Investigations on optical communication links for high data rate in 5G systems

Ph.D. Thesis booklet for the dissertation

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March 2020.

1. Introduction

The 5G mobile network targets wireless connection capacity up to 10 Gbit/s. For this purpose, I propose a method to considerably increase capacity. I show how to compensate the linear and nonlinear effects using a different prototype in optics and radio over fiber based on polarization multiplexing, soliton propagation, modelling, etc.

Enabled by coherent and non-coherent detection techniques, advanced modulation formats improve spectral efficiency to support the growing demand of capacity in fiber transmission systems. Coherent detection retains both the amplitude and phase information of the received signal, allowing digital signal processing (DSP) to compensate for linear optical channel impairments such as chromatic dispersion (CD) and polarization mode dispersion (PMD).

Polarization mode dispersion is a physical phenomenon in optical fiber that causes light pulses to spread in time. I study the impact of this phenomena on many optical parameters (fiber length, BER, bit rate, signal amplitude, modulation, etc.) using simulations, experiments and measurements.

Polarization also occurs when light is scattered while traveling through non-isotropic medium. When light strikes the atoms of a material it will often set the electrons of those atoms into vibration. The vibrating electrons then produce their own electromagnetic waves that is radiated outward in all directions. This newly generated wave strikes neighboring atoms, forcing their electrons into vibrations at the same original frequency. These vibrating electrons produce another electromagnetic wave that is once again radiated outward in all directions. This absorption and reemission of light waves cause the light to be scattered the medium. This scattered light is partially polarized.

The deployment of an optical cable containing several fibers is a very expensive investment. Therefore, increasing the capacity of existing optical links is an important issue. For that purpose, polarization multiplexing is a cost-effective approach. Polarization multiplexing means that there are two optical beams with perpendicular polarizations on the same fiber. The two waves can carry different information.

I present experimental procedures to validate some challenging issues. One of them is the crosstalk. For reducing the crosstalk, a new approach is suggested. By applying that method in the experiments, the achieved measurement results prove the applicability of the Pol-Mux technique in links for high-speed long-distance transmission.

Moreover, based on the simulation and measurements results, I have achieved optimum system performance and I was able to reduce the PMD effect using pre- and post-compensation. I also have improved the Pol-Mux technique using coherent detection in case of 4/16-QAM and 16/64-QAM modulations.

I investigated the modulation part. The Mach-Zehnder modulator is widely used for optical intensity modulation. It's often applied version is the single drive Mach-Zehnder modulator. That is relatively simple and can work at high modulation frequencies up to the millimeter wave band. It is well-known that Mach-Zehnder modulator exhibits higher modulation nonlinearity with increasing driving voltage. However, there is another property which is not dealt with in detail yet: the Mach-Zehnder modulator has a parasitic phase modulation beside the useful intensity modulation. The parasitic phase modulation can cause different disturbing effects during the propagation of modulated signal. I tested the source of phase modulation and its effect on the modulation characteristics.

The Pol-Mux technique is very practical for branching application. Using the arrangement of the block diagram (1) channels can be inserted into existing optical links for a specific section of the link. That architecture is suitable especially for connections between a central station and the radio base stations in a mobile network. That solution is very flexible and can utilize the existing optical network without disturbing it. The polarization beam splitter or combiner has the same structure because it is a passive reciprocal component. Therefore, the concept of the block diagram can also be applied in the case of duplex communication on the same fiber.

In some cases, a radio base station of mobile network is at a remotely located place, far from the existing optical network. For that section, usually a wireless connection is established. That solution can be easily applied to the radio over fiber (RoF) technique, extending the optical section. In this case several radio base stations can be connected via an optical link carrying several radio frequency subcarriers. The RoF concept can be applied very well also at millimeter wave frequencies. The optical fiber is more and more frequently used for connecting the radio base stations into the mobile networks. However, there is a significant drawback, fiber dispersion, and due to fiber dispersion, I obtain pulse broadening which deteriorates signal reception. The pulse broadening is dependent on the length of fiber and the bit rate of signal transmission

The radio over fiber concept can be applied for different connections in a mobile network. One example is when a central station is to be connected to a radio base station by an optical link. In that case, the aim is to perform most of the signal processing in the central station and to obtain a very simple radio base station. That arrangement is especially important in the millimeter wave band because then there are smaller cells and therefore more radio base stations. In this application the radio over fiber link is the best choice because it produces the millimeter wave carrier modulated by the information. Therefore, this signal can be radiated without any further processing (except amplification and filtering). I propose to apply also the polarization multiplexing method to increase capacity.

