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Assembly of micro parts (RIA)

TINKER

FABRICATION OF SENSOR PACKAGES ENABLED BY ADDITIVE MANUFACTURING

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Demonstrator of LIDAR sensor package fabricated using TINKER platform

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AUTHOR

Author	Institution	Contact (e-mail, phone)
Thierry Mourier	LETI	thierry.mourier@cea.fr

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Point of Contact	Name: Thierry Mourier Partner: LETI Address: Commissariat à l'énergie atomique et aux énergies alternatives MINATEC Campus | 17 rue des martyrs | F-38054 Grenoble Cedex Phone: +33 (0)4 38 78 25 40 E-mail: thierry.mourier@cea.fr
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Executive Summary

The Lidar demonstrator developed in the Tinker platform is based on the integration of the Optical Phase Array use-case reported in work package 6 in a mobile mock-up allowing the visualization and characterization of the Laser beam scanning in agreement with the Autonomous driving specification given in work package 2

The Optical Phase Array (OPA) beam steering device is based on the implementation of advanced 3D integration technologies such as mid-process TSV and advanced packaging through the use of small pitch flip chip soldering of tin silver micro-bumps of the Photonic device (OPA) on an electronic interposer.

After completion of the flip chip of the PIC on the EIC, the device was wire bonded to a daughter board and a 8 channel fiber array pigtailing ensures the external Laser signal distribution in the 256 channels through the Si/SiO2 wave guides.

The whole system was then incorporated in a mobile mock-up to validate the last parameters and allow a visible demonstration of the laser beam steering

This report describes the whole demonstrator integration

Table of Contents

Introduction

The vision of TINKER is to provide a new cost- and resource efficient pathway for RADAR and LIDAR sensor package fabrication with high throughput up to 250units/min, improved automation by 20%, improved accuracy by 50% and reliability by a factor of 100 to the European automotive and microelectronic industry via additive manufacturing and inline feedback control mechanisms. Autonomous driving and self-driving cars represent one prominent example for the use of microelectronics and sensor, most importantly RADAR and LIDAR sensors. Their respective markets have a big potential, e.g. it is estimated that the market size of LIDAR in automotive will double itself in the next two years (within 2020 to 2022).

Figure 1: TINKER overview

The public awareness and the industrial need for further miniaturization of such sensor packages is the main driver of ongoing efforts in the automotive sector to be able to integrate such devices into the car body like in the bumpers and head lamps instead of attaching them (e.g. on top of the car in case of LIDAR device). Safety (for the driver and others) is the most important key aspect of the automotive sector. Therefore, high-value and high performance RADAR and LIDAR systems are required for advanced driver-assistance systems (ADAS) as well as robotic cars. Current bottlenecks are the relatively large size of such sensor devices, their weight and power consumption. Since these factors are highly limited within cars, further miniaturization and improving functionality and efficient use of resources is highly demanded.

Description of deliverable

Reliability tests of RADAR sensor packages and printed waveguide antennas, benchmark to existing devices and antennas.

1. LIDAR demonstrator concept

The Lidars aimed to be used in mobile applications such as autonomous driving or robotics need to be small, cheap and present high performances thus requiring high number of channels.

Choice was made of building the scanning device of the Lidar using silicon technology on 200 or 300 mm wafers which is a necessary pathway to reduce the costs and increase the integration density. The technology proposed in CEA-LETI, named Optical Phase Array is based on the realization of optical structures (grating couplers, wave guides, splitters and extraction antennas) for a 1550 nm made of Silicon and silicon oxide. The deviation of the beam is generated by a thermal phase shift provided by the heating of each channel waveguide by a resistive Titanium nitride structure (A wave front correction, due to the change in refractive index "n" of the guides, allows the fundamental mode of the spotlight to be oriented. The change in refractive index is achieved by varying the temperature using heating resistors and the Joule effect.).

The signal will present a 2π phase shift and a +/- 20° deviation.

The first integration of such Photonic device lead showed significant issues in the potential industrialization coming from the very high density of the wire bonding from the Photonic device to the electronic board.

To overcome these limitations, choice was made for Tinker platform to ensure the distribution of the channel signals on the whole surface of the die back side (while only the edge of the dies can be used for wire bonding) using Through Silicon Vias (TSV) technology coupled to a flip chip of the PIC on a silicon interposer. In tinker project, the interposer will be a simple passive silicon interposer to validate the TSV/Flip chip technology but the concept of the interposer is much more flexible and enables heterogeneous integration in the future. As an example, the CMOS DACs used for current distribution and heating of the individual channels can also be flipped-chipped on the same interposer instead of being part of the motherboard and the same approach can be applied to most of the sub elements of the final Lidar (On-chip laser, filters, detection and signal processing calculator ...).

After the completion of the OPA use case and test of the beam performance at the wafer level, the OPAs are diced to individual chips, their connection to the daughter board is ensured by wire bonding and the laser signal distribution is provided by the pigtailing of a 8 channel fiber array on the input grating couplers of the photonic die

To allow the real time demonstration of the beam steering and validate the beam characteristics at long distance, the OPA is then mounted on a platform including a copper heatsink, an air-cooling device representing the air vent in a moving vehicle and the external connection of the fibers with the laser.

At least, the assembly is inserted in a mobile carriage including an emissive screen and an Infra-Red camera to visualize the beam in order to be carried on different locations and ensure live demos. The final demonstrator does not represent a final Lidar configuration but is based on an optical bench and ensure the simultaneous capabilities for demonstration and beam characterization.

2. Fabrication Process

The silicon technology part of the platform was focused on the wafer level processing of the OPA wand the silicon interposer followed by the flip chip of the PIC using fine pitch copper pillar µbumps and Tin silver soldering.

This was done on the 200 mm silicon platform of CEA-LETI. Initially, the photonic part of the chip was supposed to be performed on 300 mm wafers and the substrates had to be diced to reduce them down to 200mm. 2 main reasons made us switch to a full 200 mm processing. The first one is the wafer integrity and switching down from 300 to 200 mm is risky for the wafers.

On the other hand, the 300 mm process was brand new in 2022 when the photonic phase of the project was supposed to be performed and implied the use of our immersion 193nm scanner. Following the Covid impact on the chip Manufacturing volume, CEA decide to transfer the scanner to ST microelectronics in Crolles who faced a lack of lithography capacity and the re-qualification of the process as well as the lot processing in this phase was estimated long and uncertain. We decided to do the whole wafer processing in 200mm and redirect the process steps difference to what appeared as a critical point faced but unexpected : the critical thin die warping and the interest of moving from mid-process TSV to TSV last technology more compatible with a further volume processing.

The global processing was largely reported in the work package 6 but following paragraphs gives a summary of the achievements obtained in Tinker project.

2.1. Photonic processing

2.1.1. Conventional photonic technology on silicon

The photonic phase is not completely new and has already been done on previous lots but remains a new technology. It is based on using the conventional materials from a typical silicon platform to design and realize photonic structures for a 1550 nm signal management. Figure 2.1.1 gives an overview of typical structures obtained on the demonstrator lot

Figures 2.1.1.1 give design and image if the typical structures found in a photonic device.

