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WP7 Intermediate Report:
Signal Processing & Optical Communications

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Contents

1. Work package summary

MICROCOMB WP7 Report

Work package title: ***Microcomb technologies for signal processing and optical communication***

Participating partner	**Principal Investigator**	**ESR**
1 – BATH	D.Skryabin	ESR N° 5 - Mr Vladislav Pankratov; ESR N°6 – Mr Zhiwei Fan
2 – EPFL	T. Kippenberg	ESR N°3 – Mr Mikhail Churaev; ESR N°4 – Mr Connor Skehan (left project) ESR N°14 – Mr Aleksandr Tusnin
4 – CUT	V.Tores-Company	ESR N°2 – Mr Krishna Twayana
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
12 – IBM	P.Seidler	ESR N°12 – Mr Alberto Nardi
Lead Beneficiary	7 – KIT / C.Koos	

Frequency combs provide a multitude of unique features that make them perfectly suited for signal processing at RF and THz frequencies. As an example, soliton combs consist of phase-locked carriers that can be individually modulated by an array of electro-optic modulators having typical bandwidths of tens of GHz, thereby synthesizing broadband optical waveforms which may have arbitrary non-periodic shapes. Similarly, soliton comb generators can serve as low-noise microwave oscillators, exploiting the strong phase correlation between neighbouring tones. While basic viability of such schemes has been demonstrated using conventional frequency comb generators, real-world applications and industrial pick-up have so far been prevented by the complexity and the cost of the comb source.

Chip-scale frequency comb generators have the potential to change this. In particular, we will aim at exploring and experimentally demonstrating the potential of chip-scale frequency comb and comb-soliton sources for generation, processing and detection of broadband optical waveforms, with the long-term goal to demonstration frequency down-conversion to RF and THz frequencies.

Within the work package, researchers have been broadly exploring applications associated with RF and THz signal processing based on micro-comb technologies, develop numerical and theoretical approaches and make integrated devices for these applications. Chip-scale comb sources are also natural for realizing massively parallel wavelength division multiplexing in optical communications. We will investigate the opportunities that the broadband phase coherence of microcombs offers to mitigate nonlinear distortions in the fibre transmission channel. In addition, we will explore what has become the next frontier in fibre-optic communication research: space division multiplexing. The focus will be in establishing new multiple-input multiple-output processing schemes for few-mode fibre transmission, where the line spacing stability of the comb can bring advantages over multi-wavelength laser source

2. Partner progress on tasks in Work Package 7

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.

Milestones	
MS3	*ESRs 5 & 6 (Bath) have numerical codes for modelling of comb solitons and comb generation in the experimental schemes developed by consortium*
MS4	*Demonstration of octave spanning dual dispersive wave comb spectra, solitons and low phase noise microwaves on SiN and GaP platforms*
MS5	*Transmission improvement in single mode fibre by a factor of 2x via mitigation of nonlinear distortion*
MS6	*Demonstration of a fibre connected comb base spectral processor; photonic wire bonding technique learned*
MS7	*Operational proof of concept SiN spectrometer chips*

2.1. Task 7.1 On-chip RF to optical link via a dual dispersive wave soliton

Beneficiaries and partners involved in the task: ESR 3 and 4 (EPFL), ESR 6 (BATH); VLC Photonics; LiGenTec

Objectives of this tasks are to identify niche opportunities for field deployment of microresonator combs in fibre-communication links.

ESR 3 and 4 (EPFL):

Generation of dissipative Kerr solitons (DKS)[1] in microresonators allows accessing stable and broadband optical frequency combs with high repetition rates (GHz-THz range). Soliton dispersive wave emission in a photonic chip–based microresonator is akin to the generation of Cherenkov radiation[2] enables generation of fully coherent frequency comb spectra, with increased bandwidth that extends out of the anomalous GVD regime. However, to date, almost all coherent solitonic states have been observed only in individual optical microresonators, which requires accurate dispersion design for a dual dispersive wave generation (non-zero higher-order dispersion D_3 & D_4).

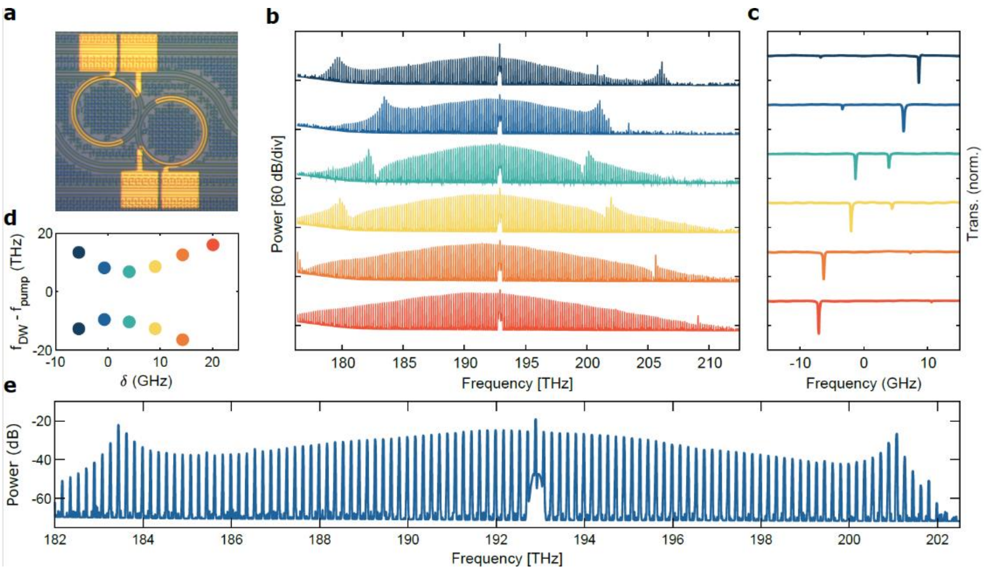

Figure 1: Dual dispersive wave generation in coupled microresonators: (a) Image of the device with integrated golden microheaters (b) Dual dispersive wave DKS spectra for different heating power (c) Corresponding optical transmission lines (d) Dispersive wave position as a function of inter-resonator detuning (e) Flat comb spectrum with dual dispersive wave feature.

Beside our ongoing efforts in ultrabroadband DKS generation in single resonators, EPFL started to investigate new regimes of DKS states in photonic lattices built up from strongly coupled Si_3N_4 microresonators. Coupling of an additional resonator induces cavity resonance splitting (see Figure 1 c). The distance between the hybridized resonances is given by $\Delta\omega = \sqrt{4J^2 + \delta^2}$, where J corresponds to the coupling strength and δ to the inter-resonator detuning[3] Since the position of symmetrically

[1] T. J. Kippenberg *et al*., "Dissipative Kerr solitons in optical microresonators" *Science* 361.6402 (2018).
[2] V. Brasch *et al.*, "Photonic chip–based optical frequency comb using soliton Cherenkov radiation," *Science,* 351.6271 (2016).

[3] M. Zhang *et al*., "Electronically programmable photonic molecule" *Nat. Photonics,* 13.1 (2019).

spaced dispersive waves depends on the relative offset between two hybrid resonant modes, it can be directly controlled by changing the inter-resonator detuning δ. The control is realized by directly fabricating gold microheaters on top of the resonator cladding (see Figure 1 a), in collaboration with Dr. Paul Seidler at IBM Research Zurich. We adjust the relative detuning d of the dimer over the range of 19 GHz using integrated microheaters, which corresponds to the tuning of dispersive wave positions over a range of 10 THz as depicted in Figure 1. **ESRs Mikhail Churaev and Connor Skehan** carried out work on experimental investigation of soliton generation in photonic dimer systems.

Another approach of tuneable dispersion system is the concept of alternating dispersion couple chains, being developed at EPFL. In the simplest case, an alternating dispersion chain can be formed by two resonators with equal D_1 and opposite D_2 parameters (see Figure 2). In such a system, the hybrid mode dispersion profile strongly depends on the relative intrinsic resonator detuning. Therefore, it should be possible to "program" the dispersion profile electrically by shifting the relative detuning using microheaters, enabling generation of multiple dispersive waves at some specific spectral regions of interest. Currently EPFL is working on the fabrication and first measurements of such devices. **ESR Mikhail Churaev** carried out work on design and measurements of the first alternating dispersion devices.

