Riga Technical University
Institute of Telecommunications

RIGA TECHNICAL UNIVERSITY
Faculty of Electronics
and Telecommunications

«Development of optical frequency comb generator based on a whispering gallery mode microresonator and its applications in telecommunications» (1.1.1.1/18/A/155)

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2022

Project summary: <u>description of project objective</u> (1/2)

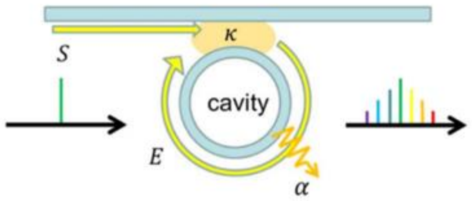
The ”***Development of optical frequency comb generator based on a whispering gallery mode microresonator and its applications in telecommunications***” addresses challenges to develop, construct and test a comb generator prototype for telecommunication applications. In particular, the focus of this project is to obtain new knowledge on whispering gallery mode resonator-based optical frequency combs (WCOMBs). More specifically experimentally develop WCOMB as a multiwavelength light source for or use in fiber optical transmission systems(FOTS)

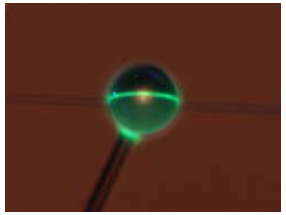
The project aims to obtain new knowledge on whispering gallery mode resonator-based optical frequency combs (WCOMBs) and to develop, construct and test a comb generator prototype for telecommunication applications.

<u>The created WCOMB will achieve the following requirements:</u>

- ✓ *provide a frequency comb in the optical C-band (1530-1565 nm), with the number of channels corresponding to 2n (n – integer number) that is typical number of FOTS solutions (such as 8, 16 channels)*

- ✓ *channels' spacing interval between the (WGM) resonator's frequency comb maximum peaks corresponds to the spacing intervals of wavelength-division multiplexing (WDM) transmission system data channels specified by (ITU-T G.694.1) recommendation (such as 100 and 50 GHz).*

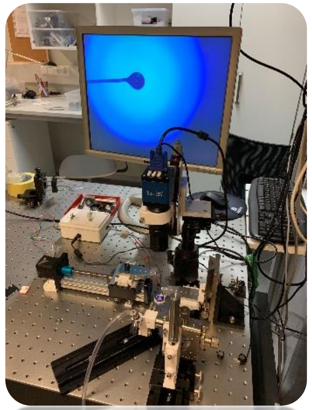


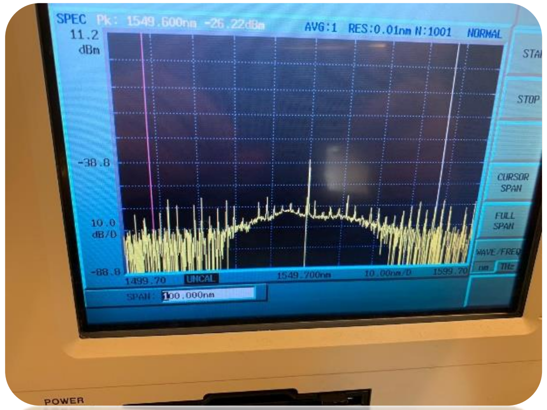


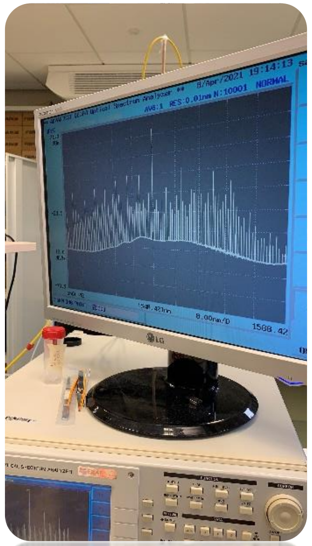
Project summary: <u>description of project objective</u> (2/2)

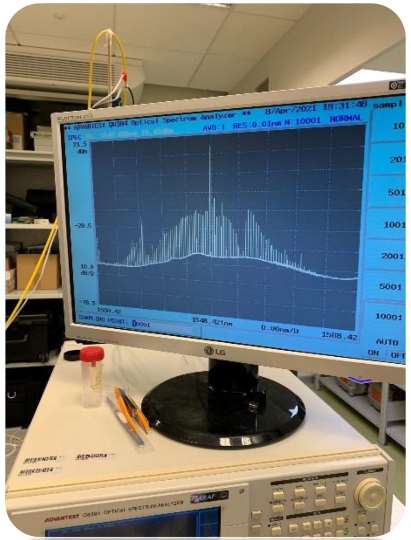
- ***<u>In fiber optical communication systems</u>*** for data channel typically a *<u>single light source is used</u>*, for example, WDM systems. To enlarge the data transmission rate, multiple light sources can be used WDM data transmission technology (*where laser arrays are used as a light sources*) is expensive due to the need for many lasers that have to be synchronized.

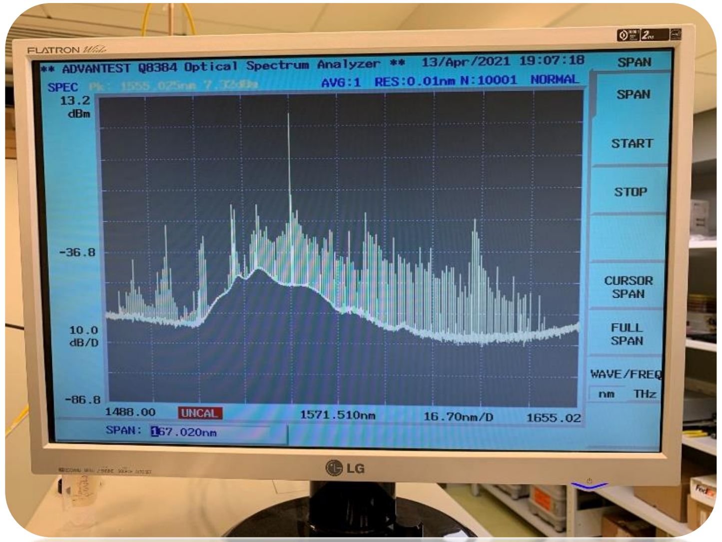
- Microresonator optical ***<u>frequency combs OFC have applications in the field of Telecommunications</u>***. WCOMB ***<u>use a single pump source and then generates spectra of various peak frequencies</u>***. Each of these frequencies can be used as data channel light source in fiber optical transmission systems. Therefore WCOMB is smaller, less energy consuming and less expensive that standard laser arrays (multiple separate laser sources).











WCOMB project realization process: brief overview

- **2.1.** Research on existing types of WCOMB generators, solutions and their use in fiber optical communication systems;
- **2.2.** The development and construction of portable WCOMB as multiwavelength light source for application in fiber optical communication systems;
- **2.3.** Mathematical modelling of a WCOMB based optical communication system;
- **2.4**. Lab tests of WCOMB integrated in fibre optical communication system;
- **3.1**. The adjustment of a portable WCOMB prototype for field tests in commercial fibre optical communication system infrastructure;
- **3.2.** Validation of a portable WCOMB prototype in commercial fibre optical communication system;
- **4.1**. Publication of scientific articles in magazines and conference proceedings included in the Web of Science or SCOPUS (A or B) databases;
- **4.2.1.** Patent preparation and application.

