactures precision light-based curing equipment. The EFOS Biomedical Division employs light in a host of human-related including: photodynamic antimicrobial chemotherapy, wound sealants, and photodynamic therapy. EFOS was recently purchased by EXFO.

2.1.3 Medical/Biological

QLT Inc. – Located in Vancouver, QLT was formed in 1981 and became a public company in 1986. It employs 350 people and generated revenues of $50 million in 2000. QLT Inc. is a research-based company that focuses on developing and commercialising pharmaceutical products for use in photodynamic therapy. The company recently developed PHOTOFRIN®, the world's first approved PDT drug used in the treatment of various cancers.

DUSA – DUSA was formed in 1991 to investigate photodynamic technologies for the detection and treatment of dermatological diseases and cancer. The company, which is based in Toronto, has just released its first products.

DigiOpt – Founded in 1999, DigiOpt is developing medical imaging technology in optical microscopy and microimaging. These technologies are broadly applicable in medicine, biological research, and industry.

2.1.4 Imaging/Displays

DALSA – Based in Waterloo, Ontario, DALSA is a leader in the design, development, manufacture, and sale of high-performance imaging products. DALSA reported revenue of $53 million in 2000 and invested $11.8 million in research and development. The primary areas of research are CMOS image sensors and medical imaging products. DALSA provides substantial financial support for University researchers. DALSA's image sensor chip and electronic camera products are based on charge-coupled device (CCD) technology and the CMOS imager. Principal markets for DALSA products include machine-vision product inspection, document scanning, postal sorting and electronics inspection.

iFire – iFire is a research and development company that was launched by the Westaim Corporation. Initially called Westaim Advanced Display Technologies Incorporated the company became iFire Technology Inc. in February 2000 and is based in Toronto. Nine years of research at iFire have culminated in the development of a low-cost solid-state flat panel display based on electroluminescence. It is currently pursuing efforts to commercialize its flat panel technology.

2.1.5 Photonics Start-ups

The most remarkable development of late in the Canadian photonics industry has been the large amount of start-up activity in Ottawa, Montreal, Vancouver and Toronto. In Ottawa alone there have been over one hundred photonics-related start-ups in the last year. This activity results from a number of factors:

- academic and government laboratories that sponsor innovative research
- the availability of a significant number of highly skilled personnel from industry, universities and government
- the growth of the Internet and the resultant need for photonics communication links
- availability of venture capital

This last point is especially significant; it has been estimated that as much as $1 billion of venture capital was invested in Ottawa high technology companies in 2000. Some small photonics companies who recently received funding are: Solinet Systems Inc. – funded with US$15M to develop high-speed optical Internet systems; Tellamon Photonic Networks Inc. – funded with $31M to produce optical components for transmission systems; Zenastra Photonics Inc. (formerly Nu-Wave Photonics) – funded with over $100M to develop low-cost integrated waveguides; MetroPhotonics – funded $62.5M to develop integrated waveguide switching technology; Innovance Networks – funded $110 million to develop optical network technology; Tropic Networks – funded $92 million to develop optical internet solutions. Optenia was recently funded to develop integrated DWDM products.

2.2 Industrial Organizations

In Canada there are a number of national, regional and local industrial organizations and consortia that promote photonics. In addition, there are numerous organizational initiatives that undertake to promote clusters presently forming in the Toronto area, the Lower Mainland of British Columbia, Ottawa, Montreal and Quebec City. This section provides a short description of each organization and outlines its membership and mission.

2.2.1 Canadian Photonics Consortium (CPC)

The Canadian Photonics Consortium (CPC), founded in February 2000, is a national consortium of 17 organizations, all of which support or engage in photonics-related research or exploitation activities. The Consortium is working to solidify and advance Canada's position as a globally recognized leader in the field of photonics. Its overall objective is to assist Canadian photonics companies and institutions by facilitating collaboration and knowledge management in order to support, maintain and extend industry's capabilities and global competitiveness. An initial goal is to work with industry, government, academia, research institutions and other stakeholders to develop a Photonics Technology Roadmap (PTRM). This roadmap will identify the technological challenges facing the Canadian Photonics industry over the next 10 years, and map out the steps necessary to ensure that Canadian industry remains a world leader in this area. Other goals include support for the collaborative development of technology in Canada and helping to influence Government policy – particularly as it relates to the development of highly qualified personnel and the setting of research funding priorities

2.2.2 Strategic Microelectronics Consortium (SMC)

The Strategic Microelectronics Consortium is an industrially centred, non-profit organization of national scope. SMC was formed to promote the growth of microelectronics in Canada. It has defined its objectives as the following: to develop a national strategy for sustained growth of the microelectronics sector; to be an industrial advocate for a national strategy for the microelectronics sector; to create and implement programs to move the national strategy forward and to facilitate networking and collaboration among its members. Although SMC's primary focus is microelectronics, photonics is of great interest to a large number of SMC members. The membership of SMC is extensive and represents almost the entire Canadian microelectronic industry.

2.2.3 Ottawa Centre for Research Innovation (OCRI)

The Ottawa Centre for Research Innovation is a not-for-profit organization based in Canada's capital region. Its membership is comprised of both large and small companies, government bodies, and academic institutions. OCRI has 580 members and it represents the interests of the entire Ottawa region. Its primary goal is to foster the development and commercialisation of technology generated in the Ottawa area. OCRI also facilitates networking between members and directly funds research chairs. It offers support at all levels of the educational system; its projects have ranged from the development of secondary school programs to the funding of PhD studies. OCRI plays a significant role in initiating the formation of strategic research alliances for the benefit of its members and the Ottawa region.

2.2.4 British Columbia Photonics Industry Association (BCPIA)

The British Columbia Photonics Industry Association is a B.C.-based organization representing a cluster of industrial and academic groups with an interest in photonics. BCPIA, which was formed in April 1999, represents all areas of the B.C. photonics industry. Its members are involved in a variety of photonics areas including: lasers, sensors, telecommunications, imaging, remote sensing and vision. The primary goal of the association is to promote local industry abroad and to assist educational institutions in producing trained personnel.

2.2.5 Ottawa Photonics Cluster (OPC)

The Ottawa Photonics Cluster, formed in November 1999, is an industry driven association representing the interests of Ottawa's rapidly growing photonics industry and local academic groups as well as federal and provincial government agencies and departments. Its goals include helping to increase local investment, facilitating communication between members and supporting photonics-related human resource initiatives. Industrial members range from large multinationals such as Nortel and JDSU through established firms such as Chipworks, Neptec, Optiwave and OZ Optics, to startups such as Edgeflow, Obtenia and Zenastra.

2.2.6 Cité de l'optique

Cité de l'optique is a Quebec-based industrial consortium that promotes photonics and optics in the Quebec region. The organization, which was founded in June 2000, acts as an industrial centre and supports research in the Quebec photonics industry.

2.2.7 Groupe optique/photonique Quebec (GOPQ)

The Groupe optique/photonique Quebec is a non-profit corporation that works to promote and develop the optics and photonics industries in the region of Quebec. Its mission is to facilitate industrial networking, lobbying, and training. There are currently fifty-one members including EXFO Electro-optics, COPL, INO, CIPI and the Quebec Cité de l'optique.

2.2.8 L'institut photonique de Montréal

L'institut photonique de Montréal is an association of Montreal-based universities and businesses formed to promote photonics in the region. The mission of the cluster will be: to increase the industry's visibility; to encourage industry networking and partnerships; encourage investment; provide a vehicle for industry, educational, and research institutes to develop a joint program to produce skilled manpower; and to lobby governments on issues of importance for the Montreal photonics industry. Founding members include L'École Polytechnique de Montréal, McGill University, MPB Technologies, Lumenon Lightwave Technologies, Bragg Photonics Inc., ETF, and Technocompetence.

2.2.9 Ontario Photonics Technology Industry Cluster (OPTIC)

The Ontario Photonics Technology Industry Cluster is a consortium of high technology companies and organizations in southern Ontario. Its mission is to: support the growth of the optics and photonics industry; aid the global marketing of photonics products; enhance communication; facilitate strategic alliances and investment; improve education in optics and photonics; and represent the industry's interests with economic development agencies. Current members include Photonics Research Ontario, DALSA and Coherent Inc.