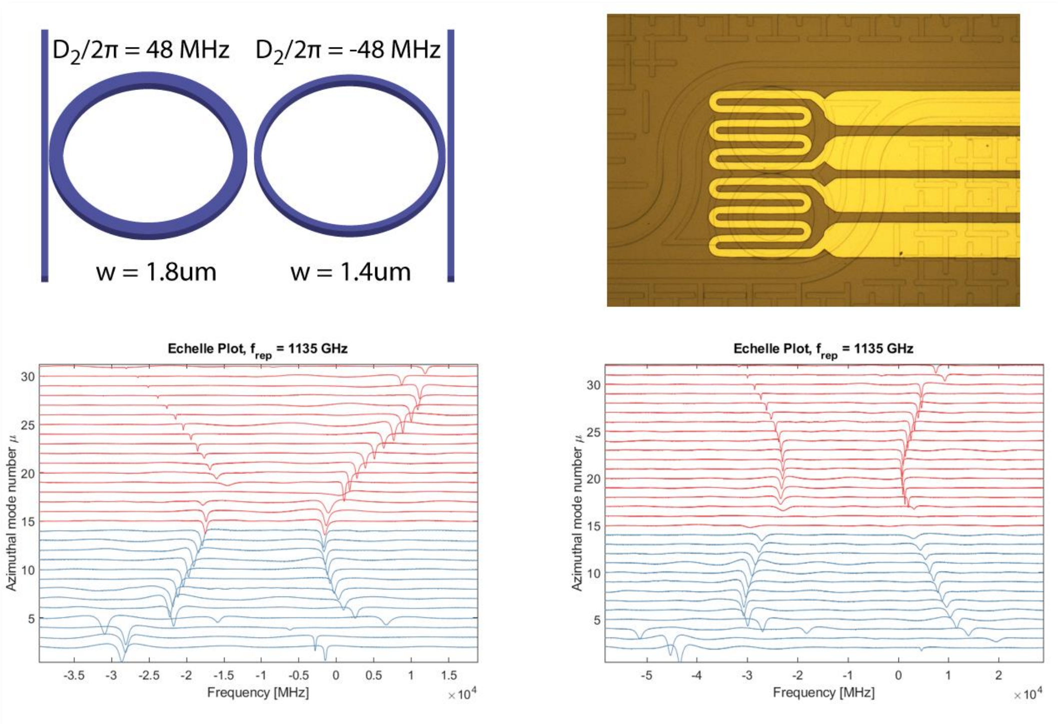

Figure 2: Alternating dispersion coupled resonators concept. (1) Schematics (2) Image of a fabricated device with microheaters for thermo-optic tuning. (3)-(4) Linear measurements of the devices showing changeable dispersion profiles.

Publications:

A. Tikan, J. Riemensberger, K. Komagata, S. Hönl, **M. Churaev, C. Skehan**, H. Guo, R. N. Wang, J. Liu, P. Seidler, T.J. Kippenberg, “Emergent Nonlinear Phenomena in a Driven Dissipative Photonic Dimer”, preprint: arXiv:2005.06470v2, invited for resubmission in Nature Physics.

Talks at conferences:

A. Tikan, J. Riemensberger, K. Komagata, S. Honl, **M. Churaev**, **C. Skehan**, H. Guo, R. N. Wang, J. Liu, P. Seidler, and T. J. Kippenberg, "Dissipative Kerr solitons in a photonic dimer”, in CLEO: QELS_Fundamental Science, 2020, paper FTh1A.5

ESR 6 (BATH):

Bath has developed the model for counterrotating light in micro-resonators with the high repetition rates[4]. Based on this model, the detuning can be tuned to control nonlinear interactions between the counter-propagating fields, which constitutes a new approach to control creation or destruction of solitons. Bath has successfully demonstrated management of frequency conversion by controlling and the soliton blockade using this method[5], (see Fig. 3 below).

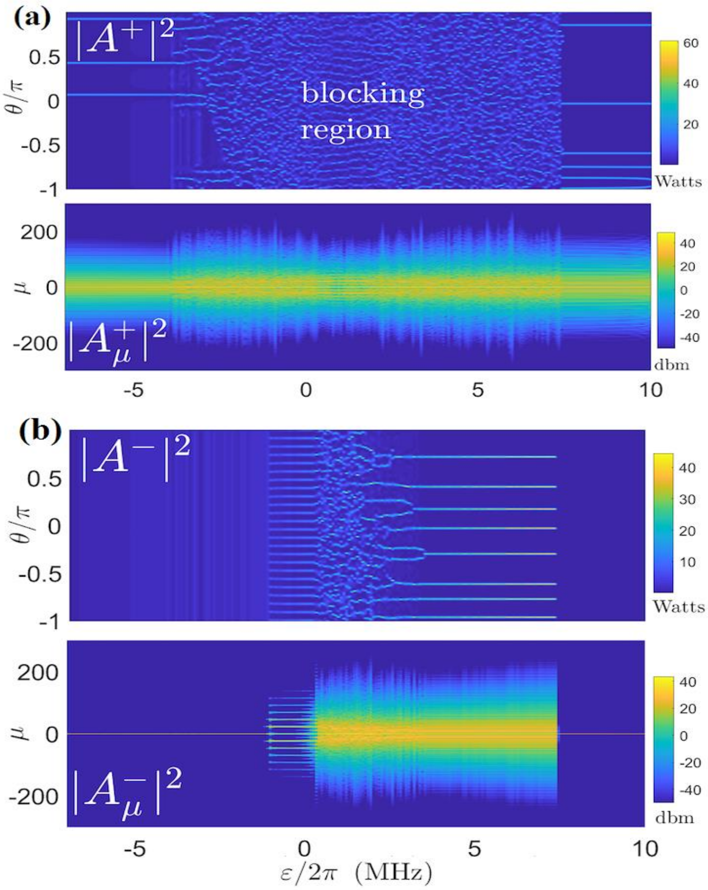

Figure 3: Soliton generation and blockade for counter-rotating fields can be achieved by the adiabatic modulation on offset frequency $\epsilon = \omega_+ - \omega_-$ ('+,-' account for two pump frequencies). Panel (a), soliton blockade effect in clockwise field is captured when the offset frequency is scanning from negative to positive. Panel (b), real-time wave dynamics for counter clockwise field corresponding to (a).

Our future plans are to extend our investigation by studying the dual-wave interactions with high-order dispersions in SiN microresonators.

Publications:

Z. Fan, and D. Skryabin "Soliton blockade in bidirectional microresonators", Optics Letters, (2020) https://doi.org/10.1364/OL.409362

[4] D. Skryabin, "Hierarchy of coupled mode and envelope models for bi-directional microresonators with Kerr nonlinearity" *OSA Continuum* 3, 1364 (2020).

[5] Z. Fan and D. Skryabin, "Soliton blockade in bidirectional microresonators," *Opt. Lett.,* (accepted) (2020).

2.2. Task 7.2 Generation of low noise microwaves using a temporal soliton

Beneficiaries and partners involved in the task: ESR 3, 4 and 14 (EPFL), ESR 12 (IBM)

Objectives for this task are to explore the potential of chip-scale frequency comb sources for generation, processing, and detection of broadband optical waveforms.

ESR 3, 4 and 14 (EPFL):

EPFL has successfully generated low-noise dissipative Kerr solitons in Si_3N_4 in the microwave K- and X-band in 2018 for the first time.[6] Within the ongoing effort to improve the performance of the integrated microwave oscillators in the framework of the Microcomb ETN program, we have conducted a series of phase noise measurements using a packaged silicon nitride device. To this end, we investigate a wide variety of conditions. First, we use a free-running ECDL to pump our chips and measure the phase noise of the output soliton. Next, we stabilize only the RIN of the laser, and measure the phase noise again. Third, we phase lock our driving laser to a 1 Hz reference source as provided by Menlo Systems, but allow the output power to fluctuate. Next, we lock both the frequency and power of our laser and measure the result. The results show that RIN to Phase noise transductions are indeed relatively low (being only driven by ultimately weak effects such as nonlinear phase shifts and thermorefractive noise), and is ultimately not the limiting factor in the phase noise of the output (see Figure).

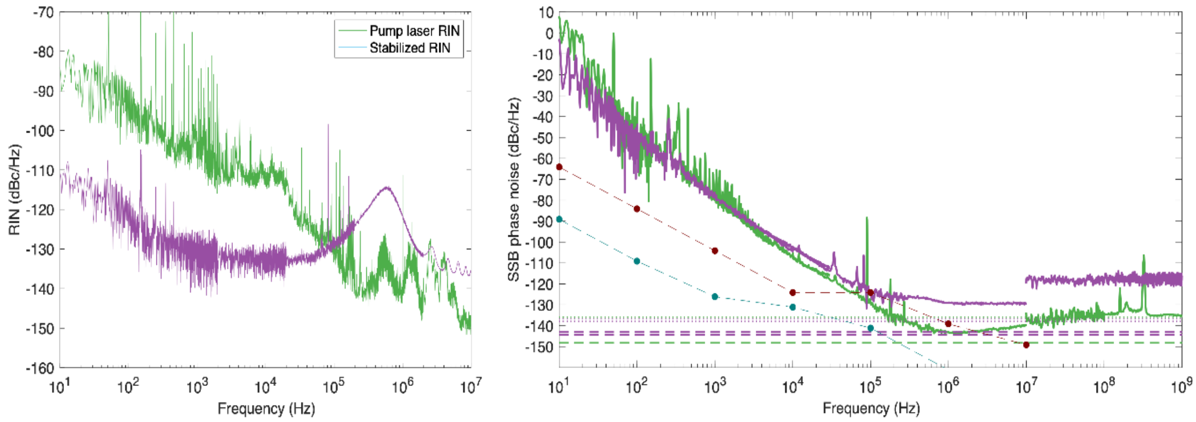

Figure 4: Low phase noise soliton generation at microwave frequencies. Left: Residual intensity noise (RIN) with (purple) and without (green) active stabilization. Right: Corresponding microwave phase noise of soliton repetition rate beat note.

