3D SENSING - LIDAR

INTRODUCTION AND EXECUTIVE SUMMARY

The markets for LiDARs are rapidly growing, and integrated photonics is well positioned to provides the LiDAR solutions of the future achieving significant penetration in these markets. The reader should be aware of the disparities in the markets makes the production of a roadmap for LiDAR challenging. The main market in terms of volume is still seen as the automotive but the specifications required by such a market are the most demanding.

To obtain a final document that is of manageable size and useful, we have chosen to focus on the LiDAR architecture where photonics is the key enabling technology namely the FMCW type of LiDAR and the different implementation of such architecture in the SiPh, SiN and IIIV.

With these caveats in mind, the Purple Brick Wall charts for PIC based LiDAR sensing show either the existence of, or the projected development of various components required for the sensing industry across a timeline until 2040. The black font text shows what is reasonably expected based on current efforts, and the red font text highlights components that require major funding/research to bring to commercialization due either to a technology (design, material, process etc.) barrier or a cost barrier. What separates the red text from the black text are gaps in technology represented by purple bricks, and hence the name purple brick wall. Development to fill these major technology gaps may not be funded by industry, which often seeks a quick return on investment (ROI). As an alternative, these gaps should be used to generate potential research topics for government funding highlighting new science which promises that a breakthrough is possible and imminent.

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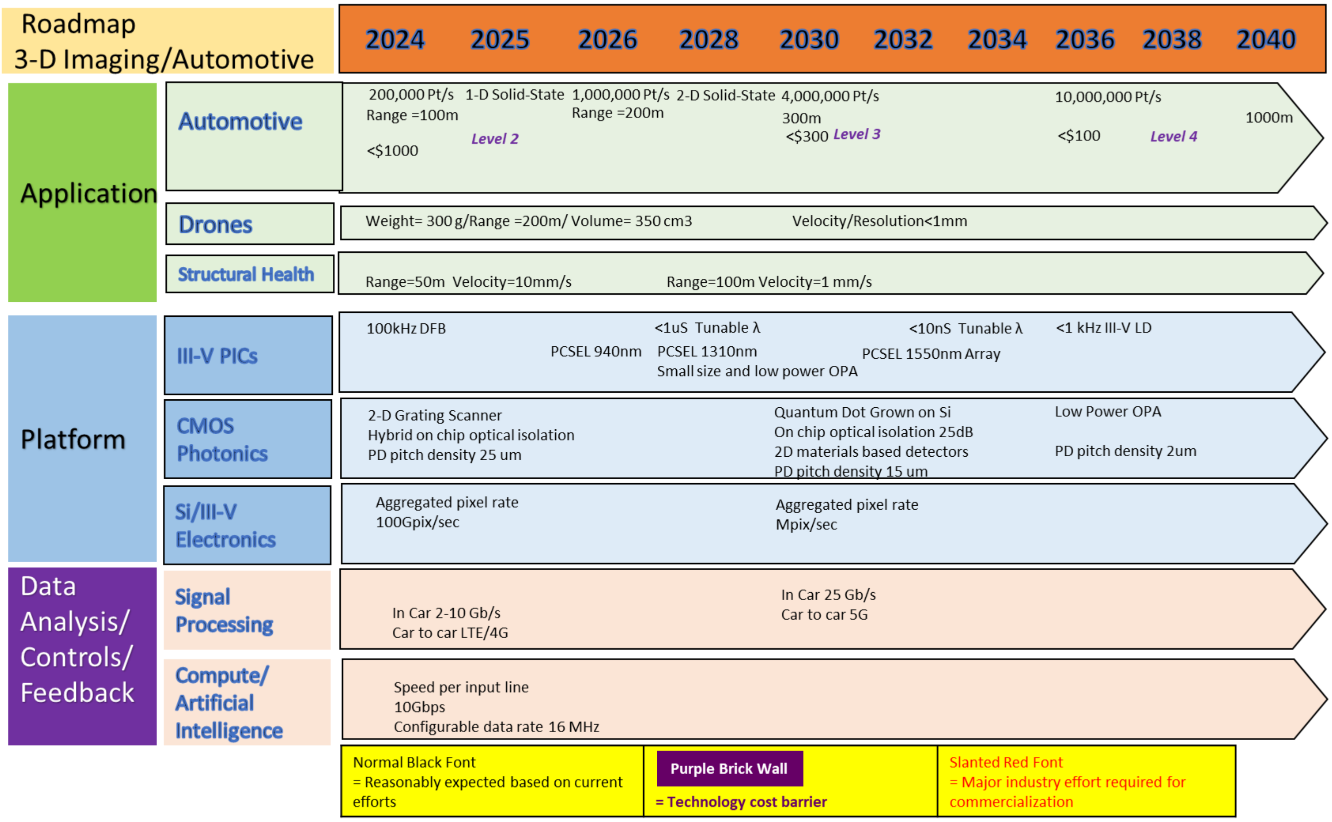


Figure 1: Purple Brick Wall for 3D Sensing and Lidar

The goal of the IPRS-I road mapping work it to address fundamental road blocks in technology to achieve the required goals in different market segments. The role of photonic integration in the success of 3-D sensing products and the advantages provided by integration are key drivers. It is further believed that PIC based LiDAR solutions will be a leading market.

