POLYmer based electro-optic PCB motherboard integration with Si_3N_4 Chiplets, InP Components and Electronic ICs enabling affordable photonic modules for THz Sensing and quantum computing applications

Deliverable D2.1

Use cases, system requirements and KPIs of POLYNICES demonstrators

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TABLE OF CONTENTS

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LIST OF ABBREVIATIONS

DRW	Dielectric rod waveguide
ECL	External cavity laser
EOPCB	Electro-Optic Printed Circuit Board
EU	European Union
FMCW	Frequency Modulated Continuous Wave
OBFN	Optical beamforming network
PIC	Photonic integrated circuit
Radar	Radio detection and ranging
RF	Radio Frequency
InP	Indium phosphide
GA	Grant Agreement
PCB	Printed circuit board
PIC	Photonic Integrated Circuit
PZT	Lead Zirconate Titanate
QIP	Quantum Information Processing

EXECUTIVE SUMMARY

The present document, D2.1 “Use cases, system requirements and KPIs of POLYNICES demonstrators” reports on the definition of the use cases, system requirements and key performance indicators of POLYNICES demonstrators.

POLYNICES aims to introduce an innovative photonic integration technology compatible with wafer-scale processes, reducing module production costs significantly. This involves developing a polymer-based Electro-Optic PCB (EOPCB) motherboard to accommodate LioniX’s proprietary Si_3N_4 (TriPleX) chiplets, InP components, and micro-optical elements. POLYNICES paves the way leading to a tremendous customization and scalability potential with minimal effort and cost. Different functionalities can be installed in the motherboard by selecting the chiplets, or the same chiplet can be installed multiple times, to scale-up the circuit. The ultimate ambition of POLYNICES is to make available a technology for PIC fabrication that will be easily accessible to by the SMEs of the photonic industry in order to empower them to design complex and multi-functional devices with unparalleled capabilities. POLYNICES has identified potential in emerging applications such as THz spectrometry for thickness measurements and quantum information processing as two application areas that can be truly revolutionized by its technology.

More specifically, POLYNICES will develop for the first time a fully integrated optoelectronic single- and multi-channel frequency modulated continuous wave (FMCW) THz spectrometers enhanced with beam steering capabilities for plastic pipe inspections and universal quantum information processors with unprecedented performances. For each prototype, the high-level system designs as well as the system requirements have been defined and reported. Based on these requirements, the system and component specification and thus the functional designs of each prototype will be defined and reported in D2.2.

Keywords: Use cases, FMCW THz spectrometer, quantum information processor, system requirements

1 Introduction

The present document, Deliverable – D2.1 "Use cases, system requirements and KPIs of POLYNICES demonstrators" is devoted to the description of the applications scenarios and identifies a first set of the system specifications and requirements that will serve as a guide for the design and development of POLYNICES prototypes. This deliverable is a public report and consists of the basis for the work to be carried out in the rest of the work packages

Following this introduction, the document comprises three more sections:

Section 2 that set the framework of the target domains that POLYNICES technology can truly revolutionize and provides an overview of the two main application areas, the non-destructive THz spectrometry and quantum photonics.

Section 3 that elaborates on the selected application scenarios for both families of prototypes.

Section 4 that reports on the system requirements as they have been derived from the application scenarios.

2 POLYNICES's Target Domains: Exploring Application Areas

2.1 Overview of THz spectrometer

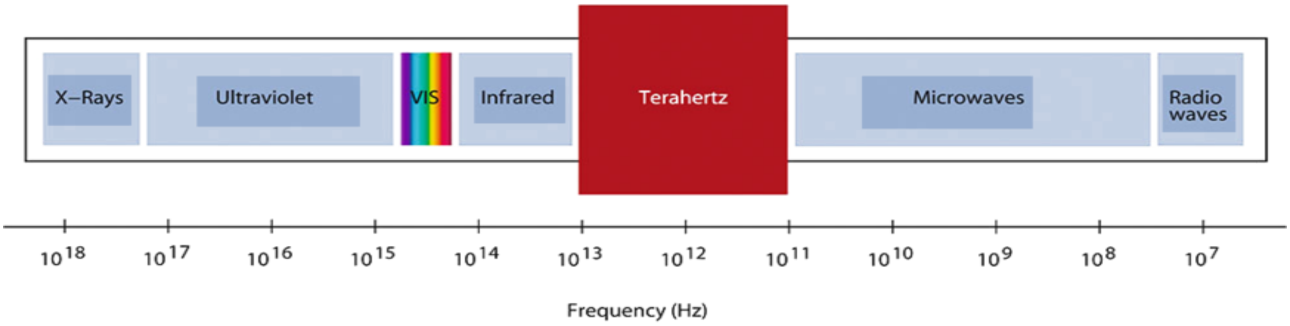


Figure 1. The regions of the electromagnetic spectrum from x-ray to radio waves. The terahertz region lies between 10^{13} Hz and 10^{11} Hz.

Terahertz waves have unique properties for various applications in industry and science. Located between microwaves and infrared waves they combine good penetration ability with submillimeter resolution. For this reason, terahertz instruments can be deployed contactless and non-destructive. One popular concept to generate and detect terahertz waves is called frequency modulated continuous wave (FMCW) radio detection and ranging (radar). The FMCW radar was originally developed to measure distance or speed of a moving object and is commonly used with microwave radiation. Yet, other properties of the object such as thickness or spectroscopic information can be determined as well. Unlike pulsed radar, it uses a sender of continuous electromagnetic radiation, whose frequency is swept through the desired spectrum. The information about the object is deduced from either the Doppler shift, the arrival time, or the amplitude of certain frequency signals at the detector. With the advent of terahertz emitters and receivers, the FMCW concept has been adapted from the microwave region to the terahertz region, especially for non-destructive testing applications. Today, terahertz FMCW spectrometers are used in industry, for example, for plastic pipe inspection and thickness metrology, either in the form of a robust handheld scanner or a fully integrated and automated system for inline production monitoring.

A terahertz FMCW radar is typically realized using one of two main technologies. The first one is based on purely electronic "classic RF" components such as RF multiplier devices, the second technology is based on a combination of lasers and semiconductors. Hereby, a photosensitive semiconductor is used to convert the light of two photo mixed lasers into terahertz radiation. Both approaches have their merits. The benefits of the RF technology are cost effectiveness, higher levels of output power, robustness, and compactness of its components. The drawbacks, however, are the lower operating frequency range of about 100 GHz to 500 GHz and the limited tunability of a few 10 GHz. This limits the lateral and depth resolution of the RF-FMCW system and restricts its area of application. For example, only plastic pipes with a wall thickness of not less than a few millimeters can be measured. Furthermore, several individual terahertz devices are required to cover the full frequency range. In comparison the photonic approach is superior in terms of tunability and frequency range. A spectral range from 50 GHz up to several THz can be covered by a single optoelectronic terahertz instrument, thus enabling measurements of plastic pipes with a wall thickness down to 10 micrometers. A state-of-the-art optoelectronic prototype system (T-Sweeper) has been developed by the Fraunhofer Heinrich Hertz Institute (HHI) [1]. The disadvantages of this system are the higher equipment costs and the size of the system and components as it is based on bulk optoelectronics components.

Figure 2. All-fiber terahertz spectrometer from FhG-HHI, operating at 1.5 µm optical wavelength with up to 70 traces per second and a bandwidth of 2 THz.

As of today, because of the higher equipment cost and size of photonic instrumentation, only the RF-FMCW technique has found its way into industrial applications, while optoelectronic systems are primarily used by research groups. The focus of the POLYNICES project is to bring optoelectronics out of the scientific labs and into industries by addressing the cost and size issues with photonic integrated circuits.

2.2 Overview of quantum information processors

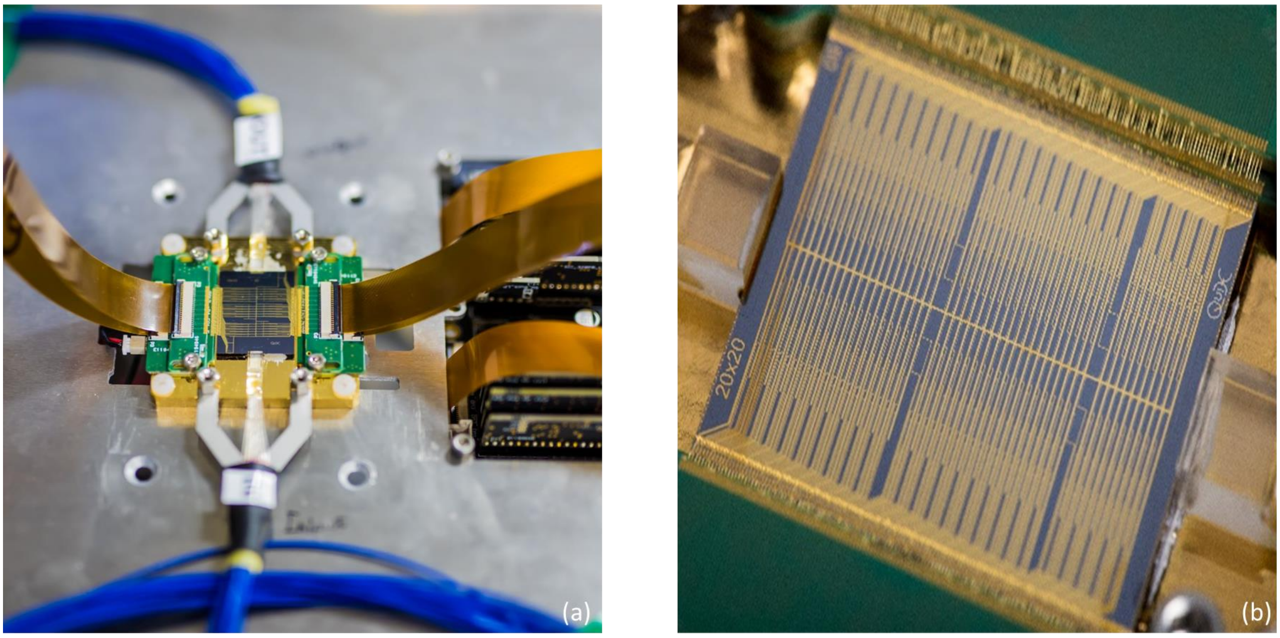


Figure 3. (a) 12-mode and (b) universal photonic processors for quantum information processing, fabricated by QuiX Quantum.

The advent of computers has revolutionized our lifestyles, significantly influencing our communication, work processes, and societal structures. However, classical computing faces limitations as chip sizes reach or fall below 8 nm, leading to a rising significance of quantum principles. Consequently, Moore's law, which governs the exponential growth of computing power, will begin to encounter challenges.

