D4.2 Demonstration of high-speed receiver module and evaluation of performance of the PIC

Grant Agreement number: 820466

Project acronym: CIVIQ

Project title: Continuous Variable Quantum Communications

Funding Scheme: H2020-FETFLAG-2018-03

Deliverable reported: D4.2 Demonstration of high-speed receiver module and evaluation of performance of the PIC

Due date: 31/09/2021

Name, title and organization of partner:

Tobias Beckerwerth, HHI

Stefan Richter, MPL

Alberto Hinojosa, VLC

Eleni Diamanti, CNRS

Christoph Marquardt, MPL

Project website address: http://civiquantum.eu/

Contents

This project has received funding from the *European Union's Horizon 2020 research and innovation programme* under grant agreement No 820466.
www.civiquantum.eu

1. Introduction and objectives

The work package 4 (WP4) of Advanced Components aims at providing a clear vision towards the photonic integration of CV-QKD systems. In general, the goal is to achieve the optimum system performance of current and future systems meanwhile allowing the miniaturization and thus integration of CV-QKD systems, sub-systems and components. To this end, it is necessary to develop high-performance components and sub-systems, which fulfil the specific and very diverse system requirements for CV-QKD and classical systems. Additionally to the performance, the development of advanced components is also targeting a very versatile functionality to cover different system schemes.

To address these two contrary aspects, naming performance and functionality, different material platforms for discrete building blocks as well as employable integration techniques are investigated. Building blocks with different functionalities on different material platforms are defined and separated in a manner, that these sub-assemblies can be integrated in existing process flows. In that way, the feasibility of integration and miniaturization of CV-QKD systems will be guaranteed. The sub-assemblies should also be designed using a generalised approach to satisfy a wide range of different system requirements and allow scalability of future CV-QKD systems.

Methodologically, the development of the components is planned in two stages. In the first stage, discrete components or sub-systems should fulfil all the system requirements while, in a second stage, components are considered, which can demonstrate the technical feasibility for full integration.

Therefore, different material systems and integration approaches are considered to design and fabricate Photonic Integrated Circuit (PIC) based components. As most promising material systems to allow miniaturization, integration and high performance, SiNx and InP are considered, to realize advanced photonic components for next-generation PIC based CV-QKD systems. It should also be evaluated how these components and sub-assemblies can be integrated and fabricated using more sophisticated techniques.

The main objective of WP4 is to develop key components required in CV-QKD systems, in particular, CV-QKD transmitters and receivers, quantum random number generation devices and signal processing electronics. All the components should satisfy a very generic functionality for different system designs, but also have the potential for scalability to address a future market penetration. Most relevant for D4.2 is Task 4.2 “Demonstration of high-speed receiver module and evaluation of performance” (HHI, MPL, VLC, CNRS) (M04-M36)”. As described in the DoA:

- ICFO, CNRS and HHI will derive the requirements regarding the functionality and the performance for a CV-QKD receiver fitting to the systems specifications for future CV-QKD (class B) systems

This project has received funding from the *European Union’s Horizon 2020 research and innovation programme* under grant agreement No 820466.
www.civiquantum.eu

- VLC and HHI will derive the required customized building blocks for the implementation of a fully integrated receiver PIC
- HHI is covering the assembling and packaging of the receiver PIC to a fully integrated photodetector module
- MPL does an characterization and evaluation of the receiver module in order to test its capability for system integration

2. Work progress and achievements during the period

The development of a generic high-speed CV-QKD receiver yielded two fully packaged photodetector modules compatible with an existing evaluation platform, which are based on established data-com technology.

Figure 1 Fabricated CV-QKD receiver module for single polarization in a butterfly package with 2 pairs of balanced photodiodes, optical hybrid, and transimpedance amplifier as well evaluation board compatible also for polarization-multiplexing

The receiver is based on a monolithic photonic integrated circuit for quantum technologies (QPIC) on an InP platform comprising two pairs of balanced photodiodes and the 90° hybrid for single polarization, which have been fully packaged and assembled with a TIA. The butterfly package and the evaluation board offer the opportunity also to use it for detection schemes using polarization multiplexing. The local oscillator (LO) is separately packaged and based on an existing commercially available low-linewidth laser from LioniX/ CHILAS. Since the laser technology is also formed by an InP gain chip fabricated at HHI, which is hybrid integrated with a SiNx cavity, it has the potential to be completely packaged as one receiver QPIC in future work. This concept of hybrid integration of existing PICs from different material platforms can also be expanded to other components and sub-components. Consequently, the deliverable is not only demonstrating a functioning high-speed receiver for CV-QKD, but also drawing a vision for the photonic integration of future CV-QKD systems.

This project has received funding from the *European Union's Horizon 2020 research and innovation programme* under grant agreement No 820466.

