Deliverable 9.1

WP9 Intermediate Report:
Hybrid Integration and Packaged Solutions for Comb Generator Modules

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0.2	03/12/2020		Final draft circulated to the Consortium, including WP Leaders, for feedback
1.0	18/12/2020		Final version with the Consortium's input

Lead Beneficiary	1. University of Bath (BATH)
Collaborating Partners	2. Ecole Polytechnique Federale de Lausanne (EPFL) 3. NPL Management Limited (NPL) - TERMINATED 4. Chalmers Tekniska Hoegskola AB (CUT) 5. Universiteit Gent (UGent) 6. Universitat Politecnica de Valencia (UPV) 7. Karlsruher Insitute Fuer Technologie (KIT) 8. Menlo Systems GmbH (MENLO) 9. Max-Planck-Gesellschaft Zur Feorderung De Wissenschaften EV (MPQ) (Institute for Quantum Optics) & (Institute for the Science of Light) 10. Kungliga Tekniska Hogskolan (KTH) 11. Albert-Ludiwigs-Universitaet Frieburg (FRB) 12. IBM Research GmbH (IBM)

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Contents

1. Work package summary

MICROCOMB WP9 Report Work package title: ***Hybrid integration and packaged solutions for comb generator modules***		
Participation partner	**Principal Investigator**	**ESR**
1 – BATH	D.Skryabin	ESR N° 5 - Mr Vladislav Pankratov; ESR N°6 – Mr Zhiwei Fan
5 – UGENT	B.Kuyken	ESR N° 1 – Mr Ewoud Vissers
6 – UPV	P.Munoz	ESR N°11 – Mr Louw Roel van der Zon
7 – KIT	C.Koos	ESR N° 15 – Mr Yung Chen; ESR N° 16 – Mr Innokentiy Zhdanov
8 – MENLO	R.Holzwarth & K.Stockwald	ESR N°7 – Mr Ignacio Baldoni
Lead Beneficiary	5 – UGent/ B.Kuyken	

The outside-laboratory applications of frequency combs require the development of packaged solutions. Traditional high-power light sources that pump a microresonator are relatively bulky and difficult to operate. Hence, a packaged customer ready device is required, and appropriate techniques need to be developed. In this workpackage we will develop first such devices using microcombs for astro and optical data processing applications using building blocks developed in other WPs. Here, they will rely on so called photonic wire bonds to connect the different components. A more advanced solution to the problem is to use chip-scale light sources integrated on the same chip with a microresonator. Therefore, important objectives of this work package are to develop a device that is an electrically powered turn-key system with a single fiber output. This approach relies on the heterogeneously integrated mode-locked lasers that have III/V gain sections, amplifiers, saturable absorbers that are all electrically pumped on a single silicon chip. Having a transportable frequency comb generator would allow to increase the exposure of microcombs. Since the performance of the sources as well as their robustness is key for this, we will test them in as standalone devices in the labs of MENLO. This research WP is linked to the intensive courses 2, 6 in WP 5 and it comprises activities of the associated ESRs as outlined in the tasks listed below. Technical details of the tasks can be found in the descriptions of the various ESR projects.

2. Partner progress on tasks in Work Package 9

Milestones	
MS3	*ESRs 5,6 have numerical codes for modelling of comb Solitons and comb generation in the experimental schemes developed by consortium*
MS7	*Operational proof of concept SiN spectrometer chips*
MS10	*Operational and characterised microring resonator for generation of a visible, broadband and flat spectrum with mode spacing > 10GHz suitable for integration into AstroComb module; design of the module*
MS12	*The module 8 - MENLO 24 operational and characterised microring resonator for generation of a visible, broadband and flat spectrum with mode spacing > 10GHz suitable for integration into AstroComb module; design of the module MS12 hybrid integration of III/V source and comb generators on SiN platform for dualcomb spectroscopy*

The research progression reports covering work packages WP7 -WP10 were gathered on a quarterly basis from September 2019, as then ESR recruitment started taking up the momentum, until December 2020. This periodical review allowed the Coordinator and the beneficiaries working on the results delivery, to identify any difficulties and keep the project on track.

