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RIGA TECHNICAL
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Toms Salgals

DEVELOPMENT AND ASSESSMENT OF A SPECTRALLY EFFICIENT HYBRID OPTICAL COMMUNICATION SYSTEMS

Summary of the Doctoral Thesis

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RIGA TECHNICAL UNIVERSITY
Faculty of Electronics and Telecommunications
Institute of Telecommunications

Toms Salgals

Doctoral Student of the Study Programme "Telecommunications"

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DOCTORAL THESIS PROPOSED TO RIGA TECHNICAL UNIVERSITY FOR THE PROMOTION TO THE SCIENTIFIC DEGREE OF DOCTOR OF SCIENCE

To be granted the scientific degree of Doctor of Science (Ph. D.), the present Doctoral Thesis has been submitted for the defense at the open meeting of RTU Promotion Council on 9 September 2022 at the Faculty of Electronics and Telecommunications of Riga Technical University (RTU), 12 Azenes Str., Room 201.

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DECLARATION OF ACADEMIC INTEGRITY

I hereby declare that the Doctoral Thesis submitted for the review to Riga Technical University for the promotion to the scientific degree of Doctor of Science (Ph. D.) is my own. I confirm that this Doctoral Thesis had not been submitted to any other university for the promotion to a scientific degree.

The Doctoral Thesis has been prepared as a thematically united collection of scientific publications. It comprises 13 scientific articles and publications in conference proceedings indexed in SCOPUS, WoS, and IEEE databases. The Thesis has been written in English; the total number of pages is 246.

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Finally, the biggest thank you goes to my family and friends for the day-to-day support and faith in my strength.

Thank you!

Toms Salgals

LIST OF ABBREVIATIONS

* Numerical initial abbreviations
3G – Third Generation
4G – Fourth Generation
5G – Fifth Generation
AEQ – Adaptive equalization
AON – Active optical network
ARoF – Analog Radio-over-Fiber
ASI – Institute of Astronomy and Spectroscopy
AWG – Arrayed Waveguide Grating
BBU – Base-band unit
BER – Bit-Error-Rate
BPF – Bandpass Filter
BS – Base Station
C-Band – Conventional Band
CD – Chromatic Dispersion
CEPT – Committee of the European Conference of Postal and Telecommunications Administrations
CO – Central Office
C-RAN – Cloud/Centralized Radio Access Networks
CW – Continuous Wave (Laser)
DB – Duobinary
DCF – Dispersion Compensating Fiber
DCM – Dispersion Compensating Module
DCI – Data Center Interconnection
DMD – Differential Mode Delay
DSO – Digital Storage Oscilloscope
DSP – Digital Signal Processing
DTU – Denmark Technical University
DWDM – Dense Wavelength Division Multiplexing
EDB – Electrical Duobinary
EPON – Ethernet Passive Optical Network
FBG – Fiber Bragg Grating
FB – Feedback
FBT – Feedback tap
FEC – Forward Error Correction
FFT – Feed-forward taps
FOTS – Fiber optical Transmission systems
FSPL – Free-Space-Loss
FSR – Free spectral range
FWM – Four Wave Mixing
HD-FEC – Hard-Decision Forward Error-correction Code
HS-PON – High-speed Passive Optical Network
IEEE – Institute of Electrical and Electronics Engineers
IF – Intermediate Frequency
IM-DD – Intensity Modulation Direct Detection
IoT – Internet of Things
IP – Internet Protocol
IPF-RAN – Institute of Applied Physics of the Federal Research Center of the Russian Academy of Sciences
ISI – Intersymbol interference
ITU – International Telecommunication Union
ITU–T – International Telecommunication Unit
KTH – Royal Swedish Technical University
KPI – Key performance indicators
LNA – Low Noise broadband Amplifier
LO – Local Oscillator
LTE – Long Term Evolution
LU – University of Latvia
MCF – Multi Core Fiber
MIMO – Multiple-Input-Multiple-Output
MZM – Mach-Zehnder Modulator
NF – Noise Factor
NG – Next-generation
NG-PON – Next Generation Passive Optical Network
NG-PON2 – 40-Gigabit-capable Passive Optical Network
NOE – Nonlinear Optical Effects
NRZ – Non Return to-Zero
NRZ-OOK – Non-Return-to-Zero On-Off Keying
ODN – Optical Distribution Network
OFC – Optical frequency comb
OLT – Optical Line Terminal
ONT – Optical Network Terminal
ONU – Optical Network Unit
OOK – On-Off-Keying
OPB – Optical Power Budget
OSNR - Optical Signal-to-Noise Ratio
P2P – Point-to-Point
PAM – Pulse-Amplitude Modulation
PAM-M – Multi-level Pulse Amplitude Modulation
PIN – Photodiode – Positive-Intrinsic-Negative (photodiode)
PON – Passive Optical Network
RAN – Radio Access Network
RoF – Radio-over-Fiber
ROP – Received optical power
RU – Radio Unit
SAD – Symmetrical Adaptive Decorrelation
SDM – Spatial-Division Multiplexing
SMCF – Single mode Multicore fiber
SNR – Signal to Noise Ratio
SMF – Single Mode Fiber
TI – Institute of Telecommunications
VDC – Volts of direct current
WDM – Wavelength Division Multiplexing
WDM-PON – Wavelength Division Multiplexed Passive Optical Network
WGM – Whispering Gallery Mode
WGMR – Whispering Gallery Mode Resonator
WSS – Wavelength Selective Switch
WS-WDM-PON – Wavelength-Selected WDM-PON
WR-WDM-PON – Wavelength-Routed WDM-PON
VR – Virtual and augmented Reality
XG-PON (10G-PON) – 10 Gigabit Passive Optical Network

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1. GENERAL OVERVIEW OF THE THESIS

1.1. Introduction

The rapid growth of Internet traffic requires the improvement of telecommunications network infrastructure by increasing data transmission speed [1]. Passive optical access networks (PONs) are one of the most popular low-cost optical networks. Standardized PON network solutions already have a number of improvements related to data transfer speeds for end-users. In order to obtain spectrally efficient data transmission, the infrastructure of PON networks is provided using a wavelength division multiplexing (WDM) technology [2].

The demand for large-scale data transmission is growing exponentially due to the implementation of new technologies (e.g., Internet of Things (IoT), 4K/8K television, virtual and augmented reality (VR), etc.). For the enormously growing number of end-users who require more bandwidth, the solution is spatial division multiplexing (SDM) technology for new fiber optical communication systems [3]–[4]. Multicore fiber is being explored as a new solution to meet the growing data traffic in optical networks [5]. A single-core single-mode optical fiber is limited by the possible data rate and is limited by the amplifier bandwidth and nonlinear optical effects (NOE) [6].

The solution to the improvement of telecommunication systems is to improve the optical communication lines, which use non-return-to-zero (NRZ) modulation formats. Instead of using multi-stage pulse-amplitude modulation, abbreviated as *PAM-M or M-PAM*, where several bits are encoded at one signal level. The multi-level pulse amplitude modulation (PAM-M) modulation format is relatively easy to implement, offers a relatively easy trade-off between performance and the level of complexity of its implementation, and can provide a cost-effective solution for telecom service providers [7].

The traditional mobile radio access network (RAN), which combines baseband signal processing and radio functions in each base station, is used in the long-term evolution (LTE) solution in fourth-generation (4G) mobile technology as well as third-generation (3G) mobile technology. The next, fifth-generation (5G) mobile technology must provide at least 10 times higher data rates, spectral efficiency, and energy efficiency than current 3G, 4G/LTE mobile technologies. The technical requirements for fifth-generation (5G) technology can be met by wavelength division multiplexed fiber-optic passive access networks (WDM-PONs) based on a centralized optical data network architecture, as well as the use of higher radio frequency bands, such as millimetre-wave (24–86 GHz) frequency band [8].

Therefore, to ensure faster data transmission, it is necessary to create an architecture of a new solution for optical access communication systems, ensuring improvement of performance, functionality, and capacity. The widely used fiber optic WDM-PON system can be technologically transformed into a hybrid Analog Radio-over-Fiber (ARoF)-WDM-PON system without the need to replace existing network elements, simply by integrating the mobile transmitter unit (BBU) and mobile base station receiver unit (RU) into the existing WDM-PON communication systems without changing the rest of the broadband Internet network architecture and optical line terminals

(OLT), as well as optical network terminals (ONT). Within the research framework carried out in this Thesis, the architecture of a hybrid ARoF-WDM-PON transmission system capable of providing optical signal transmission for broadband internet services and 28 GHz (ka-band) millimeter-wave signal transmission over single single-mode fiber (SMF), following 40 Gigabit Passive Optical Network (NG-PON2) requirements, was developed.

The low-cost concept, which can provide an attractive solution for the development of hybrid optical communication systems combining broadband Internet and mobile fiber transmission, is considered a solution for the architecture of the next generation (NG) PON network. Kerr optical frequency combs (OFCs) using different types of whispering gallery mode microresonators (WGMRs) have already shown different applications and, in particular, their applications in fiber optic communication systems replacing laser light sources at specific wavelengths [9]. In addition, OFC generators are used in technologies such as optical clocks [10], ultra-stable microwave generation [11], applications requiring accurate optical frequency reference, quantum applications [12], and optical communications [13], etc. The application of WGMR-OFC light sources in WDM fiber optic communication systems covers application scenarios ranging from short reach, such as data center interconnection (DCI) to access layer fiber optic networks [9]–[14]. The Kerr OFC comb generators, which are physically implemented on silica microsphere resonators or micro-rods, demonstrate a new technological solution capable of providing an attractive solution for telecommunication fiber optic networks with low implementation costs and energy efficiency.

1.2. The aim and theses of the dissertation

Summarizing the above-mentioned facts about the directions of development of mobile communications and fiber optic transmission systems, the following **aim of the Doctoral Thesis is proposed:**

Experimentally develop hybrid fiber optical wavelength division multiplexed communication system solutions and evaluate their performance with spectrally efficient intensity modulation formats.

To achieve the aim set, the following theses were put forward:

1. In high-speed PON (HS-PON) transmission systems using 10 Gigabit PON (XG-PON) components, the maximum transmission distance in the optical C-band with a bit error rate BER $\geq 1\times10^{-3}$ can be realized using electric duobinary (EDB) modulation format, while the PAM-4 multilevel modulation format can achieve the maximum transmission speed per λ.
2. 5 Gbit/s PAM-4 gross-rate transmission over a joint 20 km optical fiber and at least 3 meter mm-Wave wireless link can be achieved with BER $\geq 1\times10^{-3}$ threshold by using heterodyne detection and photonic up-conversion technique in 28 GHz Ka-band having 2.5 GHz analog bandwidth.
3. The transmission of 2.5 Gbit/s NRZ-OOK modulated 28 GHz mm-wave radio signals and 10 Gbit/s NRZ-OOK modulated optical signals per optical channel via 20 km optical fiber in hybrid ARoF-WDM-PON communication system can be realized using wavelength-routed

WDM-PON architecture (WR-WDM-PON) for channel interval (ΔF) > 100 GHz, whereas wavelength-selected WDM-PON architecture (WS-WDM-PON) must be used for $\Delta F \leq$ 50 GHz.

4. The newly generated harmonics of the silica microsphere whispering-gallery-mode resonator (WGMR)-based Kerr-OFC light source can be used in WDM-PON communication systems with 10 Gbit/s data rate per λ without adaptive equalization, while in DCI data transmission systems adaptive equalization is required at data rates up to 50 Gbit/s per λ.

1.3. The main key tasks of the Doctoral Thesis

To achieve the set goal of the dissertation and to prove the proposed theses, it is necessary to perform the following **key tasks:**

1. Evaluate the use of multilevel PAM-M and EDB intensity modulation formats in mathematical modeling environment to increase the maximum transmission distance in 10 Gigabit PON communication systems with intensity modulation and direct detection (IM/DD) without exceeding the BER $\geq 1\times10^{-3}$ of the received signal.
2. Experimentally and in a mathematical modeling environment evaluate the effect of chromatic dispersion (CD) and its compensation methods for increasing the maximum transmission distance in NRZ-OOK and PAM-4 modulated IM/DD WDM-PON communication systems with data transmission speeds up to 40 Gbit/s per λ, without exceeding the BER $\geq 1\times10^{-3}$ of the received signal.
3. Experimentally evaluate the application of spectrally efficient PAM-4, PAM-8, and EDB modulation formats to increase the data transmission speed up to 56 Gbit/s per λ with and without the use of adaptive equalization in high-speed PON (HS-PON) IM/DD transmission systems using 10 Gigabit PON (XG-PON) components and without exceeding BER $\geq 1\times10^{-3}$.
4. Experimentally evaluate the application of a combined solution of spatial (SDM) and wavelength division multiplexing (WDM) technologies in a 7-core single-mode multi core fiber (SMCF) for the development of a spatially multiplexed NRZ-OOK modulated 2.5 Gbit/s per λ fiber optical IM/DD communication system.
5. Experimentally and in mathematical modeling environment evaluate the application of heterodyne detection and 28 GHz mm-wave radio signal photonic up-conversion technique, providing transmission of 2.5 Gbit/s NRZ-OOK modulated and spectrally efficient up to 5 Gbit/s PAM-4 modulated signals over a joint 20 km optical fiber and at least 3 meter mm-wave wireless link.
6. Experimentally and in a mathematical modeling environment, develop and evaluate a hybrid ARoF-WDM-PON transmission system capable of providing the principle of backhaul operation for 2.5 Gbit/s NRZ-OOK modulated 28 GHz mm-wave radio signal and 10 Gbit/s NRZ-OOK modulated optical signal transmission per channel through a 20 km fiber optical line.