2.1. Requirements and technical approach

In a dedicated meeting of all participants of work package 4 (advanced components) and work package 7 (CV-QKD systems) a summary of all important technical requirements regarding its functionality and performance was worked out. To share a common clear vision towards the photonic integration of CV-QKD systems, the systems under development (class B systems) were evaluated regarding their different functionality demands and divided into a base set of components or building-blocks. The full definition of the receiver requirements was derived by system partners (ICFO, CNRS, AIT, MPL) in order to fulfil the requirements to a wide range of system designs. In return, it was evaluated which system architectures are more suitable for photonic integration. The integration partners (HHI, VLC) translated the system-blocks into a photonic blocks schematic.

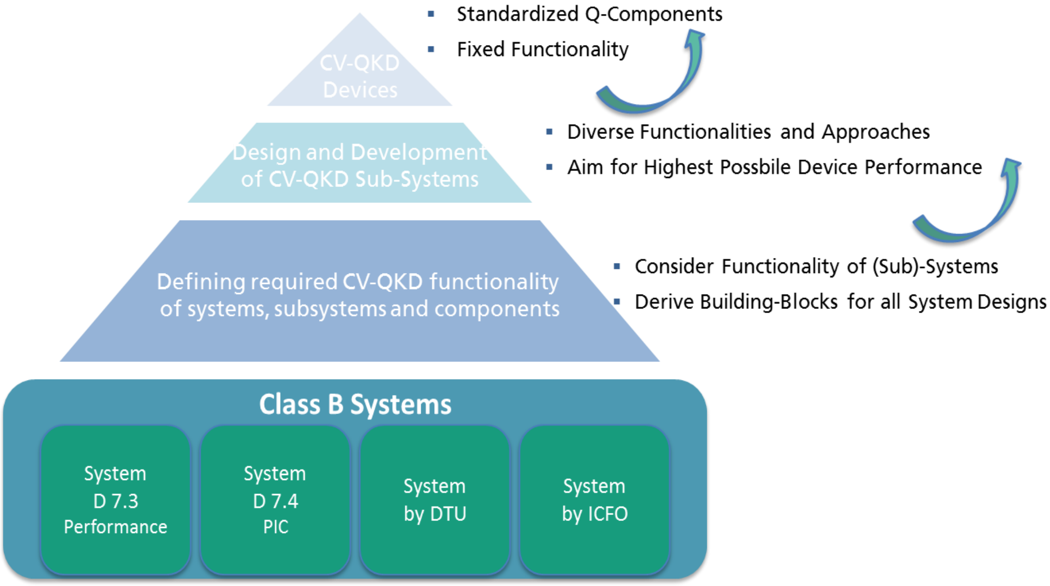

Figure 2 Bottom-Up approach of WP4 to derive requirements

Additionally, the building blocks were classified regarding specific performance metrics to hit the requirements, e.g. extinction ratio, bandwidth or linewidth. In general, the performance is addressed to satisfy the system with maximum requirements.

Device	Component	Unit	Min	Typ	Max
Receiver module	Local oscillator linewidth	kHz	< 50	40	10
	Local oscillator output	dBm	> 3	10	14
	PD responsivity	A/W	> 0.15	0.16	0.2
	PD f3dB bandwidth	GHz	> 37	43	45
	Clearance	dB	> 3	10	15

Table 1 Requirements in functionality for CV-QKD receiver

As a conclusion, it was reasonable to develop high-performant sub-components, which can work stand-alone as discrete fiber connected components, but which are also compatible

This project has received funding from the *European Union's Horizon 2020 research and innovation programme* under grant agreement No 820466.
www.civiquantum.eu

with a hybrid or monolithic integration approach to simplify the integration of future more complex circuits. As most promising material systems for the CV-QKD receiver development, SiNx as well as InP are considered, to realize advanced photonic components for next-generation PIC based CV-QKD systems. The full list of requirements for the receiver is presented in Table 1.

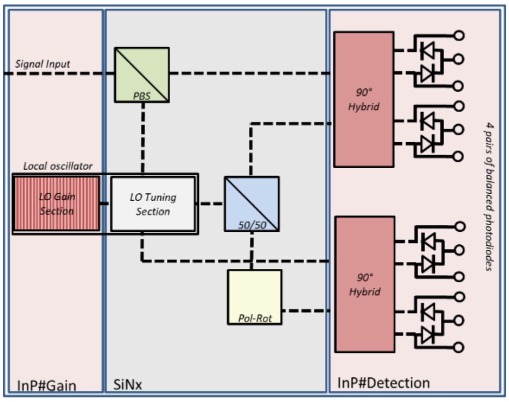

Figure 3 Proposed blocks diagram for the CV-QKD receiver PIC. (Acronyms) LO: local oscillator, PBS: polarization beam splitter, 50/50: beam splitter, Pol-Rot: polarization rotator