2.3 University Research and Training

The Canadian post-secondary education system provides a steady stream of highly qualified personnel for the photonics industry. This section gives an overview of the role of Canadian colleges and universities in training future employees (and employers). This is followed by a discussion of government, college and university initiatives that aim to increase the number of trained personnel produced for the photonics industry.

2.3.1 Overview

Canada has an extensive government-funded post-secondary education system; there are ninety-one institutions of higher learning across the country. This system is based on two different types of institution, that is, the college and the university. The provincial governments heavily support both colleges and universities. As a result, both types of institution are able to offer moderate tuition fees and substantial enrolments. Financial support is also provided in the form of student loans.

Colleges are non-degree-granting institutions offering technical or vocational courses. Typically, colleges offer industrially focused programs of two to three years duration. These programs are intended to produce trained people such as electrical technicians. Colleges are very sensitive to industrial needs and responsive to market trends. They are excellent sources of high quality skilled workers.

Canadian universities are degree-granting institutions that vary widely in size. The largest universities will have enrolments of up to 50,000 students, while smaller institutions may only have a few thousand students. All the universities are of uniformly high quality. Their structure, operation and purpose are very similar to that of American state universities; both undergraduate and graduate programs are generally offered. University professors typically have a mix of research and teaching responsibilities.

The university programs of most relevance to the photonics industry are Electrical Engineering, Engineering Science, Engineering Physics and Applied Physics. Almost all universities offer programs in Electrical Engineering and Physics and the larger universities have very substantial undergraduate and graduate programs. Undergraduate programs are of four years duration (except in Quebec where they are three or four years). Completion of a Bachelor of Science degree in engineering is a prerequisite for obtaining professional status (P. Eng.). A significant number of students obtain bachelor's degrees in photonics-related programs; 1889 electrical engineers, 249 engineering physicists and 623 physicists graduated in 1998. These numbers are growing and CITR predicts that by 2003, 2800 electrical engineers will graduate annually.

Canadian academic research has a long history of international recognition and success. It is funded by a mixture of government and industrial funds and is seen a primary source of innovation in the Canadian research and development environment. Well-established research programs in both Electrical Engineering and Physics are present at all moderate to large universities. These programs produce a considerable number of highly trained personnel. In 1998 the number of master's and doctoral degrees granted in relevant areas was as follows: Electrical Engineering: 490 MScs and 177 Ph.Ds; Engineering Physics: 67 MScs and 17 PhDs; Physics: 177 MScs and 171 PhDs.

2.3.2 Undergraduate and Technical Training

There have been a number of initiatives oriented towards increasing the production of post-secondary graduates for the high technology industry. Some of these initiatives had their origins in governmental responses to industrial concerns about a future need for skilled workers. Other initiatives originated in local institutions as a response to regional needs.

Government Initiatives

Although education is primarily a provincial concern in Canada the federal government has instituted a number of programs to support undergraduate training. The Canada Millennium Scholarship Foundation, announced in 1998, was established to manage a $2.5 billion endowment from the Government of Canada. This foundation will provide 100,000 scholarships each year to help students finance their post-secondary studies. There is also a well-established federal student loans program that provides ongoing financing to students.

Recently, a number of provincial programs have been initiated to specifically address the need for an increase in the number of trained people for high technology industries. In Ontario, the Access To Opportunities Program (ATOP) has provided a total investment of $228 million over the first three years of the program. ATOP is jointly funded by the province and industrial contributions. The ATOP initiative will more than double university undergraduate enrolments in computer science and high-demand engineering programs. Enrolment is also to be increased by more than 50% in related college programs. A similar Albertan program called the Access Fund is in place to increase student enrolment in key growth areas. Operated by the Alberta Ministry of Learning the fund has financed an increase of about 100% in Electrical and Computer Engineering enrolments at the undergraduate level.

A second Ontario program is the SuperBuild initiative, which is a response to a predicted rise in university enrolments. This initiative will see the Ontario Government spending $742 million this year alone as they build and modernize universities; $660 million of the total will be directed towards new capital projects. It is anticipated that spaces for 57,000 additional students will be created through SuperBuild.

University Initiatives

Canadian universities have responded to industrial demands and government initiatives by expanding engineering departments and establishing new programs. All through Canada there has been a considerable enlargement of both Electrical Engineering and Applied Physics programs. In the National Capital Region Carleton University has established two new degrees, the BSc in Engineering Physics and the BSc in Applied Physics. The curriculum of these two new degrees was designed specifically to have a large photonics component. Industrially focused co-operative programs in Electrical Engineering have also been established at Carleton University and the University of Ottawa.

Using the ATOP program as a foundation, the majority of Ontario colleges and universities are attempting to double the number of graduates in the information technology area. An indication of the importance that Canadian universities place on information technology can be found in recent reports on strategic direction filed in response to the Canada Research Chair program (described below). Almost all of the universities indicated that information technology was a key area of future expansion.

It has been widely acknowledged that there is a need in the Canadian economy for the re-skilling of underemployed, but well-educated personnel. One program that addresses this need is O-Vitesse. This program is offered by Vitesse (Re-Skilling) Canada Inc., an independent, not-for-profit organization created by the National Research Council, The University of Ottawa and Carleton University. Its initial objective was to provide a means of re-skilling personnel to meet a need for software-engineering workers. Recently, the mandate of the program has been expanded to include re-skilling for photonics work. The photonics re-skilling program provides a university-level education in photonics and lasers that prepares the student for employment in the telecommunications industry. It is expected to graduate 350 Photonics Engineers per year by the year 2003.

College Initiatives

Colleges are also establishing photonics programs in response to industrial requirements. Specific photonics initiatives are being developed in collaboration with industrial consortiums. One example of such an initiative is the new photonics program involving Niagara College, Algonquin College and Photonics Research Ontario. This program is a pilot project, which, if successful, will be extended to other Colleges.

In Ontario there is a new, collaborative initiative between colleges and universities in order to establish non-accredited engineering degrees in high demand areas such as photonics.

2.4 Summary

The growth of the Canadian photonics industry is associated with a number of different factors, which can be outlined as follows. Groundbreaking research at large industrial, government and academic laboratories has spurred the formation of numerous small “offshoot” companies. The scientific and industrial activity of these companies has tended to attract similar enterprises, resulting in the formation of technology “clusters”.

Canada’s education system has also played an important role, as it has demonstrated its responsiveness to industry needs; most colleges and universities have taken the initiative in forming strong links with industrial partners. In addition, both the federal and provincial governments have been very aggressive in providing a good business environment for high technology companies, as they have come to recognize the importance of high technology in today’s information-based economy.

Finally, Canadian access to international markets is of prime importance. American markets are accessible due to the North American Free Trade Agreement while Canada has historical trading links with the United Kingdom and Europe.

3. Photonics Research in Canada

This section outlines the structure of photonics research in Canada. It provides an overview; a delineation of government initiatives that promote research; a list of the primary research-funding organizations; and two lists of institutes that feature concentrations of photonics research.

The overview provides a description of the basic role of academia, government funding bodies (provincial and federal) and universities in supporting Canadian scientific research. This is followed by a short description of a number of government initiatives that aim to increase the amount of photonics research in Canada. The primary organizations that co-ordinate and fund photonics research are then discussed. The two lists provided enumerate a) government or industrial organizations and b) universities.

In this section industrial research is not comprehensively covered. A great deal of industrial photonics research is being undertaken in Canada, however, due to the proprietary nature of this research this document will not discuss it in any detail.

3.1 Overview

In Canada, a wide range of organizations carries out photonics research. Larger companies such as Nortel Networks, JDS-Uniphase and Lumonics have undertaken significant levels of industrial research and development, while smaller companies have tended to focus their efforts on particular applications. Industrial research is not the whole story, however; universities and government-supported research institutes (such as the National Research Council (NRC)) are also active in the photonics area. Most universities in Canada have professors and graduate students engaged in photonics research, and some universities have established research groups to support this work. The National Research Council has made an invaluable contribution by providing guidance in the development of a national research effort in photonics. A leading example of this was the formation of SSOC.

Canadian university research in photonics is funded by a mixture of government and industrial grants. The primary fund-granting agency is the National Science and Engineering Research Council (NSERC). Currently NSERC has a budget of $538 million. Its mandate is to directly support university research and university-industrial partnerships. One of its primary objectives is to support the advanced training of highly qualified people for industrial placements.