WCOMB project realization process: Research on existing types of WCOMB generators, solutions and their use in fiber optical communication systems *(D2.1.)*

- ✓ According to the project timetable, the project activity was implemented from Q1 to Q2. **Task T2.1 is completed resulting in report D2.1** about existing of whispering gallery mode resonators, e.g., by their types, their solutions, and realizations for different applications and especially for use in wavelength division multiplexed fiber optical communication systems.

- ✓ The first section of this report includes an **overall evaluation of whispering gallery mode (WGM) resonators, classification and realization by the implementation type of WGM resonator** for frequency comb-based generator including main implementation parameters on the resulting frequency comb generator.

- ✓ **This study resulted in the Quantum Electronics 2020**. Part of this paper is devoted to the frequency comb generation process, main microresonator parameters such as free spectral range (FSR) and Q-factor, used optical frequency comb (OFC) generator parameters and resulting frequency combs, as well as the implementation of OFC for optical data transmission.

- ✓ The second section focuses on the overview of the difficulties and limitations of using a Kerr comb for data transmission by its type – ring resonator and crystalline frequency comb source, for implementation in telecommunication systems.

- ✓ **The outcome of this research activity is a description of the further technology development path within the WCOMB project.**

WCOMB project realization process: The development and construction of portable WCOMB as multiwavelength light source for application in fiber optical communication systems *(D2.2.)*

- ✓ This project activity was implemented from Q1 to Q8, according to the project timetable. Based on the knowledge obtained from the first activity of WP3 the **project team in tight cooperation with enterprise partner AFFOC Solutions developed** experimentally an **WCOMB prototype in the fiber optical transmission systems (FOTS) laboratory** of RTU, adapted **for use in FOTS** as a solution for a multiwavelength light source.
- ✓ Constructed **prototype provided stable operation of optical frequency comb generated lines in the optical C-band** (1530-1565 nm) region with the number of channels corresponding to 2^n (n – integer number) where **channels spacing interval between the resonator lines corresponds to** the spacing intervals of wavelength-division multiplexed **(WDM) transmission system data channels specified by (ITU-T G.694.1)** recommendation.
- ✓ The developed prototype was tested and validated in the laboratory of Fiber Optical Transmission at RTU IT where **stabile operation of two newly generated carriers** (from 7-carrier OFC) having the highest peak power are valid for application in fiber optical communication systems (sufficient optical signal-to-noise-ratio (SNR) of generated OFC harmonics) **for time period of 10 hours.**
- ✓ The most significant results were published in a scientific paper accepted by the journal "Optics Express" (**Q1,** IF = **3.669,** CiteScore = **4.56,** indexed in SCOPUS, citation index of which reaches **"at least 50% of the average citation index in the sector"**).
- ✓ At the end of this activity a **scientific report D.2.2. has been written** where all measurements and obtained data are discussed in more detailed aspects.

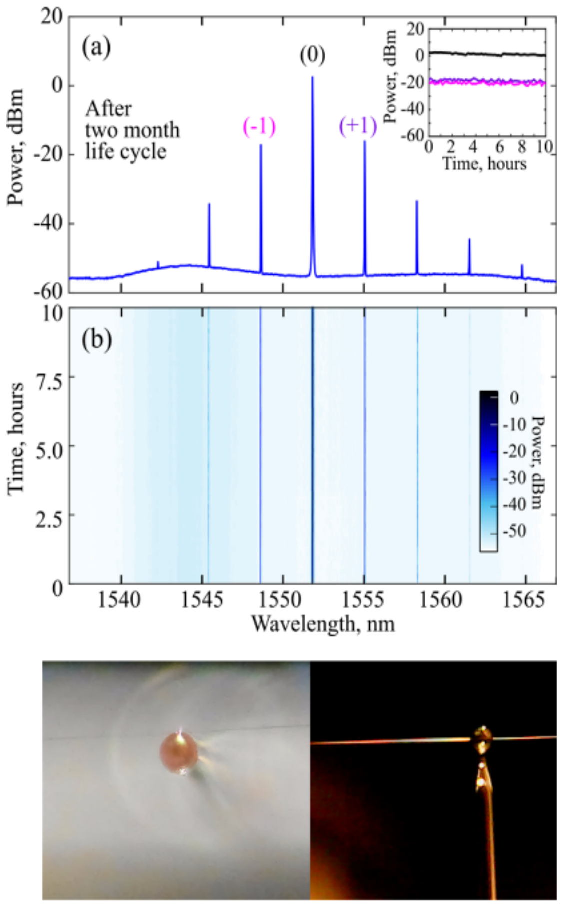
WCOMB project realization process: Mathematical modelling of a WCOMB based optical communication system *(D2.3.)*

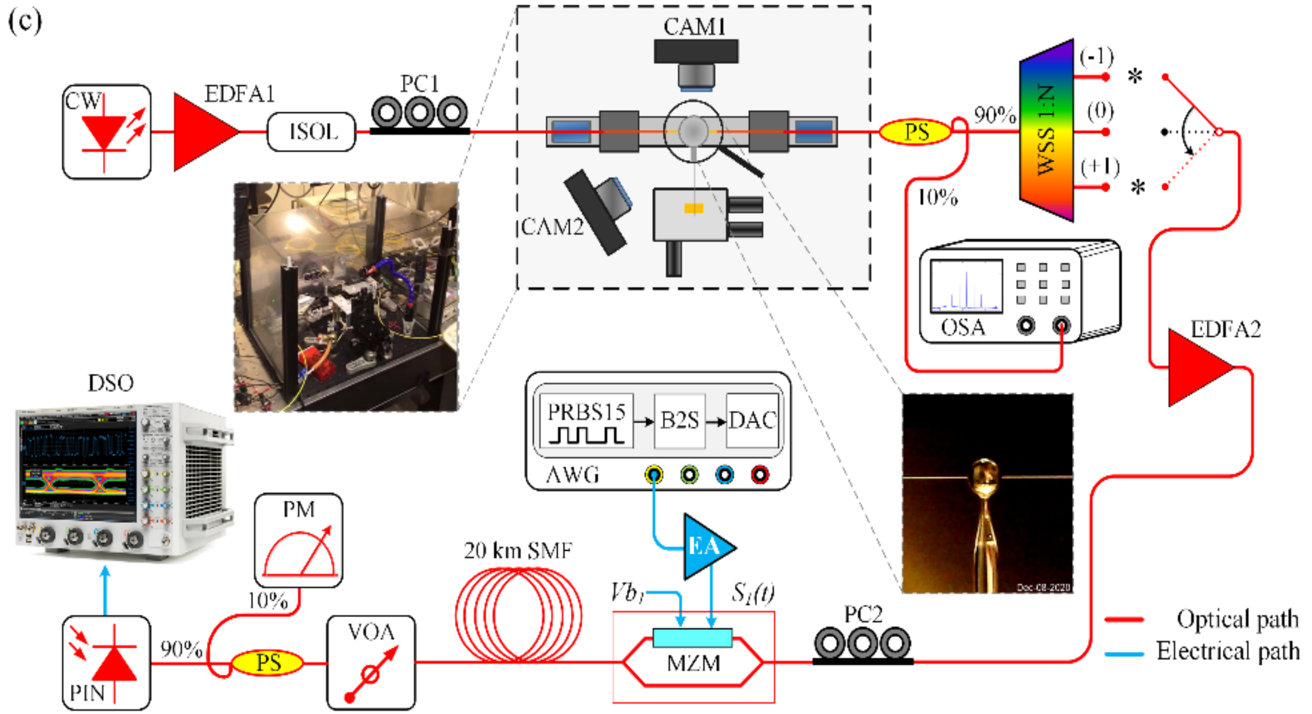
- ✓ This project activity was implemented from Q2 to Q8. This activity was performed in parallel to activity 2.2, therefore providing good alignment between both activities and mutual complementarity of performed analysis. During this activity, **integration of an experimentally measured optical frequency comb (OFC) into a developed mathematical simulation model of fiber optical communication system based on whispering gallery mode resonator-based optical frequency comb generator (WGMR-OFC) was evaluated and obtained.**
- ✓ The first section of the report includes the description of the **realized simulation model of fiber optical communication system and integration of OFC into this model.** The second section **evaluates the WMGR-OFC capabilities to ensure system performance in different architectures**, typical metro-access optical network distances, and data speed rates.
- ✓ **Developed simulation model meets the technology readiness level – TRL 3** (which includes the experimental testing of the concept using analytical research to confirm the forecasts about technological components).
- ✓ The most significant results from simulations with VPIphotonics software were published in a scientific paper accepted by the journal "**IEEE Access**" (**Q1,** IF = **3.745,** CiteScore = **3.9,** indexed in SCOPUS**,** citation index of which reaches **"at least 50% of the average citation index in the sector**").
- ✓ **At the end of this activity a scientific report D.2.3. has been written** where all measurements and obtained data are discussed in more detailed aspects.