The full receiver PIC and its schematic block diagram is presented in Figure 3. Additionally, a suggestion for the material platform derived. For the fabrication of different building blocks of the receiver, photonic platforms are compared regarding the availability and the specific requirements derived in collaboration with WP7 (see Table 2). The requirement of a low linewidth laser makes it mandatory to combine an InP gain chip with a cavity with low losses. In the first device generation, the functionality is separated in three different parts for a combined QPIC, namely the InP#Gain section, the SiNx for LO tuning and the InP#Detection. By this approach, for later generations of the receiver the performance and functionality can easily be adjusted by only replacing a dedicated part of the receiver PIC. Further, it allows to address technological issues without running a full fabrication process.

	MPW photonic platforms				**Dedicated photonic platforms**		
Component	HHI JePPIX *InP*	SMART JePPIX *InP*	Cea LETI *SiPh*	TriPleX HHI *SiNx + InP*	SMART *InP*	Cea LETI III-V Lab *SiPh + InP*	HHI *InP*
Laser	✓	✓	x	✓	✓	✓	✓
90° Hybrid	✓	✓	✓	✓	✓	✓	✓
Photodiodes	✓	✓	✓	✓	✓	✓	✓
PBS	✓	x	x	✓	✓	x	✓
PBC	✓	x	✓	x	✓	✓	✓
SSC	✓	x	x	✓	x	x	✓

Not ful-fill requirements
under investigation
Satisfy requirements

✓ available
X not available

unding from the *European Union's Horizon 2020 research and innovation programme* under grant agreement No

Table 2 Platform evaluation for different receiver sub-components

Some benefits of the HHI MPW platform are the number of suitable photonic blocks such as spot-size converters for efficient coupling to standard single-mode fibres (SMF), as well as the availability of polarization converters to rotate from TE o TM, together with polarization splitters to separate both polarization with an extinction ratio (ER) higher than 25 dB. This reflects the implementation of possible CV-QKD schemes using polarization multiplexing. Still, for the implementation of a low-linewidth laser a monolithic integration is crucial and challenging.

Due to the stringent requirements on laser linewidth below 100 kHz on the system, the partners agree to focus efforts on monolithically integrating the detection stage with photodiodes and a 90° hybrid, but using an external laser. The external laser is realized using a SiNx cavity, which allows to follow the same approach used for the transmitter development. This opens the path to fully integrate the laser in future device generations, when the InP#Gain section and the InP#Detection section will be monolithically integrated.

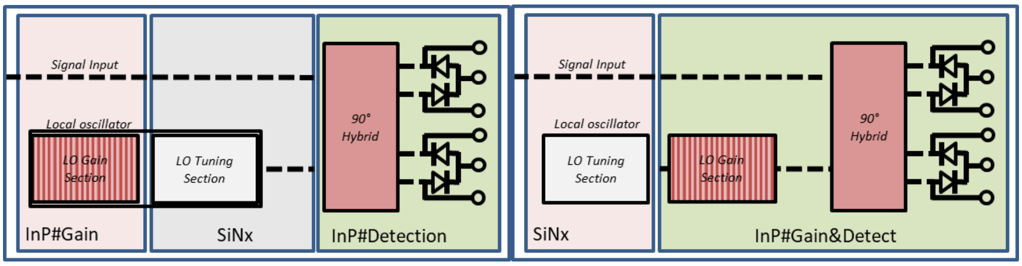

Figure 4 Proposed blocks diagram for future CV-QKD receiver PIC to reduce the number of hybrid integration steps. Simplified SiNx PIC with same number of sub-PICs (left) and with a reduced number of hybrid integrated PICs (right)

In a more sophisticated system approach, there is no need for a dual polarization detection scheme. Therefore, no building blocks for polarization rotation or polarization beam splitting are required. The resulting simplification reduces the PIC complexity and also offers the opportunity to reduce the number of sub-PICs. Since the approach with three different sub-PICs (left) has the potential to be applied for dual-polarization system architectures while maintaining the same sub-components on the InP platform, this receiver scheme is targeted in the development of task 4.2 within the work package 4 (Advanced components). For the first generation of the receiver development, the local oscillator compromising a InP#Gain section and the SiNx cavity will be packaged separately from the photodiodes integrated with a trans-impedance amplifier (TIA).

2.2. Fabrication and assembling of the CV-QKD receiver

As the heart-piece of the receiver, the InP detection section is formed by two pairs of balanced photodiodes and a 90° optical hybrid. The detection PIC is monolithic integrated in InP and

This project has received funding from the *European Union's Horizon 2020 research and innovation programme* under grant agreement No 820466.

assembled with two optical fibre inputs for the signal (S) and the local oscillator (LO) and electrically packaged with a low noise TIA.