NSERC provides support for fundamental and applied research in a number of ways. Direct funding is awarded in the form of research grants. The Research Partnership Program provides industrially focused grants by matching industrial contributions. Industrial research chairs are also available under this program.

One very significant federal government initiative has been the Networks of Centres of Excellence (NCE) program. This program provides funding that enables institutes, university researchers and industrial partners to engage in collaborative multidisciplinary research. One important role of the NCEs is to provide a framework for national cooperation, bringing together a wide array of talent from industry, government laboratories and academia.

There are three photonics-related NCEs. The Canadian Institute for Photonic Innovations (CIPI) provides funding for a wide range of photonics research. The Canadian Institute for Telecommunications Research (CITR) funds research in photonics interconnect systems. Finally, Micronet is an NCE with a mandate to fund pre-competitive research in microelectronics.

Provincial governments also have programs to support university research. These programs are usually industrially focused, and are often coordinated with federal programs.

Canadian university research is generally organized into groups of graduate students and research personnel working under the direction of a professor. The active role of NSERC, the NCEs and the provinces in funding university photonics research has encouraged the development of a strong industrial focus. In addition, collaborative research initiatives with industrial partners have become common.

3.2 Government Initiatives in Research

This section describes a number of significant government initiatives that aim to support and increase the level of technical research in Canada. These programs address needs for both operating funds and capital for infrastructure.

3.2.1 Canada Foundation for Innovation (CFI)

The Canada Foundation for Innovation was established by the federal government in order to support Canadian research. It was inaugurated in 1997 with a primary mandate to provide infrastructure to facilitate research innovation. CFI has a budget of $2.4 billion that it invests in capital projects (in collaboration with industrial members). For any given project CFI contributes 40% of the financing with the remainder coming from industrial contributions and provincial agencies.

CFI has directly funded a large amount of infrastructure for photonics research. Total funding in excess of $7 million has been granted to facilities for research in areas such as ultrafast lasers; fibre optic communications; laser-based micromachining; photonics components for telecommunications; laser surgery and biophotonics. In addition, over $10 million of funding has been granted for medical research in imaging. The Canadian Light Source (CLS) Project at the University of Saskatchewan is a major photonics facility partially funded by CFI. The estimated cost of the project is $173.5 million, of which CFI will contribute $56 million.

In addition to directly funding photonics research CFI has provided grants for related areas such as microelectronics, telecommunications and advanced materials.

3.2.2 Canada Research Chairs

A second federal project is the Canada Research Chair initiative. The Government of Canada has provided $900 million to support the establishment of 2,000 Canada Research Chairs in universities across the country by 2005. The primary goal of this program is to create world-class research centres that achieve the highest levels of excellence. In order to qualify for this program all universities were required to submit a plan outlining the strategic direction of the institution. Most Canadian universities have identified information technology as an area of future expansion. A number of universities have also indicated that photonics in particular will be an area of growth.

3.2.3 Ontario Research and Development Challenge Fund (ORDCF)

The Ontario Research and Development Challenge Fund (ORDCF) is an Ontario government-funded program that promotes research collaboration between industry and universities. It has a commitment both to excellence in research and high technology job creation. ORDCF is supported by government funding of $500 million and $2.5 billion from partner contributions. ORDCF provides funds for equipment, operating funds and facilities. One objective of ORDCF is to attract and keep world-class researchers in Ontario.

ORCDF's funding for photonics-oriented projects totals more than $50 million. Some specific photonics-related ORCDF projects are: the Centre of Excellence in Semiconductor Diode Laser Research, at McMaster University; the Bell Emergis University Laboratories Institution located at the Universities of Toronto and Waterloo; and the National Capital Institute of Technology in Ottawa. A number of other ORCDF projects involving photonics research at the University of Toronto are: The Centre for Studies in Molecular Imaging**;** the Laser Micromachining Research Facility; and the Printing on the Molecular Scale Institution.

3.2.4 Canadian Photonics Fabrication Centre

The National Research Council (NRC) has put forward a proposal to build a Canadian Photonic Fabrication Centre. The estimated cost of the Centre is $45 million. This facility would fabricate unique optoelectronic and photonics components for Canadian researchers. It would also expand the existing photonics fabrication and testing capabilities of the NRC. A primary role of the proposed Centre is the training of students in fabrication techniques and the testing of photonics components. The Centre would also provide prototyping services to Canadian industry.

3.2.5 iCore

iCore is a program put in place by the Alberta Government to support university research in information and communication technology. The primary goal of the program is to create research chairs in this area. It also aims to increase the level of funding to graduate students in electrical engineering. The funding level of iCore is $10 million annually.

3.2.6 eMPOWR

eMPOWR is a joint university and industrial effort whose goal is to lobby the federal government for $500 million, in order to address the need for highly qualified personnel in photonics and electronics. The aim of eMPOWR is to expand university capacity in microelectronics, photonics, optoelectronics, wireless and radio frequency engineering. Industrial members include Nortel Networks, JDS Uniphase, Mitel Corporation, Sierra Wireless, Tundra Semiconductor, PMC Sierra and Gennum Corporation.

3.2.7 Canadian Microelectronics Corporation (CMC)

The Canadian Microelectronics Corporation (CMC) is a not-for-profit organization established in 1984 to provide technology infrastructure to universities that have research and educational interests in microelectronics and closely related areas, for example, optoelectronics and MEMS/micromachining. CMC provides software for the design of integrated circuits and devices, engineering services for component manufacturing, and instrumentation for the testing of components. The infrastructure is geared towards silicon devices, but access to other technologies has been provided, for example, gallium arsenide and MEMS. Anticipated expansion of CMC's support for optoelectronics involves design tools, test instruments and manufacturing. CMC is collaborating with the National Research Council in regard to the proposed Canadian Photonics Fabrication Centre. CMC also holds a major grant from NSERC and manages resources for universities participating in the CFI-funded system-on-chip research network.

3.3 Primary Photonics Research Organizations

This section lists the primary organizations that fund photonics. These organizations provide guidance and structure to the financial support of photonics research. Other funding comes directly from NSERC to university professors.

3.3.1 Canadian Institute for Photonic Innovations (CIPI)

CIPI is a network established under the NCE program. Its mandate is to harness and develop the talents of Canadian researchers in industry, government institutions and universities in order to place Canada at the forefront of photonics research in the 21st century. CIPI has sixty-five internationally recognized researchers at twenty-four universities in eight provinces as well as over forty affiliated industrial members and a dozen government laboratories. The research program encompasses nanostructures, telecommunications, ultrafast laser technology, biomedical applications, precision laser-based measurements and environmental monitoring. CIPI, whose funding was initiated in 1999, currently has a budget of $4.1 million. Under CIPI's auspices the amount of high quality research produced in Canada has already increased significantly.

The stated objectives of CIPI are: to develop a national network for photonics research in Canada; to increase the amount of world-class research performed in Canada; to create 1,000 person-years of additional photonics training for HQP (Highly Qualified Personnel); to accelerate the rate of technology transfer to the marketplace and to investigate possible applications of photonics in such areas as the elimination of disease and the prevention of environmental degradation. In February 2001 CIPI added a dozen promising new investigators to its rosters, many of whom had recently returned to Canada after receiving their training in the U.S.

3.3.2 Photonics Research Ontario (PRO)

Photonics Research Ontario (PRO) is a provincially funded centre of excellence. Its mandate is to enhance the competitiveness of Ontario's photonics industry. It provides research and development funds to facilitate technology transfer to industry and to train personnel. PRO maintains three photonics facilities; the Photonics Facility, the Laser Micromachining Facility (LMF) and the Biophotonics Facility. The Photonics Facility supports general work in photonics. It employs seven people. The LMF is an advanced laboratory facility that has been designed to address growing industrial and academic demand for high-precision laser-optical tools. The LMF was established as a collaborative enterprise between PRO, Materials and Manufacturing Ontario and the University of Toronto. The Biophotonics Facility consists of 280 sq. m of laboratories and offers a range of equipment and trained scientific/technical staff trained in pre-clinical and clinical evaluation of novel optical applications in diagnostic and therapeutic medicine.

3.3.3 Canadian Institute for Telecommunications Research (CITR)

The Canadian Institute for Telecommunications Research (CITR) is an NCE that funds research in the area of telecommunications. CITR has a budget of $1.6 million. It supports 300 researchers from eighteen universities. CITR has funded work on local optical interconnects at the chip, package and board levels. The purpose of this research is to investigate the use of free-space optical interconnects with transfer rates of terabits per second. A second initiative is the development of a fibre-based technology for local area networks with interconnection distances of over 100 meters.