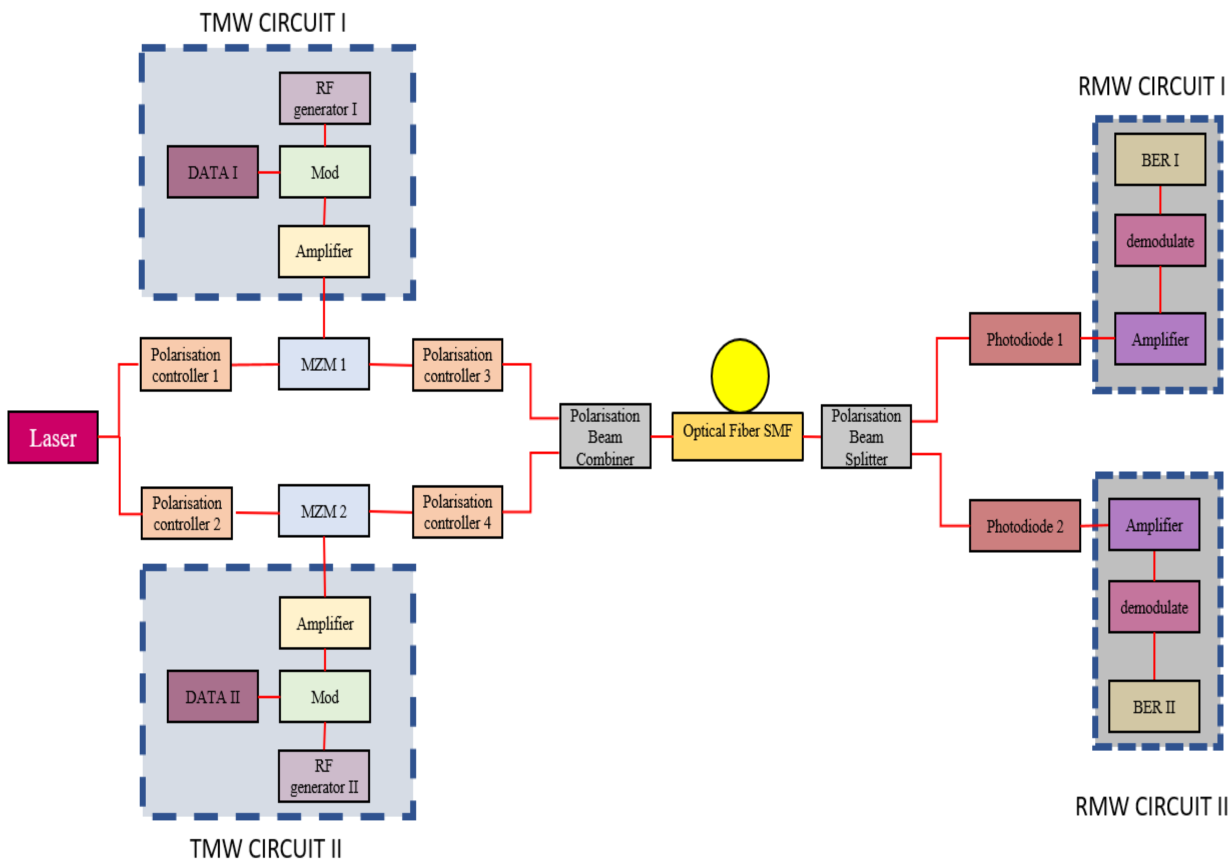
In the developed experimental link two optical sources are used with the same or almost the same frequency: 193.5 THz. Their output power is almost the same: 12 dBm and 13 dBm. The frequency stability is better than 1.10^{-6}. This very high frequency stability is necessary because 60 GHz millimeter wave signal is generated by mixing the two optical beams. For that purpose, I use a local oscillator laser operating at 193.440 THz frequency. Then the mixing product is at 60 GHz.