2.2.1. Fabrication and integration technique

The local oscillator consisting of an InP gain chip fabricated at HHI and the SiNx cavity in combination with an electronic control unit are provided from LioniX / CHILAS B.V.

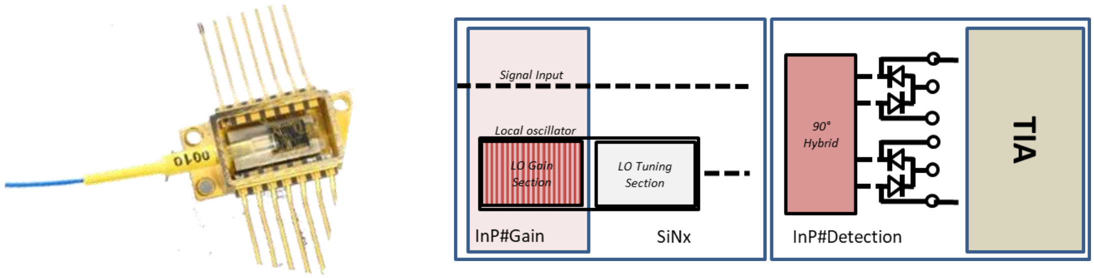

Figure 5 Tunable narrow linewidth laser provided from CHILAS as local oscillator for CV-QKD receiver (left) and schematic block diagram of fully integrated CV-QKD receiver (right)

This laser is based on a technology, which is compatible to the other receiver components, which is suitable for future co-integration with the detection PIC and the TIA. As a core element of future CV-QKD systems, the receiver is based on proven telecommunication components. The technology is built on a hybrid integration technique to easily expand the functionality, e.g. polarization multiplexing, local and transmitted LO signal and allowing high-speed for a versatile and agile system integration with deployed and existing infrastructure. By this approach, the development of an integrated receiver in WP4 is not only providing an advanced component for CV-QKD, but also a more generic tool-box which can be adapted for diverse telecommunication systems.

2.2.2. Receiver PIC characterization

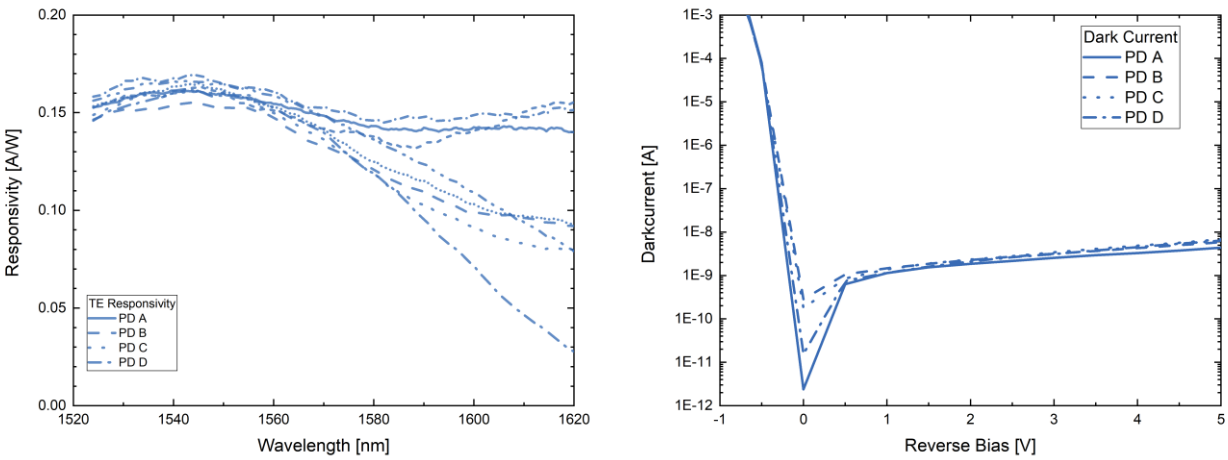

Figure 6 Responsivity and dark current of the fabricated InP detection PIC

This project has received funding from the *European Union's Horizon 2020 research and innovation programme* under grant agreement No 820466.

The InP PIC with the detection stage including two pairs of balanced photodiodes as well as the optical hybrid is characterized and evaluated. The responsivity as well as the dark current is measured for all 4 photodiodes (A-D) independently and presented in Figure 6. At a centre wavelength of 1550 nm the responsivity succeeds 0.15 A/W for all photodiodes, when coupling the receiver PIC from both fibre inputs. The dark current at the operational reverse bias voltage of 2 V is below 5 nA (see Figure 6).

2.2.3. Receiver assembling and packaging

The detection receiver PIC is assembled and co-packaged with a low-noise TIA in a butterfly package. The two optical fibre inputs are coupled using a fibre-array to guarantee a high external quantum efficiency (QE), but also a balanced characteristic between the different output channels OUTP0, OUTN0, OUTP1 and OUTP1. As an indication of a balanced characteristic between the different RF outputs, we expect the same photo currents at VPDS0 and VPDS1, when coupling through the two fibre inputs for LO and Signal.