3.3.4 Communications and Information Technology Ontario (CITO)

Communications and Information Technology Ontario (CITO) is an Ontario-Government funded Centre of Excellence with the mandate to strengthen the global performance of Ontario's information technology, digital media and communications industries. CITO funds 109 research projects, and makes a special effort to support industrially partnered efforts. Current areas of research include WDM systems, tuneable lasers and optical switching.

3.3.5 Micronet

Micronet is another NCE that supports photonics activity (though its primary focus is microelectronics). Micronet's budget of $4.9 million supports 82 faculty members and 322 graduate students. Photonics projects that are currently funded include X-ray imaging systems, integrated circuit design for optical communications and integrated single chip cameras.

3.3.6 Centre for Manufacturing of Advanced Packages (CMAP)

The Centre for Manufacturing of Advanced Packages (CMAP) is an ORCDF-funded initiative to support research in advanced packaging for electronics and photonics. Member-universities include Carleton University, The University of Toronto and University of Waterloo. There are a number of industrial members including Celestica and Alcatel. At present most research is in electronics packaging, though CMAP is actively seeking projects in photonics.

3.3.7 Materials and Manufacturing Ontario (MMO)

Materials and Manufacturing Ontario (MMO) is an Ontario Centre of Excellence committed to making connections between the best university research and the needs of Ontario industry. MMO supports research, develops industrial/academic partnerships, trains graduate students and promotes the transfer of knowledge and technology to industry. MMO is a not-for-profit corporation supported by the provincial government, industrial contributions to research programs, and revenues from the commercialization and licensing of intellectual property. MMO supports photonics projects in opto-electronics, including the development of red-emitting electro-luminescent thin film phosphors, nanolithography for quantum devices and distributed feedback lasers.

3.4 Concentrations of Photonics Research in Canada

Photonics research in Canada is progressing on a broad front with almost all universities in the country now involved. There are also a number of well-funded government and private organizations that have strong photonics research programs. The two lists below feature Canadian institutions with concentrations of photonics research. The first list describes research institutes that have a photonics focus. The second list describes universities that have concentrations of photonics research. It should be remembered that neither list is comprehensive because work in this field is widely spread among many institutions.

3.4.1 Research Institutions

Institut National d'Optique/National Optics Institute (INO)

INO started its activities in 1988. It is a private not-for-profit corporation whose mandate is to provide optics/photonics R&D support to the optic industry as well as industries in other domains. Their activities include internal research, R&D contracts and pre-production contracts. INO currently has 220 employees working in four main areas, digital and optical systems, photonic materials and processes, laser system technologies and photonic and guided-wave optics. Applications domains cover optical communication, security, forestry, transport, manufacturing, environment, etc. INO has been the wellspring of twelve new high tech companies.

Communications Research Centre Canada (CRC)

Communications Research Centre Canada (CRC) is a research institute at the Federal Department of Industry that specializes in communications technology. This organization has been involved in photonics research since the late 1960s and several CRC inventions have led to the successful development of a family of fibre optic-based components for the rapidly growing broadband telecommunications market. Current research work is focused on photonic components for broadband communications systems, including high-speed optoelectronic integrated circuits, planar lightwave circuits and fibre-based optical devices. Testbeds for the evaluation of optical components in operational network environments complement the photonics research and development activities. CRC is planning a major expansion of its photonics research program over the next few years, including the creation of a $30M on-campus Centre for Photonic Components and Systems Research.

National Research Council (NRC)

The National Research Council (NRC) is the country's largest government-funded research institution. Its mission is to provide leadership in scientific and technical research and promote the dissemination of information and technology within Canada. Photonics research at NRC is concentrated at the Institute for Microstructural Sciences (NRC-IMS). One of IMS's primary goals is to address the needs of the information technology sector; in order to achieve this goal, IMS has focused much of its resources on optical communications. IMS capabilities include: thin film processing; semiconductor manufacturing; nano-engineering; and materials analysis.

Work at IMS is centred on applications of optoelectronics and integrated photonics. Specific projects include: WDM for local area networks, semiconductor laser integration, optical switching technologies using silicon-based photonics and thin film optical filters. NRC has a strong mandate to interact with industrial partners, as is evidenced by the fact that it has initiated substantial technology transfers to industry. It is also taking the lead in promoting the formation of technology clusters. In addition, a number of significant photonics start-ups have been spawned by NRC research.

A second center of photonics activity at NRC is the Institute for National Measurement Standards (NRC-INMS). The Institute has programs in both physical and chemical metrology. The institute also undertakes photonics research in lasers, photonic switching, optical waveguides and optical interconnects.

TRLaboratories

TRLaboratories is a large, not-for-profit information and communications technology research consortium. TRLaboratories has an annual budget of roughly $10 million and supports research laboratories in Edmonton, Calgary, Regina, Saskatoon, and Winnipeg. The TRLaboratories Photonics Research Program is focused on finding ways to utilise the untapped optical bandwidth of optical fibres, expanding the capabilities of WDM and developing low cost optical switches.

National Capital Institute of Technology (NCIT)

National Capital Institute of Technology (NCIT) is an ORCDF/CIF-funded initiative in pre-competitive telecommunications research. The four primary partners are Carleton University, University of Ottawa, CRC and NRC. Industrial supporters include Nortel and Alcatel. NCIT's photonics research is focused on future generations of optoelectronics technologies and on the development of novel materials, devices and components for all-optical networks. The three primary areas being supported are: high-speed reconfigurable optical routers for optical packet switching, the use of organic materials for communication and millimetre wavelength optoelectronics.

Canadian Light Source Inc. (CLS)

Canadian Light Source Inc. (CLS) is building a $173.5 million synchrotron facility in Saskatchewan. Funding for the project comes from a mixture of federal, provincial, municipal, industrial and academic sources. This facility will be used to accelerate electrons to nearly the speed of light, thereby producing very high intensity infrared, ultraviolet and X-ray light beams. These high-intensity light beams will be used to study the fundamental physics of matter down to the level of the atom. They will also be used for a wide variety of technological studies including: pharmaceuticals, biotechnology, petrochemicals, semiconductors, advanced materials, MEMs components, and medical imaging. CLS will have an important role to play in the development of technology for the fabrication of photolithography masks with track dimensions smaller than 0.1 µm. These masks will have applications in many technologies such as deep sub-micron semiconductor devices, photonic devices, MEMS and nanoscale structures.

3.4.2 Universities

There is no central database of photonics research at Canadian universities. This deficiency makes it difficult to summarize the state of photonics work at these institutions. As a general rule, however, almost all universities have professors working in the area. The list that follows describes some of the major photonics research efforts being undertaken by Canadian universities. The list is not exhaustive.

University of Alberta

The University of Alberta has a long tradition of undertaking fundamental work on lasers and photonics. The departments of Electrical and Computing Engineering (ECE), Chemistry and Physics have researchers in CIPI and links with TRLabs.

The ECE department's current photonics research includes: industrial and medical lasers; sensor systems; ultrafast laser techniques for material modification; waveguide components; integrated optics; nano-structure laser machining; and optical detection systems.

Research at the Department of Chemistry includes; nanostructured semiconductor devices; solar cells; and organic optical materials.

Photonics research at the Department of Physics includes ultrafast micromagnetics, ultrafast spectroscopy of materials (including nanostructures), non-linear optical properties of organic polymers (all-optical switching), and picosecond time-domain response of fast photodetectors.

University of British Columbia

Photonics research at the University of British Columbia is primarily undertaken through the Advanced Materials and Process Engineering Laboratory (AMPEL). AMPEL is a multidisciplinary research centre maintained by both the Faculty of Science and the Faculty of Applied Science. AMPEL currently consists of 160 researchers, mainly from the Departments of Chemistry, Electrical and Computer Engineering, Metals and Materials Engineering, and Physics and Astronomy. The centre is located in an 8,000-sq.-m building and includes clean room facilities for the fabrication of semiconductor devices. A wide range of optical instrumentation for photonics work is available.