The emitted laser beam usually has elliptic polarization. A polarization filter is applied to have linear polarization. That beam is modulated by a data stream. Then the modulated beams are adjusted to get orthogonal polarization and they are combined by a polarization beam combiner. The local oscillator laser beam is added by 45˚polarisation to the modulated beams with two orthogonal polarizations. The resultant optical beam is transmitted over a single mode fiber (SMF) to the reception side. In the receiver a polarization beam splitter (PBS) separates the two polarizations and by optical detection two 60 GHz modulated millimeter wave radio frequency (RF) signals are obtained, then these signals are amplified and radiated from the radio base station. The complete connection is tested by measuring the bit error rate (BER) and eye diagram. In the experiment the bit rate and fiber length were varied.

Having tested the radio over fiber link, the experiment is extended to the wireless section, i. e. the 60 GHz signal is radiated and received in a short distance. This way an integrated optical millimeter wave link is tested which connects the central station with the subscribers. The wave propagation problems of the wireless section are not tested. The measurement results are presented in the dissertation. The bit rate and fiber length are varied.

Finally, in the last part I study the relation between PMD and soliton. I use intensity modulation to encode the information to be delivered, and polarization to separate multiple channels. Polarization division multiplex (PDM) transmission based on the nonlinear Fourier transform (NFT) is proposed for optical fiber communication. The NFT algorithms are generalized from the scalar nonlinear Schrödinger equation (NLSE) for one polarization to the MANAKOV system. The NLSE describes the propagation in an optical fiber considering both linear and nonlinear phenomena in the fiber.

The technique of optical solitons thus appears today to be extremely promising for the transmission of very high digital rates, with potential performances which are out of the reach of conventional so-called 'linear transmission'. I use non-linear effects until I find the perfect balance (linearity + non-linearity = 0) to produce a soliton wave that propagates without deformation, i.e. to retain its shape and speed during propagation in an optical fiber. I also showed how solitons are used as information carriers in WDM systems when propagating in the same channel and in the adjacent channels.



Block diagram 1: presenting the Pol-Mux transmission channels

2. Theses

My research topic was to improve optical connections for meeting the increased requirements of 5G mobile networks. For that purpose, I have chosen the new polarization multiplexing (Pol-Mux) method. According to this method the optical beam has two orthogonal polarizations and they are used for transmitting two independent information. That is an attractive behavior because it can provide double capacity. My research work covered many aspects of that new approach. My plan was to investigate the possibilities and constrains of Pol-Mux method. That approach was a not sufficiently developed yet. In the literature, there were very few publications, which were mainly theoretical works and almost no measured results. I carried out detailed simulations to see the capabilities and constrains of the new approach. Later I performed detailed experimental investigations as well.

I mention that at the start of my study there were already publications on the polarization division multiplex (PDM) method, which is a different approach. PDM is used in wavelength division multiplex (WDM) systems to increase the separation between the adjacent optical channels. In this approach the optical channels have different wavelength and the optical beam of each channel has orthogonal polarization compared to the adjacent channel providing this way an additional separation between the adjacent channels. However, in this new approach, which I investigated, i.e. in the so-called Pol-Mux approach each optical beam has two orthogonal polarizations doubling this way the capacity of each channel. In the Pol-Mux approach the cross-polarization coupling is a challenging problem.

Thesis I.

My first work was concentrated on the problems and characteristics of an optical link with single polarization. Its results are summarized in the first Thesis. The main effects are caused by the polarization mode dispersion (PMD). The first thesis contains mainly the relationships between the link parameters and polarization mode dispersion. Therefore, I start my research by studying the dispersion phenomena, their behavior, effects and disadvantages, etc. in the optical network. [C6] [C7] [C14] [C15]

Sub-Thesis I.1.:

I simulated PMD effects on many optical parameters (*L*=130 km, SSMF….), and its advantage, behavior, effects as well.

- The results for the impact of the quality factor versus fiber length are the more the fiber length (≥100 km) increases, the quality factor decreases by more than 10%.
- When the bit rate is 40 Gbit/s, the quality factor is good (Q = 6). When the bit rate further increases, the quality factor decreases.
- If the PMD is higher than 0.5 ps/km$^{1/2}$ the quality factor decreases, e.g. if PMD is 1 ps/km$^{1/2}$ the Q is less than 2, the signal is completely distorted.
- When PMD is higher than 0.5ps/ km$^{1/2}$ the BER becomes worse.