WCOMB project realization process: Lab tests of WCOMB integrated in fibre optical communication system *(D.2.4.) (1/5)*

- ✓ **Implementation timeline of the activity has been adjusted**: Modification of the contract from 26 March 2021 – the activity start scheduled for the 9th quarter of the project.
- ✓ To the best of our knowledge based on literature analysis, **we experimentally for the first time present a designed silica microsphere whispering-gallery-mode microresonator (WGMR) OFC as a C-band light source** where 400 GHz spaced carriers provide data transmission of up to 10 Gbps NRZ-OOK modulated signals over the standard ITU-T G.652 telecom fiber span of 20 km in length.
- ✓ The part of the most significant achieved results during this activity already was published in a scientific paper accepted by the journal "**Optics Express**" (**Q1,** IF = **3.669,** CiteScore = **4.56,** indexed in SCOPUS, citation index of which reaches **"at least 50% of the average citation index in the sector"**).
- ✓ As well WCOMB performance evaluation in fiber optical system (based on short-range data centre interconnection (DCI) architecture, with 2 km SMF fiber span) at different data transmission rates and modulation formats was preferred in the FOTS laboratory. The **achieved higher-level data rates up to 50 Gbit/s per channel by use of WGMR-OFC as light source will be published** in scientific article - journal paper "**MDPI Apl. Sc.**" (**Q2,** IF = **2.736,** indexed in SCOPUS, citation index of which reaches **"at least 50% of the average citation index in the sector"**). At the moment **scientific article is prepared and submitted by the project team members.**

WCOMB project realization process: Lab tests of WCOMB integrated in fibre optical communication system *(D.2.4.) (2/5)*





Acronyms: CW – Continuous wave laser, EDFA – erbium-doped fiber amplifier, ISOL – fiber optical isolator, PC – polarization controller, CAM – microscope with zoom camera, PS – power splitter, OSA – optical spectrum analyzer, WSS – wavelength selective switch, MZM – Mach-Zehnder modulator, AWG – arbitrary waveform generator, B2S – bits to symbol mapping, DAC –digital-to-analog converter, EA – electrical amplifier, SMF – single mode fiber, VOA – variable optical attenuator, PM – optical power meter, PIN – photodiode, DSO – digital storage oscilloscope, DSP – digital signal processing.

Fig. 1. *Measured OFC performance over a 10-hour period: (a) optical spectrum with inset representing captured power stability, and (b) power distribution stability over the wavelength. (c) The experimental setup of the designed silica microsphere WGMR-OFC as a light source where 400 GHz spaced carriers provide NRZ-OOK modulated 2.5 and 10 Gbps data transmission over 20 km SMF fiber. Insets show tapered fiber and silica microsphere resonator positions of coupling conditions and WGMR-OFC reduced humidity and dust-prevention cover box.*

WCOMB project realization process: Lab tests of WCOMB integrated in fibre optical communication system *(D.2.4.) (3/5)*

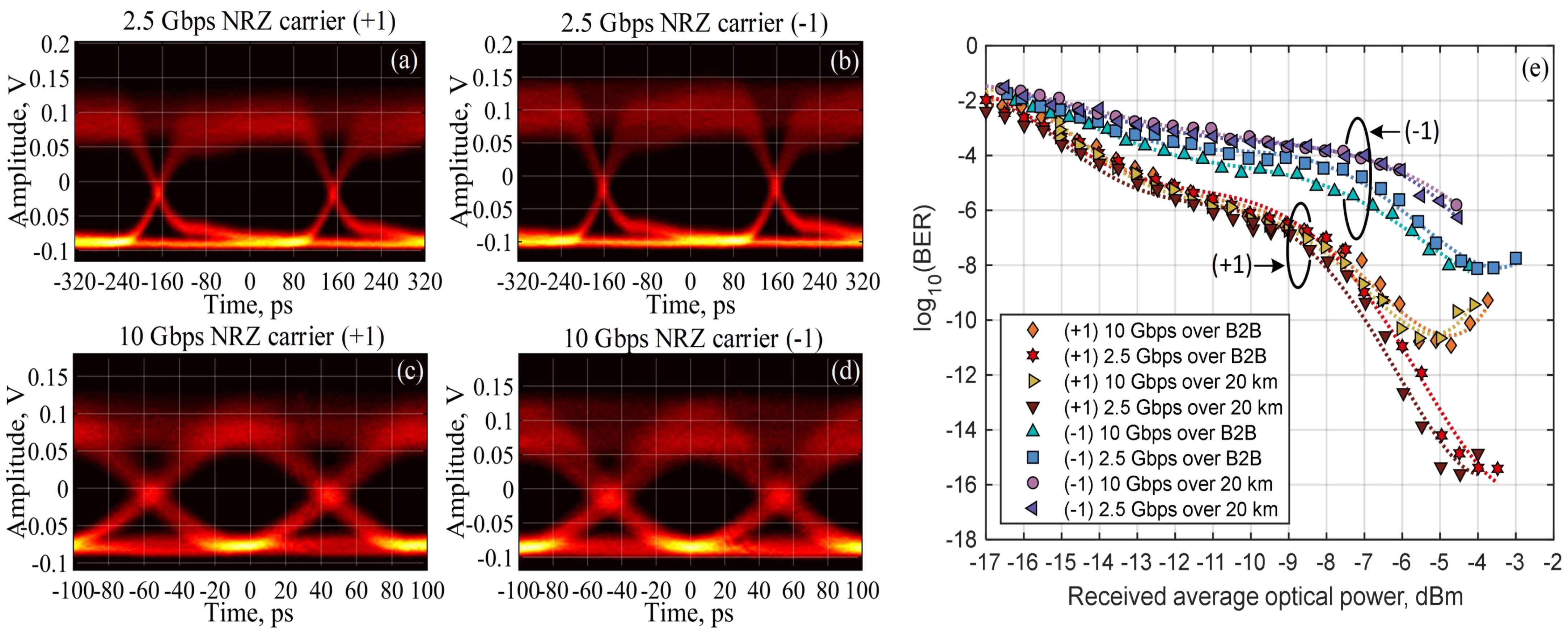


Fig.2. *Eye diagrams of the received signal after 20 km transmission over SMF fiber at a data rate of 2.5 Gbps for (a) carrier "+1" and (b) carrier "-1", and at a data rate of 10 Gbps for (c) carrier "+1" and (d) carrier "-1", and (e) the plots of BER vs. average received optical power in B2B and after 20 km transmission of the NRZ-OOK modulated signal with bitrates of 2.5 and 10 Gbps for "+1" and "-1" carriers.*