As society advances, it becomes more dependent on computing for crucial tasks like evaluating potential new drugs, forecasting climate changes, mitigating natural disasters, and ensuring secure computer encryption. To propel the digital revolution further and embrace the possibilities of the technology era, we must move towards the next phase: quantum computing. Nonetheless, the majority of contemporary quantum computers rely on stationary qubits for data storage and transmission, despite their remarkable capabilities, they are not without significant constraints.

These machines offer an unparalleled level of power, with certain reports suggesting an improvement of up to 10 orders of magnitude compared to the most advanced classical supercomputers. Nevertheless, they do have some disadvantages:

1) Qubit decoherence – the loss of quantum properties due to small disturbances in the qubit environment.
2) Scalability – most current quantum computers are challenging to scale without increasing interference and error occurrence.
3) Hardware and temperature requirements – to minimize noise, many quantum computers require cooling to a little above absolute zero (-273.15 °C).

There are a handful of other companies developing photonics processors which are built on silicon nitride chips (Q.ANT (DE), PsiQuantum (US), and Xanadu (CA)). However, without QuiX's proprietary TriPleX technology, they are limited in scalability (e.g., 4 qu-modes for PsiQuantum and 12 for Xanadu vs 20 for QuiX Quantum) and continue to suffer excessive propagation and coupling losses (2-4× worse than QuiX Quantum).

At QuiX Quantum, we have designed a cutting-edge quantum photonic processor that represents a significant milestone towards the realization of the first universal quantum processor and, ultimately, a universal quantum computer. Our quantum photonic processor is a versatile interferometer with low-loss properties, supporting multiple optical modes and reconfiguration. It empowers users to execute controlled interference between optical channels in both classical and quantum realms.

QuiX Quantum's processor excels in multiple aspects, boasting an industry-leading number of optical channels (20), remarkably low loss (2.9 dB Insertion Loss), and impressive transformation fidelity (99%). Designed to be turnkey, the processor allows end users to provide their desired optical transformation along with the required light, and our specialized control software takes care of the rest of the process. Figure 3 (a) and (b) show the 12-mode and the 20-mode quantum information processors, designed by QuiX Quantum based on the TriPleX platform.

The QuiX Quantum processor represents a significant advancement in quantum processing and marks a crucial milestone towards achieving universal quantum computing. Diverging from other cutting-edge quantum processors, this photonic processor employs a novel information-carrying method called qu-modes. Qu-modes utilize the discrete quantum states in a quantum harmonic oscillator (light) to encode data. This approach offers the remarkable advantage of a practically infinite number of states compared to conventional computer bits or even state-of-the-art quantum bits (qubits). Consequently, it has the potential to store and transmit an infinitely larger amount of data.

Nevertheless, there are challenges and limitations to overcome, primarily concerning optical losses and the intricate engineering required to incorporate an appropriate number of qu-modes into a single processor. Despite these hurdles, the potential benefits and capabilities of qu-modes make the effort well worth undertaking in the pursuit of quantum computing advancements.

The QuiX Quantum's photonic processor comprises an optical chip that receives light (qu-modes) emitted by single photon sources. Using an interferometer, the qu-modes are encoded onto our processing chip, and the computation results are obtained through a set of single-photon detectors. To ensure stability, the entire processor is enclosed in a temperature-stable, plug-and-play control box, which comes fully calibrated and includes dedicated control software. Our processor stands out from competing photonics systems due to its exceptional TriPleX waveguide, providing various distinctive benefits over other photonics technologies.

Advantages of TriPleX based QIPs

In terms of a photonic processor, QuiX Quantum suggests several advantages over other quantum computing technologies:

1) No vacuum is required, the processor operates at atmospheric pressure.
2) Stable at room temperature, no need to cool to sub-Kelvin Temperatures (almost absolute zero).
3) Compatible with CMOS fabs and more easily integrated into current supply chains.
4) High scalability and secure supply chain thanks to fibre optic interconnects rather than superconducting qubits.
5) Ultrahigh GHz bandwidth clock speeds possible.

Compared with other photonics systems, our processor is built on an innovative TriPleX silicon nitride waveguide, which offers several unique advantages:

1) Drastically reduced propagation losses from 0.2-1.0 dB/cm for other technologies to just 0.05 dB/cm.
2) Reduces coupling losses from 1.0 dB per facet to 0.5 dB per facet.
3) Increases demonstratable scalability from 1-12 qu-modes for other technologies to 20 qu-modes.

2.3 POLYNICES photonic integration approach and applicability in FMCW THz spectrometer systems and quantum information processors

The current methods of packaging photonic components are insufficient to meet the growing demands of the market in terms of large volumes and cost, therefore transition from device-level packaging to wafer-level packaging emerges as a promising solution. Packaging at the wafer-level can leverage developments in electronic packaging, and with the use of new substrates to co-package photonic and electronic devices in more compact sub-systems. This is the direction that the POLYNICES project is taking, aiming to create a new integration platform. This platform relies on applying layers of polymer through spin-coating onto a printed circuit board (PCB) substrate, creating a robust electro-optic PCB (EOPCB) motherboard. The key advantage here is that polymers can be spin-coated onto almost any surface. The initial step involves selecting the appropriate stack of materials for the PCB, ensuring it possesses optimum dielectric properties to support high frequencies.

The EOPCB motherboard will be constructed through the integration of spin-coated polymer layers and precisely fabricated waveguides, designed and routed according to the specific photonic architecture of the demonstrators. Strategic recesses will be meticulously established at defined locations on the motherboard to facilitate the seamless coupling and integration of various photonic chiplets and micro-optical components, including GRIN lenses and non-linear crystals.

The polymer stack forming the EOPCB will undergo controlled etching down to the underlying Cu layer to create recesses with an approximate area of 1x1 cm^2, which will serve as host sites for the diverse TriPleX chiplets. Depending on the particular chiplet type, these recesses will be adjusted in terms of their precise shapes. Additionally, smaller recesses with dimensions on the order of a few millimetres will be formed to accommodate micro-optical elements such as GRIN lenses and PPKTP crystals. Ensuring precise alignment, the depth of these recesses, especially concerning micro-optical elements, will be meticulously regulated to align with the waveguides.

POLYNICES takes advantage of PolyBoard’s material ability to be spin-coated on virtually any surface and TriPleX’s dense integration ability and complementarity of the two platforms and combines them in a disruptive photonic integration platform with all performance and cost credentials for strong technical and commercial impact. POLYNICES has the potential to provide a new generation of powerful, vertically integrated PICs and devices that are co-packaged with electronic ICs on the same System in Package. It first bridges the photonics and electronics worlds by combining the PolyBoard with high-frequency PCB substrates, developing for the first time an Electro-Optic PCB platform with high quality optical properties and good high-frequency capabilities for realizing low propagation loss optical waveguides and antennas. The tremendous potential of the platform becomes evident when considering the powerful toolbox already developed for PolyBoard, like the micro-optical bench, that will be also transferred to the polymer based EOPCB motherboard, including PolyBoard’s excellent hybrid integration abilities with a variety of complementary material platforms like InP and TriPleX, making it the ideal motherboard to host these PICs.

POLYNICES invests in hybrid integration as it allows efficient optimization of each PIC separately, resulting in the best possible performance. TriPleX brings its technology as chiplets with ultra-low power consumption, thanks to the PZT actuators, and low-loss, high complexity circuits that will be hosted in the EOPCB to further advance the functionalities of the platform. Flip-chip integration of these complex TriPleX chiplets is a wafer scale compatible process, which, combined with the passive alignment using vertical alignment stops it allows truly high-volume, cost-effective production and great commercialization potential. Adding to this the direct attachment of the chiplets’ electrodes to pads on the EOPCB eliminates scalability issues related to the routing and wire bonding of large number of pads at the edges of the PICs, it is obvious that the optical alignment and electrical connection becomes a one step process.

The project paves the way to a tremendous customization and scalability potential with minimal effort and cost. Different functionalities can be installed in the motherboard by selecting the chiplets, or the same chiplet can be installed multiple times, to scale-up the circuit. The ultimate ambition of POLYNICES is to make available a technology for PIC fabrication that will be easily accessible by the SMEs of the photonic industry in order to empower them to design complex and multi-functional devices with unparalleled capabilities in emerging applications such as Terahertz spectrometry for thickness measurements and quantum information processing.

The pursuit of cost and size reductions in the realm of optoelectronic-based terahertz spectrometers holds significant advantages. In this context, the innovative approach of the POLYNICES project comes to the forefront, aiming to tackle both of these critical challenges through the application of photonic integrated technology.

The envisioned electro-optic board, a central outcome of the project's efforts, stands as a potential game-changer in the landscape of terahertz technology. By leveraging this advanced board, the project anticipates achieving substantial reductions in both the physical size and associated costs of terahertz components, effectively bringing them to a comparable scale with that of conventional RF electronics.

As part of this transformative shift, the dimensions of terahertz spectrometers, typically occupying a 19" rack with two height units, are projected to undergo a remarkable reduction. This shrinkage is envisaged to result in a remarkable transformation, condensing the once extensive setup into the compact form factor of a euro-format board. This transition holds great promise, not only in terms of practical space utilization but also in terms of enhancing the portability and integration of terahertz technology.

Equally compelling is the prospect of cost reduction facilitated by the POLYNICES project's approach. The traditional expense associated with terahertz components is expected to witness a substantial reduction, potentially reaching a significant factor of two to three. This envisioned cost reduction has far-reaching implications, making terahertz technology more economically accessible and potentially unlocking a broader range of applications and adoption.

Cost and size reductions for optoelectronic-based terahertz spectrometers would be advantageous. With its approach to photonic integrated technology, the POLYNICES project addresses both issues. The envisaged electro-optic board would make it possible to reduce the size and costs of terahertz components to a comparable level with classic RF electronics. The size is expected to shrink from a 19" rack with two height units down to the size, while the costs may be reduced by a factor of two to three.

POLYNICES will also tackle the integration and scaling challenges of quantum processors by following many innovative paths. Firstly, by investing on low power consuming (< 1 μW at DC) PZT phase shifters on TriPleX platform to replace the heater electrodes of the PICs, secondly, by developing 8x8 matrices in low-loss (< 0.05 dB/cm) TriPleX chiplets as photonic building blocks that will be flip-chipped and combined in the low-loss polymer EOPCB motherboard to realize high-order optical mode quantum processors, thirdly, by integrating the pump light sources on the motherboard, and lastly by integrating the non-linear crystals and the squeezed light state generation circuits on the motherboard as well. Novel light sources at 780 nm will be used for this purpose.

3 POLYNICES’s Application Scenarios

3.1 Application scenarios for the FMCW THz spectrometers

The following sections outline application scenarios where POLYNICES technology can help optoelectronic terahertz spectrometers to replace existing technology or find new use cases. The first two scenarios involve measuring thickness, which is a typical use of terahertz radiation. Terahertz communication is the subject of the third application scenario, where optoelectronics will probably find usage in the frequency band between 100 GHz to 500 GHz. Figure 4 shows a compilation of all those use cases and explains why the Polynices technology is suitable for them.

