AEROSPACE

Content

EXECUTIVE SUMMARY

Introduction: In the aerospace market it is increasingly recognised that PICs are a technology offering a strong potential to improve performance of the existing aerospace system based on electronic or photonics solutions. PIC technology is likely to become an enabler of new market applications and verticals such as embedded structural health monitoring, free space optical (FSO) links, on-board connectivity or remote sensing. Aerospace applications are continually seeking stringent improvements in size, weight, and power (SWaP) along with improved reliability, which the reduced component count and size of ASPICs are capable of delivering performance gains. Unlike other markets such as data-centres, aerospace applications are capable of paying a premium to attain these improvements, making the aerospace market an ideal market for early adoption of PICs for commercial applications.

Aerospace covers a broad spectrum of photonics applications, in particular Telecom, Datacom and Sensing applications, which cover many of the application sub-catagories mentioned throughout the IPSR-I roadmap.

Current status: PICs are being actively adopted for numerous aerospace Sensing and Datacom applications. There is also increasing industrial aerospace research and development as demonstrated by the growth in the number of aerospace PIC patent applications.

Both ESA, NASA and governmental space agencies across the globe continue to be actively investing in the developments of core PIC technology development with numerous programs. ESA's photonics roadmap outlines its expectation for the European satellite primes (Airbus, OHB, Thales Alenia Space) to be offering a demonstrator for PIC based photonics solutions and it is expected that PICs will be the adopted "standard" over the decade 2020-2030.

Main challenge: For increased growth in the adoption of PICs in Aerospace the main challenges are typically related to cost, power consumtion and performance. All of them can be addressed by improving foundry process capability, packaging, and the high reliability qualification standards. Performance metrics of aerospace products typically have stringent tolerances, and a lack of mature supply chains with large variation in expected performance or process capability is slowing the product development cycle and adoption of PICs.

Needs: In the near term the aerospace market seeks improvements in the core technology readiness level of existing PIC capabilities, focusing on improving the reliability to deliver predictable photonics performance throughout the supply chain. Longer term developments are typically looking for greater improvements in power usage, which may be attained by either better hybrid combinations of PIC platforms or increased monolithic integration of electronics and photonics.

Needs < 5 years

- Reduced Foundry process variance
- Qualified packaging for harsh environemnts
- Qualified PIC and associated electronics, e.g. drviers and TIAs
- Reduced DC power consumption
- Improved SOA efficiency
- Improved laser efficiency

Needs 5-10 years

- Improvement in temperature control
- Novel packaging (removal of "gold box")
- Broadband and linear components

Needs 10-20 years

- Use of uncooled PICs
- Less than 5 mW/Gbps for fibre optical links

INTRODUCTION

The aerospace industry encompasses the human effort in science, engineering and business to fly in the atmosphere of Earth (aeronautics) and surrounding space (astronautics). Aerospace organizations research, design, manufacture, operate, or maintain aircraft and/or spacecraft. Aerospace activity is very diverse, with a multitude of commercial, industrial and military applications.

Along with public space programs, many companies produce technical tools and components such as aircraft, spaceships, and satellites. Some well-known companies involved in aerospace programs include Airbus, Thales Alenia Space, Boeing, Lockheed Martin, MacDonald Dettwiler, Northrop Grumman, Amazon and SpaceX. This chapter focuses on the European aerospace industry that develops and manufactures civil and military aircrafts, spacecrafts, helicopters, drones, aero-engines, satellites, space probes, and other systems and equipment. The industry also includes companies that provide support services such as maintenance and training.

Within aerospace, aeronautics can be of greater economic interest than astronautics, for space drives qualification and performance reliability of aeronautic systems, including spinoff from space developments. In general, aeronautics is one of the EU's key high-tech sectors in the global marketplace. During 2015 more than 2,000 aeronautics, space, and defense companies in Europe employed more than 750,000 people and generated a turnover of close to \$170 billion. The industry is highly concentrated in terms of the few large enterprises involved EU-countries. Employment in the European aerospace sector is particularly significant in the United Kingdom, France, Germany, Italy, Poland, Spain, and Sweden.