WCOMB project realization process: Lab tests of WCOMB integrated in fibre optical communication system *(D.2.4.) (4/5)*

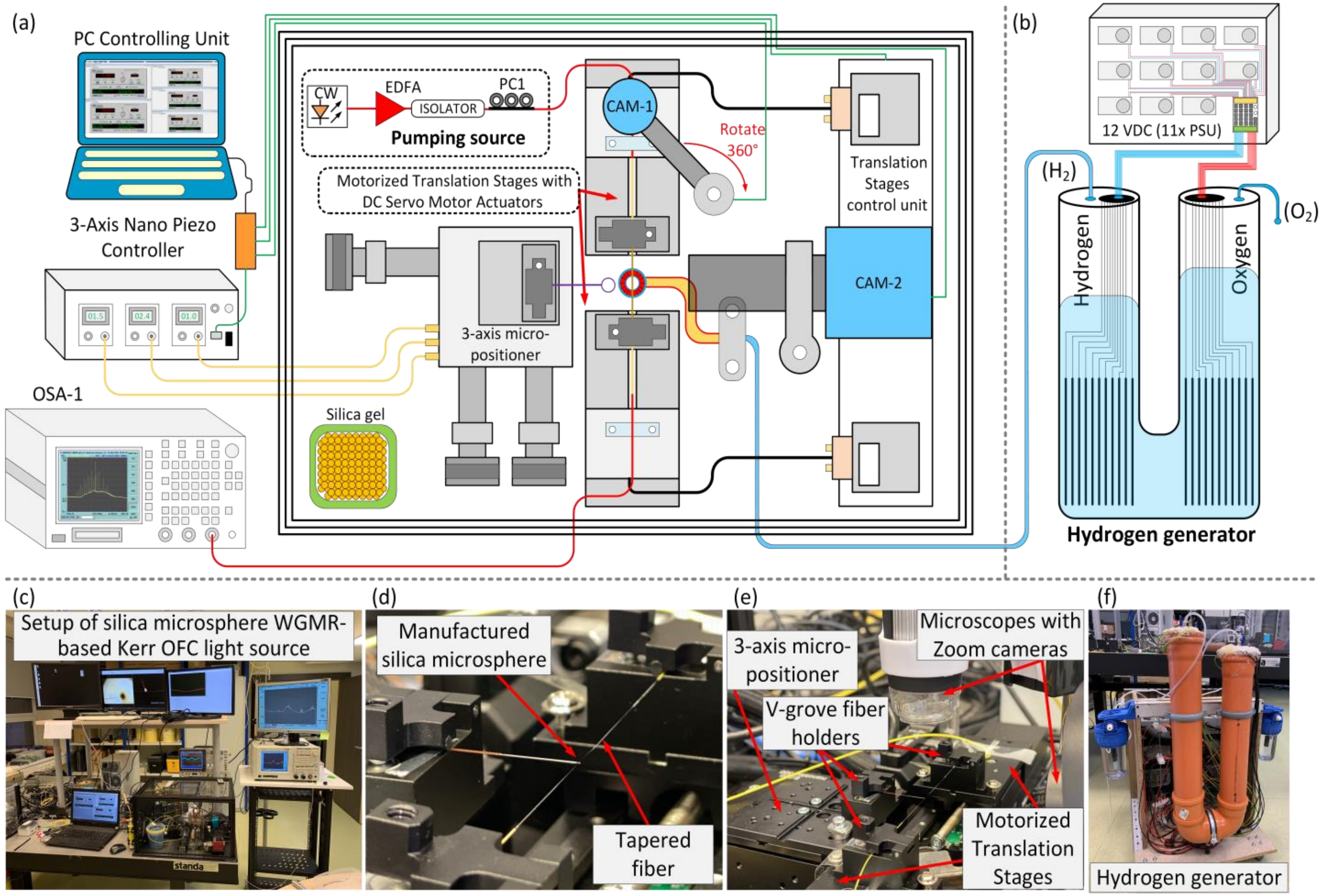


***Fig.3.** (**a**) Experimental setup illustrating the developed silica microsphere WGMR-based Kerr-OFC as light source for optical communications. (**b**) Schematic of a Hydrogen generator for pure generation of hydrogen (H_2) and oxygen (O_2) by electrolysis of water. (**c**) Captured setup of silica microsphere WGMR-based Kerr-OFC light source. (**d**) Tapered fiber and silica microsphere resonator positions inside of enclosure box for the dust and airflow prevention. (**e**) The 3-axis X, Y and Z micro-positioner stage with a built-in Piezo controller and compact motorized translation stages together with zoom microscopes used to monitor the position of the WGMR resonator. (**f**) Hydrogen generator for pure hydrogen and oxygen production.*

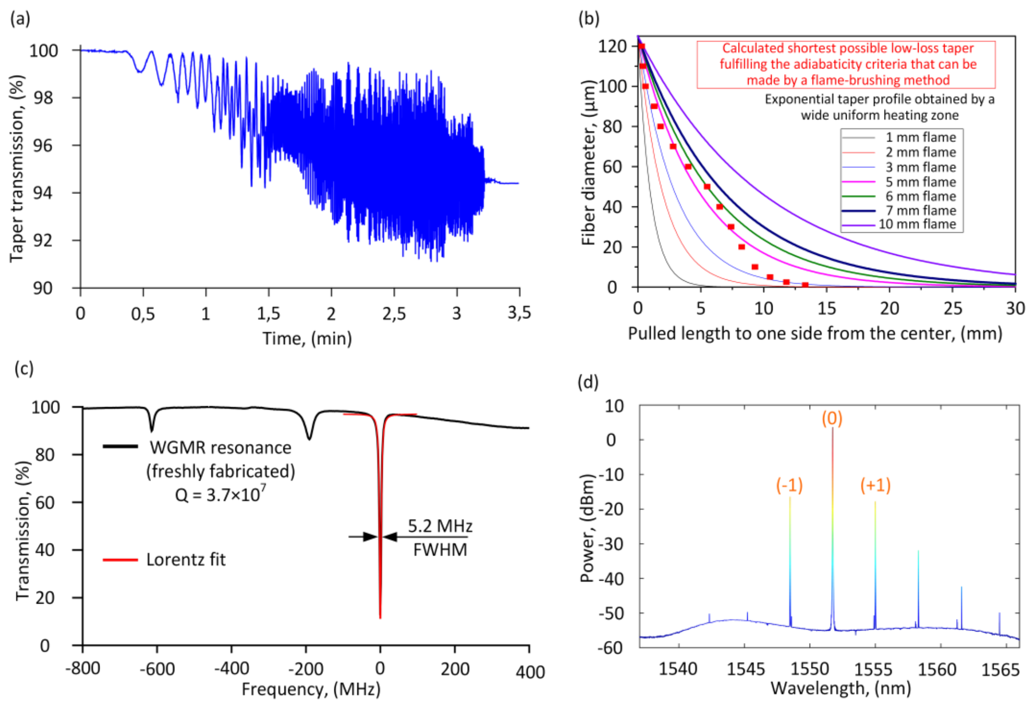


***Fig.4.** The characterization of the tapered fiber and its coupling conditions with the silica microsphere: (**a**) spectra of the adiabatically tapered fiber recorded for the overall transmittance analysis and (**b**) the calculations of pulled one side fiber length at hot zone from center versus fiber diameter at tappered section. (**c**) Experimentally observed (from the microsphere excited by the tapered fiber) WGM resonances of the Kerr-OFC at optical C-band used for the Q factor calculation and (**d**) optical spectra of the generated silica microsphere WGMR-based Kerr-OFC comb source.*