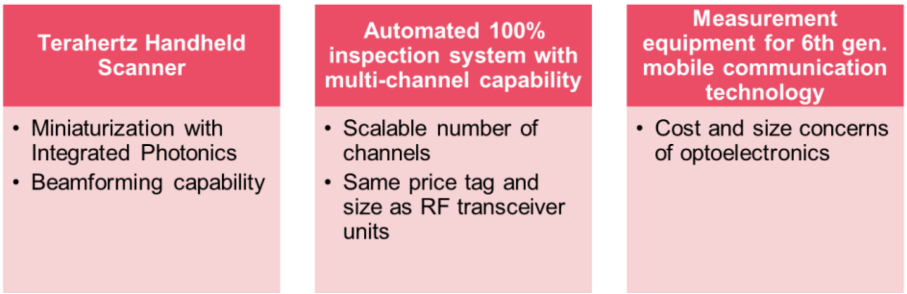


Figure 4. The three identified use cases of POLYNICES technology in the field of THz spectrometer. In addition, the reason for this technology for the cases.

3.1.1 Terahertz Handheld Scanner

Small and portable handheld scanners, such as those used for flexible and selective wall thickness measurement, are one possible use case for POLYNCIES technology. A plastic pipe and a cutting-edge FMCW terahertz handheld scanner based on RF electronics are shown in Figure 5. The scanner has an electronic radar chip with a tuning bandwidth of around 10 GHz that operates at a frequency of about 120 GHz. The portable scanner provides the ability for non-destructive, contactless measurements, which is utilized, for instance, in the industrial packaging industry.

Figure 5. State-of-the-art handheld scanner for pipe inspection based on RF-electronics. Ref: www.inoex.de

POLYNICES technology will enable the development of a terahertz handheld scanner based on optoelectronic components. With the specifications planned by the project, it will be possible to increase the thickness measurement resolution by a factor of 3 - 5 to approximately 50 µm.

3.1.2 Automated 100% inspection system with multi-channel capability

Another application scenario is the inline thickness measurement of plastic pipes. Here, an automated 100% inspection system with multi-channel capability is necessary to allow a 360° analysis of the moving pipe. Figure 6 and Figure 7 show two state-of-the-art measurement systems from different vendors. The system in Figure 6(left) from vendor 1 contains eight independent RF transceivers (black boxes). While the pipe is pushed through the toroid during production, the eight sensors monitor the thickness of the pipe at eight different positions at the same time. Inline quality control often requires measuring the sample under test at several different positions at the same time. Therefore, easily scalable numbers of independent measurement channels are beneficial. Figure 6 (right) shows a system from a second vendor featuring the same concept, but this time as a single channel version.

Figure 6. Examples of automated 100% inspection systems with multiple terahertz transceiver units Ref.: (left) www.inoex.de (right) www.sikora.net

Figure 7 shows a fully integrated production line for plastic pipes. The production line includes two wall thickness measuring tools (cf. Figure 3) from vendor 2. By reaching the same price tag and size, POLYNICES technology would make it possible to replace the RF transceiver units (black boxes in Figure 6 left) with optoelectronic terahertz sensors. Like the terahertz handheld scanner, this will again improve the resolution of the wall thickness measurement from 2 mm to approximately 50 µm and allow pipe manufacturers to measure pipes with wall thicknesses much less than a few millimeters as well as increase their precision.

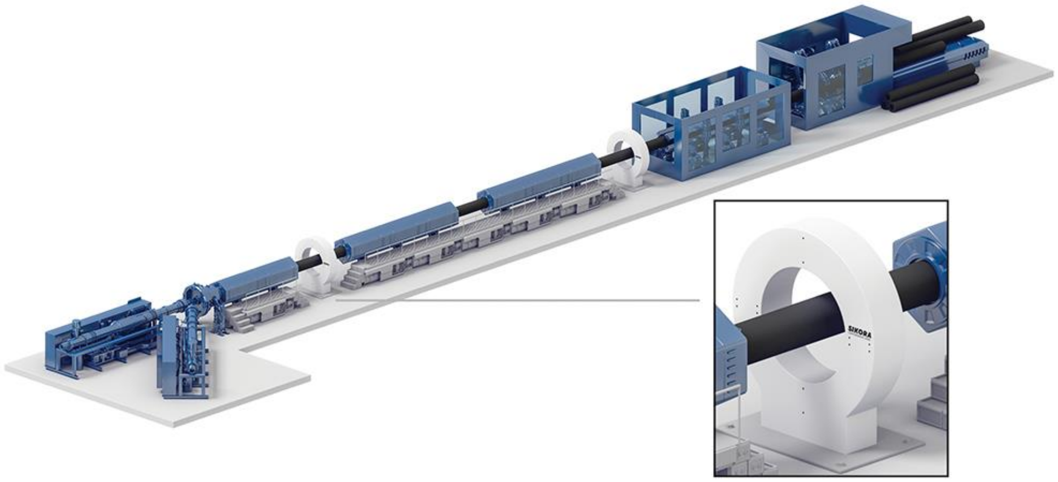


Figure 7. plastic pipe production line with implemented wall thickness measurement system. Ref.: www.sikora.net

3.1.3 Measurement equipment for 6th generation mobile communication technology

Terahertz technology has some potential applications in the field of communication, particularly for the upcoming wireless communication standards like 6G. Currently, 6G is expected to come into operation around 2030 and will use frequencies between 100 GHz and 500 GHz. The new standard is supposed to have ultra-high data rates of T-bits per second. Therefore, terahertz communication based on photonic technology will be a compelling alternative, because it addresses current issues like the scarce spectrum and the wireless systems limited capacity. Research is being conducted worldwide to achieve the proposed specifications, and it is not yet clear which technology will be applied. However, it is very likely that photonic approaches will also find their use, as they feature a broad tuning range from 50 GHz to several THz and can outperform classic RF-components at high frequencies above 300 GHz in terms of phase noise, stability, and linearity. An application scenario can be foreseen in measurement equipment such as network and spectrum analyzers, as it will be quite challenging for the electrical approach in the frequency range. Figure 8 and Figure 9 show examples of state-of-the-art measurement equipment.

Figure 8. State of the art measurement equipment Ref: www.Rohde-Schwarz.com

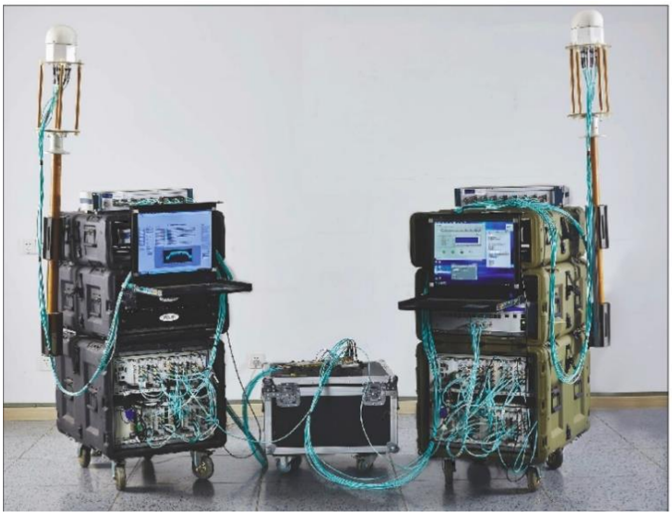


Figure 9. Channel Sounder used for 5G applications Ref.: Yang et al.; IEEE Wireless Communication 25, 16-22, 2018.

Three potential use cases were identified for the POLYNICES technology in the measurement equipment for terahertz communication:

- THz Channel Sounder and/or Communication System
- THz Network Analyzer
- THz Spectrum Analyzer

While the previously stated technology for pipe monitoring has already been adopted by industry, with clearly specified requirements, work on 6G is still part of research. Due to this, no additional requirements are provided in section 4. But addressing costs and size concerns of optoelectronics will help pave the way for photonics into 6G applications. We will continue to keep an eye on new developments in this area throughout the project and afterward, and we will periodically update this section in the months to come.

3.2 Application scenarios for the quantum information processors

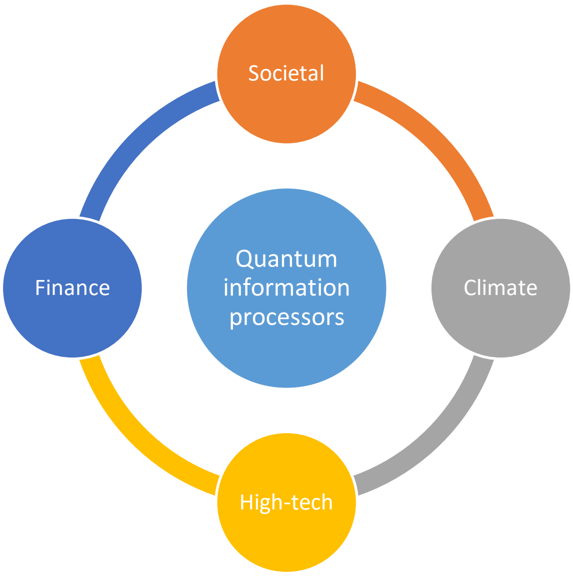


Figure 10. Application scenarios of universal quantum information processors.

Several application scenarios stand to benefit from quantum computing, as described below.

1. **Societal**
   Quantum computing will improve drug development, unlock personalized medicine by speeding up biochemical quantum calculations for a potential drug candidate molecule screening. As well as giving better insight into the interaction of pharmaceuticals on individuals. Another important societal application would be reduction of fraud, identity theft, and other electronic crimes by rapidly identifying breaches, creating more secure encryptions, and more stable system architectures.

2. **Climate**
   Quantum computing can drastically increase prediction accuracy of natural disasters. Equally, according to several McKinsey reports, quantum computers will play a major factor in limiting global warming to 1.5 °C through climate modelling and contributions to net-zero critical sectors. For example, in solar energy, calculations have shown that new perovskite-based solar cells could double the efficiency of today's state-of-the-art technologies, but only quantum computing can precisely simulate perovskite structures with a wide range of structures and compositions. With quantum-level calculations, one can model natural disasters, climate change patterns with much more precision as compared to classical computers.

3. **High-tech**
   Quantum computing simulates battery chemistry in ways which are unachievable with classical computers. McKinsey predicts that new cathode and anode materials developed with quantum simulations can improve battery energy density by up to 50%. In the construction sector, quantum computing has shown the potential to simulate theoretical materials combinations to reduce the carbon footprint of cement with a net global impact of 1 gigaton of carbon per year. Quantum calculations applied in chemistry can help to identify new candidates for green fertilizers, energy-efficient catalysts, and more. With vast increases in the number of calculations possible, artificial intelligence and machine learning stand to make substantial leaps and bounds once given quantum computational platform.