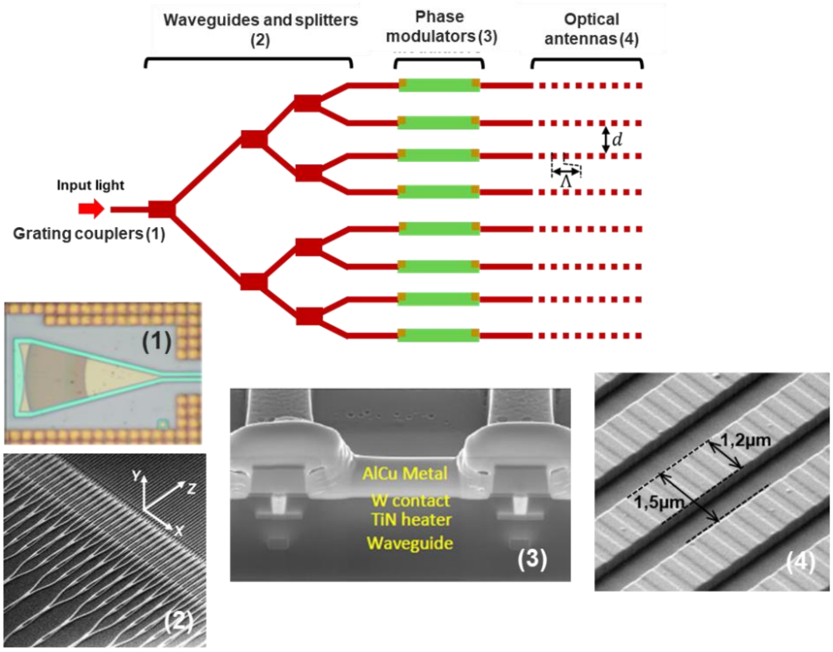


Figure 2.1.1.1: Photonic structures of the demonstrator lot – 1) input grating coupler- 2) Wave guides and beam splitters)- 3) Heaters for phase modulation- 4) beam output antennas

2.1.2. Fabrication of photonic structures by additive technology

In the Tinker project, a novel fabrication approach for OPA and optical waveguides was developed in WP5 by the consortium comprising Inkron, Profactor, LETI, and EVG. The new approach is based on a single step Nanoimprint lithography step. The initiative began with the development of new high refractive index materials, reaching >1.9 and progressed through the formulation of innovative inkjet-compatible resists.

Subsequently, it advanced through fabrication processes to demonstrate and test the overall procedure for OPA and optical waveguides in two approaches (Figure 2.1.2.1) .

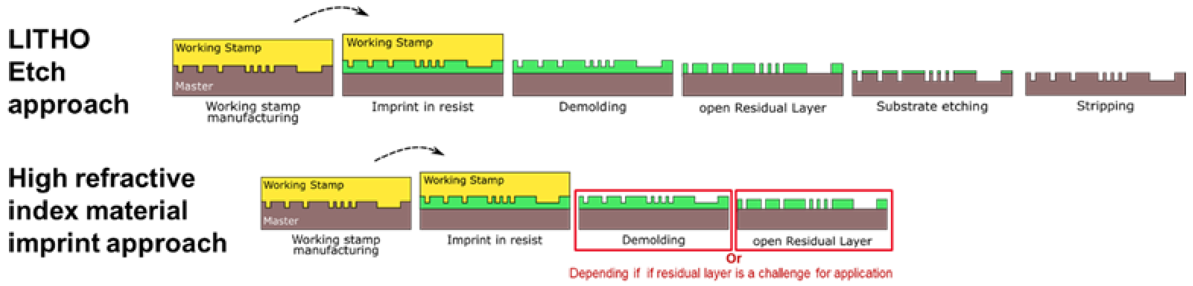


Figure 2.1.2.1 Approaches developed for the OPA and waveguide fabrication in WP5 base on NIL processes.

Additionally, a small series was successfully demonstrated by using the new developments and industrial EVG tools. Additionally, a small series was successfully demonstrated using EVG tools (Figure2). Optical test on waveguide obtained from optical lithography step and imprint lithography step reveal the high quality of the imprinted waveguides surpassing the quality of conventional manufactured waveguides. Additional information can be found in the final report, along with deliverables within WP5.

	Coupling Loss (dB)		Central Wavelenght (nm)		Propagation loss (dB/cm)
Lithography	Mean	3σ	Mean	3σ	
Optical	-2.4	0.2			1.2
Imprint	-2.2	0.1	1521	17.02	1

Table 2.1.1.1 : Optical test on waveguide obtained from optical lithography step and imprint lithography step

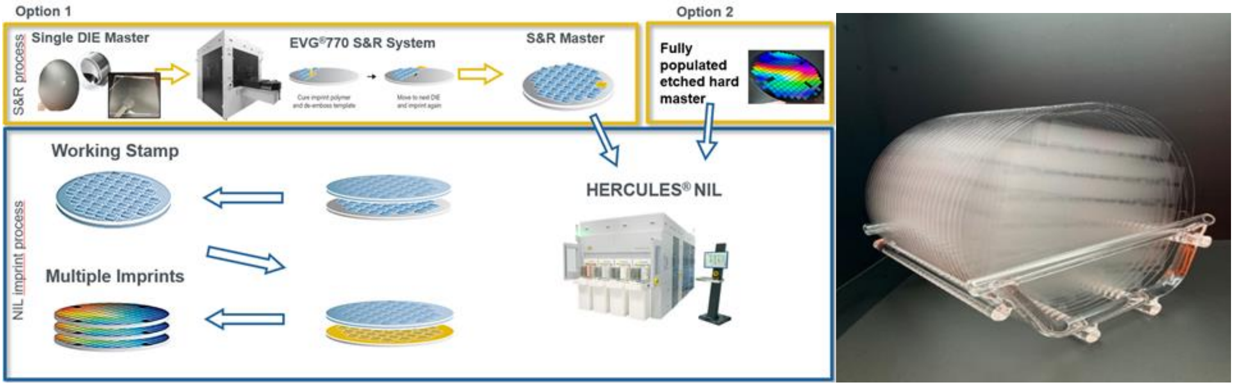


Figure 2.1.1.2: Schematics of small series production and demonstration on EVG equipment.

Outlook: Throughout the project, numerous insights were gained into the imprint process, material behavior, and design constraints. These can be considered in future developments of OPAs, paving the way for future production using NIL.

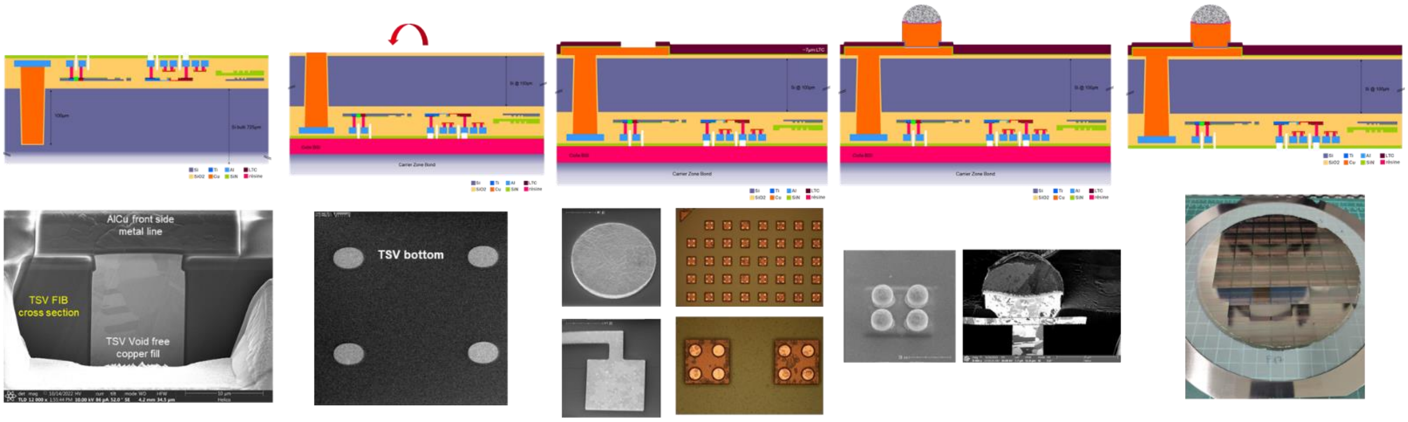
2.2. TSV

Initial choice for Through Silicon Vias and electric signal transmission from the backside of the die instead of lateral wire bonding was made on mid process TSV. Among the different ways to perform the TSV, these TSV are the denser and most performant. On another hand, they have the drawback to be limited in terms of diameter and aspect ratio. In Tinker, the TSV are 10µm diameter and 10:1 aspect ratio leading to a final silicon thickness around 100µm. As the OPA is a large circuit (21x5 mm), and that photonic processing necessitate to work n SOI substrates which are stressed ones, the deformation of the die at the end of the process could be severe and present a critical impact on the ability to perform the flip chip. This item will be described in the Flip Chip paragraph.