7. Experimentally develop silica microsphere whispering-gallery-mode resonator WGMR-based Kerr-OFC as a multi-wavelength light source capable of providing an optical frequency comb in the C-band, where the number of newly generated harmonics corresponds to 2^n (n – integer number) used in ITU-T G.694.1 FOTS solutions, and evaluate their application for the transmission of NRZ-OOK modulated signals in such IM/DD systems with data transmission speeds up to 50 Gbit/s λ.

1.4. Research methods

To perform the tasks outlined in the Doctoral Thesis and to analyze the problems, mathematical calculations, numerical simulations, and experimental measurements have been used. Numerical simulations were implemented in RSoft OptSim and VPI Design Suite simulation software, which are based on the nonlinear Schrödinger equation using the Split-Step method, the Fourier transform, and the Monte Carlo method for estimating the bit-error-rate (BER).

The spectra and power of the electrical and optical signals were used to evaluate the quality of optical signals in the simulation environment and experimental implementations. The quality of the received electrical signals was evaluated using bit error rate BER and eye diagrams. In the implementation of experimental systems, in some cases the quality of electrical signals received in real-time measurements was evaluated by the quality (Q-factor), from which the bit error rate BER of the transmitted signal was calculated, as well as in some cases offline digital signaling processing (DSP) was performed in MatLab computing environment for adaptive post-equalization and processing of the obtained results.

Scientific experiments described in the Doctoral Thesis and their results were carried out at the Institute of Telecommunications (TI) of Riga Technical University (RTU), Institute of Astronomy and Spectroscopy (ASI) of the University of Latvia (LU), Danish Technical University (DTU) in Denmark, and at the Department of Applied Physics of Royal Swedish Technical University (KTH) in close collaboration with the Swedish research institute RISE Acreo in Sweden and using video calls for online experiment measurements during the COVID-19 pandemic (digital laboratory work called "Zoom-lab") in close collaboration with the Institute of Applied Physics of the Federal Research Center of the Russian Academy of Sciences (IPF-RAN) in Russia.

1.5. Scientific novelty and main results

Novel achievements of the Doctoral Thesis are as follows:

1. The most suitable intensity modulation formats (NRZ, PAM-4, PAM-8, EDB) for NG-PON2, XG-PON/HS-PON transmission systems depending on their application have been determined, as well as the application of NRZ and PAM-4 modulation formats in ARoF has been evaluated in WDM transmission systems for the transmission of 28 GHz (ka-band) millimeter wave radio signals, providing the principle of backhaul operation.
2. Factors influencing the BER and transmission distance of the received signal in the wavelength division multiplexed IM/DD PON and ARoF topology transmission systems

(*dispersion, application of intensity modulation formats*) were evaluated, as a result in a mathematical simulation environment and experimental realization the methods of the received signal quality improvements were analyzed and improved.

3. The combined application of space division (SDM) and wavelength division multiplexing (WDM) technologies to increase the data rate of multi-core single-mode (SMCF) fiber in the development of NG spectrally efficient spatially capacitive IM/DD PON and RoF communication systems have been evaluated, and the factors (*crosstalk, differential mode delay*) influencing the received signal quality have been identified for multicore optical fiber.
4. The available up-conversion techniques of optical signals to 28 GHz (ka-band) millimeter wave radio signals in the RoF solution has been evaluated, and the hybrid ARoF-WDM-PON communication system has been experimentally developed for 2.5 Gbit/s NRZ and 5Gbit/s PAM-4 modulated data per channel transmission of 28 GHz (ka-band) millimeter-wave radio signals, providing the principle of backhaul operation via 20 km of SMF fiber.
5. Under the requirements of NG-PON2 (ITU-T G.989.3) recommendation, a hybrid ARoF-WDM-PON communication system has been experimentally developed and evaluated in mathematical simulation environment showing capable transmission of NRZ modulated data transmission speed up to 10 Gbit/s per channel for the internet broadband transmission and of up to 2.5 Gbit/s per channel transmission for a 28 GHz (ka-band) millimeter-wave signal transmission over a 40 km SMF fiber optic line.
6. A new innovative whispering-gallery-mode resonator WGMR-based Kerr-OFC light source based on silicon microspheres (SiO_2) has been developed, where with the newly generated harmonic of the light source: WDM-PON communication system solutions can transmit data at speed in the channel of up to 10 Gbit/s without AEQ, while applying for DCI system solutions it is possible to perform data transmission with data transmission speed in the channel up to 50 Gbit/s with use of AEQ.
7. A new innovative silicon microsphere and/or micro-rod whispering-gallery-mode resonator WGMR-based Kerr-OFC has been developed as a multi-wave light source, where the number of generated harmonics corresponds to 2n (n – integer number) used in FOTS solutions, and the inter-channel spacing between newly generated harmonics corresponds to ITU-T G.694.1, which is capable for use in communication system transmitting NRZ modulated signals at data rates up to 50 Gbit/s per λ.

Practical value of the Doctoral Thesis

1. A patent developed in Latvia: "*Hybrid fiber optic access system for transmission of millimeter-wave radio signals through a fiber*", No. (P-19-73).
2. A patent application has been developed in Latvia "*A multi-wave light source for data transmission in fiber optical telecommunication systems developed on a silica microrod resonator*" (submitted patent application).
3. At the Institute of Telecommunications of RTU ETF have been developed a new NRZ modulated up to 2.5 Gbit/s and spectrally efficient PAM-4 modulated up to 5 Gbit/s per

channel ARoF-WDM PON communication system model for the transmission of 28 GHz millimeter-wave radio signals through a 20 km fiber, (*is proposed for further experimental research*).

4. At the Institute of Telecommunications of RTU ETF have been experimentally developed and evaluated in mathematical simulation environment a new M-PAM modulated hybrid ARoF-WDM-PON communication system model capable for transmission of NRZ modulated data transmission with speed up to 10 Gbit/s per channel for the internet broadband transmission and of up to 2.5 Gbit/s per channel transmission for a 28 GHz (ka-band) millimeter-wave signal over a 40 km SMF fiber optic line, (*is proposed for further experimental research*).
5. At the Institute of Telecommunications of RTU ETF have been developed a new 4-channel 100 GHz spaced NRZ modulated dense wavelength division multiplexed (DWDM-PON) transmission system model able to provide a total data transmission with a total speed of 160 Gbit/s by using a symmetrical adaptive decorrelation (SAD) for channel separation in the optical C-band over 40 km using a symmetrical adaptive decorrelation, (*is proposed for further experimental research*).
6. At the Institute of Telecommunications of RTU ETF have been developed a new innovative silicon microsphere and/or micro-rod whispering-gallery-mode resonator WGMR-based Kerr-OFC light source, which is capable for use in communication system transmitting NRZ modulated signals at data rates up to 50 Gbit/s per λ, (*is proposed for further experimental research*).

The results obtained in the dissertation were used within the following projects:

- PostDoc project "*Next Generation High Speed Fiber Optic Access Systems (NG-FAST)*" No. 1.1.1.2/VIAA/1/16/044;
- ERAF project "*Development of optical frequency comb generator based on a whispering gallery mode microresonator and its applications in telecommunications (WCOMB)*" No. 1.1.1.1/18/A/155;
- ERAF project "*Ring-Resonator Modulators for Optical Interconnects (RINGO)*", No. 1.1.1.1/21/A/052.

1.6. Structure of the thesis

The dissertation is prepared as a thematically unified a set of publications on development and evaluation of a spectrally efficient hybrid optical communication systems and their elements.

1.7. Publications and approbation of the Thesis

The results of the Doctoral Thesis are presented in 13 scientific articles and in publications in conference proceeding indexed in SCOPUS, WoS, and IEEE databases. The author has altogether 30 publications. The Latvian patent has been granted for the technology "*Hybrid Fiber Optic*

Access System for the Transmission of Millimeter Wave Radio Signals Through Fiber", developed within the framework of this work. The developed technology "*A multi-wave light source for data transmission in fiber optical telecommunication systems developed on a silica microrod resonator*" within the framework of the Thesis has been submitted to the Patent Office for consideration in order to apply for the Latvian state patent.

The results of the Doctoral Thesis have been presented at 13 international scientific conferences:

1. International conference Photonics West 2021 Digital Forum. Presentation: I. Brice, K. Grundstein, A. Sedulis, **T. Salgals**, S. Politis, V. Bobrov, and J. Alnis, *"Frequency comb generation in whispering gallery mode microsphere resoantors*", March 6–11, 2021.
2. 64th International Conference for Students of Physics and Natural Sciences – Open Readings 2021. Presentation: K. Draguns, I. Brice, **T. Salgals**, and J. Alnis, "*Dispersion Engineering of Whispering Gallery Mode Resonators for Frequency Comb Generation and Telecommunication Applications*," March 16–19, 2021.

- 4th International conference "Quantum Optics and Photonics 2021", online Zoom, April 22–23, 2021.Presentations:
   3. I. Brice, **T. Salgals**, V. Bobrovs, R. Viter, and J. Alnis, "*Whispering gallery mode silica microsphere resonator applications for biosensing and communications*".
   4. **T. Salgals**, J. Alnis, R. Murnieks, I. Brice, J. Porins, A. V. Andrianov, E. A. Anashkina, S. Spolitis, and V. Bobrovs, "*Microsphere-based OFC-WGMR multi-wavelength source and its applications in telecommunications*".

5. Photonics & Electromagnetics Research Symposium (PIERS 2019), China, Xiamen, 17–20 December 2019. Presentation: **T. Salgals**, A. Ostrovskis, A. Ipatovs, V. Bobrovs, and S. Spolitis, "*Hybrid ARoF-WDM PON Infrastructure for 5G Millimeter-wave Interface and Broadband Internet Service*".
6. 60th RTU International Scientific and Technical Conference, October 15, 2019. Presentation: "*Cost-effective high-speed up to 32 Gbit/s WDM-PON next generation access network performance analysis*".
7. 60th RTU International Scientific and Technical Conference, October 15, 2019). Presentation: "*Evaluation of Optical Frequency Comb Generator Based on WGMR Microresonator and its Applications in FOTS*".
8. RTUWO 2018 – Advance in Wireless and optical Communications. Presentation: „*Evaluation of 4-PAM, NRZ and Duobinary Modulation Formats Performance for Use in 20 Gbit/s DWDM-PON Optical Access System*".
9. RTUWO 2018 – Advance in Wireless and optical Communications, Chair of Section "*Optical communications*", Riga, Latvia, 2018.

10. 59th RTU International Scientific and Technical Conference, November 2018. Presentation: "*Evaluation and Development of Next Generation Spectrally Efficient Access Optical Networks*".
11. 58th RTU Student Scientific and Technical Conference, June 2017. Presentation: "*Research and evaluation of the Next-generation spectrally efficient optical communication systems*".
12. 58th RTU International Scientific and Technical Conference, October 2017. Presentation: "*Performance evaluation of PAM-4 modulation format in optical access networks*".
13. 57th RTU International Scientific and Technical Conference, November 2016. Presentation: "*Evaluation of Dispersion and Nonlinear Effects in a 10 Gbit/s WDM Transmission System*".

