Investigating The Role of Photonics in Industrial Automation and Control Systems

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Abstract

Photonics is a rapidly growing field that has significantly impacted on various industries, including industrial automation and control systems in different fields. This paper investigates the role of photonics in enhancing efficiency, accuracy, and reliability in industrial automation and control systems. The paper provides an overview of the principles of photonics and its application in industrial settings, highlighting the benefits and challenges associated with its adoption. Through a comprehensive review of existing literature and case studies, this research paper aims to shed light on the potentials of photonics technology to revolutionize the way industrial processes are monitored and controlled. The findings of this study will offer valuable insights for researchers, engineers, and industry professionals seeking to harness the full potential of photonics in industrial automation and control systems.

Keywords: Photonics, Industrial Automation, Control System, Revolutionize

1.0 INTRODUCTION

The word photon, which refers to the smallest unit of light, is where the word photonics originated. In photonics, signals are generated, detected, as well as manipulated via transmission, emission, signal processing, modulation, switching, amplification, and sensing (Amiri et al., 2018). It is a method of producing and managing radiant energy in the form of photons, which are quantum units. The development of semiconductor technology is essential to the miniaturization and high-speed operation of integrated circuits.

Unfortunately, high levels of power dissipation, resistance, and faster speeds are required for the miniaturization of circuit components and parts. This may be related to an increased susceptibility to synchronization of signals. Scientists are now turning back to light instead of electrons as the information carrier in an effort to improve high-density integration and system performance(J.D. Joannopoulos, et al 1997). As previously mentioned, one of light's advantages over electrons is its ability to move more quickly in dielectric materials than electrons can in a conductor. This allows for the large-scale information transmission of data per second. When compared to metals, the bandwidth of dielectric materials is larger. While electronic systems like telephones have a bandwidth of only a few hundreds of kilohertz, fiber-optic communication systems have a bandwidth of approximately one terahertz.

Additionally, photons interact less than electrons, which helps to minimize energy losses. It was also mentioned that photonics is a relatively new field and that the word "photonics" was originally coined as an analogy for electronics. The primary distinction between these two terms was addressed: photonics deals with the control of photons (in free space or in matter), whereas electronics deals with the control of electric-charge flow (in vacuum or in matter). It is evident from this description that there are areas where the disciplines overlap. It's possible that electrons regulate photon flow and vice versa. It also illustrates how crucial light's photon nature is to understanding how various optical devices work(Saleh & Teich, 1991).

With several industrial organizations projecting a growth rate of roughly 25%, photonic technologies have a great deal of potential to impact the economy in the coming decades. CPIC's study estimates that the industry is worth $650 billion globally, and by 2020, it was expected to have hard a market value of over €600 billion(CPIC, 2016).

Numerous fields, including laser, optics, fiber-optics, opto-electric devices, alternative energy, healthcare, telecommunication, agriculture, aerospace, defense/security, and many more, have made extensive use of photonics technology.(Amiri et al., 2018). The power source is an essential component in the use of nanophotonic devices. Promising technologies for more affordable and extensive energy conversion in solar cells are available for solar-powered sources. The downsized version can also be integrated as integrated power sources into nanophotonic systems to create a self-sufficient system. Many applications requiring the tight confinement of optical fields exist for nanoscale photonic devices, such as enhanced solar cells, information and communication technologies, sensors, and lighting. These devices can effectively focus the optical field into a nanometer-sized volume(Zhang et al., 2014).

The development of new optoelectronic devices with improved performance, lower cost, and energy efficiency is facilitated by photonics technologies. In order to accomplish this, photons in semiconductors and bulk crystals in LEDs and lasers could be manipulated. These days, meta-materials and crystals are used in optical computers. Nanowire photonics could be used to control light and pulse at submicrometer volumes. Due to its high transparency and low sheet resistance, graphene photonics devices perform better in transparent conductors than semiconducting materials. Another use of photonics in medical imaging is optical coherence tomography (OCT) techniques, which provide high resolution three-dimensional images and non-invasive treatment for brain tumors. Surveillance, reconnaissance, and intelligence gathering all make use of photonic systems and sensors. Photonic communication was used to transfer terabits of data. Most industrial machine applications, especially those involving computer numerical control machines, have online monitoring, inspection, and measuring capabilities. This paper discussed many industrial applications of photonics. Consequently, a comprehensive examination is necessary for the utilization of photonics in numerous fields, such as aerospace, medicine, manufacturing, and alternative energy. This paper focused on the development, applications, and comprehensive review of photonics (Zhang et al., 2014).