EPFL has proposed a novel frequency division technique that relies on combining of soliton microcombs and semiconductor gain-switched lasers[7]. While the former has successfully been applied to low-noise RF generation, the latter provides with flexible and tunable repetition rate. By injecting soliton microcomb with a repetition frequency of f_{rep} into distributed feedback laser operating in

[6] J. Liu et al., Nanophotonic soliton-based microwave synthesizers, arXiv:1901.10372

[7] W. Weng et al., Frequency division using a soliton-injected semiconductor gain-switched frequency comb, Science Advances 6 (2020)

gain-switched mode. By choosing the gain-switching frequency f_gs close to a subharmonic frequency of f_{rep} (i.e., $f_{gs} = f_{rep}/n$, n positive integer), we achieve locking regime where intrinsic phase noise of the synthesized micro-wave signals lower than that of f_rep by a factor of n^2. We demonstrated noise reduction using a crystalline magnesium fluoride whispering gallery mode resonator with free spectral range (FSR) of 14.09 GHz. The phase noise reduction of 6 and 9.5 dB has been achieved for$f_{gs} = f_{rep}/2$ and $f_{gs} = f_{rep}/3$ respectively (see Fig. 4).

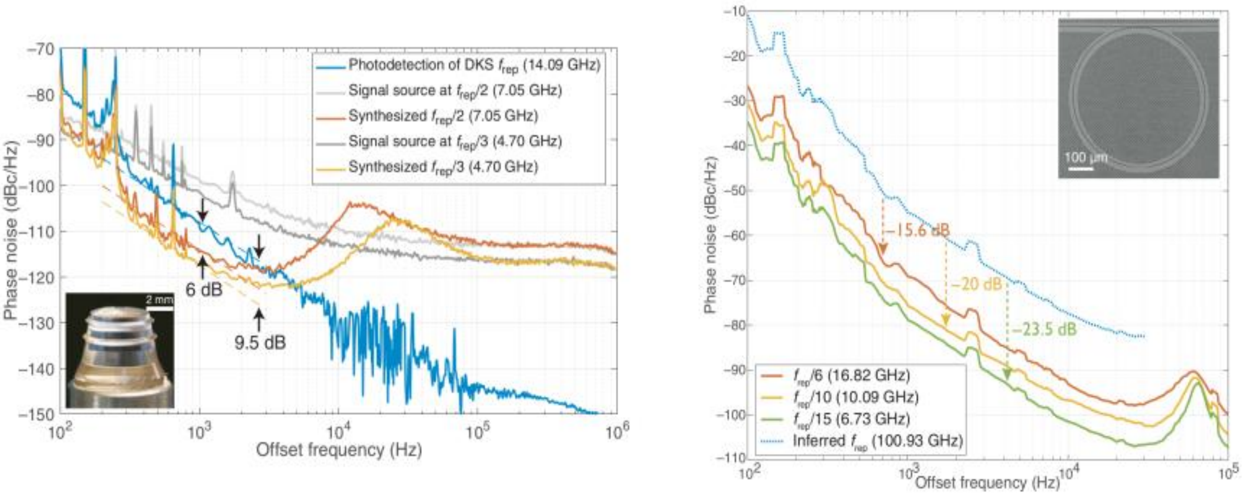

Figure 5: Phase noise spectra of synthesized microwave signals. Left: 14.09 GHz magnesium fluoride whispering gallery mode resonator. Right: 100.93 GHz silicon nitride microring resonator.

Next, we employ the introduced scheme to silicon nitride microring resonator with an FSR of 100.93 GHz, which repetition rate cannot be measured electronically. We demonstrate generation of synthesized microwaves at 6.73, 10.09 and 16.82 GHz with phase noise suppression (see Figure). Since both devices, the gain-switched laser and silicon nitride microresonator, are chip-based, our technique opens possibilities to fully integrated and highly tunable micro-wave sources and detectors.

In the meantime, **ESR Aleksandr Tusnin** theoretically investigated influence of electro-optical RF modulation on soliton dynamics. We have considered an optical cavity with quadratic (χ^2) and cubic (χ^3) optical susceptibilities under modulation at FSR frequency[8].

[8] A.K. Tusnin, A.M. Tikan, T.J. Kippenberg, Nonlinear states and dynamics in a synthetic frequency dimension, Phys. Rev. A 102 (2020)

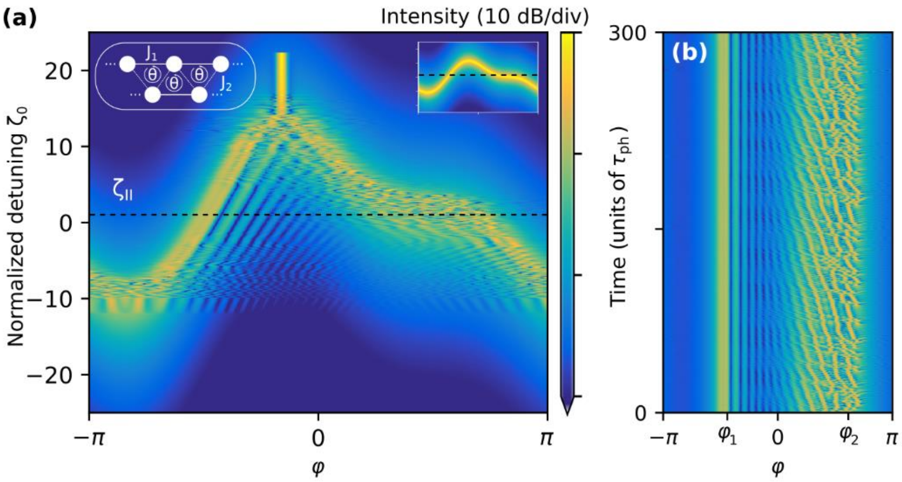

Figure 6: Soliton and band soliton in a cavity under two-tone RF modulation. Left: intracavity dynamics for different laser detuning. Right: Spatio-temporal dynamics of coexisting coherent and incoherent structures at fixed detuning.

The latter brings an additional degree of freedom to the system, enabling direct control of soliton position inside the cavity as well as appearance of new stable dissipative structures which exists due to interplay between bloch waves in the created synthetic frequency dimension and four-wave mixing processes. The novel structures, termed band soliton, appeared to be highly stable and can even simultaneously coexist with incoherent pulses inside the cavity (see Figure). The discovered features make the combined χ^2-χ^3 platform of interest for low-noise microwave generation.

Publications:

A.K. Tusnin, A.M. Tikan, T.J. Kippenberg, Nonlinear states and dynamics in a synthetic frequency dimension, Phys. Rev. A 102 (2020). DOI: 10.1103/PhysRevA.102.023518

In order to achieve direct on-chip electro-optical link, EPFL and IBM developed direct bonding of LNOI (Lithium Niobate on Insulator) wafers with silicon nitride Photonic Damascene platform. The combination of these materials enables fabrication of photonic integrated circuits exploiting χ^2-nonlinearity and preserving extremely low loss, characteristic to the photonic damascene platform. The main advantage of this approach is lavoidance of lithium niobate etching. In such a hybrid structure, the silicon nitride waveguides should be as close as possible to the $LiNbO_3$ film (see Figure) According to FEM simulations, more than 45% of optical mode can be confined in the commercially available 300 nm lithium niobate thin film for an optical wavelength of 1550 nm and for 100 nm of silicon oxide between the two materials. This means that only one half of the optical mode propagates in the lithium niobate and therefore is not affected by the electrical field.

The confirmed low optical losses of the combined platform make it a perfect candidate for all the applications involving electro-optical conversion: phase and amplitude EO modulation, quantum transducers, RF generators, microcomb self-referencing, etc. **ESR Mikhail Churaev** works on the design and testing of the devices.