Sub-Thesis I.2.:

- The energy will turn on the slow axis of polarization, and exchange energy with the polarization of the original state. These proper modes vary randomly along the length of the fiber.
- The coupling in strong mode opposes the broadening of signal propagation. The polarization state is located on the northern hemisphere of Poincare sphere and the degree of polarization (DoP) is about 99.851% (supposed *L*=200 km, 40 Gbps, SMF, PMD=0.5 ps/km$^{1/2}$)

Sub-Thesis I.3.:

As an example, I investigated a D-WDM system at 112 Gbit/s per channel using 9 modulated channels in PMD QPSK with modulation speed equal to 28 Gsymbol/s and space between channels of 50 GHz. I determined the influence of chromatic dispersion and PMD on quality factor distribution.

- The width at 5 per 1000 of the maximum normalized occurrences ΔQ5% of 2.2 dB and 1.5 dB respectively for the "with DCF" and "without DCF" configurations.
- The Q factor is improved in the presence of PMD. I note that the width ΔQ^2 5% is greater in the case "with DCF" and without PMD (ΔQ^2 5% = 2dB) whereas it is smaller when I emulate a PMD of 30 ps (ΔQ^2 5% = 0.6dB).
- I demonstrate the broadening of short (Dirac σ-shaped) pulse caused by PMD. I conclude that the probability distribution function of group velocity dispersion (GVD) between the principal state of PMD (0.5 ps/km$^{1/2}$) generated by the component agrees well with Maxwellian probability distribution. The bit rate was 40 Gbit/s for 200 L=km distance of SMF.

Sub-Thesis I.4.:

To obtain good signal transmission with polarization mode dispersion compensation, both pre- and post-polarization compensations are used by inserting polarization controllers before and after the fiber.

Polarization by scattering is observed as light passes through the atmosphere. Twenty “partial” pulses (or delay times) are suitable in case of fixed lengths of a scattering section in a fiber. That gives an idea about the importance of the variable scattering section length (non-zero scattering section dispersion). In case of N identical scattering segments only N delay times (or partial pulses) are produced. When non-zero dispersion of the scattering length is used, the number of delay times (partial pulses) is increased (to 2 N).

- In case of fixed scattering section length, the Q-factor is a periodic function of the wavelength. AND spectral interval should be less than the spectral period of DGD

- In case of variable scattering section lengths, I have no periodicity, the periodicity is related to the spectral periodicity of DGD

Thesis II.

The second thesis deals with the transmission problems of Pol-Mux approach. An important question is the effect of the polarization extinction ratio (PER) concerning the crosstalk and link quality. For characterization the bit error rate (BER) and the eye diagram are used.

The increase in the number of users and the bandwidth demand per user have forced service providers to explore higher frequencies. The Pol-Mux technique is a countermeasure to that problem. Therefore, as a new approach it has been applied. I introduced 90˚ phase shift between the two optical waves. That way there are two orthogonal coherent beams in the time or frequency domain when using simulation and measurements [j2] [c10] [c13] [s19] [c12] [j1] [j5].

Sub-Thesis II.1.

- By using polarization controllers (PC) to keep the orthogonality between the two channels by 90˚, the effect of crosstalk has been reduced significantly. A bit error rate better than 10^{-6} has been achieved using different fiber length and 12 Gbit/s modulation speed.
- Integrating polarization beam splitters and beam combiners improves the Pol-Mux network structure, which results in the BER of 10^{-10} for less than 100 km fiber length.
- The choice of polarization phase of polarization controller is extremely important to obtain a good transmission quality.

Sub-Thesis II.2.

- The impact of data sequence on the transmission performance has been investigated in terms of Q factor and BER considering different modulation formats like 4/16-QAM and 16/64-QAM.
- As PER increases polarization crosstalk reduces. With sufficient polarization extinction ratio, the polarization crosstalk can be reduced substantially. In the simulation the PER should be ≥22 dB.
- Based on Pol-Mux measurement I recognize that the BER and bit rate has inverse relation.
- The Pol-Mux simulation with 4/16-QAM shows the relationship between symbol error rate (SER) and PER. The SER for 4QPSK is higher compared to 16-QAM at the low PER.

Sub-Thesis II.3.

- Incoherent detection and differentially coherent detection offer good power efficiency only at low spectral efficiency, because they limit the degrees of freedom available for encoding of information.