Within the Electrical and Computing Engineering Department the Ultrafast Electronics and Fibre optics Laboratory is pursuing photonics research in three areas: fundamental photonics science, fibre optics and microelectronics. The latter two areas are being investigated with a view to the development of industrial applications. Specific projects include: analog fibre optics for cable television transmission; fibre-based optical amplifiers and distributed feedback lasers.

Carleton University

At Carleton University the Faculty of Science and the Faculty of Engineering and Design are undertaking photonics research. The two main concentrations of activity are in the Department of Chemistry (Carleton University Laboratory for Advanced Materials Research) and the Department of Electronics.

The Carleton University Laboratory for Advanced Materials Research focuses on the development and application of organic/polymeric electrochromic materials and non-linear optical polymers. One major area of interest is the use of innovative organic materials in optoelectronic devices. Anticipated applications include displays, lasers and waveguides.

The Department of Electronics has been active in photonics research for many years; historically the department has had a strong focus on telecommunications. Previous research includes; the formation of polymer waveguides on silicon substrates for integrated optics; and electro-optic switching in SiGe waveguides. Current research includes: electro-optic switching in waveguides formed on InP substrates; micromachined-based optical switches; CMOS imagers; photodetectors; and the thermal behaviour of integrated optical devices. A new initiative in laser positioning, trapping, cell manipulation and optical Micro-Electro-Mechanical Systems (MEMS) activation is being put in place.

École Polytechnique de Montréal

At the École Polytechnique de Montréal the Physics and Technology of Thin Films research group in the Engineering Physics Department is undertaking work in fundamental and applied research on materials for photonics. Areas of specialization include; materials-based work in compound semiconductors grown by MOCVD; thin films fabricated by excimer laser deposition; and non-linear optical glasses and low-pressure plasma-deposited organic and inorganic thin films. This research is leading to the development of materials for static and dynamic integrated-optics devices, such as power dividers, multiplexers, modulators, sensors, lasers and detectors. Other projects focus on silicon-compound materials, such as amorphous, polycrystalline and porous silicon for imaging applications.

The Engineering Physics Department has a number of photonics-oriented laboratories, including: the Optical Fibres Laboratory; the Optoelectronic Laboratory; the

Photo Acoustic Spectroscopy and Laser-Ultrasonics Laboratory; and the Laser Processing Laboratory.

Institut National de la Recherche Scientifique (INRS)

Institut National de la Recherche Scientifique (INRS) is a degree-granting post-graduate institute that is primarily involved in fundamental and applied research. The laser-material interaction group is studying the following applications: the use of very powerful, ultra-fast laser pulses for material processing; the use of ultrafast high power lasers for dynamic imaging; the use of lasers in medical imaging; and basic high-powered laser science.

Université Laval

The Centre d'Optique, Photonique et Laser (COPL) at Université Laval is a major focus of optics and photonics research in Canada. COPL, which was formed in 1988, is a joint endeavour of professors in physics and engineering at Université Laval. COPL is involved in research in a wide range of photonics applications, though there are four areas of specific focus: lasers and guided optics; telecommunications; non-linear optics and laser/matter interaction; and optical imaging. COPL actively encourages fundamental research as a potential source of future technical innovation. COPL also has very strong links to industrial partners, with many research projects being closely tied to industrial applications. Current laser research includes: solid state lasers, semiconductor lasers and ultra-fast laser pulses. Projects in optical communications include photonics switching, waveguides and Soliton propagation. Other research involves optical information processing, including optical memories, optical devices and holography. COPL has a significant laboratory infrastructure, with a variety of laser systems, optical characterization equipment and fabrication facilities. It should also be noted that Université Laval acts as host to the Canadian Institute for Photonic Innovations (CIPI).

McGill University

The Electrical and Computer Engineering Department at McGill University has a Photonic Systems group. The primary focus of this group is telecommunications. Other research includes: micro-optical components and systems for WDM; optical communication systems; parallel optical interconnects; and emerging technologies. Optical applications of MEMS are also being investigated.

McMaster University

The Centre for Electrophotonic Materials and Devices at McMaster University is dedicated to research in optoelectronic and electronic devices. The Centre has fourteen faculty members. Research activities include: molecular beam epitaxial deposition of semiconductor materials and structures for optoelectronic applications; and various processing technologies necessary for optoelectronic device fabrication, including ion implantation and metal-semiconductor contact formation.

In the Electrical and Computer Engineering Department, the Photonics Research Group specializes in photonics modelling, optical communications and network research. The primary focus of the Group's research is photonic devices and systems with emphasis on semiconductor laser diodes, the packaging and integration of photonic devices and sub-systems, and fibre optic communication systems.

The Engineering Physics Department has a long history of research in photonics. Recent activities in the department include the development of quantum effect devices, optical coatings and passivation layers, and new phosphors for luminescent displays. Current interests in the department include the development of novel, integrated laser-modulator systems and the development of compact picosecond laser sources.

The Physics Department is also conducting photonics research. Current investigations include: lasers; non-linear optics; intense picosecond laser pulses and short-lived phenomena in very intense laser fields.

Research in medical photonics at McMaster includes photodynamic therapy, laser photocoagulation, optical spectroscopy and imaging.

Université de Sherbrooke

The Department of Electrical Engineering and Computer Science at Université de Sherbrooke has a significant photonics device fabrication facility. Previous research involved integrated optoelectronics, with projects in integrated laser diodes and passive optical devices. Recent work in the department has centred on the fabrication and testing of quantum well heterostructure laser diodes. Another project currently underway is the fabrication of nano-structures in GaAs**.** This involves the creation of quantum structures using e-beam techniques to produce lithographs with sub 50-nm resolution. Researchers are actively investigating the photonic properties of these nano-structures.

University of Toronto

The Electrical and Computing Engineering Department at the University of Toronto has a photonics group consisting of seven professors. The research interests of this group range from fibre optics to laser technology. The group's main research areas are: integrated optics; laser design and applications; lightwave technology; non-linear optics; optical communications; optoelectronic devices; and ultrafast optical phenomena and devices.

The Ultrafast Photonics Laboratory is affiliated with the Electrical and Computer Engineering Department. The Laboratory has two main areas of interest: the investigation of the optical properties of semiconductor materials for ultrafast all-optical signal processing and photonic devices, and the development of fibre grating technology for optical communications, sensing, and biomedical applications.

The Departments of Chemistry, Medical Biophysics and Physics are also undertaking photonics research. In the Department of Chemistry, the investigation of photochemistry and the use of photonics to better understand molecular motions is producing results that are very well respected world-wide. The Department of Medical Biophysics is investigating optical imaging, the medical use of lasers, and photonics-based cancer treatments. The Department of Physics has a large group in quantum optics and condensed matter physics; this group is studying the fundamental interaction of photons with matter.

University of Waterloo

The Electrical and Computer Engineering Department at the University of Waterloo supports photonics research in two areas. The Silicon Devices and Integrated Circuits group is undertaking work in CCDs, and optical and X-ray imaging. The RF/Microwave and Photonics Group has an ongoing project in photonic components and systems. This group has a particular interest in the design and analysis of optical components used in telecommunications optical links.

In the Physics Department research groups are involved in three areas: confocal microscopy, laser science and ultra fast lasers. The first group is developing sophisticated optical imaging techniques for medical, scientific and industrial applications. The laser science group is investigating a wide range of laser science and laser/matter interactions. The third group is involved in the generation and application of very fast, intense laser pulses.

University of Western Ontario

At the University of Western Ontario the Chemistry Department has significant research projects in photochemistry, photophysics, nanotechnology for photonics, high-resolution spectroscopy, laser-molecule interactions and precision measurements.

York University

York University has over a dozen faculty members involved in photonics-related research in the Physics, Chemistry and Earth Science Departments. The Physics Department has been expanding its research program in Modern Optics and Spectroscopy to include ultra-high precision measurements based on lasers, laser cooling and atom trapping. There is also overlap with the research of the Centre for Atmospheric Chemistry, which has pioneered the use of laser diodes for environmental monitoring. The Earth Science Department has substantial experience in designing, constructing and operating airborne and space-borne imaging spectrometers for studying the Earth and its atmosphere.

4. Research Opportunities in Photonics

This section describes areas of future development and expansion in Canadian photonics research. Telecommunications is one of the most promising fields, and as such it will be discussed in detail. Other areas for future development will be outlined, including: optical interconnects and computing; micromachining; biophotonics; nanotechnology; imaging; display technology; and material research. The material from this section was compiled from a number of sources that are listed in the appendices. These sources included reports from CPC, and roadmaps from the National Electronics Manufacturing Initiative (NEMI) and OIDA.