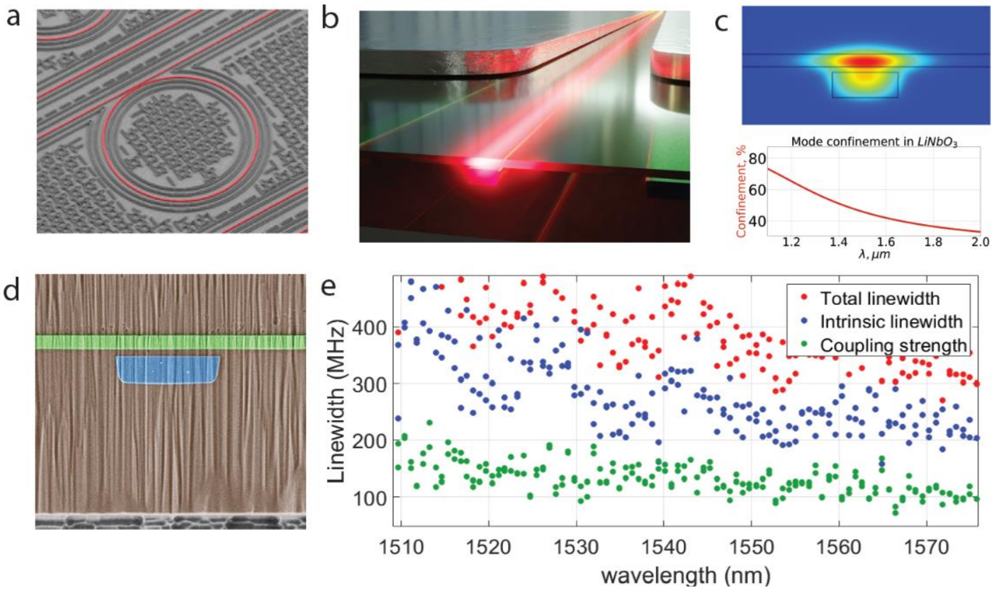

Figure 7: (a) SEM image of Photonic Damascene circuits. (b) Artist's view on the hybrid structure. (c) FEM simulations of modal profile and confinement in LN (d) SEM cross-section of the bonded structure (e) Measured optical resonance linewidth.

<u>Talks at conferences:</u>

Mikhail Churaev, Simon Honl, Rui Ning Wang, Charles Mohl, Tianyi Liu, **J. Connor Skehan**, Johann Riemensberger, Daniele Caimi, Junqiu Liu, Paul Seidler, and Tobias J. Kippenberg, "Hybrid Si_3N_4-$LiNbO_3$ integrated platform for electro-optic conversion", in CLEO: Lithium Niobate Integrated Photonics, 2020, paper STh1F.3

ESR 12 (IBM):

IBM has not been doing any work on task 7.2 in the period from January 2020 through December 2020. (Note: ESR 12 started on 12 January 2020.) The primary focus of the work has instead been to first demonstrate soliton formation with GaP microresonators. Work on task 7.2 will begin once solitons can be reliably observed.

Note: IBM has however contributed to WP7 through task 7.1 in collaboration with the EPFL. (See section 2.1.)

2.3. Task 7.3 Theory of an octave wide self-referenced comb-solitons emitting two dispersive waves (Miles)

Beneficiaries and partners involved in the task: ESR 6 (BATH), ESR 3 (EPFL)

Objectives for this task are to develop specific technical concepts and to experimentally demonstrate the potential of these concepts.

ESR 6 (BATH):

Bath has developed a theory for modelling counter-rotating waves in a microresonator from coupled-mode equations. The model is reshaped in the high-repetition-rate regime, compared to traditional Lugiato-Lefever equation (LLE), the CW states will be the same, but it can embrace different properties for multi-frequency states. The dispersive wave emission will be considered under such a regime.

ESR Zhiwei Fan started his research on bi-directional microresonator in October 2019. In the period of 2020, he developed codes for computation on stationary solitons, the modulational instability analyses for the solitons, and for real-time dynamical simulations. In the next stage, **ESR Zhiwei Fan** will introduce the extensive frequency conversion for octave-wide frequency combs based on the developed codes.

2.4. Task 7.4 Integrated spectral processors for comb-based arbitrary waveform generators

Beneficiaries and partners involved in the task: ESR 11 (UPV); VLC Photonics; LiGenTec

Objectives for this task are to develop theory of solitons interaction with dispersive wave for RF to optical link.

ESR Roel van der Zon was employed on 3rd December 2019, hence, in the period of December 2019 to February 2020, ESR was gaining knowledge on solitons and the devices that can be used for spectral processing. From February 2020 ESR Roel van der Zon's objective was to design and simulate components needed for spectral processing:

- An arrayed waveguide grating (AWG) and interferometers with thermal tuners.
- A mid infrared (MIR) setup will be built.

Introduction to the research problem

For a spectral processor we need a wavelength splitter and control over phase and amplitude. UPV choose to go for an AWG in combination with Mach Zehnder interferometers (MZI) structure.

In order to design an AWG knowledge is needed of the following parts and their aspects. For the array of waveguides the phase difference created by the length difference is of importance. For the slab couplers a relation between phase or amplitude and the in or output ports needed. For getting a correct set of parameters, which generally consist of the lengths of the array waveguides and the placement of the ports, one can follow general design rules or simulate the whole design. ESR 11 chose the latter strategy because it gives both an accurate design as well as insight and understanding.

For the design of an MZI we need a coupler, we choose for an multi-mode interferometer (MMI), and phase tuners, which will be thermal tuners. An MMI can be designed according to a set of rules but should be simulated and finetuned for good results.

Research results achieved by date

For running an AWG simulation, the parameters for the waveguides that will be used are needed. These were found with a cross section simulation, and these are quite generic.

For setting up the AWG design model ESR Roel van der Zon chose 3 different layout styles: a Smit layout, an orthogonal and Alcatel for which the dimensional parameters can be used to match a desired design. For the model, the effective indices of the slab coupler, straight waveguides and radius dependent bend waveguides are taken into account. The result of the model is a flexible design script which takes AWG design parameters like the slab coupler focal length and m-number, then matches it to an actual layout and correctly places the in/outgoing ports. Fig. 8 shows an example design and its corresponding response. The AWG is matched to a 100 GHz spaced comb at 1550 nm centre wavelength.

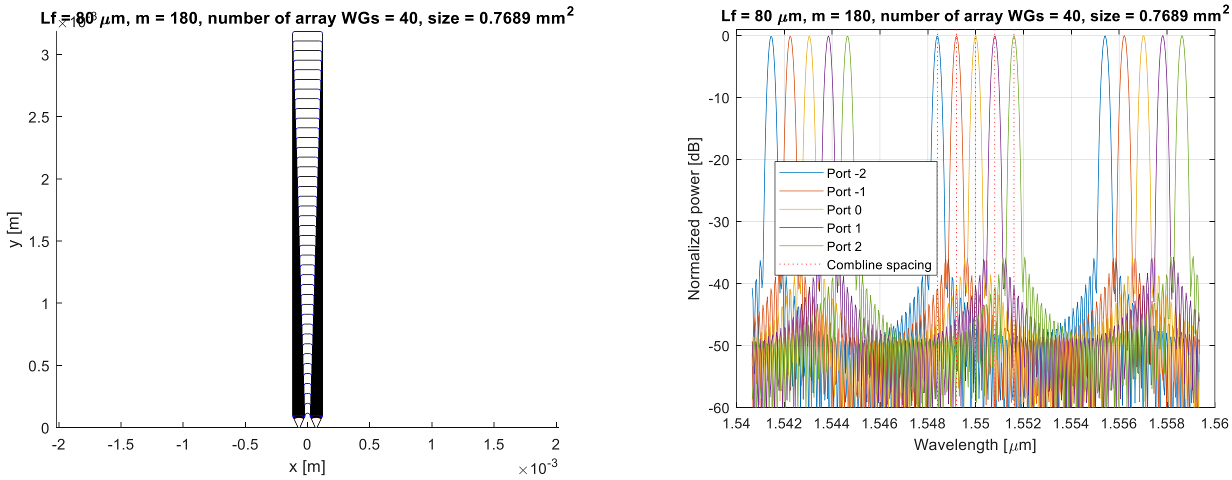

Figure 8: Left: Example layout of a 5 port orthogonal design AWG. Right: Spectral response of a 5 port AWG.

Below (see Fig. 9) are presented two other design layouts with the same output result.