Thesis III.

The third thesis discusses the application of the radio over fiber (RoF) concept. This thesis contains mainly experimental results and measurement data. That thesis presents the advantages of application possibilities, like achieving double capacity, inserting new channels into an existing optical link, reducing latency, increasing system reliability, etc.

There is an increasing demand for improved capacity in mobile networks. That means faster signal transmission and high capacity to fulfil the subscriber’s requirements. To achieve that goal the used radio frequency band should be pushed to higher frequencies, mainly into the millimeter band e.g., into the 60 GHz band. [c11] [j3] [m20] [j4] [c16].

Sub-Thesis III.1.

- The radio frequency signals are transmitted by polarization multiplexing over a 25 km long single-mode fiber.
- I conducted systematic eye-diagram and BER measurements of 0, 1, 2, 7 and 25 km with bit rates of 1, 2, 4, 8 and 12 Gbit/s bit rates. It was proven experimentally, that the proposed architecture provides a good bit error rate around 10^{-8}.
- I applied two laser beams with a 60 GHz frequency difference between them. A 60 GHz radio frequency wave is obtained by mixing the two laser beams at the radio base station. The generated radio waves carry information.
- As a further improvement information is transmitted by optical waves with two polarizations. For the wireless link, I use millimeter wave radiation also with two polarizations. This way I create a complete combined optical wireless system.

Sub-Thesis III.2.

This approach can be used advantageously in the following applications:

- To achieve double bandwidth,
- To increase the capacity,
- To insert a new channel into an existing optical link,
- To generate microwave or millimeter wave carrier frequency in the radio base station,
- To reduce the latency of signal transmission.

In every case the stabilization of frequency and reduction of noise are substantial issues.

Sub-Thesis III.3.

A combined optical and wireless system has been developed links using polarization multiplexing has been developed and tested in the laboratory.
A signal with 12 Gbit/s bit rate was transmitted over a 7 km long combined link with about 1.10^{-8} bit error rate. The result is much better than the already published data, which were measured on links transmitting signals with 2.5 Gbit/s bit rate.

Thesis IV.

The fourth thesis presents the advantages of soliton propagation in WDM systems. The spectacular growth of the Internet and telephone traffic forces the network operators to increase the transmission capacity of their terrestrial fiber networks. Using the wavelength division multiplexing (WDM) technique multiple Gigabit/s capacity is available in a single fiber. The polarization domain wall solitons (PDW) have significant perspective. This method contributes to the challenge of optical telecommunications by making transmission lines that best preserve the standard of the signals move in SMF fiber. I used soliton as information carriers both for short and for long distances with high capacity, good quality factor and high speed [n18] [c8] [c9] [n17].

Sub-Thesis IV.1.

There are several problems: the laser sources are not strictly monochromatic and further problems are because of the nonlinearity like SPM, XPM, FWM. For compensating the nonlinear effects, I apply proper fiber dispersion. As a solution, I propose a hyperbolic secant pulse shape (soliton).

Sub-Thesis IV.2.

In an optical link applying dispersion management, i.e. when the chromatic dispersion is compensated for every channel then the EDFA type optical amplifier can be well applied for soliton pulse amplification or regeneration.

Sub-Thesis IV.3.

There are some constraints like channel spacing, amplifier noise, collision of solitons and crosstalk between the channels. They become serious problems with the increase in the number of channels due to system nonlinearity. I numerically confirm the theoretical hypothesis on the design principles of soliton transmission in WDM systems. It is important to mention that without the advent of the monitoring techniques and filtering, soliton systems would not provide their benefits. The optical soliton thus appears today to be extremely promising for the transmission of very high digital data rates, with potential performances that are out of reach of conventional so-called 'linear' systems.

3. Publications

Journal papers

[j1] Nada Badraoui, Tibor Berceli: “Enhancing capacity of optical links using polarization multiplexing”, Optical and Quantum Electronics, Vol.51, No.9, p.310, Springer, 2019.

[j2] S. Singh, S. Singh, Nada Badraoui, Tibor Berceli, A. Alomainy: “Design and analysis of all-optical up- and down-wavelength converter based on FWM of SOA-MZI for 60 Gbps RZ data signal”, Photonic Network Communications, Vol.34, No.2, pp.288-297, 7 April 2017. DOI: doi.org/10.1007/s11107-017-0696-x.