2.1. Task 9.1 Hybrid integration of III/V source and comb generators on SiN platform and demonstration of the low RF noise properties

Beneficiaries and partners involved in the task: ESR 1 (GENT)

Objectives of this tasks are to demonstrate low noise RF signals and dual-comb spectroscopy using on-chip microcomb generators with integrated III/V-on-silicon sources.

A butt-coupling setup was built to allow hybrid integration of an RSOA with an external chip-based cavity. The first goal was to demonstrate mode locking in a hybridly integrated mode locked laser using an RSOA from a SMART MPW run, and a Silicon Nitride external cavity chip fabricated in our own cleanroom. The Silicon nitride cavity needed several design cycles to work, taking up 10 months, partly slowed down due to COVID-19 restrictions. The first experimental results of a hybrid integrated mode locked laser have been obtained. Currently, detailed measurements are being performed, after which an article will be written. The current laser has a repetition rate of 15.5 GHz. A design with a repetition rate of 2.2 GHz is already fabricated and will be measured after the current design.

2.2. Task 9.2 Hybrid integration on SiN platform of the comb sources for dual-comb spectroscopy

Beneficiaries and partners involved in the task: ESR 1 (GENT)

Objectives for this task are to develop a numerical model for a comb generator with an integrated laser source.

Task 9.2 will be addressed in the later stage of the project

2.3. Task 9.3 Demonstration of packaged comb generator modules with integrated pump sources and amplifiers for optical data processing

Beneficiaries and partners involved in the task: ESR 15 (KIT); ESR 11 (UPV); ESR 7 (MENLO); VLC; LGT

Objectives for this task are to demonstrate packaged microcomb devices with conventional sources for data processing and astro applications.

ESR 11 (UPV) and ESR 7 (MENLO):

Task 9.3 will be addressed in the later stage of the project.

ESR 15 (KIT):

Conventional frequency combs are generated by a mode lock laser system operating with Titanium-sapphire laser or fiber optics. They are relatively bulky and the line spacing of the comb is in the order of several hundred MHz. In the past ten years, a new technology to generate frequency comb emerged. By exploiting the $X^{(3)}$ nonlinearity, frequency comb can be generated in a microresonator with the line spacing range from several GHz to THz. Our goal is to build a packaged Kerr comb generator module. It will rely on hybrid integration techniques and photonic wire bonds to connect a pump laser, a nonlinear microresonator, and a fiber as the output of the comb source. We aim at using the module for applications like optical data processing, metrology, and spectroscopy. For example, this comb source module can be further used in another EU project TeraSlice as the light source of chip-scale Photonics ADC system.

A schematic diagram of the packaged Kerr comb generator module is shown in Fig. 1. A commercial laser is used as the pump source. The laser chip is bonded on a carrier and then is attached to a submount. The output of a laser is connected to the edge coupler of SiN microresonator chip via photonic wire bonds. By tuning the bias current of the laser or the heater on the microresonator, the detuning between pump frequency and resonances can be adjusted and a Kerr comb can be generated. If the detuning is tuned carefully, soliton can also be generated. Again, the output of the SiN chip is connected to a fiber array via PWB, thus the frequency comb can be used as the light source for many applications. Consider the packageability, a single-mode fiber array is used instead of a single-mode fiber. The advantage of this approach is that connecting the chip to laser and fiber via PWB can avoid the requirement for active alignment. At the same time, long term stability will be improved.

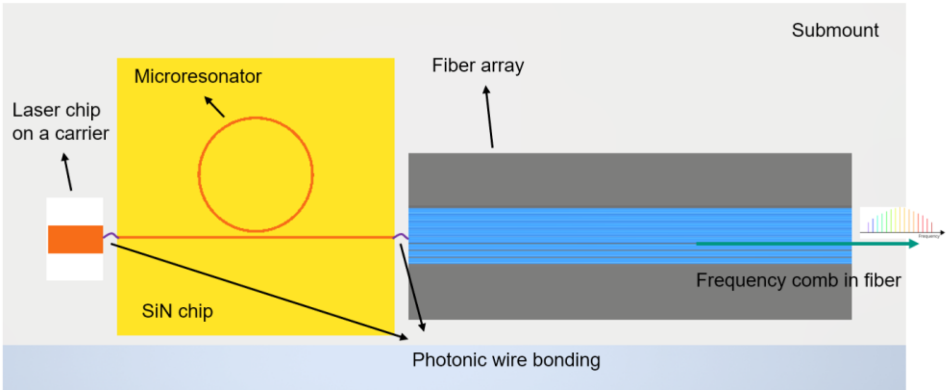

Figure 1: Schematic diagram of an integrated Kerr comb generator module.