SITUATION ANALYSIS

KEY DRIVERS: COST, PERFORMANCE, SIZE, MARKET

Five main trends impact industries in the global manufacturing sector. These key drivers are (1) growing market demand, (2) supply costs, and (3) technology and innovation to address cost, performance and size, as well as (4) business risk and (5) policy regulation. Commercial aerospace is roughly a \$300 billion global industry.

The opportunities for photonics in aerospace focus on lower volume applications which represent a medium sized opportunity for integrated photonic technology since it is less cost sensitive compared to many other market opportunities.

Several trends impact the aeronautics market. Combined, these trends depict a gradual shift of the global aerospace manufacturing footprint toward the Asia-Pacific region. Such shift will serve growing local demand and respond to local government action that seeks to exploit a cyclical upturn in demand to attract investment in local manufacturing. Given the five- to seven-year time investment to build up manufacturing capacity, the "nationally important" status of the industry, and the risks that players involved face in intellectual property, quality certification, and collaboration in both product development and manufacturing, these shifts in the aerospace footprint may continue to lag behind the footprint shifts of other manufacturing industries.

Technological leadership and innovation are becoming the major competitive differentiators, most notably in terms of costs, energy, and environmental performance. The market demands shorter cycles of new technology integration. In addition, competitors enter the market with an aggressive approach on prices. Recent studies[1] forecast that in 2050, innovative products and services demanded by the market will be based on state-of-the-art design, manufacturing and certification processes as well as support tools with a significant reduction of the environmental impact as well as the development, manufacture, and in-service costs. The development and deployment of new structural technologies may have the greatest impact on the reduction of weight and operational costs of aircraft compared with other technologies for several aircraft configurations.

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[1] ACARE SRIA for 2020-2050.

IDENTIFYING PARADIGM SHIFTS AND POTENTIAL MARKET OPPORTUNITIES

Integrated Photonics as a solution platform is breaking through in aerospace. With the arrival of smart innovations that allow optical chips to be integrated efficiently into actual commercial aerospace products, an increasingly growing range of applications is emerging. New solutions for harsh environments that could not be achieved before by using conventional techniques are becoming viable. Stringent requirements about size, weight, and power (SwaP), footprint, and high reliability through dedicated thermal and mechanical control can now be realized using integrated photonics technology. New smart materials and innovative technologies are essential towards overall cost reduction of air travel by addressing aircraft weight and operational costs.

Integrated Photonic Circuits (PIC)-technology is key to achieving these objectives. One of the arising market opportunities for PICs is the integration of dedicated sensing solutions toward Structural Health Monitoring by enabling significant in-service inspection costs reduction. Aspects like damage and impact detection; shape sensing of morphing structures; structural load monitoring; multi-parameter sensing of temperature, humidity, pressure, and other parameters; and multi-point based distributed sensing can be realized efficiently now without structural and operational impact with PIC based optical fiber technology for high performance sensing and Datacom. As of today, this promising outlook to the future is available now and the answer to the growing needs in aerospace.

Another interest for aerospace applications is to make use of highly reliable fiber optics for Telecom and Datacom. The compatibility of PIC-components for data communication and fiber optic signal processing and distribution enables the full integration of their functionalities on a single chip. The trend toward miniaturization, by combining the required features into a single-PIC design is enabled by circuit simulators for photonic integrated circuits such as ASPIC. ASPIC modules can have peer-to-peer capability, leading to reliability. These features for instance comprise integration of data transfer through known ASPIC functionality, spectral separation of a light source specifically for Sensing or Datacom, and the ability to do time-interleaved sensing through multiple fiber optic channels using PIC based optical switching, subsequently providing redundancy.

Integrated Photonics is destined to play a major role in many future applications spread to various applications in aeronautic markets.