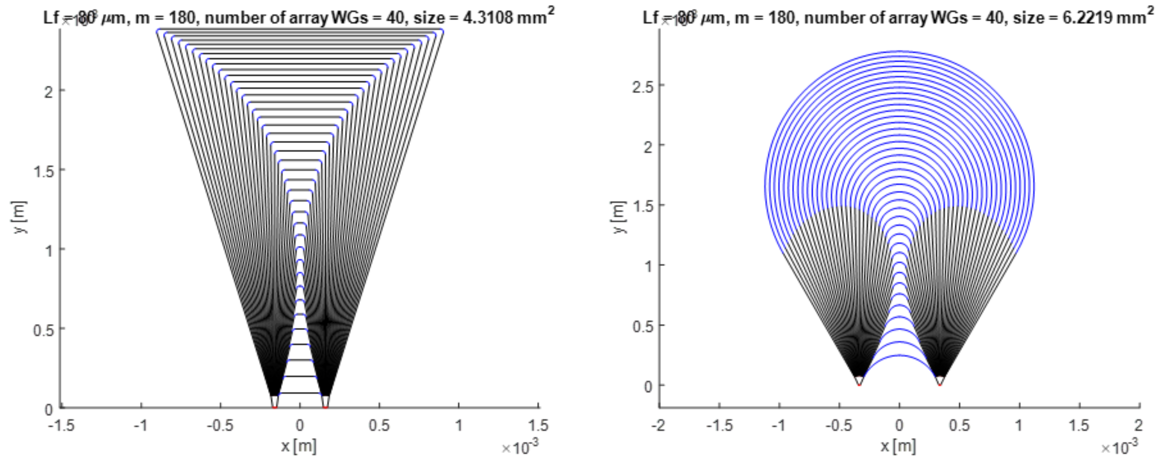

Figure 9: Left Alcatel design layout AWG. Right: Smit layout design with pathlengths calculated to precisely match the phase.

These designs are checked for some fundamental and fabrication rules, like for the waveguide spacing. This design strategy allows us meet different requirements without having to re-design the whole device, because all parameters are free of choice.

The MATLAB designs have now been transferred to an optoDesigner script. The script automatically generates an AWG according to the specification input. For this script the orthogonal design was used, this design is the most simplistic in terms of limitations and has, apart from bends, only vertical and horizontal waveguides what will improve the accuracy when fabricated with E-beam lithography. When using E-beam lithography the design will be written in sections, writing fields, in between which stitching errors might occur. When using horizontal and vertical waveguides these are better defined and in our case, we can choose the direction with the lowest error.

UPV ran simulations using OptoDesigner for the MMIs needed in MZI. Firstly, a general rule of thumb was used to find the width, length, and port placement. Then, it was finetuned by hand. Below (see Fig. 10) a 2D Beam propagation method (BPM) simulation of two MMIs is shown, when adding a thermal tuner it would be a functional MZI.

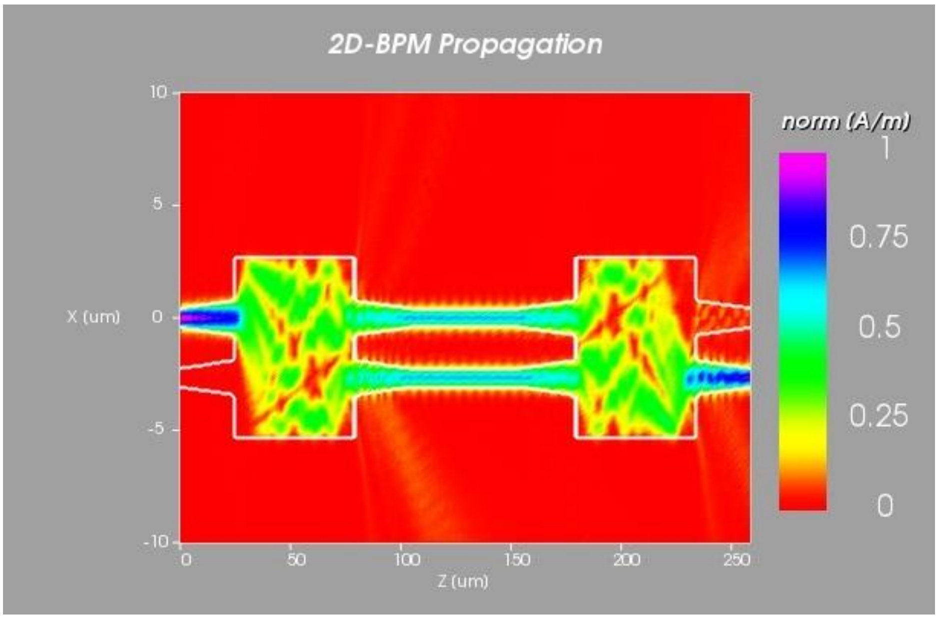

Figure 10: The 2D-BPM simulation result of a 2x2 MZI without a phase difference in the paths.

The following step is to select a design for fabrication at Chalmers' fab. For this ESR11 re-run the simulations using their platform parameters with the goal to find an optimum 9 port AWG which can be combined with MZIs.

The MZIs are specified for Chalmers' specifications as well as heaters for thermal tuners are defined and added to the design. First drafts of the layout have been made and a final design will soon be finished for production. Below (see Fig. 11) is a layout example of a spectral processor.

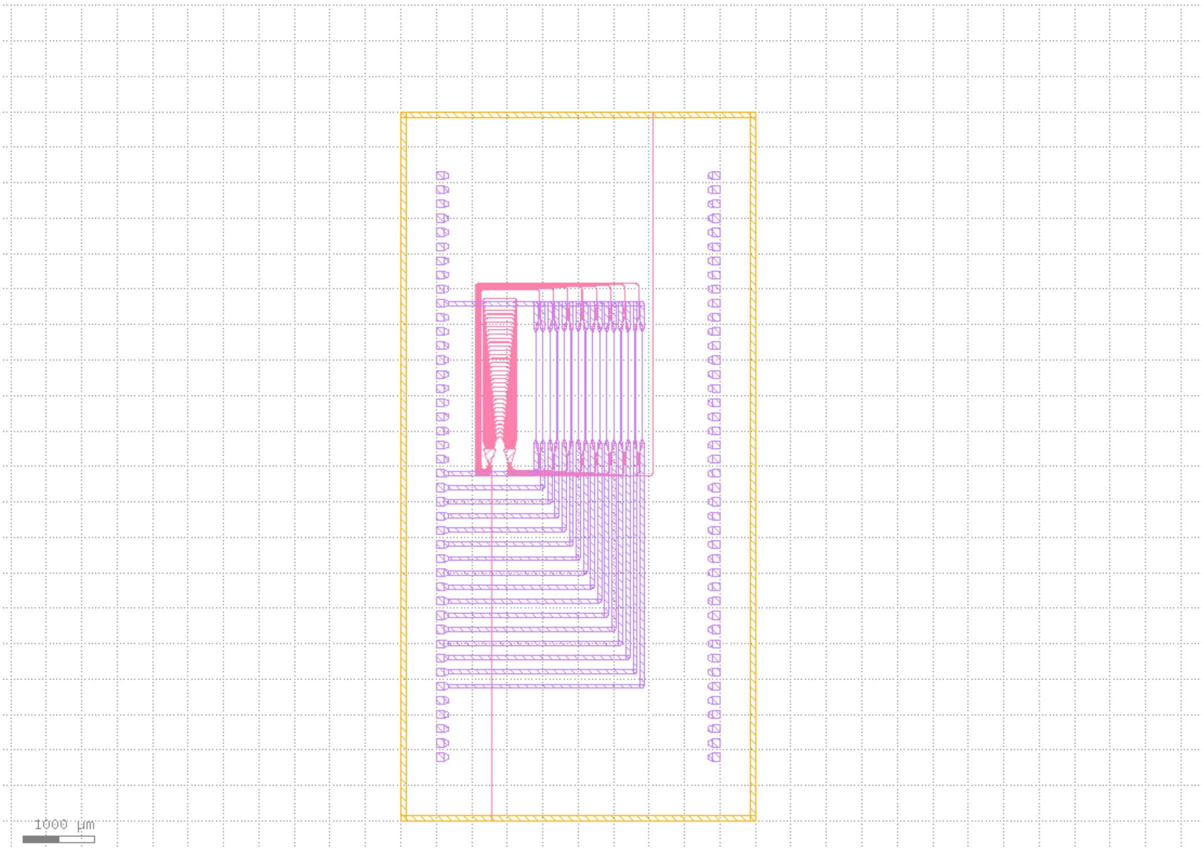

Figure 11: A eight channel spectral processor constructed of a 9x9 AWG with a loop back connection through a set of MZIs.

The spectral processor consists of an AWG connected loop back with a series of MZIs. This gives control over the phase and amplitude of 8 channels. The side channel will not be altered. Other designs that will be included in the layout are two AWGs connected with a series of MZIs in between and a design where we can use a separate channel for the in- and output. This in order to have control over all combline channels present in the output.