The results of the Doctoral Thesis are presented in 13 scientific articles and publications in conference proceeding indexed in SCOPUS–, WoS, and IEEE databases:

[PAPER-1] **T. Salgals**, S. Spolitis, S. Olonkins, and V. Bobrovs, "Investigation of 4-PAM modulation format for use in WDM-PON optical access systems," *2017 Progress In Electromagnetics Research Symposium – Spring (PIERS)*, pp. 2450–2454, St. Petersburg, Russia, May 22–25, (**2017**), DOI: 10.1109/PIERS.2017.8262162

[PAPER-2] **T. Salgals**, L. Skladova, K. Vilcane, J. Braunfelds, and S. Spolitis, "Evaluation of 4-PAM, NRZ and Duobinary Modulation Formats Performance for Use in 20 Gbit/s DWDM-PON Optical Access Systems," *2018 Advances in Wireless and Optical Communications (RTUWO)*, pp. 134–138, Riga, Latvia, Nov. 15–16, (**2018**), DOI: 10.1109/RTUWO.2018.8587887

[PAPER-3] A. Udalcovs, **T. Salgals**, L. Zhang, X. Pang, A. Djupsjöbacka, S. Spolitis, V. Bobrovs, S. Popov, and O. Ozolins, "Optical Power Budget of 25+ Gbps IM/DD PON with Digital Signal Post-Equalization," *Applied Sciences 10(17)*, 6106, (**2020**), DOI: https://doi.org/10.3390/app10176106

[PAPER-4] A. Korra, **T. Salgals**, J. Porins, E. Kazoks, R. Miho, and S. Spolitis, "Performance Analysis of Cost-efficient High-speed up to 32 Gbit/s WDM-PON Next-generation Access Network with Dispersion Compensation," *2019 PhotonIcs & Electromagnetics Research Symposium – Spring (PIERS-Spring)*, pp. 2671–2678, Rome, Italy, June 17-20, (**2019**), DOI: 10.1109/PIERS-Spring46901.2019.9017854

[PAPER-5] **T. Salgals**, A. Supe, V. Bobrovs, J. Porins, and S. Spolitis, "Comparison of Dispersion Compensation Techniques for Real-Time up to 160 Gbit/s DWDM C-Band Transmission", *ELEKTRON ELEKTROTECH 26(2)*, 85–93, (**2020**), DOI:10.5755/j01.eie.26.2.25892

[PAPER-6] G. K. M. Hasanuzzaman, S. Spolitis, **T. Salgals**, J. Braunfelds, A. Morales, L. E. Gonzalez, S. Rommel, R. Puerta, P. Asensio, V. Bobrovs, S. Iezekiel, I. T. Monroy, "Performance Enhancement of Multi-Core Fiber Transmission Using Real-Time FPGA Based Pre-Emphasis", *Asia Communications and Photonics Conference (ACP)*, Guangzhou, November 10–13, (**2017**), DOI: 10.1364/ACPC.2017.M2H.1

[PAPER-7] **T. Salgals**, L. Skladova, J. Porins, V. Bobrovs, and S. Spolitis, "Analog Radio-over-fiber WDM-PON Architecture for 5G Millimeter-wave Interface," *2019 Photonics & Electromagnetics Research Symposium – Spring (PIERS-Spring)*, pp. 2679–2686, Rome, Italy, June 17–20, (**2019**), DOI: 10.1109/PIERS-Spring46901.2019.9017431

[PAPER-8] **T. Salgals**, I. Kurbatska, V. Bobrovs, and S. Spolitis, "Research of PAM-4 Modulated WDM-PON Architecture for 5G Millimeter-wave Hybrid Photonics-wireless Interface," *2019 Photonics & Electromagnetics Research Symposium - Fall (PIERS – Fall)*, pp. 728–734, Xiamen, China, Dec. 17–20, (**2019**), DOI: 10.1109/PIERS-Fall48861.2019.9021846

[PAPER-9] **T. Salgals**, A. Ostrovskis, A. Ipatovs, V. Bobrovs, and S. Spolitis, "Hybrid ARoF-WDM PON Infrastructure for 5G Millimeter-wave Interface and Broadband Internet Service," *2019 Photonics & Electromagnetics Research Symposium – Fall (PIERS – Fall)*, pp. 2161–2168, Xiamen, China, Dec. 17–20, (**2019**), DOI: 10.1109/PIERS-Fall48861.2019.9021479

[PAPER-10] E. A. Anashkina, V. Bobrovs, **T. Salgals**, I. Brice, J. Alnis, and A. V. Andrianov, "Kerr Optical Frequency Combs With Multi-FSR Mode Spacing in Silica Microspheres," *IEEE Photon. Technol. Lett. 33(9)*, 453–456, (**2021**), DOI: 10.1109/LPT.2021.3068373

[PAPER-11] E. A. Anashkina, M. P. Marisova, **T. Salgals**, J. Alnis, I. Lyashuk, G. Leuchs, S. Spolitis, V. Bobrovs, and A. V. Andrianov, "Optical Frequency Combs Generated in Silica Microspheres in the Telecommunication C-, U-, and E-Bands", *Photonics 8(9)*, 345, (**2021**), DOI: 10.3390/photonics8090345

[PAPER-12] **T. Salgals**, J. Alnis, R. Murnieks, I. Brice, J. Porins, A. V. Andrianov, E. A. Anashkina, S. Spolitis, and V. Bobrovs, "Demonstration of a fiber optical communication system employing a silica microsphere-based OFC source," *Opt. Express 29(7)*, 10903-10913, (**2021**), DOI: 10.1364/OE.419546

[PAPER-13] **T. Salgals**, J. Alnis, O. Ozolins, A.V. Andrianov, E. Anashkina, I. Brice, R. Berkis, X. Pang, A. Udalcovs, J. Porins, S. Spolitis, and V. Bobrovs, "Silica microsphere WGMR-based Kerr-OFC light source and its application for high-speed IM/DD short-reach optical interconnects", *Applied Sciences 12(9)*, 4722, (**2022**), DOI: 10.3390/app12094722

2. MAIN RESULTS OF THE DOCTORAL THESIS

The dissertation has been prepared as a thematically unified set of scientific publications. The results are presented in 13 scientific publications. The first chapter of the dissertation describes the topicality of the research, evaluates the aim and theses, describes the main tasks, research methodology and the structure of the work and the main results.

The second chapter of the dissertation describes the wavelength division multiplexed fiber optic communication systems, i.e., assessment of the development of passive optical access networks (PON) and data center interconnection (DCI).

The third chapter discusses the evaluation of the application of spectrally efficient multi-level pulse amplitude modulation formats to increase the performance of WDM-PON systems (*first contribution comes from [PAPER-1], [PAPER-2] and [PAPER-3]*).

In the fourth chapter, the evaluation of the received signal quality depending on the applied optical transmission environment for the implementation of a high-speed spectrally efficient WDM-PON broadband transmission system is performed. The analysis of the received signal quality under the influence of nonlinear optical effects (NOE) and chromatic dispersion (CD) is performed, as well as the application of space division multiplexing (SDM) technology for the implementation of a spectrally and spatial efficient wavelength division multiplexed optical communication system is evaluated (*contribution comes from [PAPER-4], [PAPER-5] and [PAPER-6]*).

The fifth chapter summarizes the application of the radio-over-fiber (RoF) as the solution for future cellular mobile communications, including the fifth-generation (5G and beyond) technological implementation solution. Within the framework of the dissertation, a spectrally efficient next-generation optical system for the transmission of millimeter-wave radio signals over fiber was experimentally developed for future cellular mobile communications as well as a new hybrid fiber optic transmission system architecture capable of broadband Internet data transmission and radio signal transmission over a single optical fiber was developed (*contribution comes from [PAPER-7], [PAPER-8], and [PAPER-9]*).

The sixth chapter describes the implementation of a new type of spectrally efficient WDM transmission with a new novel silica microsphere whispering-gallery-mode resonator WGMR-based Kerr-OFC multi-wave light source. At the moment, for the first time in the world, high-speed data transmission of experiments using harmonics generated of WGMR-based Kerr-OFC was demonstrated. The *results of this world-class experiment are described in the publication where the first author and principal investigator is Tom Salgals* - "*Demonstration of a fiber optical communication system employing a silica microsphere-based OFC source*", Optics Express (Q1 Journal). The use of WGMR Kerr-OFC light sources for short reach, such as data center interconnection DCI, to transmit NRZ encoded signals at data rates up to 50 Gbit/s per wavelength is also substantiated and experimentally demonstrated a *new record in the current field* (*contribution comes from [PAPER-10], [PAPER-11], [PAPER-12], and [PAPER-13]*).

In Conclusions, the comparison and evaluation of the experimental and simulative results are performed, and the answers to the key tasks and theses set in the dissertation are given.

3. SUMMARIES OF CHAPTERS 3–6 OF THE DOCTORAL THESIS

3.1. *Chapter 3:* Application and evaluation of the spectrally efficient modulation formats sustainable to increase the performance of WDM-PON transmission systems

The chapter *evaluates the application of spectrally efficient multi-level pulse amplitude modulation formats to increase the performance of WDM-PON system.*

In Subchapter 3.1, spectrally efficient multi-level pulse amplitude modulation format applications for WDM-PON network solutions are discussed. There are two main architectures for implementing fiber optical access networks – passive optical networks PONs and active optical networks (AONs). According to [15], further enhancements of PON standards have already been discussed, considering the increase in per-channel line rates from 10 to 25 Gbps. Moreover, the possibilities of increasing per-wavelength data rates to 40 Gbit/s have also been studied widely [15]–[16]. It should be underlined that the utilization of the traditional non-return-to-zero NRZ modulation for high per-wavelength data rates may cause significant technical difficulties in terms of both transceiver bandwidth capability and fiber dispersion [17]. Consequently, the choice of modulation format significantly influences the performance reach, bit error ratio BER, capacity and receiver sensitivity of fiber optical access network. However, very few publications are available that evaluate the utilization of NRZ, PAM-4, and EDB for supporting different data rates keeping the same physical structure and key parameters of the transmission system. However, it would allow comparing the modulation formats in terms of the best performance for each per-wavelength data rate. In research done during the Doctoral Thesis, the same parameters of the transmission system for each data rate (except data rate related) were used. That allows tracking the change in the performance of each modulation format caused by the utilization of the corresponding data rate. Thus, ensuring for each data rate the determination of the most suitable modulation format among the investigated ones. The current research evaluates four modulation formats – PAM-8, PAM-4, EDB, and NRZ. During the research, all parameters of the transmission system's elements remain the same, excluding the data rate related. The performance of investigated modulation formats (namely PAM-8, PAM-4, EDB, NRZ) was evaluated in terms of the impact of transmission distance, received power, and receiver bandwidth on the BER.

In Subchapter 3.2, *a 4-channel simulation model in RSoft Optsim Optical Systems simulation software was developed to evaluate the performance of PAM-4 modulation format use in current 10G WDM-PON optical access networks. The goal of this simulation model was to evaluate the performance and maximum reach as well as minimal channel spacing for PAM-4 modulated WDM-PON system with four 10 Gbaud/s (20 Gbit/s) channels*, under the condition that it is still possible to achieve a bit error ratio (BER) of 10^{-3} [18]. The central frequency is 193.1 THz and channel spacing is chosen 50 or 100 GHz according to the ITU G.694.1 recommendation. For extension of transmission distance by dispersion compensation, the Fiber Bragg Grating (FBG) dispersion compensation module (DCM) in the simulation model was also implemented. It was shown that maximal transmission distance with BER below FEC limit of 10^{-3} for 100 GHz spaced

PAM-4 WDM-PON system can be increased by 15 km or 25.4 % (from 59 to 74 km) if dispersion compensation with FBG-DCM is implemented. Moreover, in the case of 50 GHz channel spacing, which was minimal, ensuring BER < 10^{-3}, maximum transmission system reach can be increased by 14 km or 24 % (from 58 to 72 km) by using additional dispersion compensation with FBG-DCM (see *Fig. 1*).

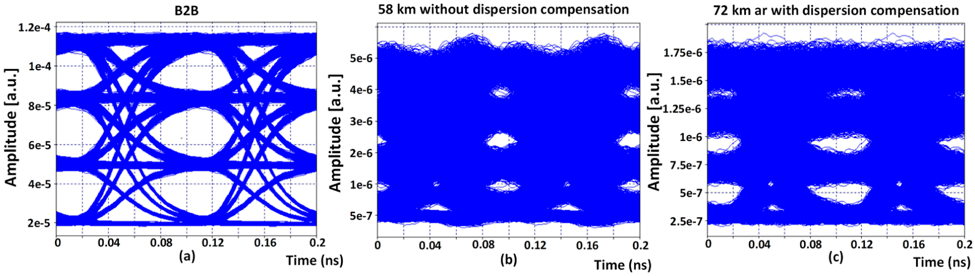


Fig. 1. Eye diagrams of the received signal: (a) after B2B transmission; (b) after 58 km transmission without the use of DCM module; and (c) after 72 km transmission with dispersion compensation by a FBG DCM unit for 4-channel 50 GHz spaced WDM-PON system with PAM-4 modulation format.

