A SEMINAR REPORT ON
“PHOTONICS IN SPACE”

Submitted in partial fulfilment of the requirement for

the award of the degree of

BACHELOR OF TECHNOLOGY

IN

ELECTRONICS AND COMMUNICATION ENGINEERING

Submitted by

G.ARAVIND KUMAR (17091A0408)

(ESTD-1995)

DEPARTMENT OF ELECTRONICS AND COMMUNICATION ENGINEERING

RAJEEV GANDHI MEMORIAL COLLEGE OF ENGINEERING AND TECHNOLOGY

(AUTONOMOUS)

Affiliated to J.N.T.U.A - Anantapur, Approved by A.I.C.T.E., New Delhi,
Accredited by N.B.A. & NAAC with ‘A^+’ Grade - New Delhi, NANDYAL –
518501, Kurnool Dist. A.P.

Year: 2017-2021

RAJEEV GANDHI MEMORIAL COLLEGE OF ENGINEERING& TECHNOLOGY

(AUTONOMOUS)

Affiliated to J.N.T.U.A - Anantapur, Approved by A.I.C.T.E., New Delhi, Accredited by N.B.A. & NAAC with ‘A^{+}’ Grade - New Delhi, NANDYAL – 518501, Kurnool Dist. A.P.

(ESTD-1995)

CERTIFICATE

This is to certify that **G.Aravind kumar (17091A0408)** of B. Tech ECE final year has carried out the seminar work on “**PHOTONICS IN SPACE**” under my supervision, in partial fulfillment of the award of degree of **B. Tech** in Electronics and Communication Engineeringin **R.G.M.C.E.T,** Nandyal for the academic year 2017-2021.

Head of the Department

Dr. A. Sathish **M. E. Ph. D., MISTE, MIETE**

Professor & HOD

Department of ECE

Place: Nandyal

Date:

CANDITATE'S DECLERATION

I hereby declare that the report titled "**PHOTONICS IN SPACE**" submitted towards completion of Technical Report in IV Year 2nd Semester of B. Tech (ECE) at the RAJEEV GANDHI MEMORIAL COLLEGE OF ENGINEERING & TECHNOLOGY, Nandyal.

Is an authentic record of my original report and is prepared by me. I have not submitted the matter embodied in this report for the award of any other degree in any other institutions.

By

G.ARAVIND KUMAR

17091A0408

Dept. of ECE RGMCET

ACKNOWLEDGEMENT

At the outset, we would like to express our sincere and grateful thanks to the managementof Rajeev Gandhi Memorial College of Engineering & Technology, under the leadership of **Dr. M. SANTHIRAMUDU**, Chairman for providing us an opportunity to fulfill our aspirations.

Our special thanks to **Dr. T. JAYACHANDRA PRASAD**, Principal, Rajeev Gandhi Memorial College of Engineering & Technology, for providing all the facilities and guidelines, required for our academic pursuit.

Our special thanks to **Dr. A. SATHISH,** Head of the Department (ECE), Rajeev Gandhi Memorial College of Engineering & Technology, for providing all the facilities and guidelines, required for our academic pursuit.

By

G.ARAVIND KUMAR

17091A0408

LIST OF CONTENT

Chapters Names: Page No:

LIST OF FIGURES

CHAPTER 1

1. INDRODUCTION

1.1 Introduction

Photonics deals with the generation, manipulation/control, and detection of light waves and photons. Its key enabling potential has been demonstrated for several years in many application areas, such as telecommunications, energy, lightening, environmental monitoring, robotics, industrial production, biomedicine, medical imaging, displays, homeland security, aerospace, defense, and many more, so that its worldwide market is expected to exceed 600 billion Euro in 2020.

In the last decades of the 20th century, photonic devices and optical fibers dramatically improved the performance of the telecommunications systems, also providing the infrastructure for Internet development and its exponential growth in the last few years . In the same years, laser technology has radically modified some of the key manufacturing processes such as welding, cutting, and drilling, also enabling very precise manufac- turing techniques at the micro/nanoscale. Photonic technologies, espe- cially optical imaging for intraoperative surgical guidance and medical lasers, are currently widely used in several fields of surgery .

The enabling potential of photonics in space engineering has notably grown since the 1960s, when the only photonic devices on satellites were the solar cells. In recent years, photonic components and sub- systems have been crucial for many functions on board a spacecraft, e.g. data han- dling, attitude and orbit control, as well as strain/thermal mapping. Currently, many payloads for both Earth observation and scientific mis- sions include a wide variety of optical and opto-electronic components, such as lasers, detectors, modulators, lenses, gratings, mirrors, and so on.

In this chapter, the three segments comprising a space system are briefly introduced and the criteria for space missions and orbit classifica- tion are introduced. Finally, an overview of the space applications of photonics is provided.

1.2 Space system segments

The three segments typically forming a space system are the space seg- ment, the transportation segment, and the ground segment. The space segment includes the payload and the satellite platform carrying it, while the transportation segment provides the transport into space of both the satellite platform and its payload by a launcher. The ground segment con- trols and monitors the spacecraft and its payload, and processes the data provided by the payload.

The payload is the hearth of the space system, being conceived and developed according to the purpose of the space mission, and its features strongly influence the design of both the satellite platform and the trans- portation/ground segment. A wide variety of payloads has been developed since the beginning of the space age. The most common payloads are spectrometers, radiometers, magnetometers, cameras, radar systems, transmitters, and atomic clocks for navigation/positioning, transponders for satellite telecommunications, and rover vehicles. The sub-systems forming the satellite platform are listed in Table 1.1, where the basic func- tionality of each sub-system is mentioned.

The transportation segment includes the launch vehicle, e.g. a rocket such as Atlas V or Ariane 5, equipped with appropriate propellants, and the launch infrastructure. The main components of the launch vehicle are the mechanical structure, propellant tanks, engines, attitude control sys- tems, and flight monitoring systems. In the launcher, the thrust is gener- ated by igniting two propellants, the fuel and the oxidizer, in the thrust chamber. Chemical reactions between the propellants produce very high- temperature gases that expand through a nozzle.

The ground segment includes the control center, where the spacecraft is monitored and controlled, and the ground stations network receiving and transmitting data to/from the spacecraft

Sub-system	Basic function
Mechanical structure	Accommodate all other sub-systems
Power supply	Generate and efficiently distribute electrical energy within the spacecraft
Thermal sub-system	Keep the temperature of spacecraft components within appropriate intervals
Attitude control	Real-time monitor and control the attitude of the spacecraft in space
Communications	Transmit/receive data (telemetry data, commands, and payload data) to/from the ground stations
Data processing and handling	Process and handle data on board the spacecraft
Propulsion	Change the orbit of the spacecraft

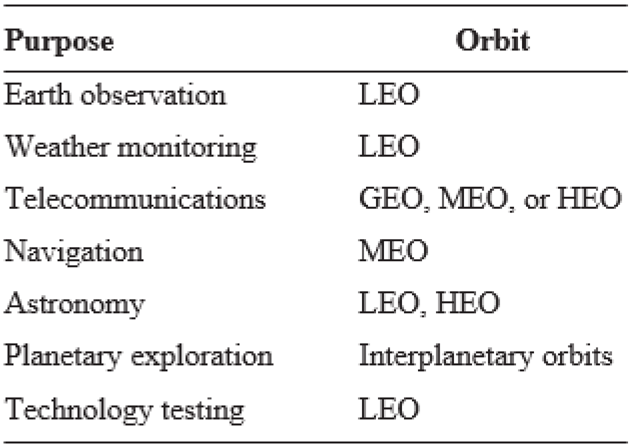
Table 1.1. Sub-systems format the satellite platform

1.3 Classification of orbits and missions

Space missions can be classified according to the area of application, while the orbits are classified according to their shape and the altitude. There is a strong correlation between the target mission of a spacecraft and its orbit. The vast majority of all the orbits selected for space missions are around the Earth. The low Earth orbit (LEO) is a near-circular orbit with altitude ranging from 300 km to 1,500 km, while the so-called geostation- ary orbit (GEO) is a near-circular orbit having an altitude of about 36,000 km. The near-circular orbits at intermediate altitudes, from 1,500 km to 36,000 km, are called medium Earth orbits (MEOs). Highly elliptical orbits (HEOs) are elliptical orbits with satellite distance from the Earth at the peri- gee < 1,000 km and satellite distance from the Earth at the apogee > 36,000 km. The geostationary transfer orbit (GTO) is a highly eccentric orbit in which a satellite is temporarily placed before reaching the GEO orbit.

Spacecraft for planetary exploration are placed in interplanetary orbits and their distance from the Earth is up to several billion kilometers.

The most common purposes of the space missions are listed in Table 1.2, with the identification of the orbits typically used.



Purpose	**Orbit**
Earth observation	LEO
Weather monitoring	LEO
Telecommunications	GEO, MEO, or HEO
Navigation	MEO
Astronomy	LEO, HEO
Planetary exploration	Interplanetary orbits
Technology testing	LEO

Table 1.2. Typical purposes of the space missions.

1.4 Overview of the space applications of photonics

Although some photonic sub-systems for the transportation segment and the ground one have been developed in the last few years, most of the space applications of photonics are relevant to the space segment, i.e. payload and satellite platform.

In some kinds of payload such as cameras and spectrometers, optical and photonic components have been widely used for several decades, while the use of photonic technologies within radar, telecom, and naviga- tion payloads is certainly less mature, in spite of some technological demonstrators having already been developed.