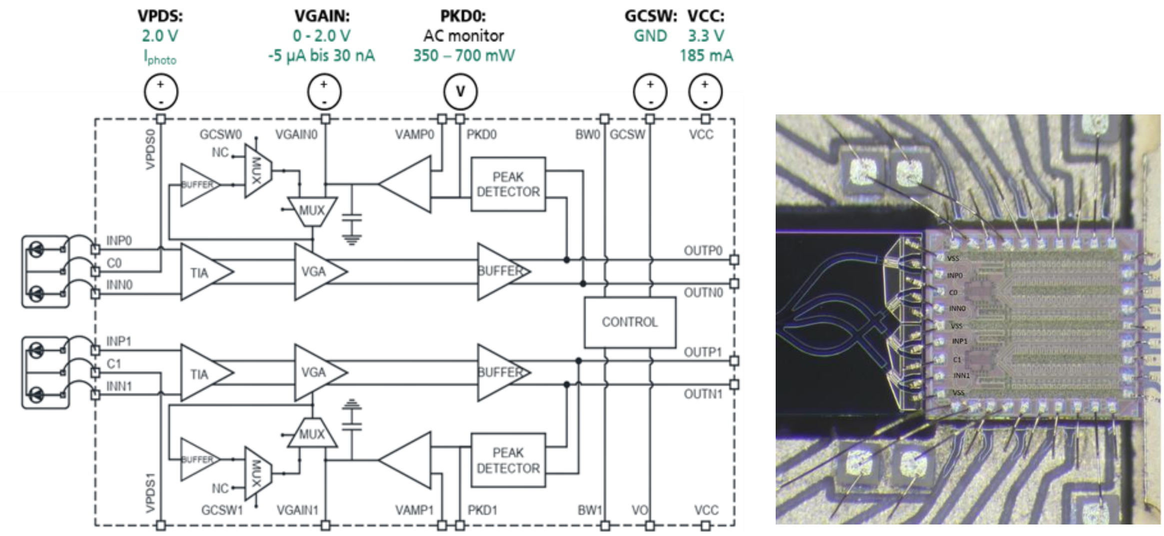

Figure 7 Receiver circuit with TIA electronics as schematic block diagram (left) and as fabricated (right)

The electronic circuit of the InP detection PIC and the TIA is shown in Figure 7. It is operated in manual gain mode to adjust the electronic RF output power properly. The operational bias voltage for the photodiodes is set at VPDS with a voltage of 2V. The gain can be adjusted by VGAIN with a voltage from 0 – 2 V and the TIA is biased with 3.3 V. PKD0 is an output linear to the RF output ranging from 350 to 700 mW. The electronic assembling and packaging war carried out in two iterations using the same components. The resulting butterfly packaged was then set up to an evaluation board for RF characterization up to 67 GHz using SMP (G3PO) interconnects.

Due to the higher optical input power, the S21 small-signal response of the 1st generation receiver shows a higher output power, but high-pass characteristics as a result of an insufficient contact at the output ports. Further the RF response has a significant drop in the range of 27 GHz. In addition, the photodiodes at OUTP1 and OUTN1 show a high dark current of 60 µA after the wire bonding. To solve the issue of low RF output in the frequency range from 5 to 10 GHz and the increased dark

This project has received funding from the *European Union's Horizon 2020 research and innovation programme* under grant agreement No 820466.
www.civiquantum.eu

current, this process was repeated with the same set of components. Furthermore, silver glue was used to improve the contact characteristics between the butterfly package and the evaluation board and the capacitance of the photodiode was adjusted. As a consequence, the frequency response of

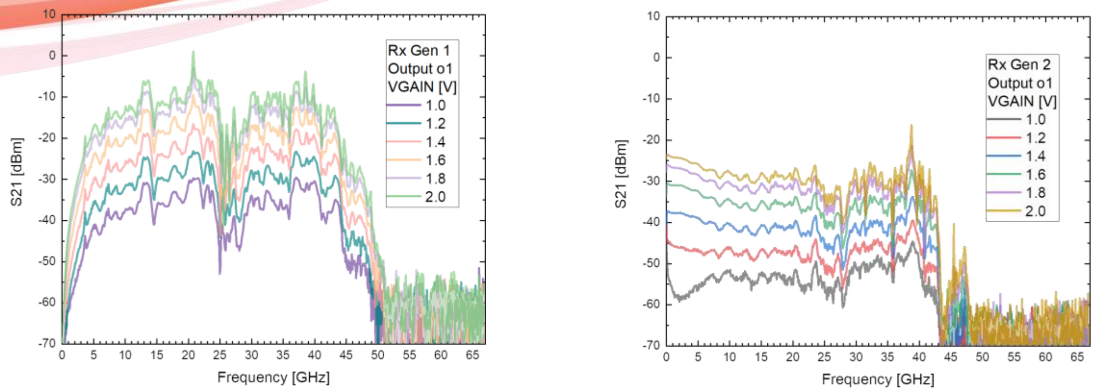

Figure 8 S21 response for generation 1 (Gen1/ left) and generation 2 (Gen 2/ right) of developed CV-QKD receiver