To anticipate this issue that can be a significant one in further manufacturing, another type of TSV was introduced in the late phase of the project. The TSV LAST. In this integration, TSV is performed at the end of the wafer processing. It allows thicker silicon thickness and by the way will reduce the deformations, but this will be at the expense of the integration density of the connections. In this configuration, the TSV are of 60µm diameter, and the flip chip will be limited to 40µm bumps. However, we plan to have both TSV tested on our device use case and if possible within the project timeframe integrated on the demonstrator.

After the TSV is performed, a backside processing recovers the electrical contact with the front side, generate the signal routing in RDL copper lined and generates the Tin silver solder microbump by electroplating. In Tinker process, the bumps for Mid process TSV are 20µm diameter and 40 µm pitch

Figure 2.2.1 shows images of the realisation of the TSV and the backside processing whereas figure 2.2.2 shows the final result of a cross section done on the demonstrator lot.



TSV processing
Front side metallization

Bonding (temporary glue)
Thinning
Back side contact

Back side copper RDL
Polymer passivation

SnAg µbumps

Electrical test
Debonding
Individual die dicing

Figure 2.2.1: Integration scheme and images of the TSV and µbumps processing

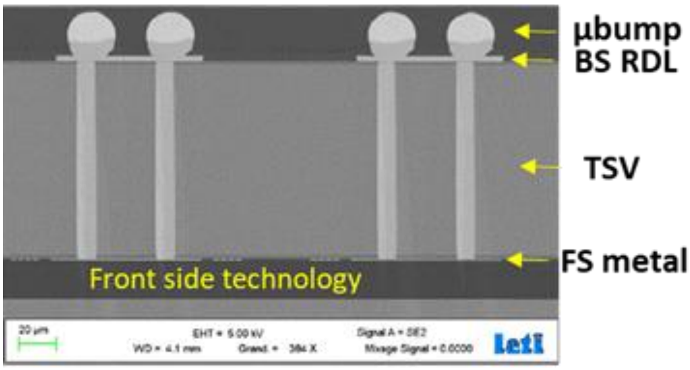


Figure 2.2.2: cross section of the final OPA connections showing the TSV connected to the front and backside metals and the Microbumps (picture taken before debonding)

As discussed, the TSV last can be an attractive option for further manufacturing of photonic devices requiring medium density interconnects but sensitive to die warping. The process of the demonstrator including TSV last is still on the way and final reporting will be given at the end of the project but figure 2.2.3 shows the patterning and metallization of 60 to 80 µm diameter TSV with silicon thickness up to 300µm. In this configuration, the TSV cannot be filled anymore and a few µm thick copper liner is performed to realized simultaneously TSV and RDL metals.

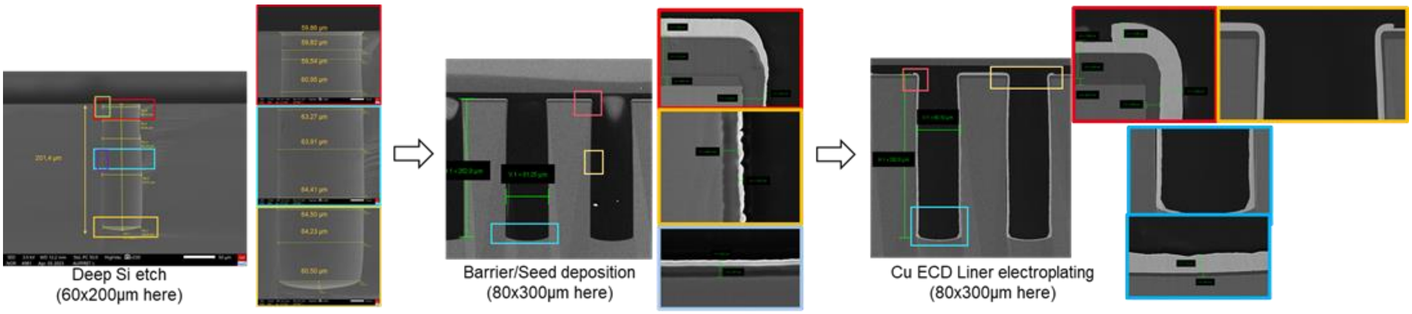


Figure 2.2.3: TSV last option development – Deep Si etch (left) and barrier/seed and electroplated copper liner (middle and right) developments

2.3. Interposer

For the Tinker project, the interposer will consist in a simple passive interposer with a design made to compare the standard packaging of the OPAs and the advanced 3D/Packaging technologies developed in the project.

The main features of the interposer are the metal line for electrical interconnects and the Under Bump Metallization (UBM) pads designed with 2 CuNiAu metal stacks depending if the pads are used for flip chip for which gold layer must remain thin (<300nm) and is only used to passivate the Nickel or for wire bonding where the bonding is ensured by gold itself that need to be thicker than 1µm.

Figure 2.3.1 shows different phases of the realization of the interposer and the final result on 200 mm wafers

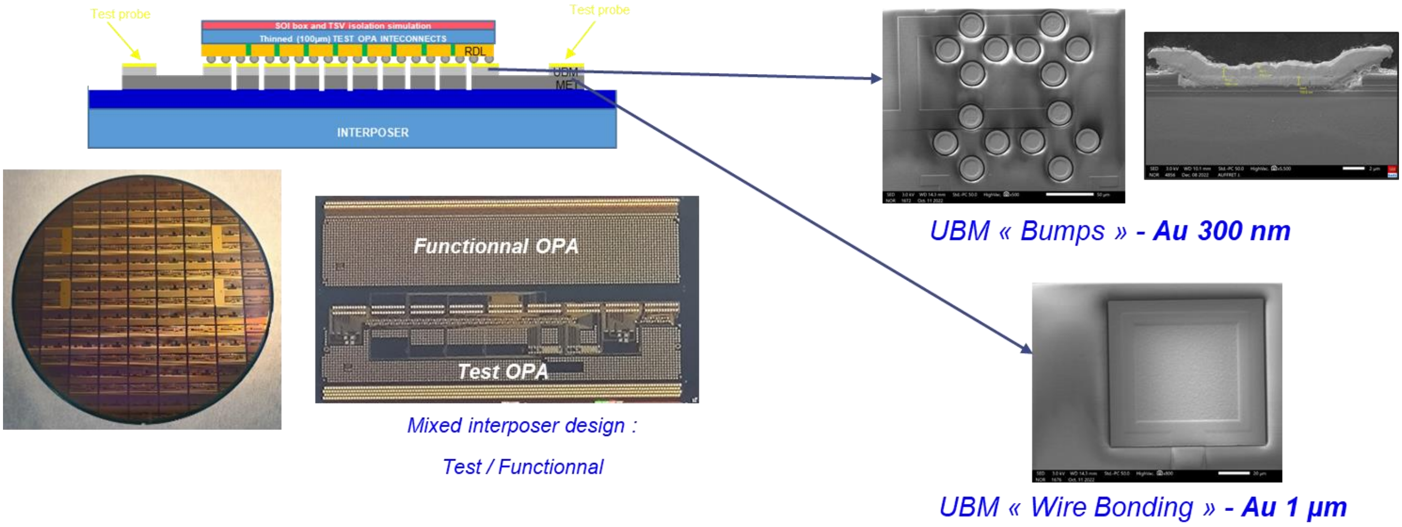


Figure 2.3.1: ***Silicon interposer processing***

2.4. Flip chip Process

In order to promote the electrical connexion between the photonic device (OPA) and the silicon interposer, choice was made of Flip chip of small pitch copper pillars with tin silver solder bumps.

The diameter of the µbumps will be of 20 µm with a 40 µm pitch. The soldering is a 2% silver content tin/silver alloy deposited by electroplating.