Photonics can play a key role in nearly all sub-systems forming a satellite platform due to its intrinsic advantages with respect to conven- tional technologies. Opto-electronic gyroscopes have routinely been included in attitude and orbit control systems for several decades, and some important advantages of optical fibers in the implementation of on-board data buses have been proved in several space missions, starting from the 1990s. Since their first utilization in space, in 1958, the solar cells have been included in the power supply sub-system of all satellites. Mapping of strain and temperature in some critical sections of the space- craft can benefit from fiber Bragg grating technology, whose space appli- cability has already been proved. Finally, optical wireless links to transfer data from one satellite to another or from a satellite to a ground station have been successfully demonstrated in some recent space missions.

In this last case, the ground station is equipped with an appropriate optical terminal, including many photonic components. This is one of the emerg- ing applications of photonics in the ground segment.

Some launchers are equipped with opto-electronic gyros for attitude control, while the fiber Bragg grating technology seems to be very advan- tageous to monitor the tanks in some kinds of launcher.

CHAPTER 2

2. PHOTONICS AND OPTICAL COMMUNICATION

2.1 Introduction to Photonics and Optical Technolgies:

Light influences our lives today in several ways that we could never have imagined just a few decades ago. Light will play an even more significant role in the future, enabling a revolution in world fiber-optic communications, new modalities in the practice of medicine, biotechnology, optical sensing, lighting and exploration of the frontiers of science, and much more.

We are beginning to see the fruits of the scientific discoveries of the last three or four decades. The development of the laser in the 1960s produced light with a property never seen before on Earth. Coherent light can be directed, focused, and propagated in new ways that are impossible for incoherent light. This property of laser light has made possible fiber-optic communications, compact disks, laser surgery, and a host of other applications.

Applications of incoherent light abound as well, including optical lithography systems for patterning computer chips, high-resolution microscopes, adaptive optics for Earth-based astronomy, infrared sensors for everything from remote controls to night-vision equipment, and new high-efficiency lighting sources. Although optics is pervasive in modern life, its role is that of a technological enabler. It is essential, but typically it plays a supporting role in a larger system.

2.2 Definition of Photonics and Optical Technologies:

Photonics is the field of science and engineering encompassing the physical phenomena and technologies associated with the generation, transmission, manipulation, detection, and utilization of light.

Three major developments which enabled the developments during the last 40 years.

- Invention of the laser
- Fabrication of low loss optical fibers
- Introduction of semiconductor devices

2.3 Key technologies for the next century:

- ✓ Photonics and Optical technologies
- ✓ Nanotechnology,
- ✓ Biotechnology

2.4 Optics:

2.4.1 Introduction to Optics

Based on the inventions the following disciplines were created:

- ✓ Electro-optics
- ✓ Optoelectronics
- ✓ Quantum electronics
- ✓ Quantum Optics
- ✓ Light wave technology

Electro-optics is generally reserved for optical devices which electrical effects play a role (laser and electro-optic modulators and switches)

Optoelectronics typically refers to devices and systems that are essentially electronics in nature but involve light (examples are light-emitting devices, liquid crystal displays and sensor arrays).

Quantum electronics is used in connection with devices and systems that rely principally on the interaction of light and matter (e.g. lasers and non linear devices)

described the studies of quantum and coherence properties of light.

Light wave technology is used to describe devices and systems in optical communication.

2.5 Areas of major importance for the future:

Optics for Military and Surveillance applications:

- ✓ Surveillance
- ✓ Night Vision
- ✓ Laser Systems Operating in the Atmosphere and in Space
- ✓ Fiber-Optic Systems
- ✓ Displays (e.g. light weight, 360° displays)

2.6 Optics in Manufacturing:

- ✓ Use of Light to Perform Manufacturing
- ✓ Use of Optics (optical metrology) to Control Manufacturing
- ✓ Specific Industrial Applications
- ✓ Increasing Use of Optics in Manufacturing

2.7 Manufacturing Optical Components and Systems:

- ✓ Low-Cost Manufacturing of Specialty Optics
- ✓ High-Volume Manufacturing of Optics
- ✓ Crosscutting Issues

2.8 Photonics and Optical Technolgies:

During the last decade the term photonics has come in use. This term, which was coined in analogy with electronics. It reflects the growing tie between optics and electronics stimulated by the increasing role of semiconductor materials and devices in optical systems.

Electronic involves the control of charges and Photonics involves the control of photons. The terms optics and photonics are not clear separated. Therefore, we will not clearly distinguish between the term optics and photonics.

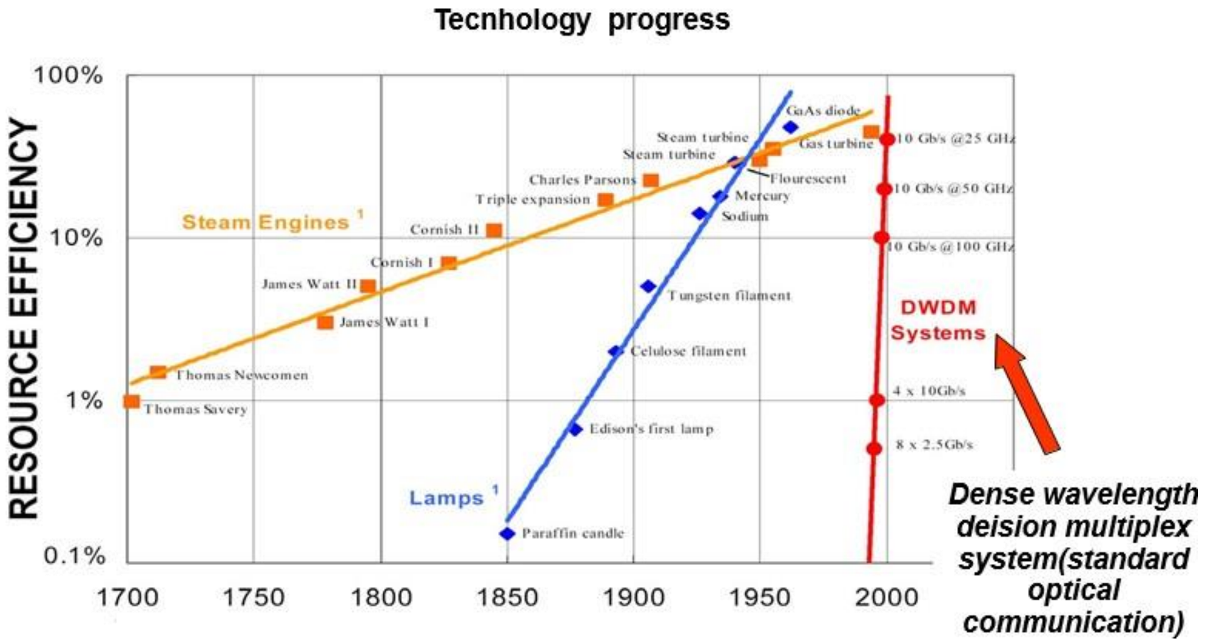
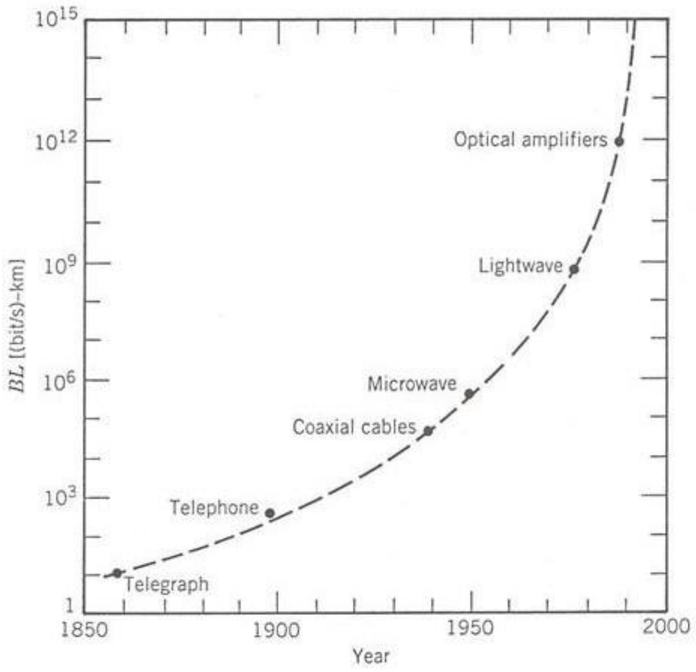


Fig: 2.1 Technology progress

2.8.1 Need for optical fiber communication :



(Increase of the bit rate-distance product BL for different communication technologies overtime)

Fig: 2.1 optica fiber communication

2.9 Health Care and the Life Sciences:

In medicine, optics is enabling a wide variety of new therapies, from laser heart surgery to the minimally invasive knee repairs made possible by arthroscopes containing optical imaging systems. Optical techniques are under investigation for noninvasive diagnostic and monitoring applications such as early detection of breast cancer and “needleless” glucose monitoring for people with diabetes.

Optics is providing new biological research tools for visualization, measurement, analysis, and manipulation. In biotechnology, lasers have become essential in DNA sequencing systems. Optics is playing such an important role in the life sciences and medicine that organizations concerned with these disciplines need to recognize and adjust to these developments.