the Gen 2 receiver assemble shows satisfying characteristics in the low frequency regime from 0 -5 GHz, while the drop at higher frequencies of around 27 GHz is reduced. We conclude, that issue is resulting from the RF packaging and can be worked out in future work. Moreover, we are working on a third generation with an optimized receiver packaging and assembling and expect to achieve bandwidth above 40 GHz. In that manner, we can provide receiver modules, which are not only compatible to CV-QKD but also for classical coherent communications at 56 GBaud.

3. Evaluation of developed receiver module

The integrated coherent high-speed receiver was characterized by HHI and MPL in order to assess the suitability of the receiver for coherent (classical) optical communication and for implementing CV-QKD protocols with sending rates of several GHz. For the full characterization of the receiver module, the 3-dB bandwidth (f3dB) as well as the linearity and the noise floor were measured for two channels of the receiver module of 2nd generation.

To evaluate f3dB, the S21 small-signal was measured for a frequency range from 0 to 67 GHz using a vector network analyser (VNA). The drop of 3dB at a specific frequency referenced to the DC output at 0 GHz is determined as the f3dB frequency (see Figure 9).

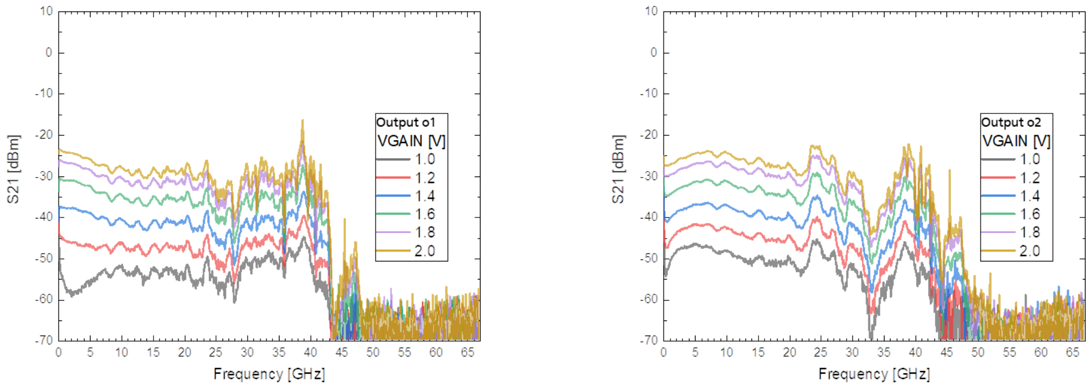

Figure 9 Bandwidth measurement at two outputs of channel 0 and channel 1 of the high-speed receiver module

This project has received funding from the *European Union's Horizon 2020 research and innovation programme* under grant agreement No 820466.
www.civiquantum.eu

The f3dB bandwidth for both outputs was determined to be at least 7 GHz for all different gain voltages at output o1. When neglecting the drop between 0-10 GHz at higher gains, we can find even 25 GHz f3dB-bandwidth at a low gain voltage of 1.2 V. At output o2 the bandwidth succeeds more than 27 GH for all different gain settings. The receiver small-signal response shows a dip at the frequency range for 25 to 30 GHz at output 1 and still a steep drop at a frequency of 33 GHz for output 2. For output o2, the bandwidth is sufficient for 28 GBaud or 50 GBbaud and even beyond.