Using two AWGs has a slight disadvantage in terms of space and matching but solves the problem in a straightforward way. The matching problem will be solved by using a thermal pad on the AWG array of waveguides.

For the second idea two solutions are proposed. The use of a repetitive AWG and one of the side channels for the in- and output, the downside is that the repetitive spectrum will cause unwanted comblines to be present in the output. Another solution can be an AWG with a central input that is half the channel spacing from the neighbouring channels. In this way the central waveguide will not carry a combline itself and the lack of phase and amplitude control is not of importance. See Fig. 12 below. The requirement for this strategy is sufficient physical space between the channels. That results in a larger footprint in general.

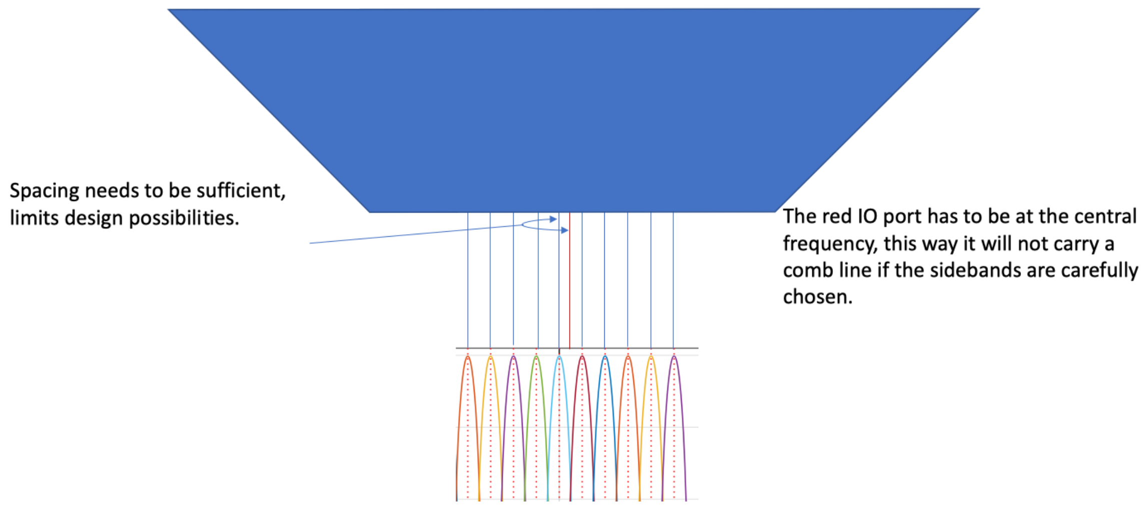

Figure 12: An AWG slab coupler input design where an central port placed at half the channel spacing is added in order to have a in-/output for the spectral processor that does not carry a combline.

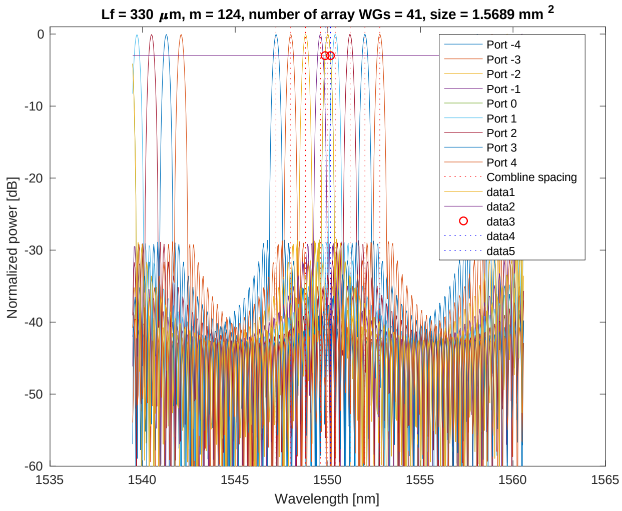

Figure 13: The spectral response of an AWG with a central channel placed at half the channel spacing.

Next to the spectral processor test structures are added to use the Optical Frequency Domain Interferometry (OFDI) method as presented in the Microcomb training delivered by Professor Daniel Pastor[9]. The MIR test setup is now assembled and ready for use, except for the design work.

Planned future research directions

After finalising a design, the above needs to be translated to a layout, which then can be produced. The goal is to improve the AWG model. The next step is to include polarisation rotation in the bend waveguides.

When we have a produced a chip, it needs to be characterized to see where both the AWG model as well as the AWG performance can be improved.

We are now working on a production strategy, as the several steps of the production process will be carried out by different fabs.

I will perform measurements to get hands on experience with the (OFDI) technique with already available chips. UPV will also investigate the possibilities of using a 6-axis positioner in combination with a fibre array to make OFDI measurements with only on chip devices and delay lines.

[9]"Full-field photonic components and integrated circuits (theory)" by Universitat Politècnica de València https://www.microcomb-eu.org/upv-course

2.5. Task 7.5 Ultra-broadband signal processing using chip-scale frequency comb sources

Beneficiaries and partners involved in the task: ESRs 15 & 16 (KIT); LiGenTec

Objectives for this task are to mitigate nonlinear effects in single-mode fibre communication systems using the broadband phase coherence of microresonator combs.

Note: The **ESR 15 Yung Chen** was employed on 17 March 2020 and the recruitment process for the **ESR 16 Innokentiy Zhdanov** had not been completed until 10 September 2020.

KIT shared a link to the open access publications at KIT: KITopen (https://www.bibliothek.kit.edu/cms/kitopen.php), where the open access research publications for MICROCOMB will be submitted.

Phase analysis of the frequency comb systems is a very important task in order to create high precision measurement systems and impact of different factors on performance research. Today frequency combs are very promising for data transmission, distance measurement, spectroscopy, and other applications. Some of them are limited by the phase noise of the comb source at the state-of-the-art. In order to determine the phase noise of the microresonator frequency comb one can use the multiheterodyne technique with coherent detection. This will help us to measure the complex amplitude of the input signal and extract the RF linewidth, phase-noise and FM-modulation noise. The typical scheme of the coherent multiheterodyne coherent phase measurement is presented in Fig. 14

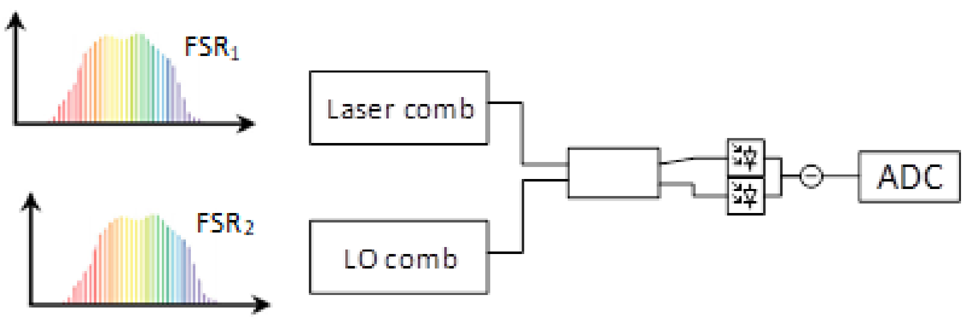

Figure 34 Scheme of multiheterodyne detection of complex amplitude of the RF beating comb.

With this coherent heterodyne scheme, one obtains the so-called beat notes between the signal and local oscillator combs. The aim is to measure the phase noise of these beat notes. It can be evaluated by extracting the whole complex signal from these beatings with usage of Hilbert transform[10] or 90° optical hybrid[11]. The first approach seems to be more preferable, because of the lack of additional losses that can affect SNR of the beat notes. Once, the phase noise of all these beat notes is determined, the phase differences can be computed in the following way.

$$\begin{aligned}\Delta\phi(t) &= (n-n_c)\left(\phi_{\mathrm{RF}}(t)-\varphi_{\mathrm{RF}}(t)\right)-(m-n_c)\left(\phi_{\mathrm{RF}}(t)-\varphi_{\mathrm{RF}}(t)\right)+\alpha_{nm}\\ &= (n-m)\left(\phi_{\mathrm{RF}}(t)-\varphi_{\mathrm{RF}}(t)\right)+\alpha_{nm}\end{aligned}$$

Where, n and m – beat orders of the signal and local comb correspondingly, n_c - carrier numbers. The presence of the difference of n and n_c leads to the opportunity to measure as low phase noise as high (n-n_c) value. So, if two different notes are separated as far as possible with enough SNR level, it will help to detect lower phase noise. In order to use the maximum SNR, it is a task to minimize losses on a receiver. One of the alternatives is to use Bayesian filtering with Hilbert transform DSP. That is why this technique seems to be attractive for the characterization of the noise and leads to several kHz linewidth measurement.