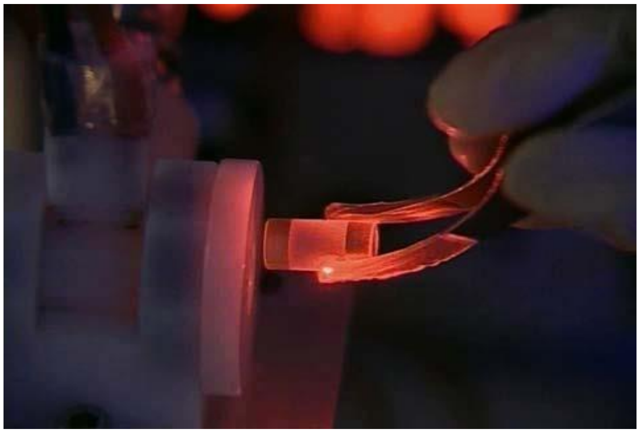


Fig: 2.3 Florescence of a sample.

2.10 Optical Sensing, Lighting, and Energy:

Fig: 2.4 Berlin by night

Advances in lighting sources and light distribution systems are poised to dramatically reduce the electricity consumption now devoted to lighting. Innovative optical sensors are augmenting human vision, showing details and revealing information never before seen: infrared cameras that provide satellite pictures of clouds and weather patterns; night-vision scopes for use by law

enforcement agencies; infrared motion detectors for home security, real-time measurements of industrial emissions, on-line industrial process control, and global environmental monitoring.

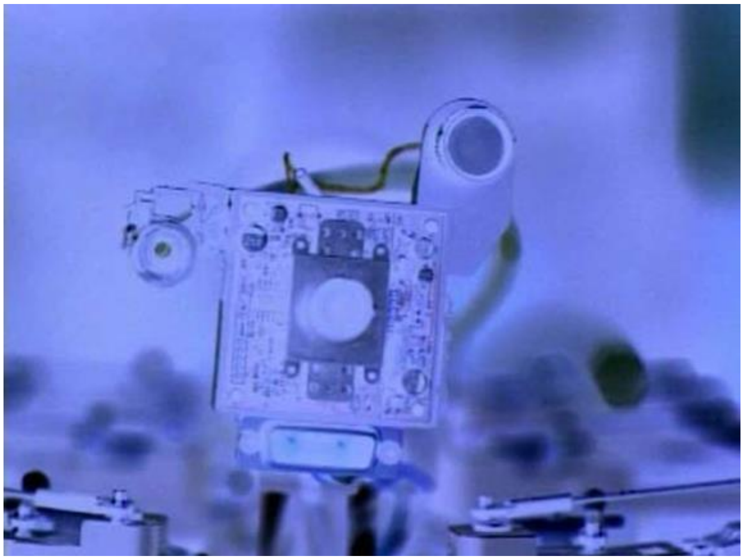


Fig: 2.5 Robot equipped with optical sensors

High-resolution digital cameras are about to revolutionize and computerize photography and printing, and improvements in photovoltaic cells may permit solar energy to provide up to half of world energy needs by the middle of the next century. These developments will affect energy and environmental concerns on a national scale.

2.11 Optics in Manufacturing:

Optics has had a dramatic economic influence in manufacturing, particularly since the advent of reliable low-cost lasers and laser-imaging systems. Optical techniques have become crucial in such diverse industries as semiconductor manufacturing, construction, and chemical production. Every semiconductor chip mass produced in the world today is manufactured using optical lithography

Just making the equipment for this business is a $1 billion industry, and it ultimately enables a $200 billion electronics business.

Fig: A laser was used to write into a human hair**.**

Other applications include laser welding and sintering, laser model generation, laser repair of semiconductor displays, curing of epoxy resins, diagnostic probes for real-time monitoring and control of chemical processes, optical techniques for alignment and inspection, machine vision, metrology, and even laser guidance systems for building tunnels.

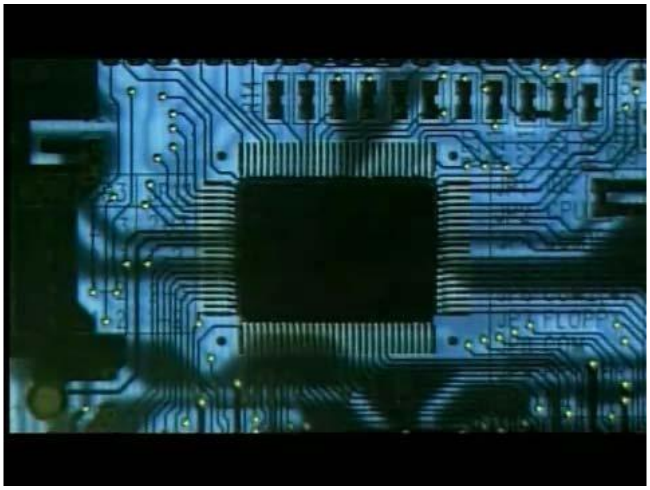


Fig:2.6 Visual inspection during the manufacturing of electronic components.

2.12 Optics for Military and Surveillance applications:

In area of military applications, optical technology has become ubiquitous, from low-cost components to complex and expensive systems. Sophisticated satellite surveillance systems are a keystone of intelligence gathering. Night-vision imagers are in use. Lasers are used for everything from targeting and range finding to navigation.

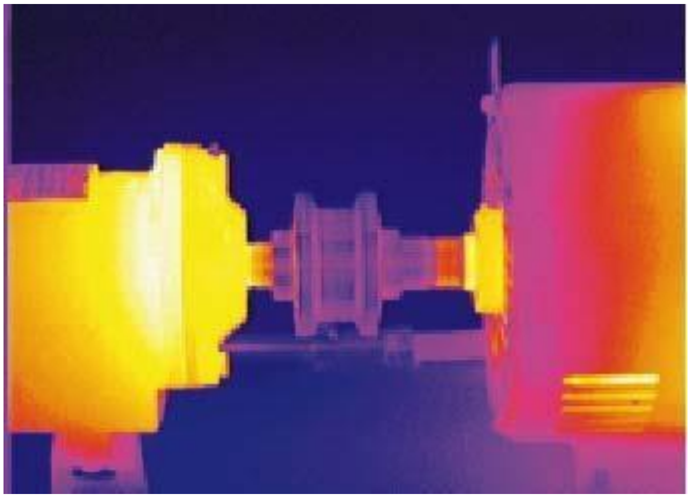


Fig:2.7 Infrared vision systems.

2.13 Manufacturing of Optical Systems and Components:

As the impact of optics has increased, changes have become necessary in how optical components and systems are designed and made.

Another is a better understanding of the characteristics of optical materials, from glasses to polymers to metals, thus permitting broader use of these automated technologies. Another is a better understanding of the characteristics of optical materials, from glasses to polymers to metals, thus permitting broader use of these automated technologies

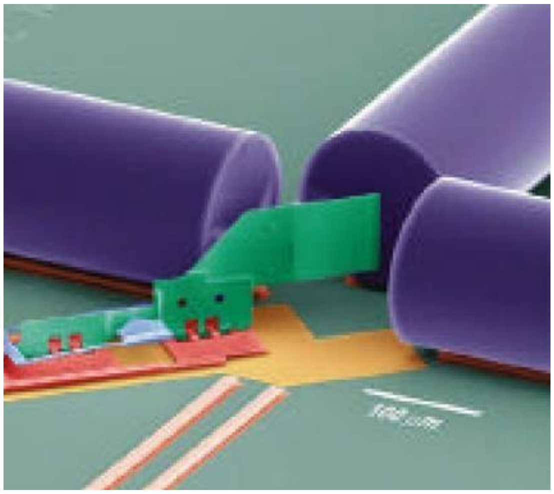


Fig: 2.8 Optical switch (Bell Labs)

2.14Key Conclusions and Recommendations:

Optics is an extraordinarily strong and dynamic field. Its diverse applications are making important contributions to society in areas that range from telecommunications to medicine to energy to military applications.

2.15Vision of the Future:

Developments in optics that will change our lives in ways that today we can hardly even contemplate. In almost every major area described in this report, we expect optics to change our world. The future will undoubtedly surprise us, but here is one possible vision: We imagine the entire world linked together with high-speed fiberoptic communications, as ubiquitous as today's telephone system, made possible by advances in optical materials that enable the mass production of inexpensive, very high quality optical components and systems.

This will result in the growth of very high speed Internet data and video transmission and other new broadband communications services. In health care, the development of optical ways to monitor human processes could have an enormous impact on diagnosis and treatment. We dream of a day when people have personal health monitors that can monitor their health cost- effectively and noninvasively by evaluating the optical properties of their blood and tissue. We also foresee a growing impact of optics in many other areas of diagnostic and therapeutic medicine, biomedical research and our quality of life. Facing a world enveloped in greenhouse gases, we will have to consume energy more wisely. Highly efficient lighting technologies will significantly reduce the energy it takes to illuminate the world. Solar cells will reduce our dependence on fossil fuels by making electricity from the light of the sun. In industry, optical sensors and infrared imagers will make significant inroads into process control for manufacturing and materials processing Factories will employ optical sensors extensively in the manufacture of everything from textiles to automobiles, and digital cameras will substitute for film in printing and photography. In the electronics industry, which relies on photolithography to create circuit patterns on chips, producing features smaller than 0.1 µm will require optical steppers that use soft x-ray or extreme ultraviolet light optical components for these machines will have unprecedented optical figure and atom level surface smoothness. Optics will be used in the detection of chemical and biological weapons. This omnipresence will depend critically on the availability of low-cost optical systems, many of them developed for commercial use; unique military needs for performance and reliability.