4.1 Overview

Photonics is an area that holds out a great deal of promise for the future. It is certain to attract a great deal of attention from researchers, as they engage in both fundamental scientific enquiry and applied work. Industrially focused research will be driven by the possibility of improving existing technologies. On the other hand, fundamental scientific work will produce novel solutions to current problems and also initiate the emergence of new technologies. It is predicted that areas of high activity will be optoelectronics, telecommunications, biophotonics and nano-technology.

It is very difficult to predict the way research will evolve in a wide-ranging, complex discipline such as photonics. Some areas, such as telecommunications are well established industrially. In these fields a degree of consensus is generally found on the goal of current research, if not the technological solution. Other fields such as biophotonics and nanotechnology are very much emerging sciences. Any prediction of the nature of future development in these areas is risky at best.

Research in optoelectronics components will have broad application across a number of sectors. The OIDA has predicted that optoelectronics will play different roles in the development of a number of industrial sectors. It is expected to be the dominant enabling technology in information transmission, display technologies and imaging applications. In areas such as sensors, general lighting, power generation and information storage it will compete for market share with other technologies. In some applications such as logic processing it is expected to become a niche solution for high-end applications.

A key factor in the future development of photonics will be the convergence and crossover of technologies from different areas. We have already seen the application of technologies developed for the telecommunications industry in other sectors. One example of this is the widespread use of fibre and semiconductor laser technology in the medical and industrial sectors. Integrated optoelectronics is another technology for which crossover applications are anticipated. Telecommunication requirements will prompt research into low-cost integration of electronics, lasers, detectors, integrated waveguides and optical switches. It is certain, however, that these devices will be used in applications such as sensors, optical interconnects, medical photonics systems and industrial equipment as components are developed and costs are reduced.

One very important factor in the future development of photonics will be the evolution of synergies with other emerging technologies. One example of a new technology that will develop in concert with photonics is nanotechnology. Nanotechnology is the manipulation of material at the molecular level, with the aim of creating a wide variety of structures and devices. It encompasses phenomena ranging from the direct manipulation of proteins and cells using lasers to self-replicating machines and nano-computers. Nanotechnology is predicted to be of great importance in the coming decades, and its development will both enable and depend on photonics research. That is, photonics will be needed to create nanotechnologies and in turn nanotechnology will generate new photonics applications and devices.

The influence of new materials research is an additional factor in the evolution of photonics. Photonics research has historically been driven by fundamental studies in the optical properties of materials and investigations of the interaction of light and matter. Continued exploration will certainly lead to new breakthroughs and improved technologies. One example of promising new materials research is optically active polymers, that is, newly developed polymer materials that show remarkable optical characteristics. These polymers may well represent a superior choice of material for current photonics components.

The following is an attempt to outline some of expected areas of growth and opportunity in the Canadian photonics industry.

4.2 Optoelectronics integration

Cost reduction and increased functionality will drive the increased integration of optical and electrical components. Optoelectronic integration will be an enabling technology for many sectors including; telecommunications, imaging, medicine and optical interconnects. There will be significant competition between different technologies. For example, silicon-based techniques offer a very mature fabrication base and ease of integration with established electronics capabilities in CMOS and bipolar technologies. The realization of LEDs and laser diodes in silicon will have a significant impact on the integration of optoelectronic and electronic circuits. Technologies based on GaAs, InP or other III-V compounds offer significant fundamental advantages in the generation and detection of light. Polymer-based technologies, though immature, offer potential advantages in speed, functionality and simple processing. Other technologies such as MEMS and nanotechnology may play a significant role in the development of integrated optoelectronics; tuneable VCSEL lasers and optical switches provide examples of this.

Initial information from the CPC roadmapping initiative has identified optoelectronics integration as a key area in which Canada must develop more expertise. Optoelectronics integration was also predicted to be a primary driving force in the creation of new economic activity. Research in this field is currently underway at a number of industrial, academic and government laboratories, but the consensus is that this must be built on and enhanced.

4.3 Telecommunications

In Canada, photonics research in the telecommunications field is well developed. A significant amount of research funding is allocated to investigation of photonics technologies for optical communications links. This funding sponsors work that builds on very substantial previous successes at industrial, government and academic laboratories. Research in this area is generally very industrially focused and encompasses most anticipated needs of the industry over the short-term. Continuing to build on the considerable expertise in this area is obviously of importance to Canada's continued prosperity in the world telecommunications market.

The presence of receptor companies for new technology is an important factor in the successful application of any research. Systems-level integration is available through Nortel and Alcatel; these companies can provide resources that are not available to individual researchers. Large component manufacturers such as JDS-Uniphase provide a natural receptor for device-level research. On the other hand, smaller firms and research-intensive start-ups offer considerable growth potential. The collaboration of these companies with academic and government laboratories should be encouraged, as their success will be essential to the continued growth of this sector in Canada.

4.3.1 Core network links

The evolution of long-haul optical links will see the introduction of denser WDM technologies with increases in the number of data channels. By 2005 it is predicted that WDM will support up to 800 channels. Research and development efforts in WDM technology such as tuneable lasers, optical switching, and wideband optical amplifiers are areas in which Canadian researchers will be able to build on previous experience. Research into the production of low-dispersion fibres and techniques such as Soliton transmission will be key to enhancing performance. This area was identified by the CPC as a field of opportunity for Canadian researchers.

4.3.2 Local optical network links

It could be argued that the most significant growth in optical communications will be the development of optical networks for the consumer market. "Getting fibre to the home" has been identified as a prime objective for the United States photonics industry. The construction of the last few kilometres of the information super highway, or Fibre-To-The-Home (FTTH) will create a large market for photonic and electronic components. It is anticipated that the most common networks will be of the cable TV type, in which most signals are broadcast. The development of centrally switched fibre-optic star-networks is also a possibility; the very simplicity of these types of network makes them worthy of consideration.

The use of optical technology in local networks and computer-to-computer links will require significant cost reductions in the optical components. This will be a primary incentive for the integration of optical components onto a single chip. The push for lower costs may produce different solutions than have previously been seen for long-haul WDM networks, especially as competition from wireless and cable technologies will be involved. Low-cost solutions, such as the use of plastic fibre and LED light sources, may imply a compromise in performance. There are certainly prospects in this field for Canadian-based research; indeed a number of institutions are already investigating this area.

4.3.3 All-optical networks

The anticipated introduction of all-optical networks represents a major change in optical networking. An all-optical network will involve a minimal number of electronic components, with all switching, multiplexing, routing and transmission being performed optically. Such a network offers substantial improvements in transmission rates and performance. Two different technologies are emerging as contenders – optical TDM and optical WDM. Although both technologies theoretically provide similar capabilities, each has unique advantages.

Optical TDM (OTDM) involves the creation of a very fast, single-channel fibre link in which the time division multiplexing of the information is achieved by optical modulation. This solution offers the advantages of very large-burst information transfer rates and improved network performance. The successful application of OTDM will require the development of very high-speed optical modulators, OTDM multiplexers and demultiplexers, optical switches and buffers.

Optical WDM (OWDM) involves the routing of a number of lower speed data streams by wavelength. Each information channel is carried on a separate frequency as with current WDM systems. Data is routed by optically separating out a channel by means of wavelength. This data stream is then transferred to the correct network node using optical switches and routers. OWDM is very flexible, and it allows both digital and analog signals to be transferred on the same network. Before OWDM systems can be built it will be necessary to develop tuneable laser sources, wavelength converters, add/drop OWDM multiplexers and wavelength routing components. In addition, both OTDM and OWDM will require the development of better optical amplifiers, high-speed optical switches and lower-cost component technologies.

The ultimate optical network solution would involve the optical routing of individual data packets. This would require the development of optical components such as buffers, logic, routers and wavelength converters. This development of this application is far off, but Canadian researchers are already laying the groundwork for it.

The development and institution of all-optical networks is predicted to be at least five to ten years in the future. There would appear to be a real opportunity for Canada to take a leading role in the development of these systems, because Canadian research into all-optical networks emerges as a natural extension of previous work in telecommunications. Long-term funding for basic research in academic and government laboratories is the key.