APPLICATION EXAMPLES

Three promising application examples of PIC in AeroSpace are:

- **Communication**
  - Intra-platform communication (within an airplane or satellite platform)
    - Microwave Photonics
      - generation , detection and processing (filtering, beamforming, switching etc.) of RF signals in the frequency range between S-band to W-band
    - High Speed Digital links
      - Transceiver and fiber connectivity (high data rate up to 112 Gb/s)
  - Inter-platform communication (between airplines, satellites and HAPS)
    - QKD
    - Optical Inter-satellite links
      - High-power, high-efficiency optical amplifiers
      - High sensitivity detectors and transmitters for hundreds Gbps links
      - Optical beamformer

- **Sensing**
  - Intra-platform fiber based sensing
    - Structural monitoring,
    - Damage detection,
    - Shape monitoring, and
    - Extreme loading conditions.
  - Remote sensing
    - LIDAR

COMMUNICATION

Optical communication is the exploding technology for terrestrial usages where our daily life is highly depenedent on it. High speed Internet is only possible with fiber optic technology where the core is optical components (Laser, modulator, amplifier, fiber and photodetector). The same concept is applied for the Aerospace applications. The communication satellites are providing internet, TV broadcasting to the ground users. The demand for high connectivity for 5G is counting on the satellite network together with the ground fiber network. Here some of these applications (functions) are briefly introduced. One example of such high throughput payload is shown in Figure 1:

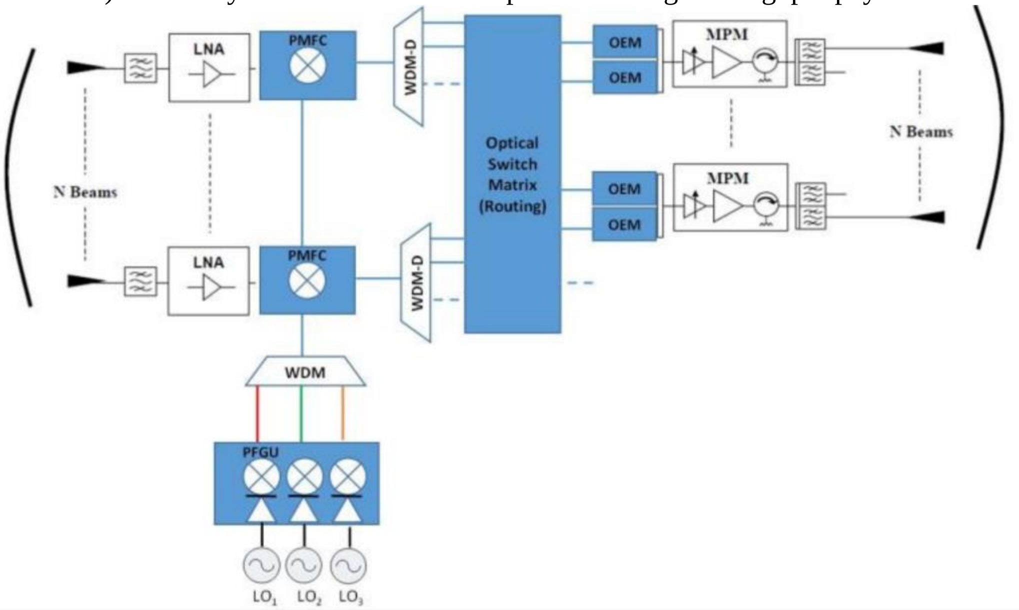

Figure 1: Simplified Payload Block Diagram Using Photonic Equipment [1[2]]

FREQUENCY CONVERSION:

Down/up conversion is the necessary part of most communication satellites, enabling a high degree of flexibility and functionality. Down-converters translate an incoming uplink RF and microwave signals to a lower intermediate frequency that can be sent to an analog-to-digital converter (ADC) for further processing. For the downlink data transmission, the analog chain of the transmitter up-converts the IF signal to the desired RF carrier. This frequency conversion greatly simplifies the ADC and DAC architectures and lowers the power consumption.