The role of optics in research, which already cuts across nearly all fields of science and technology, will be limited only by our imagination. High-power laser systems will make possible the construction of particle accelerators that extend the energy frontier for experiments in particle physics. Lasers will manipulate individual atoms in light traps. Laser interferometer experiments may unravel the mysteries of gravity. Femtosecond visible and x-ray sources will provide new tools for understanding the dynamics of materials. As the importance of optics grows, colleges and universities will be challenged to meet the educational needs of a growing work force. In time, we expect the field of optics to become a discipline, as computer science has over the past few decades, and to become recognized as such in educational institutions around the world.

CHAPTER-3

3. PHOTONIC INTEGRATED CIRCUITS

3.1 Introduction:

Diamond offers outstanding optical and mechanical properties, which are fundamental for realizing a platform for integrated photonic circuits and especially quantum information technologies. Waferscale applications in photonics have been enabled by the continuous progress in the synthesis and processing of chemical vapor deposition (CVD) diamond. CVD diamond in particular provides high quality optical material with reproducible properties and template sizes which are compatible with PIC fabrication. Particularly relevant are a large refractive index and a wide transparency window spanning visible and infrared wavelengths, which make diamond a prime candidate for realizing integrated photonic circuits. The refractive index of around 2.4 in the visible and near infrared (NIR) wavelength regime provides a large index contrast to optical buffer layers with lower refractive index and thus allows for tight confinement of light in diamond waveguides (Hiscocks et al., 2008; Phillip and Taft, 1964). The large electronic bandgap of 5.5 eV opens a transmission window from ultraviolet (UV) wavelengths and stretching to the very far infrared (Dore et al., 1998; Mildren and Rabeau, 2013; Mollart et al., 2003). Importantly, the large bandgap also prevents two-photon absorption even in the visible and NIR regime, which, for example, plague silicon photonic circuits at higher optical powers. The high thermal conductivity and low thermo-optic coefficient of diamond, in contrast, also allow guiding of modes with high optical power in waveguide devices (Nebel, 2003). By exploiting a relatively high nonlinear refractive index (Boyd, 2008; Levenson and Bloembergen, 1974) ($n2 = 1.3*10^{-19}$ $m2W^{-1}$ for visible wavelengths) diamond furthermore provides attractive platform for integrated non-linear optics

Photonic integrated circuits (PICs) have materialized into of the leading platforms for implementing photonic quantum technologies (O'Brien et al., 2009; Tanzilli et al., 2011) for applications in secure quantum communication (Martin et al., 2012), enhanced quantum sensing (Matthews et al., 2011), and quantum information processing (Politi et al., 2009). Linear optical circuits based on lithographically patterned waveguides provide a scalable approach for manipulating quantum states of light (Carolan et al., 2015), and guarantee high fidelity of quantum operation due to inherent stability and accurate control of interacting modes in on-chip interferometers (Laing et al., 2010). PICs also provide numerous ways to support the generation of non-classical light (Spring et al., 2017). Equally important, waveguide based photonic circuits allow for the characterization of single photon states using integrated single-photon detectors (Pernice et al., 2012). Since the demonstration of active waveguide components individually, integration of all resources for functional quantum devices on a common platform has been a key technology driver to enable continuous increase in complexity of quantum photonic (Wang et al., 2018), and enhance the stability and scalability of quantum photonic technologies. Despite significant effort, finding an optimal material platform for this endeavor has been challenging. Complementing leading silicon photonic approaches, diamond-based PICs offers significant advantages, which have contributed to the attractiveness of this material choice.

While the properties mentioned above find numerous applications in classical integrated optics, in view of quantum photonic devices diamond offers additional benefits. In particular, optically active defect centers have attracted intense interest. Currently over 500 so-called color centers are known in diamond, which cover a wide range of emission wavelengths from the UV to the NIR (Zaitsev, 2001). Such color centers can be used as a stable source of single photons and, in some cases, also provide a controllable coherent electron spin (Jelezko et al., 2004; Kurtsiefer et al., 2000). Prominent color centers in diamond, such as the nitrogen- or silicon-vacancy center (NV, SiV), are of particular interest as they are long-term stable. In addition, a low density of phonon states (diamond provides the highest Debye temperature of ~ 2000 K) causes low electron-phonon coupling, which implies that they can be used for single photon generation even under ambient conditions (Becker & Becher, 2019; Lee et al., 2012; Leifgen et al., 2014). Thus, by integrating these color centers directly in monolythic waveguides, diamond can provide a single material platform for quantum photonic applications.

For implementing reconfigurable photonic building blocks with low dissipation, diamond also offers outstanding mechanical properties, including an exceptionally high Young's modulus of 1100 GPa. Together with low thermo-elastic dissipation due to its high thermal conductivity (Najar et al., 2014), diamond has therefore emerged as a prime material for implementing mechanical resonators operating at high frequencies without suffering from significant damping (Burek et al., 2016; Mitchell et al., 2016; Rath et al., 2013a). Such devices are particularly attractive for applications in precision sensing (Hanay et al., 2012; Tao et al., 2014). Going beyond sensing devices, combining optical and mechanical degrees of freedom in waveguide-based components allows for reconfiguring integrated photonic circuits with optomechanical components. These devices modulate the effective refractive index of a guided mode due to the displacement of a mechanically moveable part placed next to a waveguide, which in turn induces a phase shift to the propagating light field (Poot and Tang, 2014a; Rath et al., 2014). Integrated phase shifters form key elements for reprogramming diamond-based quantum photonic circuits (Ma et al., 2011; O'Brien et al., 2009).

Last, as a counterpart to waveguide integrated single photon sources, single photon detectors can be seamlessly integrated with diamond PICs. Superconducting films can be deposited on top of diamond waveguides and used for the realization of integrated superconducting nanowire single-photon detectors (SNSPDs) (Rath et al., 2015). In combination with the above mentioned devices, these components provide a complete toolbox for realizing a diamond-based integrated quantum photonic architecture.

3.2 Background and Primary Advantages offered by Integrated Photonics

The invention of the transistor and subsequent advent of integrated circuits technology is widely considered to be one of the most significant discoveries of the 20th century. In 1958, the monolithic integrated circuit was developed at Texas Instruments to replace previous time-intensive methods of hand-soldering discrete elements[1]. Since these initial innovations in the late 1950s and 1960s, the progress and development of semiconductor industries has experienced continued rapid growth, with Moore's Law describing a doubling in the number of transistors achievable on integrated circuits every two years. The idea of an optical equivalent to integrated electronic circuits—integrated optics—was first proposed by Stewart Miller of Bell Labs in 1969[2], who suggested that a "complex patterns of optical wave circuits, whose communication function might be somewhat analogous to that of lower frequency integrated circuits,could be fabricated in a sheet of dielectric using photolithographic techniques."

The idea of using integrated photonics to scale multiple optical components on a single monolithic chipoffers significant advantages for use in computing and communications systems. As bandwidth requirements continue to increase for communication amongst electronic devices in data centers, problems associated with loss, dispersion, and cross-talk become pronounced in conventional copper channels. Initial interest in integrated photonics has been particularly concentrated on the realization of optical interconnects for data centers using vertical-cavity surface-emitting laser technologies[4]. Advantages pertaining to the use of photonics in communications systems include larger bandwidths than those achievable with electronic systems (on the order of 10-100 THz), minimal loss and electromagnetic interference, lower required powers, and potential improvements in security.

Early advances in integrated photonics recognized that micron-scale waveguides could be fabricated using existing CMOS process, even with substantial differences in refractive indices of silicon and silicondioxide required. The promise of scalable existing manufacturing techniques and the potential integration with silicon electronics motivated growth of commercial integrated photonics companies in the late 1990s and early 2000s. Since this time, the development of integrated photonics circuits has been characterized by impressive demonstrations, such as the establishment of active on-chip components including amplifiersand lasers, and the development of robust 500 GB/s transmitter and receiver photonic integrated circuit modules[7]. The possible applications for photonic integrated circuits (PICs) using silicon and other materialsplatforms, such as compound semiconductors, extend beyond telecommunications for possible use in disposable high resolution biosensors, optical storage, displays, and sensing for navigation/positioning purposes. Early efforts to investigate the potential of integrated photonics for space-systems applications appear promising with respect to radiation hardness; to date, radiation tests of integrated photonics devicesat anticipated dose levels for space missions have not affected device performance, for both silicon and indium phosphide material platform gallium arsenide (GaAs) materials platforms. Photonic integrated circuits have been fabricated on a wide variety of materials, ranging from standard element semiconductors and compound semiconductors to dielectric materials and nonlinear crystal materials. Different types of materials possess specific physical properties that may make them more or less preferable for any given individual application in integrated optics. Examples may include the use of lithium niobate to fabricate low- loss waveguide devices or integrated flexible chalcogenide glass to make photonic crystals with mechanical flexibility[10]. However, todate, the largest financial investments that have been directed towards standardization of materials in fabrication ecosystems have been primarily focused on silicon and indium phosphide photonic integrated circuits.