WCOMB project realization process: Lab tests of WCOMB integrated in fibre optical communication system ***(D.2.4.) (5/5)***

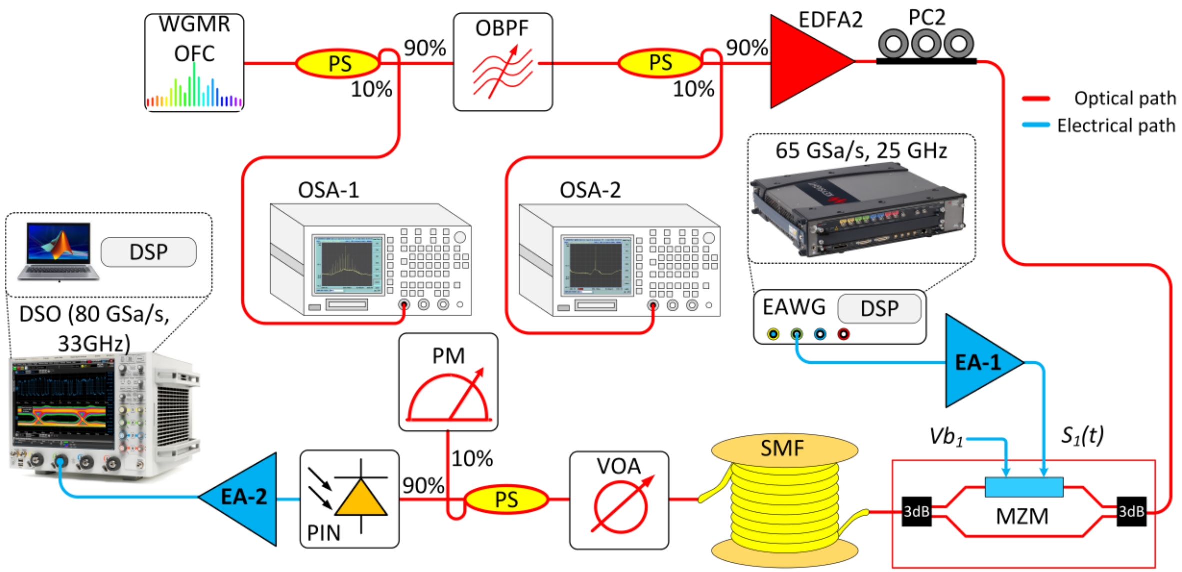


Fig. 5. *Experimental demonstration of the IM/DD optical interconnect relying on the in-house-built silica microsphere WGMR-based Kerr-OFC as a light source generating 400 GHz spaced optical carriers that are used for up to 50 Gbps/λ NRZ-OOK modulated signal transmission over a 2 km long SMF link.*

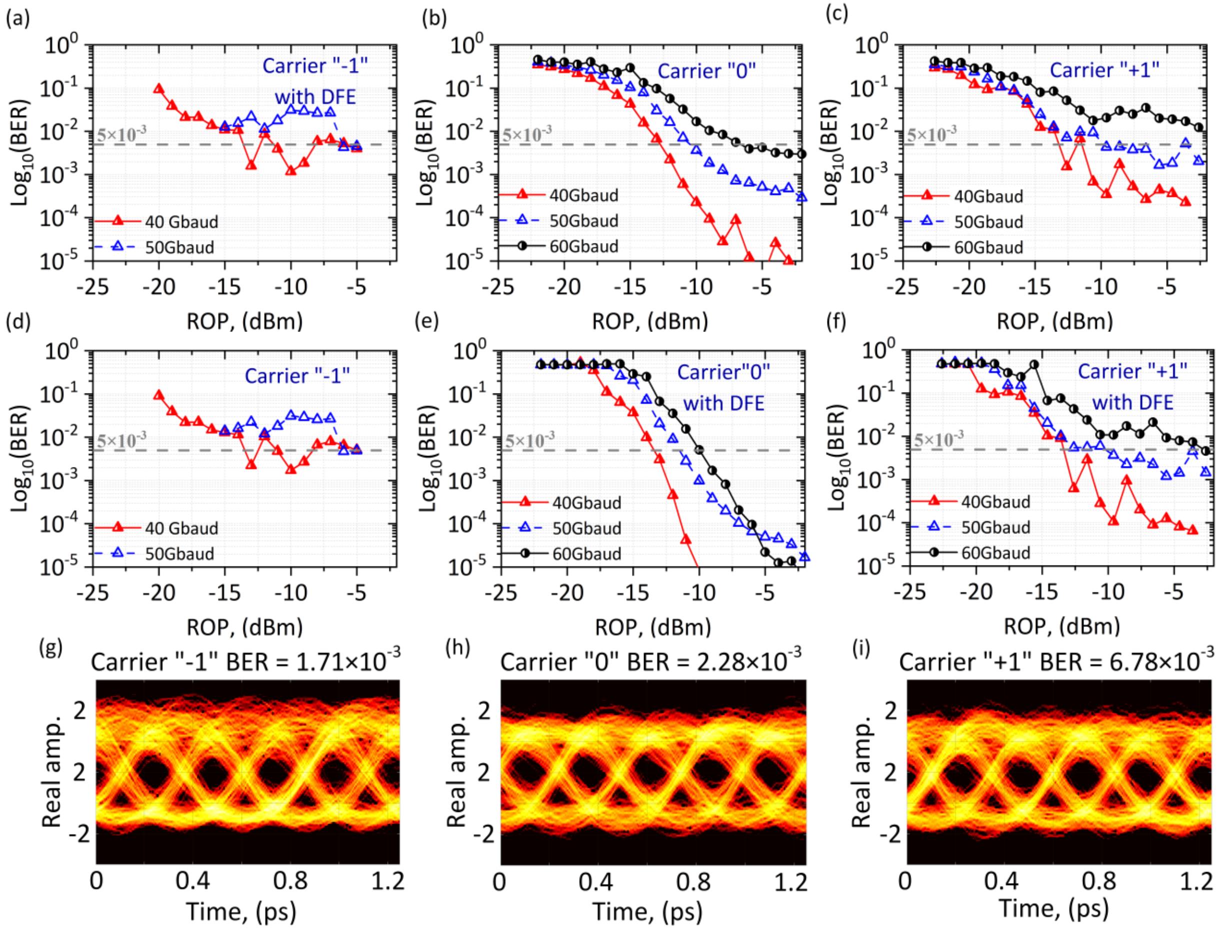


Fig. 6. *BER versus ROP for the IM/DD communication system where the Kerr-OFC light source carriers "-1", "0" and "+1" can be used for NZR-OOK signals transmission with baudrates up to (**a**) 50 Gbaud (**b**) 60 Gbaud and (**c**) 50 Gbaud without any post-equalization. If the post-equalizer with 33-FF&15-FB taps is used, the BER is significantly improved for carriers "-1", "0" and "+1" up to (**d**) 50 Gbaud (**e**) 60 Gbaud and (**f**) 60 Gbaud. Received signal eye diagrams for carriers: (**g**) "-1", (**h**) "0" and (**i**) "+1" captured at ROP of -10 dBm in the 40 Gbaud case.*