In order to induce four-wave-mixing in the microresonator, strong pump light is needed. We choose a laser chip with output power in the range from 100 mW to 200 mW, which should be sufficient to generate Kerr comb with the intrinsic Q factor of the microresonator as high as 9 million. We expect to receive the high-power laser chip at the beginning of 2021.

To minimize the loss of photonic wire bonds, mode field matching between two coupling interfaces is of crucial importance. Base on the mode field diameter (MFD) measurement, the MFD of the edge coupler of the microresonator chip is around 1.4 um. This value is relatively small for the photonic wire bonding technique because a typical voxel (volume pixel, which can be seen as the minimum writing volume of photonic wire bonds) size in the vertical direction is roughly at the same value. The voxel size can be reduced by decreasing the dose. However, whether the photoresist can be fully polymerized and whether the bonds are mechanically stable with a lower dose need to be further investigated.

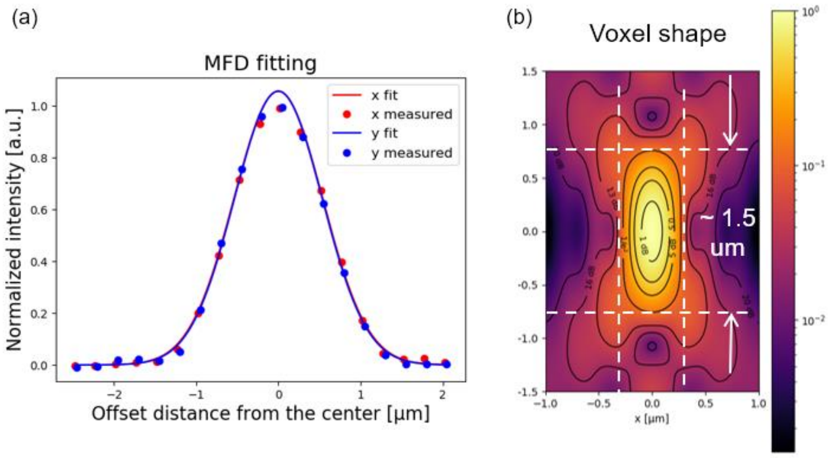

Figure 2: (a) The mode field measurement and fitting of the edge coupler of a SiN microresonator chip. The mode field diameter (MFD) is around 1.4 um based on the Gaussian fitting. (b) the normalized intensity of the voxel of direct laser writing used for photonic wire bonding. The typical voxel in vertical direction is around 1.5 um.

Among all kinds of frequency combs, solitons are a special kind. Due to the coherent nature of the broadband spectrum, a soliton is preferable in many applications. To generate soliton, the detuning between the pump line and the resonance of the microresonator needs to be tuned carefully. We plan to tune the pump current of the laser diode and the heater on the microresonator to adjust the detuning. At the same time, the phase of the back-reflected light due to Rayleigh scattering in the microresonator also needs to be tuned so that the self-injection locking technique can be used to lock the resonance and the pump line.

The photonic wire bonds (PWB) between SiN chip and single mode fibre array will be developed in the first step. A submount for the SiN chip and fiber array is designed and fabricated. After successfully connecting the SiN chip and fiber array, the stability of Kerr comb can be tested using this module. Next, we will develop PWB for the high-power laser chip and then connect the laser chip to SiN chip. A fully integrated Kerr comb generator module combining a laser chip, a SiN microresonator, and a fiber array will be assembled in the final step.

2.4. Task 9.4 Modelling comb generation with an integrated laser source

Beneficiaries and partners involved in the task: ESR 5, 6 (BATH); ESR 1 (GENT); LUCEDA

Task 9.4 will be addressed in the later stage of the project.

2.5. Task 9.5 design of a fully packaged microcomb system for high precision spectroscopy in astronomy

Beneficiaries and partners involved in the task: ESR 7 (MENLO)

We develop a packaging solution for a microresoantor. We use a 14-pin butterfly package comprising a thermo-electric cooler underneath the chip as well as a thermistor to monitor the temperature. On-chip heater elements will later also be included as thermo-optical actuators. Optical fibers going in and out supply the chip with continuous-wave pump light and extract the comb light. In a first step, we are developing a packaging solution for a pump wavelength of 1550 nm which is the standard wavelength in telecom and fiber lasers. Later versions will work at 1050 nm for operation in our calibration system for astronomical applications.