Frequency mixers are commonly used for down/up conversion, although the function can also be performed with a sampling structure. This latter approach allows the ADC clock to serve as a system LO, greatly simplifying the RF frontend architecture. Sampling downconversion can be performed in a single step rather than the multiple mixers and LOs needed (depending on the input frequency) in some superheterodyne receivers. The same mechanism can

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[2] J. Anzalchi, "Towards Demonstration of Photonic Payload for Telecom Satellites" ICSO, 2018.

be applied to up conversion concept with a symmetrical design architecture. In addition, a broadband sampler enables the satellite to be more flexible in term of bit rate and also carrier frequency selection. However the problem with this high speed samplers in comparison with a passive mixer is their power consumption. Schematic of a communication satellite payload receiving front-end is shown in Figure 2. Frequency generation and conversion (Electro-Optical Frequency Conversion (EPFC)) units are presented.

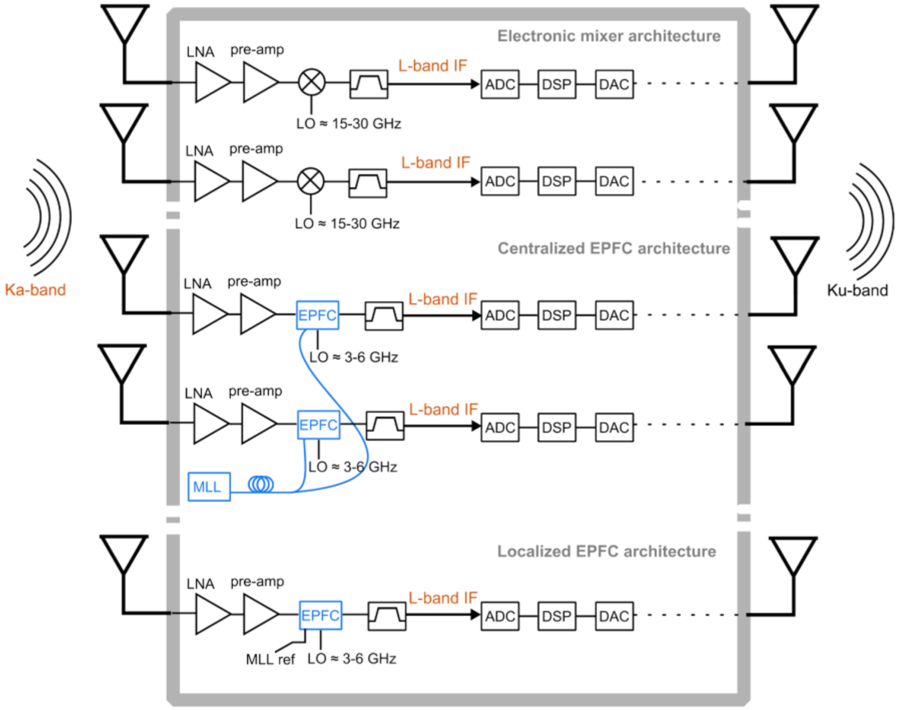

Figure 2: Schematic of Communication satellite payload [[3]2]

FREQUENCY GENERATION:

For the Space application, tunable and low phase noise LO signal generation is highly desired. This LO could be used in the frequency felexible satellite. Optical technology based LO generation has been studied in the past decades. Several examples of RF signal generations have been demonstrated in the past both based on fiber optics as well as PICs. RF signals are generated using heterodyne process inside the broadband photodiode. The coherent optical tones can be generated using two phase lock lasers, optical frequency combs or opto-electronic oscillators. The greatest advantage of using optical heterodying for RF signal generation is the excessive tuneability, however the frequency stability and spectral purity of such generated RF signals need to be controlled. In turn, this creates a need for an optical source with reduced sensitivity to temperature changes.

OPTICAL SWITCH MATRIX:

The optical switch is at the core of the photonic payload. It enables the routing of signals from any input port to any output port providing a high flexibility to the payload which is not digitally processed. It is fully transparent and can handle 1.55 µm signals independently of their wavelengths, intensity and modulations.