WCOMB project realization process: The adjustment of a portable WCOMB prototype for field tests in commercial fibre optical communication system infrastructure *(D.3.1.) (1/2)*

- ✓ This project activity is from Q8 till Q11. Based on the knowledge obtained from the activities of WP2, the **project team in tight cooperation with enterprise partner AFFOC Solutions carry out activities related to developed portable WCOMB device prototype adaptation for field testing purposes and validation in real fiber optical communications systems infrastructure.**
- ✓ Constructed tapered fiber based systems are portable, however, they are bulky. Several different solutions to size down the system have been explored. It was found that it is important to be able to re-adjust the resonator coupling position, therefore compact XYZ stages based on material flexure mechanism have been considered. Tests with different filters and moisture control are being done to slow down the degradation of the WGM resonators.

WCOMB project realization process: The adjustment of a portable WCOMB prototype for field tests in commercial fibre optical communication system infrastructure *(D.3.1.) (2/2)*

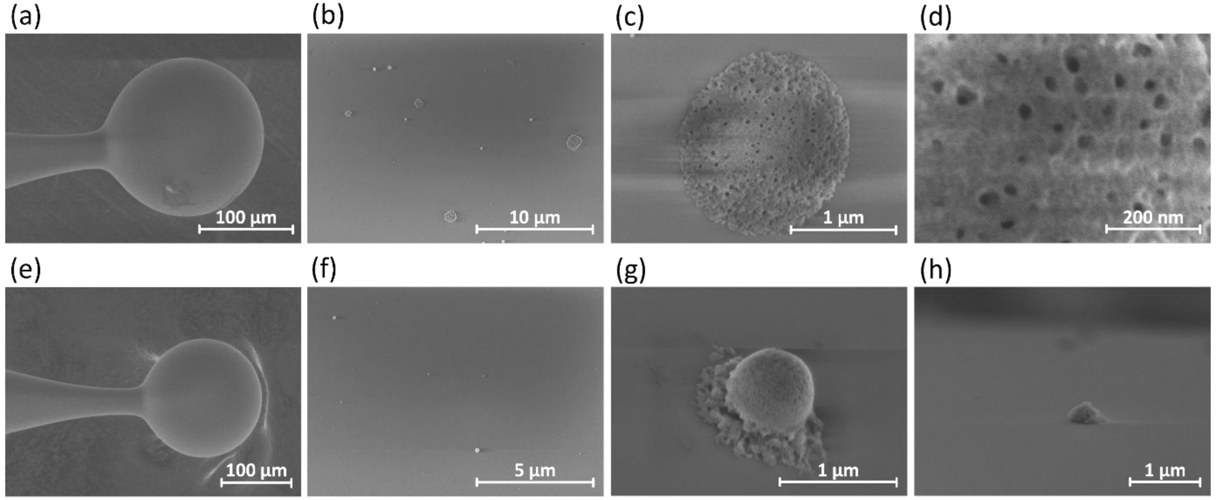
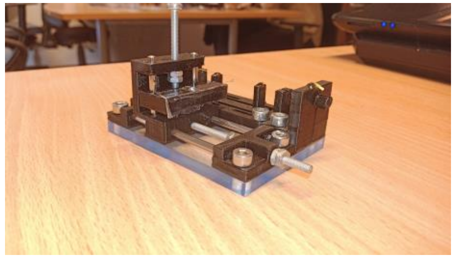
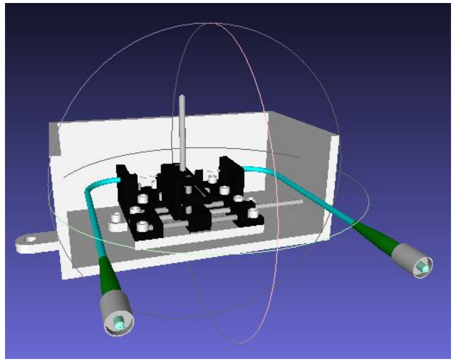
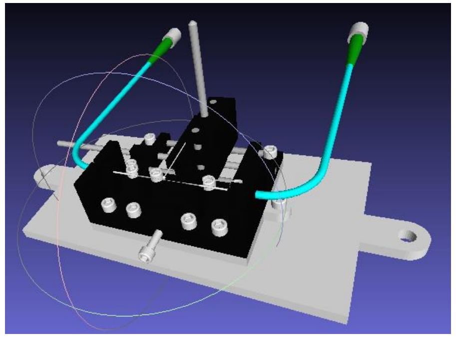
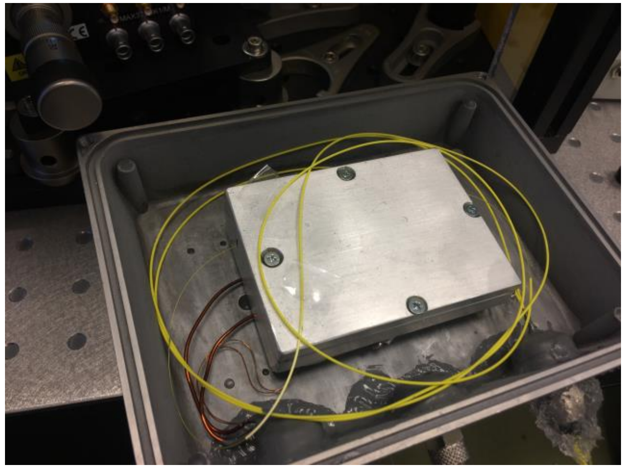


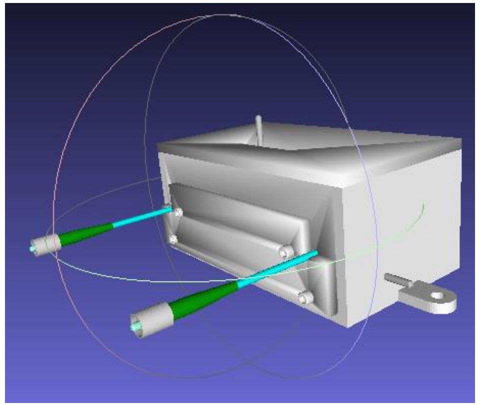
Fig. 7. *Illustration of 170 µm SiO2 microsphere resonator scans captured by SEM at 3 kV after artificial degradation by 100% humidity exposure: (**a**) 4.1 mm @×400 times, (**b**) 4.0 mm @×5.00k times, (**c**) 4.0 mm @×45.0k times, (**d**) 2.9 mm @×180k times, and captured illustrations for newly fabricated 170 µm SiO_2 microsphere: (**e**) 4.0 mm @×300 times, (**f**) 4.0 mm @×10.0k times, (**g**) where evaporated silica from the arc fusion splicer discharge at 4.0 mm @×50.0k times, and (**h**) nanoscale particles at 4.0 mm @×30.0k times were observed.*











WCOMB project realization process: Validation of a portable WCOMB prototype in commercial fibre optical communication system *(D.3.2.) (1/3)*

- ✓ During consideration of different options, it was found that the **department of Information Technologies (IT department) of Riga Technical University (RTU) is one of the members managing the Latvian academic core network.** This network is being developed to establish data transport **infrastructure between different universities and scientific research institutions to provide them with access to RTU** High performance computing centre **located in Kipsala, Riga and therefore share computing resources.** This academic data center also has a **well-established optical cable infrastructure** linking it to other parties of this network (**including links to the largest telecommunications operators**, like "*Latvia State Radio and Television Centre*", *LMT*, *tet*, *Telia*). RTU Institute of Telecommunications (RTU IT) is located in the Faculty of Electronics and Telecommunications (FET) and **there is already an existing fiber optical cable line between the Academic data center premises and the FET building**.