Two methods were investigated to realize this flip chip: thermocompression and Mass reflow and will be performed on two sites: BESI (industrial equipment supplier) and CEA-LETI (RTO).

- The thermocompression method, which consists in applying simultaneously downforce and temperature raising to solder meting temperature is considered as robust and easier to carry on as it compensates the die deformation during the whole solid/liquid phase and is less sensitive to the surface state of the UBM and the solder during bonding. However, this method is slow because of temperature rising and cooling for each attached die and only considered for development.

- On the opposite, much more interesting for volume manufacturing, the Mass reflow process consists in doing the Pick and Place of all dies on a wafer and perform a collective reflow step at the end of the pick and place. However, the pick and place is a solid/solid attachment and contact between solder and UBM must be guaranteed for each individual bump during the whole pick and place phase leading to a strong sensitivity on die warpage and solder oxidation.

In TINKER process, the TSV induce a thin substrate (100µm) at the end and a large die to bond (22x5 mm) with thick stressed layers (passivation, metal, SOI substrate). This results in a severe deformation of the photonic die of 200µm which is critical considering the 15µm thickness of the solder (figure 2.4.1). The early experiments in mass reflow without force support carried out at BESI showed clearly a lack of contact in the centre of the die while edge is connected (figure 2.4.2). This is why BESI switched to a high speed thermo-compression process, where the die is supported by the heated bond tool throughout the liquification and solidification of the bumps. The reference bond line setting is similar to the “edge” bumps shown in Figure 2.4.2. The final TINKER reference process developed in WP3 has a cycle time of less than 10 seconds. With a dual gantry setup, like in the Datacon 8800 TCadvanced used in this setup, more than 700 components per hour can be bonded already. Further optimization of the tools and subsequent process studies may push the throughput beyond 1000 components per hour. The details are reported in WP 3.

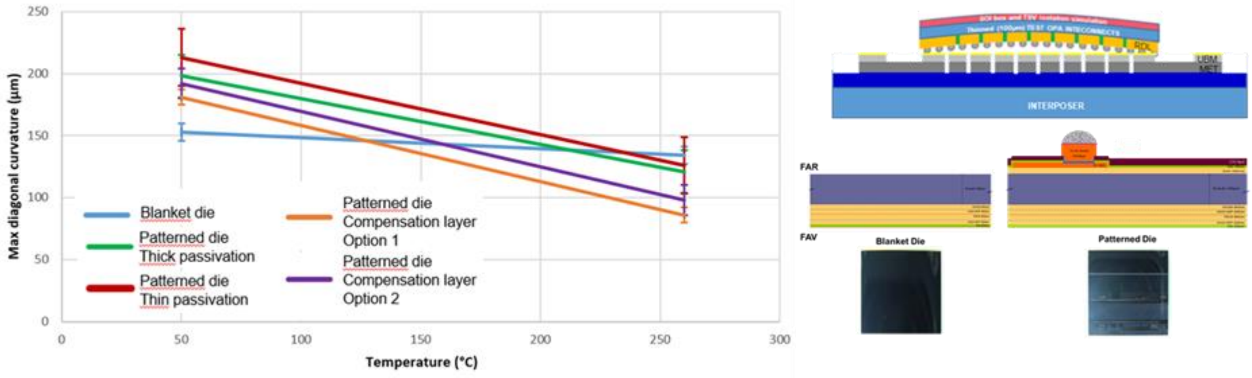


Figure 2.4.1: Tinker OPA die warpage versus temperature

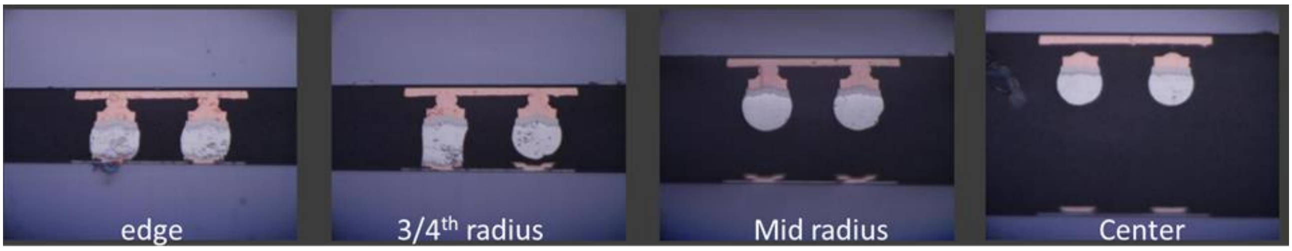


Figure 2.4.2: Mass reflow flip chip trial at BESI: evidence of deformation impact on electrical contact. For thermocompression, a bump shape similar to the ”edge” bumps was set as reference.

Optimization of the flip chip process was made and according to the fact that die deformation is decreasing when temperature increases, as it can be noticed on figure 2.4.1, by a factor of 2, both thermocompression and a mass reflow process including a high down force and 200°C temperature during the pick and place phase allowed expected results. Figure 2.4.3 shows cross sections of both processes on initial prototypes, confirmed by electrical results on figure 2.4.4 on which long daisy chains crossing the die edge are fully connected. At least, figure 2.4.5 shows a final cross-section of the demonstrator using thermocompression for this figure.

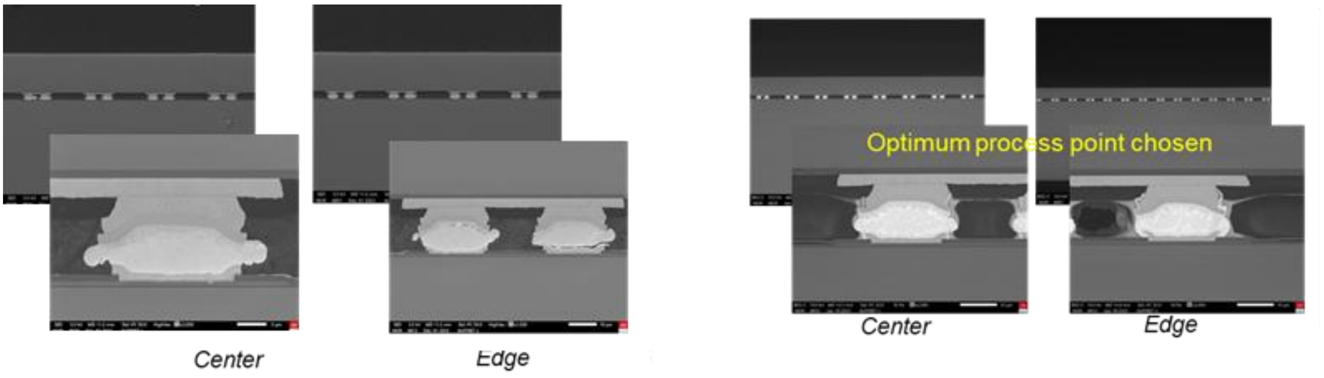


Figure 2.4.3: Thermocompression (left) and mass reflow at 200°C (right) cross sections of Tinker prototypes