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[3] K. V. Gasse, "*Ka-band to L-band frequency downconversion based on III–V-on-silicon photonic integrated circuits", CEAS 2017.*

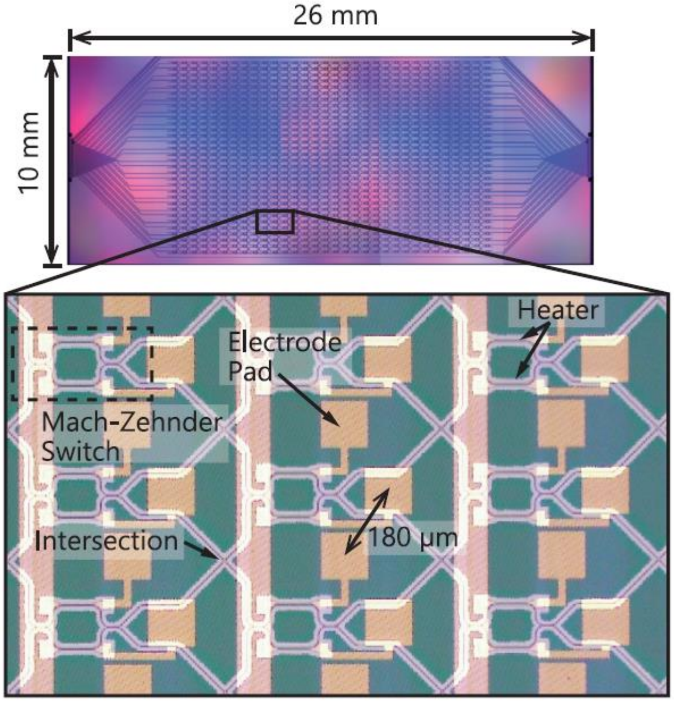

Figure 3: PIC based 32x32 Si Switch matrix [3][4]

OPTICAL INTER-SATELLITE LINKS (O-ISL)

Optical ISLs offer a very attractive solution for intersatellite links providing multi gigabit per second data rate capabilities. In addition, optical communication links offer high operational security and immunity to interference sources while benefitting of a non-regulated optical frequency spectrum. Different scenarios have been envisioned so far for the O-ISL: LEO constellation, GEO-GEO link, UAV/LEO-GEO link, etc.

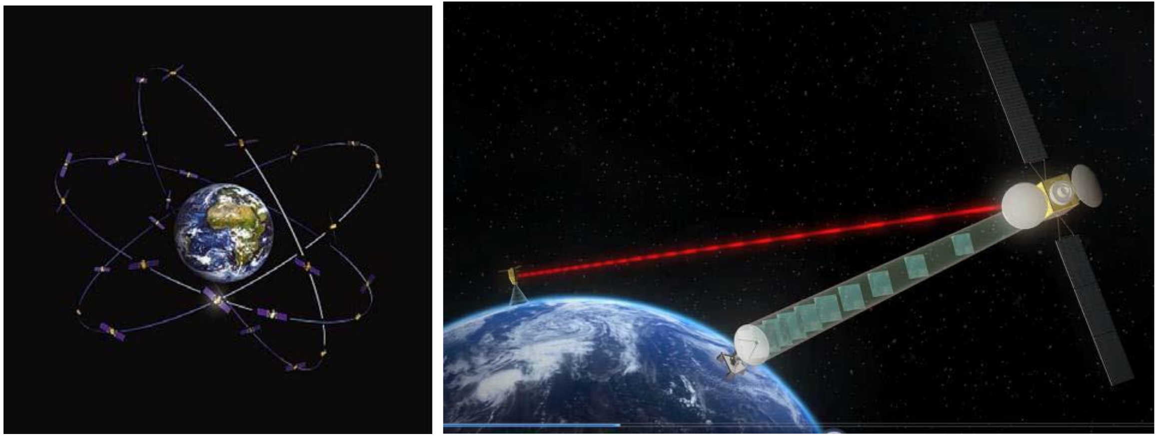

Figure 4: Galileo satellite constellation with 24 active satellite in a Walker constellation (left), LEO/UAV to GEO optical link (right) [TESAT].

These high throughput links with aggregate data rate of up to 100s Gb/s, provides a compactness, low mass, low power approach which is beneficial for the launch phase as well as operational phase. It can potentially save power consumption due to:

- Multiple lasers can be integrated in a single die with a single TEC.