The use of silicon (Si) for integrated photonics offers the advantage of existing mature CMOS fabrication technologies and compatibility with CMOS-based electronics. The ubiquitous use of CMOS technologies for integrated electronics means that existing fabrication capabilities can provide reliable, high-volume manufacturing techniques with exceptionally high levels of precision11. As one of the most abundant elements on Earth, silicon may be used for the development of devices on-chip that are able to replace previous bulk functions and deliver improvements in both size and cost.

A broad array of on-chip optical components have been fabricated using silicon substrates, including asignificant number of waveguide-based devices, such as individual channel waveguides, ring resonators, and Mach-Zehnder structures, which have then been assembled to produce more complex integrated photonic circuits[13]. Silicon waveguide structures are effective at guiding light at relevant telecommunications wavelengths, with current propagation losses less than 1 Db/cm. Additionally, Siliconstructures can deliver tight mode confinement that allows for the use of efficient geometries without extensive bend losses. In addition to standard crystalline silicon, amorphous silicon has also been used in the fabrication of integrated photonic devices, and also provides low propagation loss.

In contrast to devices fabricated on silicon, which has an indirect bandgap, one of the primary benefitsof using indium phosphide is the ability to fabricate active optical components on chip. III-V semiconductors like InP have direct bandgaps, which means that they can efficiently absorb and emit photons that have energies in the range slightly above their individual bandgaps. The greater electron mobility of indium phosphide as compared to silicon may also allow for higher- power and higher-frequencyapplications relevant for optical communications[15]. The most well-established photonics foundry ecosystem in Europe is primarily based on the development of InP devices and has standardized fabricationprocesses for such active components as semiconductor optical amplifiers (SOAs) and distributed Bragg reflector (DBR) lasers.

Ongoing research and development efforts continue to investigate a range of materials platforms for the development of photonic integrated circuits. In addition to the consideration of silicon and indium phosphide as separate monolithic materials platforms, heterogeneous integration of specific optical components has also been completed on-chip. Heterogeneous integration by direct wafer bonding of a III-V active region has been completed on pre-patterned silicon-on-insulator (SOA) waveguides. This technique has since been used to demonstrate numerous discrete active devices in conjunction with siliconbased passive optical devices.

3.3 Structural Building Blocks:

Integrated photonics circuits consist of numerous scaled optical components incorporated on a single chip, with either monolithic or heterogeneous integration, dependent on materials selection. Unlike integrated electronic circuits, in which the fundamental building block is the transistor, a variety of different optical building block structures are used in integrated optics. The following is an abridged list of frequently implemented building blocks in PIC designs and a brief overview of their associated functions. PICs can contain both active and passive components, in which active building blocks involve dynamic interactionsbetween the material platform and light, such as amplification[18]. Different fabrication services/ecosystems provide foundry-specific building blocks libraries with detailed descriptions of individual element parameters and restrictions on component functionality and integration.

3.4 Sample Building Block Components

3.4.1 Waveguides:

Integrated photonics structures known as waveguides are the simplest available structures for guiding lightand interconnecting different elements on an optical chip. These optical waveguides are created to confinelight by fabricating a specific waveguide structure on a layer of low refractive index material, such that thelight is guided through the process of total internal reflection (e.g. for silicon integrated photonics structures,a layer of silicon dioxide is used). A variety of fabrication techniques exist for integrated photonics waveguides based on the intended material used for the photonic integrated circuit: channel waveguides on semiconductor and crystal materials are typically fabricated using conventional lithographic methods and some form of epitaxy, waveguides in transparent glasses may be fabricated using pulsed laser beams, etc.The selected material platform dictates the design rules for waveguide structures, limiting specifications such as a waveguide bend radius. Different fabrication techniques may be designed to optimize specific waveguide parameters subject to the application of interest, including the index contrast, operational wavelength-needed for the intended application, and input/output losses.

Many forms of channel waveguide geometries have been developed to optimize different parameters; the most common structures for silicon photonics are the buried channel, strip, and rib waveguides. The following schematic details the range of waveguide structures implemented in integrated photonics devices:

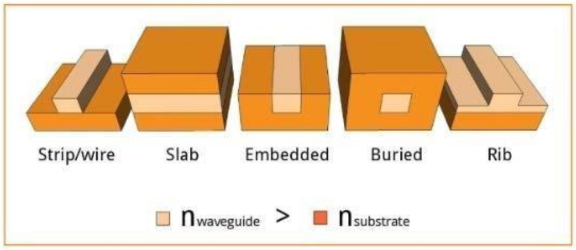


Figure 3.1: Common waveguide building block geometries for PIC-device

Selection of a waveguide structure will be dependent on the advantages offered with respect to a specific application. For example, in a slot waveguide—which consists of two strip waveguides—light is confined in the aperture structure between the two regions of higher index material. This type of geometryis ideal for applications such as biochemical analyte-sensing, where the guided electromagnetic field will be localized in the region of desired overlap with the chemical of interest[23]. These and other types of waveguide geometries can be used as fundamental building blocks to construct more complex structures, including splitters, parallel directional couplers, etc.

3.4.2 Multimode Interference (MMI) Based Couplers

Multimode interference (MMI) couplers can serve a power splitters and combiners in integrated photonics circuits on different materials platforms and can offer wider fabrication tolerances than those ofdirectional couplers. Modal excitation of multimode waveguides can be achieved through the process of self-imaging, in which a specific input profile can then be subsequently reproduced while traversing throughthe waveguide[25]. These reproductions can be formed as single images or multiple images depending on thesize of the multimode waveguide. MMI couplers have a discrete number of input singlemode waveguides connected to output singlemode waveguides, with common input-output configurations of 1x2, 1x4, 4x4, etc.

These input and output waveguides are connected by a wide multimode waveguide, and the distributioninput at the multimode waveguide thus excites a series of eigenmodes with different propagation constants.MMI couplers are designed so the interference of the eigenmodes produces a distribution where the powerat the input waveguides is then evenly distributed across the output waveguides[4]. MMI Couplers are able to provide routing and coupling across wide bandwidths and are largely polarization sensitive[26]; this makesthem one of the best options as splitting components in integrated photonics devices and a foundational building block for constructing Mach-Zehnder Interferometers.

3.4.3 Mach Zehnder Interferometers:

Interferometers are the primary building blocks for use in many applications that involve optical systems; specifically, the Mach-Zehnder Interferometer is a common tool for use in applications such as high speed optical modulation and biochemical sensing[27]. Depending on intended the application, the Mach-Zehnder Interferometer can act as a passive device or as an active device, based on whether or not an electric field is applied to one of the arms for use in electro-optic switching[25]. The structure of an integrated Mach-Zehnder Interferometer (MZI), as illustrated below, consists of an input waveguide, a Y- junction that divides the input wave evenly across two separate arms, and an output waveguide where the field recombines from the two arms:

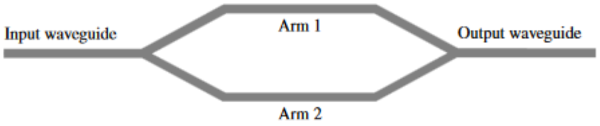


Figure 3.2: General Structure of an Integrated Mach-Zehnder Interferometer

When the input field passes through the two arms and recombines at the output waveguide, the two fields may no longer be in phase as a result of variation in optical path lengths of the two arms[22]. For chemical sensing applications, one of the arms serves as a reference waveguide, and the other as a functionalized sensing waveguide, such that the measured phase difference provides information about thechanges in refractive index that occur in the presence of a target-analyte. For use in switching, the relativephase of the two arms can be dynamically altered by using phase modulators to produce modulated intensityoutputs.

The outline provided of the above structures gives brief insight into the possible functions achievable using passive integrated photonics structures. Other frequently implemented passive structures include different types of couplers/splitters, arrayed waveguide gratings (AWGs), and microring resonators.Specifically, arrayed waveguide gratings (AWGs) are used to multiplex/de-multiplex input signals of closely aligned wavelengths that enter through the associated input waveguides, functionally acting as an optical prism[28]. Microring resonators are structured such that an optical waveguide is looped back on itself,and is able to achieve resonance when an optical path length equals an integer number of relevant wavelengths. The possible functions for these types of structures are numerous, extending to use in label- free biosensing and to applications as filters and modulators[29]. In addition to these passive building block structures for PICs, the library of active building blocks available for use in integrated optics has continuedto increase, particularly for InP integrated photonics devices. Available active building block structures presently include distributed feedback (DFB) lasers, distributed Bragg reflectors (DBR) lasers, and semiconductor optical amplifiers (SOAs).

CHAPTER 4

4. SPACE SYSTEM APPLICATIONS FOR PHOTONICS

There exist many areas of overlap regarding the benefits of integrated photonics devices for both terrestrialand space applications; however, the improvements offered by the scalability of size, weight, and power for integrated photonics are of significant value when considering the cost per pound to fly instruments onspace missions. Most recently, NASA's Space Technology and Mission Directorate (STMD) has awarded Early Stage Innovation awards to university-led teams for research involving integrated photonics devices in optical communications. In addition to these awards, the NASA Goddard Space Flight Center has announced plans for the development of the first integrated photonics modem, with ananticipated test datein 2020 on the International Space Station. While many of the clearest pathways for space based devices using PICs involve the development of technologies for communications systems, the scope of impact of integrated photonics extends to an array of fields, including sensing, biological applications, navigation, and imaging. In addition to the following proposed application areas for space-systems technologies, a Department of Defense has released a Technical Assessment of Integrated Photonics with further relevantareas of investigation.