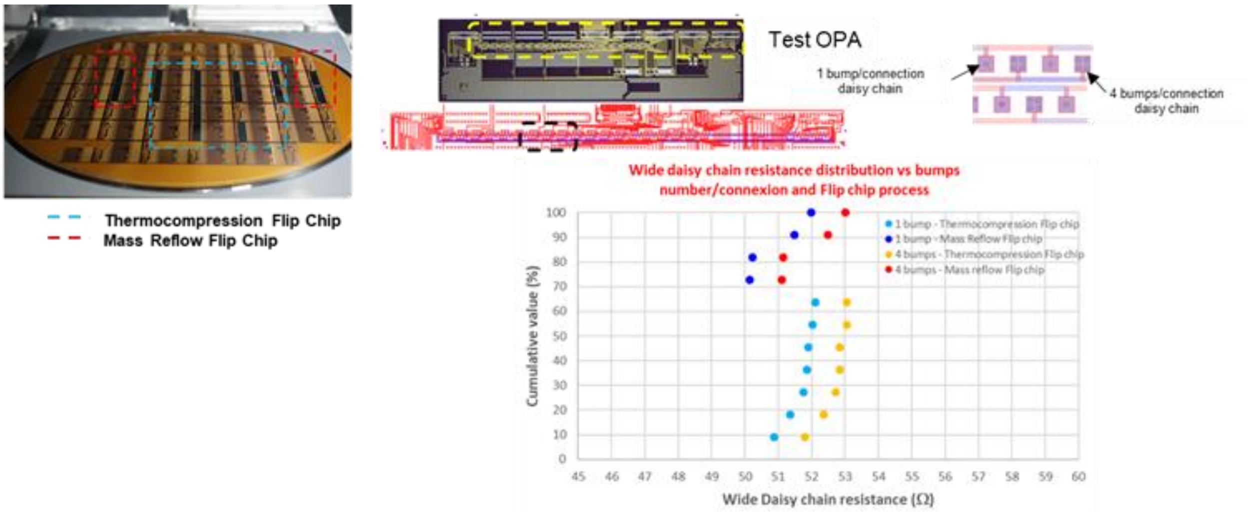


Figure 2.4.4: Electrical cumulated distribution of a wide daisy chain crossing the OPA edge length with single bump or 4 parallel bumps configurations with both thermocompression and high temperature mass reflow flip chip

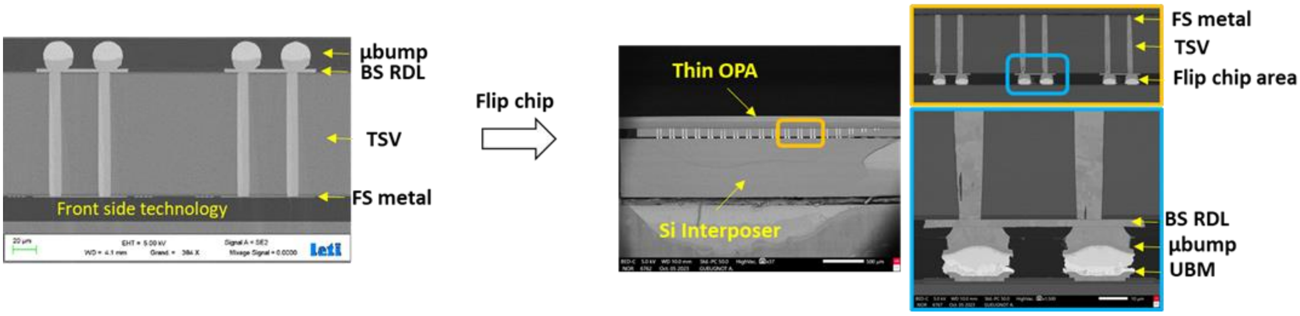


Figure 2.4.5: Final cross sections of the Tinker demonstrator OPA before (left) and after (right) flip chip process

3. Realized demonstrators

The Tinker Lidar demonstration was performed to, on one hand, measure the performances of the OPA use case and, on the other hand, build a mock-up demonstrator to ensure live demos of the Tinker OPA beam steering.

The work was done in the following phases

3.1. OPA

All integration parameters being fixed in the work package 6, a die to wafer assembly was carried out both at CEA-LETI and BESI to generate the demonstrator die. Figure 3.1.1 shows on the wafer hybridized at BESI on the left and the one made at LETI on the right. BESI focused on the thermocompression while both thermocompression and mass reflow were carried out at LETI

After the assembly, both wafers were tested on a prober. Goal was to provide electrical testing of the passives and validation of the connectivity of all channels for the best dies. In parallel, optical functionalities of the OPA were measure but due to the availability of the optical part of the prober, this could only be provided on LETI wafer. However, the results show that electrical tests are sufficient to select the best dies to be fully assembled in the demonstrator as the 3D integration and flip chi don’t change the optical characteristics of the photonic device. The description of the prober is shown in figure 3.1.2

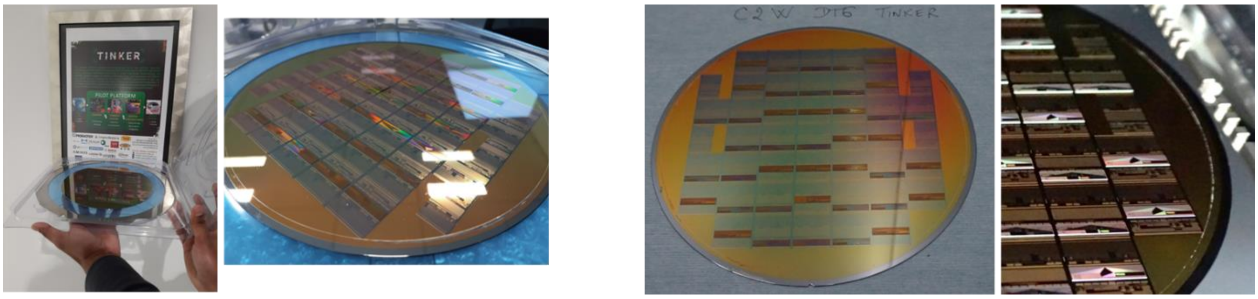


Figure 3.1.1: Full wafers hybridization of Tinker OPA on silicon interposer done on both partner sites: Besi (Left) and CEA-LETI (Right)