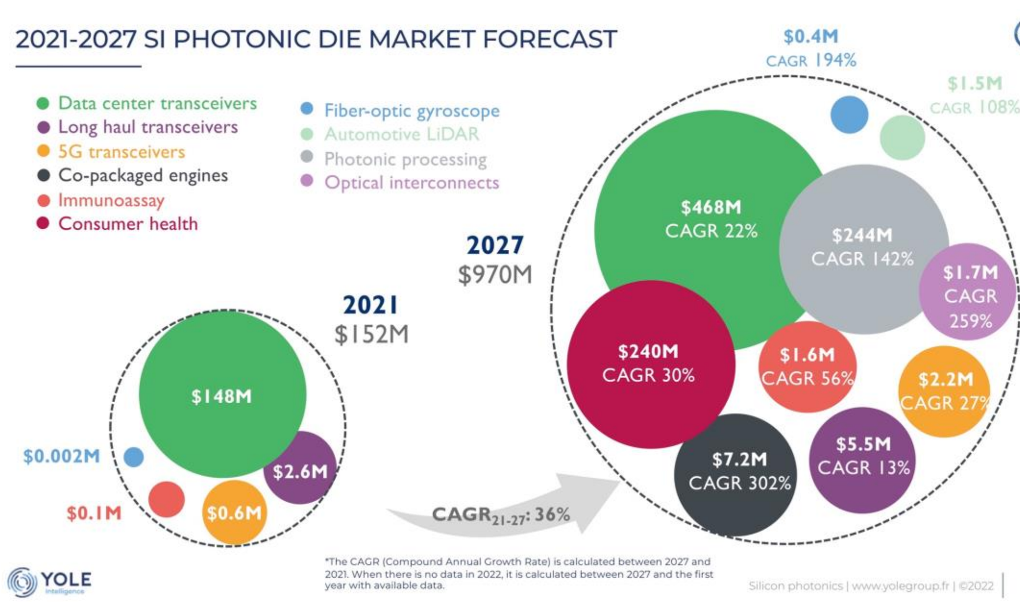


Figure 2: Silicon Photonics Market Forecast

Technology needs

Several integration technologies exist to tackle LiDAR and 3-D sensing markets. The fundamental approach that is best suited is the integration of the photonics functions onto a single chip. There are three main technology approaches that are available today:

- Silicon Photonics Integration
- Dielectric Photonic Integration
- III-V Semiconductor Integration

The emergence of Dielectric Photonics integration is a technology approach that is based purely on Silicon Nitride or Silicon OxyNitride deposition process to enable integrated circuits. The advantages of SiN/SiON over silicon waveguides are three-fold:

- Lower Insertion loss
- High Power Handling
- Low waveguide loss

The key point to note is that SiN is used as a waveguide technology in silicon photonics foundries, but always in conjunction with Silicon waveguides for the electronic switch elements. Whereas pure dielectric integration utilizes switch within the Planar Lightwave Circuit (PLC) of the dielectric element, in a similar fashion to Silicon.

Photonic Integrated Circuits

The concept of integrated photonic circuits (PICs) is similar with integrated electronics. Many different functionalities such as light generation, detection and manipulation can be produced during a single process flow. In integrated photonic circuits these functionalities are: coherent light generation, detection, modulation, guidance, phase and polarization control. The building blocks supporting those manipulations are presented on Fig. 3.

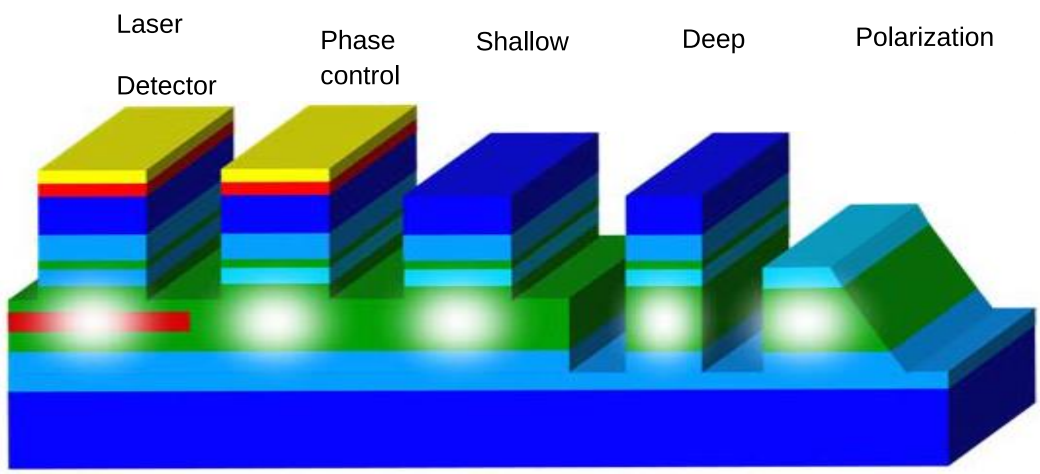


Figure 3: Schematic cross-section of the basic building blocks in a generic process.