In Subchapter 3.3, *8-channel DWDM-PON simulation models were created with the goal to evaluate maximum transmission reach using different modulation formats: PAM-4, EDB, and NRZ.* The first simulation model with PAM-4 modulation was performed with a 10 Gbaud/s symbol rate, providing 20 Gbit/s data rate per channel. The second simulation model with DB modulated transmission system was realized with a 20 Gbit/s data rate per channel. The third simulation model is based on NRZ transmitter and realized with the same 20 Gbit/s data rate per channel as the DB modulated transmission system. *The main task of this subchapter is to compare the performance of PAM-4, DB, and NRZ modulated optical signals for use in DWDM-PON transmission system and to find out maximal network reach of each particular modulation format.* After transmission (by 50 GHz spacing interval), it was concluded that the largest network reach was provided by the EDB modulation format, which extends the reach of optical network up to 62 km, ensuring BER < 10^{-3}. The PAM-4 modulation format provided successful transmission over up to 50 km and NRZ up to 27 km long SSMF optical spans with BER below the defined threshold.

In Subchapter 3.4, it is shown how PON architecture considered for the 10G operation can be used for 25+ Gbps operation enabling full compatibility with XG(S)-PON and 10G-EPON. *As 10G PON systems are not capable of supporting future services, especially in the fifth generation (5G) mobile networks, 25G is the next evolution step that must be taken* [19]. Recent ITU-T recommendations for passive optical networks PONs, ITU-T G.9807.1 (symmetric 10G PON (XG(S)-PON)) and ITU-T G.989 (next-generation PON2 (NG-PON2)) describe the transmission requirements for line rates of up to 40 Gbit/s per channel, while new recommendations for higher line rates (e.g., G.HSP.Req, G.HSP.comTC, G.HSP.50Gpmd, G.HSP.TWDMpmd) are under active development [20]–[22]. The enhancements being discussed for the next-generation PON standards include the increase in channel line rates from 10 to 25 Gbit/s [15]. Now, the 100G-EPON standard is still under development by the Institute of Electrical and Electronics Engineers

(IEEE) P802.3ca Task Force. It is intended to scale up to 25 Gbit/s or 50 Gbit/s per single lane capacity while reusing the existing infrastructure of 10G-EPON [22]–[24]. Overall, the future PON is currently under development and standardization for future broadband network solutions beyond 10 Gbps [25]–[27]. The evolution towards higher line rates is mainly driven by point-to-point (P2P) connections and wireless fronthaul, e.g., the next generation of mobile cellular networks (i.e., 5G and beyond 5G), where a 25 Gbps could be needed soon for either backhauling or new interfaces supporting the functional splits. However, due to cost considerations and commercial viability, it is desired to re-use some components from 10 Gbit/s transceivers operating in 10G PONs [28]. Bandwidth limitations from electrical and electro-optical components increase significantly due to the utilization of signals with higher line rates. *Therefore, this part of the research aims to bridge the knowledge gap by countifying the gain that digital signal post-equalization has on the optical power budget in IM/DD PONs with NRZ-OOK, EDB, PAM-4, and PAM-8 formats*. The experimental setup of a 25+ Gbps IM/DD PON system is shown in *Fig. 2*.

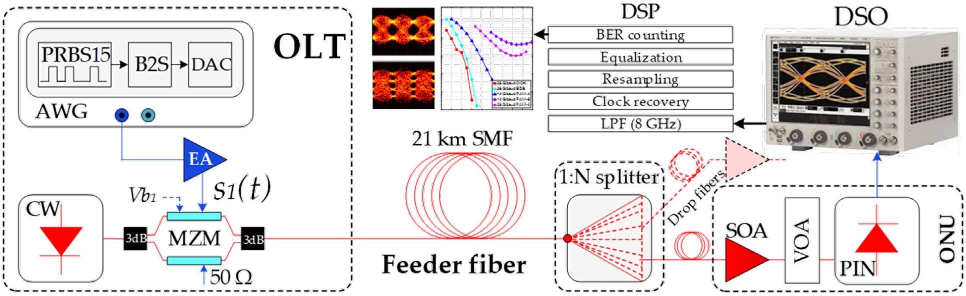


Fig. 2. Experimental setup of the 25+ Gbps IM/DD PON system used for the power budget comparison.

Here is reveal how the signal post-equalization impacts the achievable optical power budget of the IM/DD PON system. Before optical power budget analysis, the summarized analyses for pros and cons of transceivers exploiting the modulation formats of the interest is shown in ***Table 1***.

Table 1

Pros and Cons of Transceivers Exploiting the Considered Intensity Modulation Direct Detection (IM/DD) Schemes

Modulation format	Spectral efficiency	Transmission reach	Power consumption	Transmitter simplicity	Receiver simplicity
NRZ	–	–	+	++	++
EDB	+	++	–	–	–
PAM-4	++	++	– –	– –	– –
PAM-8	+++	+	– –	– –	– –

The optical power budget values (together with the corresponding values of the available power margin) obtained for all considered cases are summarized in ***Table 2***.

Table 2

Optical Power Budget and Available Power Margin for the Explored Alternatives and Post-equalizer Structures (Number of FF and FB Taps)

Signals	**w/o**	**4-FF**	**9-FF&5-FB**	**43-FF&21-FB**
28 Gbaud OOK	–	29 dB/5.1 dB	31 dB/7.1 dB	31 dB/7.1 dB
28 GBaud EDB	27 dB/3.1 dB	29 dB/5.1 dB	30 dB/6.1 dB	30 dB/6.1 dB
14 Gbaud PAM-4	26 dB/2.1 dB	27 dB/3.1 dB	27 dB/3.1 dB	27 dB/3.1 dB
14 Gbaud PAM-8	–	–	–	–
28 Gbaud PAM-4	–	–	22 dB/−1.9 dB	23 dB/−0.9 dB

Figure 3 shows BER curves and eye diagrams for the 28 Gbaud OOK/EDB/PAM-4 and 14 Gbaud PAM-4/8 modulated signals in the IM/DD PON systems. First, the system performance without any post-equalization (***Figs. 3(a), 3(c)***) is analyzed, and then, focus is on improvements that the linear post-equalization offers (***Figs. 3(b), 3(d)***).

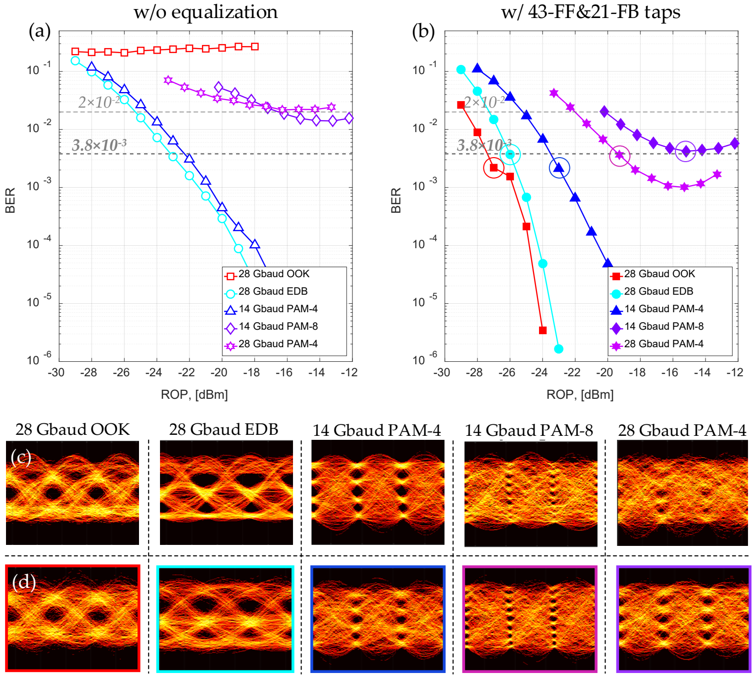


Fig. 3. Quality of transmission characteristics for the 28 Gbaud OOK, 28 Gbaud EDB, 14 Gbaud PAM-4, 14 Gbaud PAM-8, and 28 Gbaud PAM-4 signals in the IM/DD PON system: ***(a)*** *BER vs. received optical power (ROP) before the digital post-equalization;* ***(b)*** *BER vs. ROP after the digital post-equalization employing 43-FF&21-FB taps;* ***(c)*** *eye diagrams captured in the ONU at the highest ROP and before the digital post-equalization; and* ***(d)*** *eye diagrams captured in the ONU and ROP values that ensure BER $< 3.8 \times 10^{-3}$ after the digital post-equalization.*

The obtained results show that (i) 10G PON component bandwidth is enough to achieve net-rates above 25 Gbit/s; (ii) linearity of the optoelectronic components allows operating them using schemes with multilevel modulation formats; and (iii) in combination with the digital signal post-equalization, the obtained optical power budget is compliant with E1 class (OPB = 18–33 dB). The 28 Gbaud EDB and 14 Gbaud PAM-4 schemes can be used in PONs even without any post-equalization. Finally, data rates up to 56 Gbps can be supported by the PON employing the PAM-4 modulation. Although a 1:32 splitting ratio might not be feasible due to high insertion loss of such a splitter, it provides the optical power budget of 23 dB. Therefore, the considered IM/DD PON alternatives together with digital signal equalization have the potential to ensure the sustainability for future PONs with line rates well beyond 25 Gbit/s in the access segment of optical networks.

3.1. *Chapter 4:* Impact assessment of the used optical transmission environment for the received signal quality to develop a high-speed spectrally efficient WDM-PON broadband transmission system

In Chapter 4, *the evaluation of the received signal quality depending on the applied optical transmission environment for the implementation of a high-speed spectrally efficient WDM-PON broadband transmission system is performed.*

Subchapter 4.1, evaluates the transmission performance depending on data rate per channel. *The purpose of this research was to evaluate the performance of investigated 100 GHz spaced WDM-PON transmission system with the most often used transmission speeds of up to 32 Gbit/s per channel and obtain the maximum reach of the system with chromatic dispersion (CD) compensation, under the condition that it is still possible to achieve forward error correction pre-FEC BER of 1×10*$^{-3}$*.* Firstly, experimentally, single-channel passive optical network PON performance after 80 km transmission through standard single-mode fiber (SSMF) span, with additional use of implemented dispersion compensation module FBG-DCM, was preferred. Secondly, the additional effect of crosstalk is obtained with a simulative-experimental model. The purpose of the experimental section was to observe experimental system physical parameters and the impact of used components. Therefore, the properly adjusted 16-channel WDM-PON transmission system model was created in the newest RSoft OptSim simulation software. According to ITU-T G.989.2 Next-generation PON standard (NG-PON2), definition of ODN length of 40 km and 80 km SMF was chosen [20]. It was shown that with the use of FBG-DCM for dispersion compensation in 100 GHz spaced NRZ-OOK modulated 16-channel WDM-PON transmission system, the maximum achievable transmission distance for the system operating at bitrates of 25, 28, and 32 Gbit/s per channel was 105 km, where the BER of received signal was 3.9×10^{-4}, 9.9×10^{-4} and 7.5×10^{-4}. However, with 10 Gbit/s operating data rate per channel, maximum achievable transmission distance was 109 km, where the BER of received signal was 8.1×10^{-4}. The second-best result with 106 km maximal achieved transmission distance was with operating data rate of 20 Gbit/s per channel, where the BER of received signal was 9.4×10^{-4}

Subchapter 4.2, *demonstrates the evaluation of the performance of experimentally developed dense wavelength division multiplexed DWDM transmission system and compares the most often commercially used CD compensation techniques such as CD compensation based on dispersion compensation fibers (DCF) and compensation based on fiber Bragg grating FGB dispersion* compensation module (DCM). The CD post-compensation is consecutively investigated by using: (1) tunable fiber Bragg grating dispersion compensation module (FBG-DCM), which has 3.5 dB insertion loss at λ = 1550 nm wavelength, dispersion coefficient of –680 ps/(nm × km); and (2) dispersion compensation fiber (DCF) spool with a length of 5.684 km, which has 4.75 dB insertion loss (at λ = 1550 nm reference wavelength) with a dispersion coefficient of –686.76 ps/nm/km and –2.48 ps/nm^2 dispersion slope was used as well. During the experiment it was concluded, that additional insertion losses in dispersion-compensating optical fiber DCF line and affection of NOE on transmitted signals lead to performance decrease of experimental 4-channel 100 GHz spaced DWDM optical transmission system, where the BER at operating 20 Gbit/s and 40 Gbit/s bitrate per channel of received signal was 5.8×10^{-2} and 1.27×10^{-5} due to optical power level on photodiode (PIN) photoreceiver –1.65 dBm and +2.36 dBm. After decreasing the total optical link length by replacing DCF and applying for fiber Bragg grating tunable DCM module, the NOE effects are reduced significantly, where the BER of operating at 20 Gbit/s and 40 Gbit/s bitrates per channel was 5×10^{-2} and 2.45×10^{-5} due to optical power level on PIN photoreceiver –0.21 dBm and 3.3 dBm.