We were able to successfully package a silicon nitride microresonator chip with a 20 GHz free spectral range for operation at 1550 nm. The combination of thermo-electric cooler and thermistor allowed us to accurately stabilize the temperature at setpoints between 20°C and 35°C, which we used to tune the chip resonances relative to the laser wavelength. Lensed fibers at the in- and output provided a total through-coupling efficiency of 8 %. Although we expect that significantly higher efficiency should be possible, this was enough to generate a comb spectrum with an external amplified laser.

We are currently making significant changes to improve our packaging setup. Yellow filters for the illumination of the stereomicroscope will prevent glue from hardening prematurely. We are also testing other kinds of glues and chips with optimized waveguide structures at the facets. With this, we are confident that our next packaging tests will yield significantly higher coupling efficiencies of about 20%. Later this year, we plan to start testing our packaging techniques for operation at 1050 nm in wavelength.

According to the original project plan, we anticipated two-month secondment of ESR11 (Ignacio Baldoni) from Menlo Systems to EPFL in July/August 2020. The current situation with Covid-19 makes it very hard to plan secondments, which normally take a decent amount of preparation. Therefore, we plan to deviate from the project plan and anticipate the secondment for summer of 2021.

2.6. Summary of publications, talks and conferences

Microcomb Early-Stage Researcher webinars:

- 4 April 2020 https://www.microcomb-eu.org/esr-intro-webinar
- 26 October 2020 https://www.microcomb-eu.org/26-october-webinar
- 7 December 2020 https://www.microcomb-eu.org/7-december-webinar

2.7. Planned Secondments

ESR/ month	5 BATH	6 BATH	3 EPFL	14 EPFL	13 MPL	2 CUT	1 GENT	11 UPV	15 KIT	16 KIT	7 MENLO	8 KTH	9 MPQ	10 FRB	12 IBM
ESR/Month															
1 (2019)															
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8															
9															
10															
11									LGT	EPFL					
12	EPFL								LGT			BATH			BATH
13 (2020)	EPFL							CUT	LGT			BATH		BATH	
14															
15		MPL				BATH	Luceda	LGT					GENT	Toptica	
16		MPL				MPL	Luceda	LGT					GENT	Toptica	
17						MPL		LGT					GENT	Toptica	
18															
19	IBM		VLC	IBM	MPQ		BATH		GENT	CUT	EPFL	Toptica		KTH	UPV
20	IBM		VLC	IBM	MPQ	Toptica		VLC	UPV	CUT	EPFL	Toptica			
21		MPQ			Airbus	Toptica						Toptica			
22						Toptica									
23			LGT										MPL		
24			LGT							Menlo		CUT	MPL		EPFL
25 (2021)			LGT				IBM		EPFL	Menlo		CUT	MPL		EPFL
26															
27	GENT				Airbus										
28		FRB			Airbus										EPFL
29		FRB			Airbus										EPFL
30															
31		CUT		Menlo			MPQ	KIT			KIT			BATH	
32	FRB			Menlo			MPQ				KIT EPFL				
33		KTH		Menlo							EPFL	Toptica			
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	Original secondment schedule as per GA
	Completed secondments
	Virtual secondments delivered by online meetings via Zoom and Teams
	Estimated plans for secondments providing the lockdown restrictions are lifted
	Beginning of each project year