Typically, all essential photonic devices can be put on a single chip. Various lasers such as tunable, DFB, DBR lasers, high speed modulators and photodetectors, waveguiding devices such as splitters, (de)multiplexers, wavelength selective devices and various reflectors.

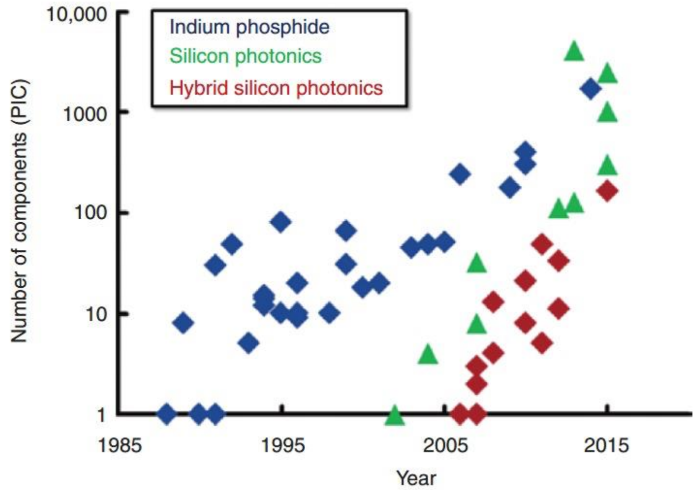
III-V Devices

Photonic integrated circuits are rapidly advancing in the field of LiDAR. Photonic integrated technologies, such as silicon/nitride photonics and indium phosphide-based devices, are enabling the creation of compact and efficient LiDAR systems with higher performance and lower power consumption. These technologies allow for the integration of multiple optical components, such as lasers, modulators, detectors, and waveguides, onto a single chip, which reduces the size and complexity of LiDAR systems. Moreover, the use of silicon photonics in LiDAR is particularly attractive because of its compatibility with existing semiconductor manufacturing processes, which can result in lower costs and faster time-to-market. As photonic integrated technologies continue to advance, the development of high-performance and cost-effective LiDAR systems is expected to accelerate, leading to a wider range of LiDAR applications in various industries, including autonomous vehicles, robotics, and environmental monitoring.

This technology already successfully exists on the market last two decades. Integrated photonics occupies a significant niche in already established markets such as tele and data communication. Many companies, who have their own established fabs, are selling complex and reliable circuits such as coherent transceivers for a long reach communications. There are several different PIC technologies on the market which try to improve parameters such as size, weight and power (SWaP).

PICs for LiDAR can be produced using various technologies exploiting different materials depending on a target applications. Polymer and Silicon Nitride PICs are mostly used where low optical loss is critical, such as quantum applications. Silicon PICs exploit high index contrast and can deliver PICs with the smallest footprint per device available at the market. Apart from that silicon leverages established processes from mature electronics industry, where old fabs can be used which are outdated for modern electronic chips. Thanks to a large throughput of electronics fabs, Silicon PICs can supply the demand, which is needed for datacom communications, however, due to an indirect bandgap, light source can't be put directly on the silicon chip. This technology use Indium Phosphide to supply a laser source and thus, extra mechanical assembly is necessary. Indium Phosphide technology has advantage of having a light source together with other photonic components on chip and full integration can be accomplished without mechanical assembly. This technology found a wide applications in telecommunications where high data rates (up to 2.4 Tb/s) need to be transmitted. All those technologies are already existing for communication market and continue its development towards large volumes and low cost for potential high threshold entry markets such as LiDAR.

There been a lot of developments in recent years regarding combining these two technologies via heterogeneous integration. Figure 4 show a rapid growth of these circuits after demonstration of heterogeneously integrated laser on silicon by John Bowers (UCSB) in 2006.



M. Heck, "Highly integrated optical phased arrays: photonic integrated circuits for optical beam shaping and beam steering", Nanophotonics 2017, 6(1)

Figure 4: Distribution of materials systems for photonoics applications

The main challenge to define the roadmap for heterogeneous integration is to understand which approach is more feasible: to build to separate fabs for silicon and III-V and combine them together via transfer printing or introducing III-V to a CMOS fab which can bring extra contamination and complicate the process which, in turn, increases the cost of PICs.

There are a lot of developments on III-V roadmap regarding its application in LiDAR. Open access fabs are looking into high speed and high power platforms, utilizing undoped III-V substrates and improved modal gain within quantum well systems, respectively. Undoped substrate will enable better RF performance which will enable >50GHz modulators for faster scanning. At the same time, high power platform with improved efficiency will allow less power consumption and high optical output power which is one of the key parameters for LiDAR. Apart from that, the control and stability of laser operation is required, which brings the need to develop an uncooled laser which sinks heat directly to a packaging module without introducing Peltier thermoelectric control.

All of these developments making PICs are favorable for ADAS and other sensing applications.