2.0 Photonics Application

One important enabling technology that is widely used is photonics. While photonics is not a term you hear very often, it is the foundation of many common technologies, including those that use, create, detect, or modify light. Since the invention of the laser in the 1960s, photonics has advanced significantly and is now a significant part of many industries, including advanced manufacturing, telecom and data communications, healthcare, aerospace, energy and the environment, food and agriculture, and more(Carlos, 2016).

2.1 Photonics Application in Food and Agriculture

These days, photonics is used extensively in agriculture. Without sensors and cameras on tractors and drones to enable soil and crop analysis and identify areas needing fertilizer application, precision agriculture is difficult to imagine. The ideal time to harvest crops is also predicted using photonics. Photonics can be used to sort fruits when combined with machine vision equipment. The growth of city farming is greatly aided by lighting in the agricultural sector (Carlos, 2016). Urbanites can obtain fresh and hygienic food by cultivating fruits and vegetables in vertical farms with the help of LED lighting. Similarly, photonics technologies can guarantee food safety. Before vegetables and other agricultural products reach the consumer's table, contaminants are found using spectroscopy.

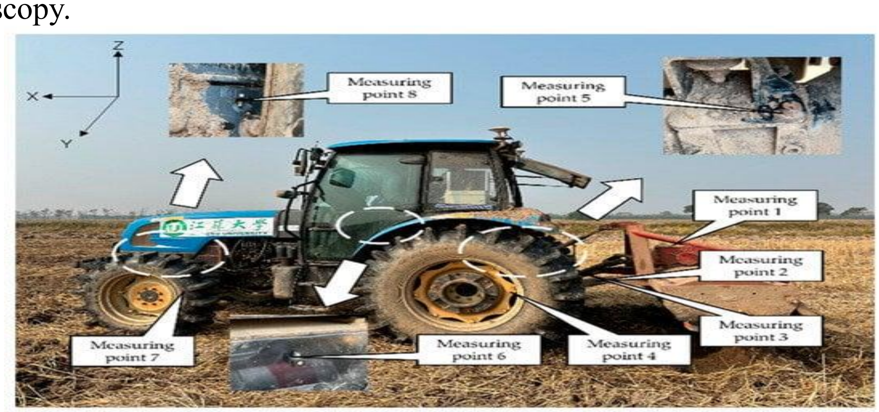


Figure 1. Installation location of each sensor.

2.2 Photonics Application in Advanced Manufacturing:

Automation in the manufacturing industry has been made possible in large part by the advancement of laser technology. Products can now be made more sustainably and with higher quality thanks to laser light devices. The increasing trend of product customization, particularly in consumer electronics products like digital cameras, smartphones, smart televisions, and video game consoles, has been maintained by the versatility of laser devices. The production of semiconductors now heavily depends on photonics technologies. The mass production of semiconductor chips would not be feasible without the use of optical lithography technology. Additionally, photonics has become essential to machine vision, optical inspection technologies, curing epoxy resin, controlling and monitoring chemical production, and other advanced manufacturing processes(Carlos, 2016).

Figure 2: Artificial Intelligence in Manufacturing (USA, 2019)

2.3 Photonics Application in HealthCare and Medical

Photonics has some genuinely groundbreaking uses in the medical industry. Medical diagnosis accuracy may be improved with the help of photonics innovations. To detect and prevent serious diseases like cancer, for example, it is possible to combine imaging technology with laser and light therapy. Additionally, photonics applications can enhance patient treatment plans and reduce the number of hospital days. The non-invasive nature of light makes it possible to do away with operations and needle pricking's (Radanliev, 2024). Blood sugar level, for example, can now be analyzed by just looking through the skin and without using a needle(Amsalu & Palani, 2020). Today, photonics is widely used in laser eye surgery and will soon allow for the restoration of blindness. The field of photonics has seen recent advancements that hold great promise for the prevention of infectious diseases. The use of photonics technologies can be essential to preventing malaria worldwide. It is theoretically possible to identify a mosquito and use a laser to kill it when combined with a camera! Additionally, a refrigerator can be powered by photovoltaic panels mounted on a camel, enabling the delivery of life-saving medication to isolated desert locations (Carlos, 2016).