[j3] Nada Badraoui and Tibor Berceli, “Crosstalk reduction in fiber links using double polarization”, Optical and Quantum Electronics, Springer, 2020.

[j4] Nada Badraoui and Tibor Berceli, “An Experimental 60 GHz combined radio over fiber and wireless link with polarization multiplexing”, IEEE, Journal on Lightwave Technology, 2020, submitted.

[j5] Spurious Modulation of Single Drive Unbalanced Mach-Zehnder Modulator-under process

Conference papers

[c6] Nada Badraoui, Tibor Berceli: “Behaviour of cross polarization on radio over fiber links”, 11th IEEE/IET International Symposium on Communication Systems, Networks & Digital Signal Processing, CSNDSP’2018, pp.1–5, Budapest, Hungary, 18-20 July 2018, DOI: 10.1109/CSNDSP.2018.8471775.

[c7] Nada Badraoui: “Enhanced Capacity of RoF Links by Compensation The 'Chromatic and Polarisation' Dispersion with Bragg Filter and Doubly Polarisation Signal Transmission”, Winterschool of Fiber Lasers & Optical Fiber Technology COST MP1401-FLWS18, poster p.1, Lausanne, Switzerland, 13-16. Feb. 2018.

[c8] Nada Badraoui, Tibor Berceli: “Modeling and design of soliton propagation in WDM optical systems”, Proc. of Optical Network Design and Modelling, ONDM'2017, New York, USA, IEEE, 2017. Paper: 7958524, 6 p, DOI: 10.23919/ONDM.2017.7958524.

[c9] Nada Badraoui, Tibor Berceli, S. Singh: "Distortion cancellation for solitons carrying high speed information in WDM systems", Proc. of the 19th International Conference on Transparent Optical Networks, ICTON'2017, IEEE paper: 8024967, pp.1-4, Girona, Spain, July 2017. DOI: 10.1109/ICTON.2017.8024967

[c10] Tibor Berceli; Nada Badraoui: "Parasitic phase modulation in single drive Mach-Zehnder optical modulator", Proc. of the 19th International Conference on Transparent Optical Networks, ICTON'2017, IEEE paper: 8025020, pp.1-4, Girona, Spain, July 2017. DOI: 10.1109/ICTON.2017.8025020.

[c11] Nada Badraoui, Tibor Berceli: "Proved the reliability of pol mux in radio over fiber for 5G", 21th International Conference on Transparent Optical Networks, ICTON'2019, paper Fr.D2.3, IEEE, pp.1–6, Angers, France, 2019. DOI: 10.1109/ICTON.2019. 8840577

[c12] Nada Badraoui, Tibor Berceli: "Improvements in high speed radio over fiber links using POL-MUX technique for MIMO using linear polarized antennas", COST meeting, Prague, Czech Republic, 2019.

[c13] Nada Badraoui, Tibor Berceli: "Capacity enhancement by PMD compensation in POL-MUX optical links", COST meeting, Aveiro, Portugal, 2019.

[c14] Nada Badraoui, Tibor Berceli: "Enhanced capacity of radio over fiber links using polarization multiplexed signal transmission," 20th International Conference on Transparent Optical Networks, ICTON'2018, IEEE, pp. 1–6, Bucharest, Romania, 2018.

[c15] Nada Badraoui, Tibor Berceli: "Improvements in high speed radio over fiber links using POLMUX technique," COST meeting, Toulouse, France, 2018.

[c16] Nada Badraoui and Tibor Berceli, "Integrate soliton in POL-MUX technique for compensation of linear and nonlinear effect," 22nd International Conference on Transparent Optical Networks (ICTON), Bari, Italy, IEEE, 2020, Submitted.

National conference, seminar, workshop presentations or meetings

[n17] Nada Badraoui, Tibor Berceli: "Theoretical and experimental study of the Evolution and Applications of Soliton", Mesterpróba 2017: Tudományos konferencia végzős MSc és elsőéves PhD hallgatóknak Távközlés és infokommunikáció témakörében, 4 p., 2017.

[n18] Nada Badraoui, "Propagation Problems of Solitons in Fibers", MultiScience XXXI. microCAD International Multidisciplinary Scientific Conference, University of Miskolc, Miskolc, Hungary, , Paper: C2_2, 9 p., 20-21 April 2017.