4. **Finance**
   Quantum computing has potential applications in the financial sector, including portfolio optimization, option pricing, risk analysis, fraud detection, credit scoring, and cryptography.

United Nations Sustainable Development Goals

Quantum computing has broad impacts on society and, therefore, on several UN Sustainable Development Goals. Some examples are:

SDG 3 – Quantum computing will improve the pharmaceutical pipeline through higher powered and better optimized quantum chemistry and biochemistry calculations.

SDG 11 – Sustainable Cities and Communities – can contribute to improved and optimized traffic, including connected and autonomous mobility. Also contributes to the update of electric vehicles by contributing to the development of improved battery chemistries.

SDG 12 – Responsible Consumption and Production – can help improve production and logistics optimization to reduce overproduction and waste.

SDG 13 – Climate Action – Quantum computers are widely accepted to play a major factor in limited global warming to 1.5 °C through climate modelling and contributions to net-zero sectors (McKinsey).

4 High-level System Requirements

4.1 System requirements of the THz spectrometer prototypes

To demonstrate the POLYNICES technology, two fully integrated optoelectronics FMCW THz spectrometers will be developed. **Demo-1A** will be a single-channel FMWC THz spectrometer and **Demo-1B** will advance the characteristics of Demo-1A, by supporting a multi-channel operation with beamforming capabilities. In addition to the proposed Demo-1A and Demo-1B, three precursors (**Precursor-0A, Precursor-1A and Precursor-1B**) have been included in order to enable the individual components of the final prototypes and more importantly, to provide useful feedback on the design and fabrication activities.

Figure 11 shows an overview of the respective planned modules and the components on the boards. The complexity increases as you move to the right-hand side.

Precursor 0A **Dual laser**	**Precursor 1A** **THz anten. on EOPCB**	**Demo 1A** **FMCW THz spect. (1×1)**	**Precursor 1B** **OBFN and THz anten.**	**Demo 1B** **FMCW THz spect. (8×2)**
• ECLs – 1550 nm • No EOPCB	• InP- THz PDs/PCAs with DRW antennas • EOPCB	• ECLs – 1550 nm • 1 SOA • 1 THz emitter • 1 THz receiver and 1 TIAs • Wavelength meter	• 8x8 OBFN based on Blass matrix • InP- THz PDs/PCAs with DRW antennas • EOPCB	• ECLs – 1550 nm • 8 SOAs • 8 THz emitters • 2 THz receiver and 2 TIAs • 8x8 BFN based on Blass architecture • Wavelength meter

Figure 11. Summary of the modules for the application of the THz spectrometer. Demo 1A and 1B as demonstrators for the POLYNICES technology and the three precursor modules for preliminary tests and reduction of complexity.

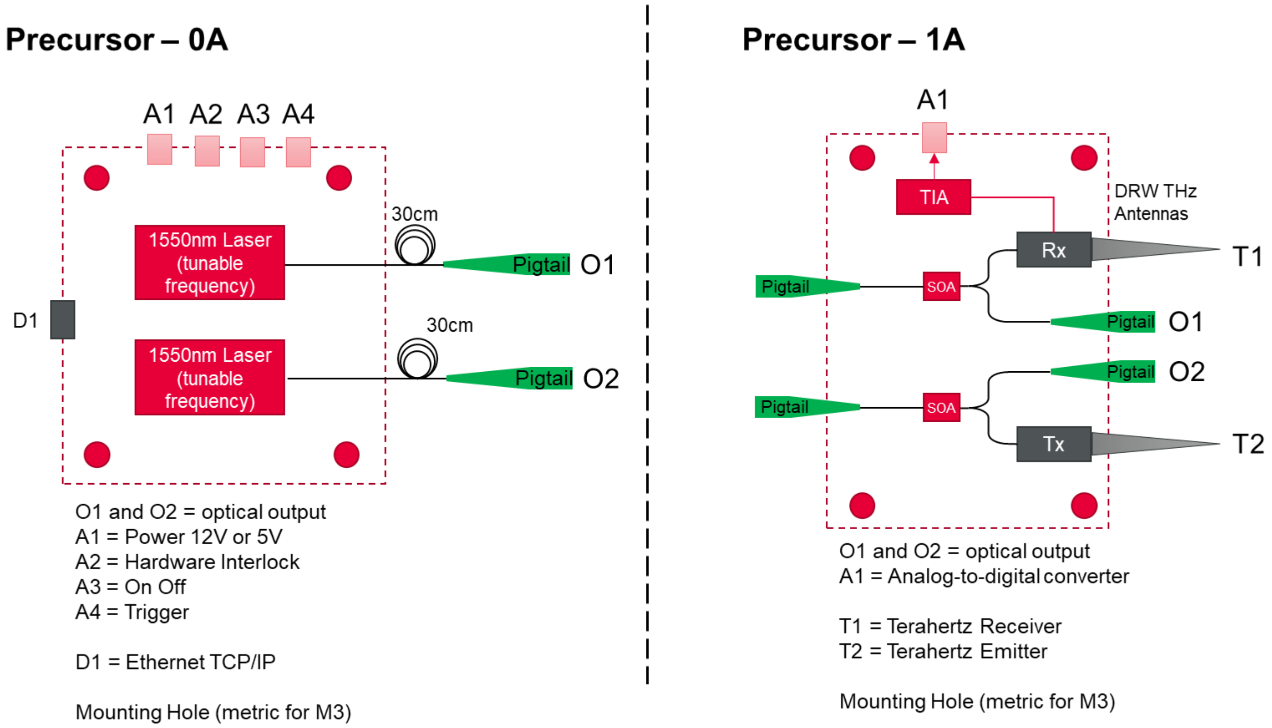
4.1.1 Precursor-0A and Precursor-1A

Figure 12 presents the high-level functional designs of **Precursor-0A** and **Precursor-1A**.

Precursor-0A will host two ECL sources, the same that will be integrated in Demo-1A and Demo-1B (see Figure 12 left). For this first prototype, the photonic integration will be based on the edge-coupling technique since the main target of the prototype is to characterize the performance of the ECLs and develop calibration and configuration algorithms that will be used for the next prototypes.

Precursor 1A will integrate InP-THz antennas combined with dielectric rod waveguide (DRW) THz antennas for transmitting and receiving THz signals (see Figure 12 right) in an EOPCB motherboard. The main target of this prototype is the experimental characterization of this EOPCB motherboard for handling THz signals.

The **Precursor-0A** will be utilized in conjunction with both **Precursor-1A** and standard terahertz antenna modules to replace the current laser sources in a state-of-the-art terahertz system. This Drop-In-Replacement is one of TOPTICA's short-term (approx. 2-3 years) exploitation plan for the early adoption of POLYNCIES technology to the portfolio and lowers the production cost of the existing system.



O1 and O2 = optical output
A1 = Power 12V or 5V
A2 = Hardware Interlock
A3 = On Off
A4 = Trigger

D1 = Ethernet TCP/IP

Mounting Hole (metric for M3)

O1 and O2 = optical output
A1 = Analog-to-digital converter

T1 = Terahertz Receiver
T2 = Terahertz Emitter

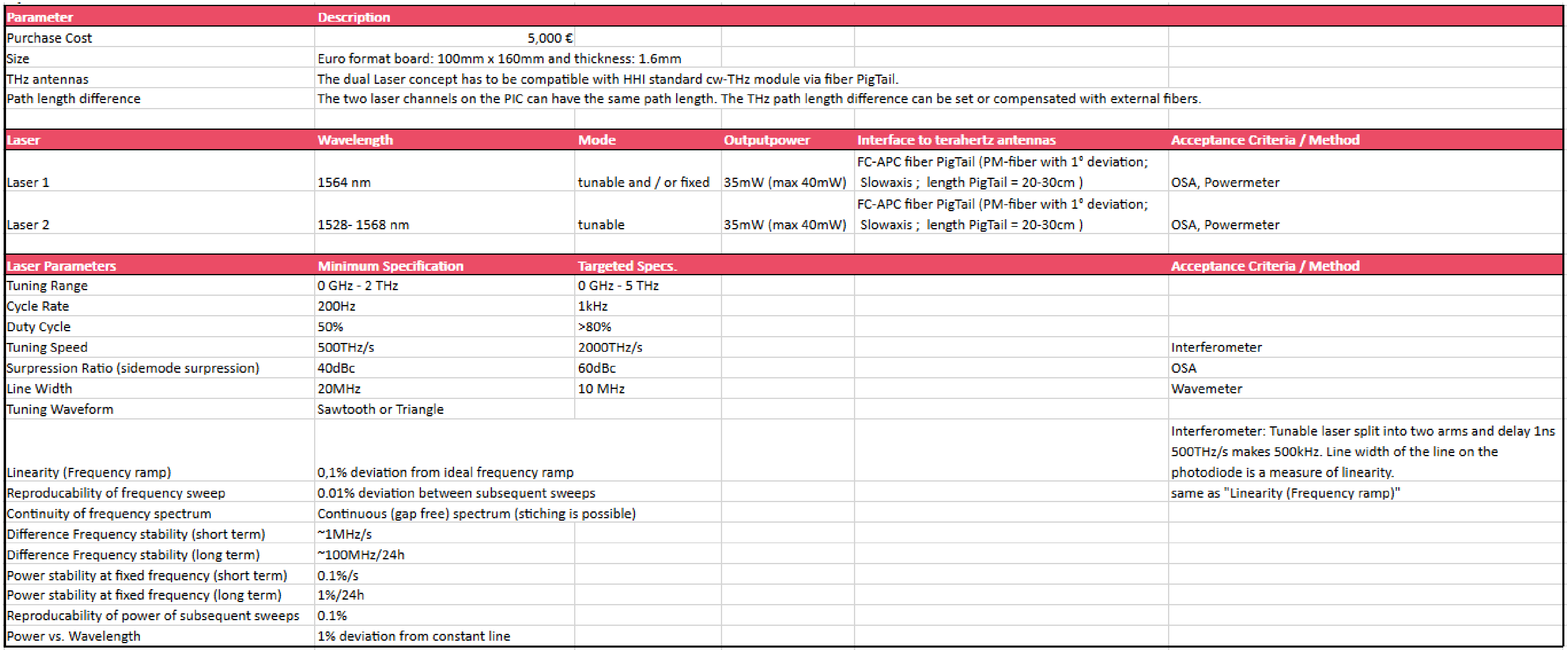
Mounting Hole (metric for M3)

Figure 12. Precursor-0A (left) with two lasers on a single board and the Precursor-1A (right) with two integrated InP THz antennas and the transimpedance amplifier (TIA) on the board.