4.4 Photonics packaging

A significant element in the cost of photonics devices is the packaging of components that have very exact requirements for optical alignment. In particular, the development of packages for integrated optoelectronic devices presents a very significant challenge. These packages carry a combination of integrated lasers, WDM components, optical switches, and electronic processing and drive circuitry. Aspects to be considered in the package design include: electrical performance; thermal management; thermo/mechanical stability; reliability; optical losses and cost.

One aspect of packaging that is key to reducing the cost of photonics components is automatic assembly. Currently, a great deal of photonics packaging and assembly is done manually. The price of integrated electronics is greatly diminished when automatic printed circuit board assembly and packaging are used. Very precise optical alignment criteria make it a significant challenge to achieve this level of automation in photonics assembly and packaging. It is anticipated that in the future, robotic technology will have an important role to play in packaging photonic, optoelectronic and integrated electronic and optoelectronic components.

Photonics may also have a role in the assembling of components. One example of this is the use of light-cured epoxy to replace the current use of soldering and electrical welding techniques.

Research into electronic and optical package development appears to be somewhat neglected in Canada despite the presence of several established packaging companies. It is important to develop technological capability in this area.

4.5 Optical interconnects and storage

Canada has a significant amount of expertise in high-speed electronics design, especially telecommunications. Companies involved in this area would appear to be natural receptors for optical interconnect technologies at the board and multi-chip module levels. Some Canadian researchers are working on the development of high-speed optical backplanes using either optical waveguides or free-space transmission, but there is definitely room for more investigation in this area. Cost will be very important in determining the feasibility of this application. It is likely that there will be a significant amount of technology crossover between areas such as local telecommunication links, optical interconnects, and optical backplanes. In all these applications the development of low-cost integration techniques will be very important.

4.6 Optical computing

Over the last thirty years improvements in silicon-based electronics have produced dramatic increases in data processing power. There are, however, fundamental physical limits on the speed of electrical circuits, mostly involving the type of material used in their manufacture, that is, silicon and aluminium. The inherent limitations of these materials have spurred the introduction of silicon germanium devices, copper metalization and organic dielectrics. Such materials will only extend the use of microelectronics technology for a few generations, however. The long-term improvement of data processing may well require a paradigm shift away from electronics. A completely new material base and methodology is likely to be needed.

One alternative to using electronics for data processing is the development of optical computing. The use of optical computing may take a number of forms. It has been suggested that on-chip optical interconnect structures may be used in conjunction with more traditional electronic logic devices. Another possibility is the development of all-optical computing devices. The first niche application for optical computing will likely be in image processing and recognition, an area in which direct optical techniques may be used to replace digital signal processing and allow for greatly improved functionality. The creation of a fully integrated optical computer is a very significant challenge. Current optical logic devices are at the same state of development as the electrical transistor was in the 1950s. The physical advantages of optical computing are not clearly defined and the integration and fabrication challenges very considerable.

The development of optical computing is not likely to be realized in the immediate future, and it should be noted that Canadian research in this area is very limited. This is due, in part, to the absence of a Canadian technology receptor. The lack of a large integrated circuit manufacturer in Canada has limited the potential for this type of research. It is true, however, that the recent arrival in Canada of STMicroelectronics and Alcatel may provide new opportunities.

4.7 Micromachining and nanotechnology

One area of research in which Canadians have an excellent reputation is micromachining. The use of micromechanical systems for optical applications such as switches is the focus of a great deal of research. The coordination of Canadian expertise in MEMS and telecommunications could lead to a synergetic effect.

As we have discussed, nanotechnology is an emerging field of great potential and it will both require and enable photonics applications. One example of an emerging science that requires both technologies is bandgap photonics. Bandgap photonics devices are created by fabricating periodic nano-structures. These devices have many possible applications in integrated optics.

Canadian research in nano-technology is at an embryonic stage. Canada possesses, however, a solid base in both microelectronics and micromachining, as well as academic excellence in the sciences. This provides an excellent foundation for future development.

4.8 Imaging, Displays, Manufacturing

Canadian research in other areas of photonics such as display technology, manufacturing, imagers and remote sensing is comparatively limited. In regions where there is industrial activity (iFire, GSI Lumonics, DALSA) there is often collaborative research with academic or government laboratories. These sorts of collaborations should be encouraged.

There may be opportunities to apply photonics technology developed for telecommunications to other fields of endeavour. One example of this is the field of integrated optoelectronics. Integrated optoelectronics technologies developed for telecommunications will be very sophisticated, and could well have applications in sensing (both direct and remote), displays, imagers and optical control systems. Another example is basic laser research in telecommunications, which is broadly applicable to other fields.

It is anticipated that imaging applications will grow significantly due to the establishment of high-capacity communication links to the home and office. Local optical telecommunications links may generate a number of imaging applications in security, manufacturing, health and entertainment. Canada has both industrial capability and academic expertise in the two technologies involved, that is, electronic imaging and high-speed optical data links. Collaborative research in these areas should be supported.

The mainstream flat panel display market is very competitive and opportunities may be limited. There are a number of prospects, however, for the development of display technologies. One opportunity would be the development of low-cost very large displays. At present, there are numerous problems involved in the fabrication of such displays. For example, CRT technology is unworkable, LCD fabrication techniques are difficult to scale to larger sizes, and other technologies such as plasma displays are currently very costly. Another possible research area would be the fabrication of high quality small displays. These displays need to have very fine resolutions, large viewing angles, good contrast, and brightness.

4.9 Biophotonics and medical applications

In many ways biophotonics and medical photonics is in its infancy. The large number of possible medical applications (imaging, surgery, low-power laser therapies, DNA analysis, cancer therapies, etc.) makes it difficult to predict which areas will undergo expansion. It is certain, however, that in the future, researchers will continue to show great interest in biophotonics and medical applications. In addition, the industrial ramifications of biotechnology are predicted to be very significant and we can be sure that photonics will play a considerable role in these technologies.

Results from the CPC roadmapping initiative indicate that medical diagnostics and monitoring applications are possible areas of growth for Canadian photonics. Other applications that would build on existing expertise are advanced microscopy, and non-intrusive imaging and surgery. One interesting application is the DNA biochip. The DNA biochip is the result of a convergence of biology, semiconductor fabrication technologies and laser-based fluorescence techniques. It is commonly used to achieve fast analysis of DNA samples. The biochip has many applications in gene mapping, disease management and biology.

There are a number of exciting biophotonics applications with much potential for the future. It would be wise for Canadian research to focus on a number of key fields and to pursue these areas aggressively.

4.10 Basic Research

The future success of Canadian photonics research is dependant on the continuation of basic studies in material processing and characterization. New developments in photonics will be based on fundamental research in physics, chemistry and engineering.

In particular, studies in quantum structures, novel semiconductor devices and new materials such as polymers will be essential to the long-term growth of the industry. In fact, these areas were identified by CPC as a key to future technologies. It will also be important to continue research into materials processing and device fabrication.

The interdisciplinary nature of fields such as nano-technology, biophotonics, medical photonics, sensors and integrated optoelectronics presents many difficulties. Collaborative work involving physicists, chemists, biologists, engineers, and medical doctors will be essential to success in these areas. In nano-technology, for example, collaborative work in photochemistry, photophysics, semiconductor engineering and matter/photon interactions will be crucial to future development.

4.11 Long-term photonics research versus technology development

In Canada the strong push towards industrial relevance has led to much research in photonics being focused on relatively short-term objectives. More long-term research, such as the development of applications whose realization may be a decade or more away, is often ignored. This is unfortunate. As an example, we must consider that the development of new materials like polymer-based optics can be considered to be a long-term research goal. Its attainment, however, is fundamental to the future development of all-optical networks. And as we have seen, research into all-optical networks and optical routing is essential if Canada wants to stay at the forefront of telecommunications photonics. Future success in this area will require fundamental materials research, component technology development and work at the systems level.

It should be noted that long-term, fundamental research in photonic science and materials is often fruitful in unexpected ways. One example of this is ultra-fast laser pulse research, an area in which Canadian scientists have developed an international reputation. Ultra-fast laser pulses were originally developed in order to study fundamental scientific questions. Only recently has the number of possible industrial applications become apparent. Ultra-fast lasers are currently being exploited in medicine, material processing, thin film deposition and material characterization.

There is a great deal of potential in Canada for further development in photonics. The best way to safeguard this potential is to ensure there is there is an appropriate amount of long-term fundamental research in proportion to short-term industrially focused research.