[s19] Nada Badraoui, Tibor Berceli: “Capacity enhancement using POL-MUX method in RoF”, Seminar, Duisburg-Essen University, Germany, 2019.

[m20] Nada Badraoui, “Photonic Integration for Aerospace, Satellite & Radar Technology” ECOST-TRAINING_SCHOOL-CA16220-170220-110341, Paris, France, 2020.

4. LIST OF CITATIONS

[r1] citation for [c6]: ref. [17] in Tomáš Ivaniga, Petr Ivaniga: “Suppression of Nonlinear XPM Phenomenon by Selection of Appropriate Transmit Power Levels in the DWDM System”, International Journal of Optics, Hindawi, 2 Jun 2019.

[r2] citation for [j2]: ref. [8] in Peterson Rocha, Tiago Sutili, Sandro M. Rossi, Cristiano M. Gallep, Evandro Conforti: “Penalty-Free Semiconductor Optical Amplifier Wavelength Conversion of 32-GBd 4-QAM Optical Carriers”, International Optics and Photonics Conference, SBFoton IOPC, pp. 1-4, Sao Paulo, Brazil, 2019. ieeexplore.ieee.org

[r3] citation for [c4]: ref. [3] in D.Vigneswaran, M.S.Mani Rajan, Bipul Biswas, Kawsar Ahmed: “Exploring next generation of IOT devices compatible few mode assisting ring core elliptical cladding optical fiber”, Springer, Wireless Networks, Oct. 2019, Springer

[r4] citation for [j1]: ref.[1] in Zhukuan Hu, Cuimei Tan, Zhenzhen Song, Zhengjun Liu: “A coherent diffraction imaging by using an iterative phase retrieval with multiple patterns at several directions”, Optical and Quantum Electronics, accepted Dec. 2019, Vol.52 No.29, 2020, Springer

[r5] citation for [j2]: ref. [13] in Mohammad Syuhaimi Ab-Rahman, Abdulhameed Almabrok Swedan: “Quadruple multi-wavelength conversion for access network scalability based on cross-phase modulation in an SOA-MZI”, De Gruyter Open, Open Physics, Vol.15, No.1, pp. 1077–1085, 2017.

[r6] citation for [j1]: ref. [3] in D.Vigneswaran, M.S.Mani Rajan, Bipul Biswas, Kawsar Ahmed: “Exploring next generation of IOT devices compatible few mode assisting ring core elliptical cladding optical fiber”, Springer, Wireless Networks, 3 Oct. 2019, Springer

[r7] citation for [p11]: ref. [10] in Abdulhameed Almabrok Swedan, Mohammad Syuhaimi Ab-Rahman: “Multi-wavelength Conversion for 10G Passive Optical Network Capacity Upgrade Based on Cross-Phase Modulation in Semiconductor Optical Amplifier”, 8th International Conference on Intelligent Systems, Modelling and Simulation, ISMS’2018, pp.136-141, 8-10 May 2018, ieeexplore.ieee.org

5. Acknowledgement

- The author acknowledges the Open access funding provided by Budapest University of Technology and Economics (BME).
- The author acknowledges the COST Project CA16220 EUIMWP for helping her research.
- The author acknowledges Andreas Stöhr and Matthias Steeg at University of Duisburg-Germany, for the promoting consultations.
- The author acknowledges Surinder Singh from Department of ECE, Sant Longowal, Institute of Engineering and Technology, Longowal, Sangrur, Punjab, India.
- The author acknowledges Leila, Graini from University 8 May 1954 Guelma, Algeria.

6. Acronyms

3G..third generation
4G..fourth generation
5G.. fifth generation
BME.. Budapest University of Technology and Economics
HVT .... Department of Broadband Info communications and Electromagnetic Theory
FWM...Four Wave Mixing
EDFA ....Erbium Doped Amplifier
GVD...Group Velocity Dispersion
MIMO ....Multiple inputs multiple outputs
PMD...Polarisation mode dispersion
Pol-Mux ....Polarisation multiplexing
PBC... Polarisation beam combiner
PBS .... Polarisation beam splitter
PC...Polarisation controller
RoF..Radio over fiber
S .... Single Mode Fiber
SPM .... Self phase modulation
WDM ....Wavelength division multiplexing
XPM...Cross (X) Phase Modulation