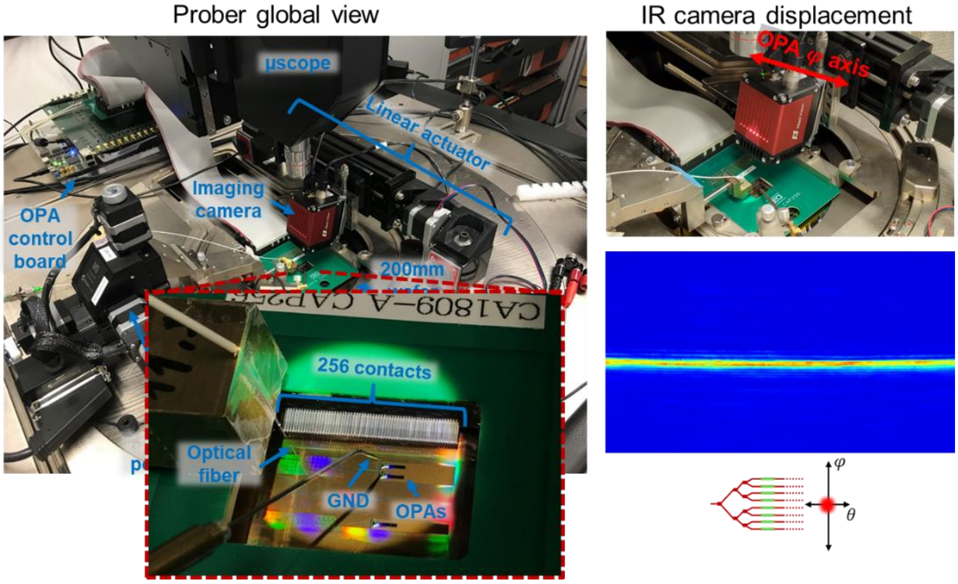


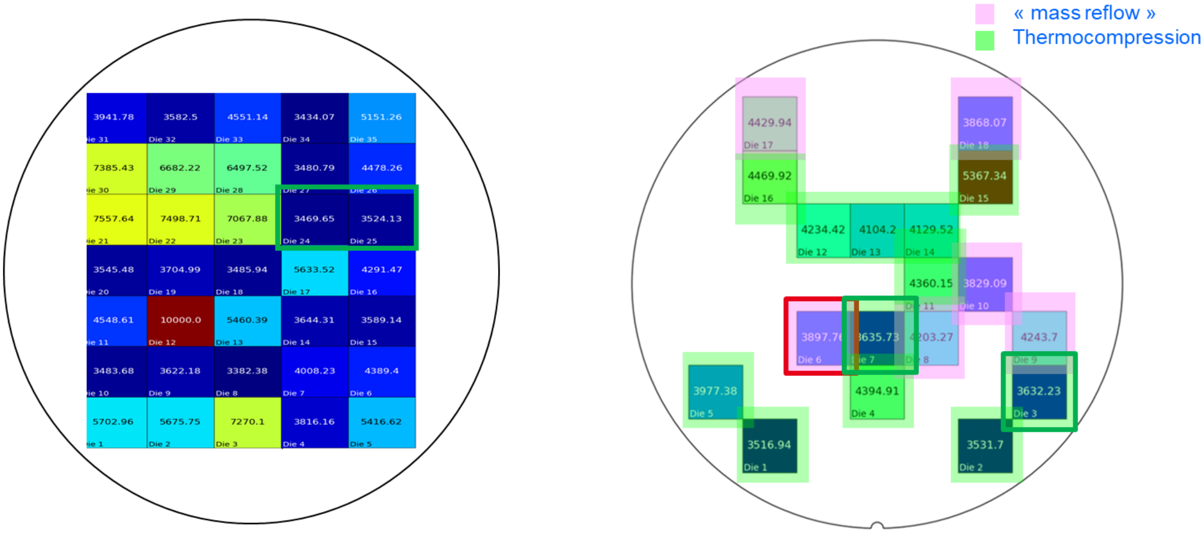
Figure 3.1.2: Schematics and view of the electro-optical prober

The Prober is a standard wafer testing semi-automatic prober equipped for OPA tests. It includes a 256 probes card to assess all channels, and optical fibre to guide the Laser beam and an infrared camera providing a mobility along the φ axe of the OPA to measure the beam steering and to validate individual phase deviation of each channel.

The mapping of the electrical measurement of the mean resistance of all channel interconnects contacts are shown on figure for both BESI (left) and LETI (right) wafers. Mass reflow functional OPAs assembly are underlined in pink while thermocompression dies are underlined in green. For BESI wafer, all dies are made using thermocompression.

The results show a resistance in agreement with the reference one measured previously on OPAs packaged with standard packaging methods. An increase of a few hundred Ω is observed due to the adding of the copper bump resistance but the 3500 Ω measured for best dies are in agreement with the specifications knowing that this is a standard design but in the case of an optimized OPA design for TSV and flip chip, the distribution of the connections on the whole OPA backside surface will lead to a significant decrease in the connexion length compared to reference. All values in the range of 3500 to 4500 Ω are representing die with almost all the channels connected. This is the case for many dies except a few ones in yellow, green or brown showing higher resistance for BESI wafers. This is clearly attributed to some connections failure coming from the transport between BESI and LETI sites which was done without the presence of an underfill thus a fragilized situation.

The surrounded dies are the one selected for the final integration in the demonstrator.



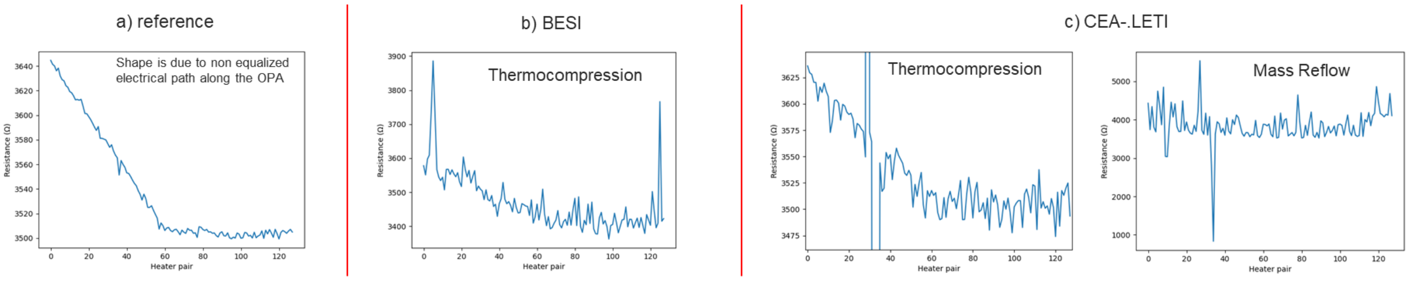
3941.78 ie 31	3582.5 Die 32	4551.14 Die 33	3434.07 Die 34	5151.26 Die 35
7385.43 ie 30	6682.22 Die 29	6497.52 Die 28	3480.79 Die 27	4478.26 Die 26
7557.64 ie 21	7498.71 Die 22	7067.88 Die 23	3469.65 Die 24	3524.13 Die 25
3545.48 ie 20	3704.99 Die 19	3485.94 Die 18	5633.52 Die 17	4291.47 Die 16
4548.61 ie 11	10000.0 Die 12	5460.39 Die 13	3644.31 Die 14	3589.14 Die 15
3483.68 ie 10	3622.18 Die 9	3382.38 Die 8	4008.23 Die 7	4389.4 Die 6
5702.96 ie 1	5675.75 Die 2	7270.1 Die 3	3816.16 Die 4	5416.62 Die 5

Figure 3.1.3: Mean resistance of channels interconnects for hybridized wafers at BESI (left) and LETI (right)

In parallel, on LETI wafer, optical characterization was done to compare the advanced 3D packaging developed in Tinker with the reference one at LETI.

Figures 3.1.4 and 3.1.5 summarize some of the results.

Figure 3.1.4 is an electrical distribution of the connectivity of all channels, made on dies presenting the best mean resistance results and could be done on both BESI (b) and CEA-LETI (c) wafers compared to reference (a). The natural slope observed on the reference curve on left, due to length variation between each channel is still present for hybridized ones but less which can be attributed to the influence of the added serial resistance of the bumps. On few channels fail which means a successful hybridization process for each die.



a) reference

b) BESI

c) CEA-.LETI

Figure 3.1.4: Resistance of individual channels pairs of the hybridized OPAs compared to reference

On figure 3.1.5 is plotted the power consumption distribution of all channels of the measured OPAs (Mass reflow and thermocompression during the 2π phase change of each. It shows a good distribution of the power with for all measurement some channels exhibiting bad numbers that could be related to non connectivity but according to the measurement expert and the complexity of the 256 probes card can also lead to some non perfect contact during the displacement time of the camera. A value of 20 mW per channel is expected and 18 mW is obtained with no change compared to the reference. This KPI is reached.

On the bottom graphs, we can see the divergence of the spot measured for all angles from –20 to 20° which is the specification to be reached. The beam steering angle is almost reached with a good beam forming for all angles and a beam divergence measured around 0.23° compared to the expected 0.2°. Results are very close to the specified KPI and the integration of Tinker features change nothing from the reference results. At least, the right figure shows one of the modulators efficiency and a good beam from $-\pi$ to π phase shift which is the last KPI verified and obtained