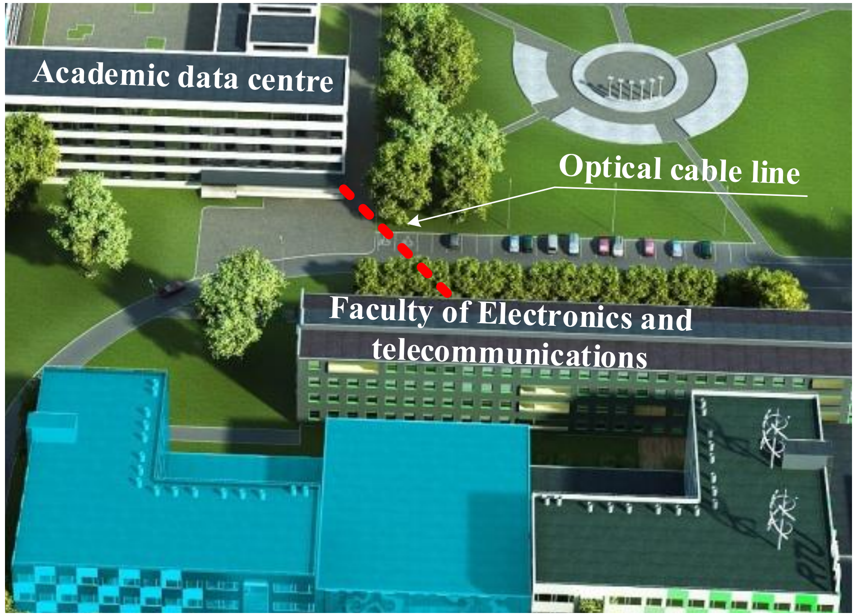


Fig. 8. *Location of RTU FET and the Academic data center in RTU Kipsala campus, Latvia.*

WCOMB project realization process: Validation of a portable WCOMB prototype in commercial fibre optical communication system *(D.3.2.) (2/3)*

- ✓ The fiber optical link that is agreed to be available for project needs is a 12 singlemode fibers line connecting the **RTU Data center in Kipsala to RTU IT department central office in Daugavgrivas street 2**. A couple of fibers in this cable is not used (acting as reserve fibers in an optical network failure situation) and the WCOMB project team has received a temporarily granted access to two fibers for the prototype validation in real fiber optical network infrastructure.
- ✓ **The total length of the cable is around 7 km and as these two fibers were connected in a loopback configuration it doubles the optical path length to 14 km.** The approximate cable route is shown in figure 3. The overall length of the fiber cable line is longer than the distance of the route. This is due to several reserve loops in several manholes across the entire route (typical cable placement practice in urban areas).

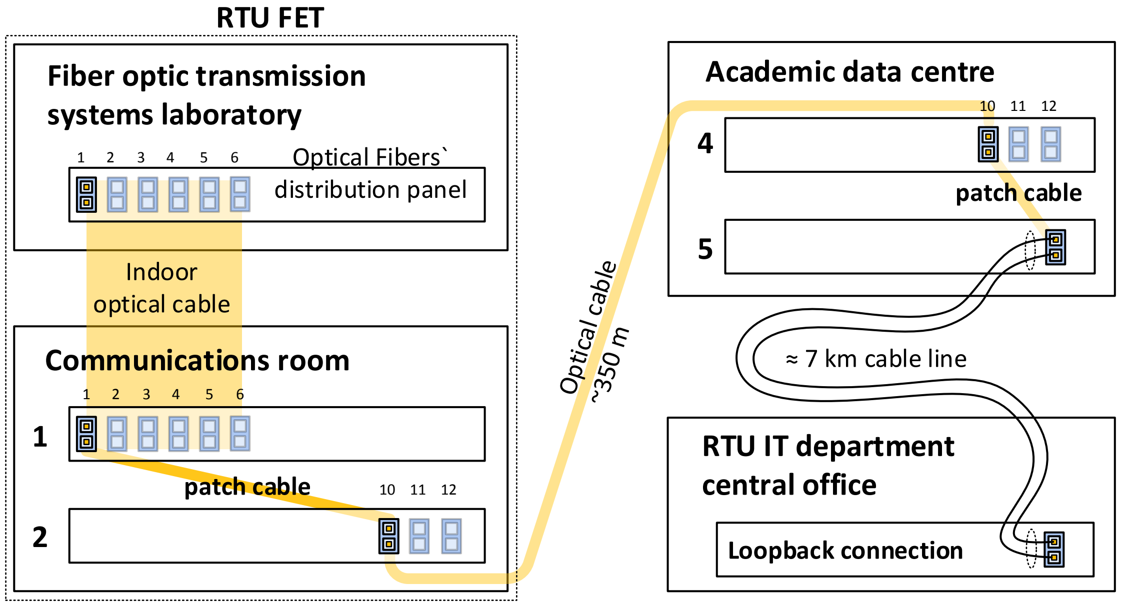


Fig. 9. *Schematic diagram of optical cable link sections and interconnections from RTU TI laboratory to RTU IT department central office and back (loop connection).*

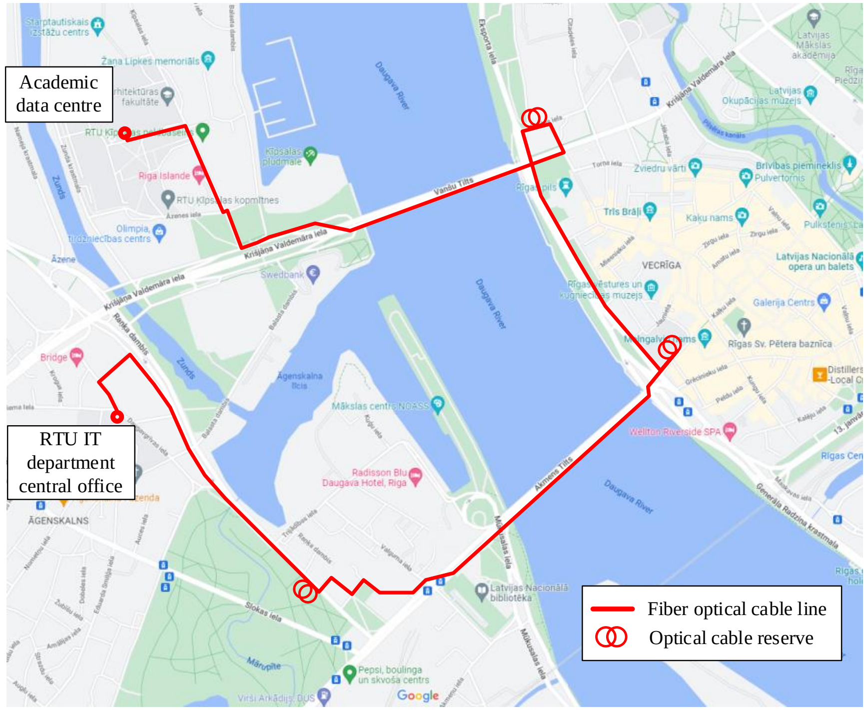


Fig. 10. *Optical cable route used for prototype validation in the deployed fiber optical cable infrastructure.*