4.1 Sensing:

NASA missions involve instrumentation for both remote sensing and direct sensing applications. Remote sensing includes such techniques as laser altimetry, LIDAR sensing, laser ranging, and spectrometry to perform observations about material objects from a distance, without coming into direct contact with the object of interest[64]. Conversely, direct-sensing requires immediate contact with targeted material or object of interest in order to register and collect the appropriate information. Direct sensors aretypically based off of laboratory instruments and are designed for use in environments where a directed signal/stimulus—e.g. an electrical signal or the presence of a chemical—can then generate relevant data ina readable output.

At this time, integrated photonics have only been incorporated in a very limited capacity for instrumentation built for remote sensing purposes. Though specific device parameters for PICs depend onbase material, device structure, and light source, the output power limitations at the scale of most integratedphotonics devices may not be ideal remote sensing applications. However, it is certainly conceivable that integrated photonics devices could be substituted in place of conventional bulk optics systems for remote sensing, provided that appropriate signal amplification can be achieved. Possible avenues for integration include systems such as the pulsed LIDAR sensing instrumentation used in the NASA ASCENDS mission for measurement of atmospheric CO_2 concentrations. The current space LIDAR instrument developed for this mission uses a tunable diode seed laser in a master-slave configuration locked at the wavelength of and power scale on an InP integratedphotonics chip with the required frequency-locking. While there have not been extensive investigations into the use of integrated photonics for remote sensing, future applications remain an active area of interestfor both U.S. and European government and industry-based research.

Examining the development of direct-sensing technologies, examples of instruments designed for previous and current NASA missions include the following: dust detectors on the Galileo spacecraft whichmeasured mass, charge, and quantity of dust particles; spectrometers on the Cassini spacecraft which can identify chemical species that form the composition of a planetary surface; and radiation assessment detectors on the Mars Rover Curiosity, which assist in characterization of the radiation environment. Thedevelopment of integrated photonics devices for direct sensing systems similar to these examples is at a more advanced stage than that of remote sensing, and there exist clear paths for translation from larger sensing instrumentation to PIC structures with improved SWaP-C characteristics.

One of the most common forms of integrated photonics direct-sensing structures involves surface sensing on waveguide-based devices, in which sensing of a chemical species is typically performed by measuring a change in the property of a waveguide refractive index. Chemical/analyte sensing can be performed using such structures as ring resonators and Mach-Zehnder interferometers with high sensitivities and low limits of detection, on the order of 10^{-7}/RIU. The chemical or analyte of interest can be sensed by passing through a functionalized surface, which then induces a refractive index change in the waveguide device so that the signal can then be processed and recorded. These waveguide-structured sensing devices have been developed for numerous liquid-chemical sensing applications, and this functionality has been extended to demonstrate on-chip mid-IR spectroscopic analysis of organic cyclohexane based-solutions. Additionally, gas detection has been achieved in silicon integrated photonics devices by using a high confinement resonant cavity made with slotted waveguides. With this structure, it is also possible able to measure effective index changes as a function of changes in index of refraction of the surrounding gas. These sensing techniques would be applicable to any future NASA missions and instrumentation involving sensing, including use on applications similar to surface chemical identification on the Mars Rover labs-on a chip or for direct atmospheric chemical analysis.

sensitivities and low limits of detection, on the order of 10^{-7}/RIU. The chemical or analyte of interest canbe sensed by passing through a functionalized surface, which then induces a refractive index change in thewaveguide device so that the signal can then be processed and recorded. These waveguide-structured sensing devices have been developed for numerous liquid-chemical sensing applications, and this functionality has been extended to demonstrate on-chip mid-IR spectroscopic analysis of organic cyclohexane based-solutions. Additionally, gas detection has been achieved in silicon integrated photonics devices by using a high confinement resonant cavity made with slotted waveguides. With this structure, it is also possible able to measure effective index changes as a function of changes in index of refraction of the surrounding gas. These sensing techniques would be applicable to any future NASA missions and instrumentation involving sensing, including use on applications similar to surface chemical identification on the Mars Rover labs-on a chip or for direct atmospheric chemical analysis.

In addition to the gas and liquid chemical sensing techniques possible with PIC-devices, integrated photonics also holds promise for use in application to radiation detection. Numerous radiation measurementdevices and experiments have been flown on missions on the International Space Station and on the Mars Rover labs to better characterize the makeup of the radiation environment around Earth and in deep-space. Improved understanding of these environments allows both for enhanced radiation protection of humans on space missions and shielding of electronic instrumentation. Recently, scintillator materials used for radiation detection have been interfaced with integrated nanophotonics, with results that demonstrated an increased light extraction efficiency. The scale of photonic crystals or microcavities used with the scintillator materials and the improvements in efficiency suggest that integrated photonics technologies could be used for lightweight radiation detection instrumentation in space.

4.2 Biological Applications

Biological sensing is also relevant to ongoing NASA missions that seek to better understand and address health concerns for astronauts during space flight. Additionally, improved sensing capabilities maybe of use for continuing investigations in the fields of astrobiology and space biology. As with the aforementioned applications in chemical sensing, the general nature of biological sensing requires the ability to identify the presence and quantity of a specific biomarker of interest, which may be accomplished by targeted binding between specific analyte-antibody structures. In the waveguide based structures of PICdevices, the device sensitivity is determined by the overlap of the evanescent field with the analyte of interest. The geometric structure, quality factor, and polarization of light can be adjusted with the intentionof obtaining the smallest limits of detection. Sensing methods can implement bulk sensing, which looks atthe variation of analyte concentration, or by surface sensing, which results from the binding of molecules to a surface on the waveguide functionalized with selectively immobilized markers. Transverse electric (TE) and Transverse magnetic (TM) mode profiles produce different field distributions in the sensing region and the surrounding materials, and so can be selected for sensing purposes based upon the sensitivity required and the distance the molecule of interest extends from the waveguide surface.

The ability to monitor metrics related to astronaut health and physiology is of value in order to understand the impact of increasing lengths of time in space on the human body. This is particularly important when considering the potential for future deep-space travel. In-flight biological sensors for astronaut health monitoring must be designed to meet many specific requirements for implementation. Among these requirements, devices must provide reliable, rapid information feedback and must be as minimally invasive as possible[79]. Integrated photonics biosensors are able to meet these requirements, andoffer further advantages because minimal analyte sample volume is required for use.

Additionally, many PIC biosensors have been developed with reusable cartridges. For example, an interferometric silicon-based photonic device was designed to incorporate a disposable microfluidics platform; this device demonstrated refractive index resolution corresponding to a protein mass coverage resolution of 20 fg/mm2[80]. Integrated photonics biosensing devices have been constructed for a range of applications, such as the detection of salmonella in blood samples. For in-flight use, appropriate monitoringfor astronaut health might include blood or salivary samples to measure metabolic information or biometricdata related to oxygen and pH levels. Parameters including reusability, increased limits of detection, size/portability, and ease of integration are all advantages of integrated photonics for the purpose of in- flight biological/health-monitoring. Continuing work, such as the development of flexible integrated photonics offer further possibilities for potential wearable health-monitoring systems.

The Photonic Biosensor for Space Applications (PBSA) project has been specifically developed to address the challenges biomonitoring of humans in the space station and to take relevant measurements forastrobiology experiments[82]. The PBSA instrument combines a lab-on-a-chip device structure and a photonic immunosensor for use in microbial monitoring. Specifically, the PIC structure for the PBSA- device involves silicon nitride rings and waveguide printed onto silicon, with the microring surface functionalized for specific target antibodies. This device can perform near-simultaneous measurement of atleast six target substances using the associated fluidic channels. Applications specifically proposed for thisdevice include the monitoring of microbial contamination on space stations or future planetary habitats.

4.3 Communications:

The development of superior optical communications systems is one of the clearest applications for the use of integrated photonics devices. Photonic integrated circuits offer the ability to incorporate multiple optical functionalities on a single chip, and are able to allow for increased bandwidth and transmission capabilities. Applications of integrated photonics may include chip-to-chip interconnects and optical transceivers for use in high volume data centers[84]. Compared to electronic counterparts for applications in communications, integrated photonics affords larger bandwidth, lower loss, requires less power, and do notrequire electro-optic conversion. Over the previous five years, U.S. corporations and industry-partners have considerably advanced the commercially available integrated optics-transceiver technologies. Acacia

Communications has developed a 400-Gbps coherent transceiver module, and Infinera Corporation offers500Gbps super-channel bandwidth for data center interconnects through its Cloud Xpress product line, in addition to its work on long-haul communications involving integrated photonics.

The possibilities for use of commercially available integrated photonics devices is relevant for use in NASA communications systems, and is an area of active research and development. The NASA STMD Early Stage Innovation Awards recently selected five university-led teams to lead areas of investigation including platforms for terabit-scale communications, modulators for high-efficiency transmitters, and space-based optical communications/ranging[87]. NASA has also recently announced the development of theagency's first integrated photonics modem that will be tested on the ISS in 2020 as a part of the Laser Communications Relay Demonstration (LCRD). The modem, known as the LCRD LEO User Modem andAmplifier (ILLUMA) will act as a LEO terminal for LCRD, and aims to reduce size and power consumptionof previous bulk optics while improving performance and reliability.