KIT will apply this technique to characterize a phase noise of the microcomb sources. ESR 16 Mr. Innokentiy Zhdanov will be involved to realization of this technique at KIT. Such data obtaining helps to suppress phase noise and improve the precision of all microcomb applications.

At the same time, KIT investigate the performance of coherent WDM system based on chip-scale frequency comb generators[12]. The influence of the power and optical carrier-to-noise ratio (OCNR) of the comb lines on the performance of the WDM link is studied. We identify two distinctively different regimes, where the transmission performance is either limited by the comb source or by the link and the associated in-line amplifiers. Our analysis indicates that, depending on the number of spans, minimum comb line powers between –25 dBm and –15 dBm and minimum $OCNR_{line}$ values between 25 dB and 35 dB are needed for link-limited transmission. We further investigate the impact of line-to-line power variations on the achievable optical signal-to-noise ratio (OSNR) and link capacity using a soliton Kerr frequency comb as a particularly interesting example (see Fig. 15). We find that OSNR levels of around 30 dB for Metro links lead to capacities of around 80 Tbit/s. We believe that our findings will help to compare different comb generator types and to benchmark them with respect to the achievable transmission performance.

[10] Brajato, Giovanni, et al. "Bayesian filtering framework for noise characterization of frequency combs." *Optics Express* 28.9 (2020): 13949-13964

[11] Kikuchi, Kazuro. "Characterization of semiconductor-laser phase noise and estimation of bit-error rate performance with low-speed offline digital coherent receivers." *Optics Express* 20.5 (2012): 5291-5302.

[12] Pablo, Marin-Palomo, et al. "Performance of chip-scale optical frequency comb generators in coherent WDM communications." *Optics Express* 28.9 (2020): 12897- 12910.

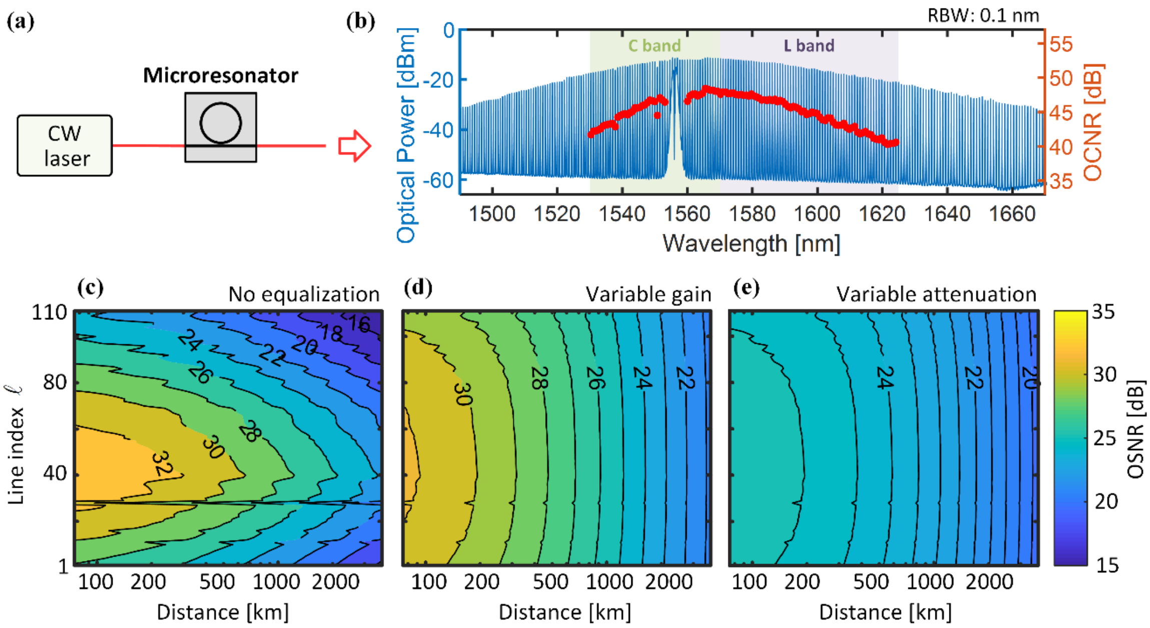

Figure 15. Single-soliton Kerr frequency combs and impact of line-to-line and variations on the OSNR. (a) A soliton Kerr comb is generated by pumping a high-Q microresonator by a CW laser under appropriate conditions. (b) Spectrum of a single-soliton Kerr frequency comb generated in a SiN microresonator. In the center of the spectrum, the comb line power amounts to – 11 dBm, and the OCNR is approximately 48 dB. (c-e) OSNR as a function of the link distance and the comb line index, ℓ, (c) without equalizing the power per line ("No equalization"); (d) for equalizing the power per line by using a spectrally variable gain in the optical amplifier after the microresonator ("Variable gain"); (e) for equalizing the power per line by introducing individual power attenuations for each channel ("Variable loss").

2.6. Task 7.6 Demonstration of few-mode-fibre transmission with microcombs

Beneficiaries and partners involved in the task: ESR 4 (CUT); TOPTICA

Objectives for this task are to realize transmission experiments in novel fibers featuring strong coupling between spatial modes.

In the framework of this ITN, CUT will explore the use of microcombs in the thulium wavelength region for advanced optical communications, including space division multiplexing. The **ESR 4, Krishna Twayana** has been working on two fronts: dispersion engineering of Si3N4 microresonators at 1.9um and dispersion measurements of microresonators using a self-referenced comb as a ruler. As of today, the ESR has already established a testbed for dispersion measurements in the C+L bands (as preliminary tests before CUT moves to 1.9um) and is benchmarking the system in terms of precision and accuracy with other techniques. From January 2020 onwards the research plans are:

(i) Establish a dispersion testbed system in the 1.9um wavelength region

(ii) Validation of dispersion-engineered microresonators in the 1.9um wavelength region

Space division multiplexing (SDM) offers the possibility to attain astonishing data rates by exploiting the space dimension in specialty fibers. SDM utilizes multiple modes, cores, a bundle of fibers or a combination of these for massive parallelization of data streams. Each spatial mode can sustain complex modulation formats and multiple wavelengths. As a result, SDM can be integrated with modern coherent optical communications and wavelength division multiplexing to reach data rates in excess of 1 Pb/s. In this context, a frequency comb has the potential to light simultaneously multiple space-frequency channels provided that it can deliver sufficient power per line, line spacing stability and low phase noise, preferably in an integrated platform such as a microresonator frequency comb. These are aspects that deserve careful attention.

By February 2020 ESR Krishna Twayana had almost done the dispersion measurements of SiN micro-ring resonators, using a fiber-based interferometer and a Menlo comb. ESR will learn and work on soliton comb generation and start coherent communication experiments. Publications planned on high-speed coherent communications using frequency comb lines for higher-order modulations.

Publications:

Zhichao Ye, **Krishna Twayana**, Peter A. Andrekson, and Victor Torres-Company "High-Q Si3N4 microresonators based on a subtractive processing for Kerr nonlinear optics", in Optics Express Vol. 27, Issue 24, pp. 35719-35727 (2019) https://doi.org/10.1364/OE.27.03571

Chalmers has developed an in-house fabrication process for silicon nitride based on standard fabrication processing that features high-confinement, dispersion-engineered microresonators with quality factors exceeding ten million[13]. Based on this approach, Chalmers has realized both soliton microcombs and dark pulse Kerr combs. The latter samples have been used, in collaboration with the Technical University of Denmark (outside the consortium partners), to realize the first demonstration of space division multiplexing with microresonator frequency combs. Concretely, 1.84 Pbit/s was attained by combining a high-power efficient microcomb source with 37-core (see results in Fig. 16[14]). This represents the highest transmission throughput ever achieved with a chip-scale comb source.

[13] Z. Ye, K. Twayana, P. A. Andrekson and V. Torres-Company, "High-Q Si3N4 microresonators based on a subtractive processing for Kerr nonlinear optics" *Optics Express* **27**, 35719-35727 (2019).
[14] D. Kong et al., "Single dark-pulse Kerr comb supporting 1.84 Pbit/s transmission over 37-core fiber", Conf. Lasers & Electro-optics, postdeadline paper JTh4A.7 (2020).