Figure 3: Medical application of Endoscopy(Atracurium, 2020)

2.4 Photonics Application in Telecommunications and Data-communications

The fiber optic technology that powers today's internet infrastructure is entirely dependent on photonics(Corriveau & Bulgarea, 2022). Data is transferred from one location in the world to another at the speed of light via optical fibers made of glass, which are thinner than a hair. It would not be possible to send emails, conduct Google searches, establish Facebook connections, or transfer images, music, and video in the manner that we do now without optics and fibers. And the trend keeps going since, according to a 2019 Cisco prediction, video content will account for 80% of all internet usage worldwide, meaning that almost a million minutes of video will be streamed online every second. In fact, photonics has made it possible to connect not only homes but also establishments, businesses, research apparatus and infrastructures, a development that has made it possible to improve services, security, employment, and education. It is therefore not unexpected that one of the primary goals is the development of photonics systems and integrated circuits, which are necessary for quicker, less expensive, and more effective internet systems in an increasingly connected world.(Hull, 2016).

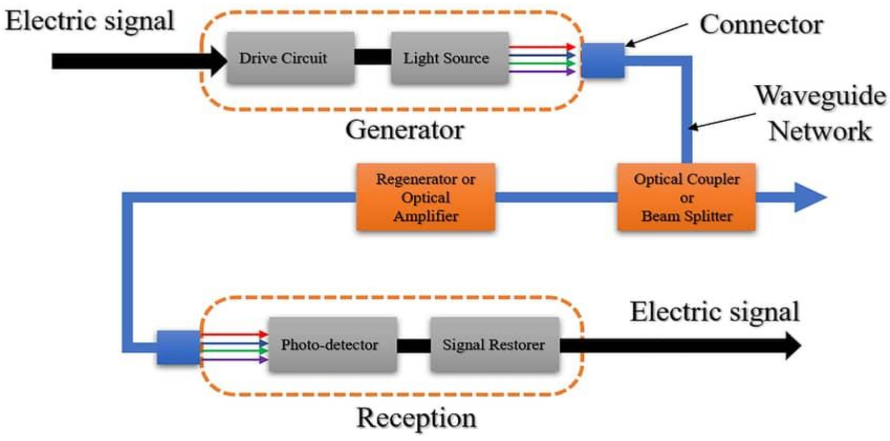


Figure 4: An Optical communication system(Hull, 2016).

2.5 Photonics Application in Automotive

In the automotive industry, photonics technologies start off by playing a part in the industrial manufacturing process. High power lasers are used to cut metal, weld metal, and perform metal marking processes. With 3D printing technology, lasers are used to cut textile, such as the airbag, in the car. Photonics technologies have also made it possible for manufacturers to possibly come up with the car of the future. Driver-less cars have previously existed only in the fertile and imaginative minds of futurists. With the significant innovation in photonics technologies in the past few years, the automotive industry has now found ways to develop autonomous vehicles. Photonics is also responsible for the development of smart vehicle technologies. From sensors that can detect environmental changes and communication systems between various devices inside and outside vehicles, to advanced systems of lighting to accentuate the vehicle's interior and exterior and night vision cameras that enable the driver to see in the dark, photonics technologies today play a vital role in ensuring road safety(Yusuf et al., 2024).