LiDAR Technologies

There are several different approach for LiDAR in the automotive space.

- Time of Flight (ToF)
- Phase Shift
- Digital Modulated
- Frequency Modulated Continuous Wave (FMCW)

The main one where a PIC based approach can be implemented is the FMCW technologie. In this technology the LiDAR modules are composed of a/or multiples laser sources and a/multiple receivers (of course the optics required to adjust the Field Of View for example plays also a key role but we will limit ourselves in the following to the PICs composing the LiDAR modules).

Scanning consideration

While FMCW provides a large number of advantages (immunity to interference, heterodyne detection) there is need to collect a large number of points. If producing arrays collecting like for SPAD cameras a full point cloud remains the target of the different companies aiming at on chip LiDAR most of them still rely on scanning.

The scanning operation is important for LiDAR from a points per second, precision, stability and reliability requirement. There are multiple scanning technologies that can be utilized to enable a large number of points/second. These include:

- Mechanical
  - Galvo Scanners (1-D and 2-D)
  - Polygon Scanners
  - Rotary Wedge Scanners
  - Risely Scanner
- Fiber Scanners
- Holographic
- MEMs Mirrors (1-D and 2-D)
- Grating Couplers
- Liquid Crystal
- Meta Material
- Tunable Lens Scanners
- Optical Phase Array (III-V or Silicon)
- Silicon Photonic Switch Array
- Switched Laser Array and Detector Array

There are distinct advantages and disadvantages to each of these scanning approaches. Each also has a different level of maturity in terms of deployment and development, which must be considered when looking at Automotive applications

The steering/scanning strategy is also critically important when deciding on the scanner approach. There are multiple options in terms of scanning algorithm. A simply summary is provided below:

Table 1: Pros and Cons of different Scan Algorithms

Method	Advantage	Dis-advantage
Beam Switching	Precise, Fast	Limited no. of points
Linear Scan	Large Field of View Large Scan Aperture	Limit on Frame Rate Dead Time
Meander Scan	Good Angular Resolution	Limited Speed/Frame Rate
Lissajous Scan	Easy to Adapt	Resonant Scanning only Inhomogeneous coverage
Conical Scan	Precise, Fast	Only a circle
Palmer Scan	Precise, Fast	Speed
Spiral Scan	Highest Resolution at center	Non Uniformity of Field of View
Rosetta Scan	Highest Resolution at center	Non Uniformity of Field of
Free Addressable Beams	Full degree of Freedom	Precision and Speed

For Automotive applications the key requirements for the scanner are:

- Field of View (FOV)
- Aperture
- Size
- Weight
- Repeatability

Beyond the scanning there are different types of LiDAR technology that can be implemented.

Silicon Photonics LiDAR

Silicon Photonics offers the to integrate LiDAR on a chip. There are different fundamental building blocks that can be utilized to provide 2-D and 1-D solutions.

Silicon photonics has several potential advantages as a LiDAR solution because of the current maturity of processes and the integration of both detection and laser emission that can be integrated into a single chip. The band gap of silicon means that the LiDAR wavelength is constrained to emitters with wavelength greater than 1100nm. This limits the emitter technology to InP based laser emitters or III-V integrated device which produce emission below the band edge of the silicon waveguide.

The distinct advantage that can be observed is the ability to produce a solid-state scanning approach by switching between optical emitters and receivers fabricated into the die.

For coherent LiDAR detection systems, the optical layout, local oscillator and emission-receive port can be easily fabricated on an 8” silicon wafer process. The detectors, analogue circuits and electrical connections can be integrated in addition.

An example of a 1-D and 2-D 32 emitter solid state scanner are shown below in Figure 5:

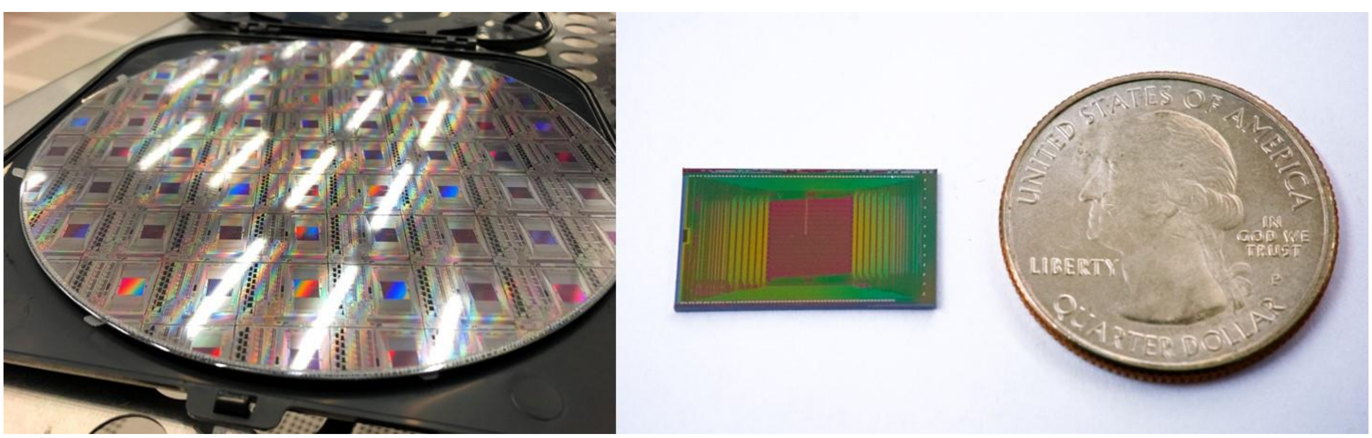


Figure 5: Solid State Scanner produced in a Silicon Foundry (Source: Voyant Photonics Inc.)