In Subchapter 4.3, the single-mode multicore optical fiber (SMCF) solution ensures space-division- multiplexing SDM technology application. The multicore optical fibers (MCFs) have also been implemented in fiber-wireless links such as a full-duplex, 802.11ac-compliant, 3 × 3 multiple-input multiple-output (MIMO) system using 7-core fiber [29], and Centralized Radio Access Networks (C-RANs) [30]. The experimentally developed setup for a 7-channel optical transmission system with a data transmission speed of 2.5 Gbit/s per λ using the NRZ-OOK modulation format via the new generation 2 km long SMCF optical fiber with seven cores, is shown in *Fig. 4*. The experimental setup includes a 2 km long 7-core MCF with 4 upstream transmission channels through Cores 0, 1, 3, 5 and 3 downstream transmission channels through Cores 2, 4, 6.

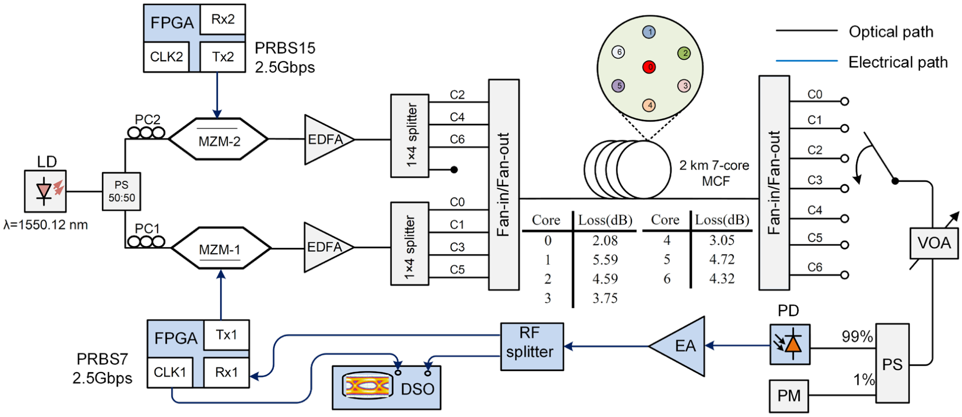


Fig. 4. Block diagram of the developed fiber optic 2.5 Gbit/s per λ NRZ modulated transmission system with 7-core SMCF fiber.

From the obtained result it can be concluded that the attenuation introduced by the SMCF optical fiber is 5 to 10 times higher than for the standard single-mode SMF fiber (0.2 dB/km @ λ = 1550 nm), which is explained by the introduced attenuation at splicing places of the SMCF fiber together with the FAN-IN and FAN-OUT transitions. The central core (Core 0) exhibits the highest crosstalk as expected, and other outer cores (1, 2, 4, 6) have roughly equal crosstalk where Cores 3 and 5 are much lower and higher than the other outer cores. The obtained BER of Core-0 in response to received optical power at photodiode (PD) is shown in ***Fig. 5***.

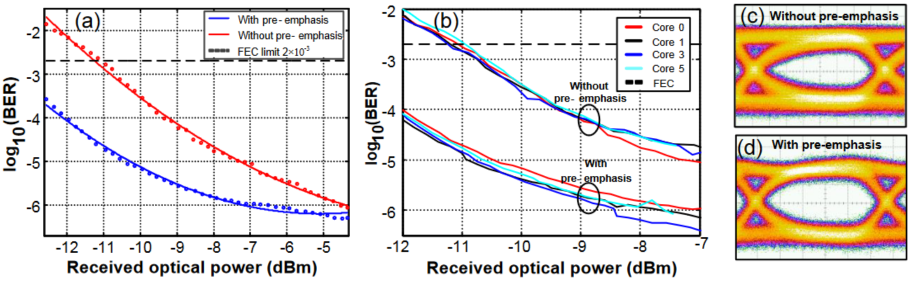


*Fig. 5. Comparison of measured BER versus received optical power of a 2.5 Gbps NRZ-OOK signal with and without FPGA equalization enabled **(a)** for central MCF core (Core 0), **(b)** central Core 0 and outer Cores 1, 3, and 5. Eye pattern of the received 2.5 Gbps signal **(c)** without equalization and **(d)** with FPGA equalization for central MCF Core 0.*

3.2. *Chapter 5:* Development and evaluation of spectrally efficient next-generation mobile optical systems for millimeter-wave radio signal transmission

Chapter *5 summarizes the application of the radio-over-fiber (RoF) as the solution for future cellular mobile communications, including the fifth-generation (5G and beyond) technological implementation solution.*

In Subchapter 5.1, the fifth-generation 5G implementation solutions and key performance indicators (KPIs) are described and obtained. The Electronic Communications Committee of the European Conference of Postal and Telecommunications Administrations (CEPT) has recently harmonized the first bands for 5G applications. These bands are 3.4–3.8 GHz (sub-6 GHz band) and 24.25–27.5 GHz (so-called 26 GHz band). Furthermore, the CEPT has identified the 26 GHz band for early European harmonization, as it provides over 3 GHz of contiguous spectrum and more favorable propagation than the higher frequency bands also under consideration. In addition to the 26 GHz band, the 28 GHz band has emerged as the second most important band for 5G networks [31]. Currently, the research and development of the 5G mobile systems at the higher frequencies, e.g., 28 GHz band, has been considered for urban areas and communication between vehicles. These unlicensed or slightly licensed millimeter-wave (mm-Wave) frequency bands are very attractive for future 5G mobile radio communication networks. Therefore, to achieve ultra-high capacity and bring ubiquitous high-bitrate wireless connectivity per mobile user, the cost-effective hybrid photonics-wireless mm-wave interface communication systems are required, where wireless transmission on millimeter-wave bands can be realized [32]. According to ITU-T G. 9803 rec. describing radio-over-fiber RoF systems, the PON network is desired for mobile fronthaul of latest 5G mobile systems with functions to provide the connection between the baseband units (BBU) pool and radio units (RU). As shown in *Fig. 6*, mobile fronthaul of 5G and beyond 5G systems over wavelength-division multiplexed passive optical access network PON can be realized using a centralized/cloud radio access network (C-RAN) architecture.

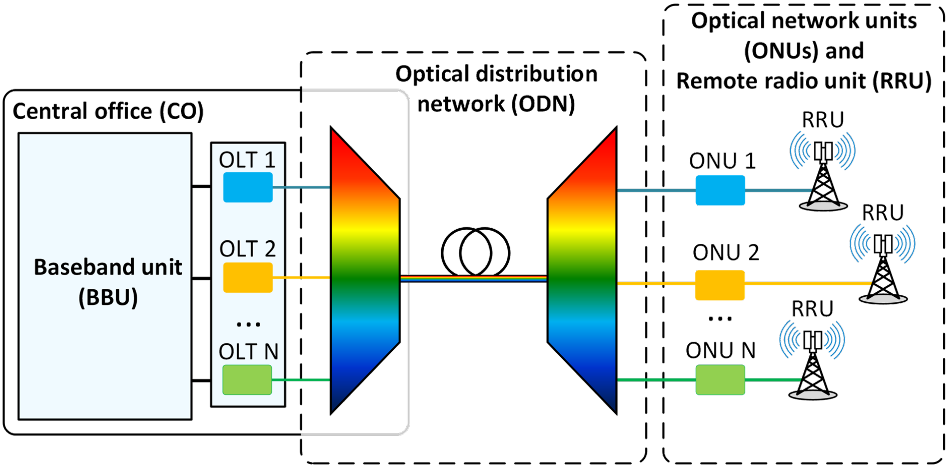
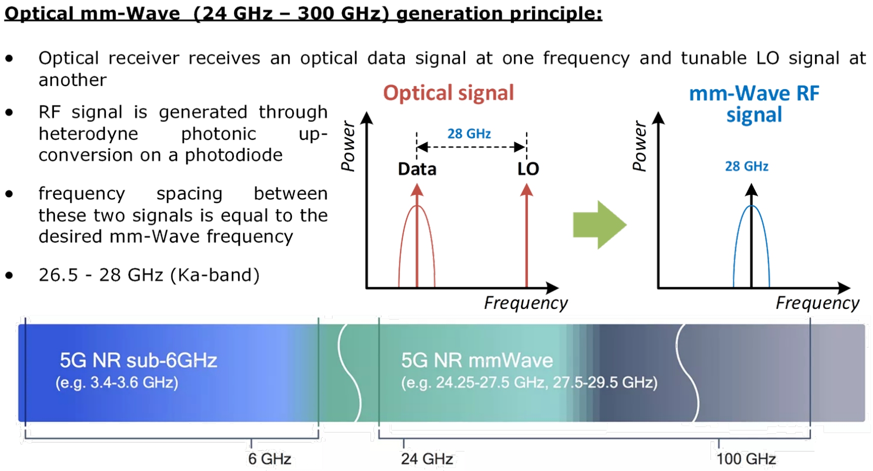


Fig. 6. Centralized mobile fronthaul over wavelength-division multiplexed passive optical access network PON.

In Subchapter 5.2, a simulation model in RSoft Optsim simulation software was created with the goal *to evaluate the performance and maximum reach for investigated A-RoF WDM-PON transmission system with four 2.5 Gbit/s NRZ-OOK modulated channels, where BBUs are implemented in CO allowing transporting of intermediate frequencies along existing fiber optical distribution network (ODN) under condition that it is still possible to achieve pre-forward error correction pre-FEC BER of 10^{-3}or lower.* The investigated A-RoF WDM-PON optical transmission system model consists of 4 channels operating at 2.5 Gbit/s bitrate each. According to ITU-T G.964.1 rec., dense WDM architecture with 100 GHz channel spacing and 193.1 THz central frequency is chosen. Three possible A-RoF system types for a different generation of mm-wave inside transmitters (Tx) of simulation environment model are investigated: **The simulation model of the first A-RoF transmitter was designed using two continuous wavelength (CW) light sources**, where one of them is directly connected to intensity Mach-Zehnder modulator (MZM). The second light source operates as local oscillator (LO). The frequency spacing between both above-mentioned lasers is set to be 28 GHz, accordingly enabling to generate 28 GHz (ka-band) mm-wave (see in *Fig. 7*).

Third A-RoF transmitter realization for intermediate frequency generation is more complex; the CW laser source is directly connected to the first MZM, the modulator BIAS point is adjusted at its zero point. Sinusoidal signal generator with 14 GHz sinusoidal electrical signal (half of proposed IF frequency) is directly connected to the first MZM electrical signal input. Afterwards, each tone is filtered out. The second optical signal is attenuated. Finally, both optical signals are coupled together and prepared for transmission in fiber optical part. The obtained BER of each A-RoF transmitter in response to received optical power at PIN photoreceiver is shown in *Fig. 8*. Results are obtained in two different scenarios, with 20 and 40 km ODN fiber length.



Optical mm-Wave (24 GHz – 300 GHz) generation principle:

- Optical receiver receives an optical data signal at one frequency and tunable LO signal at another
- RF signal is generated through heterodyne photonic up-conversion on a photodiode
- frequency spacing between these two signals is equal to the desired mm-Wave frequency
- 26.5 - 28 GHz (Ka-band)

Fig. 7. Optical mm-Wave generation by the homodyne up-conversion principle.

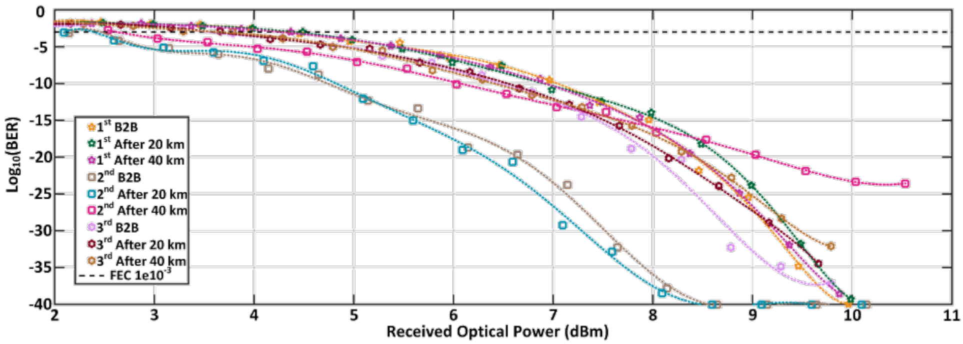


Fig. 8. Comparison of measured BER after ED versus received optical power for 2.5 Gbit/s NRZ-OOK signals depending on A-RoF implementation realization type and use of photonics up-conversion method for 28 GHz carrier frequency.