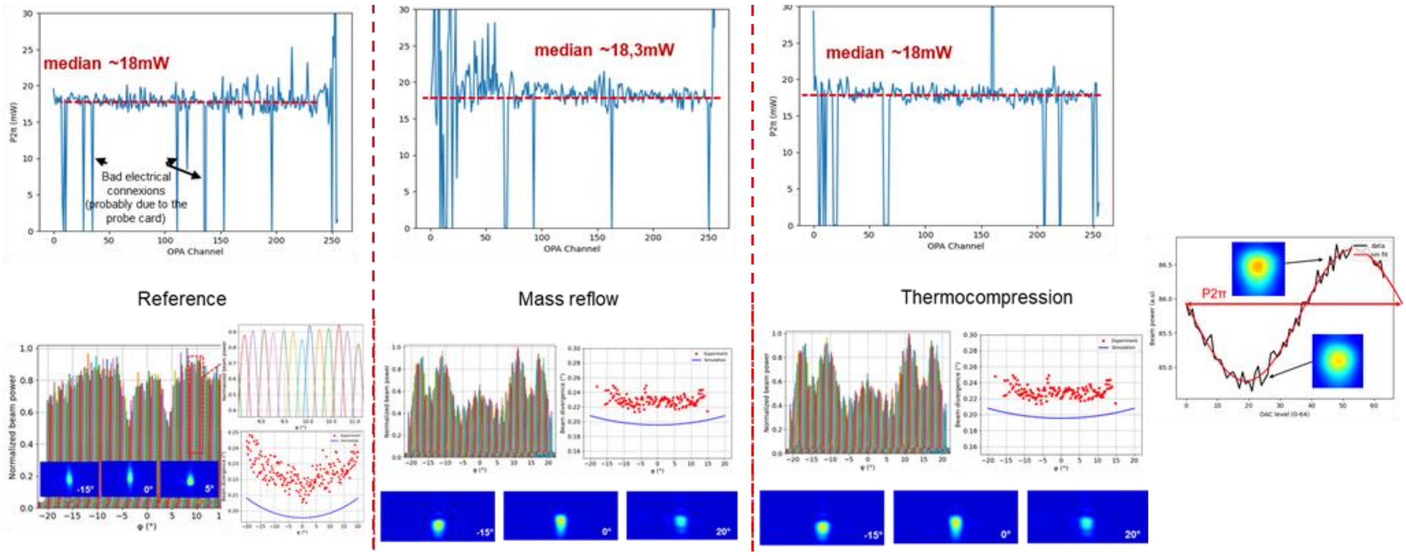
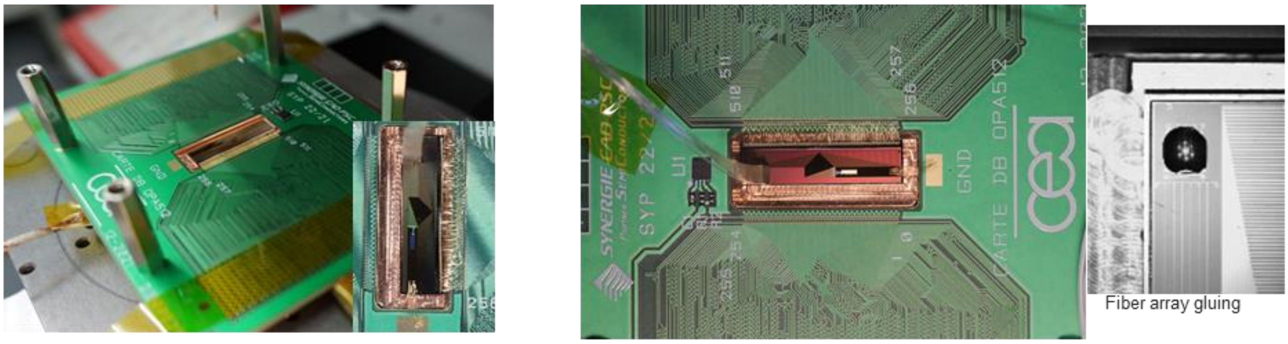


Figure 3.1.5: Optical characterization of the hybridized OPAs

3.2. Demonstrator Packaging

The chosen dies from testing were then packaged to be installed in the demonstrator optical bench

This is done through a wire bonding of the OPA channels to the PCB followed by the fibre array attach to ensure the laser beam source to the photonic die. These operations are shown for one of the die on figure 3.2.1



demonstrator wire bonding

Demonstrator fiber array attachment

Figure 3.2.1: Wire bonding of the OPA on a daughter board and optic fiber pigtailing

The assembly is then installed in a box design to bring the external connections and ensure the safety of the demonstrator by preventing any contact or movement of the elements as described in figure 3.2.2. The box is then fixed on the same support as the infrared camera and positioned in the mobile optical bench designed as a mock-up (figure 3.2.3). This operation will ensure the compatibility of the angle of the camera with the position of the beam after beam emission and reflection on an emissive screen at 50 cm distance.

This is the concept of the demonstrator: the 1550 nm beam is emitted by the OPA and reflected on the luminescent screen before being detected by the camera. This simulated the emission/reception function of a full lidar as we only focused on the emission in Tinker project. This design allows to verify the KPI measured on the prober at long distance (beam angle, beam scanning rate and beam divergence) to validate the hypothesis that even on a prober distance, the beam existing the OPA is considered at long distance.

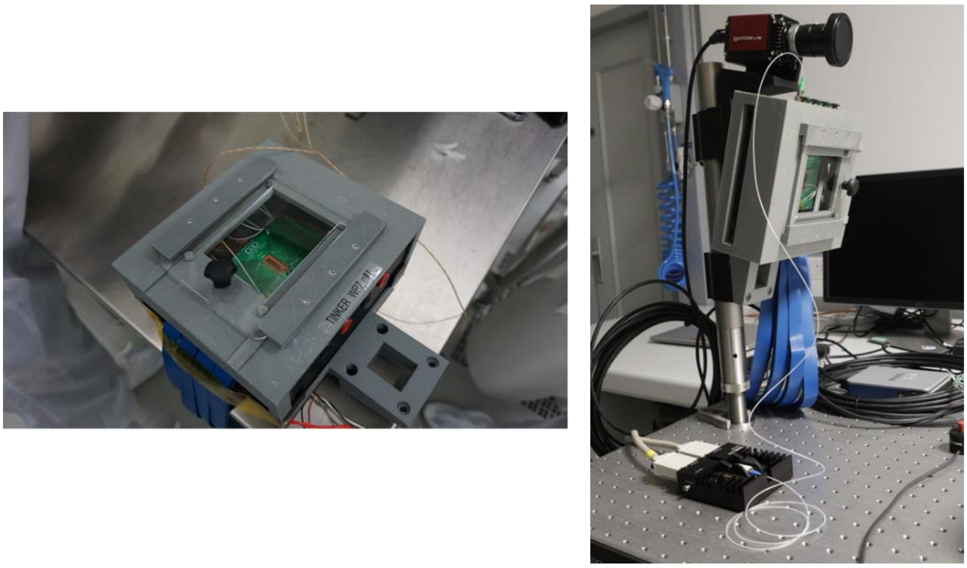


Figure 3.2.2: Installation of the OPA on the mock-up support

At the end, the whole mobile mock-up is assembled to be compatible with live demonstration of the OPA scanning and detection that will be shown at the LOPEC conference in Munich. Figure 3.2.3 shows a non-finished mock-up as the finishing and covering are on-going and the schematics of the final object