Beneficiary/PI	ESR	Secondment plans
University of Bath (BATH) Prof Dmitry Skryabin	ESR N° 5 Mr Vladislav Pankratov	Current plans for ESR Vladislav Pankratov is a month-long secondment at FRB in the Summer 2021.
	ESR N°6 Mr Zhiwei Fan	Current plans for ESR Zhiwei Fan is a month-long secondment at UPV in the Summer 2021.
Ecole Polytechnique Federale de Lausanne (EPFL) Prof Tobias Kippenberg	ESR N°3 Mr Mikhail Churaev; ESR N°14 Mr Aleksandr Tusnin	EPFL planned for the secondments to be carried out in 2020. It was more feasible to implement them at the beginning of the ESR PhD projects as they were to be trained on certain skills needed for their projects. EPFL were severely impacted by the COVID travel restrictions, as were most of the ESRs. EPFL will evaluate the secondment planning later as the COVID situation evolves.
Chalmers Tekniska Hoegskola AB (CUT) Prof Victor Torres-Company	ESR N°2 Mr Krishna Twayana	CUT prefers to wait until summer 2021 to evaluate the secondment possibilities for ESR Krishna Twayana. The reason is twofold. Firstly, the pandemic situation, which adds uncertainties to when exactly are we allowed to travel. Secondly, CUT had originally planned for ESR Krishna Twayana a visit at Pascal Del'Haye's group at NPL, UK, but since he has recently moved to MPL, Germany, it is preferable to until Pascal Del'Haye settles in his new laboratory in Germany. Chalmers are not allowed to let in visitors for the time being because of the pandemic situation. CUT will evaluate the secondment planning later as the COVID situation evolves.
Universiteit Gent (UGent) Prof Bart Kuyken	ESR N°1 Mr Ewoud Vissers	No travelling (in or out) is currently allowed at UGent, so there are currently no plans for any secondments. UGent will evaluate the secondment planning later as the COVID situation evolves.
Universitat Politecnica de Valencia (UPV) Prof Pascual Muñoz Muñoz	ESR N°11 Mr Roel van der Zon	The secondment to Chalmers will be delayed until their PCVD furnace is back and running, probably in the Summer 2021. Moreover there both institutions are limited by the restrictions imposed by COVID. Secondments to Ligentec and KIT will be evaluated later as the COVID situation evolves.
Karlsruher Insitute Fuer Technologie (KIT) Prof Christian Koos	ESR N° 15 Mr Yung Chen ESR N° 16 Mr Innokentiy Zhdanov	KIT is currently planning for the secondments and will evaluate the secondment planning later as the COVID situation evolves.

Menlo Systems GmbH (MENLO) Dr Ronald Holzwarth Deputised by Dr Klaus Stockwald	ESR N°7 Mr Ignacio Baldoni	According to the original project plan, we anticipated two-month secondment of ESR Ignacio Baldoni (ESR7) from Menlo Systems to EPFL in July/August 2020. The current situation with Covid-19 makes it very hard to plan secondments, which normally take a decent amount of preparation. Therefore, we plan to deviate from the project plan and anticipate the secondment for summer of 2021.
Max-Planck-Gesellschaft Zur Förderung De Wissenschaften EV (Institute for Quantum Optics – (MPQ)) Dr Nathalie Picqué	ESR N°9 Ms Ruyu Ma	No travelling (in or out) is currently allowed at MPQ, so there are currently no plans for any secondments. MPQ will evaluate the secondment planning later as the COVID situation evolves.
Max-Planck-Gesellschaft Zur Förderung De Wissenschaften EV Institute for the Science of Light – (MPL)) Dr Pascal Del'Haye	ESR N°13 Mr Toby Bi	ESR Tobi Bi spent the time from 21st September to 9th October 2020 at Airbus in Munich. He was testing microresonators for frequency comb generation there. The secondment was successful but MPL don't have currently further plans.
Kungliga Tekniska Hogskolan (KTH) Prof Katia Gallo	ESR N°8 Mr Halvor Fergestad	The secondment to Bath has been replaced by meetings and interactions via zoom, email and data sharing of ESR Halvor Fergestad with members of the Bath team (Prof Dmitry Skryabin and PhD student from the CPPM research group at the University o Bath - Will Rowe)
Albert-Ludwigs-Universitaet Frieburg (FRB) Prof Karsten Buse Deputised by Dr Ingo Breunig	ESR N°10 Mr Nicolás Amiune	The COVID restrictions make planning for secondments difficult, however, FRB plans to send ESR Nicolás Amiune by mid of 2021 for one month to Bath and we would host ESR Vladislav Pankratov from Bath for one month before or after that.
IBM Research GmbH (IBM) Dr Paul Seidler	ESR N°12 Mr Alberto Nardi	April-May 2021 is currently considered for secondment of ESR Alberto Nardi at the EPFL, but this still needs to be discussed with Prof Tobias Kippenberg, and it will depend on the situation at the time with COVID-19.