After extending the link section, it was concluded that maximal possible reached distance for the 2nd implemented A-RoF transmitter was 57 km with the BER of 3.6×10^{-4}, see *Fig. 9(b)*. As shown in *Figs. 9(a), 9(c)* with the 1st implemented A-RoF transmitter using one laser source as LO and the 3rd implemented A-RoF transmitter using the sinusoidal signal generator as LO, the BER of received signal was 3.3×10^{-4} and 5.1×10^{-4}, with maximum reached distances of 65 and 63 km.

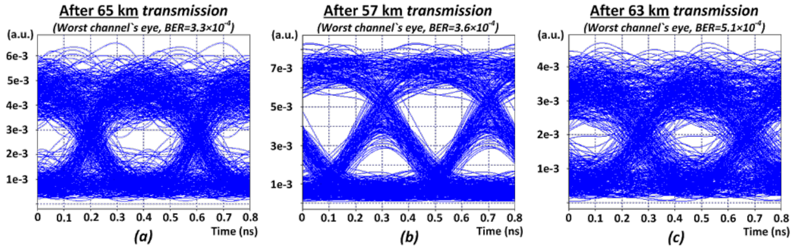


*Fig. 9. Eye diagrams of received 28 GHz carrier signal after ED detection by A-RoF implementation: (**a**) after 65 km transmission using one laser source as LO; (**b**) after 57 km use of two coupled light sources; and (**c**) after 63 km use of sinusoidal wave generator as LO for 4-channel 100 GHz spaced WDM-PON transmission system with 2.5 Gbit/s transmission speed per channel.*

In Subchapter 5.3, for research of millimeter-wave (mm-wave) hybrid photonics-wireless access system, the *VPI Photonics Design Suite* software was used. 8-channel 2.5 Gbaud per channel PAM-4 modulated WDM-PON optical transmission system with embedded analog mm-wave RoF transmission of 28 GHz mm-wave signal for 5G mm-wave hybrid photonics-wireless interface was designed and simulated. *The goal of this hybrid photonics-wireless analog mm-wave RoF-WDM-PON system simulation model was to evaluate the performance and system reach up to 40 km according to NG-PON2 link section requirements, under the condition that it is still possible to achieve pre-forward error correction (pre-FEC) BER level of 1×10^{-3} or lower*, the baseband units BBUs are located in the service provider's central office CO, allowing to transport intermediate frequencies IF over the optical front-haul network, and, lastly performing signal up-conversion in radio units RUs located at the receiver side of the base station (BS). For the generation of an mm-wave signal, on the receiver side, the simplest realization scheme was used – two coupled laser sources (CW1 and CW2). In this research, the proposed 8-channel 2.5 Gbaud/s PAM-4 modulated ARoF-WDM-PON optical transmission system with 100 GHz channel spacing is capable to provide transmission through ODN over SSMF fiber for at least 20 km with BER significantly smaller than FEC threshold (BER is 4×10^{-8}), while after 40 km transmission the BER of received and down-converted mm-wave signal was 2.8×10^{-3}, which is slightly above the FEC threshold. It means that it is technically difficult to ensure such a transmission distance of 40 km with the use of 100 GHz channel interval commercial arrayed waveguide grating (AWG). The use of 50 GHz channel spacing for such as hybrid system is limited. It is not possible to implement a 50 GHz channel interval utilizing commercial AWG where the 3-dB bandwidth is 35 GHz and, consequently, WR-WDM-PON architecture, due to the low cut-off frequency passband of AWG multiplexer/de-multiplexer, that leads to the considerable cut-off of the 28 GHz IF signal. As a result, it was concluded that the WR-WDM-PON architecture can be utilized for the generation and transmission of 2.5 Gbaud/s PAM-4 modulated mm-wave signal ensuring the channel spacing of 100 GHz, however for smaller channel spacing, e.g., 50 GHz and smaller, the use of wavelength-selective switch (WSS) with tunable bandwidth may be considered.

In Subchapter 5.4, for proof of the concept for prior obtained simulation results, the first built setup in RTU TI laboratory was a hybrid mm-wave RoF optical access system model with two separately coupled continuous wave CW laser sources, where one of them was modulated by a 10 GHz MZM modulator and driven with 2.5 Gbits/s (2.5 Gbaud /s) NRZ signal (PRBS15 pattern), as shown in *Fig. 10*. The experimental setup shows the transmission of RF 28 GHz mm-wave intermediate frequency (IF) signal (as Laser 1 has a central frequency of 193.1 THz and Laser 2 has a central frequency of 193.128 THz, forming the intermediate frequency of 28 GHz) over the optical access system and also show further transmission over the 28 GHz radio frequency, which is hard to model in the simulation environment. Major technical parameters of each component are shown on the respective component, as shown in *Fig. 10*. In the first trial, the free space distance providing line of sight conditions was 3 meters, where the free space path loss (FSPL) of the transmitted 28 GHz signal was 30.93 dB. Despite the fact that it was modulated only on one of the laser sources (Laser 1), the first tests with 2.5 Gbit/s NRZ-OOK signal showed that the RF signal at 28 GHz is non-stable, as it has carrier instability of ±80 MHz, where the carrier frequency is not exactly 28 GHz, which resulted in the reduced eye opening and jitter of the recovered 2.5 Gbit/s NRZ signal.

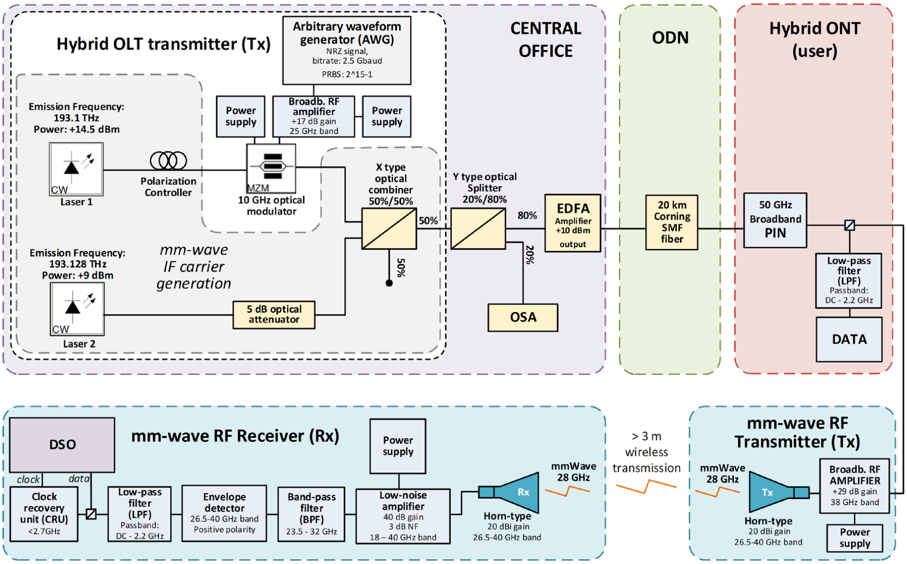


Fig. 10. The first experimental setup of 2.5Gbit/s NRZ-OOK modulated 28 GHz mm-wave hybrid analog mm-wave RoF optical access system with RF transmission distance of at least 3 meters.

Due to the mm-wave carrier frequency instability, these variations limit the spectrum-efficient 5G channel deployment. As one can see in *Fig. 11(a)*, the carrier frequency (see the spectrum on the right) is not stable and equal to 28 GHz as it should be. Also, from the eye diagram on the left, we can see the high signal to noise impact (SNR) as voltage variance of the logical "1" and "0" levels, as well as the jitter, are relatively large, therefore pushing the eye to close. The observed 28 GHz carrier frequency instability was due to the natural instability of laser sources used caused by the phase noise (see *Figs. 11(a), 11(b)*), however, for 2.5 Gbit/s NRZ signal, as shown in *Fig. 11(a)*, it was possible to provide error-free transmission over distances of at least 3 meters, where line-of-sight conditions were provided. For the PAM-4 signal instead of 2 logical signal levels, we have 4 levels, which have higher optical signal-to-noise ratio (OSNR) demands. With this experimental setup it was observed that due to the IF carrier (28 GHz) frequency instability and therefore received waveform distortions caused by it, the error-free transmission was not possible (all three PAM-4 signal eyes were closed).

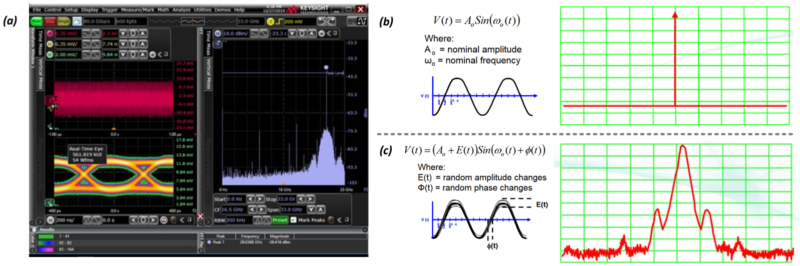


Fig. 11. ***(a)*** *Real-time 2.5 Gbit/s NRZ signal eye diagram (obtained by Keysight DSO using in-built real-time envelope detector and DC-2.2 GHz low-pass filter) and Comparison of (**b**) ideal signal and (**c**) real-world signal with random amplitude and phase changes* [33].

Subchapter 5.5 describes the system realization to mitigate the problem of 28 GHz IF frequency instability caused by laser phase noise, the way how we generate the reference laser signals (data and LO) was changed. Instead of using two independent tunable optical narrowband laser sources, only one of them (laser 1, 193.1 THz central frequency) was used, and through null-biased 40 GHz MZM modulator modulated by the sinusoidal signal, which has a frequency equal to half of our expected mm-wave frequency (14 GHz), as it is shown in the second experimental setup, see *Fig. 12*. For the generation of multiple correlated carriers, the 40 GHz MZM modulator was biased at its null point (*Vp*, around 2.7 VDC, as shown in *Fig. 12*) and driven with a 14 GHz sinusoidal signal (*Vpp* = 3.68 V) from up to 31.8 GHz Anritsu RF/Microwave Signal Generator.

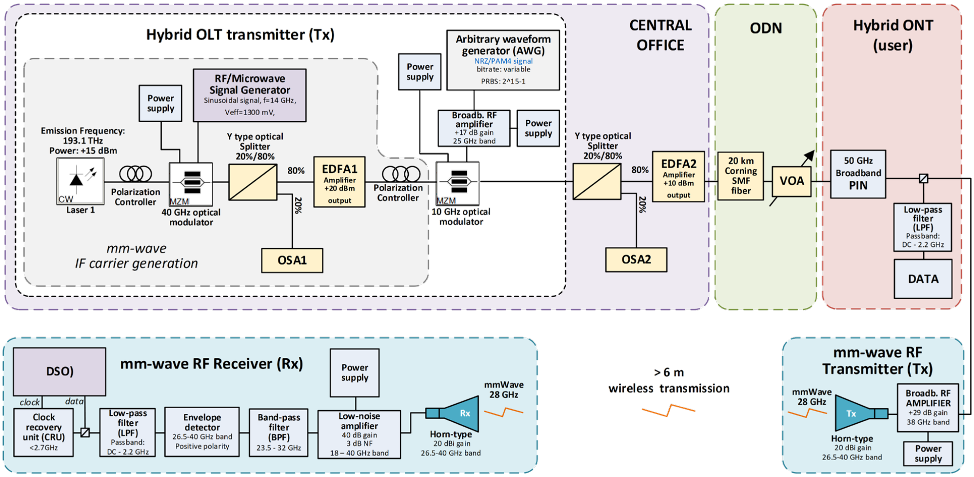


Fig. 12. The second experimental setup of variable bitrate NRZ-OOK and PAM-4 modulated 28 GHz mm-wave hybrid analog mm-wave RoF optical access system with RF transmission distance of at least 6 meters.

In such a way, on the output of the first 40 GHz MZM modulator, three optical carriers with 14 GHz spacing between every one of them was obtained, where the spacing between the first and third major carrier is about 28 GHz. Accordingly, after receiving such an optical signal with 3 carriers directly by the broadband 50 GH PIN, on the output of this PIN, an electrical signal was received, the spectrum of which contains the baseband part and two carriers: one 14 GHz and one 28 GHz carrier. Power budget calculations showed that the transmission distance, keeping the line-of-sight conditions, can be increased also up to 150 meters. Despite the fact, that we have this 14 GHz middle carrier in the electrical spectrum on the output of the broadband PIN, it has negative impact on the waveform quality of transmitted mm-wave RF signal, which reduces the efficiency of heterodyning up-conversion process, was identified as minimal, as subsequently it was naturally suppressed by our used horn-type mm-wave RF antennas (which have the passband of 26.5 to 40 GHz) and later by the limited passband of low noise broadband amplifier (LNA) (18 to 40 GHz bandwidth), filters (BPF, 23.5 to 32 GHz bandwidth), and envelope detector used.