The majority of specifications for **Precursor-0A** are based on the laser system inside the T-Sweeper prototype, which will be replaced by it. Detailed specifications of the sweeping mode's capabilities are provided because they are crucial for the terahertz application. As described beforehand, one of the relevant criteria is the purchasing price, which should not exceed 5,000€. Table 1 provides a summary of the **Precursor-0A** specifications that are required, as well as acceptance criteria and methods.

Precursor-1A consists mainly of the integrated standard InP antennas from the Fraunhofer Heinrich Hertz Institute and will be in accordance with the specifications of the standard pigtailed cw-THz modules. The pitch and crosstalk of the DRW antennas will be worked out in the project with the help of simulations. **Precursor-1A** currently has no additional requirements.

Table 1. List of specification for the Precursor-0A



Parameter	Description				
Purchase Cost	5,000 €				
Size	Euro format board: 100mm x 160mm and thickness: 1.6mm				
THz antennas	The dual Laser concept has to be compatible with HHI standard cw-THz module via fiber PigTail.				
Path length difference	The two laser channels on the PIC can have the same path length. The THz path length difference can be set or compensated with external fibers.				
Laser	**Wavelength**	**Mode**	**Outputpower**	**Interface to terahertz antennas**	**Acceptance Criteria / Method**
Laser 1	1564 nm	tunable and / or fixed	35mW (max 40mW)	FC-APC fiber PigTail (PM-fiber with 1° deviation; Slowaxis ; length PigTail = 20-30cm)	OSA, Powermeter
Laser 2	1528- 1568 nm	tunable	35mW (max 40mW)	FC-APC fiber PigTail (PM-fiber with 1° deviation; Slowaxis ; length PigTail = 20-30cm)	OSA, Powermeter
Laser Parameters	**Minimum Specification**	**Targeted Specs.**			**Acceptance Criteria / Method**
Tuning Range	0 GHz - 2 THz	0 GHz - 5 THz			
Cycle Rate	200Hz	1kHz			
Duty Cycle	50%	>80%			
Tuning Speed	500THz/s	2000THz/s			Interferometer
Surpression Ratio (sidemode surpression)	40dBc	60dBc			OSA
Line Width	20MHz	10 MHz			Wavemeter
Tuning Waveform	Sawtooth or Triangle				
Linearity (Frequency ramp)	0,1% deviation from ideal frequency ramp				Interferometer: Tunable laser split into two arms and delay 1ns 500THz/s makes 500kHz. Line width of the line on the photodiode is a measure of linearity.
Reproducability of frequency sweep	0.01% deviation between subsequent sweeps				same as "Linearity (Frequency ramp)"
Continuity of frequency spectrum	Continuous (gap free) spectrum (stiching is possible)				
Difference Frequency stability (short term)	~1MHz/s				
Difference Frequency stability (long term)	~100MHz/24h				
Power stability at fixed frequency (short term)	0.1%/s				
Power stability at fixed frequency (long term)	1%/24h				
Reproducability of power of subsequent sweeps	0.1%				
Power vs. Wavelength	1% deviation from constant line				

4.1.2 Demo-1A

Demo-1A will be a single-channel FMCW THz spectrometer and it will integrate in the EOPCB motherboard two external cavity laser (ECL) sources, operating at 1550 nm, in the form of chiplets, for optoelectronic self-heterodyne THz generation on an integrated high-speed InP-PD. The reception of the THz signal and the frequency down-conversion to an intermediate frequency will be performed by an integrated photoconductive InP antenna. Additionally, a wavelength meter based on GRIN lenses will be integrated to monitor the wavelength of the emitted light of one of the two ECL sources and thus monitor the frequency of the THz signal. Figure 13 shows a schematic of the board with the individual components and interfaces.

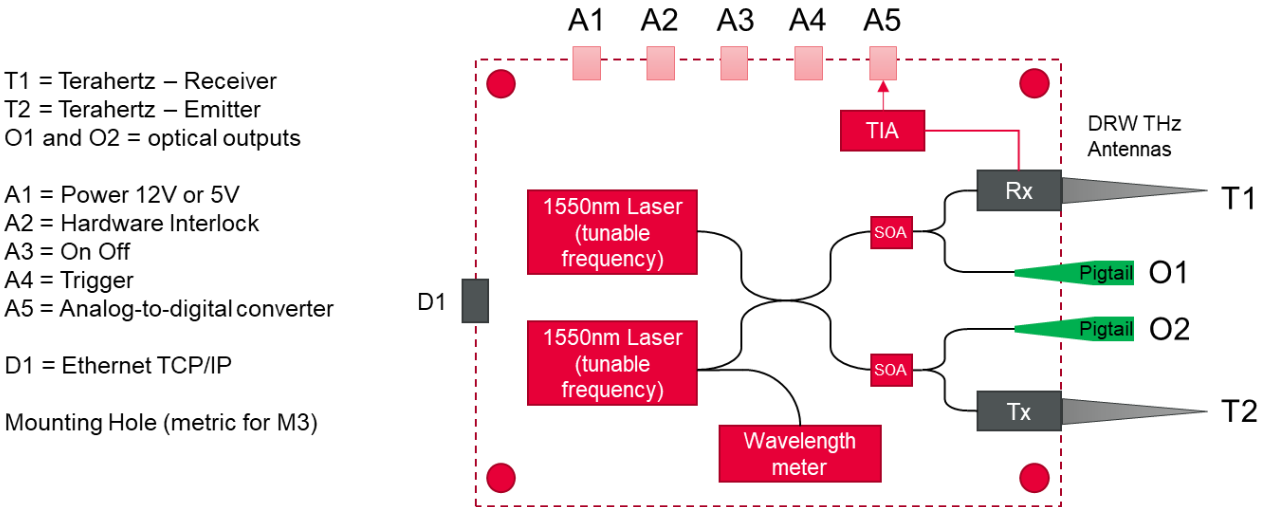
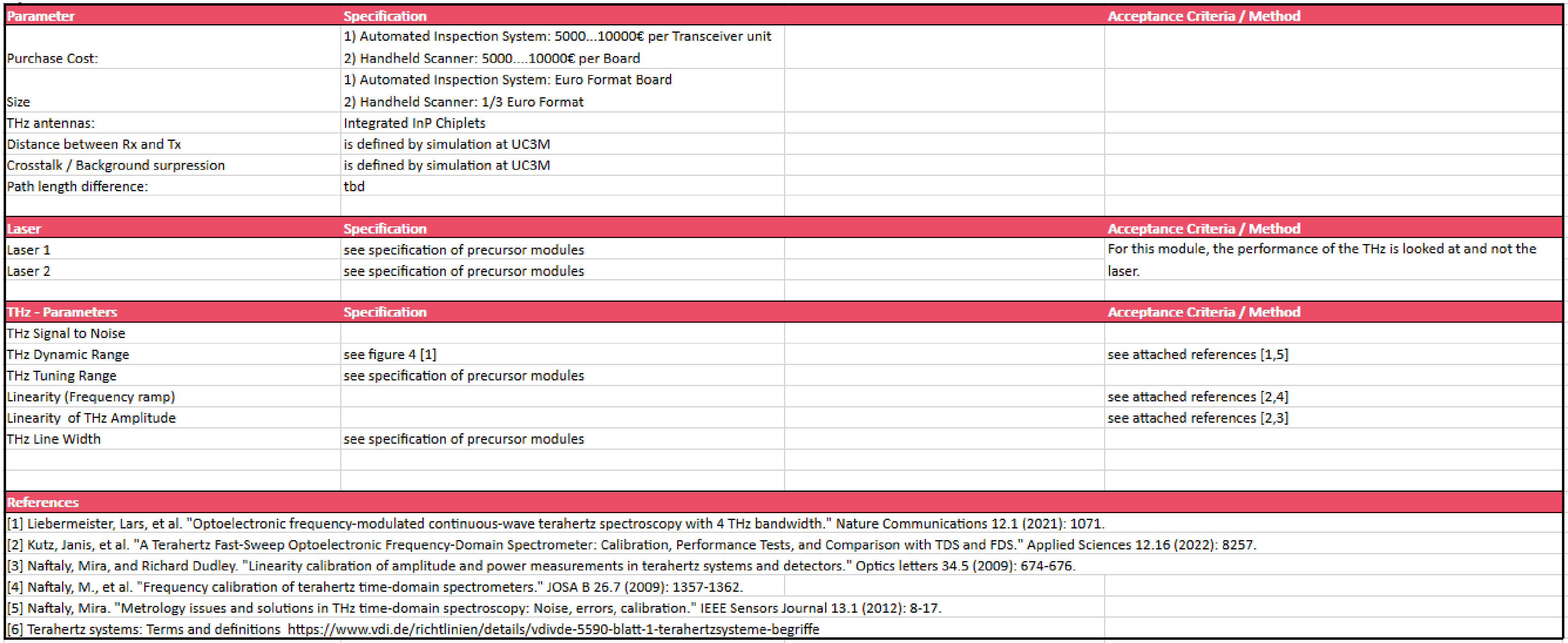


Figure 13. Demo 1A is a FMCW THz spectrometer with THz Waveguides on the integrated photoconductive antennas.

The light from the two lasers is combined and split into two arms. Following the splitter, a SOA in each arm will amplify the optical power. Each SOA is followed by another splitter. One output of each splitter is guided to an integrated antenna chiplet with a DRW waveguide. The two spare optical outputs (O1 and O2) can be used to connect standard fiber pigtailed antenna modules or to monitor. With the outputs, the laser parameters will be tested separately, and thus a potential error analysis is possible.

Again, the following table displays the specifications. For this module, only the THz specifications are considered and evaluated, for example, the system's dynamic range and linearity of the axis. Some references are given for assistance with metrology and expected values. Simulations are still required to determine details like the antennas' pitch and the resulting cross talk (see Precursor-1A).

Table 2. List of specifications for Demo 1A.