WCOMB project realization process: Validation of a portable WCOMB prototype in commercial fibre optical communication system *(D.3.2.) (3/3)*

- ✓ OTDR measurement traces are shown in figure 11. Here **(A) is a single-ended measurement trace and (B) shows bidirectional trace (OTDR measurement graph combining data from both ends).** In the bidirectional graph, an optical launch cable of 424 m is used to avoid the death zone masking the start of the cable line (reflections from the first connectors).
- ✓ **Total length of the obtained optical path: 14.034 km** with a characteristic reflection in the middle indicating loopback connection point located in the central office of the RTU IT department. Other dismountable connectors also appear with characteristic peaks in the OTDR trace. This link also consists of multiple cable sections being spliced together.
- ✓ From OTDR measurements it was also determined that **link attenuation is 15.6 dB at a reference wavelength of 1550 nm. For the 14 km long line** it could be considered as rather a high level of loss. But it is mainly due to multiple connectors joining different cable sections.

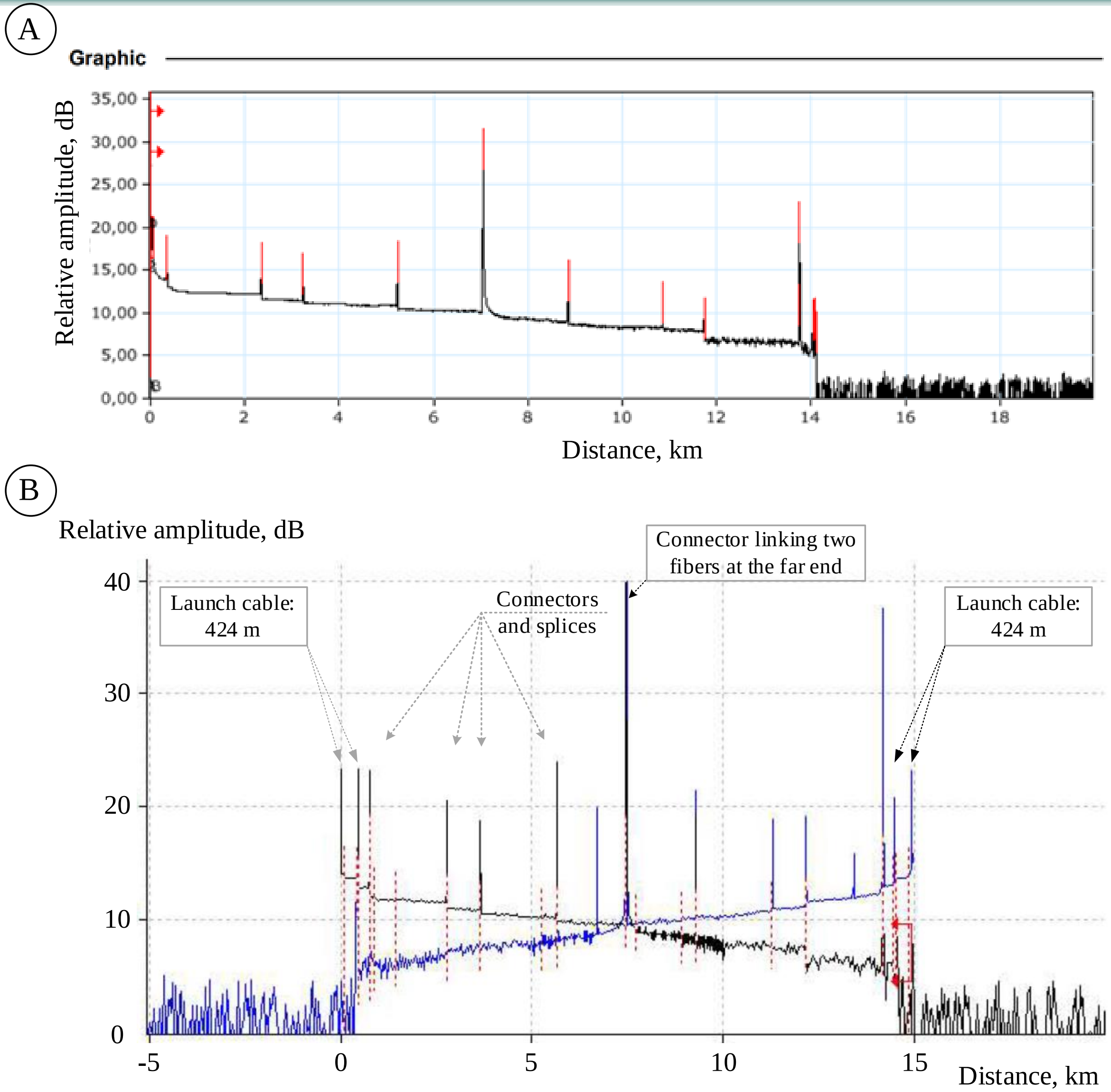


***Fig. 11**. OTDR data: (A) single-ended OTDR measurement and (B) bidirectional trace with additional 424 m long launch cable (used from both ends to avoid dead-zones).*

WCOMB project realization process: Publication of scientific articles in magazines and conference proceedings included in the Web of Science or SCOPUS (A or B) databases (D.4.1.)

This project activity is currently ongoing starting from Q4. Four research papers have been published – 2 of them in journals with the citation index at least 50% of the average citation index in the sector:

1) J. Braunfelds et al. (2020)/Frequency comb generation in WGM microsphere based generators for telecommunication applications/**Quantum Electronics (Q2)**
2) T. Salgals et al., (2021)/Demonstration of a fiber optical communication system employing a silica microsphere-based OFC source/**Optics Express (Q1)**
3) S. Spolitis et al., (2021)/IM/DD WDM-PON Communication System Based on Optical Frequency Comb Generated in Silica Whispering Gallery Mode Resonator/**IEEE Access (Q1)**
4) I. Brice et.al., (2021)/**SPIE Proceedings**
5) **T. Salgals et. al. (2022) /Silica microsphere WGMR-based Kerr-OFC light source and its application for high-speed IM/DD short-reach optical interconnects/ MDPI Apl.Sc. (Q2)**

The expected results for the mid-term of the project – at least one publication submitted for publication – have been fully achieved.

WCOMB project realization process: Patent preparation and application (D.4.2.1)

- ✓ ERAF project patent application type: "*Daudzviļņu gaismas avots šķiedru optiskajām telekomunikāciju sistēmām – WCOMB*".
- ✓ Patent application: "*Uz silīcija dioksīda mikrostieņa rezonatora veidots daudzviļņu gaismas avots datu pārraidei šķiedru optiskajās telekomunikāciju sistēmās*".

RIGA TECHNICAL UNIVERSITY

AFFOC Solutions

Thank you for your attention!

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