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[4] K. Suzuki, "Low-Insertion-Loss and Power-Efficient 32 × 32 Silicon Photonics Switch With Extremely High-Δ Silica PLC Connector"

- Amplification of wavelength multiplexed system limits the number of HPOAs.
- Low loss integration (monolithic on-chip waveguide link) reduces the need for high power lasers.

LIDAR

The IPSR-I Automotive Product Emulator contains a significant discussion on Lidar and other integrated photonic technologies for Automotive applications. In contrasting the application needs between these two similar markets, one discovers guidance as to the short- and long-term business opportunities in each market. In the Automotive market low cost and correct detection under a vast array of visual and weather conditions is essential. In the aeronautical market there are fewer threats to detect because of existing sources of information and the cost requirements are significantly relaxed. However, false results cannot be tolerated. Thus, it is anticipated that the penetration of Lidar market initially will be greater in aeronautical markets. The penetration will be slower in the automotive applications, but the value of the Automotive Lidar market will quickly exceed the aeronautical market.[5]

STRUCTURAL MONITORING

One major ambition in aeronautics and aerospace where PIC technology can play a significant role is Structural Health Monitoring (SHM) that aims to give, at every moment during the life of a structure, a diagnosis of the "state" of the constituent materials, of the different parts, and of the full assembly of these parts constituting the structure. A much-used technology is sensing by Fiber Bragg Grating (FBG)-technology in which strain in optical fibers can be measured accurately. The principle of SHM to aircraft structures can be compared to a human nervous system.

Aerospace calls for SHM capabilities in damage and impact detection, localization and identification, shape monitoring of morphing aircraft structures, high resolution distributed sensing of extreme dynamic load assessments of complex structures. The ability to combine a versatility of measurement capabilities proves an incredible appearance of applications that become possible that could not be addressed by conventional techniques.

DAMAGE DETECTION

Damage detection is a major challenge in the aviation industry, with respect to the use of composite materials in aircraft structures. As composite materials prove to be more cost effective for structures, they also exhibit damage effects that require new perspectives for detection. Delamination effects and debonding of stringer run outs are examples that barely are visible but need non-destructive testing (NDT) techniques in aircraft-on-ground (AOG) situations for assessment of the damage. The use of optical fiber sensors and the right detection and analysis approaches will be able to resolve this need in an economically viable fashion. In general, there are four consecutive levels of damage identified and associated with increasing complexity:

- Determination that damage is present in the structure,
- Determination of the location of the damage,
- Quantification of the severity of the damage, and
- Prediction of the remaining service life of the structure.

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[5] The Lidar section of the Automotive Product Emulator provides a more detailed discussion of potential applications.

SHAPE MONITORING

Conformal morphing is a new technology area for the aircraft industry. The ability of aircraft structures (wings) to change shape during flight will increase flight efficiency, and thus are of interest to the aircraft industry. Morphing wings do pose obvious challenges; one of them is to optimize the configuration of sensors and actuators for a reliable control system. A mechanical transducing device with integrated Fiber Bragg Grating (FBG) sensors can be applied to translate shape information into strain information. Using specific mathematics, these strain values are converted back into an accurate approximation of the shape.

EXTREME LOADING CONDITIONS

For extreme dynamic loading conditions, novel material characterization and *in situ* measurement techniques are developed, including material models and simulation methods for design and manufacture of aerospace composite structures, leading to a significant reduction of weight, design, and certification costs. These initiatives include the development of smart impact sensing techniques for extreme loading conditions. Their purpose is to detect and assess extreme dynamic events and their subsequent related effects, as well as determination of failure parameters leading to new material models.

ENVIRONMENTAL ISSUES

Current and future aircraft structures require high specific properties and integration of multiple functionalities to improve weight, fuel efficiency, reduce CO_2-emissions, and reduce component complexity and manufacturing/certification costs. Evaluating and certifying these new material technologies will require the utilization of the integrated photonic technologies enumerated in the previous section.