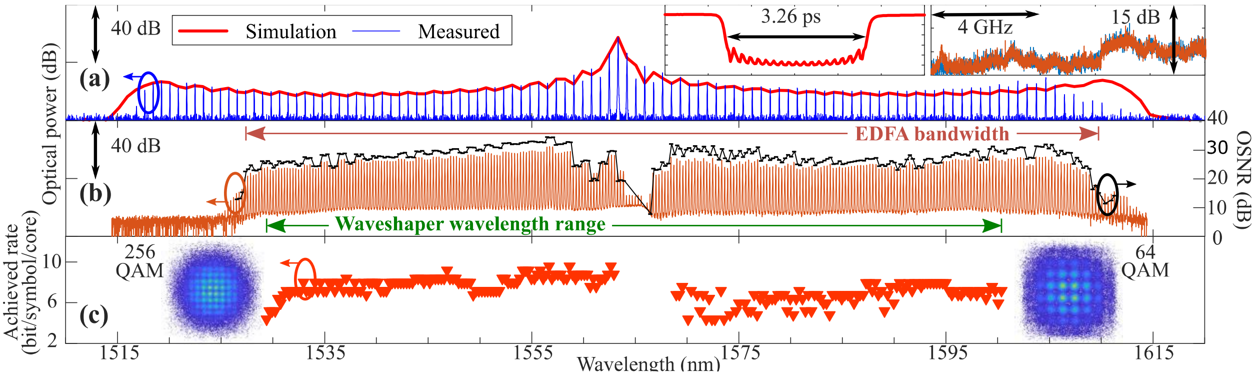

Figure 16. Reaching the petabit per second frontier with microcombs (after ref. 2 by Kong et al.). (a) optical spectrum of simulated (red) and measured (blue) dark-pulse Kerr comb. Insets show the simulated time-domain intracavity waveform and measured radio-frequency amplitude noise compared to the case when the comb is off. (b) optical spectrum of filtered and modulated comb, together with the measured OSNR per line. (c) Achieved bit rate per symbol per fiber core after FEC decoding with error-free performance. All 37 cores achieve the same data rate. Insets represent constellation maps for received 64 QAM and 256 QAM.

However, one drawback of the microcomb source utilized in the experiments described above is its reproducibility. The comb source relied on samples that featured two linearly coupled transverse modes in a single microring resonator geometry. The coupling arises from nanoscale imperfections that cannot be engineered and are only found in certain samples a *posteriori*. In a subsequent work, Chalmers has developed an arrangement of linearly coupled microresonators that overcomes this problem, where the soliton states can be accurately modeled and attained on demand, by careful design of the dual microresonator geometry[15]. This arrangement has resulted in microcomb sources featuring unprecedented conversion efficiency, spectral flatness and operation with pump power levels that render the solution compatible with photonic integration.

The results mentioned above rely on the assessment and measurement of the dispersive properties of the microphotonic devices. Here, the ESR researcher has taken a leading role in the development of an original approach based on optical frequency domain reflectometry/swept-wavelength interferometry for the assessment of integrated photonic devices. This technique allows for retrieving the complex response (amplitude and phase) of a device under test over a broad wavelength range set by the tuning range of an external cavity tunable laser diode. The main novelty of the work lies on the use of a fiber-based self-referenced frequency comb for the calibration of the wavelength axes of the tunable laser diode, allowing to cope with deviations in the tuning rate of the laser. In the context of microresonators, this technique allows for disentangling the coupling rate from the intrinsic loss contributions in the assessment of the loaded quality factors over the telecommunications C and L bands (see Fig. 17).

[15] O. B. Helgason et al., "Dissipative Kerr solitons in photonic molecules" arXiv2007.02608 (2020).

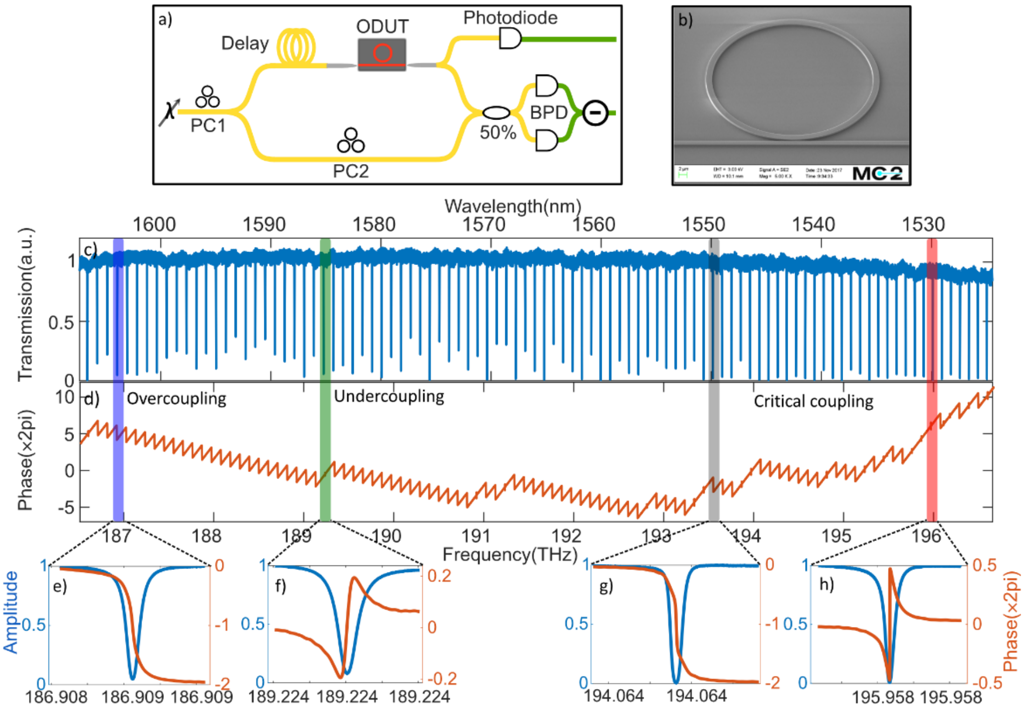

Figure 17. Comb-based swept-wavelength interferometry. a) Schematic representation of the measurement setup (self-referenced comb not depicted). b) SEM image of a typical microring resonator used as device under test. C,d) Normalized transmission scan showing amplitude and phase retrieval of the sample. Different coupling conditions can be differentiated, such as: e) Over-coupling, f) Under-coupling, g,h) Critical-coupling.

In the coming year, the ESR 4 will realize a similar testbed in the 1.9 micrometer range, with the future goal of realizing a high conversion efficiency microcomb operated with a 1.9 semiconductor laser pump. Briefly, the rationale for this research in the context of telecommunications is twofold. This is an emerging communications window that capitalizes on advances in both thulium-doped amplifiers and microstructure bandgap fibers. Thulium doped fiber amplifiers can operate over a significantly broader bandwidth than traditional erbium-doped fiber amplifiers, providing the means to extend the channel count when realizing wavelength division multiplexing. Microstructure bandgap fibers offer lower nonlinearity and are compatible with mode division multiplexing, but the losses are still higher than the theoretical limit

2.7. Summary of publications, talks and conferences

A. Tikan, J. Riemensberger, K. Komagata, S. Hönl, **M. Churaev, C. Skehan**, H. Guo, R. N. Wang, J. Liu, P. Seidler, T.J. Kippenberg, "Emergent Nonlinear Phenomena in a Driven Dissipative Photonic Dimer", preprint: arXiv:2005.06470v2, invited for resubmission in Nature Physics.

A. Tikan, J. Riemensberger, K. Komagata, S. Honl, **M. Churaev**, **C. Skehan**, H. Guo, R. N. Wang, J. Liu, P. Seidler, and T. J. Kippenberg, "Dissipative Kerr solitons in a photonic dimer", in CLEO: QELS_Fundamental Science, 2020, paper FTh1A.5

J.Szabados, D.N. Puzyrev, Y. Minet, L. Reis, K. Buse, A. Villois, D. V. Skryabin, and I. Breunig "Frequency comb generation via cascaded second-order nonlinearities in microresonators", in Physical Review Letter, paper accepted on 6 May 2020

D.V. Skryabin "Coupled-mode theory for microresonators with quadratic nonlinearity", in J. Opt. Soc. Am. B 37, 2604-2614 (2020) https://doi.org/10.1364/JOSAB.397015

Z. Fan, and D. Skryabin "Soliton blockade in bidirectional microresonators", Optics Letters, (2020) https://doi.org/10.1364/OL.409362

Zhichao Ye, **Krishna Twayana**, Peter A. Andrekson, and Victor Torres-Company "High-Q Si3N4 microresonators based on a subtractive processing for Kerr nonlinear optics", in Optics Express Vol. 27, Issue 24, pp. 35719-35727 (2019) https://doi.org/10.1364/OE.27.03571

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

2.8. 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)															
2															
3															
4															
5															
6															
7															
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			
34												Toptica			
35												Toptica			
36															
37 (2022)															
38															
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46															
47															
48															

(yellow)	Original secondment schedule as per GA
(light green)	Completed secondments
(red)	Virtual secondments delivered by online meetings via Zoom and Teams
(blue)	Estimated plans for secondments providing the lockdown restrictions are lifted
(light orange)	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.