Parameter	Specification		Acceptance Criteria / Method
Purchase Cost:	1) Automated Inspection System: 5000...10000€ per Transceiver unit 2) Handheld Scanner: 5000....10000€ per Board		
Size	1) Automated Inspection System: Euro Format Board 2) Handheld Scanner: 1/3 Euro Format		
THz antennas:	Integrated InP Chiplets		
Distance between Rx and Tx	is defined by simulation at UC3M		
Crosstalk / Background surpression	is defined by simulation at UC3M		
Path length difference:	tbd		
Laser	**Specification**		**Acceptance Criteria / Method**
Laser 1	see specification of precursor modules		For this module, the performance of the THz is looked at and not the laser.
Laser 2	see specification of precursor modules		
THz - Parameters	**Specification**		**Acceptance Criteria / Method**
THz Signal to Noise			
THz Dynamic Range	see figure 4 [1]		see attached references [1,5]
THz Tuning Range	see specification of precursor modules		
Linearity (Frequency ramp)			see attached references [2,4]
Linearity of THz Amplitude			see attached references [2,3]
THz Line Width	see specification of precursor modules		
References			
[1] Liebermeister, Lars, et al. "Optoelectronic frequency-modulated continuous-wave terahertz spectroscopy with 4 THz bandwidth." Nature Communications 12.1 (2021): 1071.			
[2] Kutz, Janis, et al. "A Terahertz Fast-Sweep Optoelectronic Frequency-Domain Spectrometer: Calibration, Performance Tests, and Comparison with TDS and FDS." Applied Sciences 12.16 (2022): 8257.			
[3] Naftaly, Mira, and Richard Dudley. "Linearity calibration of amplitude and power measurements in terahertz systems and detectors." Optics letters 34.5 (2009): 674-676.			
[4] Naftaly, M., et al. "Frequency calibration of terahertz time-domain spectrometers." JOSA B 26.7 (2009): 1357-1362.			
[5] Naftaly, Mira. "Metrology issues and solutions in THz time-domain spectroscopy: Noise, errors, calibration." IEEE Sensors Journal 13.1 (2012): 8-17.			
[6] Terahertz systems: Terms and definitions https://www.vdi.de/richtlinien/details/vdivde-5590-blatt-1-terahertzsysteme-begriffe			

4.1.3 Precursor-1B

Precursor 1B will integrate in the EOPCB motherboard an 8x8 OBFN based on Blass matrix architecture for THz beamforming and the THz antennas. The primary purpose of this prototype is to facilitate a comprehensive understanding of the OBFN's capabilities within the context of FMCW THz spectrometry. Additionally, it will serve as a platform for refining and developing configuration algorithms specific to the OBFN. These crucial algorithmic enhancements will be thoroughly fine-tuned before proceeding to the experimental evaluation of Demo-1B. This underscores our commitment to a systematic and meticulous approach throughout the project. Figure 14 shows a schematic of the precursor module 1B:

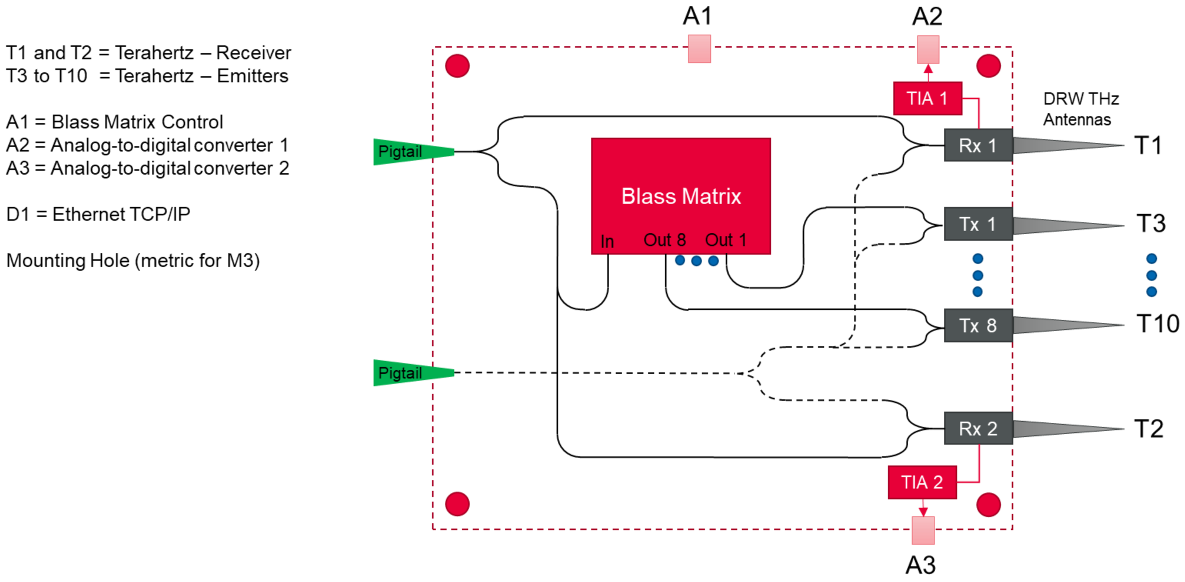


Figure 14. Precursor 1B, consisting of the Blass Matrix and integrated THz antennas. With this module the performance of the beamforming capabilities will be evaluated.

This module's goal is to activate the Blass matrix and, using it along with the integrated antennas, to achieve a THz beamforming with ±10° angle steering.

4.1.4 Demo-1B

Transitioning to **Demo-1B**, we are expanding the capabilities of Demo-1A to support multi-channel operation. This version integrates two ECL-1550 chiplets, an 8x8 optical beamforming network (OBFN) based on Blass matrix architecture for THz beamforming, high-gain arrayed THz antennas for both transmission and reception pathways, InP-PDs, SOAs for THz transmission, photoconductive antennas for THz reception, as well as TIAs and DRVs for signal amplification. Similar to Demo-1A, Demo-1B incorporates a wavelength meter to monitor the wavelength of emitted light, thereby ensuring accurate frequency monitoring of the THz signals. In Figure 10 shows a schematic of Demo 1B with the components on the board and the interfaces.

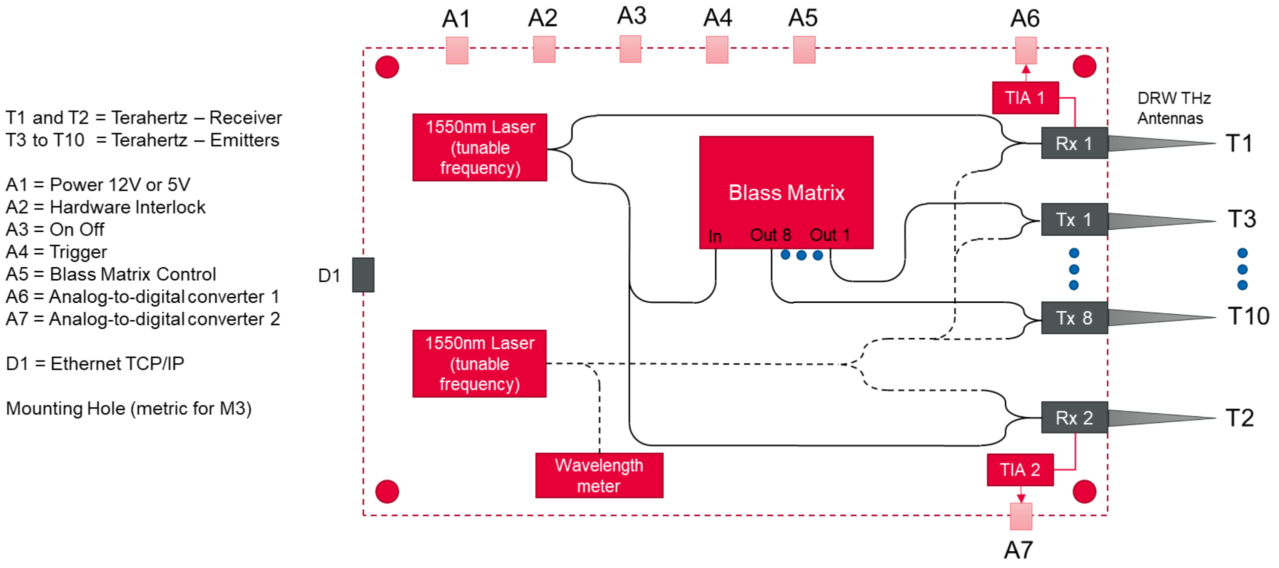
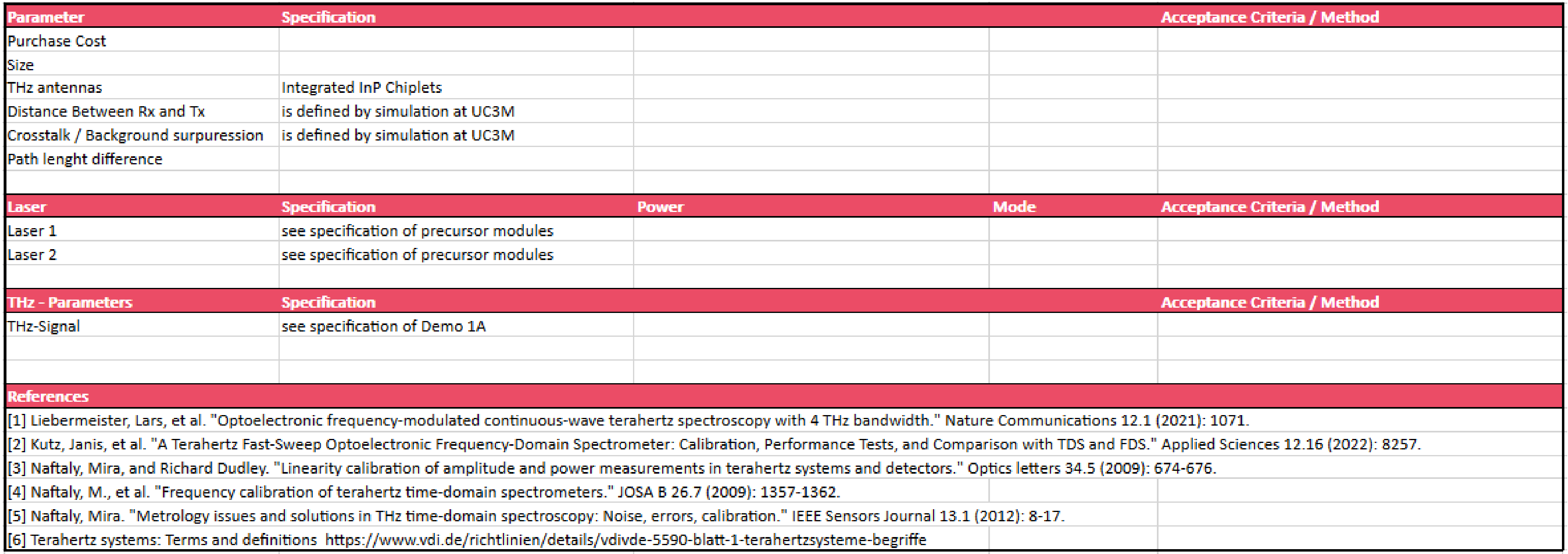


Figure 15. Schematic of the FMCW THz spectrometer (Demo 1B) with the components and interfaces.

The requirements of this demonstrator match the specifications of the previous modules, the specifications are summarized in

Table 3.