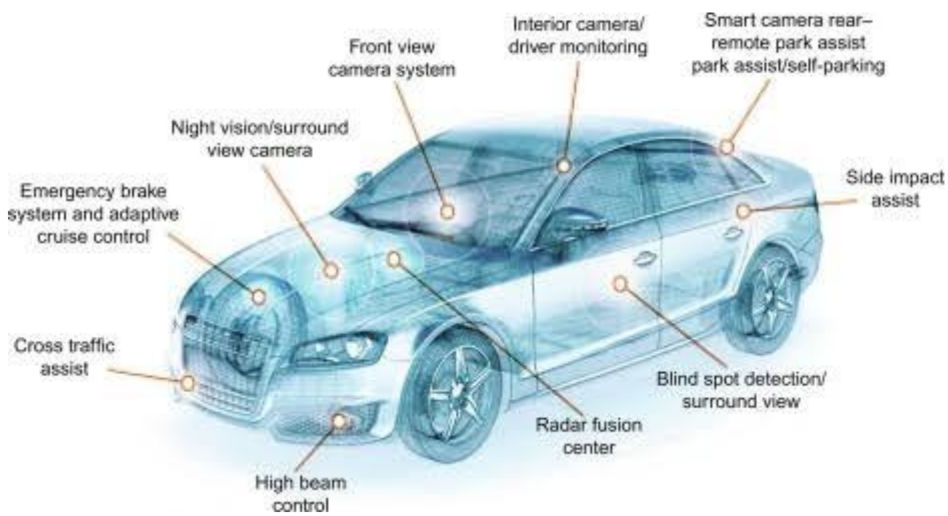


Figure 5: Automotive application with potential integration photonics content(Carol, 2021).

2.6 Photonics Application in Aerospace, Security and Defense:

The role of photonics in the advancement of aerospace technology is immeasurable. With micro and nano photonics systems, spacecraft can not only travel farther into space but can also be controlled remotely upon landing unto planets and other extraterrestrial bodies. Optic technologies can be further refined to help astronomers to employ far more sophisticated telescopes that can see further in space(Trumper et al., 2018). Photonics will also play an important role in the security and defense industry. Currently, photonics systems are indispensable in airport security, biometric identity management systems, border surveillance, and defense communications systems. Advancement of photonics technologies is also significant in producing smart weapons systems that enable the military to enhance national security and defense (Corriveau & Bulgarea, 2022). For instance, cutting-edge sensors enable the production of unmanned aerial vehicles that can be remotely controlled to discretely carry out sensitive missions. Recent innovation in photonics have also made it possible to impose stricter security measures and processes. For instance, textiles with displays that illuminate can be used by firemen so they are more visible. Light indicators can also be built directly into carpets in hotels for directions in case of fire. Police has been using photonics technologies for many years for the analysis of fingerprints in a crime scene and, in the future, with sensors that use the properties of light, police can identify in a moving car if the driver has been drinking alcohol and reduce potential accidents or crimes. Photonics technologies are also used to analyze paintings to check for other paintings and drawings that are hidden behind, to see previous versions and sketches, helping to detect fraud and forgery. Lastly, ink can be visually inspected on documents to see if someone has been cheating on that check (Carlos, 2016).

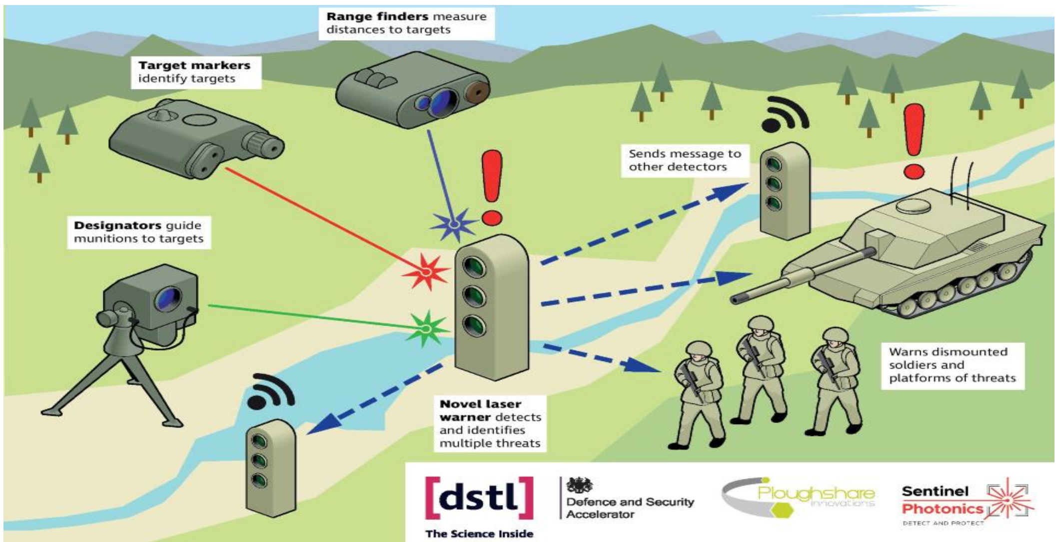


Figure 6a: Infographic showing how the novel laser warnser detects and identifies multiple threats(UK, 2021).