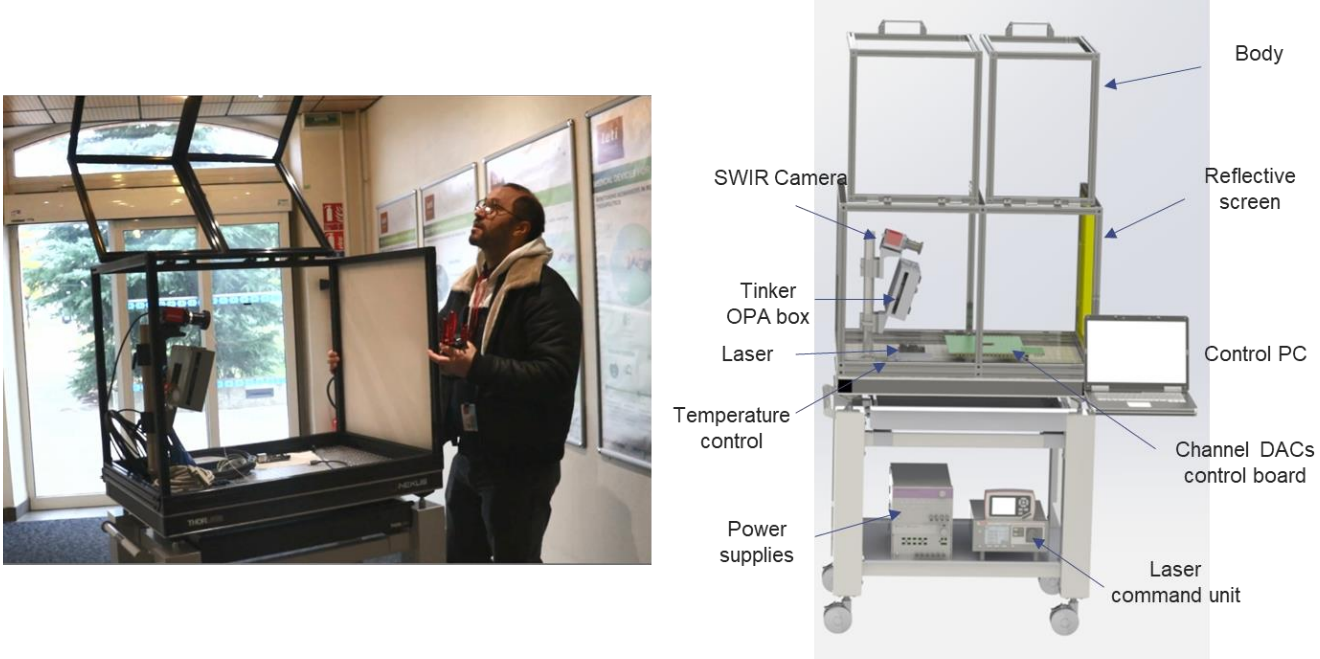


Figure 3.2.3: Final demonstration mock-up view in construction and general schematics

3.3. **Driving electronics**

The electronic card for the control of the 256 channels by a computer was designed at LETI, tested and then installed in the demonstrator. It allows the individual control heating of each OPA channel. An initial calibration (CEA-LETI procedure) step is required to form a first beam in a given position. By controlling the heaters according to the physical law of light interferences, the beam can be shaped for any angle of the scanning field (-30° to +30°).

The card is shown on figure 3.3.1

Figure 3.3.1: Electronic command card for the heating and beam phase shift of the OPA channels

3.4. **Software**

In order to ensure the command and the control of the demonstrator, the software was completely programmed at CEA-LETI. This software is based on 2 modules.

The first module, programmed in LabVIEW language ensures the control of the different elements of the demonstrator. Following parameters are controlled or measured

- Control of the laser source and its temperature
- Control of the Infrared camera and signal acquisition and storage
- Monitoring of the temperature of the OPA and the room one (ability to control the temperature is in progress)
- Control of the power unit and the cooling fans
- Data acquisition (temperature, images, videos ...)

The second module is a Python routine and acts as the interface between user and demonstrator. It includes the calibration files and the sequences chosen for beam steering management (angles, speed ...). It also includes and pilot the libraries and addressing as well as the consign files for the OPA heaters.

A parameter file is generated using the LabVIEW HMI, and then the Python script is called up using the HMI to execute the scenario for moving the spot.

Figure 3.4.1 gives an overview of the software configuration and figure 3.4.2 a typical print screen.

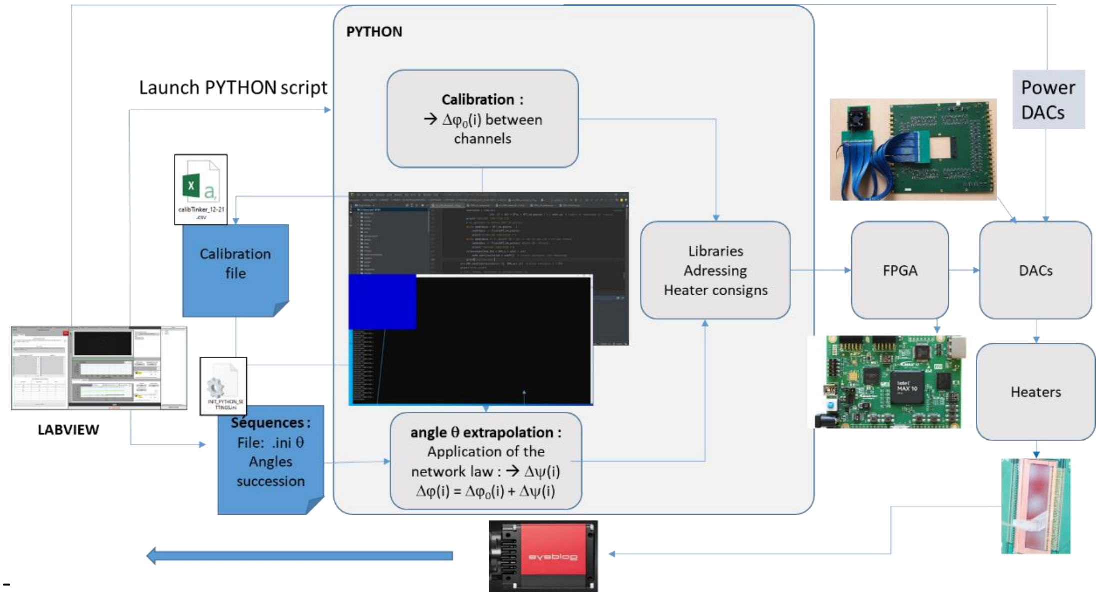


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Figure 3.4.1 : LabVIEW / PYTHON demonstrator software articulation

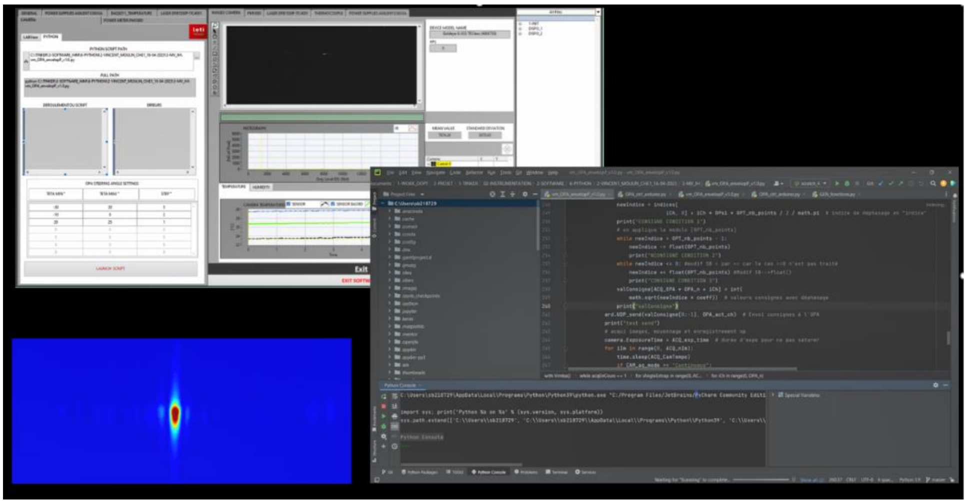

Figure 3.4.2 : Mock-up software typical print screen

4. Discussion and Results

This report shows the development of the Tinker Lidar demonstrator based on the integration of a thermally control Optical Phase Array device to generate the beam steering of a solid-state Lidar for Autonomous vehicle.

The specificity of Tinker project was to bring 3D integration and advanced packaging solutions such as TSV and flip chip hybridization of the photonic die on a silicon electronic interposer and the integration of the assembled system in a fully functional demonstrator with a mobility allowing it to be displaced as a Mock-up

The integration of the TSV was fully successful as well as the flip chip of the OPA on the interposer with excellent yield despite the difficulty of the high warpage of the die coming from final 100µ silicon thinning to allow the TSV backside contact.

Testing and further wire bonding and fibre array pigtailing of the best dies from both BESI and CEA-LETI partners allowed a full live demonstration capability of the beam steering as well as the validation of the

KPI designed for autonomous driving lidar. These major KPIs are listed in table 4.1 which show that all KPIs were reached at the end of the project

Parameter	KPI target value	Reference value	Tinker value
OPA channel power consumption	20 mW	18 mW	18 mW
Phase shift	2π	2π	2π
Long distance beam divergence	0.2 °	0.23°	0.23°
Beam angle	-20 to +20°	-20 to +20°	-20 to +20° measured, limited by construction -30 to + 30° achievable