Table 3. List of specifications of Demo 1B



Parameter	Specification			Acceptance Criteria / Method
Purchase Cost				
Size				
THz antennas	Integrated InP Chiplets			
Distance Between Rx and Tx	is defined by simulation at UC3M			
Crosstalk / Background surpuression	is defined by simulation at UC3M			
Path lenght difference				
Laser	**Specification**	**Power**	**Mode**	**Acceptance Criteria / Method**
Laser 1	see specification of precursor modules			
Laser 2	see specification of precursor modules			
THz - Parameters	**Specification**			**Acceptance Criteria / Method**
THz-Signal	see specification of Demo 1A			
References				
[1] Liebermeister, Lars, et al. "Optoelectronic frequency-modulated continuous-wave terahertz spectroscopy with 4 THz bandwidth." Nature Communications 12.1 (2021): 1071.				
[2] Kutz, Janis, et al. "A Terahertz Fast-Sweep Optoelectronic Frequency-Domain Spectrometer: Calibration, Performance Tests, and Comparison with TDS and FDS." Applied Sciences 12.16 (2022): 8257.				
[3] Naftaly, Mira, and Richard Dudley. "Linearity calibration of amplitude and power measurements in terahertz systems and detectors." Optics letters 34.5 (2009): 674-676.				
[4] Naftaly, M., et al. "Frequency calibration of terahertz time-domain spectrometers." JOSA B 26.7 (2009): 1357-1362.				
[5] Naftaly, Mira. "Metrology issues and solutions in THz time-domain spectroscopy: Noise, errors, calibration." IEEE Sensors Journal 13.1 (2012): 8-17.				
[6] Terahertz systems: Terms and definitions https://www.vdi.de/richtlinien/details/vdivde-5590-blatt-1-terahertzsysteme-begriffe				

4.2 System requirements of the quantum information processors prototypes

The QIPs that will be developed during POLYNICES projects will be based on the continuous variable discrete value (CVDV) approach. This requires squeezed light states to form GKP qubits that encode the logical information. Here, squeezed light will be generated from optical nonlinearities on-chip. Squeezed states are those whose quantum mechanical uncertainty for an operator, such as phase, is smaller than that of the corresponding ground state. When this is expressed in a squeezing level in dB, a minimum squeezing of 12 dB was identified for the creation of GKP qubits. In general, a higher amount of squeezing is beneficial for error-correctable approaches for fault-tolerant quantum computing.

Over the course of the POLYNICES project, two QIPs will be developed. Functionally both of them target the same applications and use cases described above. Methods for generation of optical squeezed states are well-known in the scientific community [2]. Squeezing can be achieved by nonlinear processes such as spontaneous parametric down conversion (SPDC) in KTP crystals [3] or spontaneous four-wave mixing (SFWM) in micro-ring resonators [4].

The main reason for such a design choice is to prototype, research, and understand which of these two effects (SPDC or SFWM) leads to more reliable results in terms of quantum computation. Another important reason for two different demonstrators with the same end-functionality is to discover the optimal technological process that could potentially be scaled up in the future.

High level diagrams addressing QIPs demonstrators (2A and 2B) are listed below. Both demonstrators will require development of co-integration of TriPleX and PolyBoard platforms, that being another significant goal of the POLYNICES project. That includes development of the alignment technology between chiplets, flip-chipping technology for bringing electrical connections together with photonic chiplets and soldering techniques in order to establish reliable electrical connections.

The basic operational principle of both demonstrators is similar:

1. Light source generates pumping laser light (ECL-775 nm or ECL-1550 nm).
2. In squeezed light generators (SQ-8 or SQ-12) CW light is being converted into squeezed state of light (quantum object).
3. In Clement matrices (CM-16x8 or CM-24x8) squeezed of light are being subjected to a number of quantum logical operations.

4.2.1 Demo-2A

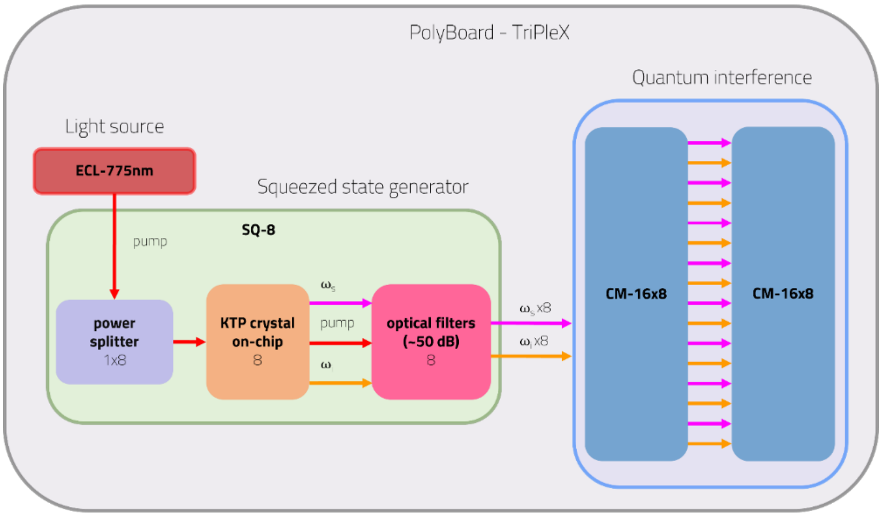


Figure 16. Demonstrator 2A will include the following components: external cavity laser (ECL-775 nm), squeezed light generation module (SQ-8) consisting of power splitter, a set of 8 KTP crystals, optical filters and Clement matrices (CM-16x8).

Figure 16 shows the high-level functional layout of Demo-2A. Demo-2A will integrate in the motherboard two (2) CM-16x8 TriPleX chiplets at the core of the processor to achieve a 16x16 matrix, thus scaling the processor without yield issues and without electrical pad density issues. It will have an integrated pump source consisting of an ECL-780, PPKTP non-linear crystals and filters for the generation of signal and idler entangled photon pairs. The output signals will be coupled by fiber array to external single photon detectors.

4.2.2 Demo-2B

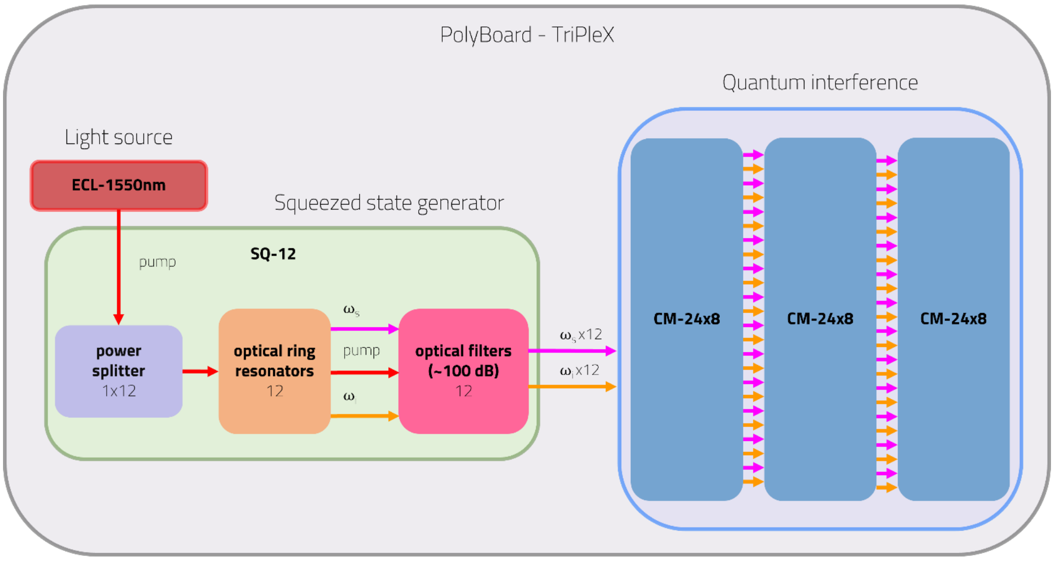


Figure 17. Demonstrator 2B will include the following components: external cavity laser (ECL-1550 nm), squeezed light generation module (SQ-12) consisting of power splitter, a set of 12 micro-ring resonators, optical filters and Clement matrices (CM-24x8).

Figure 17 presents the high-level functional layout of Demo 2B. Demo-2B will integrate three (3)CM-24x8 chiplets to form a record size of 24x24 matrix. The pump source will generate an array of 8 squeezed light states from an ECL-1550 source combined with the SQ-8 chiplet that will feed the processor. External detectors will be used also in Demo-2B.

Below we introduce requirements for two sets of components that will be used for QIPs. Novel components such as external cavity laser integrated on chip, KTP crystals integrated on chip, micro-ring resonators and (PZT) based phase-modulator are largely non-linear components design, integration and testing of which will require significant effort. Basic components such as power splitters, optical filters and Clements matrices are linear photonic integrated circuits development of which will require minimal time as those are well known components that are widely used in industry.

4.2.3 Novel component requirements

Table 4. Specification of the external cavity lasers

Parameter	**Demo-2A** ECL-775 nm	**Demo-2B** ECL-1550 nm
CW laser		
Average power (per channel)	~120 mW * 8 channels	~150 mW * 12 channels
Tuning Range	± 5 nm	± 5 nm
Tuning accuracy	0.1 nm	0.1 nm

An external cavity laser (ECL) is a type of semiconductor (InP) laser that includes an external cavity for controlling the laser's output characteristics. Unlike conventional semiconductor lasers, where the light bounces back and forth within the semiconductor material, ECLs use an external mirror or a diffraction grating to create an extended cavity for light to travel.

The external cavity provides several advantages over conventional semiconductor lasers, such as:

- Narrow linewidth: ECLs can achieve much narrower linewidths, which refers to the spectral width of the emitted light. This feature makes them useful for applications requiring precise and stable wavelength output. In the case of QIP demonstrators narrow linewidth is crucial in order to excite SPDC and SFWM in non-linear components such as micro-ring resonators and KTP crystals.

- Wavelength tunability: The external cavity design allows for easy tuning of the laser's wavelength. By adjusting the angle or position of the external mirror or grating, the output wavelength can be finely tuned over a certain range. A small tunability range is required for the on-chip integrated ECL to have freedom to compensate for unexpected resonance shift in non-linear components. Such a resonance shift may be caused by assembly process of KTP crystals or due to increased heat load on micro-ring resonators.

- Mode-hop-free operation: ECLs can operate in a mode-hop-free manner, meaning the laser output wavelength changes continuously without sudden jumps. This characteristic is beneficial for applications where a stable and continuous wavelength is required.

- Higher output power: ECLs can often achieve higher output powers compared to standard Fabry-Perot or distributed feedback (DFB) lasers, making them suitable for applications demanding more optical power. Relatively high output powers are required for on-chip integrated ECL to ensure correct functionality of a QIP. This considers power splitting, propagation losses as well as activation energy required for SPDC and SFWM processes.

Table 5. KTP crystals.