5. Conclusion and Summary

The growth of the global photonics industry is expected to accelerate. The recent dramatic expansion of the optical telecommunications markets is only one aspect of this. Other emerging areas such as biophotonics, nanotechnology, and optical computing are likely to have an equally large impact over the next five to ten years. A number of industrial organizations have predicted growth rates of up to 25% with total markets of hundreds of billions of dollars. This may well be a low estimate, as it does not take into account new technologies being created by synergies between fields such as photonics and nanotechnology. It should also be remembered that component research is only the first level of an integrated industry. As an example, the OIDA estimates that currently a $40 billion optoelectronic industry is a key enabler of a $1.5 trillion information technology sector.

Canada has an established industrial base in optical telecommunications and some very successful companies in other areas of photonics. All this industrial activity has been, at least in part, a product of Canadian research. The future success of Canadian industry is dependent on continuing, and in fact increasing, the level of research at Canadian institutions.

In this paper I have attempted to demonstrate the nature and extent of the photonics industry in Canada. Numerous photonics applications have been described, ranging from telecommunications fibre optics links to cancer treatments. Canadian photonics companies develop and market many of these applications.

Canadian photonics companies range in size from systems companies such as Nortel Networks to small start-ups. The Canadian optical telecommunications industry represents the bulk of photonics activity in the country. Individual Canadian companies have established a presence in the global market in other sectors, such as biophotonics and industrial lasers.

One outstanding characteristic of the photonics industry in Canada is the formation of geographical clusters of activity. Clusters have formed in Ottawa, the Lower Mainland of British Columbia, Toronto, Montreal and Quebec City. These clusters represent regional concentrations of companies, research laboratories and academic institutions. The scientific and industrial activity of these organizations has tended to attract similar enterprises and provide employment for large numbers of skilled personnel. Clusters are distinguished by the generation of new companies from established companies and institutions. As the clusters grow in size they become important generators of new ideas, companies and initiatives. Government and industrial consortia are playing an important role in the promotion of these clusters.

Photonics research in Canada is both extensive and widely distributed. Institutions such as NRC, INO and the universities support this kind of research. University research is funded by a number of organizations, including NSERC, NCEs and provincial granting agencies. NCEs (such as CIPI) play an important role in providing a national network for collaboration between researchers, companies and institutes. A number of new government initiatives (for example CFI and ORCDF) have provided funds for both infrastructure and research operations and have substantially increased the amount and quality of photonics research in Canada. A significant portion of the funds provided is for industrially focused work or as matching funds for collaborative projects with companies. Because of this industrial focus the best-supported research tends to be in optical telecommunications

Although it is difficult to identify research opportunities in a rapidly evolving field like photonics a number of possibilities were noted. Funding for telecommunications has produced a well-established research capability in fibre optics, semiconductor optoelectronics devices, and high-speed electronics. This capability must be expanded in order to ensure Canada's continued successes in optical communications. In particular, support should be given to the development of all-optical networks and DWDM.

Integrated optoelectronics is an area in which Canadian researchers are well-positioned for future work. This area is predicted to become an enabling technology for many sectors including; telecommunications, optical interconnects, sensors and biophotonics. The crossover of technology from one sector to another is likely to be important and Canadian researchers who are developing integrated optoelectronics for telecommunications should be encouraged to apply their knowledge to other fields.

Biophotonics and medical applications of photonics are expected to be high growth areas in the future. These areas feature a range of technologies, from established applications like laser surgery to emergent fields such as DNA analysis. This is an area in which Canadian research shows a great deal of potential.

A number of other emerging technologies such as nanotechnology, bioengineering and photonic testing of integrated circuits of will co-evolve with photonics. The synergetic relationship between these technologies presents a multitude of research opportunities. Interdisciplinary work should be pursued in these areas, particularly in nano-technology/photonics, a field in which Canada can draw on its excellent scientific resources as well as its expertise in micromachining and semiconductor devices.

Finally, it should be remembered that fundamental research in the area of photonic materials and devices must be supported. New applications and technologies are usually founded on a combination of long-term basic research and subsequent industrial development. The photonics industry in Canada has a great deal of potential, but this potential can only be realized with a strong commitment to research and development.

Appendix 1. Acronyms

AMPEL: Advanced Materials and Process Engineering Laboratory

ATOP: Access To Opportunities Program

BCPIA: British Columbia Photonics Industry Association

CARDE: Canadian Armament Research and Development Establishment

CCD: **C**harge-coupled devices

CFI: Canada Foundation for Innovation

CIPI: Canadian Institute for Photonic Innovations

CITO: Communications and Information Technology Ontario

CITR: Canadian Institute for Telecommunications Research

CLS: Canadian Light Source

CMAP: Centre for Manufacturing of Advanced Packages

COPL: Centre of Optics Photonics and Lasers

CPC: Canadian Photonics Consortium

CRC: Communications Research Centre Canada

CRT: Cathode Ray Tube

DREV: Defence Research Establishment Valcartier

DWDM: Dense Wave Division Multiplexing

GOPQ: Groupe optique/photonique Quebec

INO/NOI: Institut National d'Optique/National Institute of Optics

INRS: Institut National de la Recherche Scientifique

LCD: Liquid Crystal Displays

LED: Light-emitting Diode

LMF: Laser Micromachining Facility

LSCM: Laser Scanning Confocal Microscopy

MEMS: Micro-Electro-Mechanical Systems

NCE: Networks of Centres of Excellence

NCIT: National Capital Institute of Technology

NEMI: National Electronics Manufacturing Initiative

NRC: National Research Council

NSERC: National Science and Engineering Research Council

OCRI: Ottawa Centre for Research Innovation

OIDA: Optoelectronics Industry Development Association

OPC: Ottawa Photonics Cluster

OPTIC: Ontario Photonics Technology Industry Cluster

ORDCF: Ontario Research and Development Challenge Fund

OTDM: Optical Time Division Multiplexing

OWDM: Optical Wave Division Multiplexing

PDP: Plasma Display Panel

PRO: Photonics Research Ontario

RAM: Random Access Memory

SMC: Strategic Microelectronics Consortium

SSOC: Solid State Optoelectronics Consortium

TDM: Time Division Multiplexing

WDM: Wavelength Division Multiplexing

Appendix 2. Bibliography

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Appendix 3. Web page addresses

Organization	URL
All-Optical Networking Consortium	www.ll.mit.ed/uaon
BCPIA	www.bcphotonics.org
Carleton University	www.carleton.ca
CFI	www.innovation.ca
CIPI	www.cipi.ulaval.ca
CITO	www.cito.ca
CITR	www.citr.ece.mcgill.ca
CMC	www.cmc.ca
CLS	www.cls.usask.ca
CPC	www.photonics.ca
CRC	www.crc.ca
DREV	www.drev.dnd.ca
Ecole Polytechnique de Montreal	www.polymtl.ca
INO	www.ino.qc.ca
INRS	www.inrs.uquebec.ca
LIGHTWAVE	www.lw.pennnet.com
L'institut photonique de Montreal	N/A
McGill University	www.mcgill.ca
McMaster University	www.mcmaster.ca
Micronet	www.micronetrd.ca
MMO	www.mmo.on.ca
NCIT	www.ncit.ca
NEMI	www.nemi.org
NRC	www.nrc.ca
NRC-IMS	www.sao.nrc.ca/ims
NRC-INMS	www.nrc.ca/inms
NSERC	www.nserc.ca
OCRI	www.ocri.ca
OIDA	www.oida.org

OPC	www.ottawaphotonics.com
OPTIC	www.optic.on.ca
Optical Networks Magazine	www.optical-networks.com
Optics.Org	www.optics.org
Photonics Online	www.photonicsonline.com
Photonics.com	www.Photonics.com
PRO	www.pro.on.ca
Québec - Cité de l'optique	www.quebecciteoptique.com
SMC	www.smc.ca
The International Society for Optical Engineering (SPIE)	www.spie.org
TRLaboratories	www.trlaboratories.ca
Université Laval	www.ulaval.ca
University of Alberta	www.ualberta.ca
University of British Columbia	www.ubc.ca
University of Sherbrooke	www.usherb.ca
University of Toronto	www.utoronto.ca
University of Waterloo	www.uwaterloo.ca
University of Western Ontario	www.uwo.ca
York University	www.yorku.ca