Figure 13(a) shows the electrical signal (modulated, 2.5 Gbit/s NRZ-OOK, PRBS15) and its spectrum on the out of broadband PIN receiver. The primary focus in this image is on the spectrum (right part) – as we can see that the carrier signals are now stable in comparison to the first experimental setup. We can observe the 28 GHz carrier (27.9999 GHz) as well as the unneeded 14 GHz carrier (13.9999 GHz).

On the right of ***Fig. 13(a)***, we can see the spectrum of received 2.5 Gbit/s NRZ signal, which occupies around 2.5 GHz. Also, as one can see in ***Fig. 13(b)***, the real-time eye diagram of transmitted and received 5 Gbit/s NRZ modulated signal is wide open, therefore, it is clear that the error-free transmission (BER<10^{-9}) can be provided with such a hybrid mm-wave fiber optical access-wireless system. As one can see in ***Fig. 13(b)***, all three eyes of the received PAM-4 signal are wide open, meaning that **the error-free transmission (BER<10^{-9}) can be provided.**

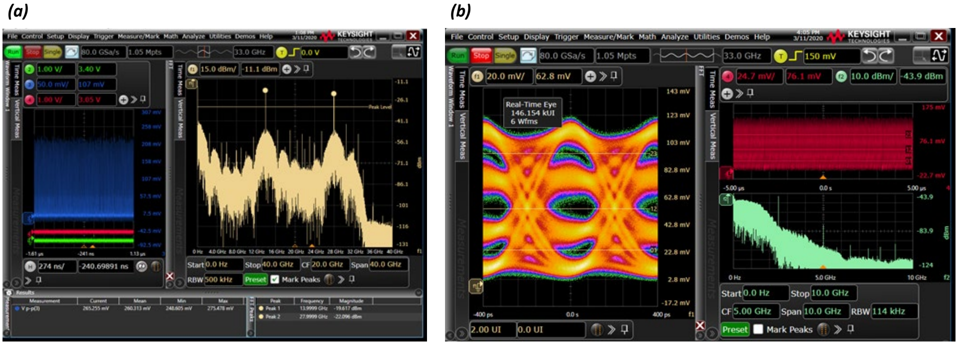


Fig. 13. *(**a**) The captured waveform and its spectrum on the RF output of the broadband PIN receiver. **Left** – waveform of mixed baseband and modulated 2.5 Gbit/s NRZ-OOK signal on 14 GHz and 28 GHz carriers (to be amplified and further transmitted to mm-wave band antenna). **Right** – spectrum of this waveform on the output of PIN receiver after 20 km transmission (captured by Keysight 33 GHz, 80 GSa/s DSO); (**b**) the captured waveform (**red, up**) of received and downconverted 5 Gbit/s (2.5 Gbaud) PAM-4 modulated 28 GHz mm-wave RF signal, its eye diagram (**left, bottom**), and spectrum (**right, green**).*

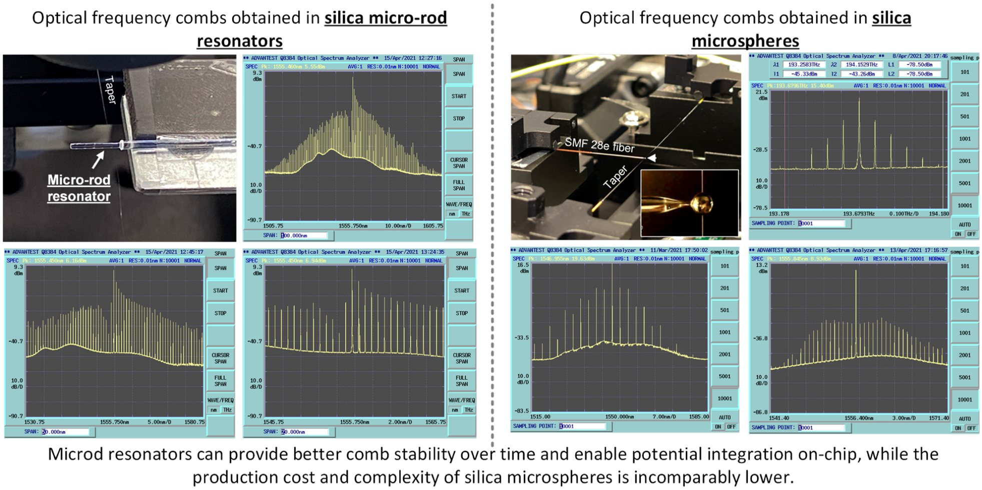
Subchapter 5.6 presents *the goal to design hybrid AROF-WDM-PON passive optical access communication system and evaluate the performance of such a data and radio signal transmission* *system, which implements baseband radio processing in a service provider's central office CO part, allows the effective provision of broadband internet and cellular data transmission between the service provider's CO and end-users.* **The transmitter part of the cellular mobile communication mm-wave interface** consists of baseband units (BBUs) integrated into the OLT of WDM-PON located on the CO side. According to the fundamental architecture of a typical RoF system for the case of downstream transmission, the CO includes OLT with four transmitters, where each of them has been modified to operate as RoF transmitter (ROF_Tx) designed for A-RoF system data containing 28 GHz intermediate frequencies IF generation. Each of ARoF transmitters located in OLT for generation of mm-wave IF signal bases on homodyne up-conversion principle and is designed by using two continuous wave (CW) laser sources with a linewidth of 30 MHz, where one of them (with +8 dBm output power) is directly connected to intensity Mach-Zehnder modulator MZM [34]. **The broadband internet transmitter part** has an optical line terminal (OLT), which consists of four transmitters (OLT_Tx) located in a CO. Each OLT_Tx transmitter contains a CW laser source (30 MHz linewidth, +9 dBm output power), which is directly connected to the intensity MZM modulator. The MZM is driven at 10 Gbit/s bit rate by previously formed and Bessel low-pass filter (3-dB bandwidth is 10 GHz) filtered electrical NRZ signal, passing from NRZ driver. The obtained BER versus received optical power at PIN photoreceiver in two different scenarios with 50 and 100 GHz channel spacing for (1st) 10 Gbit/s (broadband internet) NRZ signal and (2nd) down-converted 2.5 Gbit/s (28 GHz mm-wave 5G signal) after transmission over 20 to 40 km long ODN SSMF fiber span in 8-channel hybrid AROF-WDM-PON transmission system. After transmission with 50 and 100 GHz channel spacing trough 40 km ODN in Scenario 1 for (broadband internet service), the NRZ signal operating at 10 Gbit/s bit rate per channel was mainly affected by CD, where the BER was 1.3×10^{-38} and 9.6×10^{-37}.

3.3. *Chapter 6:* Implementation of spectrally efficient WDM transmission system with silica microsphere (SiO_2) WGMR-based Kerr-OFC light source

***Chapter* 6** *describes the implementation of a new type of spectrally efficient WDM transmission with a new novel silica microsphere whispering-gallery-mode resonator WGMR-based Kerr-OFC multi-wave light source.*

Subchapter 6.1 deals with Kerr optical frequency combs OFCs based on whispering-gallery-mode microresonator WGMR. Kerr OFCs are based on WGMR with a single laser source. More specifically, the WGMR-based Kerr-OFC comb generators physically realized on silica microsphere demonstrate [9] a new concept that provides an attractive solution to WDM-PON and intra-DCIs due to low cost and energy consumption. The intra-DCI devices and systems that rely on the sharing of computing resources require not only large capacity but, most importantly, high scalability and low energy consumption. Therefore, these requirements require new transmission technologies for short-reach communications. The main aspect of minimizing the expenses is the energy and spectral efficiency of the communication system. Both can be met by introducing an OFC generator instead of laser arrays. From the energy efficiency (as well as spectral efficiency) perspective, it is better to use a single light source instead of several lasers. **Potentially cost-effective solutions for the realization of data transmission in optical WDM networks are OFC**

generation in silica whispering gallery mode resonator – **microspheres manufactured from melted telecom fiber**, e.g., from Corning SMF 28e (ITU-T G.652), microtoroids **and resonators manufactured on the silica rod,** which is realized as the pumping of a high-quality (high-Q) optical resonator with Kerr nonlinearity using a single continuous-wave laser. When optimal conditions are met, the intracavity pump photons are redistributed via the four-wave mixing (FWM) to the neighboring cavity modes, thereby creating the so-called Kerr OFC. The exciting pump signal is launched into the Kerr-OFC resonator via a tapered fiber, and an OFC is being generated at the output of this taper. The Kerr-OFC output spectrum for optical frequency comb obtained in silica **microspheres resonator manufactured from melted telecom fiber and OFC comb obtained in the silica rod is shown in *Fig. 14.***


Optical frequency combs obtained in **silica micro-rod resonators**

Optical frequency combs obtained in **silica microspheres**

Microd resonators can provide better comb stability over time and enable potential integration on-chip, while the production cost and complexity of silica microspheres is incomparably lower.

Fig. 14. Optical frequency combs obtained in silica micro-rod and silica microspheres at RTU IT.

Kerr microresonator OFCs can achieve bandwidths of hundreds of nanometers covering different (e.g., E-, S-, C- and L-band) telecommunication bands. An OFC source can produce the grid of equally spaced (according to ITU-T G. 694.1 recommendation) optical spectral lines (carriers) needed to sustain the data channels. These comb lines are subsequently used as optical carriers for the data transmission using the intensity modulation direct detection IM/DD, where NRZ-OOK or a more complex PAM-4 modulation format can be applied. **In terms of these Thesis, the author are capable to show the obtained and published results of silica microspheres for telecommunication applications; unfortunately, the micro-rod Kerr-OFC source results (used as a light source for the telecommunication applications) are under IPR according to the ERDF project agreement.** It is important to note that at the moment, the project team is the only one in the world to experimentally demonstrate high-speed data transmission using harmonics generated in the silica microsphere. The results of this world-class experiment are described in the publication the first author and principal investigator of which is ***Toms Salgals***

("*Demonstration of a fiber optical communication system employing a silica microsphere-based OFC source*", Optics Express (Q1 Journal), 29, 10903–10913 (2021)).

Subchapter 6.2 deals with the experimental setup of the WGMR-based Kerr-OFC light source operating in the C-band and used for the generation of 400 GHz spaced optical carriers. This section also describes the fabrication process of a tapered fiber used for the coupling of light into and out of a silica microsphere and the experimental setup used for the characterization of coupling conditions between the silica microsphere and the tapered fiber. The setup used for the generation of WGMR-based Kerr-OFC is shown in ***Fig. 15***.

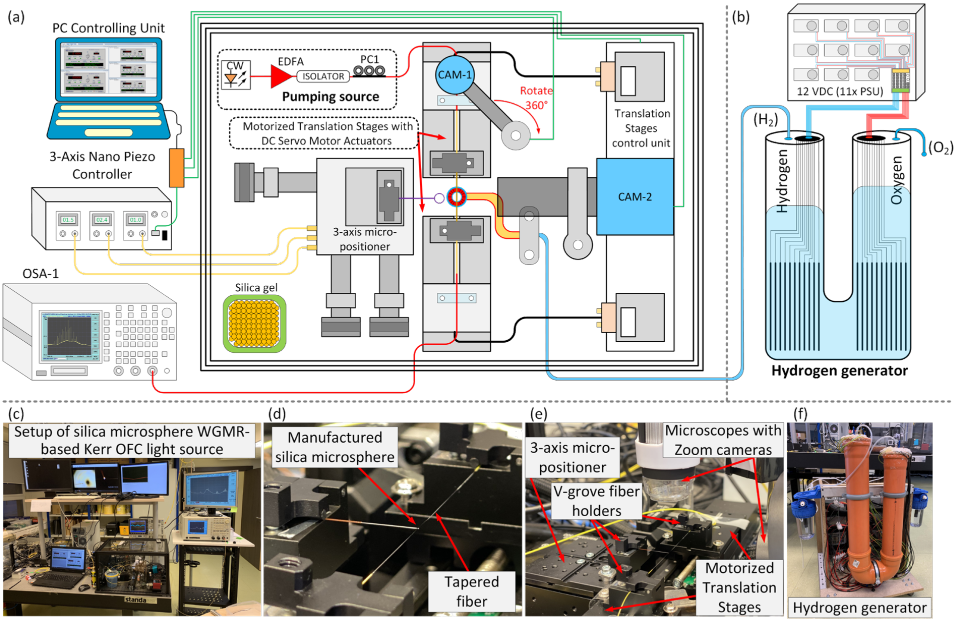


Fig. 15. *(**a**) Experimental setup illustrating the developed silica microsphere WGMR-based Kerr-OFC as light source for optical communications. (**b**) Schematic of a Hydrogen generator for pure generation of hydrogen (H_2) and oxygen (O_2) by electrolysis of water. (**c**) Captured setup of silica 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.*

Subchapter 6.3 *describes the first succesful experimental demonstration of data transmission based on OFC generated light source in microsphere resonator which has not been previously demonstrated.* It is the first experimental presentation of the 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. First, OFC generation was initiated by search for stable combs on an optical spectrum analyzer. After OFC generation it was observed that the comb lines (–1) and (+1) have a different performance, where power instability over a 10-

hour period is within about a 3 dB margin due to the impact of resonator ability to support multiple spatial modes. According to the NGPON2 requirements, the transmission distance of 20 km was chosen. ***Fig. 16(e)*** shows that the optical carrier denoted as (+1) provided the highest system performance, where the received optical power varies from –4 dBm to –17.5 dBm, and the BER of 2.5 Gbps NRZ-OOK signal is in the range from 1.39×10^{-15} to 7.76×10^{-3}. As one can see in ***Fig. 16(e)***, BER curves bending upwards are observed at relatively high detected power levels for WGMR-OFC comb carrier (+1) at 10 Gbps B2B and 10 Gbps 20 km transmission, as well as for (–1) carrier at 2.5 Gbps B2B transmission. It could be explained by detector saturation, nonlinear optical processes in the resonator or transmission fiber.