The key components in this approach are:

- Lasers
- Detectors
- Switches
- Grating Emitters

The 2-D and 1-D optical silicon emitters can easily be coupled into optical lenses to provide essentially a Camera LiDAR sensor.

Emitter Technology for Silicon Photonics

The laser emitter technology for silicon photonics can be:

- Discrete Laser
- Hybrid
- Integrated

As Silicon is an indirect bandgap material, then it does not emit light and is the principle “achilles heel” of the silicon photonics technology.

For the last 25 years researchers have developed alternative approaches to “integrate” the light source into a silicon fab. The most successful approach today is based on the work of John Bowers at the University of Santa Barbara, where development of a “wafer bonded” epitaxial hybrid laser was developed. This work in conjunction with INTEL has been the most successful implementation of lasers directly onto silicon for integration in the fab. The principle development of this technology has pushed the industry to establish Silicon Photonics as a commercial approach for photonic integration with both scale and cost. The proprietary process is only recently being pushed into a generic foundry model. Competitors to the the space include OpenLight (Juniper spin out) and Skorpios. Both companies offer an integrated laser approach similar in concept to the Intel production process today.

Several alternative approaches for the integration of the light source with silicon photonics, do still remain and we will discuss these briefly in the next sections. These approaches are currently important as LiDAR moves to a Coherent LiDAR implementation. The principle reason for this is the lack of optical isolation with the hybrid Silicon laser and issue of coherence collapse that can occur without optical isolation to the laser gain section.

Discrete Laser

Figure 6: TO-56 style Laser assembly (Source: Voyant Photonics)

Hybrid Flip Chip Laser

An alternative to fiber coupled laser devices to the silicon photonics chip is to use a hybrid integration strategy. This has been an approach that has been established utilizing a flip chip technology approach. This approach takes advantage of the established laser technology in

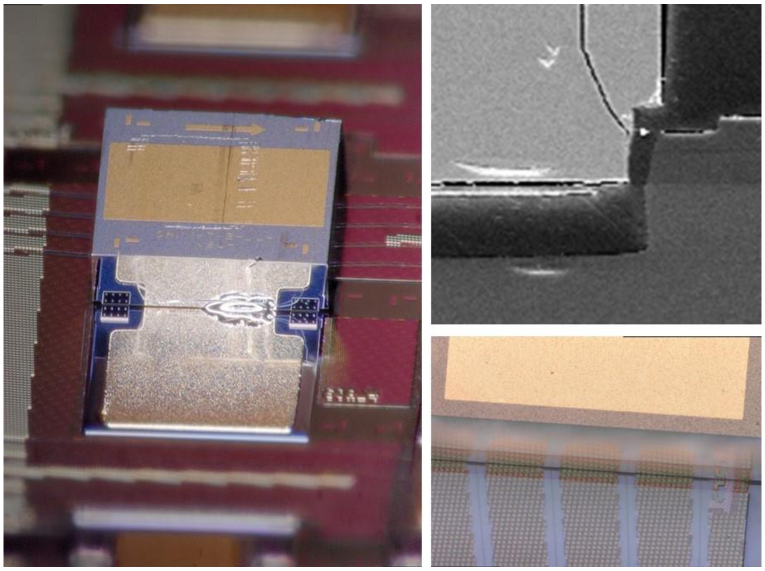


Figure 7: Flip Chip III-V integration on silicon (Source: Voyant Photonics)

III-V Photonics LiDAR

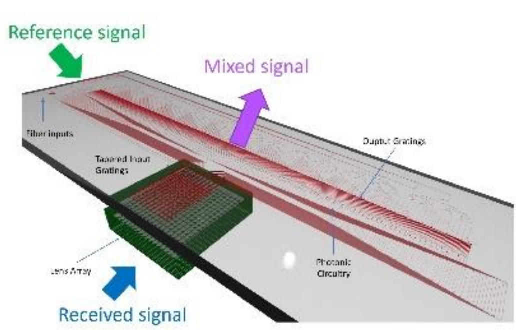
An alternative to Silicon Photonics LiDAR is using III-V integration and producing emitters, detector, laser and switches on a single III-V wafer. The III-V platform is very dependent on the substrate starting material chosen. For Short Wavelength i.e. < 1100nm this is typically Gallium Arsenide substrates. For Long wavelength devices i.e. >1100nm this is typically Indium Phosphide substrates.