4.4 Autonomous Navigation/Positioning:

Integrated photonics devices also offer potential for use in autonomous navigation and positioning systems. Ring-resonator structured sensing devices have been used for the development of integrated photonics-based optical gyroscopes. These devices are able to sense and determine angular velocity of inertial systems, which has significant applications for positioning[10]. Presently, both fiber optic gyroscopes and active gyroscopes are used in commercially available satellite navigation systems; however, the ability to use small scaled integrated photonics devices for the same purposes would allow for similar navigation systems on CubeSats. The integrated structure can also increase device reliability and potentially lower overall systems costs for positioning and attitude determination of space systems.

Integrated photonics-based optical gyroscopes—also known as integrated optical gyros (IOGs)— operate by taking advantage of the Sagnac Effect, such that the occurring rotation causes measurable phaseshifts as a function of the angular velocity[89]. At this time, several IOG device prototypes have been proposed, fabricated, and analyzed using different material platforms and design structures. These designs highlight advantages of IOG function for use in space environments, including the removal of mechanical parts, minimal required maintenance, and insusceptibility to damage or failure induced by vibrations duringlaunch[90]. Four of these device structures are highlighted in the following table, comparing materials system used and the associated figures of merit assessing the IOG performance:

IOG Device/Material:	**Highlighted Design Elements**	**Resolution:**	**Bias Drift**
1. High-Q InP IOG (2016) [91]	Sensing element: ring resonator coupled to a straight bus waveguide through an MMI coupler; operating wavelength = 1.55 µm; fully integrated InP structure using COBRA	• Use of spiral cavitysensor (Q-factor = 590,000) produced resolution ~ 150°/h	With spiral resonator, bias drift can be decreased down to ~ 1 °/h

		• Up-scaling device with spiral resonator, resolution = 10°/h	
2. Hybrid Silicon Waveguide OpticalGyroscope (2014)[28]	Fully integrated, low-loss siliconnitride spiral waveguide structure.	• Minimum value = 19°/h	Not specified; Lossreported at 1 dB/m
3. IOG using Long-Range Surface Plasmon-Polariton Waveguide Resonator (2013)[92]	Use of a Long-Range Surface Plasmon-Polariton (LRSPP) waveguide structure to overcome propagation loss/polarization extinction ratio challenges associated with conventional waveguides; LRSPP ring resonator = sensing element,consisting of a Si substrate, silver strip and Erbium-doped phosphateglass.	• Sensitivities = 10^{-3} °/hr (waveguide with single- turn resonator); 10^{-4} °/hr (waveguides with multi- turn resonator)	Reported maximumzero drift 4 orders ofmagnitude lower than conventionalsingle-mode waveguides.
4. SiO2 Waveguide Resonator used inIOG[93]	Si-based ring resonator model, made up of track-pattern ring channel waveguides. Ring resonator design fabricated using PECVD method.	• Rate detection limit of1limit of 1.7°/hr reported	Not specified;Propagation loss of 0.02 dB/cm reported

The reported quantities for measuring IOG performance indicate progressive improvements towards the development of commercially viable integrated photonics positioning systems with good resolution andminimal drift. For high-performance use in space-systems and in satellites, continued progress towards advancing resolution/drift qualifications are needed to meet application requirements of 0.01°/hr and 1°/hr,respectively.

4.5 Imaging (Astronomy)

Another area of interest for integrated photonics in space applications is the development of astronomical imaging instrumentation (“astrophotonics”). The ability to successfully integrate multiple components for imaging on a single platform can provide optimal flexibility, mechanical robustness, and resistance to negative environmental factors. Areas of application in astronomical imaging may include spatial filtering of received signals for stellar interferometry and improvement in spectrograph stability.

To date, composite multi-mode waveguide integrated optics devices have been fabricated to examine functionality as a building block structures for slit-reformating of diffraction-limited spectrographs. Thiscan help to overcome challenges associated with slit-width size and coupling efficiency and aid in low-lossreformatting, thus enabling smaller telescopes to perform high-resolution spectroscopic surveys. A proposed device structure known as a “photonic lantern,” can act as a mode-reformatting device to supportthe conversion of a multi-mode signal into a single-mode signal, thereby translating a see-limited point spread function to a diffraction limited spot. Combining the function of integrated photonics lanterns and slit-formatting techniques, integrated photonics devices could be successfully used in astronomical imaging

to take light from the telescope and focusing to a single-mode spectrograph—thereby miniaturizing the sizeand scale of the imaging system and improving the instrumentation thermal/environmental stability.

The NASA Innovative Advanced Concepts Program has also sponsored a Low-Mass Planar Photonic Imaging Sensor project, which investigated the use of PIC technologies to replace traditional optical telescopes[98]. The Low-Mass Planar Photonic Imaging Sensor was developed from the Segmented Planar Imaging Detector (SPIDER) platform that consists of densely packed white-light interferometers packed onto a PIC structure. Replacing traditional bulk optics necessary for conventional telescopes, the use of the Low-Mass Planar Photonic Imaging Sensor and associated integrated optics can supplant existing technologies at lower costs and required mass/volume. Proposed applications for this device include use asan EO-imager on a Europa mission for high-resolution imaging and remote sensing of changes in planet surface processes.

Chapter -5

5. PHOTONIC TECHNOLOGIES IN SPACE APPLICATIONS: SELECTION AND ACCEPTANCE TEST CRITERIA

5.1 INTRODUCTION

The use of photonics technologies for space application presents significant advantages due to its specific properties as follows

- Almost unlimited bandwidth (i.e. 1550nm fiber can go to several THz.)
- Reduced propagation losses at spacecraft level (due to short communication distances).
- Supports any modulation or coding format
- Immunity against electromagnetic interferences,
- Optimum mechanical properties (light weight, mechanically flexible, reduced volume, resistant against corrosion of contamination).
- Reduced noise generation and Electromagnetic immunity are clear advantages in cases where satellite operation works close to the sensors sensitivity bandwidth (i.e. natural Earth microwave emissions).
- Mechanical flexibility and low weigh of FO compared with standard hardness are an advantage when articulated systems are used or many meters of cabling are required.
- Mass reduction possibilities in case of using photonic systems may result in important cost reduction during handling and launching of the S/C.
- Huge bandwidth and multiplexing properties makes FO systems is a clear advantage for signal processing. and thermal and structure monitoring applications.
- Optical the use of optical wireless technologies will reduce cost and time in the Assembly and Test (AIT) phase.

The selection and evaluation procedures of COTS optoelectronic components for its use in space application need to be established due to the fact that no qualified components exists and that no standards are available that define the procedures to be applied for optoelectronic devices to be used in space qualifications. The following paragraphs propose a generic procedure for theselection and acceptance test criteria for optoelectronic devices, and also includes analysis related to the Specification Performance Requirements and Environment Constraints related to space applications.

Summary results of a large number of parts which has been tested by Alter are also presented to demonstrate current status of most promising technologies. Finally, one case example is presented related to optical amplifiers.

5.2 SELECTION AND ACCEPTANCE TEST CRITERIA

When COTS components have to be used in space applications because qualified components are not available, then the selection of the right component has to be made in such a way that risk mitigation techniques are applied at the time that the technical requirements of the application are met.

The following steps have to be followed:

1. Specification Performance requirements:
   a. Definition of the basic technical requirements of the application (opto-electronic parameters) with the identification of the critical parameters and their limits.
   b. Definition of specific quality and reliability requirements applicable to the application.

2. Survey of the available commercial candidates that meet the critical parameters.

3. Definition of the environmental constrains (related to the space application).

4. Trade-off through the data available for all the candidates identified in the survey, attending to the following aspects (some of them may require of visits to the manufacturers):
   a. Manufacturer experience in space application technologies.
   b. Manufacturer willingness to provide technology and reliability data and support (i.e.PCN s notices).
   c. Availability of TELCORDIA qualified devices and or TELCORDIA qualification ofthe manufacturer.
   d. Technology maturity.
   e. Availability of reliability data.
   f. Previous space heritage (if any).
   g. Available technology data (this information can be used, for instance, for the prediction of the sensitivity of the device to radiation effects).
   h. Availability of “single lot date code”.
   i. Availability of non pure-tin components.
5. Pre-selection of two or three candidates that are supposed to meet the minimum requirements.

6. To perform SELECTION TEST: Definition of the preliminary TESTS that will allow the selection of the best candidates. These SELECTION TESTS have to be designed in such away that they provide enough data to :
   a. Obtain relevant data concerning the performance of the devices when this data is not available from the trade off.
   b. Determine which of the candidates presents better performance for the application, by comparison of the results of the test performed on the candidates.

7. Pre-selection of two or three candidates that are supposed to meet the minimum requirements.

8. To perform SELECTION TEST: Definition of the preliminary TESTS that will allow the selection of the best candidates. These SELECTION TESTS have to be designed in such away that they provide enough data to :
    a. Obtain relevant data concerning the performance of the devices when this data is not available from the trade off.
    b. Determine which of the candidates presents better performance for the application, by comparison of the results of the test performed on the candidates.

9. To decide which is the best candidate for the application. This candidate will be submitted to full evaluation.

10. Evaluation of the best candidate.- The device identified as the best candidate for theapplication will be submitted to a full evaluation with the purpose of:
    a. Fully characterize the performance of the device when used in the final application interms of:
        i. Quality of package and assembly.
        ii. Reliability
        iii. Stability of the Electro-optical parameters in the full real operating temperaturerange.
        iv. Stability and performance under space radiation environment
        v. Stability under extreme mechanical efforts (shocks, vibration, acceleration)
        vi. Performance and stability under vacuum and thermal variations.
    b. Identify potential failure modes.
    c. Determine the potential limits in the application or use of the device.