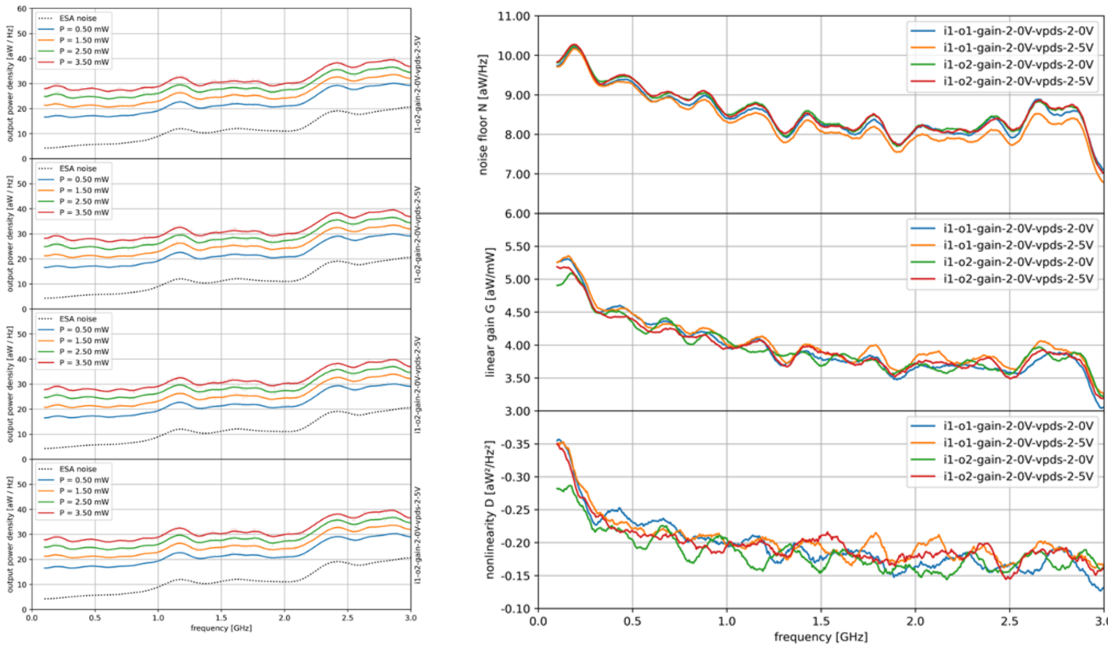

Figure 10 Spectral output power (left) and fitted coefficients for noise floor (N), linear gain (G) nonlinearity (D)

To characterize the linearity of the receiver module, the optical input was varied from 0 to 4 mW. For fixed VGAIN and VPDS settings, the optical input power was varied over 40 equidistant points in the 0.1-4.0 mW range. For each input power setting, a full-span power spectrum of the receiver output was acquired using an electronic spectrum analyser. Set to average 100 sweeps with a resolution bandwidth of 1 MHz, this yielded 40 spectrum traces of 631 data points each. This process was repeated for the two different detector outputs of the receiver as well as for VPDS settings of 2.0 and 2.5 V respectively. An additional dark noise spectrum for the ESA was acquired while the device input was disconnected and subsequently subtracted from all other traces. To simplify further processing and improve the visual clarity of plots, the obtained spectra where smoothed using a (51, 3) Savitzky–Golay filter. To quantify the degree of (non-)linearity, the following quadratic function was then least-squares fitted at each frequency:

$$P_{\{out\}}(f)\ [aW/Hz] = N + G \cdot P_{\{in\}}[mW] + D \cdot P_{\{in\}}^{2}[mW]$$

Here N is the electronic noise floor, G the linear conversion gain and D a nonlinear deviation from the ideal linear relation. The chosen power units yield a convenient order of magnitude for the parameters N, G and D.

By fitting the output power density at each frequency f, the coefficients N, G and D were derived and are presented in Figure 9 (right). To evaluate the linearity characteristics at discrete frequencies f of {0.5, 1.5, 2.5 GHz} the optical power at input i1 was ramped from 0 to 4 mW, while the output power

This project has received funding from the *European Union's Horizon 2020 research and innovation programme* under grant agreement No 820466.
www.civiquantum.eu

was measured at output 1 and 2 (o1 and o2). The gain voltage VGAIN was fixed at 2.0 V and at the photodiode the applied voltages VPDS were set to 2.0 V and 2.5 V. The linear gain at this voltage is found to be 0.5 – 0.9 N/mW. The resulting characteristics are shown in Figure 11. For optical input powers up to 4 mW, the output power density was fitted with a second degree polynomial, yielded from the coefficients N, G and D. We observe a deviation from linear characteristics of 4-5 % over all frequencies. Further the average electronic noise is 11.2 aW/Hz over the full bandwidth of 3 GHz. The resulting clearance is 3-4 dB at the maximum input power of 4 mW.