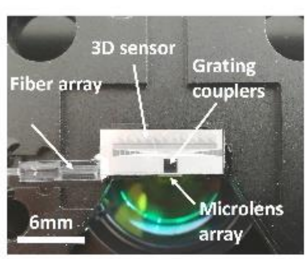
The main concerns with this approach are driven by maturity concerns of the III-V fabrication houses and cost compared to CMOS foundries and process. The typical

SiN LiDAR

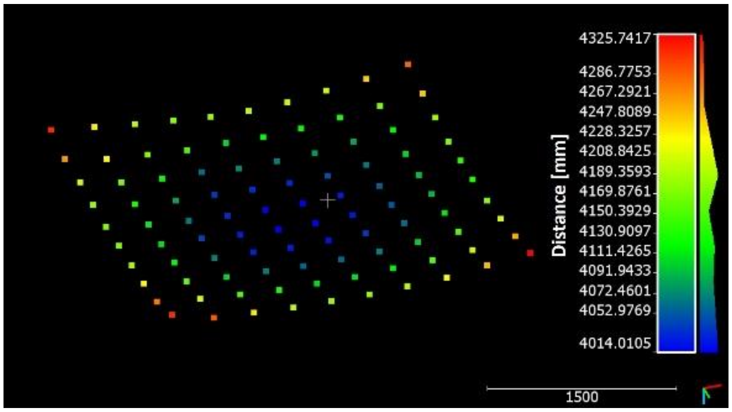
In comparison with the two platform above discussed the absence of detection and light generation brings some limits to the scaling up of such solution.

However for small number of points 2D or 1D systems can be built as depicted below.





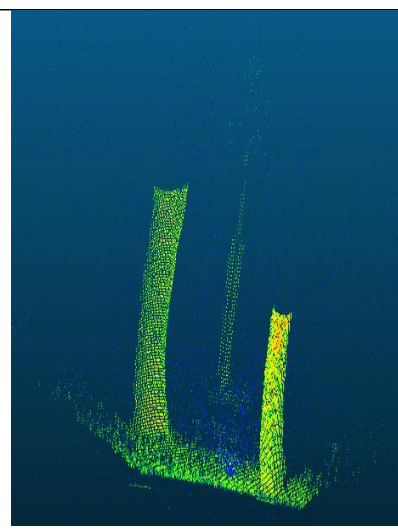
In the example presented above point cloud with 100 pts can be generated and for applications like metrology is ideal as the FMCW scheme allows accuracies in the 20 µm range.



To built denser pointcloud a 1D (one line) system can be put on a scanner like the Q1 commercialized by Ommatidia LiDAR. The possibility to access velocity with a FMCW scheme is a game changer and allows to propose competitive solutions for vibrometry by offering the measurements of the velocity across a larger number of points simultaneously.

The key components in the SiN LiDAR systems approach are:

- Laser
- Receiver
- Optics/HW



The receiver has been shown above and can only collect a limited number of point. Further the absence of detection the packaging of LiDAR in this platform a challenge.

On the laser side commercially available lasers are used (a power of 40mW allowing imaging up to 80 m). They are not integrated to the platform but definitely larger power will be required to go to the 300m range required by the automotive.

Beyond automotive

Drones and Surveillance

Today, state of the art in the compact side of the market is 350 cm³, 500 g, 8W, with the ability to reach a target at 190 m @ 10% reflectivity, with a precision of around 2 cm (1σ). Those specs are achieved by the Chinese company LIVOX with their product AVIA. This LIVOX AVIA scanner has successfully been integrated into a complete OEM mapping solution, by integrating the scanner with an inertial and navigation system, by YSCAN in 2021 for a drone partner Quantum Systems.