Parameter	Demo-2A
Wavelength	775 nm
Crystal type	Type 2, degenerate
Polling	Aperiodically polled
Photon rate	$100*10^3$ – $16*10^9$ photons/s
Internal pump suppression	60 dB
Pump power on the bus	< 100 mW

KTP is a quasi-phased-matched crystal that converts light of one wavelength into a different wavelength. This we are referring to is SPDC, a three-wave mixing process that can occur in materials with second-order nonlinear optical susceptibility, $\chi(2)$, such as potassium titanyl phosphate (KTP) (is an inorganic compound with the formula $KTiOPO_4$). This material reacts in the presence of an electric field, E(t), in a nonlinear way. This means that their polarization will depend quadratically on the applied electric field. This can lead to a down-conversion process when a higher-energetic pump photon is converted into two lower-energetic photons (usually referred to as signal and idler) of doubled frequency.

There are different variations of the SPDC process when the signal and idler have the same polarization (type-0) or orthogonal polarization (type-2), the same wavelength (degenerate) or separate wavelengths (nondegenerate), emitted along the direction of the pump beam (collinear) or at some angle (noncollinear).

We aim to use a periodically polled KTP crystals for the reason of higher photon indistinguishability [5]. High photon indistinguishability in this case means that all the photon pairs generated in the ppKTP crystal are as close as it can be copies of each other.

Table 6. Micro-ring resonators.

Parameter	Demo-2B
Wavelength	1550 nm
Pumped resonance width	1-10 pm
Resonance periodicity	1 nm
Signal/idler width	1-10 pm
Q	2-10*106
Propagation loss	0.001 - 0.1 dB/cm
Coupling	2-10 %
Effective index	1.41
Group index	1.7
Resonator escape efficiency	≥ 90%
Squeezing	> 13 dB
Pump power on the bus	< 100 mW

Spontaneous four-wave mixing in waveguide ring resonators is a promising approach to generate high levels of squeezing on compact, scalable photonic chips [6]. This approach relies on both using high-confinement SiN waveguides, leveraging their large nonlinear waveguide parameter, and ring resonators for the field enhancement to obtain the required optical intensities.

Four-wave mixing is a nonlinear process where four optical waves interact. Degenerate four-wave mixing is the process where the energy of two pump photons with frequency is transferred to a signal photon with frequency and an idler photon with frequency, as shown in Figure 18(a).

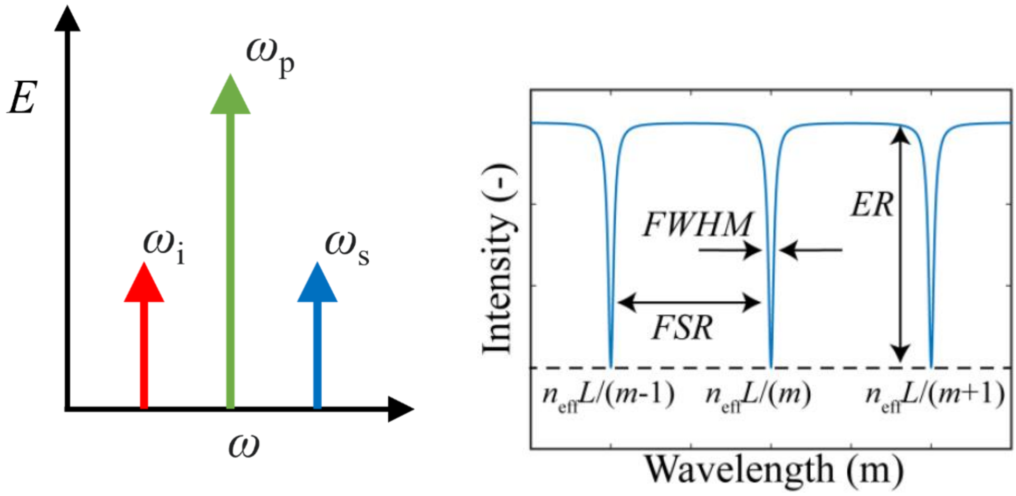


Figure 18. (Left) Schematic of degenerate four-wave mixing. (right) Normalized ring resonator transmission spectrum indicating the resonance parameters.

The important figure of merit is the photon escape efficiency from the micro-ring resonator, , it is the ratio between the outcoupling loss rate and the total loss rate including internal cavity loss and outcoupling loss. In other words, it describes the success rate of extracting a (generated) photon from the ring resonator. It is given by the ratio of the loaded quality factor over the coupling quality factor . These quality factors can easily be determined from the ring resonator design parameters [7] and in the limit of narrow resonances (i.e., FSR ≫ FWHM).

Table 7. PZT based phase-modulators.

Parameter	Demo-2A, 2B
Wavelength	1550 nm
Excess optical losses	< 0.1 dB
Vπ	< 20 V
Repeatability	> 99 %
Switching frequency	> 10 MHz
Phase stability	± 0.005 deg
Power consumption	<1 mW at 1 kHz
Footprint	< 5 mm

Phase modulation is a key enabling feature for the generation of quantum interference and as a consequence implementation of logical operations on qubits in photonic-based quantum computation. Because of that, the task of designing a reliable and fast phase modulator is of utmost importance. In POLYNICES we chose to address the piezo-electric approach to phase modulation. The idea is that the strain/stress field affects the TriPleX waveguide by mechanically stretching/compressing the waveguide along a given direction. This leads to an immediate local change of the refractive index and consequently allows to realize of quantum interference of photons propagating through the affected area of the waveguide. The piezo-electric material of choice is $Pb[Zr_xTi_{1-x}]O_3$ (PZT). It was previously shown by LioniX that this material exhibits a high order of piezo-electric effect. This allows placing PZT and corresponding driving electronics further away from the TriPleX waveguide. This spatial separation helps to decrease optical losses from the interaction of light with metal layers of driving electronics.

4.2.4 Basic component requirements

Table 8. Power splitters.

Parameter	Demo-2A	Demo-2B
Wavelength	775 nm	1550 nm
Splitter	1x8	1x12
Propagation loss	0.001 - 0.1 dB/cm	

Optical power splitters are on-chip integrated devices that perform the function of splitting an incoming optical signal into multiple output signals with specific (in our case equal) power ratios. For the QIPs being developed in the course of POLYNICES project power splitters will distribute optical power between a number of non-linear components for squeezed states generation (micro-ring resonators and KTP crystals).

Table 9. Optical filters.

Parameter	Demo-2A	Demo-2B
Wavelength	775 nm	1550 nm
Filter type	Notch Filter	
Stopband	500 pm	
Attenuation in stopband	50 dB	100 dB
Propagation loss	< 0.5 dB/cm	

Optical filters are used to selectively transmit or block certain wavelengths or wavelength ranges of a light beam. They are essential components of many photonic circuits for applications in optical computing and information processing, and telecommunications. The basic principle of optical filtering involves reflection of unwanted wavelengths and transmission of allowed ones.

Generation of squeezed states in micro-ring resonators or KTP requires high optical power levels to generate few-photon states at adjacent resonances. Therefore, resolving the squeezed states requires a high-quality optical filter that blocks the pump light with a narrow bandwidth. This type of filter is commonly referred to as a notch filter, which reflects the pump light and allows all other wavelengths to go through. Since the power of the sidebands are orders of magnitude lower than that of the pump, the required filter must have a large stop-to-pass-band-ratio. For the Polynices project, a filter with a 50- and 100-dB pump suppression were deemed necessary. Furthermore, the filter's total insertion loss for the squeezed state should also be minimal to not lose the squeezed states at the output. Here, a filter insertion loss down to 0.5 dB was considered.

Table 10: Clements matrices

Parameter	Demo-2A CM – 16x8	Demo-2B CM – 24x8
Wavelength	1550 nm	
Inputs	16	24
Outputs	16	24
Unit cell layers	8	
Number of phase-modulators (PZT)	120	276
Propagation loss	0.001 - 0.1 dB/cm	

Clements matrix in the terminology of POLYNICES project refers to a photonic quantum information processor based on Mach-Zehnder interferometer (MZI). This is the key components in implementing quantum computing using photons as qubits. The Mach-Zehnder interferometer is a well-known optical device that can manipulate the quantum state of photons through interference effects.

In this setup, single photons, entangled photon pairs or squeezed states of light serve as qubits. The MZI is configured to perform various quantum operations on these qubits, such as quantum logic gates, superposition, and entanglement generation. The MZI consists of two beam splitters and two phase-modulators arranged in a way that creates interference between the two possible paths a photon can take. This interference allows for constructive or destructive interference, effectively encoding quantum information.

Clements matrix is a well-developed component at QuiX Quantum that is being produced by LioniX.

5 Conclusions

This deliverable is the outcome of the initial work carried out in the framework of WP2 within T2.1 “*System design: Use cases, system requirements and component specifications*”.

Leveraging the technological advancements pursued within POLYNICES project, the end-users of the consortium, TOPTICA and QuiX Quantum have identified the non-destructive FMCW THz spectroscopy and quantum information processing as the main application areas, respectively.

Regarding the FMCW THz spectrometers, POLYNICES will target the development of two fully integrated FMCW THz spectrometers. Demo-1A will support single-channel operation, having one THz transmitter and one THz receiver and it stands as a compact yet substantially potent counterpart to cutting-edge spectrometer from FhG-HHI and TOPTICA, maintaining parity in capabilities while significantly reducing its physical footprint. Thanks to this reduction of size, Demo-1A holds the potential to play a pivotal role in facilitating the commercial viability of this optoelectronic innovation, particularly as it pertains to THz handheld scanners. Demo-1B comes as an upgraded version of Demo-1A, offering multi-channel operation and supporting THz beam steering capabilities. Similar, multi-channel FMCW THz spectrometers have been used commercially in inline thickness measurement of plastic pipes. POLYNICES follows a step-wise approach to the development of its technology and so, three additional precursor prototypes (Precursor-0A, Precursor-1A, and Precursor-1B) have been defined to facilitate the experimental evaluation of the individual piece parts. Apart from these use cases, POLYNICES’s unique approach of generating and detecting THz signals in an EOPCB motherboard can be seen as cornerstone technology for not only THz spectrometers but also within the framework of future telecommunication systems and test & measurement devices.

Several application scenarios stand to benefit from quantum computing. POLYNICES’s universal quantum information processors can be used in a wide range of application areas covering use cases with high social and climate impact to use cases with impact on the finance and high-tech sectors.

The identifications of the target use cases have led to the definition of the first set of system requirements of all the POLYNICES prototypes. The system requirements will be subsequently translated into system and component specifications that will define the functional layouts of the prototypes. The specifications of all prototypes as well as the initial system simulation studies are the subject of deliverable D2.2 “*Initial report on system and component specifications and system simulations*”.

LIST OF FIGURES

LIST OF TABLES

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