PRIORITIZED TECHNOLOGY REQUIREMENTS AND TRENDS FOR AVIATION APPLICATIONS

An increasing number of European patent application reflects the sizeable share of value added that is being spent on research and development (R&D). Against the background already discussed, composite materials technology is of fundamental importance to current and future aircraft structures where high specific properties and integration of multiple functionalities are essential to improve weight and fuel efficiency, and reduce CO_2-emissions, component complexity and manufacturing/certification costs.

The vulnerability of composite structures to localized, dynamic, sudden, unexpected, and extreme loads, such as foreign object damage, may result in unpredictable complex localized damage and a loss of post-impact residual strength. To fully exploit these materials in a timely and cost-efficient manner, there is a stringent need for the aeronautical industry to develop tools to confidently design, test, and manufacture composite structures, able to resist extreme dynamic loadings alongside improvement in smart sensing, inspection and maintenance techniques. Many EU projects[6] are exemplary toward meeting identified challenges:

- The European aviation industry must have the capacity to deliver the best products and services in a time and cost-efficient manner and to offer new and innovative products, vehicles and services, with improved environmental performance.
- Development of technologies and methodologies that have the potential to save costs and time across the whole life cycle of the aircraft-design, production, maintenance, overhaul, repair and retrofit, as well as certification--is a critical need.

The ambitions appear to focus on physical integration of smart intelligent structural concepts. They address aircraft weight and operational cost reductions, as well as an improvement in the flight profile's specific aerodynamic

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[6] Horizon2020, Clean Sky

performance. This challenge concerns material concepts enabling both a conformal, controlled distortion of aerodynamically important surfaces and an active or passive status assessment of specific airframe areas with respect to shape, potential damages, and material concepts.

DEVELOPMENT AND PACKAGING OF OPTICAL CHIPS

Although operational reliability is important for the practical commercial implementation of the technology, equally important factors are on-time delivery and reliable packaging of PIC-based devices. Achieving reliability requires consolidation of the supply chain that is focused on delivery of state-of-the-art technology and not on academic progress. Such supply chain collaboration eventually must lead to fast, efficient, and qualified PICs. Integrated Photonics foundry services are emerging as well as design houses to support commercialization.

Packaging requirements are application dependent, and in many cases the costs and efforts associated with proper packaging are underestimated. Packaging is usually forgotten until the PIC is manufactured, an oversight that likely results in a non-optimal working device, or an even impossible to package PIC. A PIC needs to be packaged and, as much as possible, thermally, mechanically and/or EMI isolated from the environment but still allow electronic interfacing or data processing without affecting the optical system performance. The electrical RF interface of the PIC package, which for some aerospace application will require operation up to W-band, still remains to be a challange. To connect the PIC properly to the world, certain considerations and restrictions should be included. One of the major challenges relates to photonics sensitivity to temperature changes, which for aerospace systems can vary between -20 to +85 degree C (application dependent). Heat sources have different origins and need to be dealt with in different ways. The first source is the surrounding atmosphere, including nearby heat sources; e.g., electronics and power sources; but also, chip devices can be the cause and even wire bonds' placements can have effects. The most common solution to reduce the effect of slow and fast variations in the surrounding temperature is by using a thermoelectric cooler (TEC) that typically enables a stable temperature operation window of about 70°C. The heat dissipation from the PIC package will remain very specific for space applications due to the unique thermal and vacuum environment.

Many of the aspects involved in PIC packaging relate to the operational environments. Sealing techniques differ from vacuum to humid environments, more specific thermal management and tricks to deal with heat leaks, the ability to package multiple chips each with their own properties and sensitivities, and the inclusion of front-end electronics for signal-to-noise reductions. Commercialization needs a call for standardization as a baseline; i.e., packaging rules and subsequently PIC design rules. Most markets have their regulations in which part of these requirements are described; still even for these markets, application specific requirements remain. Often very limited information exists to date on the behavior of PIC under these conditions and the special effects of long-term operation under specific conditions.

CONCLUSIONS

The Aerospace market offers an opportunity for the introduction of PIC technology into a number of well-structured sensing and data communications applications. These applications do not have hypercritical cost points and therefore represent an opportunity for market penetration and growth.

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