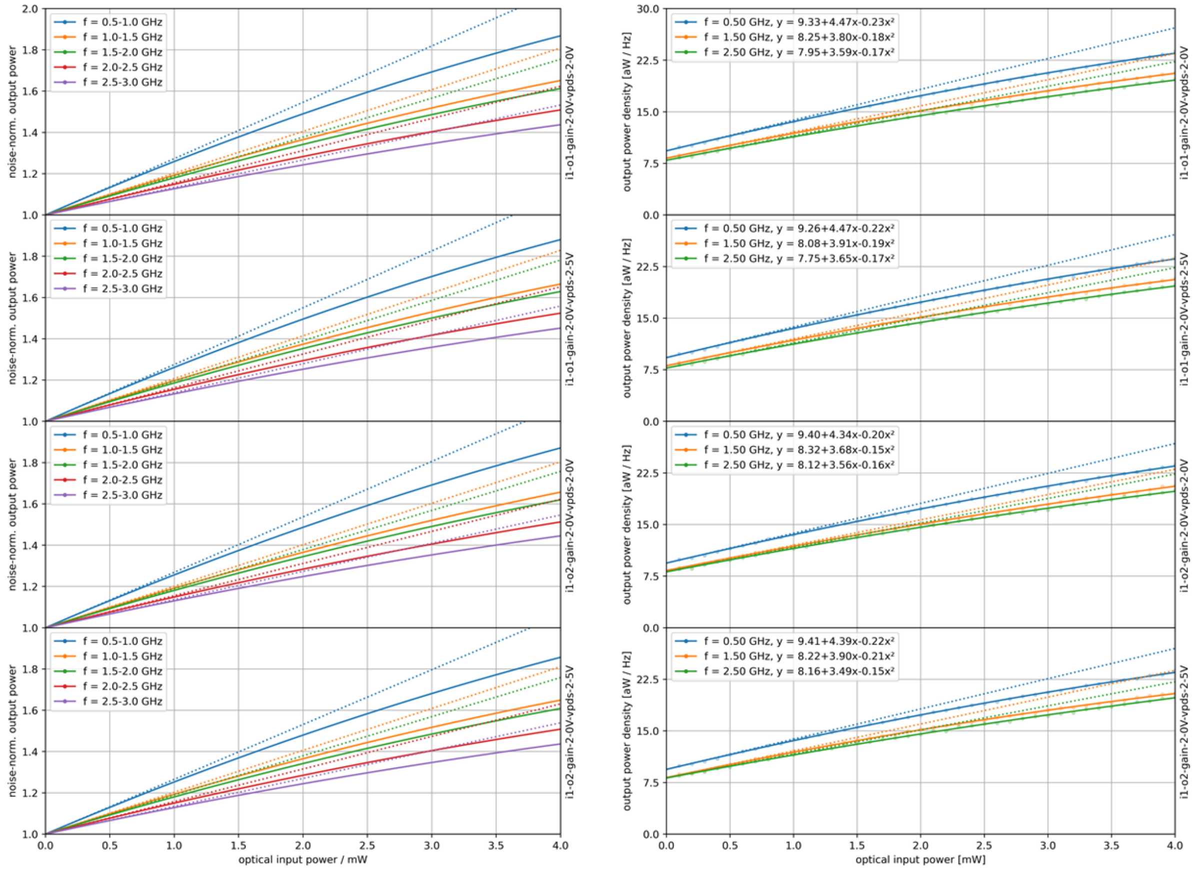

Figure 11 Linearity characteristics of high-speed receiver module at output 1 and 2 (o1 and o2) with the total RF output (left) and output normalized to units of noise floor N (right)

4. Conclusions and future work

We have reported the design, fabrication and packaging as well as the experimental characterization of a high-speed CV-QKD receiver. The receiver shows a satisfying frequency response up to 27 GHz and a good linearity in the range of up to 3 GHz with an optical input power up to 4 mW. The receiver module is compatible with classical telecom infrastructure and can be adapted for 28 GBaud QPSK

While the PIC shows a uniform and balanced characteristic for all 4 different photodiodes in terms of dark current and responsivity, the packaged receiver module does not demonstrate a satisfying RF characteristic regarding its bandwidth and linearity.
However, the linearity and the clearance need to be optimized in future work with special focus on the RF packaging and the co-integration of a low noise TIA. As we can conclude from

This project has received funding from the *European Union's Horizon 2020 research and innovation programme* under grant agreement No 820466.
www.civiquantum.eu

the very different characteristics of the different receiver outputs, the bandwidth and noise is limited from the co-integrated electronics rather than the PIC performance. A third iteration of the developed high-speed receiver with an optimized packaging is going to be fabricated and provided to the partners to the end of the project.

Still, the PIC can be optimized, when substituting the photodiodes with highly linear photodiodes and adjusting the photodiodes capacitance. We think it is worth to investigate a dedicated development of uni-travelling carrier (UTC) photodiodes, to further improve the characteristics of high-speed CV-QKD receivers. A new generation of UTC photodiodes is currently being fabricated and is going to be assembled and packaged using the same process flow.

Admittedly, the packaging process needs to be optimized, the local oscillator can be co-packaged with the PIC for detection (InP#detection) and the impact of different TIA characteristics on the overall performance should be investigated. We are confident, that following this approach allows advanced components for versatile and agile systems, which can be operated in CV-QKD as well as for classical transmission using 56 GBaud QPSK.

This project has received funding from the *European Union's Horizon 2020 research and innovation programme* under grant agreement No 820466.
www.civiquantum.eu