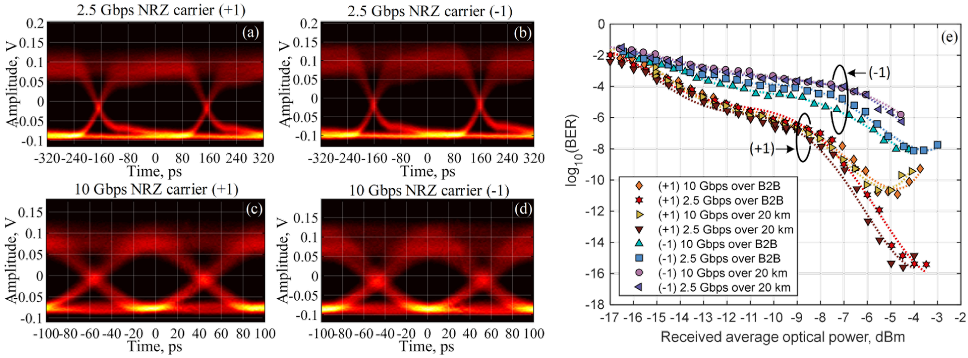


*Fig. 16. Eye diagrams of the received signal after 20 km transmission over SMF fiber at a data rate of 2.5 Gbps for **(a)** carrier "+1" and **(b)** carrier "–1", and at a data rate of 10 Gbps for **(c)** carrier "+1" and **(d)** carrier "–1", and **(e)** the plots of BER vs average received optical 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.*

In Subchapter 6.4, WGMR-based Kerr-OFC as light source is used to demonstrate NRZ-OOK modulated data up to 50 Gbps/λ over 2 km SMF link. Without the post-equalization, the received 40 Gbaud and 50 Gbaud NRZ-OOK signals are mostly below the 7 % Hard-Decision (HD-FEC) limit for the Kerr-OFC generated carriers (–1), (0), and (+1). In those cases, the main limitations are a relatively low effective bandwidth of the electrical components, ISI and the implementation penalty itself. In order to achieve higher data-rates, a dispersion-induced power fading must be reduced and signal equalization must be applied to reach the BER threshold of 5×10^{-3}. Therefore, linear equalizer (structure consists of 33-FF&15-FB taps) was chosen. The number of taps is chosen in a way to maximally improve the performance by tackling the bandwidth limitations of electrical components and chromatic dispersion. The results show that such post-equalization significantly improves the BER performance compared to the previous case without the post-equalization. The post-equalization can significantly improve the signal quality for the Kerr-OFC generated carriers (–1), (0), and (+1) or even enable new modulation format alternatives. With the linear post-equalization (33-FF&15-FB taps), the BER performance is significantly improved for carrier (+1), which allows us to achieve the BER floor below the 7 % HD-FEC limit for NRZ-OOK signals at 60 Gbaud.

CONCLUSIONS

1. To increase the data transmission distance above 27 km, WDM-PON transmission systems with 50 GHz inter-channel interval need to be replace NRZ-OOK with multi-level modulation formats (PAM-4, EDB) to ensure the transmission reach up to 50 or 62 km, where EDB modulation format applications have 19 % better transmission reach than spectrally efficient (10 Gbaud/s) PAM-4, which is explained by the distance between PAM-4 signal levels due to the effect of chromatic dispersion and SNR.
2. By evaluating the dispersion compensation methods for NG-PON2 ITU-T G.989.3 compliant WDM-PON transmission system, it is possible to provide a transmission distance of 40 km for an NRZ-OOK modulated signals with a data transmission rate from 20 to 40 Gbit/s per λ in the (C-band) range compliant FBG-DCM without exceeding the limit of the received signal ($BER \geq 1\times10^{-3}$) even with 3 dB less received signal power than in the case of DCF, significant effect on BER (2-5 BER steps at 20 and 40 Gbit/s transmission speed) arises under the influence of NOE.
3. To increase the data rate in HS-PON transmission systems, evaluating the performance provided by the intensity modulation (NRZ, PAM-4, PAM-8, EDB) after 20 km of transmission, it was concluded that at a data rate of 28 Gbit/s per λ not exceeding the $BER \geq 1\times10^{-3}$ limit value without AEQ can be achieved using 28 Gbaud/s (NRZ, EDB) and 14 Gbaud /s (PAM-4) signal modulation, while 42 Gbit/s per λ and 56 Gbit/s per λ data transmission not exceeding $BER\geq 1\times10^{-3}$ threshold can be provided by use of adaptive equalization by constellation of feed-forward (FF) and feedback (FB) taps using 14 Gbaud/s (PAM-8) and 28 Gbaud/s (PAM-4) signal modulation.
4. Based on the experimental results and the information gathered in the dissertation, it can be concluded that SMCF fibers are suitable for short-distance (≤10 km) data transmission in data center interconnection (DCI) solutions. In the combined solution of SDM-WDM technologies – in the implementation of a 7-core SMCF fiber spectrally efficient spatially capacitive IM/DD PON communication system, the factors influencing the transmission of 2.5 Gbit/s (NRZ) coded signals are unequal input losses, the optical power of the received signal in the core (~8.2 dB IL difference) is significantly affected by the BER of each signal received in the core. For the implementation of A-RoF communication systems in the combined solution of SDM-WDM technology, SMCF optical fibers are applicable in case if one SMCF fiber core is used for transmission within optical channel and intermediate frequency IF. High differential mode delay (DMD) (in the case of two separate cores of the same MCF fiber) will result in the degradation of the received signal due to the time delay.
5. In the realization of ARoF-WDM-PON optical transmission systems with intensity modulation (NRZ, PAM-4) for the transmission of millimeter wave radio signals provided by the uplink conversion technique, the BER value of the least received signal can be achieved using heterodyne transmission and detection techniques. Primarily, for the RoF transmitter implementation using one CW light source at the central emission frequency of the required

optical band area (according to ITU-G694.1) and a sinusoidal electrical signal generator as LO, where RF is half of the proposed IF frequency for the generation of the mm-wave signal. By secondary filtering the obtained F_n carrier frequency and performing (NRZ, PAM-4) modulation by combining F_n and F_{LO} in one optical channel. Using one CW laser light source in a circuit where the electrical signal generator is used as LO, the two generated optical carrier signals F_n and F_{LO} with appropriate frequency interval for the IF-generated mm-wave signal are resistant to λ non-uniformly induced oscillations depending on temperature changes (carrier instability of ±80 MHz), as well as low phase noise is provided, therefore limiting the use of phase modulation for the transmission of a millimeter wave radio signal. If both laser sources have an unstable central frequency, the mm-wave frequency also is unstable – it is drifting.

6. In the hybrid ARoF-WDM-PON communication system for the transmission of 10 Gbit/s per channel (NRZ) modulated optical signals and 2.5 Gbaud (NRZ, PAM-4) modulated 28 GHz (ka-band) millimeter wave radio signals with data transmission speed in the channel up to 5 Gbit/s through 20 km long SMF fiber line, the main factors influencing the hybrid systems performance are chromatic dispersion (CD), transmission system amplitude frequency characteristics, as well as basic free space transmission (FSPL). A 28 Ghz (ka-band) mm-wave IF radio signal cannot be implemented in ARoF-WDM-PON with a 50 GHz inter-channel interval using commercial AWG (significant effect on $BER \leq 1 \times 10^{-3}$), where 3-dB bandwidth is 35 GHz, so the WR-WDM-PON architecture results in significant filtering of the 28 GHz IF signal due to the AWG multiplexer/de-multiplexer cut-off frequency passband. As a result, the WR-WDM-PON architecture can be used for 2.5 Gbaud/s (NRZ, PAM-4) modulated 28 GHz mm-wave signal, as well as 10 Gbaud/s (PAM-4) modulated broadband Internet signals at the 100 GHz inter-channel spacing, but with a smaller bandwidth interval (according to ITU-T G.694.1) such as 50 GHz and less, are technically feasible using a wavelength selective optical switch WSS.

7. Potentially cost-effective solutions for the realization of data transmission in optical WDM networks are OFC generation in silica WGMR – microspheres manufactured from melted telecom fiber, e.g., from Corning SMF 28e (ITU-T G.652), which is realized as the pumping of a high-quality (high Q factor) optical resonator with Kerr nonlinearity using a single continuous-wave (CW) laser. Kerr microresonator OFCs can achieve bandwidths of hundreds of nanometers covering different (e.g., E-, S-, C- and L-band) telecommunication bands. An OFC source is capable of producing the grid of equally spaced (according to ITU-T G. 694.1 recommendation) optical spectral lines (carriers) needed to sustain the data channels. This advantage of the generation of several spectral lines applies also to WDM receivers, where an array of discrete local oscillators (LO) might be replaced by a single OFC. Such solutions are of importance for the fifth (and next) generations of mobile networks, where the optical signal down-conversion to millimeter wave (mm-wave) bands (e.g., Ka-band (26 –28 GHz)) by using a stable LO at the receiver side can be required as a part of the architectural solution. Silica microsphere-based OFC sources for wavelength division multiplexed (WDM) systems

cover use cases ranging from short reach fiber-optic links (e.g., as for data center interconnects (DCI)) to metro-access fiber-optic links interconnecting large geographic areas.

During PhD thesis, for the first time was present designed 170 µm silica microsphere WGMR-based Kerr-OFC as a C-band light source where 400 GHz spaced carriers provide data transmission of up to 10 Gbps NRZ modulated signals without AEQ over the standard ITU-T G.652 telecom fiber span of 20 km in length, which is suitable for IM/DD XG-PON transmission systems architecture. The designed novel light source also has the potential to demonstrate a new low-cost concept enabling an attractive solution for intra-datacenter interconnects (DCI) that can provide low-cost and low-complexity IM/DD scheme for transmission of NRZ-OOK modulated signals at bandrates up to 50 Gbps/λ over 2 km SMF link. **Such high data rates in terms of data transmission speed for silica microsphere WGMR-based Kerr-OFC light sources is a data transmission rate record of 50 Gbps per λ.** The obtained results show that pre- and post-equalization, e.g., AEQ techniques, allow to overcome the ISI and help to recover the signal from distortions caused by limited bandwidth and therefore enabling higher data-rate alternatives to intra-DCIs. For a proof-of-concept in both cases, experiments were performed with two newly generated OFC carriers with free spectral range (FSR, of 400GHz) having the highest peak optical power level.

Lower FSR between comb carriers can be achieved by using a WGMR with a larger diameter. To obtain 200 GHz spacing, one can use ~330 µm diameter silica microsphere. To obtain standard 100 GHz spacing, one can use ~660 µm diameter silica resonator. For operating with 100 GHz mode spacing, microspheres may be not a very optimal choice due to excitation of WGMs from not the fundamental mode family, so using silica microrod may be beneficial for this purpose. Moreover, when using larger WGMRs compared to 170 µm, the effective field areas of the fundamental modes will be larger, so the nonlinear Kerr coefficient γ will be smaller. The nonlinear processes leading to OFC generation depend on $\gamma \times P_{pump}$, so the pump power P_{pump} should be increased, which means that the power in each harmonic will grow too.

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