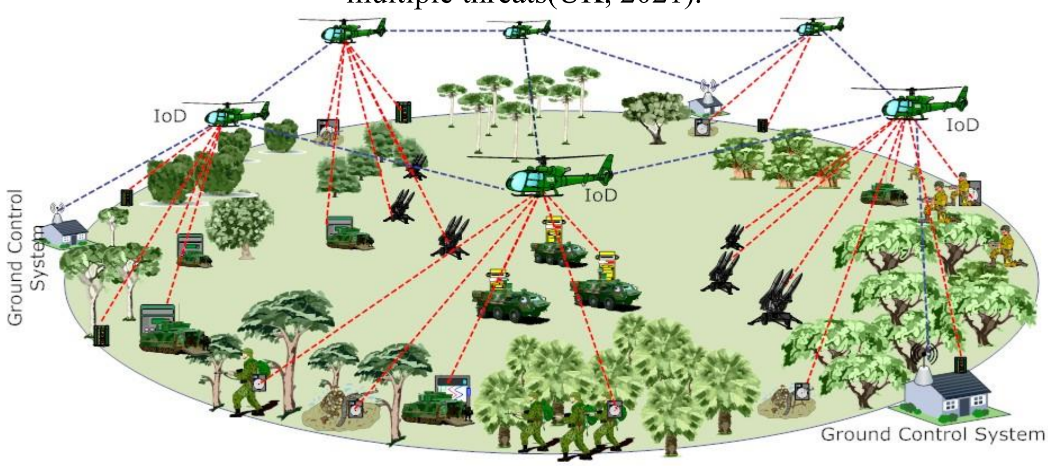


Figure 6b: Illustration of Internet of Drones (IOD) assisted battlefield scenario

2.7 Photonics Application in Environment and Energy

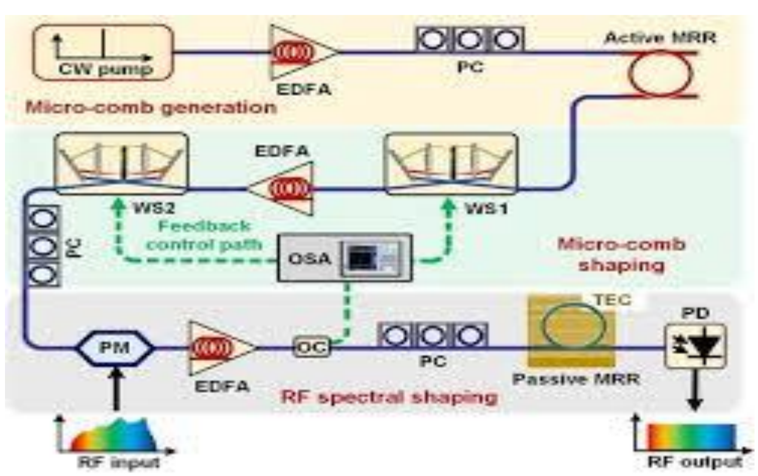
Lowering our carbon footprint and finding renewable sources of energy is critical in fighting climate change. Fortunately, photonics is on our side in this matter too. Photovoltaic systems made up of semiconducting materials capture solar energy from the sun and convert it to clean electricity(Kesari et al., 2021). Photovoltaic cells on a car could be used to power a fan to keep the car cool when it is parked in the searing heat. Photovoltaic systems can also be used to power a drone which can be kept flying in the air with the help of a laser to recharge it. Photonics can likewise be instrumental in finding ways to optimize consumption of non-renewable energy. For instance, fuel consumption can be maximized by utilizing photonics-based thermal insulation and diagnostics systems. Photonics technologies are also important in maintaining a safe and green environment. Optical systems, for example, can be used to analyze water, air and soil quality. Fibers can be employed to measure oil composition and in bridges or nuclear reactors to measure the structure of the building for safety purposes(Paranjpe, 2007). Solid state lighting such as LED can provide mercury-free lighting to illuminate homes without posing harm to the environment.