11. Visits the manufacturer may be necessary in order to analyze the results of the evaluation, check the manufacturer willingness to collaborate in technical issues and to prepare the procurement of the flight lot.

    In case the result of this evaluation indicates one or more problems that discourage its use for the application, then other candidate has to be evaluated.

12. Procurement of the flight lot.

13. Lot Acceptance Test.- In case a new lot, different from the one subjected to evaluation, has to be procured for flight purposes, then LOT ACCEPTANCE TEST have to be performed to identify any potential deviation from the performance of the evaluated lot. Note that, in case that the flight lot has not been submitted to screening, or the screening reported bythe manufacturer is not considered enough to ensure the screen out of the enfant mortality elements, then a complete screening in accordance with chart III of ESCC 5000 has to be performed

Schematic flow for optoelectronic parts selection, evaluation and acceptance procedure is provided in Chart I.

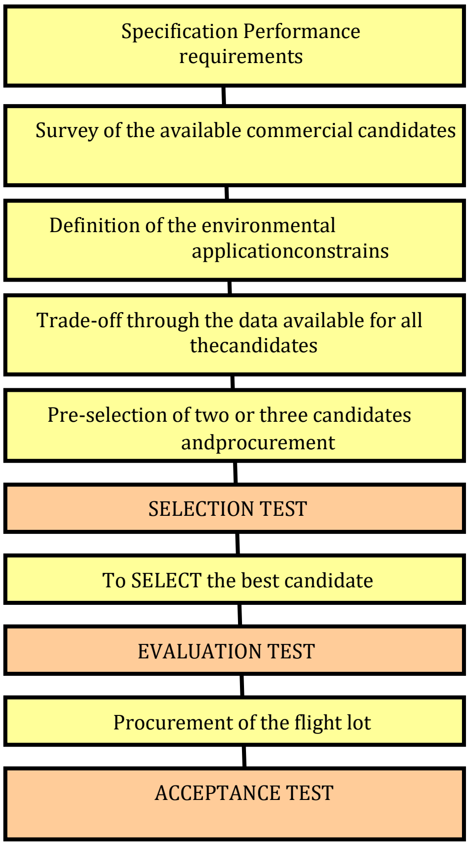


CHART 1- parts selection, evaluation and acceptance flow for cotsoptoelectronics components

5.3 SPECIFICATION PERFORMANCE REQUIREMENTS

5.3.1 Electro-optical requirements

The first step in the parts selection process is the exact definition of the electro-optical performance required for the application. This implies the clear identification of:

- Key parameters.
- Acceptable limits to the range of variation of these parameters during the mission, takeninto account:
    - Operating temperature range.
    - Environmental conditions (radiation).

The key parameters have to be selected in such a way that they allow a wide margin of potential commercial candidates at the time that the performance of the mission is not jeopardized. Some aspects will require the maximum possible flexibility. To make that flexibility possible it is necessary that the selection process is initiated at the first steps of the design, to reduce as much as possible the design related constrictions.

5.3.2 Quality requirements

Quality requirements are determined by the type of mission and application; nevertheless, it is strongly recommended to apply the quality requirements established in ECSS-Q-60A. These quality requirements have to be followed to the maximum extent as possible in terms of:

- Procurement policy
- Screening
- Package and assembly quality and testing.
- Acceptance test criteria

5.3.3 Reliability requirements.

Reliability is one of the main concerns when using commercial components in space applications. This asseveration does not mean that the commercial components are not reliable enough for their application in space, but its real reliability has to be verified. This verification can be performed by means either of the analysis of the reliability data provided by the manufacturer (if available) or by testing, in order to warranty a minimum of 10 years (typical value) of operation in space environment.

5.4 ENVIRONMENTAL CONSTRAINS

The environmental constrains imposed by the space missions are mainly driven by the conditions stress during launching and by the operation in free space. The following elements constitute the main constrains compared with the majority of the commercial applications:

- Operating temperature range
- Thermal variations
- Vibration
- Accelerations
- Vacuum
- Harsh radiation environment

5.4.1 Operating Temperature range

Typical operating temperature range warranted by the manufacturer for commercial parts goes from 0 to 40 º, while space application requires in general parameters and functional stability in the range from -55 to +125ºC (although some specific missions / applications may require ranges from -185ºC to +300ºC). The selected parts need to remain functional and parametrically stables in the specified temperature range.

5.4.2 Vibration

The capability of the optoelectronic components to survive strong vibration conditions duringlaunch is a requirement to be taken into account. Specific requirements need to be defined ona case by case mission.

5.4.3 Thermal cycles

Space hardware has to be able to survive extreme temperature cycles produced during operations due to the continuous travelling of the satellite from exposition to solar radiation toshadow during its rotation around the Earth. The mechanical stress produced by these temperature cycles may induce degradation in the mechanical parts of the component. It has tobe verified that the components can withstand the thermal cycles test designed for these purposes.

5.4.4 Accelerations

Optoelectronic parts should be able to survive hard accelerations during launch, as per the conditions given in the following requirements. Requirements must be defined on a case bycase basis although the following figure may be used as baseline.

Frequency (Hz)	*Acceleration (g)*
100	40g
2000	1000g
10000	1000g

5.4.5 Space radiation environment

Four sources of radiation can be distinguished:

- Cosmic rays: all kind of ions, but primarily protons (85%) and helium (14%).
- Radiation belts (Van Allen belts), protons and electrons trapped in the earth's magneticfield

5.5 Advantages:

- Almost unlimited bandwidth (i.e. 1550nm fiber can go to several THz.).
- Reduced propagation losses at spacecraft level (due to short communication distances).
- Supports any modulation or coding format. Immunity against electromagnetic interferences
- Optimum mechanical properties (light weight, mechanically flexible, reduced volume, resistant against corrosion of contamination).

5.6 Photonics Technologies in Space applications

5.6.1 Telecommunication Satellites Payload

- Digital Communication Links
- Analogue Communication Links
- Optical Switching
- Signal Processing
- Microphotonics

5.6.2 Spacecraft Platform

- Optical Wireless Low rate Links
- Sensors
- Pyrotechnic

5.6.3 Optical Wireless communications

- IR LEDS
- IR Photo-detectors

5.6.4 Opto-pyrotechnics LIDARS Formation flight

- High power lasers
- IR detector (1.55 to ∼4 μm)

CHAPTER -6
6. CONCLUSIONS

CONCLUSIONS

- ✓ Very few optical components are qualified for space applications. This means that COTS are necessary most of the times. A cost effective approach for selection and acceptance criteria of these COTS has been presented in this paper.
- ✓ Detailed construction analysis, endurance, radiation and environmental test performed before the complete qualification flow can be very useful for increasing the reliability of the device and reducing both the price of the selection and project qualification. It is recommended to do this prior to any project qualification activity.
- ✓ Specific test setup conditions must be considered when working with photonics parts toensure test bench is suitable to provide electro-optical characteristics while parts are being submitted to environmental test in operating conditions.
- ✓ Alter Technology Group has a large experience on EEE parts procurement as well asextensive testing on most significant photonics technologies for space applications.Reliability data are available for main parts to help on the final selection of the product for the intented application.

REFERENCES

[1] B. Bénazet, M. Sotom, M. Maignan, J. Berthon, “Optical distribution of local oscillators in future
telecommunication satellite payloads”, ICSO 2004, Toulouse, France, 2004, March 30 - April 2.
[2] Oshima, K. Nishiyama, K. Kurotori, and H. Hayakawa, “Compact Optical Fiber Amplifier”, Furukawa Review,
No. 23, pp. 71-75, 2003.

[3] C. Simmoneau, C. Moreau, L. Gasca, D. Bayart, “Alumino-silicate heavy-doped fibers for compact WDM-
EDFAs”, ECOC 2005, Vol. 4, paper Th 3.3.7, pp. 953-954, 2005.

[4] SINERGIA project. Si nanocrystals and erbium co-doped glasses for optical amplifiers. Project URL:
http://www.padova.infm.it/sinergia.
[5] D. Bayart, L. Gasca, G. Gelly, “Cladding-Pumped Erbium-Doped Fiber Amplifiers for WDM Applications”,
Alcatel Telecommunications Review, 3rd Q 2001, pp. 179-180.

[6] A. Mori et al. “Broadband Amplification Characteristics of Tellutite-based EDFAs”. ECOC-97. Proceedings of
the Conference. September 1997. pg. 22-25.
[7] A. Bjarklev, J. Broeng, and A. S. Bjarklev, “Photonic crystal fibres” (Kluwer Academic Publishers, Boston, MA,
2003).
[8] M. Caussanel, O. Gilard, M. Sotom, P. Signoret and J. Gasiot, “Extrapolation of radiation induced EDFA gain
degradation at space dose rate”, Electronics Letters, Vol. 41, N°4, pp. 168-170, 17th Feb. 2005.
[9] Generic Reliability Assurance Requirements for Optoelectronic Devices Used In Telecommunications Equipment,
Telcordia, GR-468-CORE, Issue 2, September 2004.

[10] M. Van Uffelen, S. Girard, F. Goutaland, A. Gousarov, B. Brichard, F. Berghmans, “Gamma radiation effects in
Er-doped silica fibers”, Proceedings of RADECS 2003: Radiation and its Effects on Components and Systems,
Noordwijk, The Netherlands, 15-19 Sep. 2003.