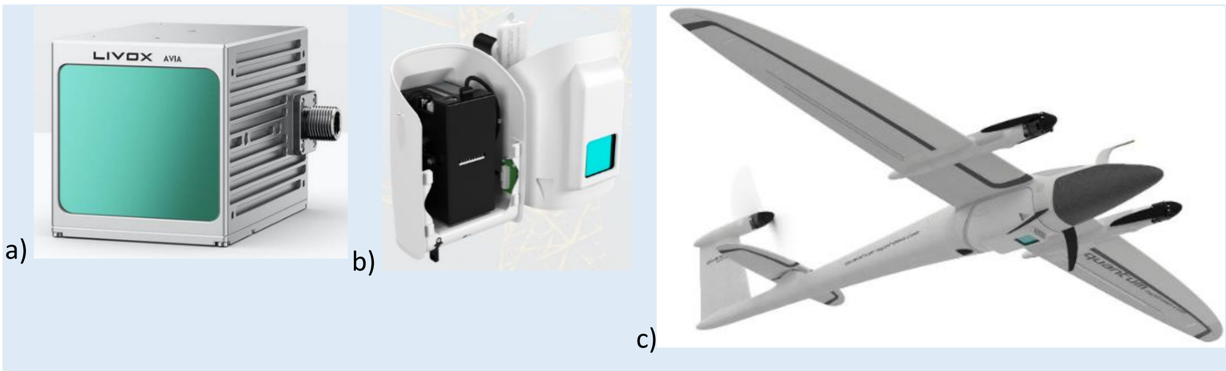
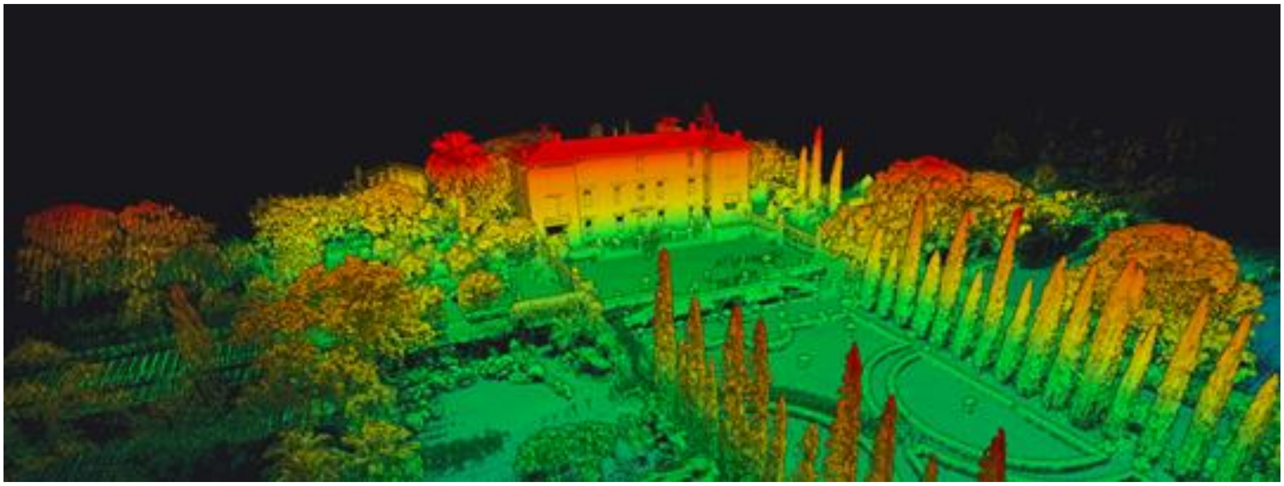


Figure 11. LIVOX AVIA scanner (a) integrated in a compete mapping solution (b) to be embedded on a drone (c)

The recent (<10 years) development of drones has enabled the use of compact LiDAR for mapping applications. However, compact LiDARs are most of the time developed for the automotive industry and are thus not perfectly suited for high precision topography from drones. Compactness, lightweight and low power consumption are determining factors when developing a LiDAR for drone operation. On top of that, a drone LiDAR suited for detailed topography mapping needs to operate at 120 m from the ground while maintaining a range precision of below 1 cm. However, those characteristics are not always needed by the automotive industry, and thus hard to find on the market.

The leading approach in LiDAR technology is frequency-modulated continuous wave (FMCW) LiDARs, that however is still rare on the compact LiDAR market. Moreover, this technology presents extremely precise measurements that would be of significant interest for precision mapping application. The ability for such technology to provide velocity of targets seems to be of great interest to develop novel applications for compact drone sensor. Velocity measurement, together with high precision 3D measurements, would be of great interest in the application of search and rescue, or infrastructure monitoring. *Velocity* is usually assessed from a static sensor position, but for the sake of productivity and efficiency, operation of the sensor from a moving platform will allow the collection of data on a larger scale. The main challenge here is to understand and correct the platform (drone) movement within the LiDAR's velocity measurements in order to deliver velocity maps that are independent from the acquisition dynamics. In order *to reduce system dimensions and cost*, an approach would be to reduce the need for aiding sensors such as inertial and navigation system. To that aim, the use of the velocity data might be of good support to assess precise drone's dynamics and correct it from the LiDAR data, and/or use it to geo-locate the target positions.

Existing research, such as Vivet *et al.*, 2013, prefigure how to perform simultaneous localization and mapping (SLAM) from a FMCW radar.



Market opportunity:

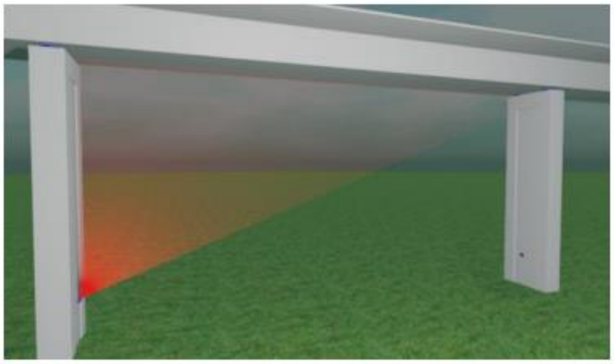
The LiDAR for drones market is estimated to be € 147M in 2022 and projected to be € 508M in 2028 growing by 28,1% per year (CAGR). The market share and growth for companies active in the field is expected to follow a similar growth rate. The new capabilities of the systems developed with a new generation FMCW LiDAR are expected to particularly interest companies doing precision inspection in the domain of aeronautics and large infrastructure construction. The other market is search and rescue, requiring fast-response survey and finding survivors after disasters.