Figure 7: Self-Cleaning Solar Cell(Virtanen, 2017)

2.8 Photonics Application in Control Systems

Photonics technology is an instrumental concept in the development of advanced control systems for industrial automations(Vaškelis Tokyo, 2018). Optical control devices such as modulators, switches, and amplifier enable precise manipulation of light signals for controlling various processes and devices.

Photonics based control systems offer high speed, accuracy, and reliability in regulating industrial operations. They can be integrated with sensing and communication technologies to create intelligent automated systems which respond to changes in the environments and optimize system's performance(PhotonicsNL, 2023).



Microwave Photonic filter via Radio frequency bandwidth(Xu et al., 2018)

3.0 The Key Benefits of Photonics Technology

- **Speed:** Because photons travel at the fastest possible speed, light pulses are the perfect means of information transmission for applications that prioritize speed.
- **Bandwidth:** The properties of light, including as its wide frequency range, various wavelengths, low signal loss, and little interference, allow for the simultaneous transmission of enormous volumes of data.
- **Energy:** Systems based on photonics are usually particularly energy-efficient since there is less signal loss over long distances.
- **Size:** A variety of photonic components can be made extremely small, such as integrated circuits, waveguides, sensors, and micro-LEDs, to reduce the physical footprint of different technologies.

4.0 The Trends in Photonics

A wider range of functionalities, reduced energy consumption, and increased performance are becoming increasingly important requirements, which is driving the need for more complex systems that require dense integration of low-power operations. Because of this, the photonics engineering is driving innovation throughout the photonics landscape by promoting the creation of small, energy-efficient, integrated systems(Scholles et al., 2023).

4.1 Miniaturization: Numerous applications, like optical sensors, micro-projectors, and smartphone cameras, have stringent weight and size requirements. Similarly, small optical components are used in wearable electronics such as fitness trackers, smart glasses, and augmented reality headsets for displays, sensors, and communication. In biomedical systems like point-of-care diagnostics and medical imaging, miniature photonic systems play an equally important role. To analyze blood samples or find biomarkers, for example, lab-on-a-chip devices may incorporate optical components, making medical diagnostics portable and easily accessible(Richard, 2023).

4.2 Integrated circuits: A revolutionary wave of innovation is sweeping the photonic integrated circuit sector to keep up with our expanding data consumption habits. Co-packaged optics and optical interconnects are providing solutions that lower latency and increase bandwidth in response to the growing need for fast, energy-efficient data transfer inside data centers(Richard, 2023).

4.3 Artificial intelligence: The limits of processing power and data handling are being pushed by photonic computing and artificial intelligence (AI), with photonic chips providing quicker and more effective computations for challenging applications. Quantum photonics is one of these cutting-edge technologies that has promise for secure communication, quantum computing, and encryption(Radanliev, 2024).

5.0 The Three Main Challenges Facing Silicon Photonics Technology

Like any cutting-edge technical profession, silicon photonics has enduring problems that require workable answers. We're looking at these obstacles and investigating workarounds for them in this study. Generally speaking, there are three main challenges:

5.1 Getting light into the Photonic Integrated Circuit (PIC)
5.2 Getting light out of the PIC
5.3 Optimizing the performance of the PIC itself

Looking at each of these in turn, and describe what the difficulty is in each case, before outlining what companies in the industry are doing to address it.

The PIC needs to be exposed to light. Precise alignment and coupling between the on-chip waveguides and external light sources are required for this. Within this approach, coupling denotes the effective transfer of light energy between the PIC and the light source. When parts are oriented correctly, there is little loss of light energy during light coupling. Additionally, this lessens signal deterioration and makes the intended optical features possible.

It takes complex engineering to achieve the ideal light-load coupling in order to guarantee efficient energy transmission and reduce losses. There are several ways to couple light into the PIC, and these can be divided based on whether the laser is external to or on the PIC. Each of these was briefly covered below.

5.1 Getting light sources into the Photonic Integrated Circuit (PIC)

A light source can be coupled with the PIC via a variety of techniques, each with pros and cons of its own. Although they provide an efficient direct path for energy transfer, waveguides can lose energy due to radiation, absorption, and scattering(Kim & Darafsheh, 2020). Fabrication mistakes can affect taper (edge coupler) devices, which gradually minimize mode mismatch by narrowing the waveguide dimensions. Grating couplers are polarization-sensitive and have a narrow bandwidth when it comes to introducing light from free space into waveguides. With their emphasis on vertically stacked waveguides, vertical couplers pose comparable difficulties. Last but not least, Spot Size Converters optimize light coupling efficiency at a cheap cost by adjusting light beam sizes between waveguides; nevertheless, they have a narrow bandwidth and necessitate accurate alignment.

For each of these techniques to achieve good coupling efficiency into the PIC, a laser must be positioned externally to the PIC and precisely aligned with the coupling mechanism. This frequently entails many production and alignment processes that raise the final product cost(Trumper et al., 2018).

5.2 Getting Light out of the Photonic Integrated Circuit (PIC)

For integrated optical devices, it's also critical to effectively extract light from a Photonic Integrated Circuit (PIC). Several techniques allow for efficient light extraction from the semiconductor. To extract light from the PIC, many of the same techniques are used to inject it. Grating couplers, for instance, work well to steer light outward by diffracting it into empty space. The constrained waveguide mode is gradually expanded by taper, which makes it easier for light to smoothly couple to bigger structures.

Dust Photonics provided two ways to extract light from the PIC. One of them attaches the fiber directly to the PIC, while the other needs extra optics to guide the light into a fiber array (Trumper et al., 2018).

5.3 Optimizing the Performance of the Photonic Integrated Circuit (PIC) Itself:

A significant amount of work has gone into Process Development Kits (PDKs). These are standardized design toolkits that semiconductor or foundry firms offer. To develop and evaluate integrated circuits based on certain semiconductor technologies, such silicon photonics, researchers and engineers can use the fundamental building blocks, design guidelines, and simulation models that they provide.

Splitters, waveguides, modulators, photodetectors, and lasers are common parts of PICs. The development and enhancement of photonic integrated circuits are aided by these kits. As PDKs have developed over time, engineers and researchers have been able to create PICs with greater sophistication. However, the need for faster communications is increasing at a quicker pace, which is bringing silicon photonics technology closer to its fundamental constraints(Eindhoven, 2015).

6.0 Challenges and Limitations faced in the Adoption and Development of Photonics

a. Limited awareness and understanding of photonics technologies among general population and potential investors.

b. Lack of skilled manpower with expertise in photonics, leading to a shortage of qualified professionals in the industry.

c. Inadequate funding and financial support for research and development activities in the field of photonics.

d. Inefficient infrastructure and inadequate laboratory facilities hinders experimentation and testing of photonics technologies.

e. The absence of a supportive policy framework and regulatory environment specific to the photonics industry.

7.0 Conclusion

Photonic technologies are incredibly fascinating and may be found practically anywhere. It's getting harder and harder to envision living without photonics. The study of photonics greatly raises and improves human life quality. It safeguards our health in addition to ensuring that we eat good meals. Photonics drives business and economic growth without harming the environment. Ultimately, it is difficult to envision a secure future without the assistance of photonics technologies.

It is also impossible to imagine a future without photonics because it is a key enabling technology. It's true that photonics engineering has a very bright future, and the field's members are proud to have contributed significantly to the development of this intriguing, important, and necessary technology all over the world.

8.0 Recommendation

1. Advocacy and Awareness Campaigns: Educating people about photonics' potential through campaigns and educational programs can foster the development of a professional community in our Nations'.
2. Knowledge Sharing Platforms: Setting up online discussion boards, seminars, and conferences among other events can assist close the skills gap and encourage professional development amongst industry experts.
3. International Collaborations: By working with foreign organizations and institutions, Nigerian specialists in photonics might have access to cutting-edge resources, financing possibilities, and beneficial research networks.
4. Institution-Industry Partnerships: Forming solid alliances between educational establishments and business sectors can support funding and research possibilities while also facilitating the transfer of technology and expertise.

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