Structure Health Monitoring

SHM aims at analysing engineering structures such as bridges and buildings over time using periodical measurements to monitor the global static and dynamic structural response, to identify changes in the material and geometric properties, and in the connective system. A major challenge in these measurements is the installation of an adequate number of sensors on operating infrastructures, maintenance and expansion of the corresponding sensor networks, which generally require an electrical or optical interconnection system and relatively complex read-out setups. On top of that, standard SHM techniques often rely on contact-based sensors, which may add challenges for the installation phase (e.g., temporary partial closing of bridges) and due to costs, a dense sensing grid is not always guaranteed.

Since most of the built environment is approaching the end of their designed life-span, there is a real need for innovative sensing technologies for detecting damage of existing civil engineering structures in an affordable and reliable way. Therefore, the objectives of the new sensing device for SHM are: (1) offering a full 3D image of the structure together with its local infrared reflectivity and operational deflection shapes of its dynamic response (2) allowing evaluation of local defects of key areas functions that LiDAR do offer.

In SHM it is important to conduct periodic and long monitoring sessions to record the variation in time of the structural response under different loading profiles and environmental conditions (e.g., harsh temperatures). All the dynamic operational loads acting on the structure constantly trigger a cyclic interplay between shear, compression and traction, which often lead to damage and fatigue failure in the long run. Updated numerical models of the investigated structure based on a plurality of information can make predictions and maintenance more predictable. An implementation of LiDAR is depicted in the figure below for the case of bridge deck monitoring. As one of the key failure mechanisms is the resistance to in-plane stresses, the use of LiDAR help calibrate and, validate the theoretical model of the investigated structure. A validated model is the basic starting point to generate reliable predictions of the future behaviour of the structure, serving for the decision-making process concerning maintenance and re-qualification activities of the investigated structure.



Robotics

According to IDTechEx, the agricultural robotics market is expected to reach 6.7 B$ in the next decade - CAGR is 13.09 % compared with 2022. Markets&markets34 on their behalf considers that he global agricultural robots market size is expected to grow from 4.9 B$ in 2021 to even 12 B$ by 2027, at a CAGR of 19.3 %. The key driver is the growing population and increasing labour shortage encouraging automation: As the agricultural labour becomes increasingly costly and scarce, attention is increasingly turning towards robotics as a key component of agricultural production. The challenges include high cost of automation for small farms and concern over data privacy and regulations. The competitors in agricultural robotics include Naïo Technologies, ecoRobotix, TerraClear, AgroIntelli. In addition, John Deere, AGCO, Kubota have developed autonomous tractor concepts. However, there are no direct competitors for the solution to be developed in the project. The solution proposed in this project differentiate from alternatives because the new technology will offer customers a complete robotic ecosystem that competitors don't currently offer. The sensors mounted on the robot allow for a much more detailed data acquisition, which results in a more precise and targeted information for specific task execution by the robot following the DSS inputs. In addition to this, the robot also includes a series of features which allow for further customization and extension of the system as architecture. Having more fine-grained, upscaled, data input allows the AI-DSS to be more precise hence to better guide the farmer. Thanks to the R&D collaborations of this project, the key benefits of the new solutions to the customers and end users are remote and real time vineyards management, as well as reducing labour time spent on some tasks, thus reducing labour cost. In comparison to what is available currently on the market (SoA), the new technology enables cost savings in average time in manual work of an average of 13 k€ per worker per year on an average surface of 20 Ha. The robot can cover a general area of 25 Ha in 20 hours estimated costs saved per year per 25 Ha is approximately 30 K€ for farmers (given AGRC current R&D data collected). If farmers can commit to a higher number of robots leased, they can save more money and have an automated farm, this is especially relevant for large vineyards (> 90 Ha). The key target group that benefits from the results is the viticulture farmers in EU. The current robotic platform will be updated with sensors and a DSS system that will help winegrowers manage their vineyards remotely. Until these days we have focused on selling robots to farmers or to farmer cooperatives that will provide a weeding service. The project will provide a new business model based on monitoring the vineyard as a service, bringing farmers a high visibility through the installation of the sensors and access to dashboard provided by the DSS. In 3 years after the project, the complete service of the robot and the capabilities built will generate a turnover of 0.4 M€ and in 5 years after the project we expect to expand our market and industrialize the product on a large scale, a new turnover of 1 M€ is expected by this activity. Our current 30 % market share on the national market and 5% in the European market is expected to grow into 10 % in 5 years after the project. The market share at the end of the project is expected at 34 % in the EU market and 40 % on the national (FR) market. The sales are expected to reach 10 M€ with the new solution. The new business process will be providing robot as a service for vineyard monitoring as an upgrade of the following solution. The technologies have a freedom to operate. If the results of the sensor can be used for the safety, a contribution in the standardization of the safety around robots can be foreseen at this stage. The new technology will offer customers a complete robotic ecosystem, which will have a wider impact on AGC's future.